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Harnessing Virtuality in the Real World
A transversal approach

DOCTORAL THESIS

Hildegardo José Quintal Noronha

DOCTORATE IN INFORMATICS ENGINEERING
SPECIALTY IN HUMAN-COMPUTER INTERACTION

UNIVERSIDADE da MADEIRA
A Nossa Universidade
www.uma.pt

June | 2021

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ORIENTATION
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Dedicated to my parents, Ana Quintal and Francisco Noronha, that have been supporting all of my work and endeavors for all these years, no questions asked.
Dedicated to the love of my life, Elsa Ferreira, that kept supporting me in these hard and chaotic times that come with writing a PhD thesis.
Dedicated to my supervisor, Pedro Campos, for believing in me and enduring a longer-than-normal PhD thesis.

"*You can use logic to justify almost anything.*
That's its power. And its flaw."
Captain Kathryn Janeway A.K.A. "Red"

Acknowledgments

I would like to take a few pages to list all the people that helped me write this thesis, in one way or another: my supervisor, my fellow researchers, people that gave other kind of support (e.g.: technical), the institutions and projects that financed and provided materials and equipment and a place to conduct my research, my family and all the others that, even tough they are not listed here, contributed to this thesis.

Supervisor

- Prof. Pedro Filipe Pereira Campos

Fellow Researchers

- Pedro Campos
- Marko Radeta
- Joaquim Jorge
- Bruno Araujo
- Luciano Soares
- Alberto Raposo
- Daniel Mendes
- Mario Sousa
- Alfredo Ferreira
- Duarte Gouveia
- Miguel Ribeiro
- Dinarte Vasconcelos
- Athanasios Vourvopoulos
- Ricardo Sol
- Nuno Nunes

Support

- Jorge Lopes
- Pedro França
- Luis Brito
- Elsa Ferreira
- Francisco Noronha
- Louis Rodrigues
- António Ramos
- Miguel Andrade
- Vitor Aguiar
- Victor Azevedo

Institutions

- University of Madeira
- Madeira Interactive Technologies Institute
- Critical Technical Practice Lab

Projects

- CEDAR[1]
- LARGESCALE[2]
- SUAVE & ETC[3]
- Estágios de Verão[4]

Family

- Ana Quintal
- Francisco Noronha
- Elsa Ferreira

---

[1] Project financed by Fundação para a Ciência e Tecnologia (FCT) - PTDC/EIA-EIA/116070/2009

[2] Project financed by Fundação para a Ciência e a Tecnologia (FCT) - Portuguese National Funds (PIDDAC) - Project Id #32474

[3] This research was partially funded by IDERAM through grants no. M1420-01-0247-FEDER-000019 and M1420-01-0247-FEDER-000038

[4] Granted by Governo Regional da Madeira - Secretaria Regional de Educação, Ciência e Tecnologia - Direção Regional de Juventude

Abstract

This thesis explores a range of Virtual Reality-related technologies in order to solve problems and expand the State-of-the-Art in the fields of Remote Collaboration, Virtual Reality, and Ocean Awareness. It also explores and harnesses the power of supporting technologies, mostly, the Internet-of-Things.

The line that separates our lives from Virtuality is becoming more and more blurred. With the rapid expansion of Virtual Reality, new problems arise, both from a technical and theoretical point-of-view. This thesis explores Virtual Reality from a low-level, ”cold metal” side - such as tracking - and a high-level, ”warm feelings” side - such as emotions. With Virtuality in mind, this thesis tries to improve Remote Collaboration based on a real-world problem of working engineers that need to cooperate in real-time engineering endeavors while not being present in the same physical space. It explores Gamification and a mix of Augmented and Virtual Reality to improve the experience quality of remote working. Finally, this thesis takes an approach to Ocean Awareness with the help of holography, green building, and the Internet-of-Things in order to build public displays that rely on data that is collected from the marine fauna, transport it, and display it in near-real-time.

This thesis also presents and discusses a set of lessons learned during these experiments and outlines a set of design recommendations for these contexts. It has a direct impact on the industries that depend on remote collaboration as well as industries that need novel ways to persuade users such as ocean awareness and human well-being and improves the State-of-the-Art in Virtual Reality.

Keywords: Virtual Reality, Remote Collaboration, Ocean Awareness, Internet-of-Things

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Chapter 1

Introduction

This thesis researches and tries to improve the current State-of-the-Art in areas close to Gamification, Virtual Reality, and Augmented Reality while taking advantage of other not-so-related technologies like the Internet-of-Things. There are three main areas that are explored in this thesis:

1. The issues related to Remote Collaboration and the people that need to work in remote locations, yet, together.
2. The awareness of the oceans and their issues, with a heavy focus on the usage of the Internet-of-Things technology. This also ends up providing some help to marine biologists.
3. Issues related, directly, to Virtual Reality. The research in this area ranges from low-level, more ”metal” issues, to high-level, more ”humane” issues.

1.1 Framing

This thesis was conducted under two research projects - CEDAR and Largescale - and research conducted outside of any project. Each project, and the project-independent research, is introduced in this section.

1.1.1 The CEDAR project

The first research project, CEDAR - an acronym for Collaborative Engineering Design And Review - was a multi-located project (M-ITI - Madeira, Portugal; IST - Lisbon, Portugal; and Tecgraf-PUC - Rio, Brazil). Its research was focused on remote collaboration using technologies related to tablets, power-walls, and augmented/virtual reality.

1.1.2 The LARGESCALE project

The second research project, LARGESCALE - an acronym for Location-based Augmented Reality Gadgets and Environment-friendly Sightseeing of Cultural Attractions for Locals and Excursionists - was based at M-ITI, in Madeira, Portugal. It was a research project concerned with improving and applying greener technology to the awareness and conservation of the oceans. It had a high focus on the Internet-of-Things but also studied awareness and green building of displays to increase said awareness.

1.1.3 Project-Independent Research

The research on this thesis were three studies conducted outside of any research project. It includes the study of emotions and relaxation using Virtual Reality and the study of arm-tracking as well as eye-tracking.

1.2 Motivation

With Virtual Reality always in mind, this thesis explores a range of topics that harness virtuality in different fields and contexts:

1. Remote Collaboration with main subtopics in navigation, communication, cooperation, annotation;
2. Ocean awareness and improvement of biologists' jobs with main subtopics in Internet-of-Things, sustainable and alternative public displays;
3. Pure Virtual Reality with main subtopics in arm and eye-tracking and emotions.

With such different subjects, the following subsections go deeper into each one of them.

1.2.1 Remote Collaboration

With the improvement of technology, in an ever more global world, remote work is on the rise. There is a growing need for professionals to share ideas, diagrams, and models with the ability to visualize, navigate and modify those in real-time and collaboratively. Gamification and a mix of Augmented and Virtual Reality can be used to improve remote working, especially when working collaboratively. Creating a way to allow people in distant places of the planet to interact and work as if they are in the same place, face-to-face could highly improve their work.

1.2.2 Ocean's Awareness and the Internet-of-Things

The oceans are one of humanity's greatest assets, and of life on Earth as a whole. With industrialization in the fast gear, pollution is a major issue. We could use new technology, and improve current technology, in order to raise awareness of problems related to the oceans and educate people about marine life. We could use tags on fauna, sensors on buoys while harnessing the power of the, relatively recent, Internet-of-Things to transport all of this information. It could help the capturing and displaying of information in real/near-real-time for both biologists and the general population with good consequences in terms of both ocean research and awareness.

1.2.3 Virtual Reality

In an age where the virtual side of our lives keeps getting increasingly important and where reality seems to be getting away from us, Virtual Reality is a very important topic. There are some subtopics of interest, ranging from low-level (such as tracking) to high-level (such as emotions), that need improvement and are explored in this thesis. The low-level subtopics are straightforward, mostly technical issues, but the high-level ones tend to get complex and, oftentimes, subjective, especially when we try to connect technology and emotions.

1.3 Problem Statement

There is a multitude of problems in the areas that this thesis touches. The following main problems were chosen:

1. How can we improve Remote Collaboration through the usage of electronic tools?
2. How can we improve Ocean Awareness?
3. Can Virtual Reality improve our Quality of Life, beyond gaming and working?
4. Does the Sample-Rate affect arm tracking?
5. Can Eye-Trackers be used as pointing device?

During the studies, each problem split into other sub-problems. More can be read in the relevant chapters, namely, in chapters 4, 5 and 6.

1.4 Hypotheses description

This thesis explores several studies, each one of them with one or more hypotheses. Here are the most important and relevant hypotheses for the thesis as a whole.

1.4.1 The CEDAR project

Related to the studies conducted in the CEDAR project, this thesis hypothesizes that:

1. Navigating and analyzing by directly pointing the tablet as a camera is faster, more intuitive and more comfortable than using a joystick.
2. Several tools can be used to improve remote collaboration, namely, video-conference, viewport sharing, avatars and camera freeze for local sharing as well as a centralized meeting leader with an overview.

1.4.2 The LARGESCALE project

Related to the studies conducted in the LARGESCALE project, this thesis hypothesizes that:

1. We can design a low cost tag that can transmit data from marine life to presentations in real/near-real-time and this creates a sense proximity between the audience and the ocean.
2. We can create a power-autonomous network that can transmit the above-mentioned data to the presentations.
3. We can create presentations that can create awareness to the oceans.
4. The LoRa technology can be used to support the previous hypothesis.
5. The LoRa technology can be used as a low power geolocator.

1.4.3 Project-Independent Research

In the remaining research, this thesis hypothesizes that:

1. Using eye-tracking directly may increase user frustration.
2. The sample-rate in arm-tracking affects user performance and comfort.
3. Virtual Reality can have a strong effect on people's ”good” emotions.
4. Virtual Reality can be used to relax people.
5. Virtual Reality has an effect in the circadian cycle.

1.5 Impact

This thesis encompasses different approaches and bring different advances in Virtual Reality, Remote Collaboration, Internet-of-Things, and Ocean Awareness, applying it to areas with significant impact. Concretely, it can be argued that the thesis impacts three main areas: (i) it improves remote collaboration for human work where teams of engineers are geographically distributed; (ii) it studies new Virtual Reality techniques for improving well-being, raising, also, new knowledge on more technical Virtual Reality issues, such as lowering the sample rate of arm-tracking systems while keeping task performance and user comfort; and (iii) using Internet-of-Things related technologies, holography and other minor constructs to bring greater awareness about ocean conservation problems.

1.5.1 Remote Collaboration

In the area of remote collaboration, this thesis presents the results from the CEDAR project, a project where this thesis contributed in the industry as well as in high-impact topics, namely, how to obtain better navigation in complex Virtual Reality 3D models, how to better manipulate CAD engineering models collaboratively and remotely, between other minor contributions. This had an obvious significant impact in the industry. Concretely, these techniques were applied in the real world of Petrobrás, a Brazilian oil company which had the complex problem of dealing with how remotely distributed teams of oil engineers could work together. Those engineers can be distributed between the Headquarters and several remote oil platforms. Dealing with this kind of remote collaboration was one of this thesis focus.

1.5.2 Ocean Awareness

Another area of impact of this thesis is related to the ocean preservation through increased awareness. This was achieved thanks to the development of a tag prototype for tracking marine fauna, combined with a LoRa network to deliver information from the tags to event presentations. It explores LoRa's maximum range in oceanic environments and ways to geolocate the tags, using the same technology as a very low power solution. A dome with a custom holography interaction device made it possible for users to become more exposed and immersed in marine fauna, thus increasing their awareness and hopefully leading to better environmental behavior. This produces a significant impact on a very timely, relevant problem: climate change and biodiversity conservation. But this impact is more than on the State-of-the-Art since the techniques produced are being used and expanded in the island by marine biologists and by tourists.

1.5.3 Virtual Reality

Finally, this thesis has an impact on the benefits to the well-being of people by using Virtual Reality. The ability to use Virtual Reality to relax people, as substitute to nature was studied during this thesis and some interesting findings spawned from it, including the fact that Virtual Nature does have a strong effect in relaxing people and that timing/light in Virtual Reality may have an effect in our circadian rhythm. Those findings are especially important during the times we go through - the Covid times - where people become very isolated and where alternatives to Nature exposure needs to be found. Further studies may point that Virtual Reality could be used as a cheap and/or quick alternative to vacations in order to relax and distress people, especially when those vacations are either impossible at the moment or due to its price. Further studies could focus on the social component of Virtual Reality to expand on the current findings.

1.5.4 Possible Cross-Area Expansions

The findings and impacts are not specialized enough to restrict it to one area. It could be expanded to affect other areas.

The findings in Remote Collaboration can be used to improve Ocean Awareness. For instance, by using a similar system where users can navigate, explore and discuss ocean issues remotely. This could be further expanded with by taking the advantage of the strong effects found in Virtual Reality to increase the Awareness effects. And this system can also be integrated to take advantage of the implemented LoRa Network and Tags.

Remote Collaboration could also take advantage of the current generation of Virtual Reality hardware to further improve itself. The tablets could become virtual or even stay physical (in order to give physical feedback) while mirroring into and from the Virtual Reality environment.

The LoRa findings, specially the Tags and the Network can also be applied in any other situation where remote monitoring (and simple acting) is required, giving it a low-cost solution (be it the explored Oil Industry or any other industry or similar situation).

1.6 Thesis Roadmap

1.6.1 Introduction

This thesis starts with a Background where it tries to introduce the reader to the topics discussed here. It, naturally, follows with a State-of-the-Art, where the reader is exposed to the research and technology that either contributed or is relevant for the rest of the thesis. It is followed by three chapters - described in the following paragraphs - that unveils all the research that was done during this thesis. Everything is, finally, closed up in the Conclusion. At the end of this thesis, a list of Publications that came from this thesis is listed.

Most of the research was done under two Research Projects (CEDAR and LARGESCALE). The other three studies were conducted as outside of any project. Taking this into account, the thesis separated the research intro three corresponding chapters (chapters 4, 5 and 6). The research done in this thesis spans on a plan that ranges from Reality to Virtuality in one axis and Emotion to Reason on the other. You can find where each research falls into this plane on figure 1.1.

1.6.2 The CEDAR project

Chapter 4 includes all the research done under the CEDAR project. Its research was focused on remote collaboration using technologies related to tablets, power-walls, and augmented/virtual reality. Following, there is a brief description of each of the studies conducted under the CEDAR project.

1.6.2.1 A Mobile System for Collaborative Design and Review of Large Scale Virtual Reality Models

Several tools and research prototypes have been developed with the goal of improving the visualization, manipulation, design, and review of 3D virtual reality models. However, most of the interactive technologies deployed in real-world engineering contexts are still difficult to use. This study presents a novel virtual reality system specifically designed to support the needs of engineering teams working at oil platforms. The system is based on multitouch and accelerometer inputs and was designed and evaluated

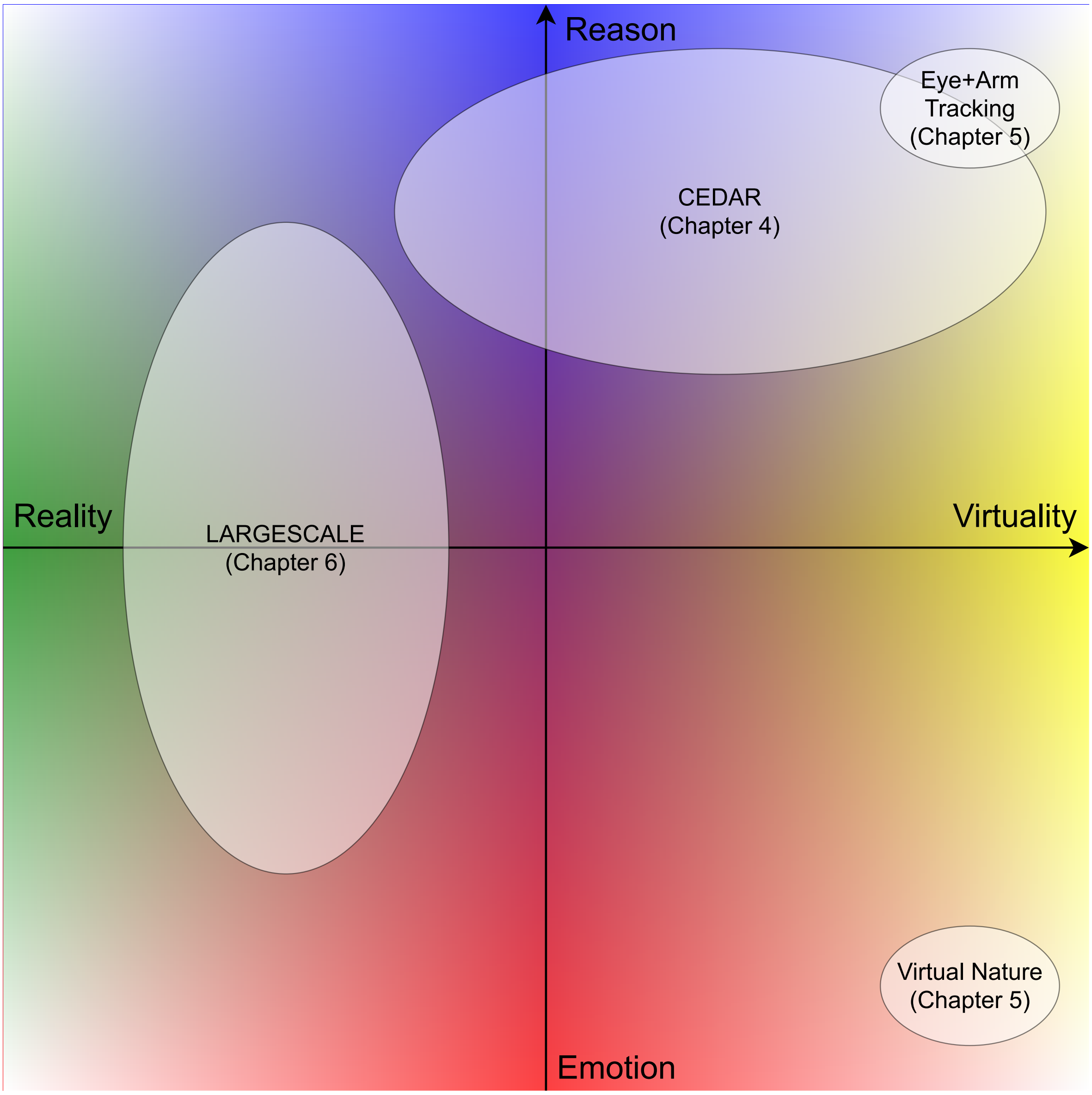

Figure 1.1: Distribution of the thesis research along the Reason/Emotion Vs. Virtuality/Reality plan

in close cooperation with researchers and engineers of a large oil industry company. The system allows the navigation, reviewing, and annotation of 3D Computer-Aided Design models in a mobile, collaborative context.

1.6.2.2 Designing a Mobile Collaborative System for Navigating and Reviewing Oil Industry CAD Models

In this study, we describe an industrial experience with the creation of a new product for collaboratively navigating and reviewing 3D engineering models, applied to the oil industry. Together with professional oil industry engineers from a large oil company, a team of HCI researchers performed task analysis and storyboards, designed, implemented, and qualitatively evaluated a prototype that combines the power of mobility brought by tablets with new navigation modes that employ every sensor present in the tablet to deliver a better experience. The system was the target of a qualitative assessment made by architects and oil industry engineering experts. Lessons learned are valuable, both in terms of performance and experience design, issues that necessarily arise when creating new collaborative virtual reality systems.

1.6.2.3 Work Analysis Methods in Practice: the Context of Collaborative Review of CAD Models

Human work interaction design is an emerging discipline that aims to encourage empirical studies and conceptualizations of the interaction among humans, their variegated social contexts, and the technology they use both within and across these contexts. In this study, we present a virtual reality system for visualization, navigation, and reviewing of 3D CAD models within the oil industry domain. This system combines a large screen interaction environment with remote mobile devices, thus allowing engineers in the field and teams in a control center to work in collaboration. To navigate through models the system uses the mobile device's camera and inertial sensors and takes advantage of recent natural interaction techniques on large screen environments. We describe and elaborate on the usage of different work analysis methods in this complex, real-world work domain. The analysis is based on (i) input from experts in the oil platform engineering field, (ii) previous and related work, and (iii) application of different methods considering the recent advances in technology. We conclude that hierarchical task analysis was not effective in obtaining a clear, common vision about the work domain. Storyboarding was the most useful technique as it promoted the discovery of novelty factors that differentiate the solution, while simultaneously supporting the human work at offshore engineering design and review sessions.

1.6.2.4 Resources Conflicts in Collaboration - From the physical world to the tablet world

Collaboration and coordination are crucial requirements of any Engineering workflow. Still, many engineering tools lack good support, if any at all, for collaboration between team members, especially if the collaboration has to be done remotely. In this position study, we propose a prototype and a study to allows us to learn how people collaborate to achieve a common goal. This prototype has two persons solving a puzzle, on two tablets, with software specially crafted to induce resource conflicts. After we get sound results, we intend to use this knowledge to build another, more engineer-centered, prototype to advance collaboration in this field.

1.6.2.5 Collaborative 3D Visualization on Large Screen Displays

Large Scale Displays, besides their visualization capabilities, can provide a great sense of immersion to a geographically distributed group of people engaging in collaborative work. This study presents a system that uses remotely located wall-sized displays, to offer immersive, interactive collaborative visualization and review of 3D CAD models for engineering applications.

1.6.2.6 A Multimodal Tablet-Based Interface for Designing and Reviewing 3D Engineering Models

The usage of multimodal user interfaces has revolutionized many different activities. However, most of the interactive technologies deployed in real-world engineering contexts are still difficult to use, especially when engineering teams need to collaboratively visualize and review large scale 3D CAD (Computer-Aided Design) models. This is the case of the oil platform industry, which necessarily involves the review and manipulation of large CAD models. In this study, we present a novel solution, based on multitouch and accelerometer input, which was designed and evaluated in close cooperation with researchers and engineers of a large oil industry company. We evaluated two different conditions: using multitouch-only input and using multitouch coupled with accelerometer-based input. Statistical analysis of quantitative data suggests that the second condition is faster and less error-prone than simply using multitouch-only input.

Additionally, qualitative data showed that users perceive the multitouch-only interface as being more accurate, but more difficult to understand and use.

1.6.2.7 Collaborative User Interfaces to Support the Oil Industry Engineering Activities

The oil industry plays a significant role in the world's economy. More importantly, it provides a set of new challenges for computing engineers, not only due to the necessity of using computing resources efficiently but especially because there is a strong need for more usable systems that can promote collaborative work. In this study, we present the design of an innovative system that supports collaborative engineering activities, which are conducted both remotely and co-located by teams of oil industry engineers. The multiple dimensions and configurations of the system are described, along with the architecture, user interfaces, and interaction techniques. What makes our system unique is the combination of these techniques and devices in a flexible approach. Also, it demonstrates the real, industrial use of digital computing systems in a cognitively intense application domain. Several evaluations have been conducted, both in the lab and in the industry field itself. Results are encouraging and are useful for designers who are interested in using computers to support industrial engineering work.

1.6.3 Project-Independent Research

Chapter 5 compiles the research conducted independently. It includes the studies of emotions and relaxation using Virtual Reality and the study of arm-tracking as well as eye-tracking. Those three studies are shortly described below.

1.6.3.1 Comparing the Levels of Frustration between an Eye-Tracker and a Mouse: A Pilot Study

This study tries to identify increases in user frustration when using Eye-Tracking devices as compared to common interfacing devices like a standard mouse. For this, we used an electroencephalograph (EEG) to measure frustration levels while users navigated within a maze using each of the referred devices. Results from the analysis performed on the EEG data indicate that Eye-tracking has the same amount of frustration as a standard mouse for common mouse tracking tasks. In addition, a correlation between the users' reported frustration and the extracted EEG data could not be found rendering the above result virtually invalid. The users' self-reported frustration lends support to our hypothesis but it is still not statistically significant and hence does not confirm the hypothesis.

1.6.3.2 How much Sample Rate is actually needed? - Arm-Tracking in Virtual Reality

There are plenty of studies dealing with the delays and other relations between head movements and visual response on Virtual Reality setups using head-mounted displays. Most of those studies also present some consequences of deviating from those values. Yet, the rest of the body remains relatively unmapped. In this study, we present the data found during our research about vision-arm coordination. This data can be used to help build better and more efficient human-computer interfaces, especially those that rely on a virtual avatar with a body and have resource restrictions like battery or bandwidth. We tested body tracking Sample Rates ranging from 15 Hz up to 120 Hz and found out no significant user performance differences. We did, however, find that a small percentage of users is, indeed, capable of noticing the changes in Sample Rate.

1.6.3.3 The Impact of Virtual Reality Nature Environments on Calmness, Arousal, and Energy: a Multi-Method Study

Virtual Reality is the current media's epitome of Immersiveness, Presence, and Suspension of Disbelief. Both research and gaming industry communities have been building on this in order to exhaustively research and explore feelings of high adrenaline, scariness, panic, and other visceral and instinctive feelings. We take the opposite approach and try to prove that Virtual Reality can also be used to induce feelings of relaxation and soothingness effectively and strongly. Therefore, it can improve the mental health of people who cannot be exposed to situations that induce said feelings. In our experiments, we prove that Virtual Reality can be used to induce a strong sense of Calmness and to reduce the sense of Arousal and Energy, with a high degree of significance, and with short-duration exposures. We also found that Virtual Reality can be used to aid the circadian cycle's regulation by exposing the subjects to a virtual sunset.

1.6.4 The LARGESCALE project

Chapter 6 presents research that tries to improve and apply greener technology to the awareness and conservation of the oceans. It has a high focus on the Internet-of-Things, but it also studied green building of displays and solutions to increase said awareness. The studies conducted under this project are explained below.

1.6.4.1 LoRaquatica: Studying range and location estimation using LoRa and IoT in aquatic sensing

While ubiquitous computing remains vastly applied in urban environments, their applications in ocean environments remain scarce due to the limitations in range and cost of current radio technology. This hinders environmental telemetry in the oceans and other remote areas. In this study, we explore the usage of IoT and Long Range Radio Communication (LoRa) in ocean environments. We study the maximum distance for LoRa and a potential location estimation based on the same technology using the passive RSSI analysis. Using three coastal-based nodes and a node mounted on a sea vessel, we report a maximum range of 83.6 km. We also achieved a location error within a radius of 3.4 km (4% of maximum distance) in the sea. These results support marine biologist expeditions, allowing them to use low-cost, long-lasting, and easy to deploy solutions for tracking marine objects and species in the open ocean, providing the data in near-real-time. We discuss the findings from used models, outlining limitations, and providing a scenario for future ubiquitous IoT applications for tracking sea objects.

1.6.4.2 AHAB'S GHOST: Improving Awareness about Whales using Holography and a Low-cost, Interactive Geodesic Dome

From Moby Dick to Free Willy, whales hold an evolving iconic value in our modern society, from hunting times a thousand years ago, until almost extinction. In this study, we present the design and initial evaluation of an intervention geared towards raising awareness about these animals' role in the ocean ecosystem. We provide a novel interactive holographic experience, exploring an inter-aquatic setting, where participants can interact with whale holograms and learn about their habits and impact on the ocean's ecosystem. The contributions are: (i) an apparatus for interactive exploration of underwater species, depicting the lifestyles and less-known facts of their behavior and habitat; (ii) holography as low-cost, sustainable, reusable, and easily reproducible by other designers of interactive systems; (iii) baseline for user experience, usability, emotional state, ecological perception and test of interaction design in communicating the facts about whales.

1.6.4.3 TRITON Tracker for Real-time Interactive Telemetry in Opportunistic Nautical-activities

While typical trackers for assessing marine biodiversity remain at a significantly high cost, ubiquitous computing and HCI remain vastly unexplored in the aquatic setting. In this study, we present the TRITON, a low-cost tracker, based on the Internet-of-Things (IoT) and Long-Range (LoRa) protocol, used for obtaining real-time telemetry in an aquatic setting. We describe the design of the interactive, mobile, wearable, and ubiquitous apparatus as a real-time interface to remote distant aquatic species. We study the robustness of the trackers, as well as added values of such interfaces, capable to retrieve and depict the remotely sensed data in real-time. We discuss the potential of such devices in pro-environmental engagement, supported by the feedback of marine biologists and local tourists.

Chapter 2

Background

In this chapter, several key concepts are introduced in a light manner. These and other aspects are afterwards expanded in the State-of-the-Art and their relevant chapters, namely, 4, 5 and 6.

2.1 Remote Collaboration

Collaboration is arguably one of the most important pillars of any society. Through collaboration, we can tackle bigger problems than we ever could if working alone, and we can take advantage of each of our expertise while minimizing our pitfalls. This also makes us move into specialization where more advanced and complex problems can get into the realm of possibility. A step further can be taken with the aid of technology allowing us to achieve collaboration between people that are not in the same geographical space - getting us to the concept of Remote Collaboration. In remote collaboration, we take advantage of electronic tools (such as computers, microphones, cameras, speakers, and special software) and the Internet to try to effectively merge multiple non-collocated workspaces into one. The workspaces can literally be on the other side of the globe, allowing persons and teams that would usually not work together to do it and in real-time. The tools used in remote collaboration can be specialized to the tasks in hand (usually custom-made - like the ones explored in chapter 4 - but there are commercially available tools - like remote surgery and excavation/heavy machinery operation or they can be general tools (such as video-chats, word processors and spreadsheet, such as, Google Docs[1] and Microsoft Office online[2]). Remote collaboration can take advantage of simple written text and go all the way to full body immersion and presence using Virtual Reality (VRChat[3] is an example of such a tool that, even though it is not targeted to be used as an industrial tool, any user can quickly and freely test it to get an understanding of the concept). All of the traditional tools can actually be used in Virtual Reality (by the usage of tools such as VRDesktop[4]), improving the capabilities of remote collaboration. Self-representation can also be important and can range from a simple colored line in a collaborative text editor to a full body, realistic avatar in Virtual Reality (check Figure 4.3 for a not-so-realistic example or VRChat for a mix of realist and cartoonish example). This self-representation helps to convey non-verbal information (gestures, facial expressions, and many more) that is usually passed on when working face-to-face but is lost with remote tools. The information can be what the user is looking at, is working at, will do next, in a multitude of options, and will speed up the work being done while reducing errors due to ambiguity or miss-interpretation of other communication channels (like saying ”left” and pointing ”right”).

2.2 Virtual Reality

The human imagination has always been a valuable asset and with it, many stories and many worlds have been built. History is filled with media through which our imagination is transmitted to others and down the times. We have also always been looking for better and more realistic media on which to create such worlds. We started with simple drawings in rocks, then the written word came (which has been extremely valuable until today), then we evolved into photography, film, and animation. But all of these media had one thing lacking: interaction. And gaming comes in to fill this missing component. Gaming allows a type of interaction and storytelling that takes advantage of that interaction to create richer and more interesting stories. With the increase of computational power and the lowering of costs of owning a personal computer, gaming got a new home. Since then, millions of computer games have been used to tell millions

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[1] https://docs.google.com

[2] https://www.office.com

[3] https://vrchat.com

[4] https://www.vrdesktop.net

of stories. However, even though gaming on a computer allowed for interaction, it still lacked realism. A couple of special games, called Wolfenstein 3D and Doom marked the passage into three-dimensional games - a major breakthrough! And a few years later, another game named Half-Life marked the passage into long story-heavy 3D and realistic games (realistic for the time it was developed). What is even more important with the Half-Life game is that it triggered the Graphics-Card market. With this piece of hardware, we have been getting more and more realistic games throughout the years. But one can only get so much realism using flat two-dimensional screens. And this is where Virtual Reality comes into play - it allows for a true depth-filled three-dimensional visualization and a plethora of other features that heavily improve on top of the screen technology. Virtual Reality is the next step in our quest for reality in our story-telling and in our media. It was only possible because the technology matured enough for us to have dense enough screens supported by powerful enough hardware - and we are actually not quite there yet. On the other hand, sound quality has been steadily improving. With the usage of some kind of 3D surround sound (either by the usage of speakers or by the usage of virtual surround headphones, the latter which, can take into account the head position to adjust the sound origin), one can add another layer to the improvement of Virtual Reality. Recent advances in body tracking, be it by the usage of cameras or by the usage of trackers have allowed for commercially available tracking to be present in Virtual Reality. Those tracking systems can range from full-body tracking (like the Microsoft Kinect[5]) to the most common hand tracking (with some systems having hand tracking, like the Valve Index's Controllers[6]. The trackers from HTC Vive[7] and the Valve Index are capable of sub-millimeter tracking allowing the user a very natural interaction with the virtual environments.

Virtual Reality has been gaining heavy traction in the last few years[8] and it is also expanding from the entertainment industry into other industries like training, military, remote operations (like surgery and excavation), remote collaboration, and even as an upgraded version of video-chat. Virtual Reality allows for a great sense of immersiveness and presence and, using the Internet, we can get all those benefits while interacting and working with from all over the world.

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[5] https://developer.microsoft.com/en-us/windows/kinect/

[6] https://www.valvesoftware.com/en/index/controllers

[7] https://www.vive.com/

[8] https://www.grandviewresearch.com/industry-analysis/virtual-reality-vr-market

2.2.1 Plausibility

Dictionary.reference.com defines Plausibility as ”having an appearance of truth or reason; (. . .); credible; believable”.

Slater [1] defines a term, very close to Plausibility, he defines Plausibility Illusion. That definition says that it is ”the illusion that the scenario being depicted is actually occurring”. The user has to believe in what he is witnessing and he has that capability, even if the scenario is not physically realistic. Yet, if this illusion is broken, it is very hard to recover. Nevertheless, the user has fully conscience that he is in a virtual world and that he can leave the virtual world any time he likes. In fact, if he does so, to do something in the real world, and then comes back to the virtual world, this breakage in the plausibility (one can not leave the real world) is simply ignored by the user and it is quickly recovered from. This perception of scenery is connected to events over which the user has no direct control but that influences him directly.

2.2.2 Immersion

Dictionary.reference.com defines Immersion as ”state of being deeply engaged or involved” and ”concentrating on one (...) subject or project to the exclusion of all others for several days or weeks”.

While immersion in virtual reality does not (currently) immerse the users for long, a metric of how immersed a user is in a virtual environment, could be, how long he is immersed in such environment, while ignoring everything around him. De la Peña et al. [2] gave a nice insight into immersion, from a virtual reality point of: ”One of the most remarkable aspects of immersive virtual environments is that people tend to respond realistically to virtual situations and events even though they know that these are not real. Even more surprisingly, this response-as-if-real (RAIR) occurs even though the level of fidelity with respect to everyday physical reality is severely reduced”.

De la Peña et al. [2] studied a less common target for immersion: immersive journalism. They argue that immersive journalism would allow a user to feel immersed in the news by means of sights and sounds of the news and, even possibly, feelings and emotions, all of this transmitted through a virtual environment using a head-mounted display or a cave. Slater et al. [3], [1] used a more hardware related approach, basically, the definition of Immersion is being based in ”a description of the characteristics of a system” (a head-mounted display is more immersive than a screen). In a paper [1], they also identify another key characteristic of immersion: that an immersive system can, in principle, fully simulate a non-immersive system but not the other way around.

2.2.3 Proprioception

Dictionary.reference.com defines Proprioception as an ”(. . .) awareness of the position of one’s body”. Proprioception is important for us to navigate and interact with our world. It informs our brain of the positions of our body allowing it to calculate the necessary movements and forces to interact with the world.

Blank et al. [4] states that proprioception is of such an importance that when someone uses a prostheses with no proprioceptive information, they have to keep the prostheses in sight for them to make correct movements. They then, ran a study providing the needed feedback and conclude that providing the proprioceptive information increases accuracy of the movements in both sighted and unsighted movements.

Boeck et al. [5] created a modeling application that, between several interaction metaphors, uses proprioception and force feedback. They propose an interaction technique that gives proprioceptive knowledge to the non-dominant hand while giving force-feedback to the other hand. They base this technique in a research [6] that connected menus to positions based on the user’s body, for easy access. They also use scaled-world manipulation, also used by Mine et al. [7], another technique that scales the world down for manipulation, reducing movement effort. Preliminary studies show that the users liked this solution but that it was difficult for them to get to the correct position in the menus. A third technique is hand-held widgets where the users have widgets attached to their hands. This technique can take advantage of the, always in mind, field of view with the user bringing the widgets into view when they need them. Mine et al. [7] also studied some gesture-based interactions based on gestures with both the hands and the head.

Rümelin et al. [8] studies the usage of large screens on vehicles and ways to avoid the gaze shift from the road to the screen based on proprioception. They compare this to a setup that uses handles and with directional touch gestures. They found out that physical handles do give a sense of orientation to the user and enable blind usage of the interface but gestures are faster.

Ruddle et al. [9] investigated the effects of walking around to improve orientation on a virtual environment by letting the users run around two virtual marketplaces of two different dimensions. They used omnidirectional treadmills as one setup, linear treadmills for walking plus a joystick to turn as another setup, rotation with the body and movement with the joystick as, yet another setup and full joystick navigation as the final setup. They found out that walking does help a great deal in orientation. Even walking in a linear treadmill and turning with a joystick shows improvements over the non-walking setups.

But the proprioception can also be damaged due to some kind of sickness or desabilitation. Bajcsy et al. [10] suggests the use of virtual reality technologies to try to rehabilitate the lost proprioception or to help relearning using other senses to compensate for that lost.

2.2.4 Presence

Dictionary.reference.com defines Presence as ”the state or fact of being present, as with others or in a place”. Sanchez-Vives et al. [11] defined presence as ”the extent to which people respond realistically within a virtual environment, where response is taken at every level from low level physiological to high level emotional and behavioral responses”.

Slater et al. [12] stated that presence is either there or not. There is no feeling of some presence. This means that one can not measure presence in a normal continuous way. They proposed the usage of a Markov Chain stochastic model of transitions between ‘present’ and ‘non-present’ states.

2.2.5 Place Illusion and Plausibility Illusion

Slater [1] defines both Place Illusion (PI) and Plausibility Illusion (Psi) as a way to avoid ambiguities from the definitions of Presence, Immersion, Plausibility and similar. He defines PI as ”the qualia of having a sensation of being in a real place”, or, simply, ”being there”. Psi is defined as an ”illusion that the scenario being depicted is actually occurring”.

Slater [1] then goes on to connect the concept of Sensorimotor Contingency (SC) to PI, with SC being defined as ”the actions that we know to carry out in order to perceive”. This concept allows him to compare PI to immersion and to state that a virtual environment can be immersive but, if it limits the SC a user can do, it will limit the PI, despite its immersiveness.

Due to the fact that PI is either present or not, Slater [1] suggests that its measure should be treated as binary. If one has to quantify its value, one can use a fuzzy estimation of it.

While PI seems to be directly connected to the actions of the user and how he perceives the world, Psi, on the other hand, seems to be more connected to events to which the user has no direct control but that, directly, affect him. Even though Slater [1] states that the user has to believe in the reality of what is happening, he also says that there is no need for it to be physically real. He makes this affirmation based on a virtual Stanley Milgram obedience experiment [13].

When PI and Psi are used in conjunction, Slater [1] states that its fusion culminates in the virtual body of the user. This virtual body can, if its movements are directly mapped and in real time, give high levels of PI. ”While PI is about how the world is perceived, the Plausibility Illusion (Psi) is about what is perceived.”, he explains.

2.3 The Internet-of-Things

The Internet-of-Things is a concept that is based on a number of physical devices interconnected and/or connected to the Internet. These devices, historically, have always been offline, even if they had some kind of digital interface or even simple connectivity (like Bluetooth). But the rise and affordability of low power microcomputers together with low power but long-range communication technologies propelled the concept of Internet-of-Things into existence. There are various competing networking technologies but the most widespread are LoRa, SigFox, and NB-IoT. Before those become common, ZigBee was the preferred communication technology (or even the simple Wi-Fi). Those technologies are usually very long range, very low power, and are either free, license-based (single pay), or requires a small monthly fee. The devices usually have sensors and/or actuators on them that allow for remote sporadic telemetry gathering and/or actions to be performed. The devices become very powerful when used in a big distributed matrix (think thousands of tiny fire-detection devices on a big remote forest). The Internet-of-Things can be used for a diverse number of objectives, such as smart home appliances, electricity, and water meters, smart watering, gates, environmental telemetry (including fire prevention and detection), trackers, alarms, and virtually anything that could benefit for long-range with sporadic small data transmission and networking. In chapter 6 we explore one of the technologies in depth - LoRa. It is an Internet-of-Things communication technology, that can be used as a cheaper alternative to current biologers (tags that are attached to animals by biologists and log several aspects of the animal and its environment).

Many studies have used LoRa or similar technologies in urban and other land environments [14] where it behaves significantly different than in the ocean environments [15, 16] which are the focus of our study. Furthermore, they only focus on small distances (under 10 km), where in this paper, we focus on large open areas. When dealing with geolocation estimation, the Lora Alliance can provide solutions using LoRa transceivers [17]. Their solutions can use two different technologies to achieve the geolocation: (i) One using the Received Signal Strength Indication (RSSI) for a coarser geolocation (1 - 2 km) and; (ii) the other which uses Time Difference of Arrival (TDoA) for a finer (20 - 200 m) geolocation.

SmartParks [9] is an example of an initiative which uses LoRaWAN geolocation technology to help with nature study and conservation. In a presentation [18] during the The Things Network (TTN) 2017 conference, Tim Van Dam [10], explained the usage of their system to cover, track and protect endangered species in natural parks. Their biggest example is the Akagera National Park with an area of 1 122 km ^{2}. Even though they managed to keep their costs relatively low, the solution is still based on large stationary gateways using additional expensive hardware. There are several projects run by SmartParks that use a similar system to protect wildlife, one of which tries to protect the black rhinos from poachers in Tanzania.

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[9] https://www.smartparks.org/

[10] https://www.wildlabs.net/users/tim-van-dam/

2.3.0.1 Data Transmission Technologies

One intrinsic characteristic of IoT is that its connectivity, even though it is made at a slow data-rate and sporadically, it is expected to be a permanent deployment with little to no maintenance. The direct consequence of this is that the battery must last years or it may have an alternative energy source (such as solar powered). This creates an issue with data retrieval since typical communication technologies are power hungry. This kind of technology is called ”Low-Power Wide-Area Network (LPWAN) and counts with several proposed and in use technologies that can be used to transmit data from the IoT devices, such as NB-IoT[11], LTE-M[12], Sigfox[13] and LoRa[14]. NB-IoT and LTE-M are both cellular-based technologies that are completely dependent on the communication companies' good will - both in terms of deployment and range as well as a monthly fee - and this fee is per company/country. Those technologies also more expensive and power hungry but do payback in terms of available bandwidth. On the other hand, Sigfox and LoRa offer more freedom. Sigfox is the midway and LoRa the other extreme from NB-IoT and LTE-M. Sigfox's network is still dependent on a company and you still pay a monthly fee but just to one company and you get world-wide coverage. It also offers the low energy consumption and long range benefits that a less complex technology offers. LoRA gets its fee from the hardware itself so it is a little bit more expensive than Sigfox to develop and deploy but it allows the developers to build their own network and deploy it without having to pay a monthly fee but, more importantly, they are not dependent on the coverage as they can deploy their own gateways anywhere. Its range is also long, similar to Sigfox. The key characteristics, such as, bandwidth and range is somewhat similar between Sigfox and LoRa (and tweakable), as shown by Mekki et al. [19]. There are also some minor pros and cons between the technologies making the choice of technology to use a case-by-case situation. A comparison between all of the refered technologies has been conducted by Lauridsen et al. [20]. They compare the coverage of each technology, in different environment setting, in an area of 7800 km^2 by measuring the percentage of lost transmissions. They conclude that cellular-based technologies perform better than the non-cellular

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[11] `https://www.3gpp.org/news-events/1785-nb_iot_complete`

[12] `https://www.3gpp.org/news-events/3gpp-news/1805-iot_r14`

[13] `https://build.sigfox.com/sigfox-device-radio-specifications`

[14] `https://lora-alliance.org/lorawan-for-developers`

based counter-parts in indoors settings - specially when deep inside. Sigfox, usually, performs, slightly better than LoRa indoors. In outdoors settings, all the technology perform similarly.

There have been several studies conducted by biologist with the aid of LPWANs. More specifically, marine biologists, can benifit more from LPWANs because most of the land is covered by one (cheap) network or another. This is not true for the oceans that are, mostly, covered by (expensive) satellite communications. Hassan et al. [21] deployed, what they call, an ”Internet of Fish”. They used a LPWAN to efficiently monitor fish, in real time, in marine farms, 2.5 km away from the shore. They recognize the benefits of LPWANs and how they can be exploited, in this case, to extract real-time telemetry data from the acoustic receivers - which would, otherwise, be offline. They consider the system to be feasible for commercial usage by citing a 90% Quality of Service on the network. On a more technical side, Gogendeau et al. [16] explored the usage of LoRa in marine environments. They explored the behaviour and interactions of several technical sides of it (spreading factor, bandwidth, coding rate) in a setting that was never studied before: the ocean. They also explore a way to geolocate 8 LoRa-based stations using the Received Signal Strength Indication (RSSI) of the system and cite a maximum usage range of the technology of 1.6 km. On previous studies we managed to achieve 83.6 km of range using the LoRa technology in a similar setting. At this distance, and at sea level, there is no line-of-sight between the antennas and the sea surface works as a mirror making it difficult to transmit to targets beyond the horizon - and impossible if the antenna is under the water-line. The transmission range is highly influenced by the environment and obstructions, such as buildings and mountains, which greatly reduce the effective range. With direct line of sight, experiments using weather balloons reached much farther and the range record keeps evolving. It started with a 702 km record. This record took two years to break with the new record set at 742 km of range, just so that it would be broken 5 hours later with a new 766 km record [22]. In contrast, studies confirm the intuitive conclusion that LoRa has a poor range in urban and mountainous environments, with many studies confirming this, such as the ones conducted by Tab et.al [23]. They achieved ranges of 9.7 km in rural environments and 4.6 km in urban environments.

2.3.0.2 System on Chip

Besides saving energy usage on the data transmission, the processor, or a system in a chip (SoC), is another target for possible savings on the IoT. There has been, for years, a constant effort to both increase processing power but also to reduce energy usage of chips. Of particular interest for the IoT are the low and ultra-low power processors. Such devices sacrifice the processing power in order to allow for less energy consumption. They also, usually, offer power-saving features that are very important in fields where the energy is very limited. A prominent player is the ESP32 SoC. An article from Last Minute Engineers [24] shows that, when all the radios are off, it consumes from 3 to 20 mA, while maintaining full processing capabilities. But it offers several levels of energy reduction, lowering the energy consumption more and more each level. The most interesting power saving mode is the Deep Sleep mode. In this mode, the main processor is shut down but a simpler ultra-low power processor stays awake. It is capable of simple tasks, including the measurement of sensors and waking up the main processor, if necessary - and the memory can still be recovered when waking up. During this time, the whole SoC consumes, and while still working, 10 μA. Its most energy efficient mode is when it enters into hibernation, where it consumes 2.5 μA and is still able of wake up by itself (either by a timer or by an interrupt).

Board	**Arduino UNO R3**	**Particle Photon**	**Pycom Lopy 4**
Weight (g)	25	5	7
Size (mm)	68.6 x 53.4	37 x 20	55 x 22
Language	C/C++	C	MicroPython / C++
Clock (MHz)	16	120	240
Power Consumption (active/sleep)	50mA/35mA	80mA/80μA	20mA/25μA
Price EUR	20	17	35

Table 2.1: Comparison of diverse microcontrollers

2.3.1 Long Range Radio Communication

Most modern electronic communication systems use either electricity or electromagnetism as a way to carry information. Those systems can either be directly connected by a conductor or the signal can be radiated through the air, vacuum or even through matter in general (buildings, cars, people) at the cost of reduced range or increased

Parameters	**Archival Tags**	**VHF**	**ARGOS PTT**	**GPS**
Power Source	Batteries	Batteries/ Solar Cell	Batteries/ Solar Cell	Batteries/ Solar Cell
Weight (g)	0.3 to 3	0.2 to 100	2 to 50/ 45 to 105	17 to 50
Lifespan	5 days to 2 years	Few days to 4 years	2 to 3 years/ 40 days to 3 years	up to 3 years
Range (km)	N/A	5 to 25	Global	Global
Location Method	GLS	Triangulation/ Homing	Doppler Effect	GPS
Positioning Accuracy	Low	Medium	High	Very High
Price USD	12 to 600	180 to 300	2900 to 4450/ 2550 to 2950	2000 to 8000

Table 2.2: Comparison of different technologies used in the ecology field

energy. Direct connections use less energy, are harder to intercept and are less susceptible to noise and interference since the medium is, usually, not shared. On the other hand, both points of the channel are fixed which constrains the mobility and the channel needs to be pre-set which increases the setup cost, specially over great distances. When mobility is a requirement the information must use a system that uses radiated electromagnetism. Several technologies exist with ranges that can go from a few meters (Infra-Red Transmitters, Bluetooth, Wi-Fi) to several thousand kilometers (Satellite), passing through those that have a range of a few kilometers (Mobile Phones, Television and Radio Broadcasts). Usually, the longer the range, the more restricted and expensive it becomes, greatly limiting its usage in usage in low cost solutions, such as in the IoT market.

One important factor of IoT is the microcontroller capable to be configured on the go. Using such kind of devices allows the reduction of high costs associated with the industrial equipment's [25]. When focusing on oceanic environments, recent study demonstrated the usage of low-cost microcontrollers for detecting and classifying the cetacean vocal calls [26]. Also, Nikita and colleges used Raspberry Pi and Arduino UNO to build a simple ROV prototype for surveillance application [27, 28]. Another microcontroller that can be used is the Photon from Particle, which is an Arduino based fully-integrated IoT platform, with Wi-Fi. This device has been successfully applied in biodiversity monitoring, and simple signal processing [29]. In our study, a LoPy4 that is a compact quadruple bearer micropython development board will be used, with

Table 2.3: Feature comparison of popular microcontrollers used in IoT

	Arduino Uno	Particle Photon	Raspberry Pi 3	LoPy4
Memory	2KB	128KB	1GB	4MB
CPU Frequency	16KHz	120MHz	4 x 1.2GHz	80-240MHz
Flash	n/a	1MB	-	8MB
Wi-Fi	n/a	Y	Y	Y
Bluetooth	n/a	n/a	Y	Y
LoRa	n/a	n/a	n/a	Y
Sigfox	n/a	n/a	n/a	Y
Power	3.3V	3.6-5.5V	5V	3.3-5.5V
Battery Charger	n/a	n/a	n/a	Y
Price EUR	20.00	16.58	36.95	59.90

the main advantage against these three microcontrollers being to allow 4 radio communication techonologies: LoRa, Sigfox, Bluetooth and Wi-Fi, and having a series of expansion boards for different purposes such as sensing, tagging and tracking. All the devices mentioned have a low-cost associated. However, in this case, LoPy4 with Pysense board has a better price/feature/energy-usage ratio, shown in table 2.3.

When understanding the long range environmental telemetry, it is known that the transmission of information using radiated electromagnetism selects its carry-wave frequency based on its necessity by taking into account its pros and cons. The longer the wave-length, the longer the effective range and penetration capability is at the cost of the available bandwidth. At the extreme range of long wave-length there is the Extremely Low Frequency (ELF) with wave-lengths of 100 000km (10^6 which are only used by the military submarines due to the enormous size of the antennas. At the other extreme which is Infrared with wave-lengths of 1 μm (10^{-6} m). As previously noted, longer wave-lengths are capable to penetrate more mass than shorter wave-lengths. The ELF, which has very long wave-lengths, can penetrate the saltwater and that is why it is used by submarines. On the other hand, common technologies, like Wi-Fi and Mobile Phones, that operate with much shorter wave-lengths, at 12.5cm (2.4 GHz) are easily blocked by walls. But, while we use technologies that use 2.4 GHz to transmit enormous amounts of data locally, ELF can transmit very far and very deep but is so slow that it takes minutes to transmit a few text characters.

A recent development has taken advantage of the analog television blackout to reuse its leftover spectrum vacuum for long-range, unlicensed communications. This phenomenon, called Low Power, Wide-Area Network (LPWAN) has two main competitors, the Sigfox and LoRa. Both work with similar frequencies (mostly around 800 and 900 MHz, depending on the territory) but use different encoding technologies, bandwidth and settings. The Sigfox is also for-profit with a royalty-based model while LoRa is an open platform. The available bandwidth is very limited (in the order of just a few hundred bits per second and with very limiting fair-usage policies) but the range can go up to a few tens of kilometers in open environments or a few kilometers in urban environments. This makes LPWAN technologies great for IoT solutions, but limited to non-real-time solutions that can wait very long to transmit small packets of information. In our study, LoRa will be used as the location of the study currently only supports it.

2.3.2 Location Estimation Techniques without satellite-assistance

In general, several techniques can be used to estimate the position of ubiquitous devices. These techniques commonly use what has become a standard of GPS. However, GPS cannot be used in some applications due to hardware, power or location (e.g. indoor) constraints.

- **Time Difference of Arrival - TDoA**

  In radio communications, it is possible to use Time Difference Of Arrival (TDoA), using from one device to various receptors, and relying on synchronized precision clocks. It can also follow the same principle using the signal strength (RSSI) instead, when precision clocks cannot be used. In given special conditions, an array of antennas can be used for the estimation of distance using the measurement of signal Angle of arrival (AoA).

  Conventional TDoA-based localization algorithms assume a perfect synchronization between the base stations and the mobile source.

  Without the synchronization process, the TDoA between the mobile source and a base station should be obtained before the calculation of the TDoA by using two-way ranging (TWR) and the other is SDS-TWR [30, 31]. Also, there have been studies reported with both indoor and outdoor experiments, trying to locate emitters with multiple receiving points [32]. These techniques however, depend on the positioning and geometry of the receivers relative to the emitter and the objects, interfering in between the line of sight. Depending on the distance that the signal can travel, this can be an effective way to locate objects, and may be used in a variety of devices that communicate through radio signals. Nevertheless, in our study, we focus on existing low-cost IoT location estimation, and we do not use this method as it requires high precision equipment [30].

- **Distance Estimation based on RSSI**
  Several research has been done by using the signal strength in the form of RSSI (Received Signal Strength Indicator) [33]. RSSI represents the relationship between a transmited and a received powers, being used to calculate the distance between a transmitter and a receiver when most of the signal propagates in a line-of-sight. Compared to the previous TDoA method, it has the disadvantage of depending on the transmitted power used, thus not being applied to all hardware, however, it has the advantage of being less costly and not requiring additional hardware. There are several techniques in estimating the distance from RSSI:

- **Bilateration**
  When the signal is only captured by 2 access points, it is possible to estimate the distances d from the signal strength captured on both receivers, and draw a radius with that distance centered on the receivers. This technique yields two possible solutions when the two range circles intersect.

- **Trilateration**
  Methods used in trilateration of devices rely on the usage of at least 3 receivers, and the interception of their radii, defined as the estimated distance that each receiver is from the emitter. This distance can be calculated from: 1) synchronized clocks between the emitter and receiver relying on accurate timestamps of emission and reception, 2) or modeled from the signal strength detected by the receiver.

- **Least Squares (LS)**
  This method is described in [34] authors in approached the location problem using multilateration with LS is to minimize the difference between estimated position $(\hat{x}_0, \hat{y}_0)$ and real position (x_0, y_0) of a node. This method usually involves some iterative searching technique such as gradient descent or Newton method.

To avoid local minimum LS must run several times with different initial starting points, which is expensive in terms of computing overhead. Moreover, it is vulnerable to location attacks since it tries to achieve a global optimum on all of the samples including those exceptional ones. A similar method is Least median square, only differing on the distance metric used, which instead of minimizing the sum of the error squares, it tries to minimize the median of the error squares.

Chapter 3

State-of-the-Art

On this chapter, all the concepts important for this thesis and its several relevant studies are explored in the literature.

3.1 Remote Collaboration

3.1.1 Applied Virtual Reality

Multimodal Virtual Reality user interfaces have revolutionized the way we work thanks to many aspects, including the combination of different input modalities [35]. The oil and gas industry is well positioned to drive the directions of future research in Virtual Reality since it is one of the biggest users of high-end hardware and software [36], [37].

Virtual environments enhance spatial perception of 3D content during design activities. Additionally, they can provide valuable insights to improve decision support with risk mitigation when used in conjunction with collaboration techniques. Following Daily et al. [38] work on virtual reality for distributed design review, different on-line collaborative CAD systems [39], [40] have been developed. However, their limited interaction capabilities prevented wide acceptance [41]. Human-to-human interaction techniques to share design ideas instantly are thus crucial to make these systems useful. We believe that technologies such as immersive visualization can significantly improve collaborative CAD by providing new possibilities to both understanding information and interacting with it.

3.1.2 Tablets and Multitouch

On the other hand, there has been some research into building virtual reality for handheld devices [42]. They take advantage of its mobility and ubiquity as well as a growing number and quality of sensors. Techniques developed for horizontal surfaces can also be applied to mobile touch devices. Boring et al. [43] proposes manipulating content displayed on a vertical display, using a mobile touch device. Nancel [44], studied uni and bi-manual interaction techniques to conclude that navigational activities, such as pan and zoom, using touch devices are both more efficient and cause less fatigue than those in mid-air.

3.1.3 Interaction, Multimodal, and Natural Interaction

Manipulation of CAD models can benefit significantly from the so-called natural interaction techniques [45]. Different navigation methods have been proposed for touch-enabled mobile devices.

Examples of multimodal user interfaces in professional work environments include real-time simulation of 3D complex phenomena, training and edutainment, telepresence and tele-robotics, and even simple business meetings [37].

Following seminal work in multimodal interfaces [35], new devices have become available to enhance interaction including multi-touch tablets combining several sensors, non-intrusive tracking solutions based on depth cameras and affordable brain computer interfaces.

There is considerable research on combining several modalities to interact with Large Screen Displays. Ni et al. [46] surveyed several interaction techniques using mid-air spacial gestures, handheld controllers or touch surfaces to navigate in 3D space. As shown by Jota et al. [47], gestures provide a hands-free solution and can be used precisely to acquire targets on the screen, while allowing mobility around the space in front of the display.

Navigation and Annotation have been revisited proposing easier design review solutions on virtual models. Both the Boom Chameleon [48] and AR-Planar [49] systems proposed a new device solution using a desktop multi-touch display on a tracked mount. While Boom Chameleon allows rotating the screen around a fixed point to observe and annotate 3D models such as using a physical moving canvas, AR-Planar proposes a more mobile setup to be used in indoor scenarios and compared it with first handled PCs. Our approach combines existing sensor based mobile devices with multi-touch navigation to propose a reliable navigation technique for on-site collaborative engineering design review tasks.

3.1.4 Computer Aided Design

Several tools and research prototypes have been developed with the goal of improving the visualization, manipulation, design and review of 3D CAD models. Giga-Walk [50] and REVIEW [51] are academic solutions for real time visualization of very large models. They use advanced techniques such as occlusion culling to achieve good performance levels. Nevertheless, they lack integration with Virtual Reality resources, such as different displays and interaction devices, while also exhibiting some difficulties when rendering complex models. Recent studies focused on the impact that CAD tools may have on creative problem solving for engineering.

Researchers, such as Robertson [52], have examined how the computational environment may influence the engineers' ability to design creatively. Surveys have shown good support for enhanced visualization and communication, circumscribed thinking – when the designer's ideas are circumscribed by the CAD tool's abilities – and for premature design fixation (premature commitment to a given design solution) [52]. Other studies went one step further and investigated how to reduce the visual cluttering through the use of auditory cues [53], an interesting approach that is currently outside of our scope, but that could be considered in the future.

The Design Review usually is conducted by several people in order to find the important points that must be developed. The traditional way, up to now, is a team of engineers looking at a blue-print and comparing with some photos. Video conference is a tool relatively well used today, but it relies on dedicated systems like those form the Polycom 1 or Tandberg 2, that are based on voice communications solutions under H.264 video codecs.

But one of the largest problems is to visualize and interact with 3D artifacts, create annotations and do some measurements in the model. 3D objects visualization and manipulation is an important resource in design review. The ability of moving, rotating and scaling objects is important for various purposes such as joining different models in a scene, viewing hidden portions of the model, planning the placement of a new piece of equipment on a plant, and simulating a maintenance or intervention operation in a process plant are also valuable tools.

Doing this visualization in a Virtual Reality solution is even more challenging, there are some coupling ways in order to integrate CAD and Virtual Reality [54], both systems needs geometry and integrated information. These systems could be connected by means of gateways from CAD to the Virtual Reality model. In this process, CAD models are converted to a format suitable for Virtual Reality. Other possibility is a common file format for both CAD and Virtual Reality models like the XMpLant [55]. CAD and Virtual Reality can also be connected by an API like the OMG CAD services interface [56], which is a CORBA-based interface standard, but the current limitation of CAD services interfaces is that it has not been widely adopted by the industry. Finally, it is possible the integration in one process, where the Virtual Reality system is integrated into the core of the CAD system [57].

The possibility to integrate additional information in 3D tools is being worked in some systems [58], [59], [60], allowing the inclusion of static and dynamic annotations. This information is very important to be managed in order to allow all the people involved in a design review to be aware of such review.

Traditional tools for design review are the walk-inside type that allows examinations by walk-throughs with a high performance on reading and displaying massive models and Division Reality [61] that is other software solution very used on the oil gas industry that allows to simulate 3D models with precise and realistic behaviors. Both of them are projected to work in a full-scale immersive environment.

Visualization technologies enhance the content knowledge within any engineering design activity. When used in conjunction with collaboration, visualization provides valuable insights for better decision support with risk mitigation. Dodd [62] has mentioned that the next big management push is the empowerment of interdisciplinary teams with collaboration tools that include remote and immersive visualization.

Li et al. [41] classified collaborative CAD tools in two main groups. The first one is related to create a seamless integration of product information from upstream design to downstream manufacturing. The second group of collaborative CAD tools, and the one we are interested in, focuses on collaboration in the domain of design, where designers can share their design results and ideas. This kind of collaborative CAD tool can be considered visualization based design systems when they provide a manner for distributed users to assist collaborative design through visualizing, annotating and inspecting design models.

A pioneer work in using Virtual Reality for distributed design review was presented by Daily et al. [38], and since then many on-line collaborative CAD systems have been developed, such as [39] and [40]. However, they have not been widely accepted due to their weaknesses in interaction performance [41]. In this kind of system, aiming at sharing design ideas instantly, human-to-human interaction is of great significance. Therefore, technologies such as immersive visualization and mobile devices, which provides new possibilities of understanding information and interacting with it, have a potential to significantly improve the area of collaborative CAD.

We focused on design review of CAD models, i.e. the process of checking the correctness and consistency of an engineering model, and performing the necessary corrections to it [63]. The application domain we chose, for reasons explained ahead, is the oil industry. In this domain, visualization techniques and multimodal user interfaces can be particularly helpful in the engineering design and review process, for instance to assess the safeness of different emergency-escape pathways in the event of an emergency occurring in the oil platform [63]. Current tools have problems dealing with models featuring a high level of details (for instance SaRaSo08), since they have to provide the user with a real time interactive visualization of the model(s). Our approach proposes the usage of mobile tablets with multi-touch input combined with motion-based input to aid these tasks. Simultaneously, it has the advantage of allowing engineers to visualize CAD models ”in the wild”, which is particularly advantageous for oil platform engineering teams.

3.1.5 Human Work Interaction Design and User Experience

Katre et al. [64] states that Human Work Interaction Design is an emerging research field within HCI that is focused on the user’s experience of tasks (procedures) and the artifact environment (constraints in the work domain). That analysis and interpretation of human work is eventually manifested in the design of novel, technology-based products, systems and applications [64].

Human Work Interaction Design (HWID) is an emerging approach that promotes a better understanding of the relationship between work-domain based empirical studies and the iterative design of prototypes and new technologies [64]. HWID's goal is to encourage empirical studies and conceptualizations of the interaction among humans, their varied social contexts and the technology they use both within and across these contexts.

To achieve this, HWID promotes the use of knowledge, concepts, methods and techniques that enable user studies to procure a better apprehension of the complex interplay between individual, social and organizational contexts and thereby a better understanding of how and why people work in the ways they do. Therefore, one of the main characteristics of HWID as an interaction design approach is to focus the analysis on the how's and why's of people's work. HWID also tries to promote a better understanding of the relationship between work-domain based empirical studies and iterative design of prototypes and new technologies. HWID's roots lie in Cognitive Work Analysis (CWA) [64], [65]. Cognitive Work Analysis (CWA) is a multidisciplinary framework for the analysis, design, and evaluation of human work developed by Rasmussen, and colleagues [65]. Its purpose is to guide the design of technology for use in the work place. CWA helps an analyst identify the activities and agents that are needed for a system to effectively fulfill its functional purpose. CWA can also be regarded as a formative process that focuses on an ever-increasing number of dynamic constraints that systems present nowadays, rather than prescriptive methods of working.

Storyboarding [66] is a common technique in HCI and design for demonstrating system interfaces and contexts of use. Despite its recognized benefits, novice designers still encounter challenges in the creation of storyboards. Many researchers have studied the benefits and disadvantages of storyboards, including Khai [66] and colleagues, who presented two formative studies designed to uncover the important elements of storyboards. According to Kevin Thorn [67], storyboard has its roots in Walt Disney's works as a way of planning his films. It evolved into today's storyboards where there is a sketch of the screen's content and a text describing it. Kevin also states that it should be used as a blueprint for a project ending up being a powerful collaborative tool for the team.

According to Jenny Preece et al. [68], Task Analysis is concerned with what people do to get things done. It is a group of techniques that, between other goals, aims to get a list of what people do, predict and evaluate the usability and performance of systems, measure learnability and system complexity. The activities required, used or believed to be necessary to achieve a goal using a particular device are, what is defined by the same authors, a ”task”. This task can be achieved using some tool, technique or skill to change the system to a desired state.

Activity-based analysis [69], in particular activity theory methods, incorporates the notions of intentionality, history, mediation, motivation, understanding, culture and community into design. In particular, it provides a framework in which the critical issue of context can be taken into account.

In hierarchical analysis [70], another work analysis method, the instructional designer breaks down a task from top to bottom, thereby, showing a hierarchical relationship amongst the tasks, and then the instruction is sequenced bottom up. Task analysis often results in a hierarchical representation of what steps it takes to perform a task for which there is a goal and for which there is some lowest-level ”action” that is performed [70].

Design review is the process of checking the correctness and consistency of an engineering project while making the necessary adjustments [63]. This procedure can avoid severe problems in the final product, since potential problems can be quickly uncovered, analyzed and resolved during the product development process. Discovering issues that otherwise would have gone unnoticed until the end of the product life-cycle. For instance, in an oil platform, it is important to assess the safeness of different emergency escape pathways access to specific parts of the installation.

3.1.6 Collaboration

Collaboration is present on the everyday life, still, it is somewhat lacking on current software [71], possibly due to the increased complexity inherent to resource conflict management. Advances are being made on several areas, as, for instance, learning [72], e-learning (such as Moodle), engineering and software development [73]. Collaboration will keep increasing due to geographically distributed teams on a ever most global job market [73].

Some collaboration tools are real-time (simulations and some engineering tools) while others are not (for instance the Moodle e-learning platform). Even when they are not real time, they can be either synchronous or asynchronous [74]. A combination of the two can be achieved, being real-time and synchronous the biggest challenge. This challenge is more so if humans are competing for resources, where collaboration becomes competition. Solutions have been found such as the usage of tokens where only the current token owner has access to a resource, partial locks that lock out only the specific resource or part of a resource that a user needs, or simply by splitting the responsibilities in a way that no user ever conflicts with another [75]. Some of the solutions found are similar to those used on hard/software resource conflicts. For instance, locking a software resource (file or database entry) is similar to locking an artefact for a human to modify.

3.1.7 Navigation

With the increase of input modalities, computational power, autonomy and network connectivity of such mobile devices, new navigation methods have been proposed. Navidget [76] presents a 2D navigation widget for 3D navigation for pen-based mobile devices using a lasso to define the point of interest and rotate around it. Multitouch based navigation interfaces such as Dabr [77], ScrutiCam [78] and Drag'n Go [79] try to propose easier navigation methods however they do not fully explore the mobility offered by existing mobile device. The Tether project [80] mimicking the moving virtual window using iPad devices, however at the cost of expensive tracking solutions which cannot be applied on outdoor scenarios.

Several alternatives to traditional desktop navigation have been proposed to ease design review tasks on virtual models. Both the Boom Chameleon [48] and AR-Planar [49] systems proposed a new device solution using a desktop size multi-touch display on a tracked mount. While Boom Chameleon allows rotating the screen around a fixed point to observe and annotate a 3D model such as using a physical moving canvas, AR-Planar proposes a more mobile setup to be used in indoor scenarios and compared it to the first handled PCs.

3.2 Virtual Reality, Feelings and Nature

3.2.1 Body Tracking and Haptics

The following paragraphs enable us to illustrate the importance of body tracking in the medical field. It also illustrates the importance of a better understanding of the intrinsic values of body tracking for each body part.

Cloete et al. [81] compared the kinematic reliability of both inertial and optical motion capture applied to clinical gait analysis. Both systems that were compared were professional, commercially available solutions and were probed at 100 Hz. They found out that the inertial motion capture had more errors than expected but found out that the problem was due to a lycra suit used and that those errors would be solved, based on a paper by Dejnabadi et al. [82], if the sensors were secured in place. On the optical side, they encountered issues with markers outside the camera view, shadows and bad marker reflections. They conclude that the reliability is comparable for lower walking speeds. They also argue that the inertial system is a lot faster to set up than the optical one. This happens because the inertial system is a lycra suit while the optical system is an 8 camera system. The same would not be true if they would compare a strap based inertial system with a 1 or 2 camera system. Cloete et al. [83] studied, a couple of years later, the same systems from a repeatability point-of-view and concluded that inertial systems give enough repeatability to be used on clinical gait analysis. They noted, though, that those systems may perform less optimal on real patients due to body characteristics affecting the sensor placement.

On the studies of the previous paragraph, they used optical tracking systems with 8 cameras. One can argue that it was to achieve a higher degree of accuracy or it may have been due to a lack of better and cheaper solutions at the time (2008 and 2010). In 2012, Wei et al. [84] proposed a motion capture method using a single depth camera and compared it with Microsoft Kinect (2012 version; the original version came out in 2010), which is also a single depth camera, and concluded that their method was more accurate.

Lorincz et al. [85] ran into a problem that could have been mitigated by the results on this paper. They ran a group of sensors on patients with some of them capturing movement through inertial sensors. Those sensors were fed by a battery and must run up to 18 hours per day. They also ran into issues with data storage and network bandwidth. The high volume of data (reported as 1200 byte/sec/node) as well as a big battery drain might come from the fact that the sensors are set at 100 Hz all the time when they could have been fine tuned to lower values while achieving a similar quality of results. The sample frequency could have been further lowered taking into account that the movements are not to be interpreted by the user in real time. The authors did throttle down the sensors when battery life was low rising the expected time of battery up to 32h, adding to the importance of more efficient sensor tuning.

Witchel et al. [86] made a comparison of four technologies applied to micro-movements. From the technologies they used, the most relevant for this paper are the 8 camera optical tracking (a Vicon) and an accelerometer mounted on the head. They found out a good correlation between both systems, except for the yaw on the accelerometer. This happens because accelerometers cannot, directly and accurately, measure yaw movements. An important find is that, even without a gyroscope, they were able to match the rotation on the head to an expensive 8 camera tracking system, proving the quality and accuracy of a (striped down, accelerometer only) inertial tracking system. Aylward et al. [87] gives us an example of implementation of inertial sensors on other fields. In this case, the paper focuses on dancing but it is also tested on baseball illustrating the potential for the tracking of high speed, high acceleration movements while maintaining accuracy.

3.2.2 Haptics

The development of haptics would, greatly, improve fields such as remote surgeries and training, prototyping, teleoperation, training in general and the entertainment industry. The most commonly available solutions are vibration and force-feedback but there are researches in textures, more realistic and general purpose force-feedback (Vs. the current specific usage on driving wheels) and solutions that try to merge with current interaction paradigms, such as the Novint's Falcon: a three-dimensional input device that gives force-feedback, also, in three-dimensions. Full-body haptic-feedbacks are, usually, achieve through the usage of exoskeletons but those, are, usually, very expensive. Another solution is a direct interactions with the brain.

Texture based haptics are one field that is continually improving over the last years.

There are ongoing research in both hardware and software. On the software side, and, as an example, Shopf et al. [88] are proposing an haptic shading framework. Mirroring this with what happened on the computer generated imagery (CGI) development, that had an enormous raise in quality, diversity and realism, when a similar framework (shaders) was developed, the haptics field may get such a development. Such tools allows people to describe and create textures (on both CGI and haptics) with ease and of high quality. On a more conservative side, Li et al. [89] propose a method of using images as a base for haptics textures. The two previous solutions, resume what makes the current CGI a success from the software point of view.

There are some solutions that try to simulate haptics without having a real haptic device. Lécuyer et al. [90] is an example of such a solution. They change the mouse pointer's acceleration depending on the texture being felt, such as would happen with the friction of a real touch. The studies that they conducted proved the solution effective on macroscopic textures – the user were able to ”feel” bumps with the technique.

Kim et al. [91] proposed an interaction technique that allows the user to feel the virtual model he is touching on a tablet surface through kinesthetic haptic feedback. For this, he built a prototype composed of three linear motors on top of which a tablet rests. Those motors raise and lower in a way that will turn the tablet on two axis giving a feel of depth. The height and orientation of the tablet is based on the position of the touch: the example given is a head model and the user can feel it touching the tablet's surface while the prototype simulates the face's surface (basically, a textureless skin). He tries a different approach from the previously developed vibration and texture feedback.

3.2.3 Natural User Interfaces

Touch-based interaction has become a very prominent kind of interaction nowadays. Virtually all mobile devices (phones and tablets) use this kind of interaction with most of them having removed all but just a few hardware keys from their design. Even if its usage becoming wide-spread was a recent development, mostly due to the growing success and price lowering of the tablet, in 1990, Sears et al. [92] had already made a study about the characteristics of the touch technology, foretelling its success. Most, if not all, the identified advantages and disadvantages still hold to this day. Some of the identified advantages, such as, ”directness”, ”speed”, ”ease of learning” and ”flexibility” as well as disadvantages, like ”arm fatigue”, are common to a full body interaction. If one uses the mobile device as a moving window to the virtual world and interacts with it through touch, one can argue that a mobile touch-based device is a cheaper and lower tech, step closer to a full body virtual reality interaction. Twelve years later and the touch interaction is such a success that there are innumerous interaction techniques. Telkenaroglu et al. [93] ran a study on several of those techniques (including some still on the proposal phase), evaluating usability, performance and error rate. They conclude by selecting the best in ”fast and precise” and ”accurate” manipulation techniques as well as the best ”navigation” techniques.

3.2.4 Eye Tracking

In 2005, Ashmore, Duchowsky and Shoemaker specified and defined four reasons why eye pointing has more problems than manual pointing [94]. The four reasons are: Eye tracker accuracy, Sensor lag, Fixation jitter, and Midas touch.

Eye tracker accuracy depends on the visual angle. The visual angle is associated with the reflection of the eye and not the actual position of the eyes when facing the screen that should be around 90◦. In less recent literature, it is possible to find references to visual angles of 3◦, however a visual angle around 0.5-1◦ is commonly accepted. This means that when looking at our 23” computer monitor with a resolution display of 1980x1080 at a viewing distance of 65 cm, the eye pointing will be limited in accuracy to around 22-44 pixels.

Sensor lag is a delay in processing the gaze position. In our system this delay is typical 0.005 seconds (200 Hz frame rates).

Fixation jitter occurs with the dwell time (or fixation time, i.e. time spent selecting through fixation) associated with eye pointing. Three types of these involuntary eye movements (micro-saccades) disturb fixation: flicks, drifts, and tremors. The biggest of these movements has a visual angle that is less than 1◦.

Midas touch is a problem defined by Jacob in 1991 that occurs because the eyes are always active making the selection task indistinct from the search task [95].

Researchers worldwide have been dealing with the above problems and trying to find ways to improve the interaction.

Mouse and Gaze Input Cascaded (MAGIC) that uses gaze to dynamically redefine the position of the cursor is one of those improvements [96]. In MAGIC after the eye redefines the cursor position the user will makes a small manual input action to select the target. MAGIC has two approaches. In the first approach, referred to as the liberal approach, the cursor moves to the top of the new target that the user looks at. The second approach, the conservative approach that, leaves the cursor at the boundaries of the target.

Salvucci and Anderson presented their intelligent gaze-added interfaces [97]. They addressed accuracy problems that we also face. In their work any target positioned where the users' eye gaze is, is a highlighted target. Then a gaze key gives the user the chance to trigger the action. The system uses a probabilistic algorithm to guess the targets the user is going to look at.

McGuffin and Balakrishnan showed that expanding targets facilitates the pointing task [98]. Their results show that working with expanding targets can be accurately modeled by Fitts' law. They have also shown that targets that expand just as the user is about to reach them can be acquired approximately as fast as targets that are always in an expanded state. They specifically found strong evidence that user performance is consistently aided by target expansion.

Miniotas and Spakov used an expansion of targets visible to the users [99]. To facilitate pointing they used dynamic target expansion for fixing the calibration of the eye tracker, basing the correction on the relative change in the gaze position after the expansion.

Ashmore and Duchowsky refined a fisheye lens to support eye pointing [94]. They hid the lens during visual search and obtained improvements in speed and accuracy. Fisheye interaction was evaluated by Fitts pointing and, a visual search. In contrast to MAGIC pointing, where the cursor was quickly moved to the vicinity of one's gaze prior to mouse movement, they directly slaved the lens to the gaze position.

EyePoint used expansions of interactive targets, and used a key for input [100]. When the key is pressed the gaze area is enlarged. When the key is released the selections are made according to where the eye gaze is. All of the above mentioned work reflect the idea that simple eye gaze interaction is not promising [96]. Quantifying this dissatisfaction by looking into frustrations levels is the goal of this work.

The merge of eye-tracking technology with EEG has only been implemented quite recently with the SMI RED-m eye tracker (SensoMotoric Instruments Co.) and the Emotiv EEG Neuro-headset for market research purposes [101]. This online analysis of emotional responses can give an insight into consumers' subconscious behavior by merging visual perception and brain response introducing a new type of marketing, neuromarketing [102].

3.2.5 Brain Interface

Brain-computer interfaces (BCI) can enable users to effectively navigate through virtual environments. Larrue et al. [103] concluded that BCI combined with visual information, eliminates intrusive devices for navigation while promoting user experiences closer to reality.

Each area of the human brain is responsible for different functions including problem solving, emotion, complex thought, movement, visual stimuli and auditory information [104]. Through the use of electroencephalography (EEG), there are different wave patterns or rhythms that are distinguished and associated to different cognitive or motor actions [105]. This kind of knowledge has been used with Brain-Computer Interfaces (BCIs) based on the pattern recognition approaches for communication and control of computers [106] ranging from brain-controlled robots, modern computer games [107], prosthetics, control systems [108] through to medical diagnostics. The mental tasks are chosen in such a way that they activate different parts of the brain. In the last few years commercial low cost EEG equipment has been introduced as an alternative game controller by various companies such as Emotiv [109], setting a milestone in user experience with brain-controlled computer games and virtual worlds [107].

Recent evaluations of the detection accuracy of such devices indicate an acceptable level of accuracy for performing mental actions [110] although for the Emotivs Affectiv Suite that is used also for this experiment, similar tests suggest that further examination is needed to verify Emotivs' ability to accurately track cognitive state [111].

3.2.6 Feelings in the Media

Older studies indicate good success in inducing a range of feelings using their current media technologies. Philippot [112] researched the capacity of film segments in, reliably and unequivocally, inducing naturally occurring emotional states on exposed subjects. They exposed the subjects to six short film segments and evaluated their responses by using three questionnaires. They found out that the films can be used to elicit emotions, in a predictable manner, in most subjects. They also found out that the Differential Emotions Scale is better at discriminating between emotional states than the Semantic Differential. Two years later, Gross et al. [113] developed a set of films to elicit eight emotional states (amusement, anger, contentment, disgust, fear, neutral, sadness, and surprise). They selected clips from over 250 films and showed it to 494 English-speaking subjects and then, based on the subjects' responses, selected 2 films for each emotional state.

3.2.7 Feelings in Virtual and Augmented Reality

An evolution into Virtual Reality was just a natural step. In 2003, Plante et al. [114] studied the possible beneficial psychological effects of doing aerobic exercise while using Virtual Reality. They concluded that Virtual Reality can enhance enjoyment, energy, while reducing tiredness, if used in such a setting. On the other hand, they discovered that Virtual Reality has the opposite effect, if used without the exercise component, by increasing tension and tiredness, and lowering the energy level. One can argue that since this is a 2003 study, the technology has evolved considerably since then and the benefits might have increased while the negative effects might have reduced or been removed altogether. Baños et al. [115] studied how the immersion affects the sense of presence by comparing Virtual Reality to both a monitor and a projection. They, later, conducted another study [116] where they expanded Mood Induction Procedures into Virtual Reality (creating a VR-MIP) and induced different moods (sadness, happiness, anxiety and relaxation) into their experiment subjects by making changes in a Virtual Environment Park. They reported a successful induction in both sadness and happiness using the VR-MIP. Felnhofer et al. [117] researched the emotional arousalness of Virtual Reality. They studied five emotions (joy, sadness, boredom, anger and anxiety) by exposing their subjects to an emotionally charged Virtual Park. They found some indications that Presence does not influence emotions in Virtual Reality.

There are also links between Presence and Emotions, in Virtual Reality, as explored by Riva et al. [118]. They explore the ability to elicit emotions in Virtual Reality, like in other medias. They also try to find a relationship between Presence, a strong characteristic in Virtual Reality, and emotions. They confirm the effectiveness of the medium in triggering Anxiety and Relaxing feelings. They found a circular interaction between Presence and Emotions where one inflates the other.

The same research trend is being expanded into Augmented Reality, as demonstrated by Mehra et al. [119] whom tried to prove the power of positive mood in the productivity of software developers through the use of Augmented Reality. They tried to improve their working environment by superimposing virtual pets and scenic features unto the real-world - their work environment.

There has been some expansion into the usage of more senses (besides vision and hearing), like demonstrated by Serrano et al. [120] who ran some experiments using Virtual Reality coupled with touch and smell stimulation in order to induce relaxation. They tested the efficacy of mood-induction procedure in a Virtual Reality (VR-MIP). A high sense of Presence was found and well as a statistical difference in relaxation. They also found no improvement while using smell but the sense of touch does improve both Presence and relaxation.

3.2.8 Virtual Reality as a therapeutical tool

Feelings in Virtual Reality have also been researched into a more therapeutically component, as demonstrated by Baus et al. [121] who reviewed an approach of running exposure therapy, specially phobias, from a Virtual Reality, which they consider to be much more expensive, to Augmented Reality, while still being effective. In Augmented Reality, Juan et al. [122] developed and tested a prototype using Augmented Reality in order to explore the treatment of acrophobia while exploring the feeling of Presence in immersive photography. They ran parallel tests using a real world staircase and in immersive photography. A System Usability Scale questionnaire was administered finding out that the sense of Presence was very high in their system but that there was a clear awareness of the Reality versus the Virtual Environment. This context was found to be useful in the treatment of acrophobia. Later, Botella et al. [123] explored the utilization of Augmented Reality in the treatment of phobias, namely, cockroach phobia. They argue that in vivo exposure is the recommended treatment. They show that Virtual Reality and Augmented Reality is an effective method of treating some of those phobias and show the advantages of using Augmented Reality as a treatment. McLay et al. [124] studied the effects of Virtual Reality PTSD treatment on Mood and Neurocognitive. They expand the results of PTSD treatment using Virtual Reality into depression and anxiety. They found significant reduction in PTSD and anxiety and significant improvement on emotional Stroop test. There was no improvement in depression nor an improvement in neuropsychologial functions. Herrero et al. [125] induced Positive Emotions through the usage of Virtual Reality in order to treat Fibromyalgia. Their experiments found no statistical relevant improvement in pain and fatigue related values. But it did show that most of the subjects showed improvements, or no change, in their mood, with only 7.5 % showing some deterioration. They indicate that Virtual Reality is an effective method of treating acute but not chronic pain. In Mental Health, Badia et al. [126] proposed an architecture that can foster emotional regulation strategies. The system can generate procedural content based on affection and was rated pleasant by the subjects.

3.2.9 Emotions in Virtual Reality

Emotional training can also be achieved by the usage of Virtual Reality, as demonstrated by Bosse et al. [127] by exploring a system where the military, the law enforcement and other high stress workers can learn to regulate their own emotions. García et al. [128] reviewed the research into how Virtual Reality can be used to treat body image disturbances. They note the lack to published controlled studies in the subject but acknowledge the great potential of Virtual Reality as a substitute for in vivo exposure.

3.2.10 The healing power of (Virtual) Nature

Nature has beneficial effects on humans. Van Praag et al. [129] studied the relaxation and well-being effects of Naturalistic environments through autonomic arousal and activation. Their study reinforced the health benefits present in exposure to natural environments. But the effects are beyond health and well-being. Bratman et al. [130] studied the effect of nature on cognitive function. They reviewed several works and proposed a system to categorize nature experiences. The beneficial effects of nature seem to cross-over to other medias. In this case, to Virtual Reality, as Browning et al. [131] found out. They researched the effect of 6 minutes 360º videos of natural settings and found out increased levels of arousal and mood. Yo et al. [132] expanded beyond nature and also explored urban environments. They found effects on both psychological and physiological values. They found out that the effects of environments in Virtual Reality map those of real life with fatigue levels and several bad feelings increasing in urban settings and decreasing in natural settings. The effects are strong enough to help people recover from stress and anxiety, as demonstrated by Yin et al. [133] in a bigger 100 subjects study. Instead of pure nature, they went with a biophilic office but the nature effect is still there.

3.2.11 Evaluating Feelings

The Multiple Affect Adjective Checklist, by Zuckerman et al. [134] and its revised version by Salkind [135] uses a list of 300 adjectives in 5 categories to evaluate common psychological traits. Osgood [136] developed a technique, named Semantic Differential, where he could compare highly subjective elements between cultures by using adjectives in a scale. Another evaluation method developed was the Differential Emotions Scale, by Izard et al. [137] where the evaluation is made on a 5 point Likert [138] scale for each of the 10 fundamental emotions. It was later expanded/improved several times, being the latter, DES-IV, by Boyle [139]. Around the year of the DES-IV improvement, Thayer et al. [140] developed a questionnaire-based test to evaluate various transitory arousal states. The test, named Activation-Deactivation Adjective Check List (AD ACL), evaluates four dimensions: Energy (General Activation), Tiredness (Deactivation-Sleep (*General Deactivation*)), Tension (High Activation (*High Preparatory-Emergency Activation / Arousal*)), and Calmness (General Deactivation (*High Activation (High Preparatory-Emergency Activation / Arousal*)). Later, the Self-Assessment Manikin (SAM) was developed by Bradley et al. [141] and manages to evaluate, in a non-verbal way, pleasure, arousal and dominance. It uses a scale of 9 pictorial elements for the subjects to self-evaluate.

3.3 The Internet-of-Things

In this IoT era, sensing and communicating is becoming inexpensive, and is a favorable occasion to explore low-cost sensing and location estimation. This opens an opportunity to obtain geotagged environment data and empower regular citizens to use these technologies, previously only available to corporations or researchers.

An experiment, conducted by [16], explored the different configurations of LoRa (spreading factor, bandwidth, coding rate) in sea environments. Trying to obtain the location of endpoints (using RSSI) which were fixed in 8 coastal locations. They claim a maximum location error of 100m at a maximum distance of 1.6km. Our study, builds upon these findings, focusing in expanding the range much further.

3.3.1 Telemetry

Biologists at the Azores project, INTERAGUA [142], [143], employ several tracking and data recovery techniques, namely satellite telemetry (ARGOS at 401.65 MHz), radio telemetry (VHF 164 and 219 MHz) and acoustic telemetry (69 and 180 kHz). Their techniques can be long (ranging form weeks to years) and short term (ranging from hours to days). The long term techniques are usually based in satellite or acoustics, have a low space-time resolution, limited sensor amount, are very intrusive and the equipment is, seldom, recovered. On the other hand, the short term techniques are usually based in radio and satellite telemetry, have a high space-time resolution, employ a multitude of sensors, have low intrusivity and the equipment must be recovered. They have issues with the development of the equipment. They have issues with the miniaturization of the equipment, due to the batteries and the flotation devices. The equipment also needs to be able to withstand the high pressure and low temperatures of the deep oceans as well as collisions with the environment and animal attacks. The data suffers from bandwidth constraints due to the high amount of data needed to be sent through a very limited channel. The fact that some of the most important behaviors happen at very small space-time scales adds to the bandwidth issue.

3.3.1.1 Very High Frequency (VHF) radio and Global Positioning System (GPS)

McCarthy et al. [144] ran a study, tagging several loggerhead turtles with ARGOS satellite tags for a duration between 2 and 10 months. They used several sensors to extract environmental data, besides the turtle's locations. The tagging of the animals requires capturing the animals for the placement of the tag but the data is transmitted using ARGOS radio-waves at 401.650 MHz to satellites. The satellites, then, forward the data to the service's servers where the researchers can access them. This solution was able to send 1329 data points on the best situation. A similar system was also used in a similar study by Freitas et al. [145]. In this case, they had to work around the data limit of the ARGOS system by compressing some data before sending it. They turned the turtle diving data into 6h diving histograms. This study, however, had a slightly longer time-span of a little more than 11 months as well as slightly more data points, at 1454. Besides location data points, the authors report a maximum of an extra 1050 dive histograms. Other environmental data was also measured and sent through this system.

3.3.2 Data Sensing In-the-Wild

Technology has played an ever-growing role in the advances and scientific findings of researchers focusing in pelagic and coastal environments. Studies focusing in behavior, movement and habitat-use of numerous organisms (e.g. fish, turtles, whales, seals) have only been possible through the development of acoustic transmitters and receivers that can be attached to the target organisms and deployed in the ocean environment [146][147][148][149][150]. Equally, ecological studies focusing on coastal habitats, marine communities and biodiversity distribution [151] have also benefited from advances in digital imagery hardware, photogrammetry software and the development of sensors designed to monitor or assess biotic and abiotic variables (e.g. temperature and pH dataloggers, underwater pulse amplitude fluorometers). Although technologies used for these applications remain at the high cost, there have been in-situ studies already used for: (i) deploying the tags on animals for tracking [152], (ii) buoy based sensors [153] for monitoring, and (iii) Remotely Operated Vehicles (ROV) and Unmanned Surface Vehicles (USVs) [154] for ocean habitat mapping. Moreover, large study corpora have been already understanding the design of underwater wireless sensors network (WSN) using radio and acoustics communications [155], and have been used in various applications for oceanographic data collection, offshore exploration, surveillance, surface water quality and navigation [156][157][158, 159]. IoT provides an enormous potential allowing remote technical diagnostics and improved safety, including management of the energy distribution, monitoring equipment, improving passenger experience, enhancing navigation and tracking cargo [160][161], etc. However, IoT remains scarce in aquatic applications.

When dealing with estimating the location, among numerous studies, Guegan et al. [15] researched the possibility of using the Power of Arrival (PoA) and trilateration to find the location of endpoints in tortoises, in both the land and the sea. They ran simulations and compared to the real world results however making no claims on the quality of the results. A following experiment, conducted by Gogendeau et al. [16], explored the different configurations of the LoRa model (spreading factor, bandwidth, coding rate) in sea environments. They tried to obtain the location of endpoints, using RSSI, which were fixed in 8 locations near the coast. They claim a maximum location error of 100 m at a maximum distance of 1.6 km. In our study, we build upon these findings, focusing on in further expanding the range.

3.3.2.1 Time Depth Recorders (TDR)

Alves et al. [162] deployed Time Depth Recorders in a group of six short-finned Pilot Whales to record their diving characteristics. The tags do not have nay data transmission capability and so it must be physically recovered. The tag that lasted the longest acquired about 5h of data, pooling the depth once every second.

In another study, Alves et al. [163] ran a similar study but with Bryde's whales. They conducted the first dive study with Time Depth Recorders on this species. On this study, besides the Time Depth Recorders, they used Very High Frequency Radio Transmitters for location but the data was still physically recovered. The tags recorded about 14h worth of data.

3.3.2.2 Biologgers

Ramírez et al. [164] monitored a small population of Bugio Petrels, during 3 years, using small Global Location Sensors weighting about 1.5 g. This type of loggers use light sensors to determine the animal's geolocation and store it locally for later physical retrieval. Since it is lacking any high power device (such as GPS or radio transmitters), this kind of loggers can work for a long time. The devices also monitored salt-water immersion, together with the light sensor, in order to analyse the bird's activity. Dias et al. [165] as well as Catry et al. [166] also ran a study using similar but heavier (3.6 g) hardware. This time, the subject were 14 Cory's Shearwater and their migration habits. They were monitored for 3 years, excluding the breeding seasons. Yet another study used the same system on the same species, this time, for 4 years. Dias et al. [167] monitored the usually light levels but also sear surface temperature and saltwater immersion of 100 specimens.

Ramos et al. [168] used geolocators to study the food habits of Macaronesian Shearwaters during 2 years.

Paiva et al. [169] also used Global Location Sensors to study 2 sub-populations of 10 Macaronesian Shearwaters during 3 years. Ramirez et al. [170] followed 26 Desertas Petrel for the duration of 4 years using Global Location Sensors.

Ramos et al. [171] monitored three species of Gadfly Petrels - the Zino's Petrel, Desertas Petrel and Cape Verde Petrel - using Geolocators.

3.3.2.3 Real-time Telemetry Systems

Telemetry is an important tool to monitor complex systems, which are often remote, in order to keep them in a healthy state. It is used in factories, networks, automobiles and a plethora of other complex systems. These systems can also be used, by biologists, to study the nature. Grothues et al. [172] deployed an array of hydrophones to study migrant macrofauna. They linked the system with radio communications in order to provide real-time telemetry data. This data was, then, fed to a mobile tracking system and a web-based system distance learning program.

To be useful, the shown data is, usually, in real time. But this can be an issue when whatever is being monitored is in a remote location and/or the bandwidth is extremely limited. The usage of a mobile phone/tablet as a display device decreases the costs associated with the telemetry system.

Technology has played a growing role in the advances and scientific findings in pelagic and coastal environments. Studies focusing in behavior, movement and habitat-use of numerous organisms (e.g. turtles, whales, seals) use acoustic transmitters attached to animals and are deployed in the sea [146]. Equally, ecological studies on coastal habitats, marine communities and biodiversity distribution [151] have benefited from advances in imagery hardware, photogrammetry software and sensor development to monitor biotic and abiotic variables (e.g. temperature, pH dataloggers, pulse amplitude fluorometers). Although technologies for these applications remain high cost, there have been in-situ studies used for: (i) deploying tags on animals for tracking [152], (ii) buoy based sensors for monitoring [153], and (iii) Remotely Operated Vehicles (ROV) and Unmanned Surface Vehicles (USVs) [173] [154] for ocean habitat mapping. Moreover, large studies have been understanding underwater wireless sensors network (WSN) with radio communications [155], and have been used in applications for ocean data collection, offshore exploration, surface water quality and navigation [156].

3.3.3 Internet-of-Things

As aforementioned, current limitations suggest that data needs to be manually and physically retrieved due to the constraints in range and costs associated with wireless communications. The need to support a massive number of devices and at the same time, using the potential of numerous IoT sensors which need connectivity through a single base station, would raise new issues and all of these aspects make the current cellular network technologies not suitable to support the envisioned IoT scenarios.

One of the essential aspects of IoT is the communication between the devices. Most of the IoT devices use short-range communication technologies to orphan devices or internet gateways. These short-range networks are very limited and nowadays we need wider coverage networks which can be used in indoor and outdoor environments. The use of LPWA technologies/devices can boost long battery life over 10 years depending on traffic and coverage needs and can be divided between licensed (Cellular IoT like NB-Iot and LTE-M) and unlicensed (LoRa and SIGFOX) spectrum. The main advantages is that it reduces operational costs, as well as the maintenance related to replace batteries or sensors in the field. These types of technologies such as LoRa have been developed to enabling Machine Type Communication (MTC) and connect sensors with ultra-low data transfer requirements.

A promising alternative solution, might be in a short-range, multi-hop technology (e.g. multipurpose technology using 2 or more nodes for exchange of payloads) [174], operating in open, industrial, scientific, and medical frequency (ISM) bands. Conversely, it could be also in long-range cellular-based using unlicensed broadbands, which are provided by so-called Low-Power Wide Area Networks (LPWANs) [175]. One of the major protagonist of LPWAN solutions available today, is therefore LoRa, and this study focuses on the IoT networks based on it. LoRa is a potential candidate as it can mitigate all aforementioned issues. It operates on open frequencies, allowing the access to citizens, while in the same time uses longer wavelengths, paving the way for both long range and low energy usage [176].

Nevertheless, most studies using LoRa or similar technologies have been done in urban and other land environments [14][177][178][179] where it behaves significantly different than in the ocean environments [15][16] which are the focus of our study. Furthermore, they only focus on small distances (under 10 km), where in this paper, we focus on large open areas. When dealing with the estimation of geolocation, Lora Alliance[1] can provide solutions using LoRa transceivers[17]. Their solutions can use two different technologies to achieve the geolocation: (i) One using the Received Signal Strength Indication (RSSI) for a coarser geolocation (1 - 2 km) and; (ii) the other which uses Time Difference of Arrival (TDoA) for a finer (20 - 200 m) geolocation. The TDoA solution's accuracy is close to a low end GPS solution, however it uses almost no energy, while the GPS chip is usually the most energy consuming component of the device. Conversely, both solutions (RSSI and TDoA) are built upon a LoRaWAN network - the Layer 2 and, partially, Layer 3 of the Open System Interconnection (OSI) Model - that works on top of LoRa, which is a Layer 1 of the same model. This solution allows for simpler endpoints that do not require any location chip that would, otherwise, increase both the financial costs and the energy usage. On the other hand, LoRaWAN shifts the costs and energy usage to the network itself requiring several expensive, overlapping and fixed gateways, at least one network server, and one ge-

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[1] https://lora-alliance.org

olocation solver. Their solutions where developed for, and work best on rural and urban scenarios, having higher accuracy on rural areas due to the lack of multipath, caused by the reflection off the buildings on urban areas. What is missing is the next phase in exploration of such technologies in ocean environments. In our study, we are exploring a low-cost solution that can keep the low energy usage on endpoints and that can be easily deployed, using buoys and/or boats, Since the TDoA is more expensive and requires additional hardware (necessary to obtain a high accuracy timer), we are exploring the RSSI solution that is given out-of-the-box.

SmartParks[2] is an example of an initiative which uses LoRaWAN geolocation technology to help with nature study and conservation. In a presentation [18] during the The Things Network (TTN) 2017 conference, Tim Van Dam[3], explained the usage of their system to cover, track and protect natural parks and endangered species. Their biggest example is the Akagera National Park with an area of 1122 square km^2. Even though they managed to keep their costs relatively low, the proposed solution is still based on large stationary gateways using additional expensive hardware. There are several other projects run by SmartParks that use a similar system to protect the wildlife, one of which tries to protect the black rhinos from poachers in Tanzania. The Finnish Reindeer Herders Association[4] provides us with another example of LoRaWAN usage, this time, for tracking and monitoring the Reindeer in a 50 square km area in Finland[180]. Instead of LoRaWAN geolocation, they use GPS and use the LoRaWAN for data transmission. The devices are much lighter, smaller, and energy efficient than the ones previously used. While these approaches use the terrestrial environment, focus of our study is on LoRaWAN applied in ocean settings.

3.4 Public Awareness

3.4.1 Technologies for engaging audiences with biosphere

While the HCI community shows an interest for aquatic setting through: visualizations of ocean-related phenomena [181][182][183], interactive installations [184][185],

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[2] https://www.smartparks.org/

[3] https://www.wildlabs.net/users/tim-van-dam/

[4] https://paliskunnat.fi/reindeer-herders-association/projects/partner-projects/finalised-projects/

games [186][187], enriching the whale-watching experiences [26], and design for play underwater [188], no prior work described holographic interaction for exploring aquatic environments.

Today, interactive technologies are applied to better understand complex phenomena like ecology and climate. The growing availability of ubiquitous technologies create opportunities to collect and interpret the massive amount of data [189], engage the audience in-the-wild [190], and promote environmental sustainability [191]. Low-cost micro controllers are capable of capturing, processing, and remotely distributing the data [173], as well as engage non-experts in citizen science activities. [192] reports on a tangible interface designed to improve children awareness of climate change and permitting them to understand the relation between CO_2 and other environmental variables. The interface uses a sensors' network gathering a set of environmental parameters to gauge CO_2 concentrations as some regions of the sea coasts of North East Italy are repopulated by flora.

Several projects depict underwater biodiversity in different ways, such as providing the video atrium and tangible user interface for exploration [193], video-mapping on top of a well known skyscraper [194], or augmenting the aquarium [195]; such endeavours remains at a significantly high cost of setup and/or lack interaction. Moreover, they require a massive amount of high-end hardware, such as countless displays and projectors. In our work, we challenge ourselves to reduce the technological input, using a simple pico projector, combining it with the well-known Pepper's Ghost Illusion.

3.4.2 Practical Holography in HCI

Holography has been known to the HCI audience and has been studied to some extent. For instance, TeleHuman2 [196], proposed by Gotsch et al., which builds upon TeleHuman [197], which was first designed by Bolton et al, was used for life-size 3D human telepresence and teleconference. A similar solution was proposed by Ito et al. [198], who investigated the use of a cylindrical hologram with a 360 degree view. They also studied two different setups, with the former being a multiplex hologram, consisting of several 2D images, combining them into an illusion of a 3D object. The latter was a laser reconstructed hologram that produced a real 3D effect, mentioning the usage of Fresnel lenses in hologram.

While such devices provide a complex setup, not all of the holographic studies use advanced technologies. For instance, Dalvi et al.'s system [199] reduced the technological input, using a computer, a transparent pyramid and a hand gesture recognition device. By using the Pepper's Ghost Illusion [200] for the setup of the holographic view, a person was able to get a 3D illusion without a parallax/stereoscopic effect. Moreover, Kim et al. [201] demonstrated a similar solution, using a gelatinous substance that, when reshaped, provides the user with a way of molding the hologram. Other scholars such as Kervegant et al. [202] gave up the usage of holograms, in favor of Microsoft HoloLens and Augmented Reality. They combined it with a haptic feedback device, allowing the user to have a feeling of touch, while interacting with the virtual object. Conversely, Bimber's solution [203] tried to provide an acceptable trade-off between hologram quality and interactivity, through the combination of optical holograms with 2D/3D graphical elements, providing a more straightforward method to animate graphical information. This approach, however, remained inherently flawed since the hologram's light interfered with the overlaid rendered graphics, suggesting that reducing the technology input remains challenging.

Throughout this manuscript, we argue that most of the development of similar systems remain either complicated or costly. Moreover, the use of 3D visualizations is becoming increasingly important to understand and make sense of complex systems as an alternative for audiences to understand complex phenomena, such as tackling the underwater ecosystems and providing evidence about the user experience, usability, emotional state, environmental engagement and interaction design as a mean to communicate the desired messages about the whales.

The remainder of the manuscript describes the further improvement of prior work based on Pepper's Ghost illusion as seen in Dalvi et al [199], significantly reducing components, while scaling it to encompass and depict the curiosities and lifestyles of one of the great whale species. Our system also attempts to counteract the cost-effectiveness issue, by employing completely upcycling materials, while significantly reducing the cost of manufacturing, reducing the footprint on environment.

Chapter 4

Improving Remote Collaboration using Virtual Worlds

4.1 Introduction

The use of advanced computer graphics and virtual environments per se has sparked a digital revolution in many activities, thanks to the novel visualization and manipulation possibilities they provide. Yet, and despite significant advances, most of the Virtual Reality interactive technologies deployed in real-world design and engineering contexts are still regarded as being difficult to use, especially when engineering teams need to collaboratively visualize and review large scale 3D CAD models. This is precisely what happens with the oil platform industry, which necessarily involves large teams that review, manipulate, and discuss around large CAD models, which are sometimes difficult to visualize and navigate through. These teams are usually composed of engineers that are in the field working together with several other engineers in a central location. One of the main objectives of the engineering departments at large industries such as oil companies is the construction of integrated information systems to control their projects, offering resources for the 3D visualization of their models with enough realism to be used for virtual prototyping, design review, change management systems, and training, among other activities. The engineering, design and review of CAD models are complex, collaborative activities, in particular when large-scale models are involved, as in the oil platform industry. Large Scale Displays offer a unique visualization environment favorable to both individual and collaborative design tasks. During the last decade, they became both affordable and easier to setup, providing highly immersive virtual environments with higher resolution and support for stereoscopic images. Multimodal user interfaces have revolutionized the way we work by combining different input modalities [35]. Together with large-scale displays, these offer ideal environments for co-located collaborative work. On the other hand, multi-touch technology has become mainstream and tablet-based multitouch has emerged as a mobile interaction style standard, especially due to the success of products such as the iPad. Such devices provide a fertile ground for the exploration of powerful remote collaboration solutions. The combination of large environments and mobile devices allows the development of an integrated solution for teams that are geographically dispersed to work collaboratively.

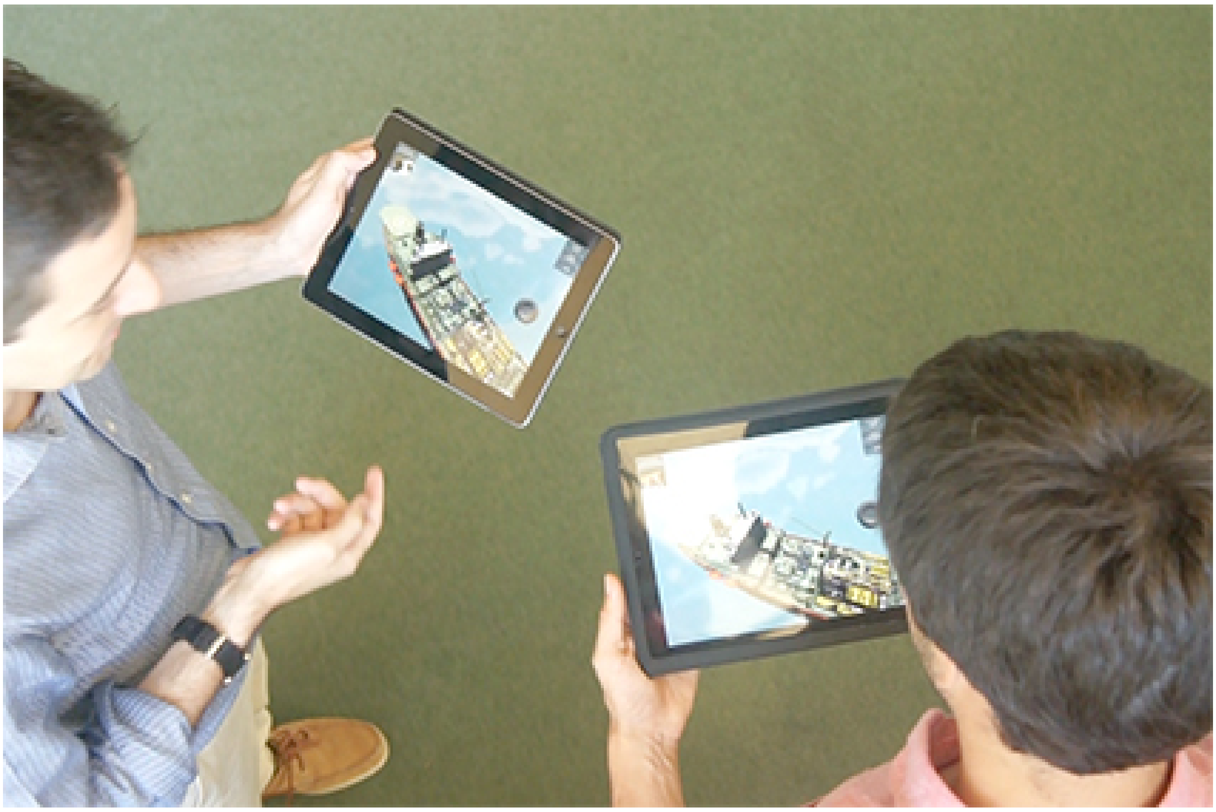


Figure 4.1: Two users having a co-located meeting

4.2 Requirements Elicitation

Several techniques were used for requirements elicitation. Task analysis such as task case maps proved ineffective, probably due to their high-level of abstraction. They facilitated communication with the oil industry experts, but were incapable of achieving a concrete shared vision about what the final product should be. We followed a user-centered methodology starting with a task analysis involving engineers operating traditional design review CAD tools on a daily basis. Via both structured interviews and informal talks, we were able to clearly identify both challenges to be tackled and real usage scenarios. In oil industry settings, large teams usually gather to review, manipulate, and discuss around large CAD models, which are often difficult to visualize and to navigate owing to their complexity. These teams typically include field engineers working at remote locations and technical staff operations at a central location. Maintenance in specific infrastructures inside an oil platform is very frequent and the technical staff has to plan how to access them beforehand. Furthermore, changes to these installations are frequent, removing and installing new components. One key goal of ours is to support engineers' field work by allowing them to visualizing in loco the procedures needed to repair devices while assessing possible interferences that are not reflected in the 3D model but exist in the real scene in close cooperation with headquarters.

4.3 Prototype

Each client implements several components for managing hardware, communication and input from users as depicted by the software architecture presented in Figure 4.8. For both clients, the User Interface is responsible for both the interaction and the visual feedback of the system. Both server and clients were developed upon Unity3D game engine. Such solution enables a common framework for both iPad and Large Scale Display client applications while reducing efforts related to software integration on different platforms. This is also a fast and reliable visualization solution for rendering complex 3D scenes on a mobile platform such as the one proposed for iPad 2 or 3 and without considerable frame-rate drop. The 3D scene repository, virtual camera and avatar representations are handled by the Unity rendering engine under the 3D Scene component. Three separate components are responsible to share virtual representation over the network using Unity remote procedure calls. The Avatar Representation synchronizes the point of view representation among all clients (iPad clients and Wall clients), i.e. both the position and the orientation of all connected users. This component works together with the Remote Visualization which will present the remote client point of views as previews or fulfilling the display area of the iPad or of the Wall. While the Viewport Sharing is responsible to share the current viewport of the client over the network. The Navigation implements the different navigation methods depending on the sensor interface provided by each client. On the iPad client's side, the Sensor Interface gives access to the iPad built-in sensors complemented with a tracking solution using a Unity3D plugin for the bird eye view mode. We use the Qualcomm Vuforia to track the iPad pose relative to an image acting as a marker. On the Wall client's side, the Sensor Interface supports several input modalities. Using Open Sound Control (OSC) as a network protocol for communication among different and independent input applications, the system is scalable enough to handle navigational interaction messages from motion sensing input devices (such as the Microsoft Kinect), game controllers (such as the Nintendo Wiimote) and the standard keyboard and mouse. Finally, both Video Camera Sharing and Voice Sharing components are responsible to abstract both the iPad's camera and microphone to support the communication between iPad clients. To support collaborative tasks between both iPad and Wall clients, the data to be sent over the network is crucial. Several types of data are transferred between clients while interacting with our system: voice, video camera and virtual camera information. To avoid communication problems, we tried to minimize data needs using compression for voice information. On each frame, the position and the orientation of all user viewports participating in the session are sent to the server and are distributed among other clients. This virtual camera data is composed of six four-byte floats plus headers (i.e., up to 576 Bps plus header at 24 frame per second). The bitrate is variable since it is frame-rate dependent, we locked it to a maximum of 24 fps. Since the data of the virtual camera is small and due to its floating nature, there is no advantage to use compression on such data or to send deltas instead of the current pose information. An alternative solution would be to pack several successive frames. However such solution would introduce lag which we avoid with the current solution. This constraint is not true regarding voice data and it benefits from compression. While uncompressed voice data can go up to 88 kBps, we use the Speex codec to compress it to one kBps mark per user. Given that each client uses up to 2 kBps (including headers), two users would demand an upload throughput of 4 kBps using our star topology network. The bandwidth needs grows exponentially for each new user according to the formula $c(n2^n)$, where c is the bandwidth that each user needs (a constant value of about 2 kBps) and n is the number of users connected to the server. For instance, a 10-user conference would require a server throughput capability in excess of 180 kBps. Such scenario might be troublesome for remote communications with an oil platform and should be improved in the future.

4.3.1 Client Types

There are two types of clients. The first one is the tablet, where the user can navigate and interact with the model. The second one is the wall, which is used for visualization and coordination of everyone as well as the model. The wall is also the only client type that can run a server since the tablet clients run on weaker hardware. The tablet clients are intended to be used by a single user while the wall is a conference/presentation client.

4.3.1.1 Tablets

Each tablet client has an avatar. This avatar serves as a three-dimensional representation of the client's current position and orientation, allowing everyone to know where everyone else is at and what they are looking at. The tablet clients can also activate the First-Person view (usually called viewport by us to avoid confusion) of a specific avatar on his own screen. This view appears as a small window allowing for his job to continue while being able to keep an eye on the other avatar.

4.3.1.2 Wall

The Walls may act as a server and a client or just as a client. The server simply forwards the orientation and position of each client as well as voice and some other less frequent data (such as what a user is pointing at). The client shows up a rotating three-dimensional model with the avatar of each tablet client moving about in real-time. It also shows a top-down map of the model with the location of each tablet client represented by a numerated icon. The viewport of each tablet client also shows up on the Walls allowing for the headquarters team to see and coordinate the movement of everyone.

4.3.2 Hardware

There are two main hardware components: the tablets, used as mobile clients and the Walls, used as either clients or clients and servers. They are closely connected to the client types described before.

4.3.2.1 Tablets

The tablets could be any kind of tablet that has enough processing power to run the client. In our case, we mostly used iPads 2. But we tested it on an iPad 3, an Android tablet, and some mobile devices with both Apple's and Google's Operating Systems.

Figure 4.2: A screen shot of the tablet's version of the system

4.3.2.2 Powerwall

The system was developed and evaluated using two geographically distinct facilities using large scale displays with different specifications. One is a 2x2 tiled display system using four Optoma EW775 projectors in rear-projection mode located in Portugal as depicted in Figure 4.8. Each projector has 4500 lumens and displays 720p @ 120 Hz. The mosaic generates 3.6 megapixel stereoscopic images thanks to a small overlap (64 px horizontal and 19 px vertical) blending at each projector. The visualization system is driven by a HP Z820 Workstation coupled with two NVIDIA Quadro 5000 behaving as a single desktop and thus simplifying the development and deployment of applications. The stereo setting uses NVIDIA 3D Vision 2 shutter glasses and an IR emitter located behind the screen. The second visualization facility is located in Rio de Janeiro (Brazil). It is composed of four Barco NH-12 projectors in a trapezoidal arrangement creating a cave-like system. The lateral screens use rear-projection while the front uses front-projection.

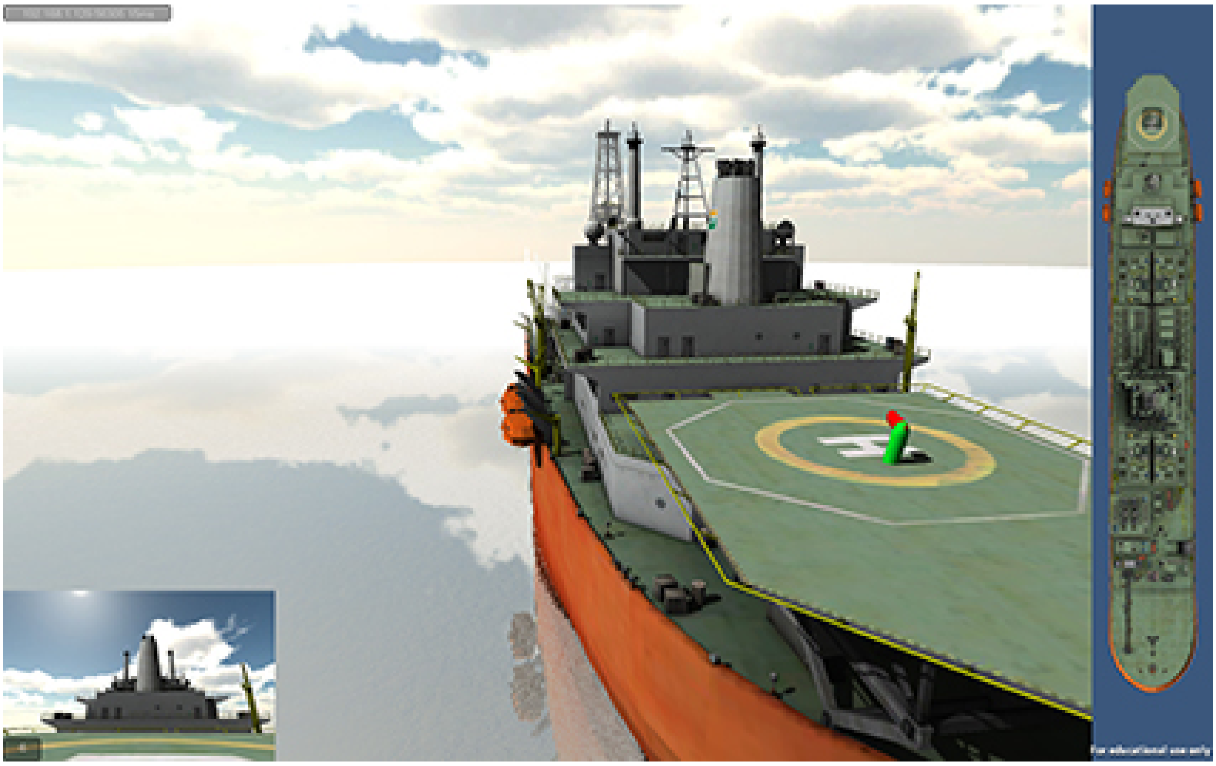


Figure 4.3: A screen shot of the Powerwall client that may also serve as a server

4.3.3 Software

The system uses Unity3D, a framework that aims to unify the development of games in several of the current gaming and mobile platforms. This allows us to easily target several platforms at the same time. The framework is also fast enough to render complex objects with simultaneous eyecandy features on any iPad 2 and above without a frame-rate drop. Vuforia was used to power up the camera tracking of the bird's eye navigation mode. It is a rather robust camera tracking / enhanced reality software that interfaces with Unity3D. A server that runs on any computer handles the communication between iPads and can also serve as a meeting hub/overseer. This system is constructed to be an out-of-the-box solution with virtually zero con- figurations needed and able to be deployed on the fly, which makes it even more adequate to the needs of offshore engineering teams.

4.4 Qualitative Assessment

A preliminary evaluation of the prototype was run first. We asked different pairs of participants to guide each other through the model using the iPad navigation method. In this preliminary evaluation, Viewport Sharing was preferred over the Avatar when guiding or following another user. The probable reason for this is that the model has a lot of obstacles which occlude the Avatar most of the time. It is only when users are near to each other that they can take advantage of the Avatar. To overcome this and get more visual cues and landmarks, some users navigated to a position high enough that they could see the whole model. On the other hand, Viewport Sharing can be disorienting since fast rotational movements performed by the user in control can be hard to follow by other users who are not controlling the navigation. Some users resisted to using the sensor-based iPad navigation, maybe owing to its novelty. However, with some practice, they did find it both easier and more fun to use than traditional touch-based interfaces. The main drawbacks were the thumb-stick metaphor on the screen which caused some problems to users less experienced with game input devices and how tiring the handling position could prove after prolonged use. To address the latter, we proposed to relax the virtual axis and to use the camera freezing feature to work as a clutch, which was also useful to prevent awkward user body postures. Afterwards, we ran a more complete qualitative user evaluation. This user evaluation was composed of a quick presentation of the system and its goals while trying not to give away to the user any information that would change his interaction in any way. Following that, users were given some time (about 30 min. each) to play around with the prototypes while talking freely about the system. This experience was voice recorded and the most important remarks about the system were written down. The users experimented with the different prototypes so they could get a feeling of the different interaction types. At the end of the evaluation, the users were given some time to talk about the system and then were asked some key questions in order to assess:

- The perception of the preferred navigation mode;
- The perception of the easiest navigation mode;
- Differences in the navigation modes with respect to the level of complexity in certain tasks;
- General feedback about the collaborative system as a whole.

Not surprisingly, the users felt that each navigation mode had pros and cons on different situations and tasks. For instance, for simple tasks the users were more inclined towards joystick and gesture-based interaction styles, while for more complex tasks they chose the virtual camera/first person navigation mode. They all agreed that this kind of system would effectively help them on modeling and cooperatively reviewing constructions and construction sites. Regarding the support for collaborative work, the feedback was particularly positive. There are very few solutions for navigating and reviewing 3D CAD models and those that exist are not mobile and/or are very difficult to use. Users even gave some examples as how they sometimes need to perform some cooperative work. In particular, the importance of several shared views, since current industrial solutions force all engineers to look at the same screen.

4.5 Work Analysis

4.5.1 Introduction

In a review session, engineers manipulate 3D engineering objects, creating annotations and performing measurements. The ability to move, rotate, and scale objects is important for various purposes, such as joining models, viewing hidden areas, planning the placement of new devices, and simulating maintenance or intervention operations in a process plant. Comments attached to objects can also be used as recommendations for project management. Figure 4.4, a screenshot taken from of the desktop-based software currently being used by the engineering team, shows a measurement made for planning the movement of a large tank in a production unit. Users create annotations to guide the maintenance procedure and animate the entire operation. Since we aim a specific domain solution with real-world application, not a lab prototype, we organized a short task analysis involving real users. From interviews and informal talks with engineers working in the oil industry we were able to clearly identify challenges to be tackled and real usage scenarios. In the following paragraphs we present our conclusions regarding interactive environments for engineering design review in the oil industry. Currently, engineering teams use mostly standard CAD tools, controlled with traditional interfaces. However, the location of elements in a 3D model of an oil platform using the standard movements of CAD software with mouse and keyboard requires some training from the user, which has to get used to specific commands. Tablets in the opposite, does not have keyboard and mouse, but have accelerometers, gyroscopes, and multi-touch support. These devices allow the user to quickly learn how to navigate in a scene very naturally. Engineers are already familiarized with this kind of devices, since they use them for several different tasks. Thus, they are keen on complementing their traditional interfaces with more natural and easy-to-use interaction environments. Due to the large diversity of tasks performed within the design review process, we focused on three different kinds of tasks, frequently performed. These are device maintenance, path validation for large volumes, and exit path checking. Maintenance in specific devices inside an oil platform is very frequently, and the engineers have to plan how to access the device, and very often they need to remove and install a new one. The major goal is to visualize in loco the maneuver to repair a device and better understand possible interferences that are not mapped in the 3D model but are in the real scene. Besides that, the access in oil platforms is limited. Then just one person in the local would be enough to communicate with an entire team in-shore. Other important usage of the proposed navigation solution is the transportation of large volumes. Since the oil rig has several pipes and devices spread all way around is essential to check if a large volume passes through the squeezed paths inside the plant. The visualization from the original point until the final place can be entirely simulated, avoiding losing time on searching a way to reach a certain location, or damaging parts of the oil platform, which can lead to a severe accident. Since the tablet is available locally, the transportation simulation can be double checked instants before the final procedure, checking if a nonplanned object is on the way, like a barrel or some other object. One other example is the possibility to check several exit paths for the oil-platform personnel in case of an accident. The virtual navigation across the narrow aisles allows a better planning for evacuations, this is extremely important since the environment is very dangerous. This procedure can even be used to train the people in the oil platform, to better explain what they are supposed to do in an emergency. Within the contexts described above, we propose an approach that combines a large-scale environment with mobile devices to provide an efficient and easy to use collaborative CAD engineering tool. Instead of relying on the latest lab prototypes, the solution we devised takes advantage of recent, but already available outside the lab environment, technologies and devices.

4.5.2 Usage of Different Work Analysis Methods

In the offshore engineering field, the project of deep-water production systems, including oil platforms, ships, and all the sub-sea equipment that plays a part in the production process, is currently designed by means of complex computer modeling systems. The design of a new production unit is a lengthy and expensive process, which can last many years and consume hundreds of millions of dollars, depending on the complexity of the unit and the maturity of the technology required to make the project technically and economically feasible. Offshore engineering projects involve not only geographically distributed teams but also teams of specialists in different areas using different software tools, both commercial and internally developed. While the interoperability of

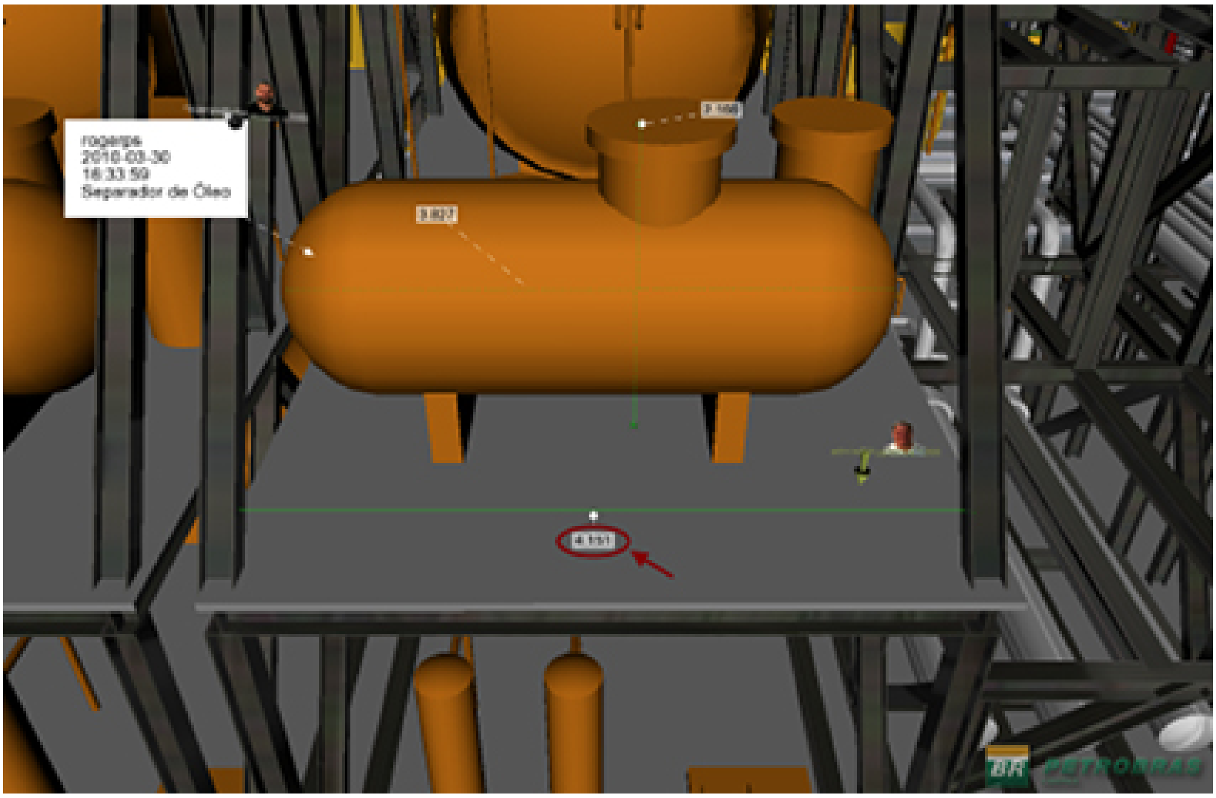


Figure 4.4: Annotation and measurement activities during design and review

those tools is still an issue, it is a mandatory requirement for any collaborative solution. One of the objectives we had was to establish a sound requirements document stating clearly the desired project's objectives, requirements, and specifications, as well as outlining scenarios for the solutions proposed and their evaluation procedures. We used the resources available at Tecgraf-PUC Rio (the research arm of Brazil's largest oil industry company, Petrobrás) [63] to conduct user observations and informal interviews with the engineers involved in collaborative engineering design and review activities. The final result we obtain is essential, since it allows us to understand: (i) the application domain, (ii) the problem of designing and reviewing CAD models, and (iii) the needs and constraints of the system's stakeholders. Additionally, and perhaps most importantly, we elaborate on the relative advantages and disadvantages we faced when applying different work analysis methods: activity-based analysis [69], hierarchical analysis [70] and storyboarding as a way to understand the value of possible solutions [66].

4.5.2.1 Activity-based analysis

4.5.2.1.1 Activity 1 – Designing and reviewing engineering models Design review is the process of checking the correctness and consistency of an engineering project while making the necessary adjustments [63]. In the session, users can manipulate objects, highlight and create annotations, do measurements, and check the proper ergonomic design. The ability to move, rotate, and scale objects is important for various purposes, such as joining models, viewing hidden areas, planning the placement of new devices, and simulating a maintenance or intervention operation in a process plant. Moreover, integration with an engineering database with the CAD system is useful to create annotations emphasizing critical parts (Figure 4.4). Comments attached to objects can also be used as recommendations for project management. Figure 4.4 shows a measurement taken for planning the movement of a large tank in a production unit. Users create annotations to guide the maintenance procedure and animate the entire operation. Finally it is possible also to confirm if the space distribution of the engineering devices conforms to the ergonomic needs for operation and maintenance.

4.5.2.1.2 Activity 2 – Riser analysis An important step in deep-water oil exploitation is the elevation of the oil from depths over one thousand meters to the surface. Oil platforms use ascending pipes, called risers, which are tubular structures that convey oil and/or gas from the wellhead on the sea floor to the platform's separator system tanks [63]. To certificate the operation of the risers for their entire lifecycle (30 years or so), simulations of the stress applied to the riser system are conducted based on meteo-oceanographic data about wind, tide and water currents. Simulations are made under extreme environment conditions to test stress resistance. It is important to perform fatigue analysis studies to evaluate the most critical regions of the risers affected by cyclical stress in order to guarantee their integrity during their lifetime.

4.5.2.1.3 Conclusions after the activity analysis The problem of providing engineering teams with effective tools for collaborative work is becoming increasingly important, not only because teams are increasingly working distributed throughout the world, but also because current tools still lack support for collaborative engineering

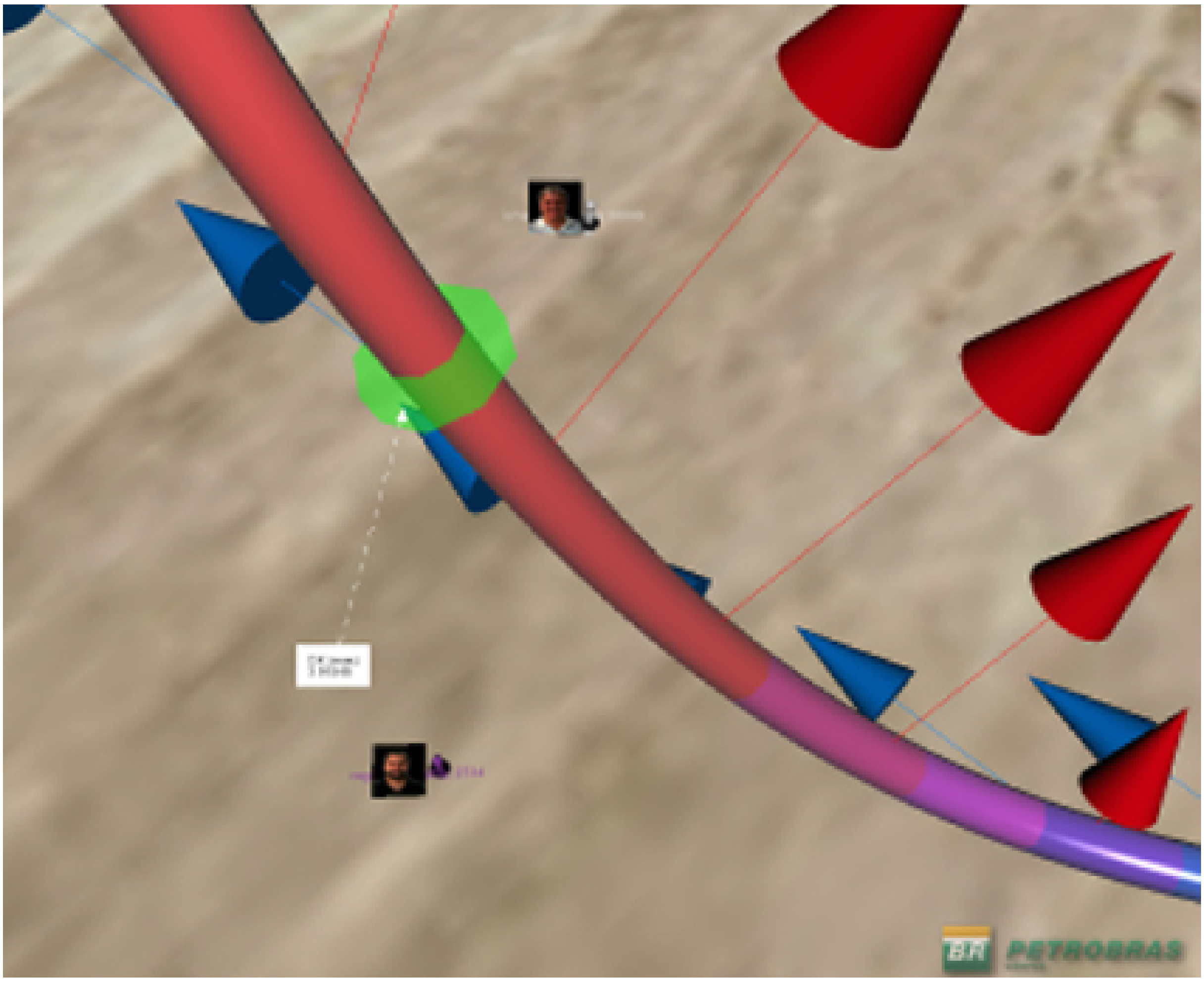


Figure 4.5: Riser analysis

design and review, either in co-located or distributed settings. The oil industry is especially well positioned as a potential demonstrator for research development in this field, since it's one of the largest user bases of high-end hardware and software. Collaborative Virtual Environments (CVEs) place the emphasis on providing a common virtual space of interaction to distributed teams, a space where they can meet as if they were face to face, while sharing and manipulating relevant work artifacts, in real time. In the case of this application domain, the oil industry, there is a relevant issue that motivates this project: the working force is aging, and the industry is not attracting younger generations of workers. Therefore, the trend of conceiving "digital oil fields" capable of being controlled remotely is becoming strategic for oil companies. The essential scenario for solving this problem is a 3D interactive environment that represents the oil platform and associated subsea equipment in a multitouch virtual control room approach. The oil industry application domain, as referred in the previous section, fits well into the design and evaluation of novel environments, because of several factors. First of all, the very nature of the work performed by the engineers themselves, which is often carried out in collaborative, geographically apart settings. Secondly, because they can provide real world data in the form of large-scale CAD models, thus acting as reliable demonstrators of the project's results. And finally, because there are – to our knowledge – very few research efforts specifically targeted at this application domain. The final product that the team performing this work analysis identified is essentially a large-scale virtual environment based on multi-touch and remote collaboration features for increased awareness and increased sense of presence among teams of oil industry engineers. The final prototype should consist of a set of computer clusters for multi-projection environments running the software designed, developed, and evaluated throughout the project. The main idea underlying this vision is that if we provide engineers with multitouch collaborative tables and walls, we can achieve a state-of-the-art environment with an interesting application to the oil industry: a system that finally allows these users to find, navigate and visualize their complex CAD models' data in a much more satisfying and effective way. This goal can be measured in two dimensions: the usability dimension, making use of well-known Human-Computer Interaction (HCI) evaluation methods and the collaborative dimension, using traditional measures for determining the levels of remote collaboration between geographically dispersed teams.

4.5.2.2 Hierarchical task analysis

In this work analysis, the hierarchical task breakdown was actually the first step the team took. The analysis was based on input from experts in the oil platform engineering field, several brainstorming sessions, semi-structured interviews, and other meetings. The result (after many iterations) is shown in Figure 4.6. One of the positive aspects was the fact that the team was able to identify the most important tasks and the most intense tasks from a cognitive perspective. The downside was that the team remained without a clear picture about what should be designed and implemented, what was more important, and what was less relevant. Other methods, as we will see in the next section, proved far more efficient in gaining a common vision.

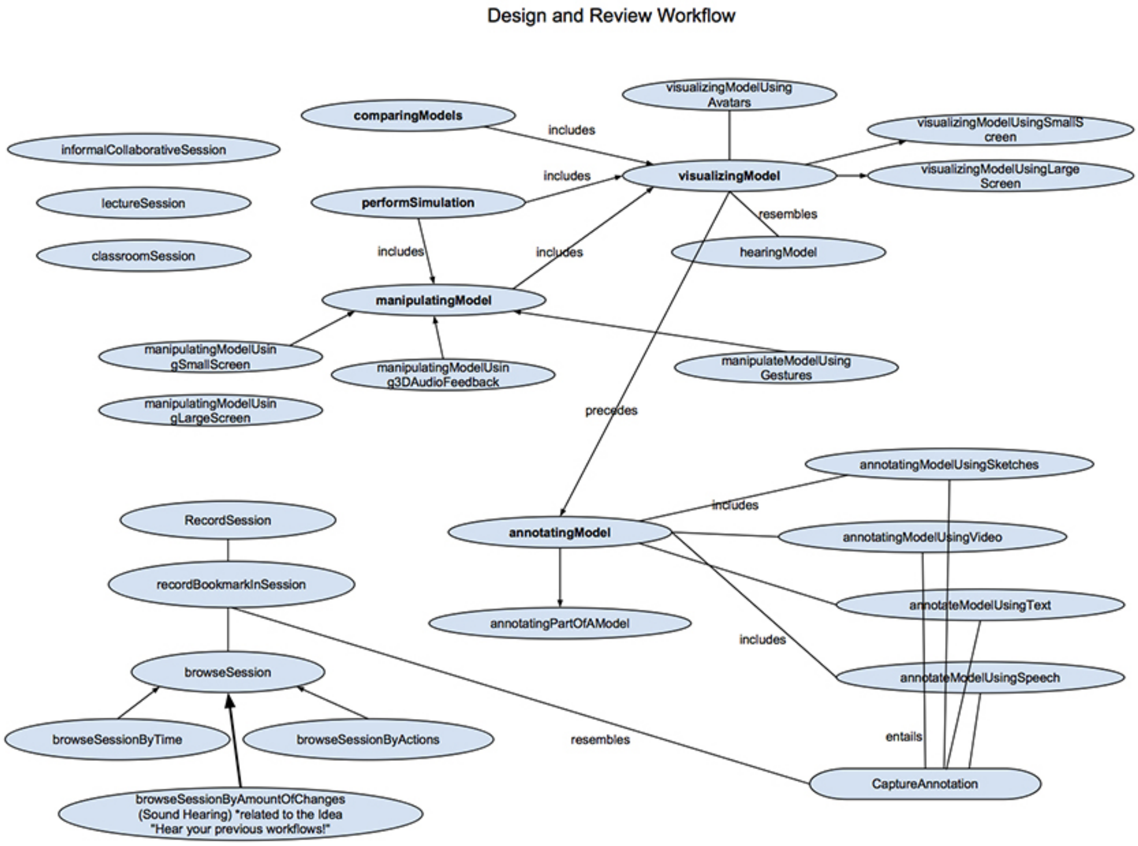


Figure 4.6: Task case map for our work domain analysis

4.5.2.3 Storyboard

In order to gather information about usage scenarios, task analysis, user profiles and context, we conducted several meetings with researchers and engineers at a large oil platform company. We complemented this analysis with research literature results. We obtained a lot of useful data and filtered out the most relevant issues to design a novel user interface aimed at supporting the engineering design and review activities. Since the team had difficulties in synthesizing the work of offshore engineering design and review teams, we decided to employ storyboards [66] to facilitate the ideation process as well as to better explore the possible design concepts. Figure 4.7 illustrates several navigation interactions that allow the user to look and move around the virtual environment. Storyboarding was particularly beneficial to this project's HCI design. It allowed matching the possibilities offered by recent advances in mobile, multi-touch technologies with the cognitive tasks at stake. After long discussions, the team chose to employ the power of tablets to create different navigation modes in a collaborative prototype where CAD models are simultaneously shared and visualized through Wi-

Fi, while the user can also video-conference with other remotely located engineers. One of the navigation modes is depicted in Figure 4.7. The storyboard illustrates the use of sensors to control the camera's orientation. Translations are performed through multitouch gestures controlling a joystick. The user is free to work whenever he wishes to, which is a significant step further regarding the current system being used by the company (based on traditional desktop-based PCs). Therefore, we can conclude that storyboarding was an effective technique to identify novelty factors that could enhance the usability of the proposed product.

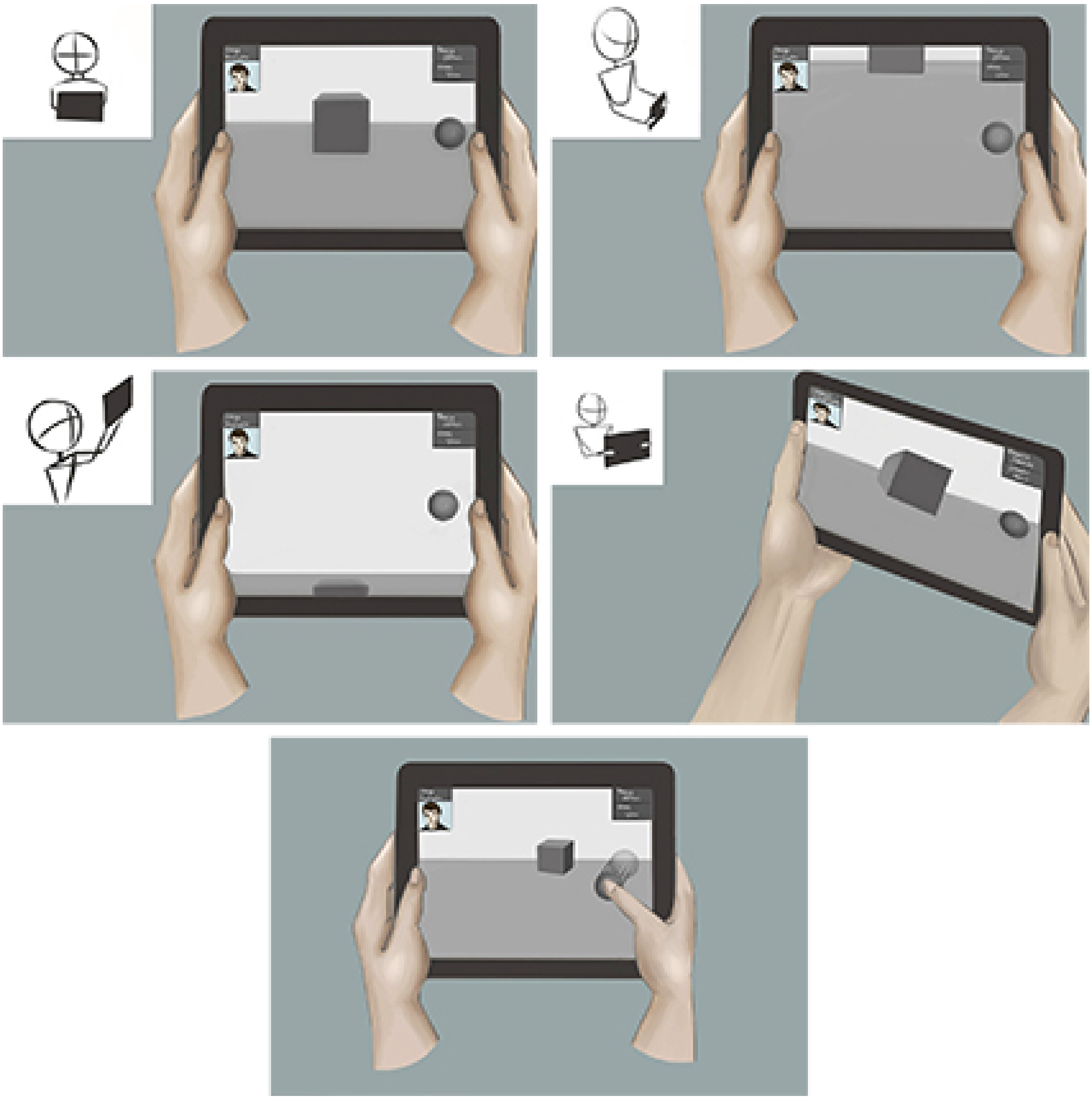


Figure 4.7: Storyboard depicting the different navigation interactions. From the top left going right and then down: Standby; Looking Down; Looking Up; Looking Right; Moving

4.5.2.4 Comparison between the different methods

Hierarchical task analysis was the first method employed in this product's HCI design. Perhaps because of that it was the method that required more effort in order to produce a reasonable set of artifacts describing the engineers' work. Task analysis taken from a hierarchical perspective had its advantages. First, it allowed the entire team to understand the priorities in the design that should be taken into account. It also had the advantage of promoting discussion around a single diagram, which made it easier to reason about human work without losing the "big picture". However, this method was the least efficient of all. The team remained without a completely clear picture about what should be designed and implemented, what was more important, and what was less relevant. Secondly, the method for trying out a more efficient work analysis was activity-based analysis. We tried to write a complete, detailed description of the collaborative engineering activities that are performed by offshore engineering teams, working both in the oil platform as well as in the central company's offices. The activity-based analysis effort was overall positive. By forcing a detailed description of the activities at stake, the team spent a lot of time and effort, but at least was able to reach a better work analysis. It allowed identifying a final concrete product, essentially a large-scale virtual environment based on multi-touch and remote collaboration features for increased awareness and increased sense of presence among teams of oil industry engineers. The disadvantage we encountered was the fact that activity-based analysis did not allow the identification of novel ideas, and the brainstorming processes that usually lead to better UI designs were not well undertaken. As mentioned before, storyboarding was the most useful technique as it allowed discovering novelty factors that differentiate the solution and improve the usability of the product, thereby supporting the human work in offshore engineering design and review sessions.

4.5.3 Conclusions

Supporting the needs of offshore engineering teams is an important industrial problem that should be addressed taking into account the rapid evolution in user interaction styles available. The potential for innovative solutions that is brought by tablet-based computing is enormous. We described the industrial creation and evaluation experience of a new mobile system for collaboratively navigating and reviewing 3D engineering models, applied to the oil industry. We highlight that storyboards and scenarios were an effective way to elicit requirements together with oil industry experts, as opposed to high-level task analysis. Our main contribution to the Human Work Interaction Design (HWID) field is the comparison of the effectiveness of different work analysis and design methods to-wards establishing a common vision regarding a new product for the oil and gas industry engineering models' review, in a collaborative manner. This is especially important for gaining new insights about the relative advantages between the different methods in a highly complex, real world work domain.

4.6 Software Architecture

The CEDAR system follows the common Single-Server-Multiple-Clients (start topology network) architecture with a small nuance: the server also acts as a client and this server can easily switch to another client, as depicted by figure 4.8.

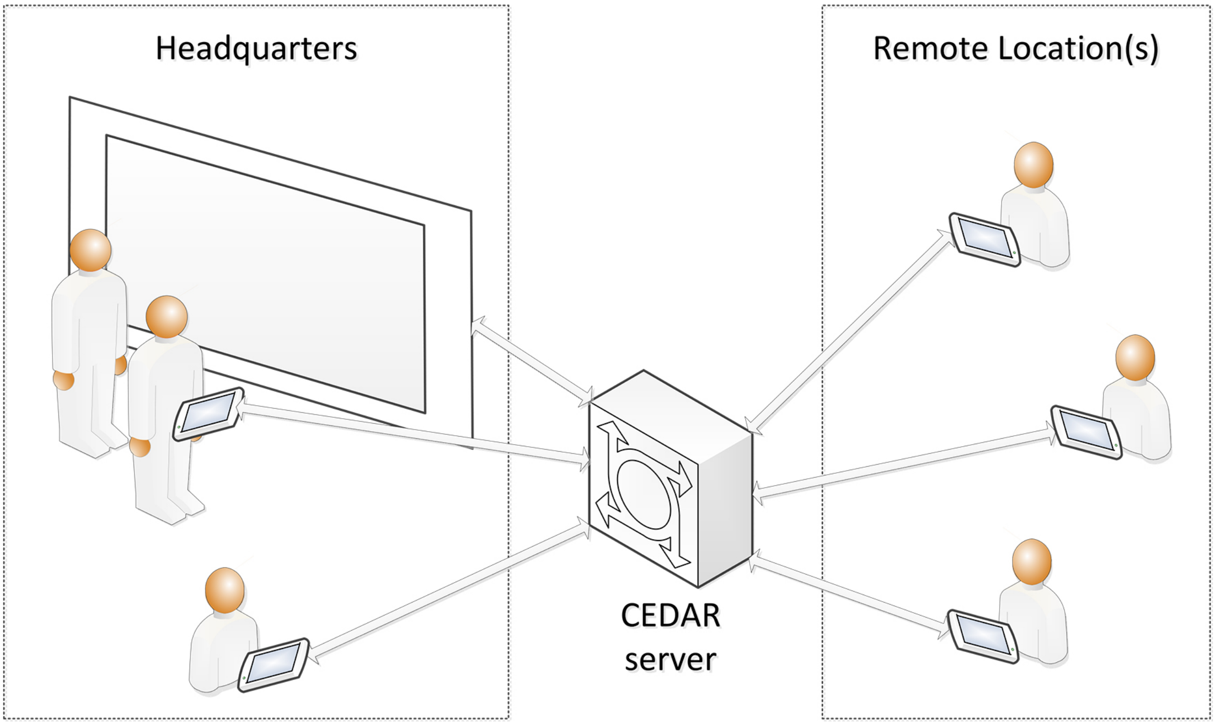


Figure 4.8: Software architecture diagram. It shows the several mobile clients and a power-wall client all connected to the server. The server can either be dedicated or any of the clients

We consider two different clients to interact with the CAD model under revision during a review session. A client running on a desktop computer connected to a Large Scale Display provides a unique visualization environment for several users discussing engineering problems. Another client, running on an iPad, offers a personal window displaying its own view of the scene. This view affords multitouch 3D navigation and can be synchronized (or not) to other clients, namely, the Large Screen Display. The main server coordinates the different clients and manages the engineering review session by forwarding both local and remote communications. By using the client application on each visualization facility, users can connect to the main server either locally or using the Internet and start sharing data between them. Both Large Screen Display and iPad clients implement specific components to manage hardware, communications and input from users as depicted by the software architecture. For each client, the User Interface is responsible for providing interaction support and visual feedback. Both server and clients were developed on Unity3D game engine. This provides a common framework for the client applications while reducing software integration efforts on different platforms. Unity3D also provides a fast and reliable support for rendering complex 3D scenes. 3D Scene Unity components are created representing the 3D scene repository, virtual camera and avatar representations. Three separate components are responsible for sharing virtual representation across the network using Unity remote procedure calls to support collaborative tasks. The Avatar Representation synchronizes the point of view among all clients on every frame, i.e., the position and the orientation of all connected users are sent to the server and are distributed among other clients. This component works together with the Remote Visualization, which presents remote client's point-of-view either as a preview or a full–display visualization. The Viewport Sharing is responsible for broadcasting the current viewport of the client to connected clients over the network. The Navigation component implements different travel methods on the VE depending on the sensor interface provided. On the iPad client side, the Sensor Interface uses the iPad built-in sensors to support multi-modal input. On the Wall client side, the Sensor Interface provides different input modalities. Using Open Sound Control as a network protocol for communication among different and independent input applications, the system is scalable enough to handle navigational traffic originating from motion sensing input devices (Microsoft Kinect), brain-computer interfaces (Emotiv Epoc) and the more conventional WIMP input devices.

4.7 Collaboration

One of the objectives of the CEDAR research project was finding ways to increase collaboration between engineers in remote meetings while reviewing CAD models. In this section there's a list of features we implemented and tested. There is also a study that was run to give us a better understanding of collaboration in this kind of systems.

4.7.1 Collaborative Features

Besides providing 3D model visualization and navigation, the CEDAR system supports several collaborative features. The system aims to improve the collaboration between users by providing both direct and indirect communication, visibility, and awareness. The first to be implemented was the voice conference. Every client (tablet and wall) are linked together on a conference call to allow them for easy communication. We then implemented a pointing feature: when double tapping on the tablet screen, an arrow appears at the tapped object. This enables an easy and quick focus on three-dimensional space for the whole team. The tablet clients can also create and move around objects. Please note that we refrained from building a full-fledged 3D-editor since what should be happening at this engineering stage is adding and moving current objects around and not drawing new ones. A feature that allows the tablets to show something locally is the camera-freeze feature: handling the tablets will always move the camera around so, if someone needs to show the current view to someone else, that view should be frozen and the user should be able to move the tablet freely. We also implemented viewport sharing. The point of view presented on a display can be shared with other users, allowing geographically apart teams to see the same. Suggested uses are: Displaying the location of small objects, guided tours and simply knowing were the other colleagues are. The commonly used avatars were also implemented. It represents the current position and orientation is presented on the environment. This affords faster recognition of where other users are located and their looking-at direction. During reviewing sessions, it is often necessary to take notes. Instead of taking these on a notebook or using a different application, CEDAR offers both sketched (using the iPad) and speech annotations that can be viewed or replayed later by users. While iPad clients support these four collaborative features, the system running on the Large Screen Display is intended to be a tool that takes advantage of its size to allow a better visualization of the objects being studied by the work team present in the room. For this reason, following a similar approach than the one used by the iPad, we currently only support two of these features: Viewport sharing and Avatars. However the Wall client also allows users to span the Viewport Sharing over the whole display area instead of only presenting it as a preview window. Such solution allows to better explore the large-scale display and also enable a user to control the view using an iPad device in the room instead of interacting directly with the Wall through gestures. Regarding the Avatar feature, as depicted in Figure 4.2, we use a red sphere to show the iPad's position inside the 3D model complementing the preview, on the bottom-left of the screen, which shows the view from the remote user.

4.7.2 Studying Collaboration

In order to improve collaboration on our system, we ran a study designed to force collaboration between two people. They were required to complete a puzzle with an interface similar to our other prototypes. This puzzle had the peculiarities of each user only knowing the correct position of half of the pieces and those pieces were laying around on top of each other. This meant that the users could not win without the help of each other.

4.7.2.1 Introduction

Taking into account the constraints of collaboration in engineering and related areas, our idea is to build and test a system that will allow a natural and efficient flow of information allowing the users – in this case, the engineers – to work on a complex virtual representation of their system, pretty much as they already do, but collaboratively. When dealing with tools that do not support collaboration, engineers either take turns handling the same tool/computer or lock a computer file or part of it for editing on different computers. Our idea is to find a way to allow the engineers to work on the same system at the same time using a minimum of locks of none at all. For this, we propose a system (described in depth on the next sub-section) that allows real collaboration by mimicking how people handle physical tools and prototypes. In the future, we want to study the interactions between the users when presented with a real-time updated representation of the system and the links to physical objects interaction. In a conventional system, the user that has the input device is the only one that can control the system. If another user wants to input, they have to switch who is holding the input device – the token. On the other hand, if the model is physical, the users can not physically handle the same piece together. A natural flow of information occurs between the users avoiding collisions. We want to study those two situations and create a virtual equivalent which is adapted to the situation: we want to study how the users handle a token and how they handle collisions/resource concurrency. Some similar studies have been made [72][75][204] but are different from this one in the following aspects: this study puts both humans on an equal position instead of a master/slave position; also, it does not give the users the knowledge of the whole puzzle, forcing them to cooperate; this study focuses on studying collaboration and not human learning and this study intends to be a pilot study on which to build better collaborative engineering tools. A prototype is being built to allow us to study those issues. This prototype runs on an iPad (2 and above). Unity3D is used as the framework which allows us to deploy on any other tablet system or even desktop systems (the later losses some key capabilities such as portability, inertial sensors, etc). Vuforia is used to enable marker tracking. The tablets are connected via Wi-Fi and communicate the position and orientation of any moved piece to keep the simulation coherent. In a first stage we are trying to find out how users behave on a collaborative jig-saw puzzle which purposely creates collision/resources concurrency. We then intend to work it up to a more complex system that better resembles an engineering tool. This system will allow the users to create and manipulate a model based on simple primitives and simple transformations. This is a simplification of engineering tools, but what we want to study is collaboration-related which can be tested on a simpler model. To achieve the first stage, we built a prototype which shows up a number of pieces on the screen. The state of those pieces is replicated to all the clients on real-time. This means that any alteration that a user makes is propagated, in real time, to all the other clients. As soon as a user touches a piece on the screen, that piece is locked allowing only him to move it around – this simulates a user grabbing a physical object. This state is informed to all the users by highlighting the piece, green for the one that can move it (the current owner) and red for all the others. All the other pieces can still be moved. This is used to study how the users handle and negotiate the tokens (the ownability of a certain piece). To add realism, all pieces are physically simulated. This means that pieces collide, have drag, and can even move other pieces when colliding. The navigation is made by tracking a marker on the table using the tablet's camera. This allows the users to easily and quickly navigate around the puzzle while solving the puzzle on the tablet's screen. To study resource collisions and concurrency, we developed a test where two users build a puzzle. First, the pieces are randomly numerated (there is no visible and guessable pattern) so the users cannot guess their correct position. Each user is told where half of the pieces need to go and are oblivious to the correct position of the other half. The pieces start shuffled and on top of one another which requires the users to handle pieces that are not their own or ask the other user to move them in order to reach the ones that are. This creates the resource collisions and concurrency that we want to study. This first test is based on equal roles for both users. No user is ever forced or even suggested to rule over the others during the test since the test presents an equal environment with equal opportunities for both users. This is still true even if more users are added to the test (up to the limit set by the number of pieces from the puzzle).

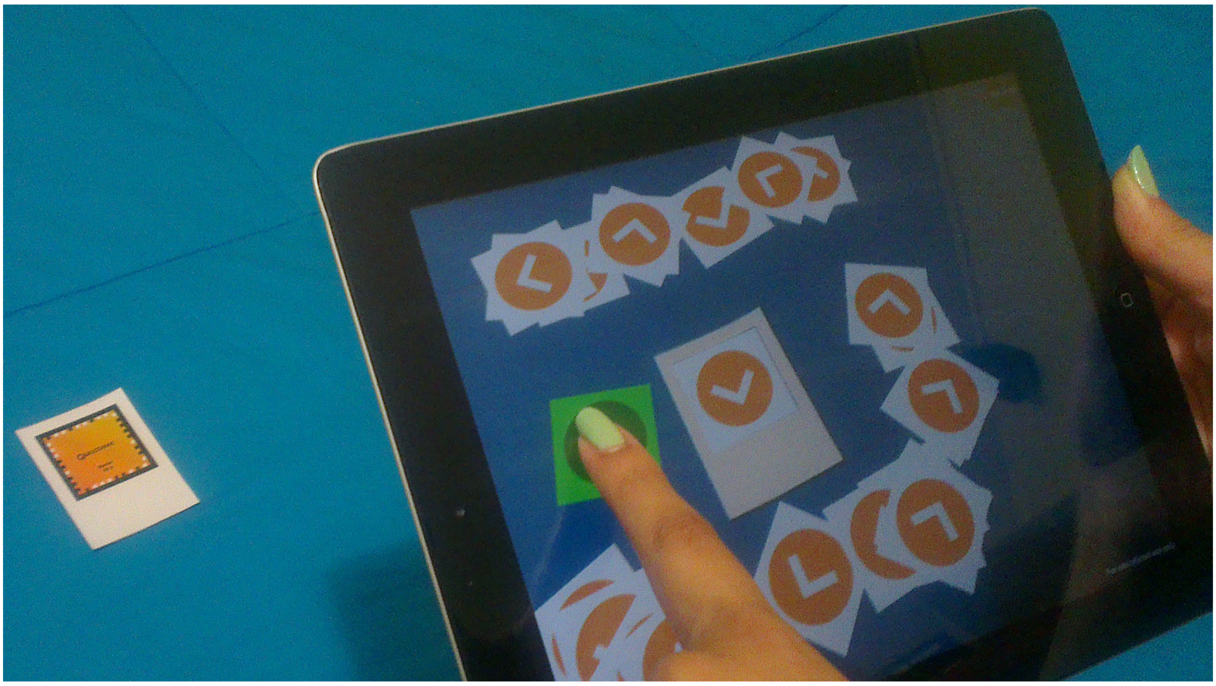


Figure 4.9: User testing the collaborative prototype. The tablet's camera is tracking the tracker allowing the user to "film" the virtual world while controlling the puzzle pieces with touch

4.7.2.2 Technical Issues

We intended to develop these tests using markers to allow the users to naturally handle a physical object as well as the iPad. This would work as an enhanced-reality window. Unfortunately, Vuforia has a very small limit on the number of markers it can track at any time (about 5), which makes it impossible to develop tests that handle several tens of pieces at the same time. We reached a middle ground using a single tracker and handling the pieces on the tablet screen. The tracker gives the users a visual and physical artifact that identifies the position and orientation of the workspace while allowing a fast and efficient navigation through it. The pieces are handled with natural gestures (you drag and rotate the virtual pieces as you would do with a physical one) on the screen. This issue ends up solving the inconsistency issue that would arise from having physical pieces: when a remote user moves one piece, the local physical piece would not move, creating inconsistency between the physical models. Still, a partial solution was developed: the tokens should have a physical and a virtual representation. They should all start in similar positions on all clients, allowing for the virtual representation to sit on top of the physical representation through the tablet's camera. When a user moves a physical token, his own virtual token moves to accompany the physical one. On the remote sides, the virtual token will also move, but the physical ones, obviously, will not. Instead, a line should connect the virtual token to the physical one, informing the users which virtual token links to which physical token. The user is given the chance to fix the tokens' position by moving the physical token to the correct position without interfering with the remote tokens, hence maintaining coherence between all users while regaining local coherence.

4.7.2.3 Measurements

Several measurements can be done in this experiment. The ones that interest us are the following:

1. Measurements that are automatically logged:
   (a) the amount of pieces moves;
   (b) the amount of own pieces moves;
   (c) the amount of colleague pieces moves;

    (d) the amount of collisions (user trying to move a piece that is locked) and
    (e) time to completion.

2. Noted by the person doing the experiment:
    (a) colleague piece move requests to be completed by the colleague;
    (b) colleague piece move requests to be completed by self and
    (c) colleague piece move requests with ambiguous actor.
3. Interview based:
    (a) the level of collaboration and
    (b) the level of frustration.

All the measurements are done by user and not by experiment. Measurements 1a) through 1c) will give us an objective measurement of collaboration. However, this measure has to be linked with 2 and a timestamp, otherwise we cannot tell if a user moved a colleague's piece to help to get it out of the way or for any other reason. Measurement 1d) will help us study resource collisions and how users handle them. All the 2) measurements will give us a less precise but better insight into what kind of communications the users naturally use, solve conflicts, and achieve a common goal. The interviews are used to give a global and subjective view of the results.

4.8 Navigation

The CEDAR system offers two natural and easy-to-use alternatives to navigate the virtual environment and manipulate the visualization. Users can either use gestures combined with a BCI device to interact directly with the projection or use an iPad device synchronizing its view with the large screens. Users in front of the Large Screen Display are tracked using a Microsoft Kinect depth camera, enabling them to point at specific locations on the 3D scene. Pointing gestures use the Kinect-computed skeleton. A ray is cast from the user head position to their hand position, over the screen to define a 2D cursor. Currently, only one active user is supported within the range of the Kinect camera. Using an Emotiv Epoc device, the user can trigger via a predefined brain

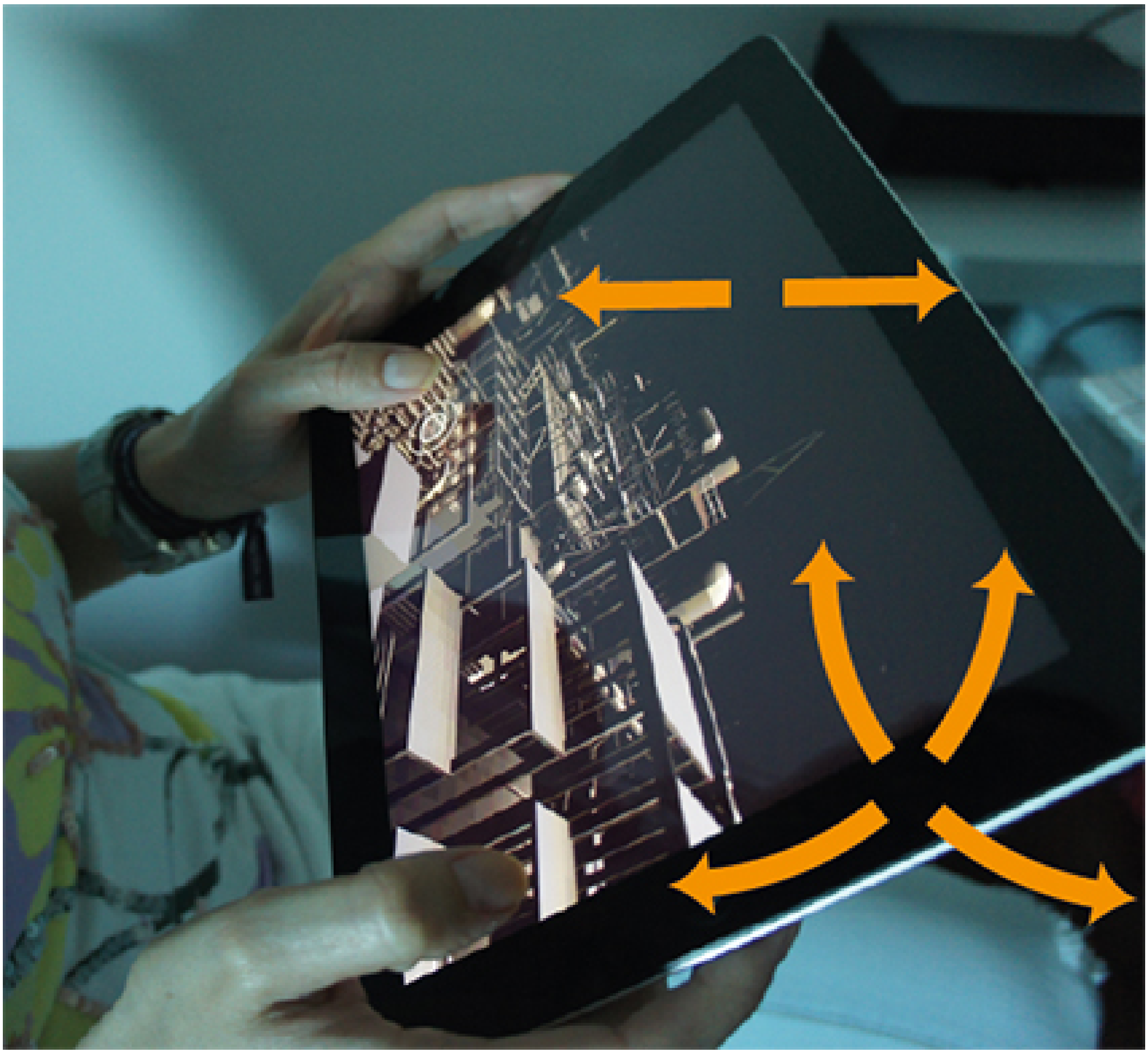


Figure 4.10: An early navigation method using two virtual joysticks

pattern to move to a specific location on the 3D scene or issue other commands to the graphical user interface, such as (un/)sharing the view with remote sites. The iPad navigation uses the device built-in inertial sensors to aim the camera in a first-person view mode, as if the user were holding a real camera to visualize the scene. Combined with an on-screen joystick, users can move around the scene as illustrated in Figure 4.2. This joystick is exponentially scaled to allow both fine movements on the center of its working area and rapid ones at its outer edges. This allows for fine navigation while examining small structures as well as very fast navigation through large models. We also provide a ”camera-freeze” mode allowing users to freeze the current view and move around the tablet without their movements changing the camera position on the large screen and without assuming stressful body postures. Further details regarding such technique can be found in [205]. In terms of capabilities and pitfalls, the First-Person View is best used to navigate through the models, if they are navigable (for instance, the model of a boat) but the Bird's Eye View should be used when showing an object, like a valve (since there's nothing to navigate about on a valve). The Bird's Eye View can also be used for a broader, tactical view where a big model is to be demonstrated as a whole (even if that model is navigable. The First-Person View is more stable (it depends on sensors that usually work on 60 to 100 Hz while still maintaining accuracy), while the Bird's Eye uses a camera that usually works at 24 Hz (frames per second), which might have some blur from the last frames and losses accuracy with distance. Still, the kinetic sensors are noise prone and use algorithms that introduce some delay. This way, fast movements may not feel so natural and responsive. Less noticeable, but still present, are the orientation artifacts that come from very sudden movements that confuse the accelerometer or those that come from a strong magnetic source that confuse the magnetometer.

4.9 User Evaluation of two Interaction Techniques

4.9.1 Experiment Group 1 – Interactions Technique

4.9.1.1 Introduction

Collaboration and coordination are a crucial requirement of any engineering workflow. These requirements are essential not only between groups of engineers, but also towards other team members as well. More challenging issues arise when the team is distributed throughout different geographic locations. In those situations, the team requires efficient and user-friendly remote collaboration tools that enable them to continue working as if they were face to face. Things may get worse when the remote location is the strict definition of “remote”, which is precisely what happens with oil platforms. In the oil industry, another requirement is therefore added: the need for small and portable devices while still maintaining processing power, communications and good energy autonomy.

Figure 4.11: A more recent navigation method using the iPad's orientation to look around and a virtual touch joystick to move around.

4.9.1.2 Experimental Setup

In order to compare the two different conditions (multi-touch-only and multi-touch coupled with accelerometer-based input), we conducted an experiment with eleven participants (three female users), all civil engineering final year students. Participants were 21-32 years old and only one was left-handed. The testing began after an initial briefing session of about fifteen minutes. We used a within-subjects experimental design where the participants performed two tasks (T1 and T2, described below), under two different conditions: multi-touch-only and multi-touch coupled with the accelerometer-based input. For the sake of brevity we will refer to these two conditions (our independent variables) as MT and MT+A. In a random order, half of the participants performed the tasks under MT and then under MT+A, the other half performed the tasks under MT+A and afterwards under MT-only. Every participant started out with Task 1 (simpler than

Task 2) and then moved on to perform Task 2. Both tasks were specifically designed in close cooperation with engineers and researchers at a very large oil industry company, with the specific goal of attaining task cases that would constitute a representative sample of the type of activities faced in the real world quotidian endeavors of oil platform engineers. In other words, our project's demonstrator subteam validated them. For each trial session, we measured the task completion time, the number of errors and the answers to a 5-point Likert scale survey about the two different user interfaces. Therefore, the experiment was a 2 x 2 repeated measures design with 2 user interfaces (MT and MT+A) and 2 tasks, T1 and T2.

4.9.1.3 Task 1: Navigating through a path

Participants started out by performing this task, which is simpler than task 2. In this task, all that the participants need to do is simply navigate through a path that is highlighted on the virtual floor of the platform, until they reach a certain spot. The task is obviously considered complete when they reach that spot.

4.9.1.4 Task 2: Placing a new device

In this task, an engineer is going through the decision-making process of placing a new device in the oil platform and choosing the best location to place it in the platform. He has to navigate through the platform taking measurements and then analyze several possible locations to find the best spot to place the new device. The task ends when the user indicates the chosen spot.

4.9.1.5 Task Completion Times

As mentioned before, task completion times were measured and Figure 4.12 shows the obtained results for the average completion times in the different conditions and tasks. In order to determine the statistical significance of these differences, we performed a two-versus MT+A) which was found to be significant with F1,10 = 5.8, $p < .05$. Under the MT condition, participants took 167.5s to complete the tasks, whereas under the MT+A condition they took 143.1s. As expected, the average completion time for task 1 was lower than task 2 (53.7 seconds versus 256.8 seconds). Therefore we concluded that the average task completion time was significantly lower in the MT+A condition. This is inline with the following results and suggests that the accelerometer input is a good solution to couple with the "move forward/backward" touch-based joystick.

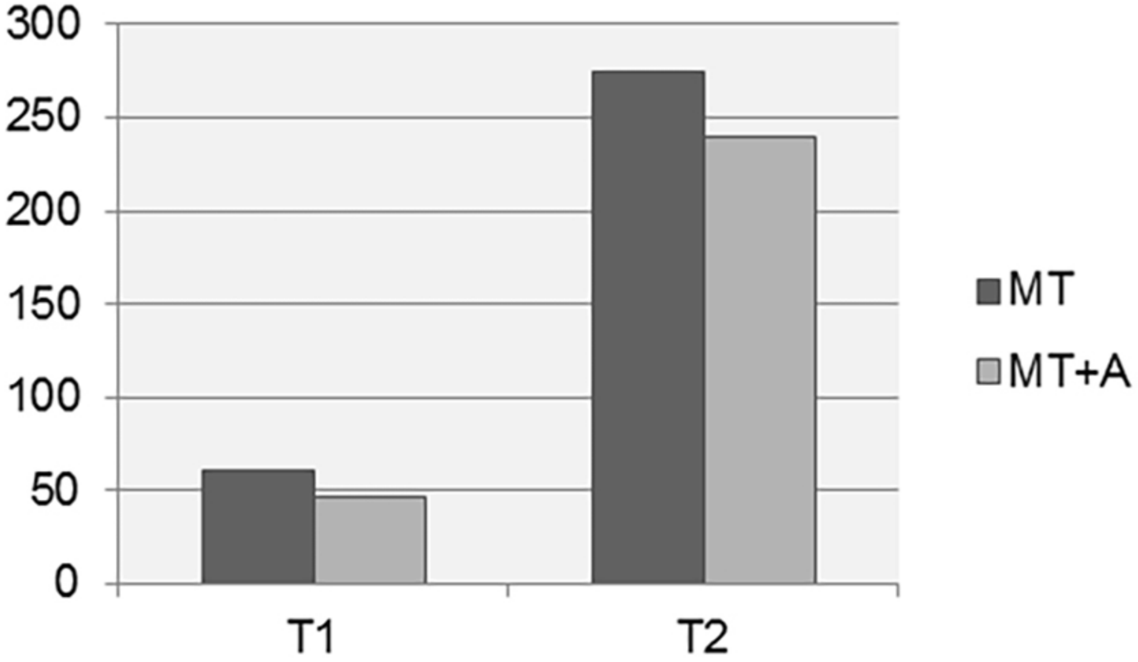


Figure 4.12: Average task completion times in seconds

4.9.1.6 Number of Errors

For this experiment, we defined the number of errors committed by participants as (i) the number of times the user deviated from the predefined path along the oil platform, for Task 1; and (ii) the number of times the user deviated from his/her desired path along the platform when trying to find a spot for placing the device, plus the number of times the user moved backwards beyond a certain threshold. This number was measured for each condition, and the results are illustrated in Figure 4.11. We performed a one-tailed t-test to assess whether or not the MT+A condition produced significantly fewer errors than the MT-only condition, at a confidence level of 95%, and we obtained t(10)=1.72, p=0.147 for Task 1. For Task 2, we obtained t(10)=2.08, p=0.012. Therefore, we conclude that the differences in the mean number of errors were not statistically significant for the first task, but were significant at 95% confidence for the second task.

4.9.1.7 Survey

After the testing phase, participants were asked to fill in a short survey with 7-point Likert scale with four questions:

1. The interaction style was easy to understand.
2. The interaction style was perceived as fast.
3. The interaction style was easy to use.
4. The interaction style was perceived as accurate.

The resulting qualitative data is shown in Figure 4.12. In general, participants perceived the MT+A condition as being easier to understand and easier to use than the “joystick”-based multi-touch-only user interface. However, the MM-only condition was perceived as being more accurate than the MT+A. With the regard to the perception of how fast a given interaction style is, we observed that the difference is very small.

4.9.1.8 Conclusions and Future Work

We presented a novel multimodal user interface specifically conceived for supporting the design and review of large engineering models at oil platform industries. We evaluated two different conditions: using multi-touch-only input and using multi-touch coupled with accelerometer-based input. Statistical analysis of quantitative data suggests that the second condition is faster and less error-prone than simply using multitouch input. Additionally, qualitative data showed that users perceive the multi-touch-only interface as being more accurate, but more difficult to understand and to use. The main limitation of our study is related to being performed in a controlled laboratorial setting. More research effort should be concentrated on the real world usage of such a system. However, the feedback from the research and engineering team at the oil industry is very positive regarding this solution, especially as it allows the navigation and annotation of the platform model in a mobile context, without loss of performance and in a collaborative way, using both Bluetooth and Wi-Fi communication protocols. As for future work, we are implementing and evaluating multi-modal annotations to the 3D oil platform model as a way to improve the reviewing engineering process. Sketches, camera-based and audio-based input could be used to achieve interesting solutions that better support the needs of offshore engineering teams.

4.9.2 Experiment Group 2 – Navigation and Review

4.9.2.1 Introduction

In order to evaluate user performance when navigating and reviewing the 3D model in a collaborative way, we conducted a series of user studies to assess the influence of the prototype's collaborative features on the completion times in collaborative 3D design and review tasks.

4.9.2.2 Participants and experimental design

A total of 29 subjects participated in the experiments in the age range of 21 to 31. A within-subject design was chosen for both tests, meaning that each participant evaluated the prototype in all the conditions. Although the current prototype allows audio-conferencing within the application, our experimental set-up did not use it, as network reliability could bias the results. Thus, the experiments were conducted in a way that did not allow any visual contact between pairs of users (guides and navigators), but allowed audio communication. This was achieved by having a thin wall separating the users.

4.9.2.2.1 Tasks Each pair of participants was given a brief (less than 3 min.) introduction to the system and to the interaction styles employed. Each participant had to play a role of guide and navigator, in random order, and both using their own tablet, which had exactly the same specs. As a guide, the participant was asked to conduct the other participant (the navigator) using voice indications so that the navigator could virtually walk through the 3D model passing by specific targets (e.g. a gas recipient, the top of a tower, a helicopter landing spot etc.) in the least amount of time as possible. In the guide view, the specific targets were made visible as cubes that changed from red to gray as the navigator reached them. These cubes were not visible in the navigator view. As a guide, the participant used the bird's eye view mode, as a navigator, the participant used the first-person mode.

4.9.2.2.2 Data gathering and analysis For later analysis and gathering of quantitative data, a server-based logging system was implemented, which automatically recorded the following parameters every frame: timestamp, the position of each user, and his orientation. Therefore, after the end of the experiment, it was possible to create a map of all navigational courses performed by the subjects, which facilitates the analysis of the different experimental modes (cameras and avatars). Completion times were also recorded and were statistically analyzed. Overall, the experiments took between 30 and 45 minutes for each pair of users.

4.9.2.3 User Evaluation

Both a qualitative and a quantitative evaluation were performed. We have not reached a large enough sample to publish any statistically significant results yet, but we provide some relevant qualitative assessments, user collaborations and we did reach some conclusions about the direction of the work. Besides some small, short and free tests, we conducted two major and organized user experiments. The first evaluation is qualitative in its nature and tries to understand user preferences on the interface usage, navigation, and interaction modes and also its collaborative features. The second evaluation is more restricted than the first one but also more organized and controlled. It is a quantitative and qualitative comparison between three collaborative modes to determine what on which one users perform better.

4.9.2.4 Experiment A

4.9.2.4.1 Introduction The first experiment used a sample of 18 users performing collaborative tasks in pairs. The user age ranged from 27 years old to 31 years old. The users had computer skills ranging from common-skilled users to computer experts. Most users had some degree of skill with touchscreens, but one admitted not to have any experience. Smartphone experience was very high and tablet experience medium. The same user that had no experience with touch screens also had little experience with smartphones and tablets.

4.9.2.4.2 Experiment Description This test requires one of the users to navigate the other user into finding a cube with a 3m side, using his/her voice, sharing each other's viewport, and viewing each other's avatar. Only the user that is navigating the other user to the cube can actually see it. And only the user being navigated to the cube can trigger it. This experiment provides the users with complete free will on choosing how to achieve the goal by using the prototype, as long as the users cannot physically see each other.

4.9.2.4.3 Results We gathered a large body of user preferences, critiques, and remarks: Some users found some resistance to the novel way of interactions but, after getting used to, they did find it more easy and fun to use than traditional touch-based only interfaces. The exception is the joystick that seems to cause some trouble to the users who are less experienced with game inputs devices. The users preferred the Viewport sharing over the Avatar. The probable reason for this is the fact that both users were both in the First-Person mode and the model has a lot of obstacles rendering the Avatar invisible most of the time. It is only when the users are nearby each other that they can take advantage of the Avatar. Curiously enough, while some users complained that the orientation moved too slow (1-1 ratio), one of them did complain that the orientation actually moved too fast. Since all users preferred the First-Person mode over the bird's-eye mode, they did not have many remarks about this mode, but they also found this mode intuitive and fun to play with. The main complaints came from a technical point-of-view: marker tracking problems and one complain about the maximum angle it supports. The user suggested using a sphere or a cube as a tracker. That option was thought of in the beginning but was discarded since the tests are conducted above water, on top of a ship. This way we saved time on implementation. The expected navigation mode to navigate the model was the First-Person mode and was actually chosen by everybody. The mode most used by the guide was also the first person mode, going against our initial feeling that users would prefer the birds-eye mode. One explanation can be that the users felt it would be easier to navigate the model in the First-Person mode and guide the other user as if they were doing it physically instead of going to a mode (bird's-eye) where they could see the entire 3D model and could guide the other user through it as if looking at a map and planning a trip.

4.9.2.5 Experiment B

4.9.2.5.1 Introduction The second test used a sample of 11 users (one gave up) also performing collaborative tasks in pairs. The user age ranged from 21 years old to 29 years old, 3 being female. The users had computer skills ranging from common-skilled users to computer experts, most of them being on the expert side. Most users had, at least, some experience with touch screens, smart-phones and tablets being the touch-screen experience good between most of them. Once more, experience with tablets was the lowest of the three conditions were used, each test going through them in a different order: (a) using camera-sharing and avatars, (b) using camera-sharing exclusively, and (c) using avatars exclusively. Additionally, one of the participants acted as a guide while the other one acted as a navigator, in order to simulate a real world situation where two engineers are remotely reviewing a design problem, navigating through the model while talking about it. The order of roles (guide/navigator) and conditions (a, b and c) were counterbalanced and randomized across all subjects. Every participant had smart-phone interaction experience, but only two of them had tablet interaction experience.

4.9.2.5.2 Experiment Description This was similar to the previous one in the aspect that it had the same goal (one of the users had to navigate the other user into a cube with a 3m side), but the conditions were much more controlled. In this case, the guide was required to use birds-eye mode to help the other user navigate through the model. The user navigating the model was explicitly required to employ the First-Person mode. Only the guide could use collaborative features except for the voice communication that was always on, no matter what the user role was. In this experiment, the guide used, besides voice, the Avatar and the Viewport sharing in any of its three possible combinations. These combinations were iterated in randomly different ways with each pair of users, to avoid biasing the results with training. All the pairs of users performed every combination, but each user had only one role (mainly because of user time constraints).The relevant aspects of the user interaction with the prototype were automatically logged and at the end the users were asked which collaborative feature they enjoyed the most.

4.9.2.5.3 Results In this experiment, most of the users preferred the Avatar. The reasons pointed by the users were that the avatar would indicate the user position and direction on the ”map” (keep in mind that the guide is on a mode - the bird’s-eye mode - that resembles a 3D map) and would also allow the guide to keep an eye on the goal. The users would also point out that the Viewport sharing could actually become disorienting. One of the users preferred the Viewport over the Avatar. Most users ended up ignoring one of the features when both were active, but, in some conditions discussed below, they would keep an eye on both. Some interesting sentences used during the tests indicate the immersion and the cooperation feeling of the users. Sentences such as ”Let´s go to (...)” were used. Keep in mind that the Guide is not moving together with the Navigator. Moreover, sentences directly indicating the usage of landmarks were sometimes used. For instance ”Do you remember of Landmark X?” or ”Go to Landmark X”. Some users complained about how tiring the handling position was. This was also noted in previous pretests and one solution we found was to relax the vertical axis. Instead of the normal 1 to 1 ratio of movement, the iPad would react more quickly, demanding less vertical movement from the user. Also, all users shared a relaxed position midway between vertical and horizontal. This position will be used as the pointing forward position since it is the most used on the prototype as well the less physically tiring. The usage of landmarks as reference points seemed to aid significantly on orientation, while users that did not use this kind of communication would, sometimes, have trouble knowing where everything was. Moreover, when good landmarks would be used, a quick model-wide transversal could occur with a single short sentence. For instance ”go to the heliport”. Good communication from both sides would decrease uncertainty since the guide would know what the navigator was thinking and could fix mistakes beforehand. The usage of both modes (Viewport and Avatar) helps to reduce disorientation and, if used correctly, it can reduce the problems of each mode. For instance, a guide could use the remote viewport when the Avatar was hidden under something, then use the Avatar for fast movement, and, finally, the Viewport again for a fine, depth-sensible, trigger of the goal. When the users did not take full advantage of the three dimensional proprieties of the model to aid in the guiding they would lose some sense of depth. The user would basically end up using a 2D version of the model. The users were aware of the capabilities of the mode but tended to forget about this. Maybe it is more of a training issue. One interesting fact is that the users who thought outside the box and actually moved to the outside the box would end up having a better orientation. ”Moving outside the box” means that the user would leave the virtual testing area and would ”fly” into to the sky to be able to view the whole model, which is a big ship, and get more visual cues and landmarks. This happens because of the complexity of the model, the lack of visibility due to obstacles, and because the users were seeing the model for the first time. Some issues could increase sample noise. For instance: if the user did not have enough dexterity to use a joystick (it did happen) the completion time would increase, not because of the mode itself, but because the user would overshoot his movements most of the time. Another example is when the user is overly careful. It may seem as a good thing, but being too careful means that the user moves slower than he could, increasing, once again, the task completion time.

4.9.2.5.4 Results The time each user took to get from the first goal to the next one was logged. Since the goals are placed in a random fashion, to avoid training, the distance between the current goal and the next one is also logged. Therefore, the dependent variable cannot be simply time. If the next goal is too far away, the user will take more time to reach it, but he can, actually, be more effective. The dependent variable called score (s) is defined by the formula $s = \delta t / \delta d$. This score is no more than the amount of time the user took to make the non-constant distance between the current and the next goal. Longer times for the same distance increase the score. If the time is kept constant, longer distances reduce the score. This means that the higher the score, the worse the user performed. Despite not having enough samples yet to have any statistical significant results, plotting a whisker boxes plot (Figure 4.13) shows a tendency of the avatar being the fastest mode to guide another user through the model, the Viewport mode being second and the mode with both active at the same time being the one to exhibit longer task completion times. These Avatar vs Viewport results were expected since using bird’s-eye mode, keeps both the navigator’s position and the goal in the guide’s field-of-view at the same time. It also provides the user direction relative to the goal in an unequivocal format. On the other side, the Viewport sharing does not display the goal unless it is close and directly in front of the user (the guide can still use the birds-eye mode to know where the goal is but he has to find out where the user is using visual cues from the environment which can, sometimes, be deceitful). It can also be disorienting since fast rotating movements can be performed by the other user movements which can be hard to follow by someone that is not making them. These rotations can be made worst if the user is navigating a tight space that gives a very small field-of-view. Additionally, the guide has to keep looking at the ”map” (the model), the goal, and the camera, splitting his focus and demanding more context switches. The combination of the Avatar and the Viewport sharing coming in last was actually a surprise. The combined usage of the two modes was expected to improve task times, but it seems that the untrained user tends to ”overswitch” modes or stick to one mode (ignoring the other completely) instead of using each of the model's strengths. Nevertheless, the sample size is still too small and these results overlap too much to exhibit a strong statistical significance.

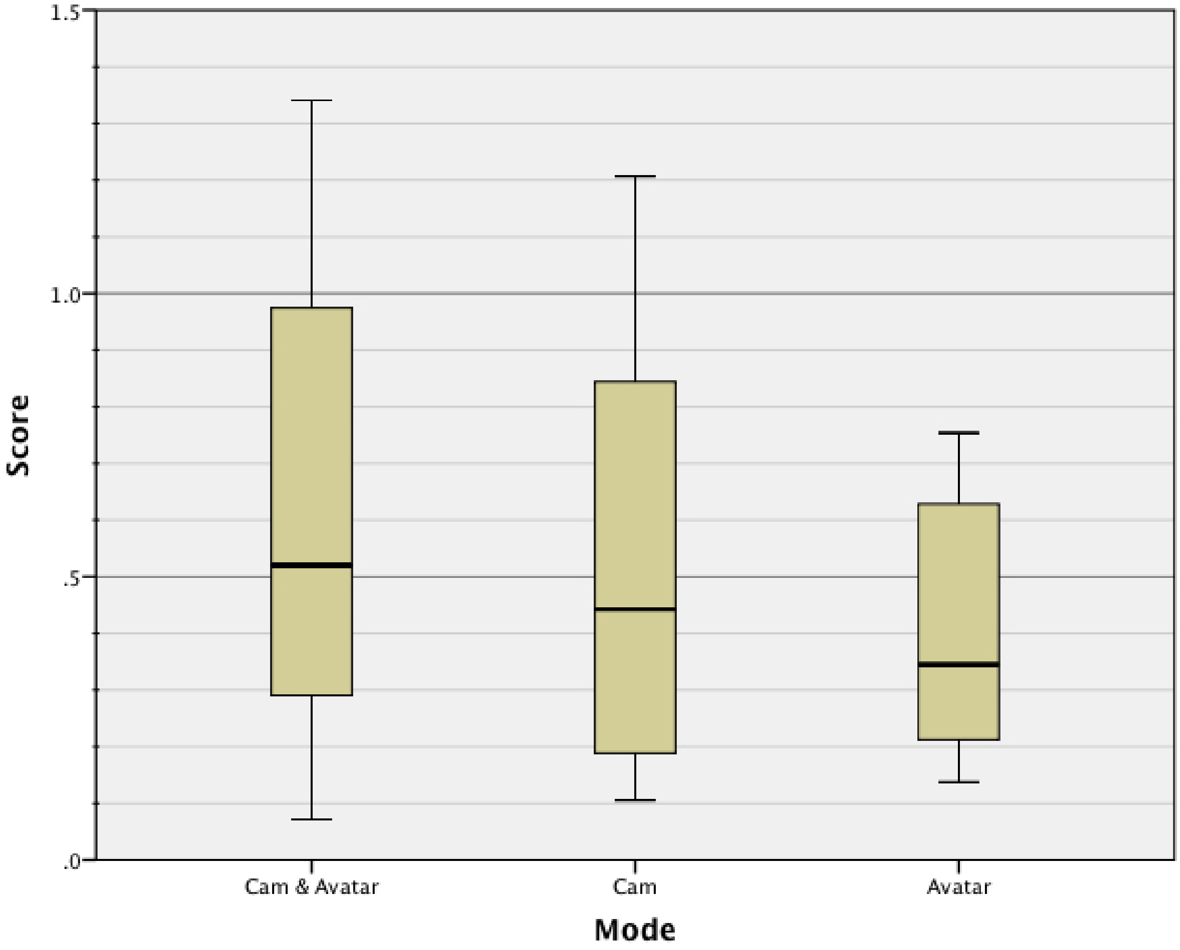


Figure 4.13: Whisker-plot showing a small tendency of performance order using the different collaboration modes

4.10 Collaborative Design Review using a Large Screen Displays and Mobile Devices

4.10.1 Introduction

Virtual reality and multimodal user interfaces have revolutionized the way we work by combining different input modalities [35]. Together with large-scale displays, these offer ideal environments for co-located collaborative work. On the other hand, multitouch technology has become mainstream and tablet-based multitouch has emerged as a mobile interaction style standard, especially due to the success of products such as the iPad. Such devices provide a fertile ground for the exploration of powerful remote collaboration solutions. The combination of large environments and mobile devices allows the development of an integrated solution for teams that are geographically dispersed to work collaboratively. Despite these significant advances, most of the interactive technologies deployed in real-world design and engineering contexts are still regarded as being difficult to use, especially when engineering teams need to collaboratively visualize and review large scale CAD models. This is the scenario of the oil industry, which necessarily involves large teams that review, manipulate, and discuss around large CAD models, which are sometimes difficult to visualize and navigate through. These teams are usually composed of engineers that are in the field working together with several other engineers in a central location. We argue that combining mobile devices and a large-scale environment, while taking advantage of natural interaction techniques [45], can provide a good solution for the collaborative review of CAD models within the oil industry. We present a novel integrated virtual reality system (CEDAR) designed to support design and review tasks using mobile devices and large-scale display (e.g. engineers at the offshore oil platform, as depicted in Figure 4.1, working with engineers at the central office in the mainland). Figure 4.1 illustrates the usage of the CEDAR system in the field, where two remotely located engineers collaboratively navigate through the Virtual Reality model. This paper is organized in the following way: First, we review the state-of-the-art in three different aspects: (i) solutions for visualization, design, and review of CAD models both in large-scale environments, (ii) the usage of small screens and inertial sensors on virtual reality environments and

(iii) collaborative solutions for the engineering design context. Secondly, we present an integrated specifically conceived through close collaboration with researchers and practitioners at a large oil company. We also describe the results from a user study where we performed a qualitative study of such solutions. We conclude by describing some of the lessons learned and outline novel research avenues for the near future.

4.10.2 Usage Scenarios

Since we aim a specific domain solution with real-world application, not a lab prototype, we organized a short task analysis involving real users. From interviews and informal talks with engineers working in the oil industry we were able to clearly identify challenges to be tackled and real usage scenarios. In the following paragraphs we present our conclusions regarding interactive environments for engineering design review in the oil industry. Currently, engineering teams use mostly standard CAD tools, controlled with traditional interfaces. However, the location of elements in a 3D model of an oil platform using the standard movements of CAD software with mouse and keyboard requires some training from the user, which has to get used to specific commands. Tablets, in the opposite, do not have a keyboard and mouse, but have accelerometers, gyroscopes, and multi-touch support. These devices allows the user to quickly learn how to navigate in a scene very naturally. Engineers are already familiarized with this kind of devices, since they use them for several different tasks. Thus, they are keen on complementing their traditional interfaces with more natural and easy-to-use interaction environments. Due to the large diversity of tasks performed within the design review process, we focused on three different kinds of tasks, frequently performed. These are device maintenance, path validation for large volumes, and exit path checking. Maintenance in specific devices inside an oil platform is very frequently, and the engineers have to plan how to access the device, and very often they need to remove and install a new one. The major goal is to visualize, in loco, the maneuver to repair a device and better understand possible interferences that are not mapped in the 3D model but are in the real scene. Besides that, the access in the oil platform is limited. Then just one person in the local would be enough to communicate with an entire team in-shore. Other important usage of the proposed navigation solution is the transportation of large volumes. Since the oil rig has several pipes and devices spread all way around is essential to check if a large volume can pass through the squeezed paths inside the plant. The visualization from the original point until the final place can be entirely simulated, avoiding losing time on searching a way to reach a certain location, or damaging parts of the oil platform, which can lead to a severe accident. Since the tablet is available locally, the transportation simulation can be double checked instants before the final procedure, checking if an unplanned object is on the way, like a barrel or some other object. One other example is the possibility to check several exit paths for the oil-platform personnel in case of an accident. The virtual navigation across the narrow aisles allows a better planning for evacuations, this is extremely important since the environment is very dangerous. This procedure can even be used to train the people in the oil platform, to better explain what they are supposed to do in an emergency. Within the contexts described above, we propose an approach that combines a large-scale environment with mobile devices to provide an efficient and easy to use collaborative CAD engineering tool. Instead of relying on the latest lab prototypes, the solution we devised takes advantage of recent, but already available outside the lab environment, technologies and devices.

4.10.3 CEDAR System

The solution proposed for this consists of a multimodal interaction room in the headquarters complemented by mobile devices to be used by engineers in remote locations and by team members at the control center. After presenting an overview of our system, this section describes our navigation techniques designed to be natural and easy-to-use, considering both visualization scenarios while supporting collaborative engineering project review.

4.10.3.1 System Overview

To address the user requirements defined in the previous section, the CEDAR system follows a star network topology connecting several clients to a central server as depicted in Figure 4.8. Two types of clients are considered in our scenario to interact with the virtual scene showing the CAD model under revision during the review session. The first type of clients are connected to the the main server using iPad devices and the second type using a desktop computer connected to a Large Scale Display (Wall). While the iPad client fosters mobility, communication, and individual usage, the Large Scale Display provides a unique visualization environment for several users discussing engineering problems at the headquarters. The main server is just used to coordinate the different clients and manages the engineering review session. It forwards both local and remote communications while logging relevant shared information. By using the client application, users can connect to the main server either locally or using the Internet and start sharing data between them. Therefore, using a local wireless network, users at the Headquarters (Control Center) analyze and evaluate the problem at first hand, while field participants can be connected via a broadband Internet connection to take part into the team discussion since we support two way audio communication. To ensure the necessary connection requirements, several steps were taken to overcome the bandwidth challenges which we will discuss in the implementation subsection. Our system was conceived to be an out-of-the-box solution with virtually zero configurations needed and able to be deployed on the fly. The simplicity of usage is especially important considering the needs of offshore engineering teams in situ.

4.10.3.2 User Interface and Navigation

The system aims at providing a natural and easy to use visualization and cooperation. To achieve our objectives, the iPad client user interface provides two navigation solutions: a first person view and bird's-eye view. These two view modes behave as if the user is holding a camera, which allows natural visualization and navigation. Despite an apparent similarity in interactions, the two view modes are quite different in both the technical and user interaction components. The first view mode uses iPad built-in inertial sensors to aim the camera in a first person view fashion, just as if the user was holding a real camera and filming around. This is complemented by an in-screen joystick allowing the user to move around as illustrated in Figure 4.9. This joystick is exponentially scaled to allow for fine movements on the center of its working area and rapid movements on the extremes. This allows for both fine navigation while examining small structures as well as very fast navigation through big models. The second view mode uses the iPad camera and a physical marker to track both the position and the orientation of the device relative to the marker. The marker is a simple image with invariant features for tracking purpose. This viewing mode behaves as if the user was filming the 3D virtual scene as it was on top of a table allowing natural movements around the marker image. This solution supports direct translation movement in an absolute referenced scenario, which cannot be done with the same accuracy using the previous built-in inertial sensor approach. Both accelerometer and gyroscope information are sensitive to numerical integration errors or drift, and even the current compass sensor is too imprecise to devise an absolute tracking solution. On the other hand, complementing existing sensors with other systems such as GPS was considered out of scope due to limited accuracy and unsuitability in indoor scenarios. The solution to use the camera to track the iPad regarding a fixed marker is both affordable and manageable, while it is accurate to support translation, rotation, and, indirectly, zooming without the need of another artificial input. In addition, such solution avoids the need of indirect manipulation paradigms as it is done by using the virtual joystick in the first-person view mode. Both navigation modes using the iPad are illustrated in Figure 4.10. At the headquarters, the main interface is provided by the large-scale display. The graphical user interface presents the current view of the 3D scene as well as the preview of remote views when the system is connected during collaborative sessions. In such a scenario, it is possible to use the iPad device to control the view activating the preview of the iPad on the whole display surface as depicted by Figure 4.11. In addition, both game controllers and a gestural based interface are supported to interact and manipulate directly the view displayed by the wall screen. We support game controllers such as the Nintendo Wiimote to rotate, pan and move forward and backward using the cross cursor button and the back trigger of the Wiimote device to switch between both rotation and translation modes. We also use a Microsoft Kinect device placed on the floor below the large-scale display to track users in front of the wall and enable to point specific locations on 3D-scene. Pointing gestures are supported using the Kinect skeleton tracking of user arms and computed using the ray from the user head position to the its hand position. Currently only one active user is supported within the range of the Kinect camera. This ray is then used to compute a 2D position on the screen acting as a cursor. By pressing the Wiimote button, the user can jump into specific locations of the 3D scene or interact with the widgets used by our interface (such as virtual buttons to connect to the server, or share the view). A different bimanual gesture mode was experimented using both hands as a cursor. While one hand was used as a reference, the relative position of the second was used to move in 3D. However, such method was not evaluated and the current system focuses on collaborative aspects around the iPad device.

4.10.3.3 Collaborative Features

Four collaborative features were implemented on the current version of our CEDAR system. These features aim to improve the collaboration between users by providing direct and indirect communication, visibility, and awareness. Below we briefly describe each of these features.

1. **Voice Communication:** this allows remote, natural communication between the users which is crucial to the success of the collaborative tasks as it will be assessed in our evaluation;

2. **Viewport sharing:** the camera of one user can be shared to other users allowing them to see what he sees. Suggested uses are: Displaying the location of small objects, guided tours and sampling knowing were the other colleague is at and what is he doing.

3. **Avatars:** an avatar representing the current position and orientation is presented on the environment. This allows a faster recognition of where the other users are located and what general direction they are looking at in comparison to the camera sharing. However, it requires the user to be on a position that gives him a direct view of the avatar. The avatar is better used with the second view mode but can work well on the first person mode if the users are close enough to each other.

4. **Camera freezing:** it allows users to freeze the current view and move around the tablet without fearing that the movements performed will change the camera position and without stressing body positions. This feature can be used when showing certain features on the models or even when working on the models themselves on future work.

While iPad clients support these four collaborative features, the system running on the Large Screen Display is intended to be a tool that takes advantage of its size to allow a better visualization of the objects being studied by the work team present in the room. For this reason, following a similar approach than the one used by the iPad, we currently only support two of these features: Viewport sharing and Avatars. However the Wall client also allows users to span the Viewport Sharing over the whole display area instead of only presenting it as a preview window. Such a solution allows to better explore the large-scale display and also enable a user to control the view using an iPad device in the room instead of interacting directly with the Wall through gestures. Regarding the Avatar feature, as depicted in Figure 4.2, we use a red sphere to show the iPad's position inside the 3D model complementing the preview, on the bottom-left of the screen, which shows the view from the remote user.

4.10.4 Conclusions

While the results of the user tests are quite positive and encouraging, we believe that further experiments must be carried out. The experiments described focused mostly on validating the collaborative navigation techniques, whilst testing the framework and the underlying communication requirements. To validate the whole solution we plan to organize a more complete study. After correcting some minor flaws identified during the last evaluation, we will ask engineers from the oil industry to accomplish complex tasks on a real-world context. From the results of such study we will be able to assert that combining mobile devices and a large-scale environment provides a good solution for collaborative review of CAD models.

4.11 Conclusion

Since this was a three year long project with multiple persons working under it, multiple papers spawned from it. On this chapter, it laid a compilation of the relevant conclusions we extracted from the research project. Supporting the needs of offshore engineering teams is an important industrial problem that should be addressed taking into account the rapid evolution in user interaction styles available. The potential for innovative solutions that is brought by tablet-based computing is enormous. The work described explores a combination of mobile devices, large-scale environments, and wireless communication to devise a novel solution to support collaborative design and review tasks in the oil industry. In the proposed usage scenario, a team of engineers in a control center must work collaboratively with engineers in remote field locations. The headquarters have a large-scale interaction environment, where engineers gather around a large display to work together. Through wireless connections, the engineers in the field use their iPads to collaborate with the team at the control center. The CEDAR system offers not only a framework to support this scenario, but - more importantly - also provides a unified user interface for both large-scale or mobile contexts. This interface allows a natural and easy-to-use interaction, aiming at improving productivity and collaboration among engineers. Since we were aiming at a real-life application rather than on a laboratory prototype, we chose to stick to off-the-shelf technologies. Therefore, besides using standard hardware, the core of the CEDAR system is the widely used Unity3D graphics engine, complemented by Vuforia augmented reality SDK and Speex codec for speech compression. Nonetheless, through a careful and well-grounded combination of these existing technologies, we developed an innovative solution to support collaboration for design and review of CAD models within the oil industry. Real users were involved in all phases of the development of the CEDAR system. Indeed, to gather information about usage scenarios, task analysis, user profiles and context, we conducted several meetings with researchers and engineers at a large oil company. To navigate the virtual environment, we propose two alternatives: iPads, that besides offering multitouch navigation can work as a second personal window on (or off) the scene while depth cameras and brain-computer interfaces provide novel approaches to interaction. To support remote collaboration between users, we developed a set of specific groupware features. We observed that none of the navigation modes we studied was perceived as being significantly better than the other. Each of them is adequate to a different set of tasks. To illustrate this, let us consider the following example: The camera tracking navigation mode can be used to present the model to a fellow engineer, allowing him to perceive where a given problem is located. Afterwards, the user can touch the position he wishes to go to and navigate around to achieve a better camera position (or in order to navigate indoors or even under tight spaces). Finally, the user can freeze the camera and start working with a single object that is yet to be positioned or removed from that location by using touch gestures. In other words, the interaction design follows along the engineers' workflow. The virtual camera navigation mode is the only mode that requires minimal training (about a few minutes). The main issue is the novel interaction style, since the users expected a physical joystick or any other kind of physical input; on the case of the tablet and in the absence of any physical input devices, users went for touch-screen interaction; this was essentially due to training (learning transfer) and pre-conceived assumptions. The second significant issue we noticed was related to the joystick. The users did not fully understand how to use it. This is fixable with a better UI design, applying, for instance, visual hints or cues. All the navigation modes studied have their applications and, from a qualitative perspective, were found to be easier, faster, and more intuitive than mouse/keyboard or joystick interactions styles. We highlight that storyboards and scenarios were an effective way to elicit requirements together with oil industry experts, as opposed to high-level task analysis. We also note that, among different navigation modes, none is highly preferred over another: They are each adequate to given contexts and conditions. Our main contribution to the Human Work Interaction Design (HWID) field is the comparison of the effectiveness of different work analysis and design methods to-wards establishing a common vision regarding a new product for the oil and gas industry engineering models' review, in a collaborative manner. This is especially important for gaining new insights about the relative advantages between the different methods in a highly complex, real world work domain.

Chapter 5

Advancing Virtual Reality for the improvement of well-being

5.1 Introduction

Virtual Reality has been having a very strong growth in both technological advancement and popularity in the last past few years. The screen technology is allowing enough pixel density to be usable in Virtual Reality and the CPU/GPU processing power is on the cutting edge of supporting those resolutions at a comfortable refresh rate. We are seeing the Virtual Reality moving away from research centers, military and other specialized targets and moving into gaming and the home entertainment industry. This is making Virtual Reality a relatively, cheap, yet very rewarding experience. Advances in technology make it so immersive and with a level of suspension of disbelief so strong that the line between reality and virtually is blurring. Now we reach at the real world where a lot of people live in big cities with no access to Nature and its healing and stress-releasing effects. And, to make things worse, we get to a pandemic that is forcing everyone indoors. We can harness Virtual Reality and its immersiveness to try to get some of those effects to those that cannot have it.

5.2 Comparing frustration levels between mouse and eye tracking based interaction

5.2.1 Introduction

Computer interface devices are continuously improving towards a more natural user interaction. Natural User Interfaces (NUI), unlike the traditional devices like keyboard and mouse, do not require training and familiarization. Devices like Microsoft Kinect (Microsoft Co.) and Nintendo Wii (Nintendo Co., Ltd.) are examples of this transition into a more compelling experience without the use of any mediatory devices that users have to learn to use and operate. Going a step further, eye-tracking interfaces using eye position and eye movement for pointing and selecting can act as Natural User Interfaces. Using an eye-tracker as a pointing device is a self-evident way of using the eyegaze as input in a computerized device. Studies conducted over the past three decades have shown that the performance of the eye-tracking devices has steadily improved in recent years [104]. A major improvement in video-based eye-tracker systems is the range of freedom given to the users head movements. Since these systems are essentially composed of video cameras and software, a substantial decrease in price is soon to be expected. Thus, these systems can potentially become part of future computers without major additional costs. Nevertheless current eye-tracking technology still fails to achieve fulfilling interaction with targets of recent applications or websites. The lack of overall performance might translate into frustration from the user's point of view. This frustration can be quantified for further analysis and performance assessment. Relating these two quantities (low performance triggering high frustration), a tool can be built for assessing future interactive systems that require speed and precision (intrinsic to user interfaces). Understanding the levels of frustration that users are exposed to can also give us an indication of the potential success of such devices. The evaluation of such a system can capture the effects on the user experience, quantitatively and qualitatively, by collecting extensive synchronized brain activity and behavioural data on users performance during the testing process. Additionally, such a system can provide us with extremely valuable data that can be used to propose a generalization of it for future systems that can eventually be used by all users, either for entertainment, education or general use. Technological advances in the synchronization of eye tracking gaze data and electrophysiological data like electroencephalographic (EEG) signals can be combined for scientific research purposes, market research, and a wide range of other application areas. EEG is already a multi-purpose scientific tool used for diseases diagnosis, biofeedback, medical applications and general scientific research. This technology and the data captured from it, can leverage the knowledge of where the users attention is focused (through the eyes) when an event is taking place. The hypothesis H1, that we try to verify, is that user frustration is higher when using eye-tracking as the input device instead of a standard mouse for common mouse tracking tasks. Our research used a questionnaire and electroencephalographic (EEG) data to analyze the levels of frustration in a sample of 10 users while they try to navigate through several labyrinths with a cursor controlled by eye-gaze or mouse system.

5.2.2 Methods

5.2.2.1 Hardware

5.2.2.1.1 EEG headset The Emotiv EPOC Headset is a neuro-signal acquisition and processing wireless neuro-headset with 14 wet (using a common contact lens liquid) sensors and 2 reference sensors being able to detect brain signals and facial expressions. An integrated gyroscope generates positional information, connected wirelessly through a USB dongle and comes with a lithium battery providing 12 hours of continuous use [109]. Detailed specifications are illustrated in Table 5.1. Sixteen (14 plus 2 reference) sensors are placed on the international 10-20 system [102], an internationally recognized method which describes the electrode placement on the scalp for EEG tests or experiments. Detailed specifications are illustrated in Table 5.1.

Characteristic	Definition
Number of channels	14 (plus CMS/DRL references)
Channel name (10-20 locations)	AF3/4, F3/4/7/8, FC5/6, P3/4/7/8, T7/8, O1/2
Sampling method	Sequential sampling, Single ADC
Sampling rate	~128Hz (2048Hz internal)
Resolution	16 bits (14 bits effective) 1 LSB = 0.51 µV
Bandwidth	0.2 - 45Hz, d. notch filters at 50Hz and 60Hz
Dynamic range (input referred)	256mVpp

Table 5.1: EEG Headset specification

5.2.2.1.2 Eye-Tracker The Tobii TX300 is an eye tracker that uses infrared diodes to illuminate the users' eye [101]. The back part of the eye, the fovea, reflects when illuminated, and this refection is then collected by the image sensor. Using this reflection, the eye tracker uses complex image processing to determine where in screen is the user looking. Detailed specifications are illustrated in Table 5.2.

Characteristic	Definition
Sampling rate (binocular/variability)	300 Hz / 0.3%
Latency	$\leq$ 10ms
Freedom of head mov. (65 cm) (w x h)	37 x 17 cm (15 x 7)
Max gaze angle	35°
Screen size	23" TFT
Screen resolution (Max)	1920 x 1080 pixel
Bandwidth	0.2 - 45Hz, d. notch f. at 50Hz and 60Hz
Response time	$\sim$5ms

Table 5.2: Eye-Tracker specification

5.2.2.2 Software

5.2.2.2.1 EEG Headset For acquiring the frustration levels, we used the Emotiv SDK. Emotiv uses a black box algorithm for the detection of cognitive characteristics in a suite called Affectiv. The Affectiv Suite reports real-time changes in the subjective emotions experienced by the user. Emotiv currently offers three distinct Affectiv detections: Engagement, Instantaneous Excitement, and Long-Term Excitement. The Affectiv detections look for brainwave characteristics that are universal in nature and dont require an explicit training or signature-building step on the part of the user.

5.2.2.2.2 Eye-Tracker The Tobii TX300 comes with several software programs. One of them is worth mentioning the Tobii Software Development Kit that enables the development of software to control the eye tracker.

5.2.2.2.3 Custom Made Software Since no current software was adequate for our research we developed our own custom software. It is composed of four main components: The Emotiv EEG interaction, Tobbi Eye-Tracker interaction, the test and a log. Both the Emotiv and Tobbi interaction components use their respective and commercially available SDKS as a base to communicate with the hardware. The logging

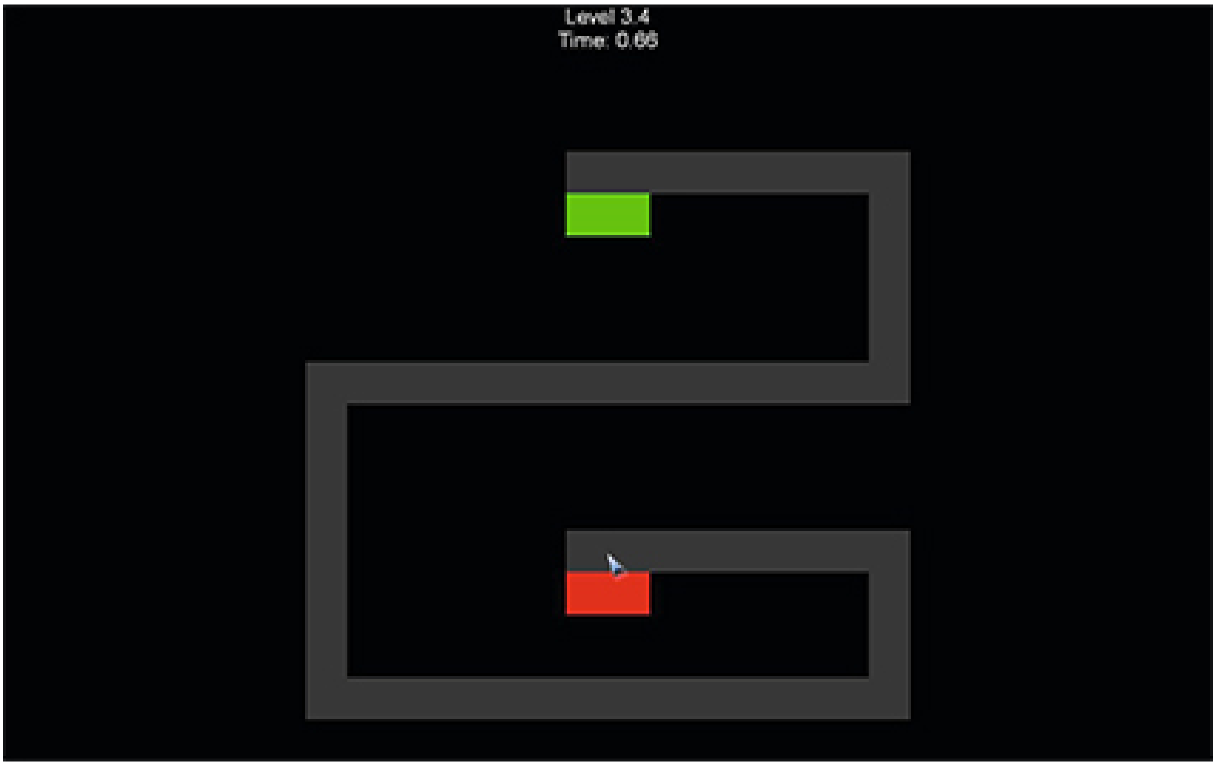


Figure 5.1: Example of a maze presented to the user

component logs the data enumerated in section 5.2.3 that is gathered from the EEG and the input method (either the mouse or the Eye-Tracker). Finally, the test component is responsible for merging all components, drawing the mazes and user interfaces, and implementing all the test logic. Figure 5.1 shows the visualization created by the software. It corresponds to the last maze of the least thickness. It illustrates an example of what the user has to traverse during the test.

5.2.2.3 Experimental Procedure

The tests are composed of a sequence of simple mazes in which the user navigates from the starting point to the end within the maze borders. If the user moves outside this area, the cursor position is reset back to the starting point. The mazes vary in thickness and in complexity (the number of curves/length of the maze). Every user navigates through a fixed number of different levels of varying thickness and increasing complexity. The first level of thickness is for training purposes. The participant using the eye-tracker, even with poor calibration, can easily control it by looking at where they want the pointer to be at. The second level is of a comfortable thickness that the user can easily navigate but where he/she has to exercise care in order not to move outside the maze limits. The last thickness is purposely thin to a degree that the failure rate increases significantly, again, with the eye-tracker (some users were not even able to complete a single maze on this difficulty) in the hope of noticing an effect in the frustration levels between the devices. Still, it is easily traversed with a mouse, making the test less artificial. Since there is repetition, the user can always come back to the mouse version to compare his performance with the eye tracker. The users have to complete the whole set four mazes times the tree thickness once for each condition (mouse Vs eye tracker) and repeat it three times. The first condition is selected randomly and from then on the user alternates between conditions. For every maze, if a user fails 5 times in a row he/she is being sent to the next maze. This number was chosen as a compromise between getting enough data and not taking too long to get it, and to avoid user fatigue.

5.2.3 Data Description

The raw data was automatically logged by custom-made software that was used for the user tests. The data was split in two files both using a standard comma-separated-values (csv) format. The first file logs the onscreen cursor position along with frustration and engagement levels sampled every frame. The second file is an event log that logs data when special events happen. The events are “Level Mouse and Level Eye”, indicating the start of a level for the mouse and the eye, respectively, “Failed”, indicating that the user moved the cursor outside the maze area, “Gave Up”, indicating that the user failed too many times and the experiment had just advanced, and finally, “Complete”, indicating that the user reached his/her goal. The first file logs the following:

- Timestamp in milliseconds, starting from the system initialization;
- Cursor Position (either by using the mouse or by using the eye-tracker), in pixels;
- Frustration Levels values between 0 and 1;
- Engagement Levels values between 0 and 1;
- The second file logs the following:

- Timestamp in milliseconds, starting from the system initialization;
- Type of Event string (single or double word) describing the event;
- Event Data string with extra data when needed, 0 if not.

5.2.4 Conditions

The test is very sensitive to the mental state of the user and external stimulation. This makes this experiment difficult to condition and control. The room where the hardware was located was not dedicated exclusively for the experiment. However, the participants did not face any interruptions or disturbance during the tests.

5.2.5 The Questionnaire

A modified version of the NASA TLX questionnaire was used for the users to fill up after completing the assessment. NASA-TLX is a workload assessment tool with six sub-scales including Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration [206]. This is used to corroborate the accuracy of the headsets frustration data. The whole questionnaire set was used, even if some questions did not seem relevant to the experiment, since some of the standard analyses require the whole data set. In Fig. 8 and Fig. 9 it is possible to analyze the questionnaire answers.

5.2.6 Sample

Since we chose Convenience Sampling as our sampling method, users were selected from friends and colleagues, as they were easily accessible to the researchers. The experiment was performed with 10 participants, 5 males and 5 females, with normal or corrected-to-normal vision. The participants were between 20 and 33 years old. All participants were regular computer and mouse users.

5.2.7 Statistical Analysis

5.2.7.1 Central Tendency and Dispersion

There are two input devices (Mouse and Eye-tracker), each one representing a condition and also two data sets that represent the same variable (the EEG data and the questionnaire answers). figure 5.2 demonstrates a large overlapping of the frustration results. This overlap is bigger for the EEG than it is for the Questionnaire.

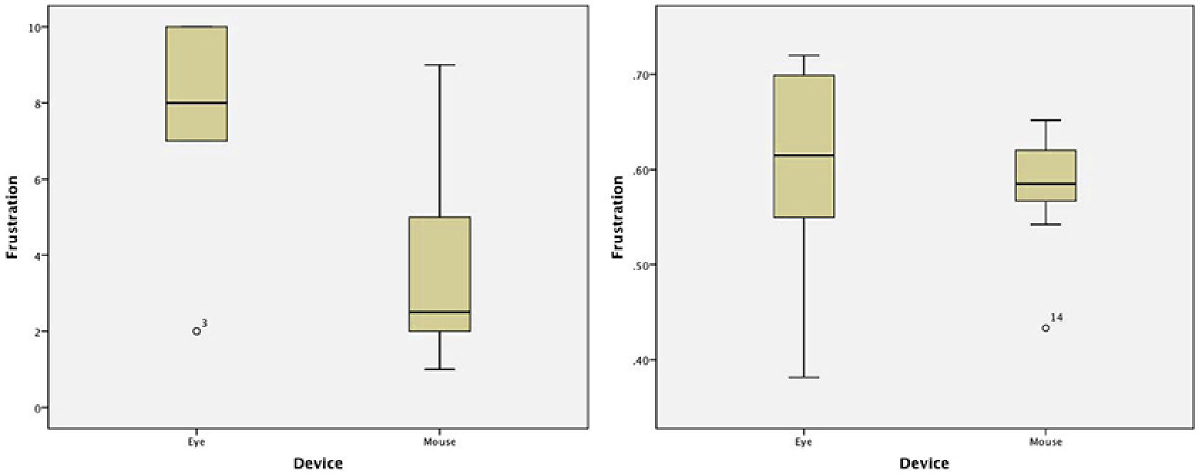


Figure 5.2: Whiskers Plots. Left: Questionnaire; Right: EEG

5.2.7.2 Data Normality

Before deciding which statistical test is appropriate for testing the hypothesis of this project, it is important to check the normality of the acquired data as a necessary statistical procedure to avoid incorrect usage of tests that require normality. The distribution of the data will help us choose between parametric or non-parametric tests. We did several tests, including Histograms (figure 5.3), QQ-Plots and several quantitative tests. These tests indicate Normality, but this was not confirmable with the current sample size.

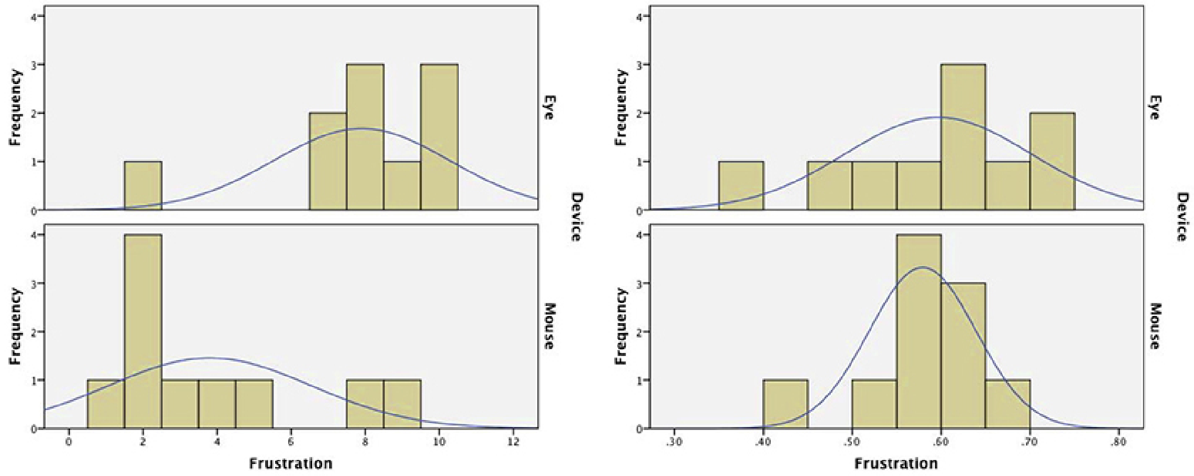


Figure 5.3: Histograms and Normality Curve. Left: Questionnaire; Right: EEG

5.2.8 Methods

5.2.9 Central Tendency and Dispersion

For the EEG Headset, the range of the ratio data is from 0.0 to 1.0. The Eye has a Mean of 0.5965, a Median of 0.6149 and a Standard Deviation of 0.10461 and the Mouse has a Mean of 0.5790, a Median of 0.5850 and a Standard Deviation of 0.06003. The Interquartile Range is 0.34 for the Eye-Tracker and 0.06 for the Mouse. This indicates a fairly larger variability in the Eye-Tracker data than in the Mouse data. Also, this value of 0.34 represents a third of the whole range, suggesting that the data might not be very good. For the Questionnaire, the data range is from 1 to 10, ordinal. The Eye has a Median of 8 and a Standard Deviation of 2.378 and the Mouse has a Median of 2.5 and a Standard Deviation of 2.741. The Interquartile Range is 3 for the Eye-Tracker and 4 for the Mouse. This represents from 33Figure 5.4 show the result of the visualization of the cursor trajectory when users navigated through the maze. One can notice higher loss of intended control while using an Eye-Tracker when compared to a Mouse for normal pointing tasks. The eye-gaze control (right graph of figure 5.4) is less accurate.

The tables 5.3 and 5.4 show the questionnaire results for the Mouse and the Eye respectively.

Tables 5.5 and 5.6 show the EEG log results for events an data respectively, it demonstrates what happens when a user fails 5 times in a row: it is considered a give up and the user goes on to the next maze.

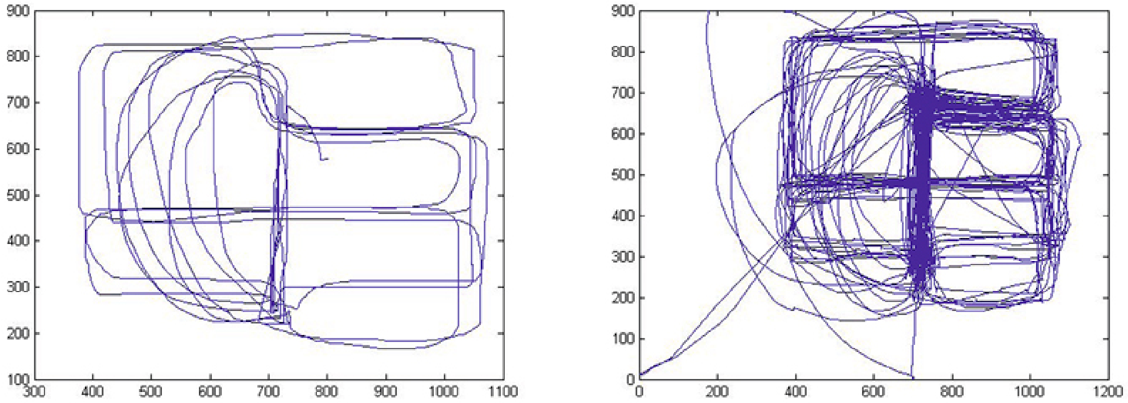


Figure 5.4: Trajectories. Left: Mouse; Right: Eye

Participant	Gender	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
1	M	3	1	7	2	3	2
2	M	2	1	1	2	2	2
3	M	3	2	3	9	3	9
3	F	3	1	1	1	1	1
5	F	4	6	5	8	7	8
6	F	3	3	4	3	4	2
7	F	2	2	3	7	3	3
8	F	5	5	5	5	5	5
9	M	3	4	6	2	4	4
10	M	2	2	2	2	2	2

Table 5.3: Mouse questionnaire results

5.2.10 Effect: EEG

5.2.10.1 Wilcoxon Signed Ranks Test

The data was found not to have a normal distribution. Due to this, a non- parametric test had to be used to verify our hypothesis. The experiment was within-subjects with two conditions (Mouse and Eye- Tracker). For these reasons, a Wilcoxon Signed Ranks test was conducted. The results of the test follow: We can infer that, from the 10 users that participated in the experiment, 4 found the Mouse more frustrating to use when compared to the Eye-Tracker, while the other 6 users felt the other way around. The T value is 22 with a $\rho = 0.575$, higher than the standard $\rho \leq 0.05$. The t-critical for a two-tail test with $\alpha = 0.05$ is 8. Hence $22 \geq 8$ then T $\geq$ t-critical. We can now conclude that we should keep the null hypothesis H0 - Eye-tracking has the same amount of frustration as a standard mouse for common mouse tracking tasks.

Participant	Gender	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
1	M	9	1	8	5	9	8
2	M	8	1	9	6	8	9
3	M	8	6	4	3	5	2
3	F	3	1	6	3	10	10
5	F	5	5	5	8	6	7
6	F	7	8	6	10	8	8
7	F	7	3	5	3	8	8
8	F	10	7	6	8	5	7
9	M	1	10	7	9	8	10
10	M	6	29	9	9	9	10

Table 5.4: Eye-gaze questionnaire results

Time	X	Y	Frustration	Engagement
121249441	801	578	0.584	0.879

Table 5.5: Event Log entry example

5.2.10.2 The Power

There is a chance that we are making a Type II error, especially due to the small sample size. In order to address this, we did a test of power to check the probability of such error. We found a power of 0.8000817, indicating a high probability of mistakenly not finding an effect that was there. Another interesting value is the number of tests we would need to perform in order to see an effect. This value is 380 tests.

5.2.11 Effect: Questionnaire

5.2.11.1 Wilcoxon Signed Ranks Test

To check the accuracy of the EEG headset data, we provided a questionnaire at the end of the tests for the users to indicate their frustration for each of the conditions (Mouse and Eye-Tracker). We then checked the correlation between the two.

5.2.12 EEG: Questionnaire Correlation

We first did a Spearmans ρ test to obtain the correlation coefficient. We got a result of ρ = -0.131. The ρcritical is 0.45 for Spearmans ρ test with $\alpha = 0.05$ for N = 20. Since —-0.131— $\leq$ 0.45, ρ $\leq$ ρcritical and so the correlation is not significant. To complement

Time	Type	Data
12149424	Level Mouse	1
12196613	Level Eye	1
12221551	Failed	0
12226329	Failed	0
12232051	Failed	0
12233392	Failed	0
12238636	GaveUp	0

Table 5.6: Data Log example

this result, we plotted the linear regression plot (Figure 5.5).

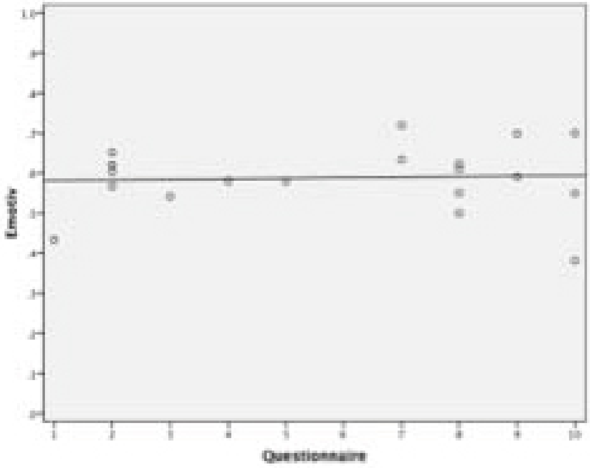


Figure 5.5: Linear regression between the Questionnaire and the EEGs Frustration

While we expected a linear relationship close to y = x, we got an almost horizontal line (closer to y = k). Looking into those results, we conclude that there is no evidence of correlation.

5.2.13 Discussion

According to the EEG data, 4 out of 10 users had higher frustration levels using the Mouse while the remaining 6 users had higher frustration levels with the Eye-Tracker and not the Mouse. The performed Wilcoxon T showed a value of T = 22, with ρ = 0.575 resulting in a non-significant result. Furthermore, the T value is higher than t-critical = 8. The sum of ranks for a less frustrating Eye- Tracker is 33 and 22 for the Mouse. However, a Type II error could be present. To investigate this, we tested the power of the test. A value of 0.8 was found, indicating a high probability of an undetected effect. As there is no clear relation between the users reported frustration levels and the frustration levels registered by the EEGs, we did a statistical analysis of the questionnaire results. We then found a T value is of 8.5 with $\rho = 0.52$, which is still higher than the standard $\rho \leq 0.05$. The t-critical for a two-tail test with $\alpha = 0.05$ is 8. This time $8.5 \geq 8$ so $T \geq$ t-critical. This value is close to the critical value but the significance is still low. Taking this subsequent statistical analysis into account, we now arrive at a different result from the one we got with the EEG. These subsequent results suggest that 8 users felt more frustrated using the Eye-Tracker as compared to using the Mouse, while the other 2 users felt the other way around. One of the users has extreme values (very frustrated using the mouse and very not frustrated using the Eye-tracker) going against both the expected results and the gathered results. Another result that is not consistent with the expected results is from a user that answered very closely for both devices (7 for Eye-Tracker, 8 for the Mouse). The lack of agreement in the data may be a due to a combination of two technical issues: First, the users tended to use the scale relatively, gathering around one of the extremes of the scale: they feel they are either very frustrated or not at all. On the other hand, EEG headsets measures absolute frustration; Second, the EEG Headset may not be accurate or sensitive enough to output good enough data for scientific usage. The amount of noise that is generated during the task performance on the headset electrodes can lead to a false classification of the frustration, as it is output from the Emotiv algorithm. In addition, the sense of frustration is subjective. The lack of agreement in the data can also be due to the small sample size or the conditions of the environment under which the experiment was conducted. Another explanation could be that the EEGs algorithm cannot really extract true frustration.

5.2.14 Conclusion

The data from our experiment was not found to be normally distributed, although it shows some tendency towards normality. Yet, given the small sample, we treated the data as not normal and performed non-parametric tests. We performed a Wilcoxon Signed Ranks test on the frustration data, which led us to conclude that we cannot reject the null hypothesis - H0 - Eye-tracking has the same amount of frustration as a standard mouse for common mouse tracking tasks. Since we suspected that the EEG data might not be accurate, supported by the strong effect power, we ran a questionnaire to gauge how frustrated the user felt while using each of the devices and then compared this data with the EEGs. A correlation was not found, suggesting that the EEG might not be accurate or that the users might be answering incorrectly. We then further analyzed the questionnaire results and found out that there was a bigger effect, even if it was still not statistically significant. Thus, we draw two conclusions: First, the frustration data from the EEGs might be inaccurate - further research is required to prove or refute this. Second, no effect was found, but both the power of the frustration data from the EEGs as well as the data from the questionnaire seem to indicate a possible missed effect.

5.2.15 Future Work

A better frustration measurement method should be found. After a sufficiently reliable method is found, a bigger sample should be acquired to gather enough information for a significant result to be achieved. Future work can also compare different kinds of input devices in order to arrive at a more complete understanding of users' frustration levels with these devices.

5.3 The influence of sample rate in arm tracking

5.3.1 Introduction

Human body-tracking or motion capture is a field that has boomed with the advent of 3D movies and that is now expanding into gaming. The techniques used for capturing the human body's movements and position have been evolving and new techniques keep emerging. Presently, the most commonly used techniques are optical/camera based and inertial based. There are other techniques such as mechanical, magnetic, acoustic, and radio reflection tracking. With cameras, nowadays, being so accessible, robust and cheap, optical-based systems are gaining momentum. Widely available high processing power coupled with ever more robust open-source algorithms make building an optical tracking system something inexpensive, sometimes even at no cost, if one has a common computer with a webcam. However, those systems are, usually, of low quality and low performance. A better solution, usually, needs a depth camera, a stereo camera, or two cameras. There are some market solutions, such as Microsoft's Kinect, that offer an out-of-the-box and relatively inexpensive solution. Unfortunately, to keep the price mark down, compromises have been made and the tracking capabilities are sometimes weak. The optical tracking systems are less expensive – at least a low accuracy and performance one – but do not allow us to extract the values we set up to extract. From the remaining available techniques, we have chosen the inertial systems. Those systems are the less expensive and easier to build while allowing us to extract the values we need with good accuracy and performance. There are inertial based market solutions that we could have just bought but those are usually expensive. An example of a cheap solution is YEI Technology PrioVR. However, the problem with a system like this is that we cannot or is not easy enough to access the low level characteristics of the sensors and set, for instance, the Sample Rate. Because of this, we decided to buy inertial sensors, sample them the way we need, and extract the values we need. Even though there are tracking systems and techniques that do not inherently have those characteristics (for instance, optical-based tracking), those systems can still benefit from this study. The benefits come from the fact that processing power, bandwidth, and costs are limited resources and knowing the lower tracking limits of each body part in different situations allows the developer to fine-tune the tracking characteristics as well as the priorities allocated to each body part. This allows the building of cheaper products while maintaining the full quality of the tracking.

5.3.2 Full Body

After a successful arm experiment, a natural evolution is to experiment with the rest of the body. It seems natural that the sample rate necessary for a good body tracking is lower for the rest of the body than it is for the arms and, specially, for the hand. Some segments, such as the back, may even require a lower sample rate. At this point, I could also try to study and find the other referred values (delays and jitter). An expansion to the full body is expected to be straightforward but with some issues to fix. First of all, and most importantly, the I2C bandwidth and address limitation: a piece of hardware that has more I2C ports should be used. This way, all the sensors can be used, at the same time, and without any kind of multiplexing and without its caveats. Secondly, such number of sensors is prone to wiring and software mistakes. Care and methodology should be exercised as well as partitioning of the sensors by member. At the moment of the full body experiment more research questions may have arisen. Or, it may arise afterwards. If so, this segment may have further development.

5.3.3 Methods

5.3.3.1 Subjects

The experiment was conducted using 41 volunteers (3 female; a mean age of 23.59 years old, ranging from 19 to 37 years old and a standard deviation of 3.8 years old). All of them had good knowledge and contact with, at least, one of the following: computers, entertainment systems and gaming systems. The closest to the tested system that any of the volunteers had contact with was one of the marketed hands free/body as a joystick gaming systems (for instance, a Kinect). No participant reported any higher degree of experiment with virtual reality other than commercial gaming. Only 2 reported having motion sickness related to vehicle and to games. All had normal or corrected to normal vision.

5.3.3.2 Materials

5.3.3.2.1 Software We used Unity3D to present the simulation to the user. The simulation was built to accept direct input from each body part, allowing the users to, directly, control their avatar's full arm. This allows them to interact with the environment and complete the set goals of the experiment. The experiment gives visual feedback based on the user's actions on a physically simulated virtual world. This physical simulation was set in place to help enhance the user's experience and allow for better interaction intuitivism. Three pieces of new software were also developed to aid the experiment: a) The software responsible for configuring, sampling, pre-processing and outputting the data from the hardware sensors (three nine-degrees-of-freedom sensors) to the computer; b) The software that connects the hardware's software to the simulation's software. We decided to have this middle layer to allow for easy expansion and integration with other future hardware controllers; and c) The software that logs the simulation and sensor data that was, afterwards, analyzed. After the experiment is complete, the logged data then needs to be pre-processed. For this purpose, For this purpose, we coded another program. The data is then fed to SPSS and/or Excel for further analysis.

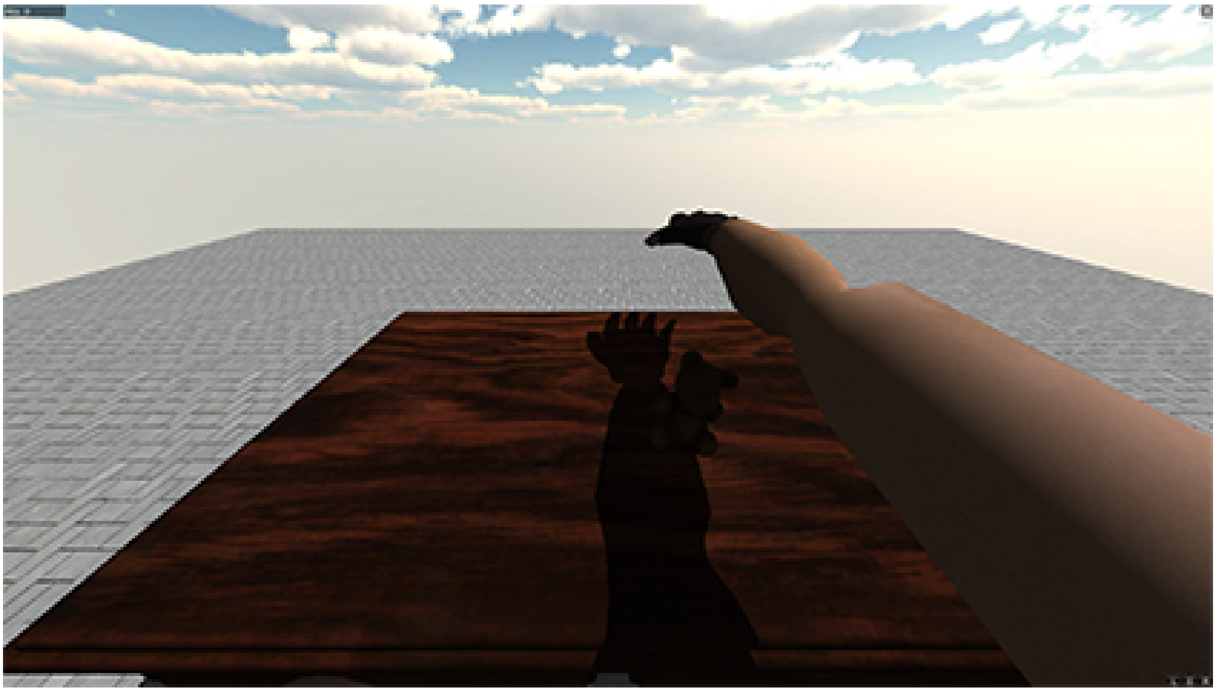


Figure 5.6: A screen-shot of the simulation showing the virtual arm during the Whackk-a-Bear experiment

5.3.3.2.2 Hardware The hardware used on this experiment was comprised of three sensors, one mini, real-time computer, a common personal computer and a couple of common standard displays. The sensors we used were three 9-degrees of freedom chips. Concretely, we used the 9DOF MPU-9150 which has an accelerometer, a gyroscope and a magnetometer in one chip. The accelerometer samples up to 1 kHz, has a selectable range of either ±2 g, ±4 g, ±8 g or ±16 g and has digital bandwidth of 16 bit. The gyroscope samples up to 8 kHz, has a selectable range of either ±250 º/sec, ±500 º/sec, ±1000 º/sec or ±2000 º/sec and also has a digital bandwidth of 16 bit. The magnetometer samples up to 8 Hz, has a fixed range of ±1200 µT and has digital bandwidth of 13 bit. The protocol used to communicate with the sensors is I2C at 400 kHz. The Sample Rates were chosen below the maximum allowed by the bandwidth in order to find the best rate for the users. The mini real-time computer was a Cubietruck, with the specific model being Cubieboard 3. This piece of hardware is, in essence, a miniaturized personal computer with the connections to allow for electronic, robotics and related prototyping. It has a dual-core ARM (Cortex A7) CPU that runs at 1 GHz and has 2 GB of RAM. Besides the normal computer's characteristics it has 54 pins that help interface with other hardware making it extremely versatile on the research and development world. The personal computer used is a common laptop. It is an ASUS N56VZ with an Intel Core i7-3610QM quad-core CPU running at 2.3 GHz, 4 GB of RAM and NVIDIA GT 650M. The Cubietruck deals directly with the sensors and sends the data to be used on the simulation on the laptop.

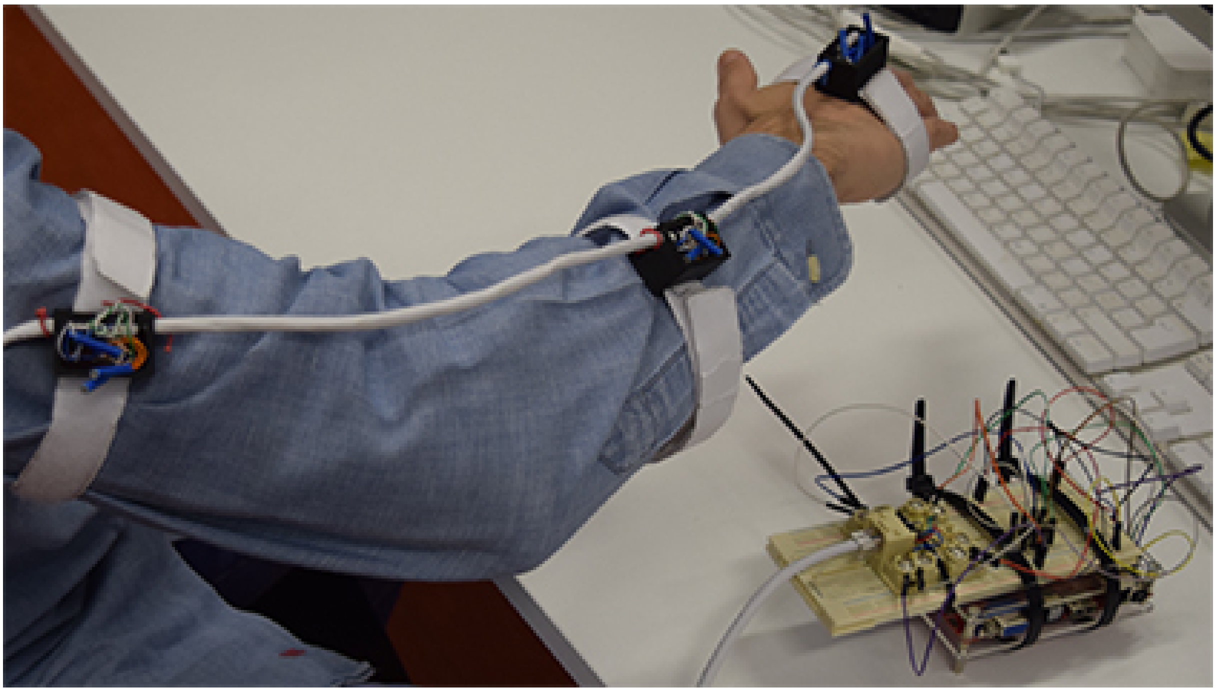


Figure 5.7: A photograph of the used hardware. Each body segment has one inertial sensor. On the bottom right we can see the Cubieboard and all the

5.3.3.2.3 Questionnaire The users were requested to fill up a printed normalized short questionnaire after each changed variable to assess extra information as well as to confirm the automatically extracted information. The questionnaire had the answers to the following questions graded from -5 to +5:

1. I felt that this iteration was -5 – Slower; 0 – Equal; 5 – Faster
2. I felt that this iteration was -5 – Less Responsive; 0 – Equal; 5 – More Responsive
3. I felt that this iteration was -5 – Harder; 0 – Equal; 5 – Easier

5.3.3.2.4 Data Logged The data logged is dependent on the sub-experiment being run at the moment. For the Whackk-a-Bear experiment, the data logged is the timestamp of the hit, the hand's position and angle as well as the bear position. For the Balance-Ball experiment the data logged was the time the user was able to balance the ball or, the time the ball took to hit the ground, if the user was not able to balance the ball.

5.3.3.2.5 Inertial Tracking The system uses a series of inertial sensors positioned on several bones (arm, forearm and hand – see Figure 5.7). The sensors are then probed by a minicomputer and the data is then treated and sent to the main computer, which should output the results in the form of a virtual avatar body movement. The three values pooled are the gyroscope's rotational speed, the accelerometer linear acceleration and the magnetometer's magnetic field. After some research and trial-and-error, we ended up using Madgwick's algorithm [42] to fuse the sensors' data. Since the sensors use variable range, we also manage those values to achieve better accuracy while maintaining the full potential range of the sensors. We start with the smallest range, which gives us the best accuracy. If the range is 90% saturated, we jump to the next range, losing precision (since the number of bits that represent the value is the same but the range to be represented is bigger) but gaining the ability to keep tracking faster/more aggressive movements. As soon as those values drop below 45% we go back to a lower range. Those values were chosen to accommodate the fact that the ranges double each time.

5.3.3.3 Experimental Setup

5.3.3.3.1 Software The first layer of software was deployed on the Cubietruck (running Linux, Lubuntu Server 13.08) where, as explained in the previous section, it extracts the data and passes it on to the next layer. That next layer of software (also running on the Cubietruck) is responsible for connecting the hardware to the simulation. It further processes the data from the sensors and sends it to the simulation. The simulation, itself, is the third and final layer of software. It runs on the personal computer (running Windows 8.1) and feeds its visual data to the screen display. The data is logged by another piece of software. There is an "offline" program that is responsible for pre-processing the logged data. It begins by doing simple data derivation (delta-time and distance) and, afterwards, it calculates the Average as well as the standard deviation. It then removes the extreme outliers (defined as values that have a distance greater than 2 standard deviation to the Average) from the samples and recalculates the Average. The reason that we remove extreme outliers is because some users broke the experiment protocol to either readjust their sitting position, a sensor or a wire that was uncomfortable or even due to a tired arm. During those protocol breakages the experiment program continued, oblivious to the fact that the user is not, actively, trying to pursuit the experiment goal, logging the experiment and keeping the chronometers going. Another issue is that some users had limited arm movement, which made them have difficulty reaching some Bears. Those values would influence the results, sometimes heavily, and so, they are considered invalid for the experiment and are removed. Taking out extreme outliers has the pitfall of having the possibility of removing valid data. For instance, a user could be extremely lucky and do a single great repetition, which would be counted as an extreme outlier and, consequently, removed. Still, this value is still an exception and we decided that removing invalid values would outbenefit the occasional luck strike.

5.3.3.3.2 Hardware Three nine-degrees-of-freedom sensors (the MPU-9150 sensor breadboard) are connected to the Cubietruck through the I2C protocol. Since the sensors can only have 2 addresses (1 switchable bit) and the Cubietruck only has 1 free I2C channel, the wiring is multiplexed using the Cubietruck General Purpose In/Out (GPIO) pins. Each address bit switch from each sensor is connected to a GPIO pin and set to 0/low (corresponding to the address 0x68). When there is a need to address one of the sensors, the correspondent pin is set to 1/high (corresponding to the address 0x69) allowing the correct addressing via one I2C address (0x69). All the wiring is made using a normal “LAN” 4 twitched pair cable that goes through the sensors plastic printed casing and connect to the Cubietruck. This was found to be a good solution since we needed a power pair and a data pair common to every sensor. Then, out of the other 4 wires, we use 3 for switching each sensor’s I2C address. The sensors were placed in the arms so we can know the current orientation of each part of the arm (hand, forearm and arm). Constraining the back of the user to an upright position, we can, through forward kinematics, calculate the exact position of each bone and feed it to the simulation. The Cubietruck is, then, connected to the personal computer through Wi-Fi using a private router (to avoid bandwidth issues). It could have been connected through a LAN cable but the Cubietruck is expected to be mounted on the user on future re-search and a cable would be cumbersome to the user. The protocol used to communicate with the sensors, the I2C, runs at 400 kHz. This gives an effective bandwidth (after the protocol overhead) of around 200 kbps usable out of the 400 kbps that the protocol offers (this value is somewhat variable but, on a typical usage, the overhead accounts up to half of the bandwidth). With 2 byte per axis per sample for any and each of the sensors times 3 chips, locking the magnetometer at its maximum (8 Hz) and coupling the accelerometer and gyroscope's sample rate we can calculate the maximum sample rate that we can sample the sensors at before saturating the protocol.

$$200kbps \geq s(ah + gh + mi) \tag{5.1}$$

Where:

- kbps is kilo-bit per second;
- s = the amount of sensors, 3;
- a = accelerometer sample reading, 2 byte times 3 axis equals 6 byte;
- g = gyroscope sample reading, 2 byte times 3 axis equals 6 byte;
- m = magnetometer sample rearing, 2 byte times 3 axis equals 6 byte;
- h = the sample rate to discover;
- i = magnetometer sample rate, 8 Hz.

$$\begin{aligned}
25600 &\geq 3(6h + 6h + 6 \times 8) \\
25600 &\geq 18h + 18h + 144 \\
25600 - 144 &\geq 36h \\
25456 &\geq 36h \\
707 &\geq h
\end{aligned} \tag{5.2}$$

This leads us to a maximum sample rate of about 700 Hz. Unfortunately, the sensors only have two selectable addresses while the computer only have one user addressable I2C port giving a maximum number of addressable sensors of two – and I needed three sensors. This demands either multiplexing or dynamically changing the address of the sensors. Either way, delays are introduced in processing and signal propagation and, at 400 kHz it, effectively, ended up reducing the maximum sample rate to about 120 Hz with some occasional pits below that value. For the future, a hardware with more I2C ports needs to be used – 1 for every 2 sensors.

5.3.3.3.3 Independent Variable The experiments explore different values of the independent variable to find out the best values and thresholds in arm tracking in virtual reality. The variable that is studied is the Sample Rate of the tracking of the arm movements using several sensors. The magnetometer is set at its maximum (8 Hz) because it is a value extremely lower than the values we were expecting as minimum. The accelerometer and gyroscope are coupled (we can do this up to 1 kHz, the accelerometer maximum). The accelerometer/gyroscope Sample Rate is then set at 15, 30, 60, 90 and 120 Hz and the experiment is run. Due to bandwidth issues on the I2C protocol, the 120 Hz may not be exactly 120 Hz. It oscillates between 110 and 120 Hz. The values mentioned above were chosen with the following criteria: 120 Hz is both the most common used value found on several hardware researched and the maximum the I2C protocol bandwidth would allow. 30 Hz is near the (arguable) human eye central “Sample Rate” and 60 Hz for the (again, arguable) peripheral vision. 15 and 90 Hz used as fillers to allow us to probe around the previous values.

5.3.3.3.4 Experimental Task After all the formalities were met and the user was familiar with the setup, the experimental task was presented to the user. The user is presented with a virtual avatar, viewed from a first person perspective (Img. 1 illustrates this). Now he/she can play around with the avatar for 30 seconds. After this period, the user’s first task started. The order of the experiments was alternated between users to avoid biasing the results based on learning effect. The Sample Rate order was always chosen by the random list generator from www.random.org/lists, a random generator marketed as a true random generator.

5.3.3.3.4.1 Task 1 – Balance Ball The user was requested to move the arm so it stays on a starting position. There, a ball was dropped after a short count down. The user was then required to balance the ball for as long as he can. A perfectly vertical shadow indicated where the ball would fall. This was used as an aid to the lack of good depth perception to the user, where the user is expected to use depth on his movements. This task was chosen to evaluate conditions where most concentration lays on controlling an object on a slow and predictable environment (the ball responds only to the gravity and the forces the user applies). We measured the time the user is able to balance the ball or, if not, the time the ball takes to hit the ground. After the user balances the ball for 5 seconds or the ball hits the ground the experiment is repeated. This goes on for 10 iterations and then the Sample Rate is, randomly switched. On each switch, the user answers the questionnaire.

5.3.3.3.4.2 Task 2 – Whack-a-Bear The user is requested to hit a teddy bear that spawns on a random position on top of a table, as if playing a game of "Whack-a-Mole". The bear was constrained inside the table surface by invisible walls so it could not fall off the table. The spawn position was set such as it could never spawn too close to the previous position so a double hit could happen. This task was chosen to evaluate conditions where fast, far away and precise movements are required due to the semi-randomness of the environment. The bear spawns 30 times for each Sample Rate, which is then randomly switched. On each switch, the user answers the questionnaire.

5.3.3.3.4.3 Questionnaire After each task was completed with a different Sample Rate, the users were given the questionnaire before proceeding to the next task. The answered value should range from -5 to +5 and it is always relative to the previous Sample Rate from the current Sample Rate perspective. A positive value should indicate an improvement and a negative value should indicate a decline from the previous conditions. A "zero" as an answer works as a neutral value and should indicate no change in relation to the previous iteration. When queried, the user was always asked in the form "Relatively to the previous trial/iteration, this trial/iteration was Harder – a negative value – or Easier – a positive value". If the user replied ambiguously, for instance "+5" a confirmation follows in the form "≪+5≫ as in ≪a lot easier than the previous≫?”. This also happened in cases of a dissonant answer such as “Very hard: +5”. The answer was requested on this double form for two reasons. First, the “negative to positive” scale is in place to reinforce the “bad to good” effect on the user’s mind. This is coupled with a named answer (“bad”, “harder”, faster”, etc) to both make the user think in what he is answering and to allow us to confirm if the answer the user gave us is really what he intended to.

5.3.3.3.5 Objective/Focus The focus is to find out what is the optimum value or range of values for comfortable interaction with a virtual environment using your body through body tracking. This particular experiment measures the Sample Rates for the different bones/articulations of the arm when viewing the movements of those in a virtual avatar’s environment. Those values are expected to either be a “solution for every case” or to be, at least, a value for slow movements and another for fast movements. This is why we ran two experiments: one slow-paced and another fast-paced. We also expect to find a difference between what the user perceives and how he performs. This is why we ran the questionnaire but also measured the users’ performance. We expect there to be a difference in the several articulations/bone groups since the mental model and focus amount is different, for instance, between the hand and the arm. Unfortunately, we did not explore this difference at this time, so the results should be considered either for the whole arm or for the hand alone, which has the most focus.

5.3.3.3.6 Data Extraction and Analysis For the “Whack-a-Bear” experiment, the user touching the bear triggers a log entry with the timestamp, the bear position and the user’s hand position and orientation. This also allows us to extract the distance from the hand’s centre and the bear to access precision. Still, the distance measurement is not a good value because the user could hit the bear with different and far apart parts of the hand and still be completely valid while giving disparate results. For this reason, it was abandoned as a relevant statistic. For the “Balance Ball” experiment, if the user is able to balance the ball for 5 seconds, the log makes an entry with 5000 milliseconds; if the user lets the ball hit the ground, the log makes an entry with the time it took from the ball being released to it hitting the ground. The subjective data is extracted from the user in the form of a questionnaire, previously described. The performance data was then analysed by calculating the Average, standard deviation and also by comparing the Averaged values of higher and lower Sample Rates (for instance, 30 Hz in relation to Average (60 Hz, 90 Hz, 120 Hz)). This allows us to try to find relations between two Sample Rates or between all those that are above or below. After those preliminary tests and analysis we performed T-Tests of Student on each Sample Rate pair for the Balance Ball experiment time that the user was able to keep the ball in balance and for the Whack-a-Bear experiment time between bear hit. For each T-Test we also calculated the P-Value, for a two tail and the Effect Size. The used confidence interval was 95The subjective data was Averaged and its standard deviation was calculated. We then proceeded to analyze discrepancies in the data (for instance, if the Sample Rate increases but the users think it was slower or harder, this indicates that the user may not be able to accurately notice (or, at least, express) what changed. We then Averaged all the increases and decreases of the Sample Rates and performed the previous stated analysis.

5.3.3.3.7 Data Validity Occasionally, some repetitions had to be aborted and then re-run due to some hardware or software failure or due to an external major influence. The data related to those repetitions have been omitted form the statistical analysis. Those events may have an effect on the experiment's results, due to a training effect or loss of concentration. Nonetheless, the effect is expected to be slim and should dissolve on the population size multiplied by the repetition amount.

5.3.4 Results

All times in this section are in milliseconds (ms), unless stated otherwise. The values (15, 30, 60, 90 and 120) on the first column represent the Sample Rate at which the experience was run and are expressed in Hertz (Hz). All the results were rounded to the 2nd decimal position. “X – Y” is the difference on the Averages. “SD” stands for Standard Deviation. “t” is the result of the T-Test of Student. “P” is the P-Value of the T-Test of Student. “Effect Size” refers to the size of the effect that T-Test of Student may have found. “X/Y” is a relation of two Averages.

5.3.4.1 Preliminary Tests

Hoping to get a first idea on the data tendency, we averaged all the logged times the users were able to balance the ball for each Sample Rate. We then calculated the Average and the standard deviation of all the Sample Rates. This gave us an idea if there is an improvement or deterioration on the users' balancing capacity. The average between Sample Rates is 1128 ms with a standard deviation of just 43 ms. This extremely small standard deviation is a good indication that the Sample Rate does not influence the users' capability of balancing the ball. Free-fall on the Balance Ball experiment is measured at about 422 ms. With an Average of 1235 ms with a standard deviation of just 82 ms. It is measured from the drop of the ball to it touching the ground. This means that the users were, in average, able to balance the ball for less than 813 ms. Since the gravity accelerates the ball, the ball is expected to be stopped midway and the user could hit the ball in the air, just like a racquet, this value is just a rough estimation of the superior limit.

5.3.4.2 Balance Ball Time

On this section we present the values of the tests performed on the data collected on how long the users were able to balance the ball on the experiment. The sample size is 41.

Pair		X - Y	SD	t-test	Power	Effect Size
15	30	-87.38	442.17	-1.27	0,21	0,20
	60	40.19	376.16	0.68	0.50	0,11
	90	-31.83	352.47	-0.58	0,57	0,09
	120	4.23	410.22	0.07	0.95	0,01
30	60	127.57	406.62	2.01	0,05	0,31
	90	55.55	379.76	0.94	0,36	0,15
	120	91.61	442.00	1.33	0,19	0,21
60	90	-72.02	434.68	-1.06	0,30	0,17
	120	-35.96	408.04	-0.56	0,58	0,09
90	120	36.06	375.47	0.62	0,54	0,10

Table 5.7: Main tests performed with the Balance Ball times

On one extreme we have the comparison between the Sample Rate of 30 Hz and the Sample Rate of 60 Hz. The tests indicate that there may be an effect (P = 0.05 with and effect size of 0.31), or, in other words, the user may be performing differently. This effect is, then, denied by the tests performed on the other, higher, Sample Rates of 90 and 120 Hz, with P-Values of 0.36 and 0.19, respectively. It is also denied by the lower Sample Rate of 15 Hz, with a P-Value of 0.21. On the other extreme we have the comparison between the 15 Hz Sample Rate and the 120 Hz Sample Rate. This has a P-Value of 0.95 and an effect size of 0.01. This indicates a very low possibility of there being an effect – an indication that the user may be performing the same on both Sample Rates. The other non-extreme P-Value results are spread, two around 0.2, other two at 0.3 and 0.36 and the remaining four ranging from 0.5 to 0.58. The following table show us the Average of the Averaged time of the users were able to balance the ball as well as the Standard Deviation (SD). The main result here is the relation between the Averaged times. If a higher Sample Rate would grant better performance, a value X / Y ¡ 1.0 should arise when comparing a lower Sample Rate to a higher Sample Rate. The opposite is also true.

Sample Rate	Time	Relative		SD
		SR	X / Y	
15	1112.96	30	0.93	308.24
		60	1.04	
		90	0.97	
		120	1.00	
30	1200.34	15	1.08	420.88
		60	1.12	
		90	1.05	
		120	1.08	
60	1072.77	15	0.96	370.06
		30	0.89	
		90	0.94	
		120	0.97	
90	1144.79	15	1.03	330.31
		30	0.95	
		60	1.07	
		120	1.03	
120	1108.73	15	1.00	301.05
		30	0.92	
		60	1.03	
		90	0.97	

Table 5.8: Relation between the Balance Ball times at different Sample Rates

There are several values that pop out on those results. Ten results out of twenty (50%) are the opposite of the expected with two results being neutral (X / Y = 1.0). If we Average all the relative results, we get an Average of 1.00 (1.00177012691068) and a standard deviation of 0.06. The Averaged times have a Standard Deviation of 47.86.

5.3.4.3 Whack-a-Bear Time

On this section we present the values of the tests performed on the data collected on the time it takes the user to hit the next spawn bear – it is the inverse of “Bears hit per second”. The sample size is 41.

Pair		X - Y	SD	t-test	Power	Effect Size
15	30	170.49	501.56	2.01	0,05	0,34
	60	86.99	398.52	1.29	0.21	0,22
	90	30.22	334.31	0.54	0,60	0,09
	120	-41.54	397.13	-0.62	0.54	0,10
30	60	-83.50	444.01	-1.11	0.27	0,19
	90	-140.24	482.66	-1.72	0,10	0,29
	120	-212.03	540.10	-2.32	0,03	0,39
60	90	-56.77	362.13	-0.93	0,36	0,16
	120	-128.52	423.76	-1.79	0,08	0,30
90	120	-71.76	394.73	-1.08	0,29	0,18

Table 5.9: Main tests performed with the Whack-a-Bear times

This time we only have one extreme – the “possible effect” extreme. Moreover, on this case, we have two values on this extreme: the 15 – 30 Hz Sample Rate pair and the 30 – 120 Hz Sample Rate (with P = 0.05 and P = 0.03, respectively). Just like with the “Balance Ball Time” results, this could indicate a possible effect, indicating that the user performs differently when going from one of those Sample Rates to the other. This result, however, is refuted by the remaining results which find no effect. There are other two results close to the threshold: the 30 – 90 Hz and the 60 – 120 Hz Sample Rate pair (with P = 0.1 and P = 0.08, respectively). The remaining results spread from P values ranging from 0.21 to 0.6. The following image shows us the Average of the Averaged Time the users took to hit another spawned bear as well as the Standard Deviation. The main result here is the relation between the Averaged Times. If a higher Sample Rate would grant better performance, a value X / Y ¡ 1.0 should arise when comparing a lower Sample Rate to a higher Sample Rate. The opposite is also true.

This time there are less unexpected results: Four out of twenty (20%) with, again two neutral results (X / Y = 1.0). The Average of all the relative results is again, 1.00

Sample Rate	Time	Relative		SD
		SR	X / Y	
15	1352.71	30 60 90 120	1.14 1.07 1.00 0.98	308,24
30	1181.97	15 60 90 120	0.87 0.93 0.88 0.85	420.88
60	1264.84	15 30 90 120	0.94 1.07 0.94 0.91	370.06
90	1347.71	15 30 60 120	1.00 1.14 1.07 0.97	330.31
120	1383.73	15 30 60 90	1.02 1.17 1.09 1.03	301.05

Table 5.10: Relation between the Whack-a-Bear times at different Sample Rates

(1.00414003911016) with a Standard Deviation of 0.094. The Averaged times have a Standard Deviation of 82.22.

5.3.4.4 Questionnaire

On this section we present the values of the tests performed on the data collected through the questionnaires. The number of users that answered the questionnaire is 41. Yet, this value is not the sample size. Since the questionnaire is performed after each Sample Rate pair, which is randomly selected, and after all the repetitions are completed, the sample size is variable and not 41. The first Sample Rate does not get an answer – only the second does. The real value is indicated on the row “Iterations”. “S” stands for “Speed” and is defined, for the user as “The feeling of how fast the user’s real arm movements are mimicked by the simulation.”. “R” stands for “Responsiveness” and is defined, for the user as “The feeling of how responsive the simulation virtual arm is to the user’s movement.”. “D” stands for “Difficulty” and is defined, for the user as “The feeling of difficultness that the user feels when trying to achieve the experiment goals.”. As stated on the previous section, the values range from -5 to +5 having a connotation of “bad to good”, or, more specifically, and since the answer is always relative to the previous iteration, “from worse to better”. Zero is neutral and represents no change relative to the previous iteration. If the user felt an improvement over the previous sample rate, it should be represented by a positive value in the following table. If it is negative, it means that the user actually felt a deterioration on the simulation. Please note that, contrary to the previous data, the neutral value now is 0.0 and not 1.0.

Sample Rate		S	R	D	Iterations
15	30	0.43	0.29	-0.43	7
	60	0.00	0.67	0.17	6
	90	1.18	1.64	0.73	11
	120	0.70	1.30	1.20	10
30	15	0.71	0.14	0.71	7
	60	0.86	0.57	0.71	14
	90	0.71	1.14	0.29	7
	120	2.00	3.00	1.25	4
60	15	-0.13	-0.50	-1.13	8
	30	0.50	-0.13	-1.13	8
	90	0.22	0.89	0.89	9
	120	0.07	0.53	0.07	15
90	15	-0.50	-0.20	-0.40	10
	30	0.14	0.71	1.14	7
	60	1.60	3.20	0.60	5
	120	0.00	0.00	0.36	11
120	15	0.22	-0.33	-0.33	9
	30	-0.29	0.14	0.21	14
	60	0.33	0.50	-0.50	6
	90	1.67	2.00	0.92	12

Table 5.11: The Averaged user answers to the questionnaire (Balance Ball)

As for the Balance Ball (Table 9), a less pronounced effect of the user noticing an improvement by going either direction from one extreme to the other is also felt here. The user is also more prone to correctly “guess” (65%) which direction the Sample Rate changed to, even is just slightly. There is a bias towards positiveness on the results. If we Average the results it will always wield a positive value (0.61, 0.86, and 0.74 for Whack-a-Bear and 0.52, 0.78 and 0.27 for the Balance Ball). If averaging everything, the value is 0.74 for Whack-a-Bear and 0.52 for Balance Ball. For the Whack-a-Bear experiment (Table 10), the user can always notice an improvement when going up from 15 Hz. But they can also notice the improvement when going down from 120 Hz, even to the other extreme of 15 Hz. In this situation, when going down, the user “feels” values around 0.5 while, when going up he “feels” values around 2.0. For the remaining of the results, the user spreads their “feelings” evenly between being guessing correctly (53%) the Sample Rate change, and not guessing.

Sample Rate		S	R	D	Iterations
15	30	1.00	1.44	1.11	9
	60	2.17	1.50	0.67	12
	90	1.64	1.55	1.45	11
	120	1.83	2.17	2.50	6
30	15	-0.36	-0.36	0.27	11
	60	0.11	0.00	-0.11	9
	90	-0.33	0.17	0.33	6
	120	0.38	1.13	0.25	8
60	15	0.50	0.33	1.17	6
	30	0.70	0.80	0.70	10
	90	0.78	0.78	0.44	9
	120	0.33	-0.25	0.08	12
90	15	-0.67	0.33	-0.33	9
	30	1.14	1.00	0.57	7
	60	0.50	1.50	1.75	8
	120	0.22	1.11	1.00	9
120	15	0.45	0.27	0.55	11
	30	-0.18	0.91	0.27	11
	60	1.00	0.67	0.78	9
	90	1.00	2.14	1.29	7

Table 5.12: The Averaged user answers to the questionnaire (Whackk-A-Bear)

The following tables respect the same nomenclature as the previous one with one addiction: the direction. This indicates which Sample Rate direction is the line being compared against. For instance, “60-Up” means that we are averaging 60 to 90 Hz and 60 to 120 Hz, while “60-Dn” means that we are averaging 60 to 30 Hz and 60 to 15 Hz. Mind that, for instance, 15 Hz can only go up and 120 Hz can only go down.

On the Whack-a-Bear questionnaire the users’ guesses are not good, neither bad (50%). On the other hand, on the Balance Ball questionnaire, the users are guessing (83%) better what direction is the Sample Rate being changed to. The questions were purposely, somewhat overlapping in meaning. This being said, we calculated the correlation between them based on the users’ answers and got the following results:

The “S”, “R” and “D” has still got the same meaning. All the results present a

Sample Rate	Direction	S	R	D	Iterations
15	Up	1.66	1.66	1.43	38
30	Dn	-0.36	-0.36	0.27	11
	Up	-0.11	0.08	0.11	23
30	Dn	0.70	0.80	0.70	16
	Up	0.33	-0.25	0.08	21
30	Dn	0.82	1.25	1.16	24
	Up	0.22	1.11	1.00	9
120	Dn	0.42	0.62	0.53	38

Table 5.13: Relation between the users‘ answers to the questionnaire at different Sample Rates (Wach-A-Bear)

Sample Rate	Direction	S	R	D	Iterations
15	Up	0.58	0.97	0.42	34
30	Dn	0.71	0.14	0.71	7
	Up	1.19	1.57	0.75	25
30	Dn	0.19	-0.31	-1.13	16
	Up	0.14	0.71	0.48	24
30	Dn	-0.50	-0.20	-0.40	22
	Up	0.00	0.00	0.36	11
120	Dn	0.48	0.58	0.07	41

Table 5.14: Relation between the users‘ answers to the questionnaire at different Sample Rates (Balance Ball)

moderate to strong correlation. Even so, after looking at the results we can see that, even after averaging, sometimes, the users feel that the virtual arm’s movement is, for instance, and at the same time, harder and more responsive.

5.3.4.5 Psycho-physiological Effects

During the experiment, not a single person reported motion sickness or any related effect. This came as a bit of a surprise since they were exposed to about 20 minutes of virtual reality with body interaction and, some of that time, with a relatively low Sample Rate. This remained true even for users that reported having felt motion sickness before on transport and while playing games.

5.3.4.6 Rejected data

There is a total of 10 tests per user, 5 per experiment, and 1 per Sample Rate. Each test is repeated 10 times for the Balance Ball (this experiment has a higher degree of

Whack-a-Bear			Balance Ball		
S - R	S - D	R - D	S - R	S - D	R - D
0.70	0.64	0.75	0.86	0.53	0.66

Table 5.15: Correlations between the different questions

repeatability) and 30 times for the Whack-a-Bear (this experiment has a higher degree of randomness). With 41 users, this makes a grand total of 410 valid logged tests. Some tests were rejected due to the issues explained before. There were a total of 47 tests that needed to be repeated. This makes up about 10% of all the tests. It Averages at 1.15 repeated tests per user. The worst case scenario was 7 repetitions on a single user. 18 users had a perfect run (44%).

5.3.5 Discussion

The user performance values mostly indicate that no effect is present. When they indicate otherwise (the 30-60 Hz comparison for the Balance Ball and the 15-30 Hz and 30-120 Hz comparison for the Whack-a-Bear), those results are denied by several other values. Since it makes no sense, one is improving in performance when going from 30 Hz to 60 Hz but not improving when going from 30 Hz to 90 Hz or to 120 Hz, those values may be disregarded as noise. This possibility is corroborated by the fact that the tests that may indicate an effect are those with the biggest standard deviation. This may be caused by an accumulated learning effect. When looking at the relation between two Sample Rates for the Balance Ball, we can, easily, see that the ratio is split between being what it is expected (improving when increasing the Sample Rate and degrading when lowering the Sample Rate) and what is not (the opposite). In fact, it lays on the 50% mark. The Whack-a-Bear is more “correct” marking at 20% contradictory results. Still, if we Average all the relations, in both experiments, we end up with a value of 1.0 for each, which indicates that, on Average, the performance is indifferent to the Sample Rate, for the tested interval. The indifference in performance was expected when the experiment was designed but only for values above 60 Hz, possibly 30 Hz. Having no performance difference between 15 Hz and 120 Hz came out as a surprise and one that is not easy to explain. We speculate that either the Kalman filter used is good enough to compensate for the lower Sample Rate or that we did not design the experiment in a way that would reach a breaking point in speed and/or precision which would allow us to reach a higher value. Still, the reason could be that, in fact, the optimum value is, indeed, around or below 15 Hz. As for what the user feels, a correct guessing of 53% and 65% for Whack-a-Bear and Balance Ball, respectively, seems to indicate that the user may not be sure what he is really feeling. It could also indicate that the user was not able to correctly communicate what he really felt or that the questionnaire was ill built or incomplete. There is also a bias towards positiveness that raises some red flags. This bias could be explained by either the user feeling a need to find an improvement, even if there is not one present (trying to please the researcher) or by the learning effect being strong enough for the user to confuse learning with technical improvement. Some users have a strong learning effect. This effect is mostly noted in those users that start with values a lot below average and then aggressively improve their values. When gathering all the tests and comparing when raising or lowering the Sample Rate as a whole, the user still cannot effectively guess the change in the Whack-a-Bear experiment (50%). Yet, 83% can guess on the Balance Ball experiment. By adding personal experience from the users' interactions during the experiments, we can state that we noticed that some users were really able to correctly and consistently guess the direction of the Sample Rate change. But, those users represent a small portion of the whole sample. Unfortunately we did not take note of the exact number of users. On the other hand, the majority of the users showed no clue of whether the Sample Rate had increased or decreased. This led us to conclude that there may be a characteristic or subpopulation that has higher sensitivity to a Sample Rate change. As of this moment we were not able to identify what characteristic or subpopulation it may be. From a design point of view, the Balance Ball experiment should be more repeatable since the ball is always dropped on the same position. This was a design choice that was made because, on the preliminary studies, we found out that the users had difficulty judging the depth at which the ball was being dropped. This happened even if the ball was casting a vertical shadow (the shadow appears exactly where it will fall). As for the lateral movement, the users still had trouble stabilizing their arm before the ball was dropped. On the other hand, the Whack-a-Bear experiment has random bear placements inside an area, always in range of the user. There is a minimum distance for it to spawn from the last position to avoid double (or more) triggers. Still, this randomness of the experiment spreads more the results. This is one possible justification for a bigger standard deviation in the performance analysis of the Whack-a-Bear experiment. We would like to extend the tests for the whole body with the possibility of studying several body parts in separate. We would also like to study other variables such as jitter or delay (this is good for networked virtual worlds). Another interest is in finding what characteristic or subpopulation seems to make some users sensitive to a sample change while most are not.

5.3.6 Conclusion

Performance-wise, we found no evidence that changing the Body Tracking Sample Rate would change the user performance when performing tasks, be it slow or fast or even precise. We found, however, that a small group of users may notice the change in the body tracking Sample Rate. We did not find where the exact threshold is, how strong that effect is, and what makes those users being able to notice the body tracking Sample Rate change. Based on the results we advise that, if one is trying to save battery, bandwidth or processor cycles, a low body tracking Sample Rate (we found no ill effects to as low as 15 Hz) could be used with no negative effects on user performance. Keep in mind that if a low body tracking Sample Rate of, let us say, 15 Hz, is used, this introduces delays of 67 ms to the virtual body movement (plus other technical delays). If using 120 Hz, this delay is 8 ms. On the other hand, if the user experience is important, a higher body tracking Sample Rate should be used. If no filter is used, coupling the body tracking Sample Rate with the (arguably) the human eye “Sample Rate” of 30 Hz or 60 Hz for fast moving images would probably be a good idea since the user may notice the “jumps” in body position changes for lower Sample Rates. Finally, we researched user performance and experience while changing the Sample Rate of the body tracking system. It did not study how changing this Sample Rate would affect offline analysis, for instance, in gait analysis. Those applications will probably have their own values and thresholds. It is also noteworthy that we researched hand and arm tracking. Using the mental model as a basis, we could argue that anything we found here stands for the rest of the body since a lot more focus is used on hand and arm movement than for the rest of the body. The big difference is that the rest of the body will have even lower thresholds than the hand and the arm.

5.4 The Impact of Virtual Reality Nature Environments on Calmness, Arousal and Energy

5.4.1 Introduction

It is widely agreed that Virtual Reality (VR) is the current media's epitome of Immersiveness, Presence and Suspension of Disbelief. The technology has very appealing characteristics that brings the user experience to a whole new level. To please the vision, it offers a wide field-of-view, stereo-vision, and the ability to look and move your head anywhere inside a virtual environment (with more degrees-of-freedom than is usually possible in other media). It also offers a greater ability to manipulate virtual objects in three-dimensional spaces, than most media, even though it is still, somewhat, underdeveloped and is, for most commercial solutions, unnatural. Finally, it enables the user to use natural locomotion to navigate the virtual environment, which, together with all the previous characteristics, pulls the user into the virtual environment in a way that was never possible before on any other kind of media. All of this creates a sense of Immersiveness, Presence and Suspension of Disbelief so great in some VR experiences and games, making it so visceral that some people completely forget that they are in a game, which triggers some extreme reactions, including an elevated sense of fear and even panic. These intense feelings have been widely explored by indie developers and is currently making its way into the AAA gaming industry, making it a contributing factor for the widespread adoption of VR. What this study explores is the polar opposite of the spectrum. Because getting automatic fear and panic reactions out of people is actually something that can be easily achieved in other forms of media (by using, for instance, the typical "jump-scare" cliché), even though that is very intense in VR. For this reason, we explored sensations such as relaxation and that soothing and warm feeling one can get, just like a sunny day at the beach or sitting by a camp fire. These feelings have been targeted before by other media, through screen savers in TV sets, computers, and mobile phones, but we argue that those feelings achieve a whole new level, visceral-like, when using Virtual Reality - similar to what can be achieved with panic and fear-like feelings.

By proving that Virtual Reality can effectively create those feelings in a heightened level, the technology can be used in many fields where mental healthcare needs a boost, from stressful work places to healthcare and elderly homes, it can even have beneficial effects in depression, especially, when people are somewhat limited in the locations that can trigger those feelings (such as in big cities, prisons, medical institutions) or when they simply lack the willingness to leave their homes.

5.4.1.1 Research Questions

Our aim is to discover how effective Virtual Reality is in quickly creating soothing, relaxing, and warm feelings. For this reason, we try to answer the following research questions, taking into account a short time exposure of 1 minute:

1. Can Virtual Reality strongly relax people?
2. Can Virtual Reality strongly increase peoples' mood?

A third research question came up when the data started to be analyzed and will be further explained later in the study:

3. Can Virtual Reality help to regulate the circadian cycle?

5.4.2 Research Methods

5.4.2.1 Apparatus

5.4.2.1.1 Virtual Reality Simulation The Virtual Reality Simulation, where the subjects are tested, was built using Unity3D 2019.4, with the High Definition Render Pipeline and the help of the built-in Terrain Tool. The SteamVR Plugin was used to handle the Virtual Reality. Assorted high-quality assets from the built-in Asset Store were used to aid in the construction of the environments. There are two environments, a beach and a forest, described below. Each environment has two time-of-the-day, totaling four different combinations that the users can experience. The experiments were built with as much visual quality as it was possible, given our time, human and financial constraints.

- Beach - A golden sand beach, near the ocean. Some palm trees paint the sand dunes behind the subjects. Assorted beach-related things are spread around the

Figure 5.8: The Beach scenery. Midday on the left; sunset at the right.

subject. The sound of waves can be heard coming from the sea. These sounds do not change between different times of the day. There are two time-of-the-day settings that subjects can experience:

  - At midday - a very high strong sun;
  - At sunset - a romantic sunset.

- Forest - A calm, tree-filled, forest. The subjects are in a small sunken glade with a fire built nearby. You can hear the fire going and a slight breeze on the trees. These sounds do not change between different times of the day. Just like in the beach, there are two time-of-the-day settings that the subjects can experience:

  - During the afternoon - the sun is comfortably midway in the afternoon creating some longish shadows while keeping good visibility;
  - During the night - the sun is long gone, giving space to a starry sky and the moon.

5.4.2.1.2 Virtual Reality Hardware We used the HTC Vive Pro as the Virtual Reality headset. No controllers are used since there is no direct user interaction, other than looking around.

Figure 5.9: The Forest scenery. Afternoon on the left; night at the right.

5.4.2.1.3 Sensors We used a MUSE S in order to sense the level of relaxation of the user. We also used a generic Heart-Rate sensor band to measure alterations in the subjects' heart-rate.

5.4.2.1.4 Computer Due to the high requirements of the current generation Virtual Reality, we used a high-end gaming computer composed of an Intel i7-9700K CPU and a Nvidia GeForce RTX2080 Graphics Card. The rest of the computer was built with relevant matching high-end components.

5.4.2.2 Questionnaires

To complement the data gathered by the sensors, we exposed the subjects to the following standard questionnaires: 1) AD ACL[140] and 2) SAM[141]. From all the questionnaires that we explored, we found these two to better evaluate the more positive and calm feelings that we are trying to research. The other related questionnaires are more focused on active and negative feelings. We also exposed the subjects to another two non-standard questionnaires. One at the beginning of the experiment and another at its conclusion.

5.4.2.2.1 Activation-Deactivation Adjective Check List (AD ACL) The AD ACL that we used is based on Thayer's original questionnaire[140]. It has the original 20 adjectives randomly distributed in order not to influence the subjects' answers and to reduce coupling. The remaining of the questionnaire is standard with the standard 4 levels that the subject can feel.

5.4.2.2.2 Self Assessment Manikin (SAM) We used a standard SAM[141] questionnaire with drawn manikins and the standard 9 levels scale but limited to Valence and Arousal.

5.4.2.2.3 Pre-Questionnaire The pre-questionnaire tries to assess the prior level of experience of the subjects in Technology, Gaming and Virtual-Reality. It uses a standard 7-points Likert-scale. All the 3 questions range from *1 - Low* to *7 - High* with a middle point at *4 - Medium*.

5.4.2.2.4 Post-Questionnaire The post-questionnaire tries to assess how the subject feels about the subject in a subjective manner. It also uses standard 7-points Likert-scales. All the 4 questions range from *1 - Not at all* to *7 - A Lot*. The questionnaire asks the subject the following questions:

1. I feel that the Virtual Reality environments relaxed me.
2. I would enjoy spending more time relaxing in Virtual Reality environments.
3. I feel that, relaxing in a Virtual Reality environment could substitute a real-world alternative, in situations where the real-world alternatives are not accessible (e.g.: prisons, remote locations, big concrete cities).
4. I would pay to enjoy spending time relaxing in a Virtual Reality environment.

The questionnaire also asks them to sort the experiments by order of relaxation.

5.4.2.3 Experimental Protocol

5.4.2.3.1 The Experiment Script

5.4.2.3.1.1 Pre-Experiment: The experiment starts with the subjects being asked to fill in the pre-questionnaire followed by the evaluation of the subjects' current mood. The mood is evaluated using the AD ACL and the SAM questionnaires. This establishes a baseline, where the subject is not yet exposed to the Virtual Reality. The two sensors (Muse and Heart-rate sensor band) are then set up on the subject. The subject is, then, asked to sit quietly on a chair, facing the wall in a silent room for 2 minutes (1 for the calibration of the MUSE S and another for the data gathering). We use this to set up another baseline, this time, for the sensors (mental relaxation and rest heart-rate), again, before exposure.

5.4.2.3.1.2 Main Experiment: The subject is exposed to each of the 4 Virtual Reality experiences in random order. It starts with 1 minute of calibration of the MUSE S followed by 1 minute of exposure to the experience. After each experiences, the subject is asked to again fill up the AD ACL and the SAM questionnaires, allowing us to assess their mood after each iteration. These 4 iterations are also experienced in the same chair, for the same 1 minute and without moving.

5.4.2.3.1.3 Post-Experiment: In the end, the subject repeats the baseline measurements to allow us to compare the before and after of the experiment. The subject is finally asked to fill up the post-questionnaire before concluding the experiment.

5.4.2.3.1.4 Duration: The experiment takes about 30 minutes per user. There are two short pre-questionnaires that are then followed by a baseline ”empty” experience that takes a little more than 2 minutes (1 min calibration + 1 min experience). The main experiment takes (1 min calibration + 1 min experience) x 4 experiments = 8 minutes. All of this is followed by another baseline ”empty” experience and the post-questionnaires. This all adds up to about 12 minutes of controlled time plus questionnaires and overheads.

5.4.2.3.1.5 Clarifications: Note that the subject is asked to remain still when being evaluated, to avoid the subject's movements to affect the heart-rate. This way, any change in the subject's heart-rate can be attributed to a mental state, instead of a physical movement. Also note that the order of the 4 iterations are picked from a previously built list. The list contains all of the possible 24 permutations. The users are then attributed sequentially until all of the permutations are tested. The list is, then, restarted. Finally, the 1 minute calibration was chosen because the MUSE S was taking somewhat below 1 minute to calibrate. In order to keep the user's experiences as similar to each other as possible, we decided to calibrate for 1 minute, even if the MUSE S was done calibrating before that. As for the 1 minute Virtual Reality experiences, please check Section 5.4.6.

5.4.2.4 Subjects

A total of 29 subjects participated in the experiments, 20 males and 9 females. Ages ranged from 21 to 39. 7 subjects had no to little experience with Virtual Reality, 18 had moderate experience with Virtual Reality and 4 had a lot of experience with Virtual Reality. The subjects were asked out from anyone in-campus (students, professors, staff, researchers, and other), including the local university, research institutes and supporting buildings. A small number of out-of-campus subjects were also used.

5.4.3 Results

We conducted t-tests comparing the baseline before the subject's exposure to the experiment and each of the 4 iterations. We also ran it against the average of the 4 iterations, the average of the 2 environments (on the 2 times of the day), and, at the end, against the after-exposure baseline (where relevant). We also calculated some simple averages, standard deviations, the effect power, and the effect size, where relevant. All this data is in several tables of the relevant subsections. Figure 5.12 also shows a box-and-whiskers chart of the data to better clarify its distribution.

5.4.3.1 Activation-Deactivation Adjective Check List (AD ACL) Questionnaire

The AD ACL Questionnaire merges the adjectives into 4 feelings: *Energetic*, *Tired*, *Tension* and *Calmness*, that we use to further our research. Our Research Questions point to an increase in *Calmness*. We make no assumptions as to *Energy*, *Tired* and *Tension* other than there may be an effect. As such, we have 4 hypotheses: 1) The *Calmness* value of exposed subjects should increase; 2) The *Energy* value of exposed

Figure 5.10: The feelings of the subjects, Before and After exposure.

subjects should be different; 3) The *Tired* value of exposed subjects should be different; 4) The *Tension* value of exposed subjects should be different.

Hypothesis 1 (Calmness) is statistically significant for the Beach Midday and Sunset but not for the Forest. It has p-values of 0.009513 and 0.000024, respectively. The increase in *Calmness* is of 0.36 and 0.52, respectively, and in a scale of 1 to 4. It also an intermediate to large effect size with values of 0.529 to 0.929.

Table 5.16: Calmness Average rating; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size.

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	2.54	0.47	-	-	-	-
Beach; Midday	2.90	0.58	+0.36	0.009513	0.990487	0.529
Beach; Sunset	3.06	0.49	+0.52	0.000024	0.999976	0.929
Forest; Afternoon	2.63	0.62	+0.09	0.239065	-	-
Forest; Night	2.50	0.69	-0.04	0.398067	-	-

Hypothesis 2 (Energy) is statistically significant for all but the Forest at Night. It has p-values of 0.002103, 0.000043, and 0.005301. The *Energetic* values always decrease ranging from 0.34 to 0.67, in a scale of 1 to 4. The effect sizes, however, are adverse for all.

Table 5.17: Energetic Average rating; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size.

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	2.54	0.72	-	-	-	-
Beach; Midday	2.21	0.80	-0.34	0.002103	0.997897	-0.688
Beach; Sunset	1.74	0.64	-0.67	0.000043	0.999957	-0.879
Forest; Afternoon	2.02	0.78	-0.52	0.005301	0.994699	-0.600
Forest; Night	2.34	0.78	-0.20	0.241870	-	-

Hypothesis 3 (Tired) is statistically significant for the Beach at the Sunset. It has a p-value of 0.00078. The *Tired* value increases 0.5143, in a scale of 1 to 4. Its effect size is medium with a value of 0.7.

Table 5.18: Tired Average rating; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size.

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	1.94	0.76	-	-	-	-
Beach; Midday	2.10	0.75	+0.16	0.10784	-	-
Beach; Sunset	2.46	0.72	+0.51	0.00078	0.99922	0.7
Forest; Afternoon	2.23	0.76	+0.29	0.10274	-	-
Forest; Night	1.96	0.76	+0.01	0.93538	-	-

Hypothesis 4 (Tension) is statistically significant for the Forest at Night. It has a p-value of 0.044 and an increase in *Tension* value of 0.31, in a scale of 1 to 4. It has a medium effect size of 0.747.

Table 5.19: Tension Average rating; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size.

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	1.31	0.33	-	-	-	-
Beach; Midday	1.26	0.32	-0.05	0.527	-	-
Beach; Sunset	1.24	0.29	-0.07	0.277	-	-
Forest; Afternoon	1.35	0.45	+0.04	0.734	-	-
Forest; Night	1.62	0.77	+0.31	0.044	0.956	0.747

5.4.3.2 Self Assessment Manikin (SAM) Questionnaire

The SAM questionnaire evaluates Valence and Arousal. We consider the scale to go from -4 to +4, with 0 being a neutral value. Our Research Questions point to an decrease in *Arousal*. We make no assumptions as to *Valence*. As such, we have 2 hypotheses: 1) The *Arousal* value of exposed subjects should be lower; 2) The *Valence* value of exposed subjects should be different.

Hypothesis 1 (Arousal) is statistically significant for the Beach (both times-of-day), the Forest in the Afternoon and the Average of all experiments. It has p-values of 0.00073, 0.00010, 0.04547 and 0.00240. The decrease in *Arousal* values ranges from 0.97 to 1.46. All the effect sizes are adverse.

Table 5.20: Arousal Average rating; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size.

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	-0.25	2.56	-	-	-	-
Beach; Midday	-1.46	2.08	-1.21	0.00073	0.99927	-0.339
Beach; Sunset	-1.71	2.12	-1.46	0.00010	0.99990	-0.384
Forest; Afternoon	-0.86	2.16	-0.61	0.04547	0.95453	-0.173
Forest; Night	-0.46	2.25	-0.21	0.27068	-	-

Hypothesis 2 (Valence) has no statistically significance in any of the experiences.

Table 5.21: Valence Average rating; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size.

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	2.00	1.54	-	-	-	-
Beach; Midday	2.07	1.59	+0.07	0.69	-	-
Beach; Sunset	2.18	1.39	+0.18	0.48	-	-
Forest; Afternoon	1.86	1.46	-0.14	0.54	-	-
Forest; Night	1.61	1.50	-0.39	0.20	-	-

5.4.3.3 Brain Relaxation

The hardware that we used - the MUSE S - has an app that outputs 3 values, measured along time: Active, Neutral, Relaxed. To merge the 3 values into 1, and since we are aiming at relaxation, we subtracted the *Active* time from the *Relaxed* time to find out the adjusted relaxed time (in 1 minute). Our hypothesis is ”The relaxed time should be higher after exposure”. We achieved statistically significant results when comparing the baseline after exposure with the baseline before exposure as well as with the same comparison with the Beach. The p-values of the t-test are 0.0122 and 0.0131, respectively, with an increase of 8.79 and 9.32 seconds of relaxation in a minute of exposure. The effect sizes are small with values of 0.414 and 0.37, respectively.

Table 5.22: Number of seconds in relaxation; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size.

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	21.21	18.08	–	–	-	-
Beach	30.54	11.19	+9.32	0.0131	0.9869	0.37
Forest	27.13	14.09	+5.91	0.1119	-	-
Beach + Forest	28.09	8.90	+6.87	0.0437	0.9563	0.263
Base-After	30.00	14.85	+8.79	0.0122	0.9878	0.414

5.4.3.4 Heart-Rate

We take the median of the heart-rate of each of the 6 measurements (before exposure, 4 virtual reality environments after exposure). We use the median, instead the average, to filter out small spikes in the heart-rate that occur due to subject movements. We then use these values to conduct the t-tests. Our hypothesis is ”The Heart-Rate of the subjects should be lower after the exposure”. We were unable to prove or disprove this hypothesis with our data. The data fluctuates around no change with no statistically significant values.

5.4.3.5 Pre-Questionnaire

We did a simple average of all the subjects answers to the pre-questionnaire. The average value for Technology Experience is of 5.68, for Gaming Experience is of 4.36, and for Virtual Reality is of 3.46. The range of it goes from *1 - Low* to *7 - High* with a middle point at *4 - Medium*..

Table 5.23: Average Hear-Rate; Standard Deviation; Difference vs. Base before exposure; p-value of the t-test; Power; Effect Size..

Measurement	Average	StDev	Delta	p-value	Power	Effect Size
Base-Before	72.88	9.85	–	–	-	-
Beach; Midday	73.29	8.74	+0.42	0.35	-	-
Beach; Sunset	72.35	8.71	-0.52	0.29	-	-
Forest; Afternoon	73.21	9.35	+0.33	0.36	-	-
Forest; Night	73.50	8.61	+0.63	0.25	-	-
Base-After	72.98	8.00	+0.10	0.47	-	-

5.4.3.6 Post-Questionnaire

We did a simple average of all the subjects' answers to the post-questionnaire. The subjects answered an average of 5.18 as to feeling that the Virtual Reality environments relaxed them, 5.07 as to whether they would enjoy spending more time relaxing in the Virtual Environments, 5.32 that Virtual Reality could be used as a substitute for the real-world in situations where the subject has no access to relaxing alternatives, and 3.32 as to they would pay to enjoy relaxing in a Virtual Environment. The range of it goes from *1 - Not at all* to *7 - A Lot*. The questions are:

- *Q1:* I feel that the Virtual Reality environments relaxed me.
- *Q2:* I would enjoy spending more time relaxing in Virtual Reality environments.
- *Q3:* I feel that, relaxing in a Virtual Reality environment could substitute a real-world alternative, in situations where the real-world alternatives are not accessible (e.g.: prisons, remote locations, big concrete cities).
- *Q4:* I would pay to enjoy spending time relaxing in a Virtual Reality environment.

5.4.3.7 Data Whiskers-and-Box

On figure 5.12 we can check the data distributions. *a - Muse:* Pre baseline; Post baseline; Experiments Average; Beach; Forest.

b - Energetic: baseline; Beach Day; Beach Sunset; Beach Average; Forest Day; Forest Night; Forest Average; Experiments Average.

c - Tired: baseline; Beach Day; Beach Sunset; Beach Average; Forest Day; Forest

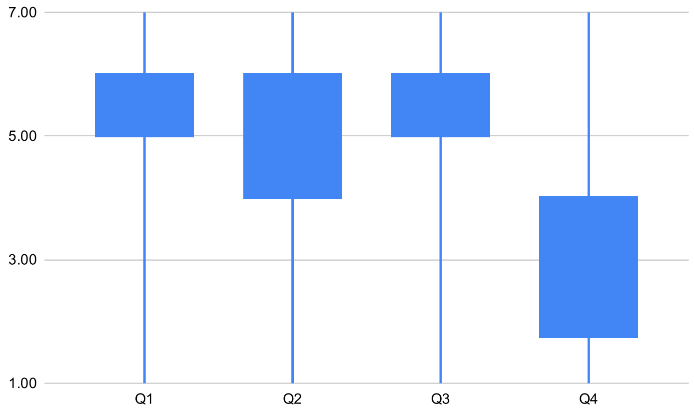


Figure 5.11: Answers to the Post-Questionnaire.

Night; Forest Average; Experiments Average.

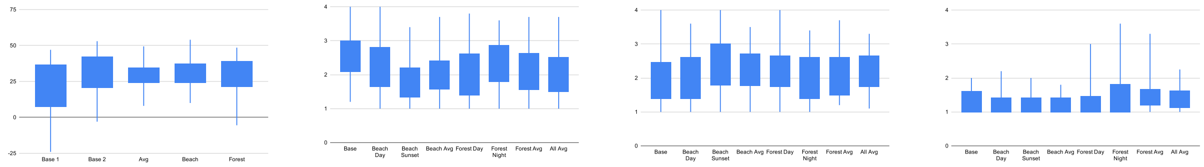
d - Tension: baseline; Beach Day; Beach Sunset; Beach Average; Forest Day; Forest Night; Forest Average; Experiments Average.

e - Calmness: Pre baseline; Post baseline; Experiments Average; Beach; Forest.

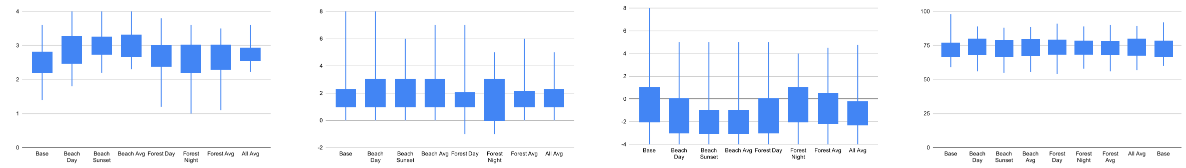
f - Valence: baseline; Beach Day; Beach Sunset; Beach Average; Forest Day; Forest Night; Forest Average; Experiments Average.

g - Arousal: baseline; Beach Day; Beach Sunset; Beach Average; Forest Day; Forest Night; Forest Average; Experiments Average.

h - Heart-Rate: Pre baseline; Beach Day; Beach Sunset; Beach Average; Forest Day; Forest Night; Forest Average; Experiments Average; Post baseline.



a - Muse b - Energetic c - Tired d - Tension



e - Calmness f - Valence g - Arousal h - Heart-Rate

Figure 5.12: Whiskers-and-Box charts for the different data.

5.4.4 Discussion

Our tests confirmed, with a very high degree of statistically significance (best p = 0.000024; Beach at Sunset), that Nature Scenes in Virtual Reality can induce a sense of *Calmness* in the subjects who were exposed to it. The effect is considerably strong (with a power of 0.999976 and an effect size of 0.929): the subjects report an average increase in *Calmness* of 0.5214 points (Beach at Sunset) in a scale ranging from 1 to 4 (AD ACL). This effect is felt even in sessions of very short duration (1 minute). There is also a decrease in the sense of *Energy*, consistent with the current literature[114], with a high degree of statistically significance (p = 0.000043; Beach Sunset). This effect is even stronger than the *Calmness*, with a decrease of 0.67 points (Beach at sunset) but its effect size is, actually, adverse (negative). The *Tired* feeling is only statistically significant for the Beach at sunset (p = 0.00078) with an increase of 0.5143 points. It has an effect size of 0.7. The *Tension* feeling has no statistically significant except for the Forest at Night (p = 0.044). Its effect size is 0.747. The subjects felt uneasy - scared even - and this can be seen in an increase of 0.3071 points in *Tension*. Some subjects even commented it directly that they were scared and/or were waiting for some kind of jump-scare. It was also rated, by most subjects, as the least relaxing of the 4 experiments. Note that the nature of the experiment was not explained to them so they did not know that we were looking into relaxation instead of fear, and some subjects were even expecting some kind of jump-scare. The data supports that there is a statistically significant (best p = 0.00010, Beach at Sunset) decrease of 1.46 points in *Arousal*, in a scale ranging from -4 to +4, in the Beach experiment. The other scenarios also have a statistically significant reduction in *Arousal* except for the Forest at Night. All of the effect sizes are adverse. The *Valence* shows no statistically significant data. Also, there seems to be little to no change in *Valence*, despite the lack of statistically significance. However, the Forest at night shows a decrease of 0.39, but not statistically significant (p = 0.20). The MUSE S shows statistically significant results for both the Beach and the second baseline, after exposure, exhibiting the respective p-values of 0.013 and 0.012. It shows a considerable increase in relaxation time of 9.32 and 8.79 seconds (in 1 minute; from a baseline of 21.21 seconds before exposure). It has small effect sizes. This seems to indicate that the effect is maintained even after the users are no longer exposed. We did not, however, measured for how long this effect lasts. The Heart-rate data did not produce any statistically significant data. There is a slight oscillation below 1 BPM, and the p-value denies us any useful conclusions.

The subjective tests point to a higher than average feeling of *Relaxation* with 5.18 points in a 7-point Likert scale. Subjects would also like to relax more, in Virtual Reality (5.07 points). This does seem to point to the fact that the subjects feel a good level of *Relaxation* during the experiments - enough for them to feel the difference at a conscious level. Some subjects also expressed this feeling with their words pointing to both a high level of relaxation and even sleepiness, despite being alone on a room with with strangers performing the experiment. However, we are aware that this is a subjective questionnaire and a matter of opinion, our low number of answers might not be representative of the population. This leads us to the next question where they give their opinion on whether or not they feel like a system like this could substitute the reality in situations where it is not possible to experience similar environments (like prisons, remote locations, big concrete cities). This may be interpreted as a loaded question and, as such, appears after the other questions to avoid directing the subjects. The subjects did answer a little bit higher - 5.32 - but still similar to the other two questions. We built the three questions to evaluate almost the same thing with, somewhat, different phrasing. And the subjects did stay around the mid 5s.

The last question asks if the subjects were willing to pay to experience more relaxation in Virtual Reality environments. Now the value does go down, as expected, to 3.32, in the same scale. This may be interpreted as an opinion on how important they feel a system like this is, despite its capabilities to perform. We feel that 3.32 is still high enough, in light of the other answers and all the experiment results. Hence, their true feeling about relaxing in Virtual Reality might be between the 3s and the 5s, pointing at a medium-strength subjective feeling.

5.4.5 Conclusion

Our experiments indicate a statistically significant and strong increase in *Calmness* and a decrease in *Energy*. There is also a statistically significant and strong decrease in *Arousal*. This is also confirmed by the subject data where the subjects feel above average relaxation (greater than 5 in a 7 point Likert scale with a central neutral point at 4) coupled with some verbal, free-form indications of such. All this data confirms our hypothesis that *Virtual Reality can strongly relax people*. The same data does not provide any statistically significant information about *Valence* so we will have to withdraw any conclusions about the hypothesis that *Virtual Reality strongly increase peoples' mood*. The hypothesis that *Virtual Reality help to regulate the circadian cycle* is, partially, confirmed. At sunset (a synchronization time for the circadian cycle), the data showed a statistically significant increase in *Tired* and a decrease in *Energy*. It also showed a statistically significant increase in *Calmness* and a statistically significant reduction in *Arousal*. These changes are also stronger in the sunset that they were for the remain of the experiments, and the 4 were felt all at the same time during the sunset. We do not make a stronger position in confirming this because we only explored a small portion of the circadian cycle. However, the data does show an influence of the (virtual) sunset. An unforeseen and unfortunate conclusion is that our subjects did not enjoy being in a Forest at night, despite it being under the full moon with a fire going nearby. There is a big decrease in *Valence*, even if not statistically significant, and a statistically significant ($p = 0.044$) moderate increase in *Tension*. The subjects corroborated this verbally. Unfortunately, this may have reduced the relaxation capabilities of the experiment as a whole, especially for the subjects who felt fear. Boyce et al. [207] points to about 30 lux being enough for the perception of safety, at least in city settings. In exceptional conditions, the moon can reach up to 32 lux. However, typical values are way below those values, which is below the safety threshold. Regardless, we can not guarantee the output of the head mounted display. At this point, we can only speculate that the lux values may not be the only factor and the forest setting and/or the absence of other humans may be what is actually causing these feelings. It can even have a cultural explanation, as Dunn et al. [208] explores. All of this confirms that Virtual Reality with nature scenarios can be used to effectively induce a strong feeling of relaxation in people. The effect seems to be strong enough to even affect the circadian cycle.

5.4.6 Limitations and Future Work

Sound: We did not consider the effect of the sound. The sound, by itself can cause effects that could interfere and conflict with our results. This should be addressed in the future by either comparing the effects of sound vs no sound or even completely remove the sound from the experiment. Different sounds could also be explored.

Comparing with the real life: We did not compare the Virtual Reality with the real life. The idea was considered but was discarded for being too difficult and expensive to take users to a beach and a forest. It would also be nearly impossible to control all the variables due to external influences (including people external to the experience).

Extra props: Having the users sit on a picnic towel or in a beach stretcher, just like it is represented on the Virtual Reality environment, could have created a stronger effect. This could be interesting to explore since the haptic feedback could add to the effects of the experiences.

Users Background: We only realized how important the users' background could affect the experiment when a user noted that he really liked the beach scenario due to his childhood. Unfortunately, by this time, it was already too late to fix the experiment protocol.

More Scenaries: We studied the effects of just two natural environments. More types of natural and even artificial environments could give us different results. One could expect that some environments would be more appealing to different people with different backgrounds and experiences.

The Heart-rate: We limited the users to sitting still during the experiences. This was a limitation that we set up due to the changes that simply moving around can do on the heart-rate. Unfortunately, this can also interfere with our results. On one side, the users are artificially ”locked-in-place” and may feel less relaxed and can even break immersion. On the other side, moving around freely could create more variable experiences for each user, which would be harder to control and measure.

One minute experiences: The choice of 1 minute of Virtual Reality experience is an arbitrary one and we did not base it in any literature. We did, however, choose the time to make up the experience time long enough to expose the users as much as possible without taking too long and negatively affect their feelings (boredom, sleepiness, willing to quit the experiment). We ended up with the value of 1 minute by running some pre-tests and trying to find out when the user was started to get bored with the experiences. With our short, informal sample, most users felt that 2 minutes was a bit too long but were perfectly fine with a 1 minute Virtual Reality experiment.

MUSE S: The MUSE S equipment used in this study had some technical issues that hindered the experiment. Namely, the calibration was mandatory every time we would log data and it would take, up to 1 minute. We encountered some users (usually with thicker and/or longer hair) that would make the MUSE S very hard to calibrate, prolonging the session behind what should be.

Sample size and protocol refinement: We feel that the whole study could benefit from a bigger sample size. Even though we did find some interesting results, a bigger sample size could definitely make a stronger case. The experiment protocol could also benefit from a refinement of the experience we gathered in this study. *Circadian cycle and the night:* We, unintentionally, found effects that are, possibly, related to the circadian cycle at the sunset and even at night. This could indicate that Virtual Reality is strong enough to even affect it and it is an interesting venue to explore in the future.

5.5 Chapter Conclusion

This chapter explored three studies that resulted in three papers. It explored the relationship between the frustration levels when using the typical mouse pointing device and eye-tracking, used as a pointing device. The study found out that eye-tracking are, indeed, a frustrating way to, directly, point at things. It can still be used as a soft and indirect select or, even better, has just a way to know where the user is looking at. It can be taken advantage of as the input in Foveated Systems (rendering where the user is looking at at increased resolution and rendering at a lower resolution farther away from the user's point of focus). It also explored the effects of sample rate in arm-tracking with results that indicate that we are not that affected by sample rate and can actually cope with a low sample rate. Despite it being uncomfortable, it does not seem to affect user's performance at a noticeable level. Finally, the possible impact of Virtual Reality in our feelings and calmness was studied. Interesting results show great promise to the usage of Virtual Reality as a relaxation and stress relief method in a world that gets farther and farther away from the nature. Virtual Reality seems to be capable of strongly affecting our emotions, not only on typical fear-related feelings (like jump-scares) but also on better feelings (like calmness). An interesting finding that will require further research is its effect on our circadian cycles.

Chapter 6

Sustainable Ocean Awareness and the Internet-of-Things

6.1 Introduction

The environment is of growing concern. With the humans' industrialization process pushing us down a cliff, the mass of aware persons grows but is still far from what it should be. Being located on an island, this project concerned itself with ocean awareness and how we could buy sustainable and attractive presentations to bring information from the ocean to the public in near-real-time. For this, we harness the power of the growing Internet-of-Things to capture, using tags, and transmit that information to the shore. We also explore the construction of (discarded) cardboard domes (where the public can be exposed to the information; please check figure 6.8), holography (that conveys visual tridimensional information; please check figure 6.8 and figure 6.9) and interactions devices (that gives another level of interaction with the information; please check figure 6.9 and figure 6.10).

6.2 Studying range and location estimation using LoRa in oceanic settings

6.2.1 Introduction

Interest for ocean exploration has been growing ever more during the last years, both in terms of natural resource scavenging, as well as in its protection and conservation. While most of the oceans remain greatly unexplored, current applications of technology in aquatic settings allow sea vessels to accomplish numerous tasks. For instance, the present tools on the market such as sonars[1] facilitate the detection of fish and other marine taxa using sound waves and Wi-Fi for communication with a mobile application. Moreover, emergency position indicating radio beacons [209] (EPIRB) using 406 MHz radio in combination with GPS, facilitate the rescue of those in need. Nevertheless, marine biologists are of crucial importance regarding oceanic studies. As they explore marine species, they focus on understanding the impact of human activities on their natural habitat. However, they often find themselves limited by the high costs of current existing technologies. These existing devices indeed, can collect valuable parameters which are crucial for studying the marine flora and fauna, their habitats, and ecosystems. However, all of these technologies have a high cost, facing challenges and risks when applied in harsh ocean settings. These challenges include dealing with poor signal propagation, salt corrosion, water and pressure proofing, battery autonomy, etc, even though some devices can use renewable energies, such as solar panels, wind turbines, or Wave Energy Converters (WEC). [210]. Another big challenge is obtaining the geolocation of the collected data. Traditionally, geolocation is acquired using satellite-based systems, which is then stored locally with other relevant data. However, satellite-based location systems are both expensive and energy consuming, and the data can only be retrieved later, when marine biologists recapture the taxa [211].

6.2.2 Application Scenario

In most cases, marine biologists study species by gathering data from animal tags either by: (i) physically recovering the tag, or by (ii) using radio (usually VHF) and

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[1] https://deepersonar.com

satellite communication (typically GPS). The former solution is long with repetitive tasks which require the recapture of the animals taking months or even years to locate again. As opposed to land animals, marine animals do not have as many physical constraints, and the ability to dive makes it very difficult to relocate them, increasing fuel costs. On the other hand, the latter solution is an improvement, using radio signals for tag recovery, providing a rough estimate of direction and range from a receiving antenna. It still requires the tags to be physically recovered to obtain back the data. Satellites also provide both remote data recovery and accurate geolocation, however, by using the GPS, the battery autonomy of bio loggers is short and the data transfer fees are high (e.g. ARGUS). Our study explores LoRa as a low-cost and long-range solution for real-time remote environmental telemetry and location estimation for future scientists, while also studying the longest LoRa range.

6.2.3 Research Questions and Contributions

While other studies focus on small distances or city environments, this study explores the issues of using long range radio (LoRa) in ocean environments, focusing on low altitudes for data collection using sea vessels, where the curvature of the Earth makes a great impact on communications range [212]. We explore LoRa as a mean for oceanic environmental telemetry as well as to approximate location without the usage of high energy devices. To achieve this, we focus on the following research questions:

[RQ1]. Which is the maximum LoRa distance in ocean environments? We explore the maximum range of LoRa signal, emitted from the sea vessel reaching the coastal nodes.

[RQ2]. How does the RSSI-based distance and location estimation behaves in ocean setting? Using several distances obtained from land and the nodes, we explore the feasibility of a generic model to estimate the distance from sender to the receiver, applied in an ocean setting.

The contribution of this study is therefore the maximum range in ocean environments and location estimation techniques using LoRa and low-cost Internet of Things (IoT).

6.2.4 Research Methods

We deployed 5 coastal-based nodes (2 failed) and 2 sea vessel nodes on the same vessel for the duration of 3 days, allowing us to test the range and location of the sea vessel.

6.2.4.1 System Apparatus

The system apparatus was based on 3 coastal nodes and 1 sea vessel node. Each node used a LoPy microcontroller, which was placed into a casing. These LoPys were equipped with a PySense expansion board granting us access to several sensors. Three coastal nodes were deployed within an average distance of 30km, at static locations facing the south of the Madeira island, Portugal. Each node has been placed on top of a 3m pole at an altitude higher than 50m from the sea level. Finally, one node was mounted on top of the sea vessel, capturing the GPS location using a PyTrack.

6.2.4.2 LoRa Settings

Instead of using LoRaWAN, we decided to use a node-to-node connection (with pure LoRa), eliminating the need for an internet connection and used unencrypted payload messages. We used the following settings for both LoRa receivers and transmitters:

- **Region**: EU868
- **Frequency**: 868 MHz
- **Transmitted power**: 14 dBm
- **Bandwidth**: 125 KHz
- **Spreading Factor**: 7
- **Device Class**: CLASS_A

6.2.4.3 Sensory Input

The sensed data were both sent via LoRa and logged into an SD card, serving to store the data when there is no line of sight.

For the purpose of this test and to ensure that no shortage of power would exist, the sea vessel node was further powered with a USB power bank. This supported to preserve its battery autonomy, and we used to sense the data each 30 seconds (plus a timeout time needed for the acquisition of GPS data).

Using this apparatus, we gathered a total of 4366 data points starting at 18:00 hours and during the following 40 hours, spanning to 3 days, including a stationary period between hour 14 to 24. Telemetry data used in this study were:

- **Battery Temperature** (Si7006-A20 sensor) measured in degrees Celsius (℃)
- **Ambient Temperature** (DS18B20 sensor) measured in degrees Celsius (℃)
- **Air Pressure** (MPL3115A2 sensor) measured in mbar or hPa
- **Relative Humidity** measured in percentage values (%)
- **Light** (LTR-329ALS-01 sensor) measured in lux
- **Acceleration** (LIS2HH12 sensor) measured in G (9.806 m/sec^2)
- **GPS** (Quectel L76-L GNSS receiver) with latitude, longitude and timestamp

6.2.4.4 Location Estimation

We explored a basic location estimation using the RSSI. Since the RSSI is in a logarithmic scale, we can either derive the linear equation for the data by: 1) turning the RSSI into a linear scale or 2) turning the distance into a logarithmic scale. We used the first approach, using a common formula (eq. 6.1) [213] for calculating the RSSI:

$$RSSI = -(10 \times n)log_{10}(d) - A \tag{6.1}$$

and reversing it to get the distance:

$$d = 10^{RSSI/10} \tag{6.2}$$

These equations use the $RSSI$ in dBm, and the distance d in meters and have tuning parameters such as n, the signal propagation constant and A being a reference received signal strength in dBm (the RSSI value measured at 1m distance). Figure 6.1 shows this geometrically, and the solution points are defined as the following [214]:

- $d > r_0 + r_1 \rightarrow$ no solution - circles are separated.

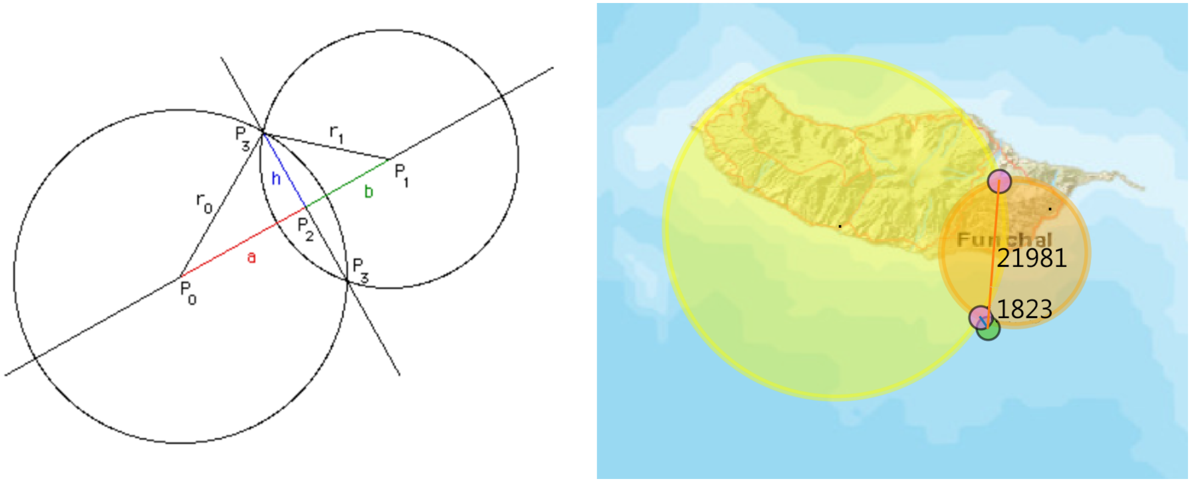

Figure 6.1: Left: Bilateration theory [214]; Right: Bilateration example with the two solutions, and an error of 1823 (excluding the solution located on land)

- $d < |r_0 - r_1| \rightarrow$ no solutions - one circle is contained within the other.
- $d = 0$ and $r_0 = r_1 \rightarrow$ the circles are coincident and there are an infinite number of solutions.

Figure 6.1 (left) shows this geometrically, and the solution points are defined as the following:

$$\begin{aligned} a^2 + h^2 &= r_0^2 \\ b^2 + h^2 &= r_1^2 \end{aligned} \tag{6.3}$$

Using $d = a + b$ we can solve for a, and it can be readily shown that this reduces to r_0 when the two circles touch at one point, i.e.: $d = r_0 \pm r_1$.

Solving for h by replacing a into the first equation, we get $h^2 = r_0^2 - a^2$. Thus,

$$P_2 = \frac{P_0 + a(P_1 - P_0)}{d} \tag{6.4}$$

And finally, $P_3 = (x_3, y_3)$ in terms of $P_0 = (x_0, y_0), P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$, is:

$$\begin{aligned} x_3 &= x_2 + -h(y_1 - y_0)/d \\ y_3 &= y_2 - +h(x_1 - x_0)/d \end{aligned} \tag{6.5}$$

When the two circles do not intercept, we only know that the solution is along the line perpendicular to P0P1 with its center in the point P2. A relaxation can be made to estimate that the solutions satisfy the $R_ij = q_j - q_k - R_ik$. Then averaging those two solutions, a single solution would fall in the equivalent of P2 when the circles do not intersect. The same principle applies when one circle is contained inside the other.

Because the RSSI is in a logarithmic scale, two approaches can be taken to derive the linear equation for the data: 1) turn the RSSI into a linear scale or 2) turn the distance into a logarithmic scale. We used the first approach, by starting from the commonly used formula (eq. 6.6 and 6.7) for calculating the RSSI:

$$RSSI = -(10 \times n)log_{10}(d) - A \tag{6.6}$$

and reversing it to get the distance:

$$d = 10^{RSSI/10\ \times\ n} \tag{6.7}$$

These equations use the unit-less RSSI, and the distance d in meters and have tuning parameters such as n, the signal propagation constant and A being a reference received signal strength in dBm (the RSSI value measured at 1m distance).

Workflow:

- Because RSSI values can be influenced by the environment around them, even the same ground truth position can suffer signal variations. To combat that, we first apply an average sliding window averaging 4 samples of data. This smooths the data for modeling as well as increasing the precision by an average.
- Use linear regression with the least squares method to both the original distance vs RSSI values, and distance vs RSSI linear using equation 6.7 with a n scale factor 6.639 (this value was found using a grid search to minimize the error).
- Use linear regression with the RANSAC method, thus discarding outliers in the data.
- Create these models for all the combinations of the different datasets for the different receivers used
- Compare the residuals from each model by applying it to all other combined datasets.

- Apply bilateration using the best models for the intersecting circles
- from the two possible bilateration, and since we know our destination is located in the sea, discard the one that is located up north on land.

Although a higher degree multilateration would usually result in better solutions, in this case bilateration was chosen for 2 reasons: 1) the land-nodes are aligned in an almost straight line with a small curvature in-land. This causes the multilateration equations to near a singularity where it is highly unstable and tends to give false results inland. 2) the nodes' RSSI values are unstable and don't provide coherent values throughout time, which translates into oscillating calculated radius from each node. Issue 2) further exaggerates issue 1) leading to the usage of a more stable, although less accurate solution: bilateration.

Figure 6.1 (right) shows an example of a bilaterated point and its comparison with the GPS data. The radius of the circles represents the distance estimated from the RSSI and the two circle intersections. From here, we can discard the intersection on land, and we end up with a point on sea with an error of 1 823m, which is an acceptable distance to locate an object in open sea.

6.2.5 Results

In this section, we present our results, namely, the maximum range obtained when sensing data from the sea, the distance estimation based on RSSI error using different data sources, location calculation and errors from the bilateration, as well as the environmental telemetry.

6.2.5.1 LoRa maximum distance

The maximum sustained distance captured by all 3 nodes was of 54.9km away from the shore with a minimum RSSI of -127. And the peak distance was captured by node Green with a distance of 83.6km and an RSSI of -126. These results were captured when the vessel was going away from the coast in a straight line.

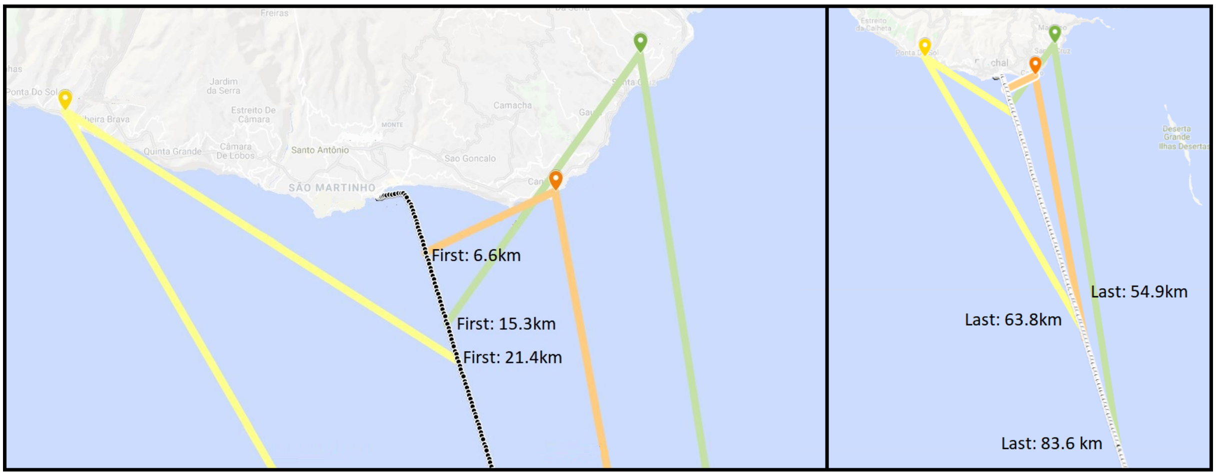

Figure 6.2: First and last detection from all 3 receivers.

6.2.5.2 Distance Estimation from RSSI

We modeled the data using both the raw logarithmic RSSI and distance values and applying the linear regression to them, and we also transformed the RSSI into a linear scale.

Due to the presence of outliers, we use the RANSAC (RANdom SAmple Consensus) method [215] iteratively using the minimum number of observations and generating candidate solutions where the maximum residual/threshold for a data sample to be classified as an inlier was the MAD (Median Absolute Deviation). This threshold is a robust measure of how spread out a dataset is. It uses the variance and standard deviation, also measuring spread, however they are more affected by extremely high or low values and non normality. [216].

In figure 6.3 we can see the variations of the different RSSI signals corresponding to the same vessel location at the different distances that the land nodes were located. While we can observe a steady progression for the orange line, we also notice many oscillations in the green and yellow even in the smoothed signal, which affect modeling. These oscillations are possibly resultant from the placement of the land nodes due to some mountains and land nearby, hindering the line of sight and the capture of the first signals.

Table 6.1 shows the residual error comparison for the different combinations of datasets and models created, combining them in pairs for the different models. We observe that the oscillations from the Green and Yellow receivers (figure 6.3) influence the inter-dataset data modeling, as the errors increase. In the LoRa context and this

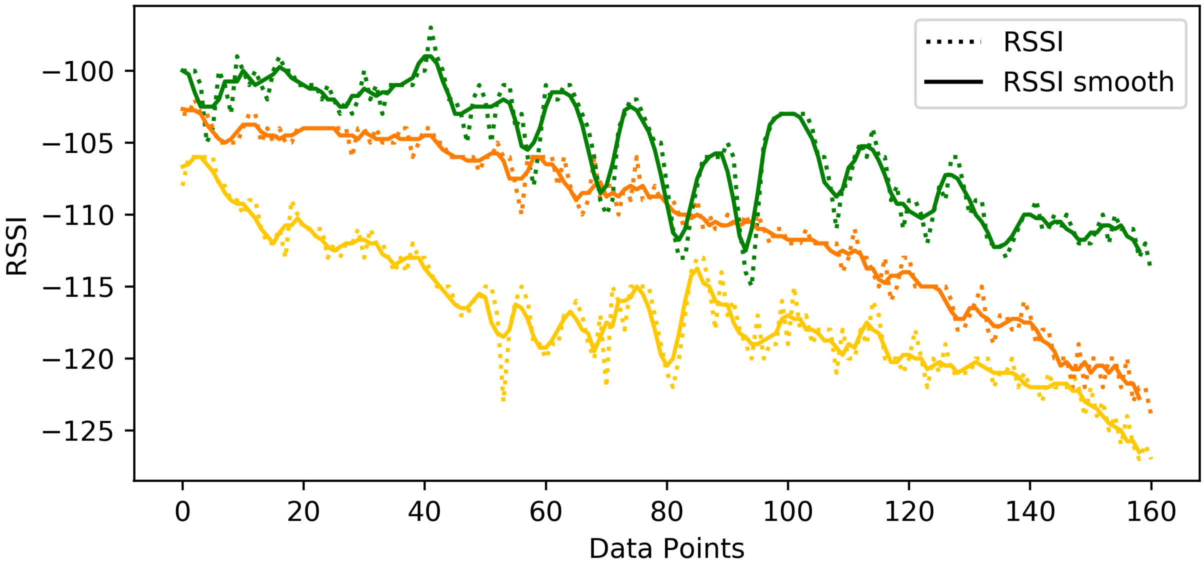

Figure 6.3: RSSI evolution of the 3 receivers by colors over the trip different distances for the same data point. Original RSSI as a dashed line and the moving average as a solid line.

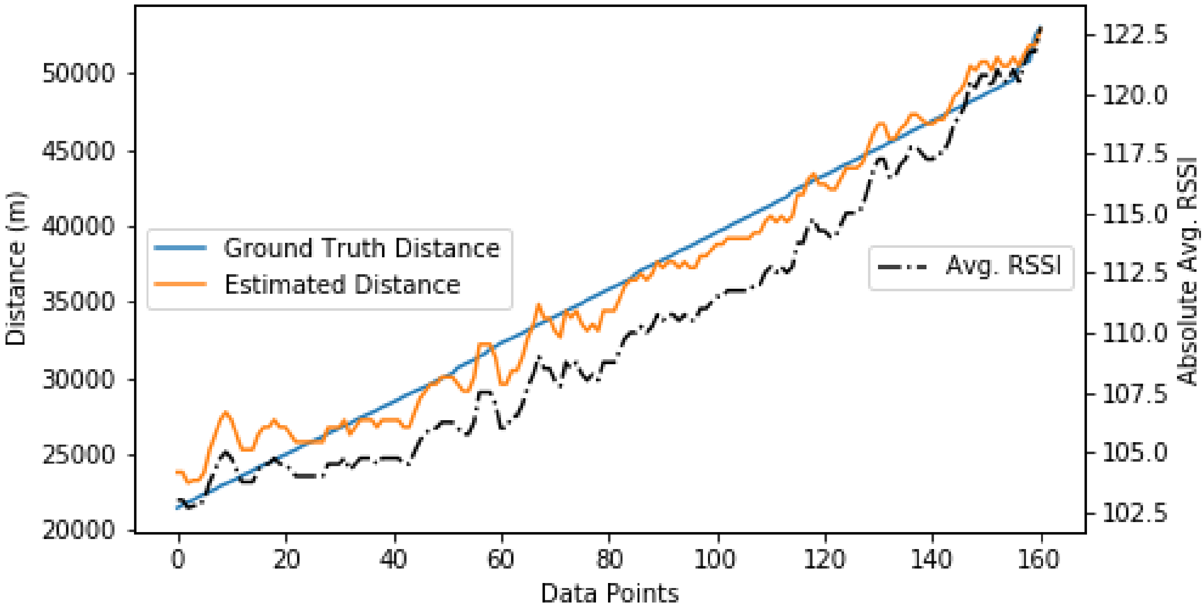

Figure 6.4: Modeling distance from Smoothed RSSI values for the case of the orange receiver, with the original smoothed RSSI as a dashed line.

Table 6.1: Error comparison (in meters) for the different models used after linearizing the RSSI

Modeled Data Sources	Dataset	Samples	Error LS				Error RANSAC			
			μ	σ	min	max	μ	σ	min	max
Individual Model	Orange	251	1.4k	1.2k	1	7.2k	1.4k	1.2k	1	7.2k
	Yellow	221	3.6k	2.1k	115	9.5k	3.6k	2.6k	7	10.6k
	Green	363	5.7k	4.8k	3	25.1k	5.7k	4.9k	61	25.8k
Orange & Yellow	Orange	251	1.6k	1.4k	6	7.6k	1.6k	1.4k	6	7.6k
	Yellow	221	4.k	2.6k	25	11.3k	4.k	2.6k	25	11.3k
Yellow & Green	Yellow	251	9.7k	4.2k	2.0k	19.5k	14.6k	5.6k	110	25.2k
	Green	363	9.0k	4.8k	8	19.7k	7.1k	5.1k	25	23.9k
Orange & Green	Orange	251	7.8k	4.7k	151	19.7k	9.2k	6.3k	39	24.3k
	Green	363	7.3k	3.9k	76	17.0k	6.5k	4.9k	8	23.1k

oceanic setting, the mean errors have a relatively low impact on the system if we look at them as a percentage of the maximum range of 83.6km and 54.9 km, the average of the combined Orange && Yellow for instance (Orange=1 578 m; Yellow=3 997 m; μ=2 788 m) represents only 3.3% and 5% respectively of the maximum distances.

6.2.5.3 Modeling Location Estimation from IoT input

For the bilateration, we needed to choose two of the receivers, and, as we noted in the previous section, the green receiver has a large error which influences its model and any other model that pairs with it. Hence, we decided to perform the bilateration using only the estimated distance from the receivers Orange and Yellow. The location estimation was modeled using bilateration with an average RSSI of 4 points. The data in figure 6.5 shows the estimation errors. Due to the low resolution of RSSI, it creates an aliasing effect which results in a grid-like pattern of location estimation with some estimation overlap (represented by the transparency).

The location estimation resulted in the errors presented in table 6.2. We can observe that the minimal errors come from the Orange and Orange and Yellow using the LS method, followed by the Yellow. As expected from the previous section, any combination that involved the Green receiver resulted in large errors due to its model and noise.

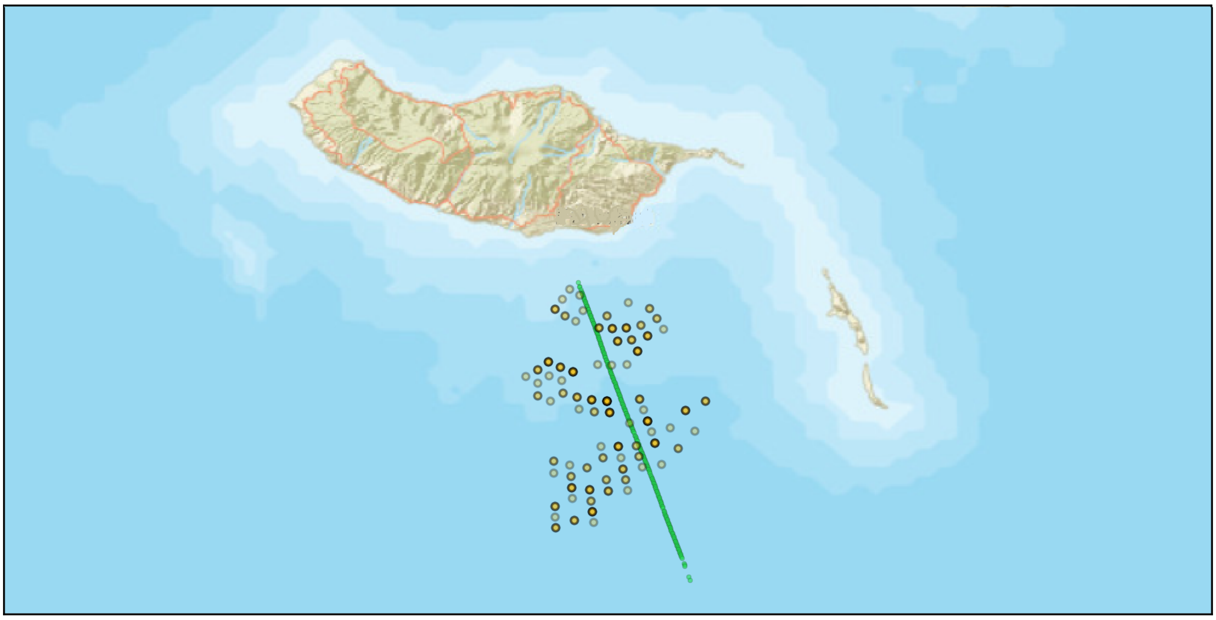

Figure 6.5: Location estimation from RSSI: GPS ground truth (green); location estimation (yellow - the darker, the more overlapped points).

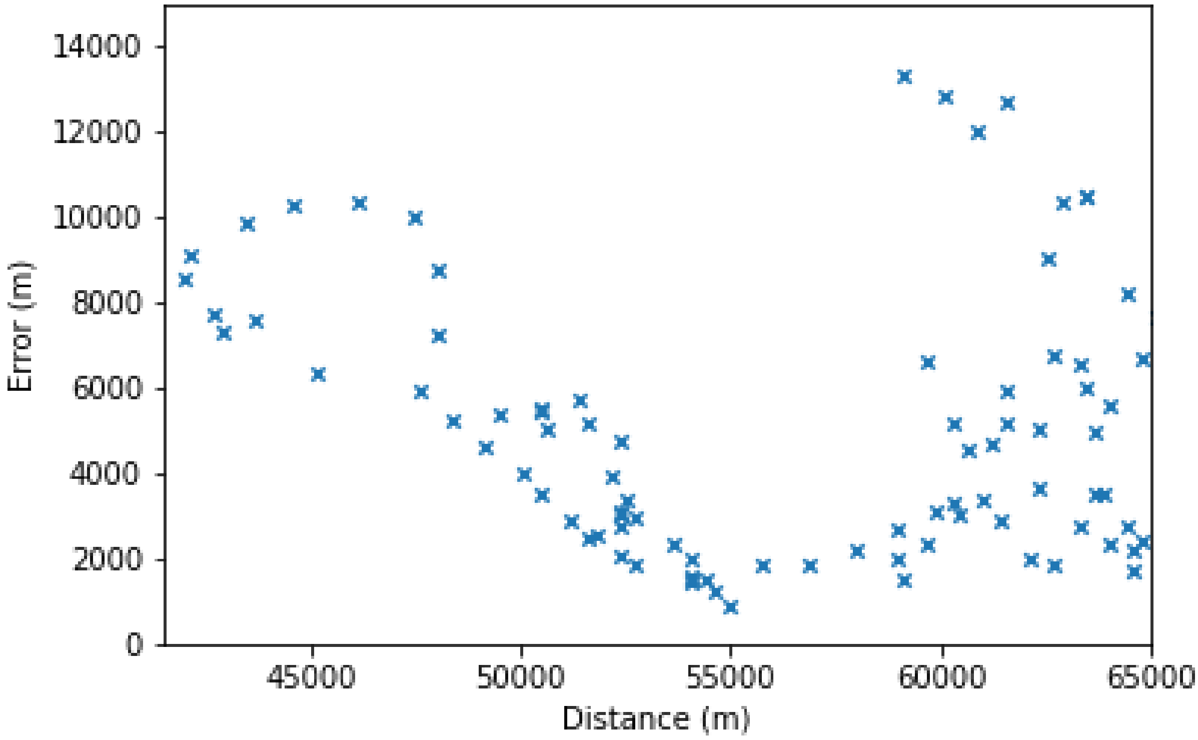

Figure 6.6: Estimated location errors (in meters) along the distance (as the vessel got further away.

Table 6.2: Comparison of location estimation errors (in meters) for the different models used for bilateration

	LS				RANSAC			
	µ	σ	min	max	µ	σ	min	max
Orange	3.4k	2.0k	231	8.9k	3.4k	2.0k	231	8.9k
Yellow	6.2k	3.7k	218	15.0k	7.5k	4.4k	244	19.2k
Green	21.3k	3.8k	14.3k	33.5k	22.0k	3.8k	15.0k	34.2k
Orange & Yellow	4.1k	2.2k	1.3k	11.4k	4.1k	2.2k	1.3k	11.4k
Yellow & Green	12.3k	2.4k	8.5k	17.2k	20.3k	2.4k	8.5k	17.2k
Orange & Green	16.3k	3.7k	10.8k	28.0k	21.7k	6.0k	11.5k	40.1k
Orange & Yellow & Green	10.6k	2.4k	6.8k	15.5k	4.6k	1.2k	2.2k	7.6k

Seeing the error in a relative perspective of the maximum distance observed in section 6.2.5.1, when comparing to 83.6km and 54.9km, for instance, the Orange and Yellow models have an average error (Orange = 5657; Yellow = 6207, µ= 5932), which represents 7% and 10.8% respectively of the maximum distances possible we achieve.

Figure 6.5 shows the estimated locations in comparison to the GPS ground truth. While many points are very close to the GPS line, we can also see the deviations that occur along the way, due to the inconsistency of the Yellow, in comparison to the Orange. In figure 6.6 we can see the progression of the error over the data points, where with the bigger the distance, the bigger the error becomes. This comes from oscillations in the lower end of the RSSI range, which, since it is logarithmic, means that small oscillations produce a large distance difference in the estimation. This error could be diminished by obtaining more points for each location, instead of just the four used in the moving average due to the sea vessel being in constant movement.

6.2.5.4 Environmental Telemetry

Here we present all data captured by the PySense on board of the sea vessel. This data corresponds not only to the received payloads on land, but also from the logged data throughout the whole trip. Figure 6.7 shows the distinctions in temperature, air pressure, and especially in light during day vs night, with the most noisy data coming from the air pressure sensor. Air pressure and humidity in this scenario can be useful to predict meteorological conditions with a sensor network of devices like these.

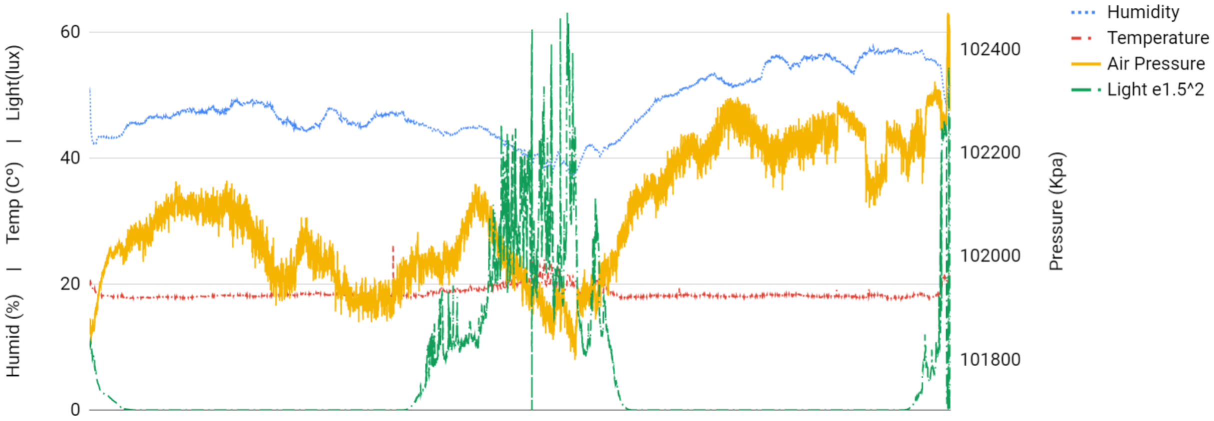

Figure 6.7: Data captured from the sensors in the LoPy 4 from the sea vessel.

6.2.6 Discussion

6.2.6.1 Maximum Distance using LoRa

During this study, we achieved a maximum range of 83.6km while using LoRa overseas. This range links a land endpoint (at an altitude of 281m) to a boat's endpoint in the middle of the ocean. This is above the manufacturers' range of 10 to 40 km but bellow a record that used a helium balloon to rise the endpoint up to 38 km of altitude before transmitting a packet to 702 km away with a transmit power similar to ours[2]. The maximum simultaneous range from all the land endpoints to the boat endpoint was of 54.9 km (at altitudes ranging from 57 m to 281 m), within the predicted range, achieved using LoPy devices coupled with 1/4 length 868MHz LoRa monopoles. No high-end and expensive gateways or antennas were used in the setup. We can all but speculate that the achieved higher ranges were due to any combination of the following explanations, as well as any other unforeseen factor:

- Having a perfect line-of-sight without obstacles or reflections. The land points were mounted facing the sea, with no obstacles;
- The altitude of the land endpoint vs the ocean endpoint. The longest range was achieved from the highest endpoint (83.6km range from 281m high) and there is a trend of declining range with the altitude (63.8km range from 185m high and 54.9 km range from 57m high). At 281 m high, the distance to the equator in direct line-of-sight, is about 60km, which is the majority of whole range, meaning that the signal still has to

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[2] https://www.thethingsnetwork.org/article/ground-breaking-world-record-lorawan-packet-received-at-702-km-436-miles-distance

travel 23km over the horizon to get to the 83.6km range.
- An improved build quality that was achieved over time. The LoRa technology was patented in 2008 and has had time to mature and improve since then.

6.2.6.2 Distance Estimation with LoRa

One of our focuses in this study was to use a low tech, low energy solution to find locations. This ruled out the power hungry satellite-based technology and expensive Time-of-Flight (ToF) based technologies. We were left out with multilateration or multi-angulation based technologies. We do not have a low-cost way to find the angle, but we do have one for range, so we used multilateration with RSSI values, to find the distance between the nodes. Since the RSSI is inherently sensitive to the environment, even after post-processing, some noise remained, as can be seen in figure 6.3. Despite that, our results show an average distance error (compared to the GPS ground truth) for the individual models that ranges from 1359 m (with a standard deviation of 1183 m) up to 5749 m (with a standard deviation of 4754 m) which represents 3.5% to 7% of the maximum range measured. The results also show individual error points with a minimum error of 1 m (that are very close to the estimated regression line) and a maximum error of 25070 m from a very noisy endpoint. Excluding this endpoint, the maximum error is less than 10 km. By combining the dataset from two endpoints, we managed to slightly improve the worst endpoint range estimation at the cost of the other endpoints. This evidentiates how sensitive the model is to noise, but it also suggests that solutions such as a higher number of endpoints or a moving average, do reduce the error.

6.2.6.3 Location Estimation using Bilateration

In our case we were forced to use bilateration. The two reasons are: 1) the land endpoints are aligned in an almost straight line with a small curvature in-land. And 2) the nodes' RSSI values are unstable and don't provide coherent values through time, resulting in different estimated distances for each node. We can fix 1) in the future by better placing or adding more nodes making a better geometry. As for 2), this would require a more expensive setup or better hardware. Using the post-processed RSSI range values and bilateration from two land endpoints, we calculated the boat endpoint's location. We then compared those values to GPS derived values to understand the accuracy and quality of our results as seen in figure 6.2. The geolocation error ranges from an average of 5 657m for the model that uses just the orange endpoint to an average geolocation error of 21 531 when using the very noisy green model. For individual points in the dataset, the results have a minimum geolocation error of 218 m and a maximum geolocation error of 33 461m, again, for the green model. If we exclude the green model, the maximum error is around 15km. Since our bilateration derives directly from the distance estimated using RSSI, all the improvements and pitfalls are shared. Although in absolute values these may seem large, in open ocean, with an average error of around 3.4km, it is possible to locate objects with the naked eye, thus this location estimation proves to be useful in such scenarios. Improvements may be done to remove the outliers from the dataset when testing against the models, reducing the error in 30-40%, however, as in real scenarios, we would not know in advance which values were outliers.

6.2.7 Contributions

We contribute with nearly 84km of LoRa maximum distance and a location error of 3.4km (4 % of maximum distance) for the long range tests. Nevertheless, other short range studies (max 2km) claim an accuracy of 100m (5% of distance) [15]. When using the real-time location of marine species, 3.4km is adequate when studying migration flows. Our main focus in this study was to use an IoT low cost and energy efficient LoRa solution that could be used in sea environments, to aid the research and conservation of marine life. We explored LoRa, how it behaves over the ocean and the extraction of geolocation of nodes using the RSSI that comes at no cost in any kind of radio communication. We delivered LoRa packets at a maximum distance of 83.6km, much more than the manufacturer claimed range (40km for Pycom LoPy4) as well as most literature.

We also modeled a bilateration and RSSI based geolocation that, even though it is far from the accuracy of the modern satellite-based technology, is low-cost both in terms of hardware/software as in terms of energy usage. The geolocation had an average error of approximately 5% of the maximum range, or about 3.4 km. This error is adequate for the study of migration patterns, the general location of animals and other situations where a pin-point location is not needed.

6.2.8 Limitations

The RSSI, being an indication of the power of the received radio-frequency (RF) signal is, at least, as susceptible to obstacles, signal reflections, distance fading, interference, and many other issues that trouble everyday's RF-based communications, as the signal itself is. This can create big issues when deriving distances from this value, as can be seen in the various charts that have RSSI plotted. Furthermore, in the open sea, we did not encounter any obstacle between endpoints but something blocking the signal would shift our calculated distances as if the endpoints were considerably farther than they were in reality. We did not consider this since this should not be an issue in the usage environment that we envisioned. But it is an issue to tackle in future studies. The RSSI is also an integer value with an inherently very limited range of values (usually 0 to -128) in a logarithmic scale. This greatly limits the resolution of the data and creates aliasing in distances because there is not enough values to represent all the distances. We did encounter this issue, but it was mitigated by the usage of a moving average that, together with the noise over time would, virtually, increase the resolution of the values, however, since your vessel was moving at a constant speed, this also limited the number of points that we could use for the sliding window in the moving average. During our practical experiments, we also had issues with 2 out of the 5 land endpoints dying out. Since we had very limited access to boats, we had to make due with just the 3 remaining endpoints. The 2 extra endpoints could have increased the quality of our study, not only because it would improve the RSSI as it would provide almost twice the amount of data to fine tune our distance model. Even though we are trying to improve trackability in the oceans, our limited access to boats forced us to conduct the study with land-based endpoints and just one boat. This may have increased the quality of the signal or even changed its characteristics in relation to what it would be if all the endpoints were located in boats.

6.2.9 Future Applications

Understanding the aforementioned contributions and constraints of applying the IoT and LoRa in oceanic environments, this research opens possibilities for numerous future use cases. Moreover, the reported techniques will use the given calculated models, which will be further verified in the wild, where RSSI and geolocation will be obtained using the real trajectories of fishing boats. Conversely, additional work will be performed on providing real-time dashboards, where it will be possible to provide additional back-end location services, including front-end user interfaces to locate marine objects such as: buoys, animals, sensors, cetaceans, and many others. In terms of battery autonomy, sensors themselves even if already energy efficient, can easily be transformed into solar powered, since the Pycom expansion boards all include battery charger circuits, thus further extending the longevity of the deployment.

Another component for future improvement is based on the fact that tourists often enjoy cetacean-seeing boat trips. At the moment, while in the search for cetaceans, the boat crew often relies on existing whale scouting locations found on land. Using our system, land nodes can save the time of whale spotters going to these locations. Moreover, tourists on sea vessels can use the derived tracking locations in real time, saving additionally the costs for fuel. This whale watching search endeavor can also be thought to be in a gamified manner. For instance, tourists can be instructed using our model that there is a given perimeter of nearby cetaceans, with indications of a rough area where they are using the location error in favor of the experience. Tourists participate in the search and in real-time update estimation of the exact cetacean position.

Since that LoRa has still a very limited range in the enormity of the oceans, remote sensors can have additional challenges delivering data. Conversely, with the need for line of sight, the curvature of the Earth can be an obstacle to estimate with more precision the exact location. To overcome this challenge, data mules can be used, serving as middleman that transmits messages to other nodes until they reach a gateway with internet connection. These mules could have fixed positions, drifting or be carried by sea vessels. Some data mules could be part of a sensor network which works as a mesh, covering the larger parts of the ocean and thus, monitoring their conditions. Finally, dozens of other sensors can be easily added to this platform to collect other information, in further scaling up the proposed system such as: turbidity, salinity, levels of dissolved oxygen, ocean depth and many others, which are crucial for studying the marine flora and fauna, their habitats and ecosystems, where an real-time monitoring brings huge benefits to the marine research and tourist communities.

Figure 6.8: AHAB'S GHOST Environment. Low-cost Geodesic Dome and Interactive Hologram based on Pepper's Ghost Illusion. From left to right: **1. DOME (outside)** - 2V geodesic structure with extended height (3m height, 6m diameter) from 100% reused cardboard. **2. DOME (inside)** - Self supported frameless support with divided triangles and MDF serving as joints. **3. HOLOGRAM (off)** - 5 sided sewed diamond-shaped acrylic as display *(top)*, and cardboard stand (1m height) for flat sheet display *(below)*. **4. HOLOGRAM (on)** - 5-sided Pepper's Ghost Illusion, revealing the underwater lifestyle of the great white whale.

6.3 Improving Awareness about Whales using Holography and a Low-cost, Interactive Geodesic Dome

6.3.1 Introduction

The iconic value of whales goes back to the use of these cetaceans as sources of food and energy, more than a thousand years ago. In the modern era, whales were depicted as monsters, like Melville's Moby Dick, and more recently connected to the rise of environmentalism and activism movements like Greenpeace[217]. Inspired by the iconic metaphors, but also the recent evidence of the role of whales in climate action, we focus here on visualizing these giant mammals to raise awareness about their importance in our planet's future[218].

6.3.1.1 Motivation

Great whales are the largest animals on Earth. With high metabolic demands, they have a significant impact on marine ecosystems as consumers and prey, and also as detritus and nutrient species [219]. As consumers of fish and invertebrates, they capture large amounts of living biomass, and because of their lower metabolic rates, they are much more efficient at capturing CO_2 than equivalent mass in smaller animals [220]. Great whales also act as a global and local vector of vertical mixing and horizontal transfer and recycling of carbon and nutrients in the ocean. Globally, they transfer horizontally between the polar feeding regions and the warmer breathing grounds closer to the equator. Locally, by mixing nutrients from the deep ocean into the surface waters and vice-versa through the release of fecal plumes and urine in their feeding areas, as they breathe, digest, metabolize or rest at or near the surface [220]. This effect named ”whale pump” plays a vital role in enhancing phytoplankton productivity in biological hotspots [220]. Phytoplankton is the primary source of food of big whales and is responsible for at least 50% of all oxygen in our atmosphere, capturing an estimated 40% of all CO_2 produced [221]. Recently, all these scientific evidence made the press by the International Monetary Fund (IMF) report on the carbon capture potential of whales as a natural solution for climate change [218]. Whales accumulate carbon in their bodies during their long lives. When they die, they sink to the bottom of the ocean. The IMF study estimates that each great whale sequesters 33 tons of CO_2 on average, taking that carbon out of the atmosphere for centuries once they die and sink into the ocean. The carbon capture potential of whales far outweighs that of trees that capture 22 Kg/year, reaching only 2,2 tons in 100 years’ lifespan. Chami et al. conclude the IMF report claiming for a new mindset: ”*Coordinating the economics of whale protection must rise to the top of the global community’s climate agenda. Since the role of whales is irreplaceable in mitigating and building resilience to climate change*,” [218]. Humans hunted and killed thousands of whales for centuries. This activity peaked during the industrial revolution when whales were a source of food but also of baleen and oil, likely the first commercially viable commodity used as a source of energy. During that period, estimates of numerical decline range from 66% to 90% of the total population[222], and the total whale biomass lowered by an estimated 85% [223]. The IMF report compares whales with trees and forests, claiming that ”*when it comes to saving the planet, one whale is worth a thousand trees*,” comparing the multiplying effect of whales in the ecosystems and, in particular, phytoplankton (which accounts for four times the Amazon forest in terms of carbon capture) [218]. This call for action was crucial for the successful social mobilization of tree planting for carbon offsetting. A similar effort to make a significant impact in the recovering of whale populations to pre- whaling levels would require policies and campaigns to raise awareness about their potential to help solve the climate crisis.

6.3.1.2 Contributions

In this study, motivated to bridge HCI with the whale population, we describe a novel interactive visualization, which focuses on depicting sperm whales and some scientific facts about their lifestyles. Such facts are: their ability to sleep vertically [224], their diet based on a giant squid [225], and the echolocation clicks' importance in prey location and capture [226]. In our approach, we combine the Pepper's Ghost Illusion (as the illustrative metaphor for Captain Ahab's illusive state and obsession to encounter and capture the great white whale), an underwater flashlight (as an interaction device) and the geodesic dome (to further immerse the audience).

Geodesic domes were popularized by R. Buckminster Fuller[3] and were widely used to design more efficient ways to improve human shelter [227]. The first worldwide acceptance of geodesic domes by the architectural community occurred in the 1954 Milan Triennale themed for "Life Between Artifact and Nature: Design and the Environmental Challenge". The theme, although it predates today's environmental crisis, it is aligned with the concept of interaction for environmental awareness of aquatic settings. Nowadays, geodesic domes are also used frequently in interactive installations and public festivals (e.g., the Burning Man) or conference meetings and concerts. For our study, we applied sustainable design principles and upcycling to build a novel kind of geodesic dome from completely reused materials [228].

Great whales are typically difficult to encounter during regular whale watching trips. When encountered, the viewing from the sea vessel remains partial, where only a small portion of the animal (e.g., a dorsal fin) is seen and for a limited amount of time. Therefore, the holographic interface supports close-up interaction and manipulation of the animal, which is rare to experience even in museum settings. The goal of this interface is to raise awareness about the lifestyle of one of the main species of great whales and to obtain a baseline to gauge users' experience and perception. Based on such goal, our study explores three research questions:

- **[RQ1]. Is interactive holography an effective method to raise awareness about underwater species such as great whales?**

  We report on a low-cost geodesic dome coupled with the multiple-sided projection based on Pepper Ghost Illusion as an interactive hologram. We use it to to

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[3] `https://fullerdomehome.com/`

portray scientific facts about sperm whales. Moreover, We perform user studies using the sets of diverse scales, including the usability, user experience, emotional, and ecological scales, in order to establish a quantifiable baseline for such *interaquatic* experiences, as well as to determine whether used interaction methods communicate the desired message about the whales.

- **[RQ2]. How do users interact with holographic information inside a geodesic dome?**
  We study how participants behave in geodesic domes and how they explore the interaction with holographic information. We provide participants with a looping video, revealing the sleeping, dieting and foraging characteristics of the sperm whale, portrayed in 3D animation. We report a set of field observations including the feedback by the participants.

6.3.2 Designing the Ahab's Ghost

In this section, we describe the physical apparatus for low-cost holography, encompassing the geodesic dome, an interactive hologram, an interactive flashlight, and the software components, all used to connect the audience with the less known facts of the whale 3D animation. In order to create an *interaquatic* experience and to depict the haunted Ahab's Ghost, the following components constitute the interactive hologram used in this study: (i) **Geodesic Dome**, as an environment to immerse the participants; (ii) **Interactive Hologram**, a low-cost 5-sided projection display based on Pepper's Ghost Illusion, used for portraying the great white whale from the Moby Dick story; and (iii) **Whalelight** - a whale-shaped prototyped flashlight, used for manipulating the white whale. In addition, (iv) **Software** was used to process data and handle the interactions.

6.3.2.1 Geodesic Dome

Since holographic projection requires a proper dark setting with no external light sources, a geodesic dome was built from reused cardboard for the holographic interaction. We gathered cardboard from a local scrapyard to challenge ourselves to reuse the existing materials as well as to build the geodesic structure, which can be easily and quickly

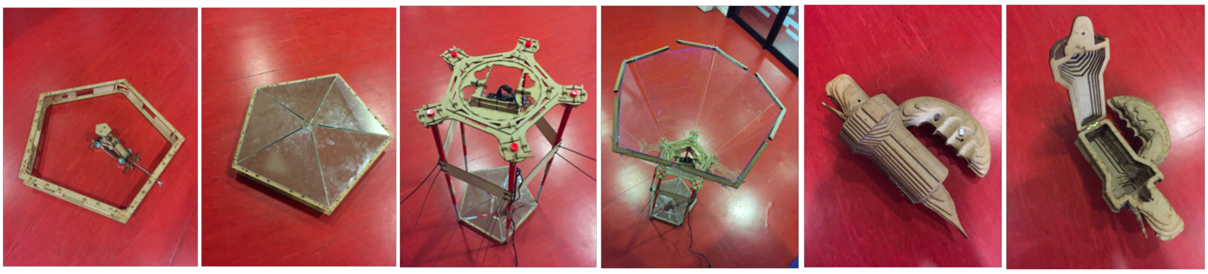

Figure 6.9: AHAB'S GHOST Hologram Prototyped low-cost solution from MDF used for Pepper Ghost illusion and interacting with the whale. Last two images depict the **Whalelight**, as an interactive flashlight used to manipulate the model of the great white whale inside of the hologram.

disassembled, shipped and re-assembled or created with printed instructions. Our rationale for creating such a structure was not just to solve the technical challenge, but to provide the intimate *interaquatic* and underwater space, to explore the depths of the whales, revealing their lifestyles at the land setting. An additional rationale for making it from cardboard was also to study participants' environmental perception. The structure of the geodesic dome was based on 2V Fuller geodesic measurements. Besides, we created the door entrance, allowing the the participation of children and disabled people (Figure 6.8). We also halved the triangles to accommodate into laser cutter, as well as to provide the self-sustaining support without any frame or support from plastic, metal, wood, glue, etc (see Figure 6.8)[4]. This allowed us to prototype an inner space of 6m diameter and 3m in height, having enough space to comfortably accommodate up to 5 people, while keeping the center of the dome free for the holographic projection. Lastly, we created the harmonic wall to support the weight of the geodesic dome without any frame. To further increase immersion into the environment, authors of the research further found vocal calls of diverse marine species, encompassing clicks, moans and whistles, typical to whales and dolphins. Post production of the sounds involved an echo effect, and the sounds were attached to the video animation of the whale. Acoustic surround sound was added in the base structure, supporting the holographic display. We created such a sonification experience to further immerse the audience.

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[4] An example of Ahab's Ghost encompassing the structure of such geodesic environment including the interactive holography may be seen at the link `https://bit.ly/2v2fPzn`

6.3.2.2 Interactive Hologram

The hologram was based on the Pepper's ghost optical illusion. It is composed of a micro projector, pointed downwards and reflecting off of five angled mirrors into the five sides of the hologram. We used five sides of the species to match the geometry of the inner space, as well as to portray the five different sides of the whale (front view, side views, back view). The projection hits a piece of horizontal white sheet, slightly below the users' vision level, creating the area for 3D model of the sperm whale. Then, five angled transparent pieces of acrylic reflect the sheet's image, creating the Pepper's Ghost illusion in the center area. In addition, acoustic stereo audio was mounted to immerse more the audience into the underwater environment, encompassing clicks, moans and whistles of diverse cetacean species.

The 3D model used for the hologram was based on Captain Ahab's unencountered and haunted leviathan[5]. Apart from the head and its distinctive shape, the role played by it in Herman Melville's Moby Dick, led to the ordinary viewer to describe the sperm whale as the "great white whale" archetype. We started designing the model while watching videos of real sperm whales sleeping, swimming and eating. Finally, we textured the model with a base color of gray to resemble a real sperm whale, then we built three animations of the whale: sleeping, swimming and eating.

Once the 3D model has been designed and rigged, it was animated depicting the whale: (i) initially sleeping in a vertical position, (ii) waking up and slowly starting to descent to greater depths, (iii) encountering and eating the giant squid the size of the whale, and (iv) returning to the sleeping state at the surface. This video was kept looped. Animation was programmed in the Unity Game Engine, which renders the hologram itself while receiving and interpreting the accelerometer data collected from the interactive flashlight (Whalelight). Our rationale for focusing on accelerometer was to rotate the model using the Whalelight, allowing the audience to inspect the great white whale. In addition, we used a low-Pass filter to stabilize the interaction due to rapid fluctuations of the received data.

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[5] In this case, Physeter macrocephalus or cachalot, the largest toothed whale and predator. This whale was chosen because it is a commonly found animal near the archipelago of Madeira. The Sperm Whale is the most massive toothed whale and it has a distinct feature: it possesses a waxy and milky substance (oil) on its head named spermaceti.

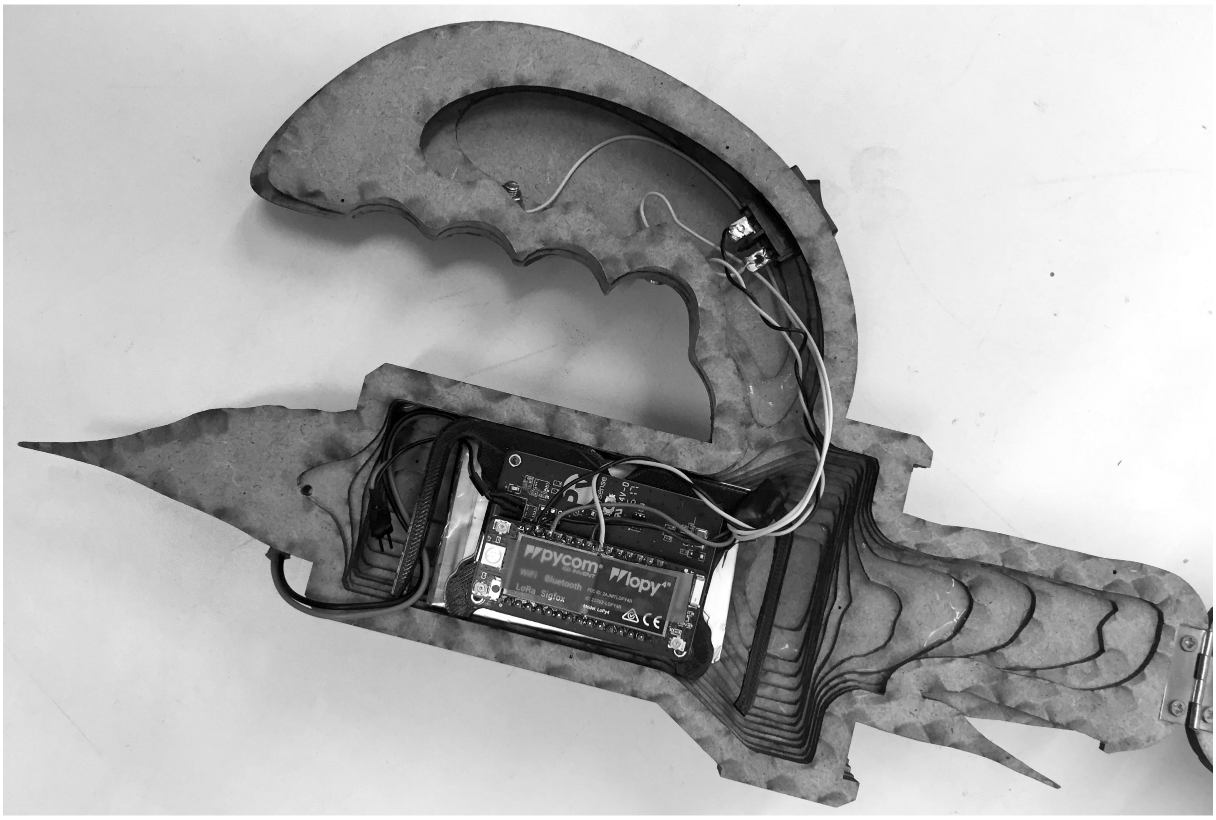

Figure 6.10: Whalelight - An inside view of the interactive flashlight, containing the embedded microcontroller in the prototyped MDF casing, serving to manipulate the object in 3D.

6.3.2.3 Whalelight

The Whalelight was prototyped out of Medium-Density Fiberboard (MDF). It is a hollow structure, shaped as the sperm whale, that encompasses the microcontroller used in the study. The rationale for using this equipment is the metaphorical interpretation of diving in greater depths, which remains inaccessible to most humans without expensive equipment. The microcontroller pools the accelerometer data, which is mapped to the 3D model's orientation, aiding in the exploration of the species in the holographic projection by the users. This happens while the participant holds and rotates the flashlight as a diving lamp. The interior assembly of the flashlight can be seen in Figure 6.9.

To start the interaction, the participant switches on the flashlight, uncovering what lies in the darkness. This is also the signal for the system to start capturing data for that specific participant. The data in question is then forwarded via Wi-Fi to a Node.JS server, running on a standard Windows 10 laptop, whose main function is to reroute the information to the previously mentioned Unity application, as shown in Figure 6.11. Moreover, this middleware was implemented, in spite of causing an additional delay between the data collection and the Unity application, for scalability and modification purposes (ex: saving data to the database, replacing the Unity application with a similar system, etc).

6.3.2.4 Software

The system's back-end is composed of a REST API and a MySQL database hosted on a Raspberry Pi 3B microcomputer. The API, developed in-house, uses FLASK libraries and a MySQL Connector. It receives HTTP calls and reads/writes the information to/from the database. This setup allows easy access to the database by all system components. The back-end system stores the answers that the users gave to a follow-up questionnaire. In order to collect survey information, we developed a simple mobile application for users to enter their survey data at the end of the experience. All these questions were presented inside of the mobile application using buttons for Likert-scale. Each button triggered a HTTP request to store the data to the Raspberry Pi database (as seen in the Figure 6.11).

6.3.3 Methodology

In this section, we describe the system and how we performed the study setup as well as how we performed the data inquiry, which was necessary for establishing a quantifiable baseline for an *interaquatic* experience. Moreover, we provide the scenario and expected interactions from the participants.

6.3.3.1 Interaquatic Experience

At the beginning of the study, the participant is provided with an interactive flashlight (Whalelight), which can be held with one hand. We did not mention to the participant what they should be using it for to allow us to explore the natural reactions of participants in *interaquatic* experience. The participant enters into the dark geodesic dome, and starts the experiment by using the thumb on the flashlight holder, pressing the physical button. This event triggers the appearance of a sperm whale inside of the holographic projection and the animation starts when the whale is awaken, dives, forages, and returns to the sleeping position. The participant approaches the whale carrying the Whalelight, and uses it to inspect the whale in real-time, exploring its details. For this study, only the rotation movement was used, where the participant can see the 360 degree view of the provided 3D animation. Afterward, the participant continues to perform the interaction, exploring the diverse sides of the holographic projection. After two minutes (the duration of the 3D animation loop), the participant is invited to join the research authors, where they leave at their pace the *interaquatic* environment. Finally, participant completes the study by filling in the post-study questionnaire, and a semistructured interview is conducted, to collect feedback from the participants.

6.3.3.2 Study Setup and Data Inquiry

In order to understand how participants explore an *interaquatic* environment with given technological constraints, as well as to establish the quantifiable baseline, we sought to combine diverse scales comprising from: (a) user experience, (b) usability, (c) emotional states, (d) ecological perception, and (e) test for understanding whether the proposed interaction design communicates the desired message about the whales. In total, 88 questions were collected, with all scales normalized to 5-point Likert, and performed in post-study, except for the questions gathered during the testing interaction design communication, which were performed in both pre- and post- studies.

Our sample size (N=20) included audience from Portugal(16), Canada(1), Italy(1), Spain(1) and Slovenia(1). Half of the participants identified themselves as female. Their age depicts a relatively young audience (M=32, SD=6.52), while all participants indicated themselves as tech-savvy. Furthermore, none of the participants were given incentives for taking part in the study. The study was performed indoors, at the university campus. All collected self-evaluation reports were composed of several measurements:

1. **User Experience** *Post-study*. For this experiment, we used the Intrinsic Motivation Inventory (IMI) and Again-Again table, revealing how the participants rate their time spent inside of the designed *interaquatic* experience.

    (a) **Intrinsic Motivation Inventory**. We used IMI [229], as it includes the set of scales to assess participants' interest/enjoyment (in further EN), perceived competence (in further CO), effort (in further EF), value/usefulness (in further US), pressure/tension (in further TE), perceived choices (in further CH) while performing a given activity, and experiences of relatedness (in further RE), thus yielding seven subscales scores.

    (b) **Again-Again**. We used this scale [230] to understand whether or not the participant would report in repeating the same experience, as such scale was also found in other studies in aquatic settings [187].

2. **Usability** *Post-study*. SUS and AttraktDiff Short scales were used to measure the performance of the interactive flashlight as a tangible user interface, used to interact with the holographic projection of the great white whale.

    (a) **System Usability Scale**. Consisting of a 10 item questionnaire, it was used to obtain the usability of the interactive hologram and its interface, mainly focusing on the interactive flashlight.

    (b) **AttraktDiff. Short version**. This particular scale measures several features of the experimental system, through 3 different subscales (Pragmatic quality (in further PQ), Hedonic Quality (in further HQ), Goodness and Beauty (in further GB)). Its objective is to clarify the relation between perceived usability of the device and beauty of the interface, and understand how did the tangible device perform when used for interaction.

3. **Emotional State** *Post-study*. Assessing affective insights as emotional states reported by the participants, were performed using SAM, Smileometer and Panksepp scales described below.

   (a) **Self-Assessment Manikin**. Participants were prompted to rate the Self-Assessment Manikin [SAM] after each task. We used SAM as it is a non-verbal pictorial assessment technique that directly measures the pleasure (in further P), arousal (in further A), and dominance (in further D), associated with participants' affective reaction to the overall experience. In the case of SAM, 9-point scale was normalized to 5-point after the study, to be consistent with other scales.

   (b) **Smileometer**. To measure the level of enjoyment, the smileometer scale [231] was used, depicting the 5 typical smiley states, encompassing from sad to happy faces depicting the overall pleasure of participants.

   (c) **Panksepp**. In addition to the aforementioned scales, participants also rated the experience by selecting the one dominant primary-process emotion among given 7 words: SEEKING, PLAY, CARE, FEAR, GRIEF, RAGE and LUST [232]. We choose this particular scale, as it is grounded on the neurophysiological aspects of the emotions, which remain less known to HCI and computing community [233].

4. **Ecological Perception** *Post-study*. In parallel to the user experience, usability and emotional states, we were interested in exploring the participant's ecological awareness, as they were inside a dome constructed completely out of recycled materials. This was assessed using the NEP scale.

   (a) **New Environmental Paradigm**. We used the revised version of the NEP scale [234], as we were focused on the current opinion of the participants regarding human impact on environment, after going through this underwater experience. Our rationale for using such scale was to correlate the

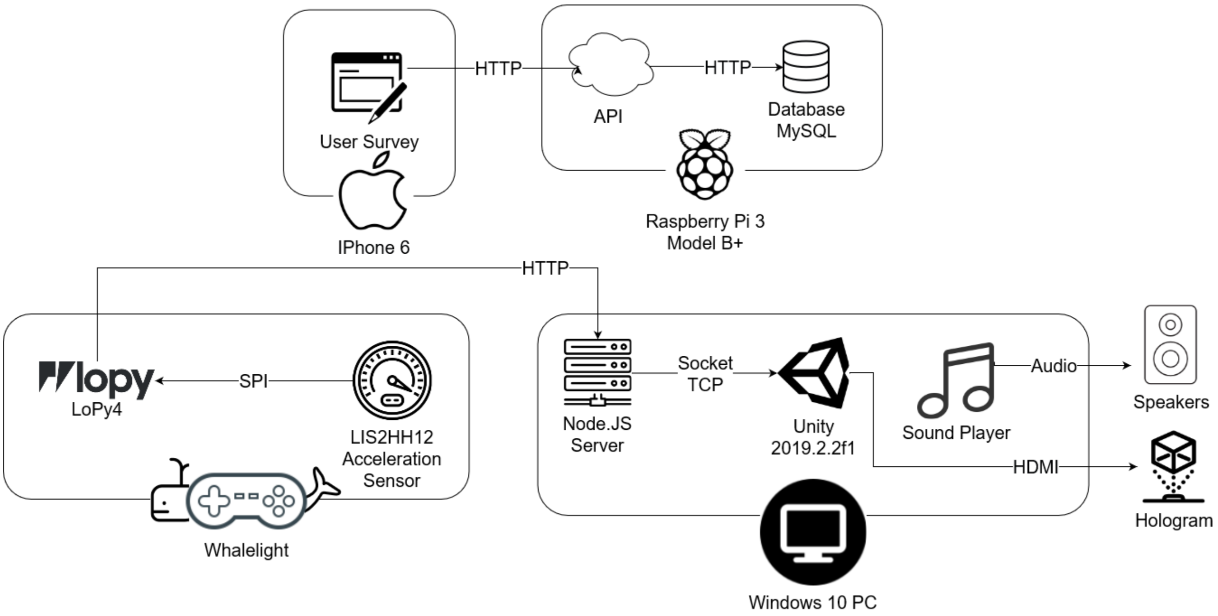

Figure 6.11: Ahab's Ghost System Architecture - Interaquatic system diagram, containing all of the used components, hardware and software in this study.

experience with environmental awareness. NEP contained 5 facets: Reality of limits to growth (in further GR), Possibility of an eco-crisis (in further CR), Rejection of exceptionalism (in further EX), Fragility of nature (in further FR) and Antianthropocentrism (in further AN).

5. **Interaction Design Communication** *Pre/Post-study*. In this particular case, we sought to understand whether interaction design used in the *interaquatic* experience actually communicates the desired messages about the whales. This was performed during pre- and post- studies, by asking the participants the next questions:

    - **[Q1] Which depth can a sperm whale reach?** Suggested answers were: ¡10m, 10m-49m, 50m-99m, 100m-1000m, and ¿1000m. The last answer was the correct one [235].
    - **[Q2] How does the sperm whale sleeps?** Multiple choices were: horizontal, vertical, upside/down, and does not sleep. In this case, the second answer was the correct one [224].
    - **[Q3] Which sounds do the sperm whales emit?** Proposed answers were: clicks, moans, whistles, and no sounds. The first answer was correct [236].

Moreover, aside from the user answered questionnaires, one of the research authors was always present inside of the dome. The main purpose was to monitor and record the participant's behavior and interactions to further complement the collected data, and analyze both the constraints of the system and the overall user experience. Lastly, in order to further determine the users' satisfaction and the usability of the system, participants were asked to provide some feedback regarding their experience.

6.3.4 Results

In this section, we report the results of the collected scales used for obtaining the quantifiable baseline during the *interaquatic* experience.

6.3.4.1 Scale Analysis

6.3.4.1.1 User Experience Regarding the IMI scale, it is possible to compare in figure 6.12 the mean scores obtained for each subscale. The Enjoyment scale (EN, M=2.91, SD=0.30) measures the intrinsic motivation of the user, Perceived Choice (CH, M=3.81, SD=0.50) and Perceived Competence (CO, M=3.08, SD=0.90) are both positive predictors of intrinsic motivation, While Pressure is a negative predictor (TE, M=1.73, SD=0.62). Effort, on the other hand (EF, M=2.55, SD=0.91), is a separate variable which is also relevant to motivation questions, while Value/Usefulness (US, M=3.53, SD=0.91) measures how useful or valuable the experience was to the users, and the Relatedness scale (RE, M=3.52, SD=0.52) studies interpersonal interactions. As for the Again-Again, mean score was 3.75 (SD = 0.91).

6.3.4.1.2 Usability Regarding the System Usability Scale, the mean obtained score for this scale was 3.86 (SD=0.97), while results for the AttraktDiff short scale were divided into its categories, each with respective subscales. Regarding the Pragmatic Quality (PQ), a mean classification of 3.40 (SD=0.44) was obtained, while Hedonic Quality (HQ) obtained a mean score of 3.75 (SD=0.46) and a Goodness and Beauty (GB) mean value of 2.93 (SD=0.46).

6.3.4.1.3 Emotional State Regarding the SAM scale, for the question *How much did this system arouse you?*, participants scored a mean of 4.00 (SD=1.52). A mean score of 2.50 (SD=0.76) for the question *How much did you find this system attractive?* and, for the question *How much dominant did you feel using this system?*, the mean score was 3.10 (SD=1.15) (see figure 6.12). Also, Smileometer's results revealed a mean score of 3.65 (SD = 0.88), while Panksepp showed the classification of the matched words with their feelings to be SEEKING (4), PLAY (13) and CARE (3).

6.3.4.1.4 Ecological Perception When understanding the participants' perception of the environmental impact caused by humans, Reality of limits to growth (GR) scored the mean of 3.77 (SD=0.65), while their perception of Possibility of an eco-crisis (CR) scored mean of 3.42 (SD=0.37). When understanding their view on the Rejection of exceptionalism (EX), the mean score was 3.30 (SD=0.72), and regarding the Fragility of nature (FR), mean was 3.23 (SD=0.53). Lastly, Antianthropocentrism (AN) facet had a mean 2.78 (SD=0.53).

6.3.4.1.5 Interaction Design Communication Regarding the questions in understanding whether the interaction design communicated properly the facts about the whale, before the experiment, 12 correct answers were provided for the first question (max depth). In further, 6 for the second (sleeping pattern) and 2 for the third (vocal call). The second set of questions obtained in the post-study after the experience, yielded 10 correct answers for the first question (max depth), 6 for the second (sleeping pattern), and 4 correct for the third question (vocal call). Results show a decrease of perception for the first question (-2), no shift in knowledge for the second question, and an increase (+2) for the third, indicating that the communicated messages using interaction design downgraded the perception for the maximum depth. Moreover, it remained the same for the sleeping pattern and increased in the vocal calls.

6.3.5 Discussion

Our research brings a multi-folded contribution to the HCI community: (i) we provide an apparatus for interactive exploration of underwater species, revealing their less known facts; (ii) contrary to existing expensive holographic setups, we enhance the holographic experience as a low-cost, sustainable solution, reusable, upcycled and easily replicated by other designers of interactive systems; (iii) we establish a quantifi-

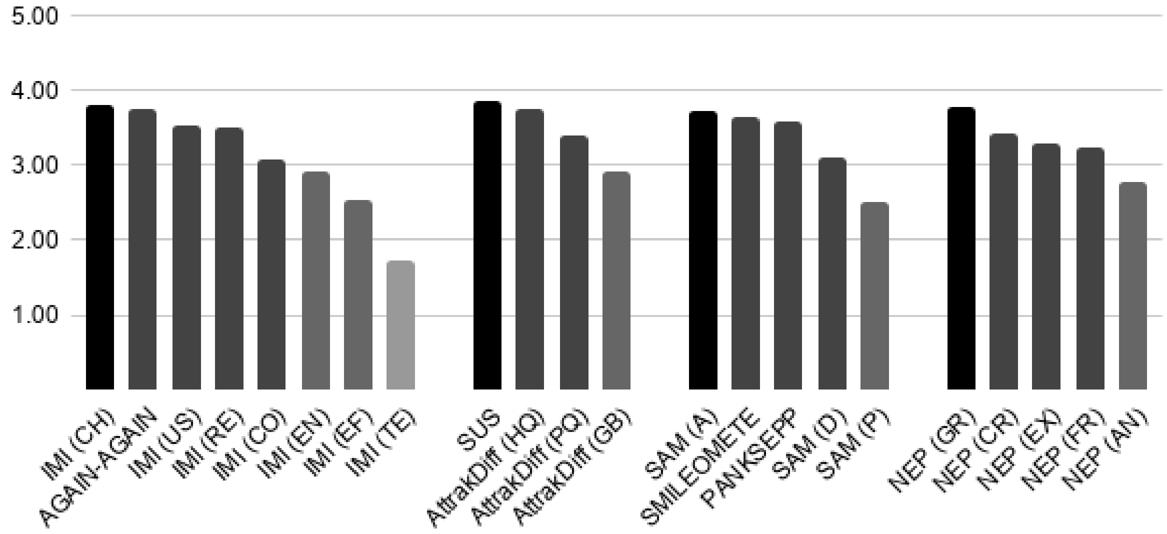

Figure 6.12: Sorted mean ratings of diverse Likert 1-5 scales by 20 participants in **AHAB'S GHOST** interaquatic holographic experience. *From left to right:* (i) **UX** - IMI and Again-Again; (ii) **Usability** - SUS and AttraktDiff Short; (iii) **Emotion** - Smileometer, SAM and Panksepp; and (iv) **Environmental** - NEP.

able users' experience baseline from the collected scales. In this section, we discuss the findings from the collected data, supporting them with the field observation and participant feedback. We summarize the contributions in design guidelines for other scholars to explore further the design of interactive holography for aquatic and environmental awareness. Moreover, we provide insight into the limitations of the *interaquatic* environment, outlining future work and conclusions.

6.3.5.1 Result Analysis

6.3.5.1.1 User Experience From the IMI scale results, we can conclude that the system expressed high scores in Perceived Choice (CH), Value and Relatedness (RE), albeit none of them actually achieved a score higher than 3.81. This can be interpreted as the user being motivated and valuing the experience. In contrast, the Effort (EF) and Pressure (TE) related data highlights possible flaws of the experience. The effort required to engage in the experience and the pressure felt by the users is something to improve. These aspects are also supported by user feedback and reported inconsistencies during the interaction (ex: the participant's confusion about the flashlight manipulation of the 3D model). Nevertheless, participants expressed a willingness to repeat the experience.

6.3.5.1.2 Usability Regarding the usability, the *interaquatic* system scored medium to high in this scale, suggesting the users actually achieved a meaningful interaction,in spite of its constraints. As for the AttraktDiff scale, the system only achieved intermediate scores. In terms of Pragmatic Quality (PQ), the system may have some issues in terms of simplicity, structure, and/or practicality. Regarding Hedonic Quality (HQ), the system may lack captivating/creative features that would attract the users. Regarding Goodness and Beauty (GB), the system has a lot of aesthetic elements that turn to be very appealing. This was also appreciated by the participant feedback (P: ”... I really enjoyed the visual environment”).

6.3.5.1.3 Emotional State Regarding the interpretation of their emotions, the SAM scale reveals the users did not feel much excitement using the system. The results also confirm the users thought the system was attractive and felt considerably in control while using it. This is confirmed by the Smileometer results, despite the systems inherent flaws, the users had a somewhat joyful experience, which is supported also by Panksepp scale, with the participants rating their own emotions to be connected with the word PLAY.

6.3.5.1.4 Ecological Perception Overall, the results provided by this scale reveal the users have some mild proenvironmental attitudes. More specifically, regarding the GR scale. Users are aware there are limits to the growth of human civilization, and the lack of regard to these limits may, in fact, lead to an imminent eco-crisis, supported by the results of the CR scale. The scores for the remaining scales suggest that, although the rejection of exceptionalism is starting to take hold (EX scale), users have yet to consider how fragile the natural balance is (FR scale), and that humanity is not above everything else (AN scale). However, it is difficult to determine if the system had any meaningful influence on the users’ concerns regarding these measurements, since they were only measured after the experience.

6.3.5.1.5 Interaction Design Communication We tested the system whether the used interactions communicate the information correctly. When observing the pre- and post- answers to the provided three questions, results indicate a decreased perception for depth (-2), neutral for understanding the sleeping pattern (0), and increased perception in understanding the type of vocal calls (+2). Therefore, participants' perception remained constant for correct answers. This suggests that the system actually showed stagnation and that interaction with the hologram did not communicate the messages about the whales. In detail, the first question (maximum depth) had a negative variation since it was not as explicit, e.g. precise depth was not portrayed in the user interface, and an interaction with the Whalelight caused participants to slightly loose the orientation. For the second question (sleeping pattern), no significance in variation in answers was observed. We suspect that it is due to the fact that the Whalelight interfered with the perception of position and motion, suggesting the need for more future tests within the given technological constraints. As for the third question (vocal calls), as sounds were our synthesized mesh interpretations (and not the real recorded sounds), we suspect that the installation needs a real recorded acoustic surrounding. This may lead to the proper sonification to be an adequate interaction design method to communicate the diverse types of vocal calls of whales. Nevertheless, obtained answers had a positive variation, albeit minimal. In general, we believe that these results are caused by the technological constraints, observing the interaction between the user interaction and the animation (rotating the animation of the whale in movement, which for this study revealed to be complex).

6.3.5.2 Field Observations

The vast majority of users quickly discovered how to use the system (90%), and we noted that as much as 75% of the users assumed that changes in the distance between themselves and the hologram could cause a corresponding variation in the size of the image. However, this specific function was not implemented due to multiple constraints, and in fact, users noted the rotation. Conversely, some of the users experienced some system flaws, mainly related to sudden holographic movements that did not correspond to their movement with Whalelight (e.g., rotation of the 3D model for 360 degrees).

6.3.5.2.1 Follow the device metaphor Interestingly, we also observed that 15% of users attempted to use the *interaquatic* Flashlight as an actual flashlight, before discovering its relation with the angle of the whale. After turning on the device, participants would generally attempt to point it around the dome with the hope it would unveil hidden objects/animals, which was opposite to the proposed holographic projection. We think this is due to the fact that the high luminosity in the room before entering the dome influenced the perception of the brightness and contrast of the hologram. Some users demonstrated a sense of confusing about how to interact with the experience. There have been also some surprising interactions, where some participants actually attempted to place the flashlight over the hologram apparatus, while other participants payed more attention to the reflected image in the sheet. Besides, two users tried to touch the hologram.

6.3.5.2.2 Manipulate only one dimension at a time Overall, from field observations, we can conclude that users were slightly frustrated in maneuvering the animated 3D model of the great white whale, as the model itself is rotating during the awakening and foraging, causing difficulties in orientation (e.g., front of the flashlight mirrors the bottom part instead of the front part). This can be supported by the SUS and AttraktDiff results, as they demonstrate a combined score of 3.48/5 for usability.

6.3.5.3 Participant Feedback

6.3.5.3.1 Explore the whole structure The overall design of the flashlight was the source of some criticism. 35% of the participants mentioned it was too bulky and/or heavy, which caused it to become a bit cumbersome. Curiously enough, despite being designed taking into consideration only right handed people, the only left-hand tester found it to be comfortable. As observed, the design also led them to believe the flashlight worked the same way like a common flashlight, in a way that it would reveal hidden creatures. Future work can study the interactions and behaviors inside of geodesic structures without the presence of holography (e.g., AR or projection mapping).

6.3.5.3.2 Allow more control Regarding the interaction with the holographic projection, and according to 50% of the users, it did not make sense that there was no zoom or translation of the object, as they were natural features that seemed to be implied. The rotation of the controller itself also resulted, according to 45%, in a confusing and unnatural interaction, caused by the conflict between their commands and the animation as well as a common failure of the sensor that generated erratic movements. This is due to the fact that we used a loop 3D animated model where the whale is diving and going to sleep, which clearly adds complexity to the interface to explore the different angles of the whale (e.g., the nose of the flashlight would point at a different angle than the whale, as it moved during the video animation). In addition, one particular user mentioned one of the holographic views was clearer than the remaining, even though it was also the hardest to control, and it was also brought to our attention that the sound wasn't synchronized with the whale's movement. Curiously, two users also mentioned the desire to communicate with the whale in some manner.

6.3.5.3.3 Size matters Some compliments were also made regarding how visually appealing was the system's aesthetics and the overall apparatus when depicting the whale, as well as the environment created by the acoustic features. Nevertheless, approximately 35% of users desired a bigger holographic model, as the whale in nature is significantly bigger. We believe it is mostly affected by the size of the dome. Moreover, they required the more meaningful interaction, and some even recommended the addition of further graphical elements that can complement the center piece (e.g., other marine taxa), as well as the gamification of the system.

6.3.5.4 Comparison with the Literature Review

This system builds upon the previous HCI research that was conducted. Their flaws have been considered during the design and development stages of Ahab's Ghost, resulting in the creation of a product based on the same optical principle as the one previously employed by others [199][200][201], known as Pepper's Ghost illusion. The contribution of this study is in turning the system itself to be less complex, reusable, and low-cost, in contrast to overly complex and expensive approaches [196][198][203]. Moreover, the proposed interaction with Ahab's Ghost deviates from those used in gesture recognition [199][202] to a more tangible approach, in an attempt to mimic an everyday object the users are accustomed to, which, in contrast, became a significant flaw in the system's usability, due to its cumbersomeness. Furthermore, this flaw is also affected by the conflict between the interaction and the animation, which is not verified in any of the prior work.

6.3.5.5 Limitations and Future Work

The work described here provides several insights on how to prepare a more robust and immersive *interaquatic* system. Also, additional assessments should be performed in the pre-study (such as emotional and environmental awareness scales), which can support the finding whether the system influenced their state of mind. Moreover, while most of the participants reported that they would like to observe a bigger specimens, we were limited with the constraint of the low-cost material and sustainable design of interactive systems, as our challenge was to use a minimal amount of technology and equipment. As the pico projector was used, clearly, less power of image we can obtain when casting and refracting the light to and from mirrors. While the provided study depicts the quantified baseline, it will be used as a control group to understand how well such *interaquatic* system performs better against the same content using the Augmented Reality (AR) and Virtual Reality (VR). Additional behavior change studies will be conducted to understand which of these immersive *interaquatic* environments may be used to boost the concrete action (e.g. whale donation, support for environmental conservation, increase of marine literacy, etc). In this study, we sought to challenge the sustainable design and system based on interactive holographic experience depicting the large-scale marine species, which remain inaccessible to wider audiences on land. Our hope is that throughout Ahab's Ghost, provided *interaquatic* system expands the state of the art and prior work in HCI, and that it will inspire future works in applying the interactive holography in an outdoor setting, and reach a wider audience, increase their marine literacy and sustainable habits.

6.4 Building a tag for low-power real-time oceanic telemetry

6.4.1 Introduction

6.4.1.1 Summary

Traditional marine monitoring techniques using satellites remain expensive[6], while biologgers struggle with the battery longevity, ranges and high costs[7]. While current solutions exist for georeference (such as VHF once the turtles are at the surface), as well as underwater triangulation (using pingers), alternative retrieval of data is offline only, where a tracker is collected from the turtle, adding more cost of time and fuel to the marine biologists. Lastly, current interfaces remain limited in using such data for the analysis. We can take advantage of LoRa and low-power microcomputers to build new tags, allowing the data to be collected and sent from remote distances with an autonomy of months.

6.4.1.2 Research Questions

TRITON is a work in progress that aims to solve and improve some of the issues here presented. We use the following research questions in order to achieve that:

- How to design a robust tracker for aquatic species?
  We prototype and perform low-cost deployment of a tag on sea vessels and study the unobtrusive mechanisms of attaching it to turtles.

- How to design an ubiquitous power-autonomous network?
  In order to support the tag and get the data to the shore, we use existing lighthouses to deploy on-shore receivers. We study the power autonomy of such devices, comparing the usage of electricity to the solar powered.

- How can a low-cost technology withstand an oceanic deployment?
  We deploy the device and compare its longevity to the existing alternatives in terms of resisting the elements, battery autonomy and communication range.

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[6] `http://www.argos-system.org/`

[7] `https://wildlifecomputers.com/`

6.4.2 Methods

6.4.2.1 The Tag

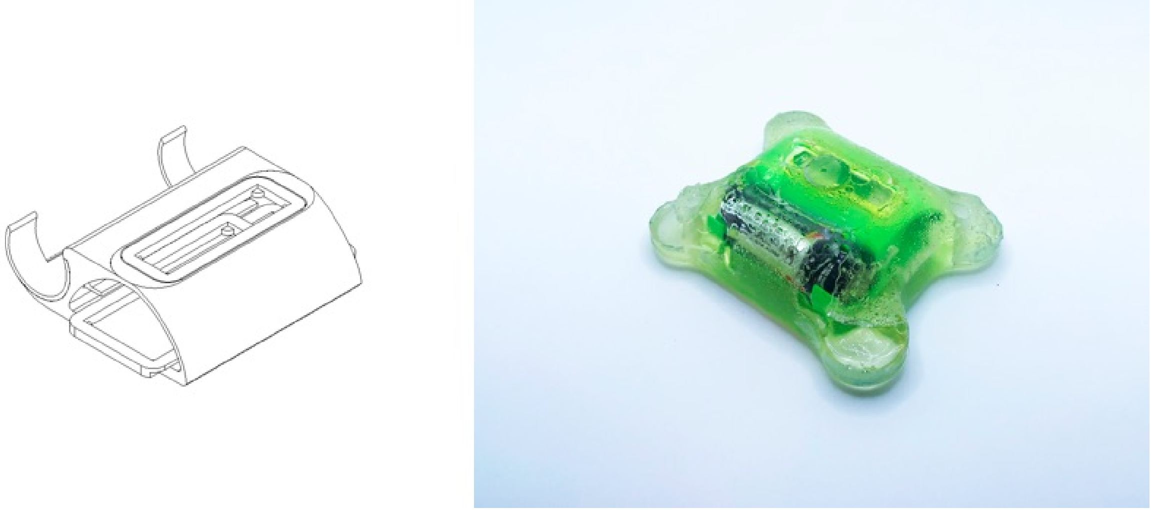

Figure 6.13: TRITON - From design to the implementation.

The tag uses a microcomputer, namely, a LoPy 4 with a battery all inside a watertight epoxy shell (Figure 6.13). A 3D-Printed structure, inside the shell, keeps everything in place. The tag is attached to the animal on the bottom side and a (bare, highly flexible) LoRa antenna comes out on the other side.

6.4.2.2 Network and System Architecture

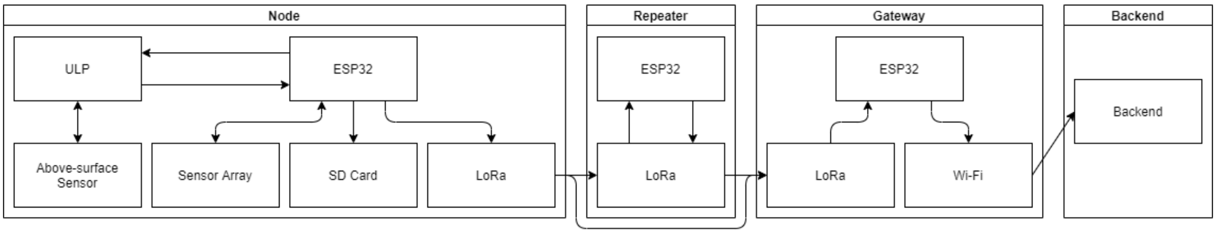

Figure 6.14: LoRa Network Architecture - Diagram of how a Node creates the Packet to send though the LoRa Network. The first row is the byte index, the second row is the bit index and the third row indicates what kind of data goes into that bit.

In this subsection, we describe the network's, as well as its components', architectures. This is presented in figure 6.14. All the nodes that compose the network are built upon the LoPy 4. The communication is raw LoRa throughout the whole network except for the communication with the backend which uses the Internet. In the following paragraphs there is a description of each one of the elements in depth. The first element on the left is the Node. It can be deployed in the wild, either attached to an animal or placed somewhere as an environmental sensor. Multiple nodes are, usually, deployed simultaneously. The nodes are expected to stay deployed for a long time and, as such, need to be extremely well optimized energy-wise. For this reason, we make extensive use of the ESP32 capability of deep sleeping, which, effectively, reduces the energy consumption of the CPU down to 10 µA for the chip while almost everything else is completely shut down. While in deep sleep, the main (ESP32) CPU is shut down and a Ultra Low Power (ULP) CPU takes over. The ULP has very limited capabilities but uses an extremely low amount of energy while being able to some very basic functions and waking up the main CPU. There are, at the moment, two ways of waking the main CPU up. One is time-based, which we use in all environmental nodes as well as in some species that can spend a lot of time on land. The other is based on an sensor, developed in-house and described later, that can detect if the node is in the water. The ULP, regularly, pools the sensor and wakes the main CPU up if the node is above water. The second element is the Repeater. Its function is very basic: forward LoRa messages that belong to the network, effectively extending the network range. It is usually, in a light-sleep state that is awaken when a LoRa packet arrives. This allows the Repeater to stay deployed and operational with just a small solar panel. The Repeaters are both optional and the network can have 0 to an unlimited number of Repeaters. Being optional, a LoRa packet can reach the Gateway directly from the Node while being forwarded by the Repeater. The third and final element of the LoRa network is the Gateway. This element, just like the repeater, first makes sure that the packet belongs to the LoRa network. It then, unpacks it and sends that node's sensor's data to the last element, the Backend. There could be multiple Gateways on the network but, optimally, the same packet should only arrive to a single Gateway. The Gateway is always connected to a permanent energy source and doesn't need to have any special energy optimization. The most rightward element is the Backend and is outside of the LoRa network, strictly speaking. It is responsible for storing all gathered data and is composed of a REST interface and a database. All the LoPy4 elements were programmed using Arduino's IDE and C++. This choice was made, even though the LoPys are built to be used with Python, as a way to reduce the energy usage as much as possible to give the Nodes (and even some Repeaters) the most alive-time

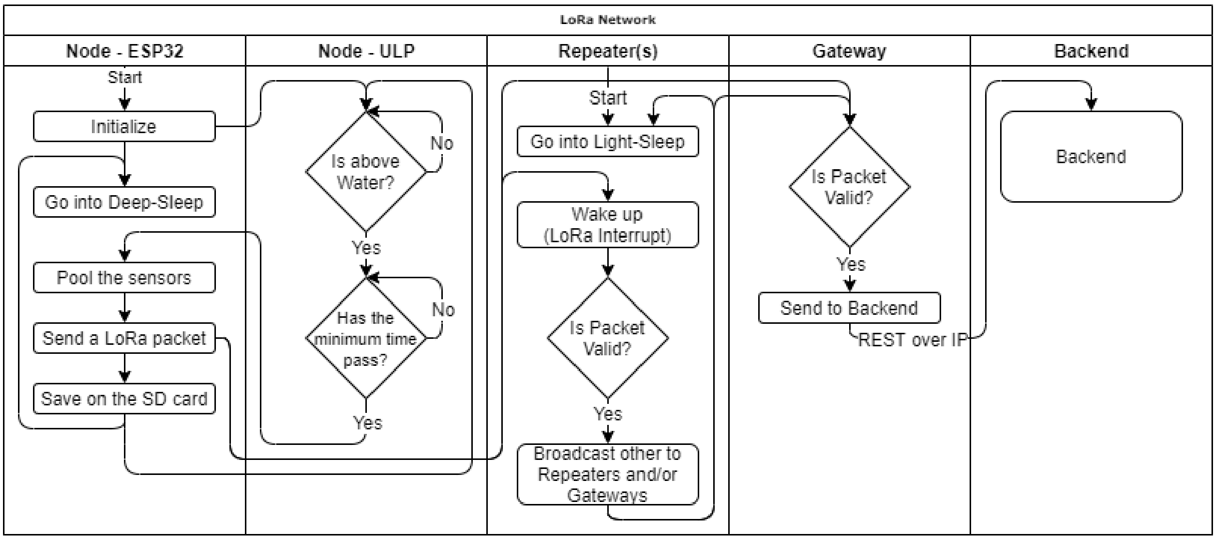

Figure 6.15: LoRa Network Fluxogram - The Network is composed of several Nodes, which have both a full CPU and a Ultra-Low-Power CPU embedded, several Repeaters and several Gateways. It all connects to the Backend.

possible.

6.4.2.3 System Fluxogram

We describe more in depth how the whole system works and the path of the data through all elements that constitute the system. The figure 6.15) gives a graphical insight on how this works out. We will describe each element individually in the following list:

1. Node: This element has, actually, two CPUs in the same chip. A normal ESP32 CPU and a Ultra Low Power (ULP) CPU. Since they do independent work, we will be treating them as two independent sub-devices that communicate between them.

   (a) ESP32: When the Node is first turned on, it configures the ULP and just goes into deep-sleep passing the workload on to the ULP. At anytime, the ULP or a timer can trigger an interrupt, effectively, turning the ESP32 back on. When this happens, it will pool the various sensors present on this Node, create the packet and send it through the LoRa. It may also create a backup on the SD Card, if present and configured to do so. It will, then, go back to the deep-sleep mode.

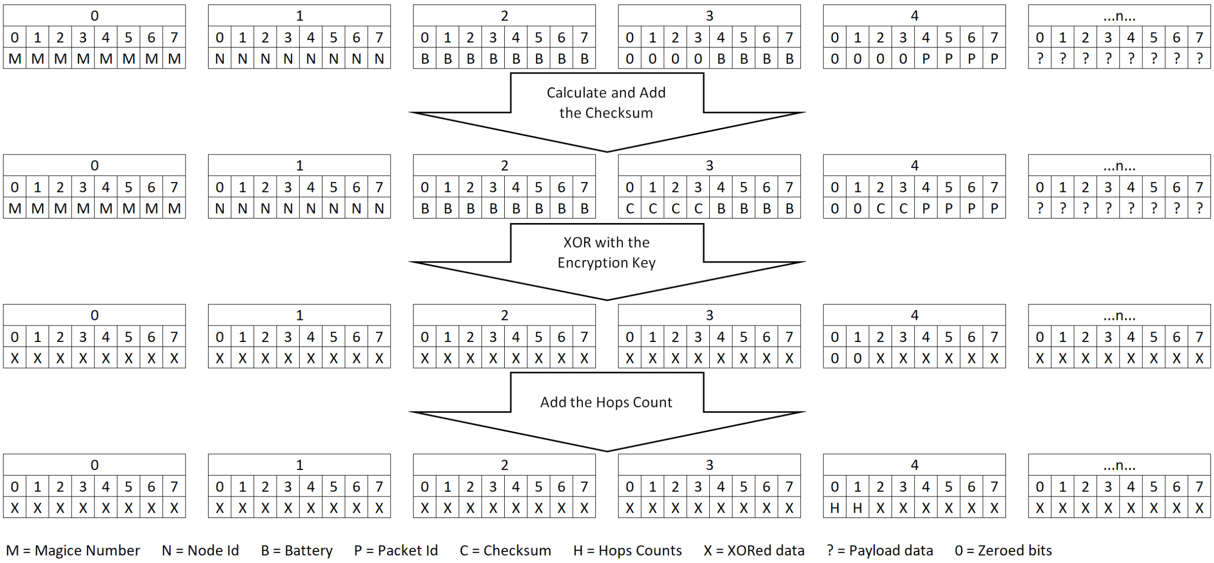

Figure 6.16: LoRa Packet - Diagram of how a Node creates the Packet to send though the LoRa Network. The first row is the byte index, the second row is the bit index and the third row indicates what kind of data goes into that bit.

   (b) ULP: The task of the ULP is a simple one. It will just, repeatedly, and in a low frequency, pool the water sensor to detect if the Node is above water. If it is, the ULP will trigger an interrupt in the ESP32 to wake it up.

2. Repeater: The Repeater normal state is in light-sleep. The LoRa module is, however, active and listening for packets. If one arrives, it wakes up the ESP32 which, then, does a very simple analysis of the packet. If it belongs to the network and the number of hops left is above 0, it re-transmits the packet and goes back into a light-sleep state.

3. Gateway: The final step of the data in the LoRa network is the Gateway. When a packet arives, it, just like the Repeater, first makes sure that the packet belongs to the network and, then, extracts all the data from the payload. Afterwards, the data is packed into a json object that is delivered to the Backend, through a REST call.

6.4.2.4 LoRa Packet

Being a public and shared asset, any LoRa network should be left as uncongested as possible, even if it is bellow the defined limits. For this reason, the usage frequency should be low and the packets' size should remain as low as possible. In our setting, we also need to keep the Nodes deployed and in working order for as long as possible and the LoRa module is a big energy hog, especially while transmitting. For those reasons, we paid special attention how we built the packets. Still, we wanted to add some security to the packets to avoid forged and fake packets poisoning the data. We also wanted to avoid wasting energy processing and retransmitting packets that did not belong to our network. With all this in mind, we designed the packet in figure 6.16) and described below. Since the bits and bytes are zero-index, and to avoid confusion between the text and the diagram, we will refer to the first byte as the ”zeroth byte”. We start by setting the zeroth byte as a 8 bit Magic Number. This number gives us a 1 in 256 chance that a packet that does not belong to our network to be processed. The next whole byte identifies the Node that sent the packet. This limits the number of Nodes in the network to 256, but this is, usually, not an issue and keeps the packet size down. It can also be expanded in the future, if necessary. We reserve the following 12 bits (the whole second byte and the 4 low bits from the third byte) for the battery raw ADC value. This amount of data seems excessive for the battery but the resolution of the value allows us to detect issues with the battery remotely. The 4 high bits from the third byte are left unchanged, for now. The Packet Id uses the following 4 bits (the 4 low bits of the fourth byte). This allows us to differentiate between 16 packets. Being this a slow throughput network, this amount is more than enough. The fourth byte’s 4 high bits are left unchanged as well. All the following bytes are payload but should be well optimized as well. When the packet is initialized with the previously described data, we calculate a simple checksum and save it in the packet using 6 bit - the 4 high bits of the third byte and the bits 2 and 3 of the fourth byte. We then do a very simple encryption of the whole packet by doing a XOR of the packet with a pre-shared encryption key. After the encryption, the number of left hops is written to the bits 0 and 1 of the fourth byte. This gives us, at most 4 repeats. Most of the network is at 0 or 1 repeat of distance affording twice as many hops than necessary. This value is added as the final step, even after the encryption and checksum steps, to allow for every easy drop of the packet or decremention of the counter before forwarding by Repeaters. If the hop value is 0, the Repeater just drops the packet without any further processing. If it is above 0, the Repeater just decrements its value by 1 and forwards the packet again, without any further processing. This allows the Repeater to save precious energy while deployed using solar panels. The Gateway does do a full packet unpack, while ignoring the hop count. It does, however, check the Node Id and the Packet Id to detect duplicated packets (due to multiple paths through the Repeaters). The unpacking is essentially, the reverse of what was described here.

6.4.2.5 Energy Optimization

Since the node needs to work for a long time on battery with no way to be recharged, the device needs to conserve as much energy as possible. With this objective in mind, the device is highly optimized utilizing only as much hardware and software resources as necessary and as frequent as strictly necessary. But all of these optimizations will mean nothing if the device is kept running all the time. We took advantage of the fact that the ULP, while using, virtually, no energy, can still run some code and access some inputs in order to create a ”on/off switch” based on whether the node is above water or not. The water capacitance is different from the air’s. This difference can be detected by the ULP to wake and shut down the main ESP32 chip if it is above or below water, respectively. When above water, it can take whatever measures it needs and quickly send the data using LoRa before the animal pulls the node bellow water again, where the LoRa radio-waves cannot penetrate. If the data needs to be collected underwater, the ULP can still wake up the main ESP32 chip in regular intervals and shut it down after the date is captured. This data is, then, sent using the ”above water method” just described. These techniques allow for a much longer battery longevity, allowing the tracking of animal or environmental telemetry for much longer than it would, normally, be possible.

6.5 Chapter Conclusion

A variety of technologies, techniques, and methods were explored on this project with the objective of increasing the awareness to the oceans’ problems and to aid marine biologists with data gathering. This thesis was involved in three studies researched by the project. The LoRa technology was strongly explored to function as a backbone to the transport of data between animal and telemetry tags, and the public displays and biologists databases. Its behavior in oceanic settings - the usage scenario in focus -

was studied and proved to provide very long range communications (despite still not being to provide any data when the fauna goes below the water-line). A rough, low-power geo-location method was also explored providing the marine biologists with a way of tracking both the animals and the tag (in order to recover it). This technology is also low-power enough to be used for long periods of time (which is a must since the tags' batteries cannot be recharged while deployed), despite its great range and robustness. To take advantage of this infrastructure, a tag was developed based on low-power devices that are now small and cheap enough to provide good alternatives to current commercially available tags. Coupled with LoRa, those tags can stay online for several months while providing data to the marine biologists. To display this data to the public and tourists, a public display was researched and a prototype was built. It consisted of a geodesic cardboard dome with a pillar inside, on top of which, an holograph is displayed to the public creating an immersive setting where the tourists can connect with the animals and the ocean.

Chapter 7

Conclusion

7.1 Thesis Overview

This thesis was written through two research projects (spawning several studies) and three independent studies. It explored, researched, and proposed ways to fix and/or improve several problems, producing an impact in several areas, direct and indirect, theoretical and technical, on the State-of-the-Art and in the industry, and even on the local population and tourism. It made a direct impact in the industry by improving remote collaboration between geographically distributed engineers. It demonstrates the quality of the effects that Virtual Reality can have on one's well-being while expanding some technical aspects. And it developed and expanded several techniques based on the Internet-of-Things, holography, and others to improve ocean awareness and marine biologists' hardware.

7.2 Objectives

The thesis completed the objectives laid down. As with any work, some of the objectives still have issues and need improvements and further research while others did arrive at a satisfying conclusion. Nevertheless, and as an intrinsic part of science, all of the objectives should serve as a base for further advancing the State-of-the-Art, even if they were not completed. All the objectives and their conclusions are better described in the following paragraphs.

7.2.1 Improve remote collaboration through the usage of electronic tools with a focus on a mix of Gaming, Augmented, and Virtual Reality

The thesis did improve remote collaboration with real industry impact. It used mostly Gaming oriented and Augmented Reality with very little Virtual Reality due to the level of the technology at the time it was under research, despite the will to use Virtual Reality. The usage of Tablets was the technology of choice with Power-Walls serving as a pivot of the collaborations.

7.2.2 Using Virtual Reality as a way to improve the quality of life of the users, beyond gaming and working

Virtual Reality was explored and expanded both technically and theoretically. But, the most important findings are in its capacity to relax people and provide strong good feeling as well as to mimic the power of exposure to nature. A surprising bonus is the hint of the effect on the circadian rhythm.

7.2.3 Explore lower-level technical issues related to Virtual Reality, namely, eye-tracking and arm-tracking

The thesis explored aspects of eye-tracking and arm-tracking. On the technical field more could have been explored but what was explored was successfully concluded with relevant improvements to the State-of-the-Art.

7.2.4 Find sustainable ways, techniques, technologies, and materials to improve awareness of the oceans

The look for sustainable ways, techniques, technologies, and materials to improve awareness of the oceans revealed some that were used, tested, and expanded. The most important ended up being the LoRa network that was explored and developed laying the backbone to an information transmission platform that helps with ocean awareness and marine biologists work.

7.3 Hypotheses

This thesis explored several hypotheses that are concluded in the following paragraphs. Some minor hypotheses were left out in their respective studies, clearing this space for the most important and relevant hypotheses.

7.3.1 Navigating and Analyzing by directly pointing the tablet as a camera is faster, more intuitive, and more comfortable than using a joystick

Using a tablet as a camera is more intuitive than a joystick. This is an intuitively achievable conclusion that was, indeed, proven. Even though it was proven that using the tablet as a camera is more intuitive, faster, and less error-prone, the difference is not that big and training may close the gap.

7.3.2 Several tools can be used to improve remote collaboration, namely, video-conference, viewport sharing, avatars, and camera freeze for local sharing as well as a centralized meeting leader with an overview

The importance and quality of said tools were explored and proven in this thesis. More common tools were merely validated but tools like viewport sharing - a kind of video conference but with the user's virtual counterpart - did show promising results in remote collaboration.

7.3.3 We can design a low-cost tag that can transmit data from marine life to presentations in real/near-real-time and this creates a sense of proximity between the audience and the ocean

We did, indeed, create such a tag and explored the transmission of data in near-real-time. Unfortunately, not enough data was gathered to find an effect in the audience.

But offline data studies did find a good public response. Further research is necessary.

7.3.4 We can create a power-autonomous network that can transmit the above-mentioned data to the presentations

By using LoRa we've proven that this network can, indeed, be used. But only low bandwidth data can be transmitted, both due to the technology limitations but also because the animals are not above water for long enough time for more data to be transmitted.

7.3.5 We can create presentations that can create awareness of the oceans

By exploring the usage of cardboard-built domes, holography, and custom input devices, we've proven that Ocean Awareness (and, probably, any other kind of awareness) can be achieved with the tools that we developed.

7.3.6 The LoRa technology can be used to support the previous hypothesis

LoRa technology does appear to be a perfect candidate for this situation but, unfortunately, not enough data was gathered to support this hypothesis. Further development is necessary.

7.3.7 The LoRa technology can be used as a low power geolocator

LoRa technology is, by itself, a low-power technology. Coupled with other low-power components (such as microcomputers), it can be exploited for low-power solutions (as opposed to GPS-based solutions which are extremely high power). As a geolocator, it did show some results but with low accuracy. If the achieved accuracy is enough for the user (like finding the general area of a whale), the technology is, indeed, validated. Otherwise, there may be better solutions available or under development.

7.3.8 Using eye-tracking directly may increase user frustration

Eye-tracking can increase user frustration if used as a way to point at targets. Eye-tracking may be used as passive trackers (for instance, to gather information of where the user is looking at for ads purposes or to enable foveated rendering) but is bad as an input element.

7.3.9 The sample rate in arm-tracking affects user performance and comfort

In arm-tracking, the sample rate seems not to affect users' performance (even though it seems counter-intuitive), at least at the sampling rate and tasks that were tested. Some users do notice the difference but some don't and it does not seem to affect comfort too much. This may change for longer than tested tasks, more stressful tasks, or lower sample-rates.

7.3.10 Virtual Reality can be used to relax people

Virtual Reality can indeed be used to relax people and with a good and strong effect. It also shows the capability of having a strong effect in other ”good” feelings. This needs more exploration but the results are promising.

7.3.11 Virtual Reality has an effect on the circadian cycle

This hypothesis was not proven but the hint of a possible effect is there and it is very interesting with strong consequences for both the market and our mental and physical health in the city. With more research, interesting and important results may be found.

7.4 Future Work

The CEDAR project is pretty much closed but, given the fact that some time has passed and Virtual Reality has improved so much since then, revisiting some concepts using current Virtual Reality technology and state-of-the-art may actually produce some interesting results. Most concepts, most importantly, navigation and manipulation, can highly benefit from current Virtual Reality. The LARGESCALE project, on the other hand, still has so much that can be, directly, expanded and improved. The LoRa network and the tags can still be greatly improved. The whole project can also greatly benefit the local tourism industry and the industry. The other direction is also true with both the tourists and the industry providing live validation of the concepts. All of this, while increasing ocean awareness. This project also did some other research to which this thesis did not relate to but that could be explored in future works. Namely, it started to explore, more directly, Virtual and Augmented Reality as ways to transmit ”green” messages to the younger and more tech-oriented public. But more pure Virtual Reality is where I would like my future research to focus on. In a near future, I would like to explore more the effects of Virtual Reality on our well-being, both physical and mental perhaps, researching if the effects that reality brings us can, and how strongly, be achieved through Virtual Reality. Finally, that hint of an effect on the circadian rhythm did leave me very curious and it is very worth exploring. I would also like to explore proprioception in Virtual Reality and, the more financially demanding, full-body tracking with haptic feedback.

7.5 Final Remarks

This thesis did expand the State-of-the-Art in several fields and gave direct contributions to related industries. It also designed and expanded several technical aspects that are in use and that can be built upon to achieve greater goals. It completed several studies and laid the foundations for more studies to be conducted either by me or by other researchers in the area. Personally, it gave me a lot of research and development experience in different areas that can be tapped into to further advance my studies.

Publications

On this chapter are listed the publications related to this thesis. The publications are listed in chronological order.

Campos, P., Gouveia, D., Noronha, H., & Jorge, J. A Mobile System for Collaborative Design and Review of Large Scale Virtual Reality Models. In Joint Virtual Reality Conference of ICAT, EGVE and EuroVR, 2012 (p. 29).

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Noronha, H., & Campos, P. (June, 2021). The influence of sample rate in arm tracking. In British HCI.

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