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Enhancing the artificial reality experience through interactive 3D holography

MASTER DISSERTATION

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MASTER IN INFORMATICS ENGINEERING

UNIVERSIDADE da MADEIRA
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Holographic Reality: Enhancing the Artificial Reality Experience through Interactive 3D Holography

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Abstract

Holography was made know by several science-fiction productions, however this technology dates back to the year 1940. Despite the considerable age of this discovery, this technology remains inaccessible to the average consumer.

The main goal of this manuscript is to advance the state of the art in interactive holography, providing an accessible and low-cost solution. The final product intends to nudge the HCI community to explore potential applications, in particular to be aquatic centric and environmentally friendly.

Two main user studies are performed, in order to determine the impact of the proposed solution by a sample audience. Provided user studies include a first prototype as a Tangible User Interface - TUI for Holographic Reality - HR Second study included the Holographic Mounted Display - HMD for proposed HR interface, further analyzing the interactive holographic experience without hand-held devices. Both of these studies were further compared with an Augmented Reality setting.

Obtained results demonstrate a significantly higher score for the HMD approach. This suggests it is the better solution, most likely due to the added simplicity and immersiveness features it has. However the TUI study did score higher in several key parameters, and should be considered for future studies. Comparing with an AR experience, the HMD study scores slightly lower, but manages to surpass AR in several parameters.

Several approaches were outlined and evaluated, depicting different methods for the creation of Interactive Holographic Reality experiences. In spite of the low maturity of holographic technology, it can be concluded it is comparable and can keep up to other more developed and mature artificial reality settings, further supporting the need for the existence of the Holographic Reality concept.

Keywords: Human-Computer Interaction · Interactive Holography · Software Engineering · Multimedia · Biodiversity Awareness.

Resumo

A tecnologia holográfica tornou-se conhecida através da ficção científica, contudo esta tecnologia remonta até ao ano 1940. Apesar da considerável idade desta descoberta, esta tecnologia continua a não ser acessíveil para o consumidor.

O objetivo deste manuscrito é avançar o estado de arte da Holografia Interactiva, e fornecer uma solução de baixo custo. O objetivo do produto final é persuadir a comunidade HCI para a exploração de aplicações desta tecnologia, em particular em contextos aquáticos e pró-ambientais.

Dois estudos principais foram efetuados, de modo a determinar qual o impacto da solução proposta numa amostra. Os estudos fornecidos incluem um protótipo inicial baseado numa Interface Tangível e Realidade Holográfica e um dispositivo tangível. O segundo estudo inclui uma interface baseada num dispositivo *head-mounted* e em Realidade Holográfica, de modo a analisar e avaliar a experiência interativa e holográfica. Ambos os estudos são comparados com uma experiência semelhante, em Realidade Aumentada.

Os resultados obtidos demonstram que o estudo HMD recebeu uma avaliação significante melhor, em comparação com a abordagem TUI. Isto sugere que uma abordagem "head-mounted" tende a ser melhor solução, muito provavelmente devido às vantagens que possui em relação à simplicidade e imersividade que oferece. Contudo, o estudo TUI recebeu pontuações mais altas em alguns parâmetros chave, e deve ser considerados para a implementação de futuros estudos. Comparando com uma experiência de realidade aumentada, o estudo HMD recebeu uma avaliação ligeiramente menor, mas por uma margem mínima, e ultrapassando a AR em alguns parâmetros.

Várias abordagens foram deliniadas e avaliadas, com diferentes métodos para a criação de experiências de Realidade Holográfica. Apesar da pouca maturidade da tecnologia holográfica, podemos concluir que a mesma é comparável e consegue acompanhar outros tipos de realidade artificial, que são muito mais desenvolvidos, o que suporta a necessidade da existência do conceito de Realidade Holográfica.

Keywords: Interação Humano-Computador · Holografia Interativa· Engenharia de Software · Multimédia · Consciencialização da Biodiversidade.

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I would like to thank my family, who has supported me throughout my entire academic life, and for who I owe my accomplishments. The person I am exists because of you, and I am forever grateful for the sacrifices you have done for me to be here today.

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Miguel Alexandre Rodrigues Andrade

[1] `http://wave.arditi.pt`

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Nomenclature

AR	Augmented Reality
CAD	Computer Aided Design
$CMOS$	Complementary Metal Oxide Semiconductor
ECB	European Central Bank
$Gbit$	Gigabit
GDP	Gross Domestic Product
HCI	Human-Computer Interaction
HMD	Head Mounted Display
MR	Mixed Reality
$PTSD$	Post-Traumatic Stress Disorder
QR	Quick Response
RQ	Research Question
SLM	Spatial Light Modulator
SoA	State of the Art
UN	United Nations
$UNSDG$	United Nations Sustainable Development Goal
US	United States
VR	Virtual Reality
ZMD	Zscape Motion Display

1 Introduction

Recent years demonstrate the pertained division amongst humanity, where global warming is still being contested, in spite of the numerous evidence supporting the existence and the severity of this problem [20,17,54,12]. Climate change remains an ongoing issue to be solved, while industrialization is still producing more technologies, which do not contribute to the ongoing debate.

Conversely, more and more anthropological activities impact the world's biodiversity, while oceans, in particular, are getting more and more exposed to humans' disrespectful behaviour, mostly by the continuous flow and accumulation of litter in marine waters. Recently, it has been estimated the Great Pacific Garbage Patch alone is comprised of 1.8 trillion individual pieces, 94% of them belonging to the micro-plastic variant, and totaling 79k metric tons [2]. Moreover, a UN study has also concluded that 40% of the world's oceans are heavily overwhelmed by some form of pollution. This affects more than 3 billion people whose lives depend on marine and coastal environments, as well as harming as much as US$ 3 trillion worth of resources per year, or 5% of the global GDP[3].

Undoubtedly, marine life is on of the greatest victims of human irresponsibility, continuously affected by entanglement or ingestion of marine litter. Inside the OSPAR region alone, multiple specimens have had their physical condition monitored since 1997, leading to the conclusion that a staggering 663 distinct species are being affected, a 40% increase from the beginning of the study. Unless a major action is taken, it is estimated that the amount of plastic in the world's oceans will surpass the number of fish by 2050[4].

Unless major actions are taken soon, humanity may indeed be heading towards a worldwide ecological catastrophe, creating a necessity for the implementation of methods and technologies that not only tackle these issues directly, but also draw attention to their existence, demonstrate the impact and the danger human activity poses to the environment, and motivates the wider population to pursue more eco-friendly habits. In this manuscript, study focuses on leveraging technology to induce more sustainable habits, by the development of interactive user experiences, based on artificial reality [21]. Research provides insight into the development of low-impact technologies, which are capable of increasing user marine literacy, and raising awareness of oceanic concerns. In the following chapter, an opportunity of how interactive technologies based on holography is depicted, invoking more sustainable behaviours.

1.1 Motivation

While there are several actions already underway to reduce this negative human impact on marine environments, multiple nations have also made commitments to counteract marine pollution. More specifically, the plan for the OSPAR Collective Actions, commits the contracting parties to take the following measures[5]: (i) Combat sea-based sources of marine litter; (ii) Deliver a cost recovery system, (ii) Combat land-based sources of marine litter (iii) Implement litter removal actions; (iv)

[2] National Geographic (`https://www.nationalgeographic.com/news/2018/03/great-pacific-garbage-patch-plastics-environment/`)

[3] United Nations (`https://www.globalgoals.org/14-life-below-water`)

[4] Ellen MacArthur Foundation (`https://www.ellenmacarthurfoundation.org/`)

[5] OSPAR Comission, Marine Litter Action Plan (`https://www.ospar.org/documents?v=34422`)

Educate and outreach the masses. While these actions pose a positive impact, there is plenty of work to be actually implemented, opening the possibility to use interactive technologies.

HCI might also contribute to these actions, mainly due to their numerous existing applications and smart environments which aid the users whilst also directing them to more informed and improved decisions. An open question remains, how can HCI be applied in an aquatic setting. Theoretically, a successful system based on HCI, that focuses in the marine litter concern, should provide the necessary influence to change the course of action, similarly to what was attempted by [55] and [69], albeit through different approaches. While holography (and interactive holography) has not been sufficiently advanced, it is possible to analyze their application in aquatic setting, and compare its effectiveness against pre-existing similar technologies.

1.2 Towards Interaquatic Holography

In definition, a hologram is defined as the process that enables the visualization of three dimensional objects on a holographic display, without the aid of any specific eye wear [15]. The general public describes holographic technology as an advanced and somewhat futuristic system that seems out of reach and restricted by the limitations of the current technology. This is mainly due to its prominence in multiple science fiction productions. The Holographic Effect was, however, first discovered and developed during the late 1940's by the physicist Dennis Gabor. The development of the laser in the early 1960's allowed the technology to advance even further, and enable the creation of the first practical optical holograms that recorded 3D objects, resulting in Dennis Gabor being awarded with the Nobel Prize in Physics in 1971 [33].

Nowadays, holographic technology is mostly applied in anti-forgery mechanisms for banknotes and various products, and scarcely in the form of actual interactive systems, which currently remain mostly high-cost, and are not available for the common user. If sufficiently developed, this technology's applications would be extensive and vastly useful to multiple industries and fields of study, such as Cinema, Television, Photography, Marketing, Architecture, Engineering, Design, Education, Geography, Medicine (local and remote surgery) and numerous others [33] [14].

While applications of holography are seen in industries, additional benefit of holography is to explore it for: (i) learning and pedagogic settings; (ii) aquatic environments; and (iii) interactivity. E.g. a participant in a museum setting can acquire more knowledge about a certain marine species, by naturally interacting with its projection, either by hand tracking or tangible interfaces.

1.3 Research Questions, Objectives and Contributions

Given the state of the art and motivation listed above, this subsection outlines the manuscript's main focus, objectives, and overall contributions to the correspondent fields of study. It is proposed for this manuscript to answer the following questions:

1. **[RQ1]. How to design low-cost interactive holographic experiences for an aquatic setting?**
   This research questions will compare the existing technologies and provide the best practices for prototyping the holographic and virtual experiences, tailored to be applied in aquatic setting.

2. **[RQ2]. How does the same interactive experience compare when it's developed for Holographic Reality and other Artificial Reality branches?**
   The same experience is developed, tested and evaluated for Holographic Reality and other Artificial Reality devices, in order to compare results for the different branches and determine how Holography stands up to its counterparts.
3. **[RQ3]. How is such an apparatus effective in increasing awareness of current marine ecological concerns?**
   Using HCI, usability and environmental scales, this manuscript provides an insight into how such apparatus can raise awareness of important oceanic concerns, and to which extent it impacts the awareness for marine ecological concerns.

Given the potential of interactive holography in increasing marine conservation and providing educational awareness, this manuscript produces the knowledge to:

1. **[O1. PROTOTYPE].**
   This step focuses on the implementation of a low-cost interactive holographic apparatus, designed in order for the system to be as natural and eco-friendly as possible.
2. **[O2. COMPARE].**
   The Holographic Reality experience was ported to other Artificial Reality devices, in order to compare the results of each available setting. These subsystems are as similar as possible to the original concept, however, they had to be adjusted to the constraints and particularities posed by each platform.
3. **[O3. IMPACT].**
   Using multiple user studies, thesis provides in depth analysis of how interactive holography affects the increase of marine concern awareness and the perception of the human impact onto the environment.

The reported research, therefore, provides multiple contributions: (i) outlines an exhaustive literature review on Interactive Holography, and Artificial Reality in general, further complemented with an overview of existing consumer products; (ii) it advances the state of the art in Holography, Artificial Reality and HCI, by exploring large-scale and low-cost technologies; (iii) increases marine concern awareness, whilst inviting the users to pursue positive sustainable actions. Given the importance of the United Nations Sustainable Development Goal 14 (UNSDG 14), focusing on Life below water, this manuscript directly contributes to targets 14.1 Reducing Marine Pollution and 14.A Increasing Scientific Knowledge, Research and Technology for Ocean Health[6]; (iv) describes a new agile development model, suitable for the design and implementation of multi-platform systems.

1.4 Organization of the Manuscript

Structure of this manuscript is as follows: (i) **INTRODUCTION**, provided the motivation, rationale, research questions to be addressed as well as the thesis contributions in creating interactive holographic experiences; (ii) **RELATED WORK**, outlines the current State of the Art

[6] United Nations (`https://www.globalgoals.org/14-life-below-water`)

and prior research in interactive holography; (iii) **METHODOLOGY**, describes the software, hardware and the overall apparatus logic, including the sample and conducted user studies; (iv) **RESULTS**, yields the results of the user studies; (v) **DISCUSSION**, depicts the findings from the results and to which extent they advance the SoA in holography, HCI and Artificial Reality; and (vi) **CONCLUSION**, outlines the pros, cons, limitations and future works in crafting interactive holographic systems.

2 Related Work

Ever since its genesis, holographic technology has failed to become a mainstream system. Despite the spark in popularity during the aftermath of World War 2, mainly caused by the available war surplus [33], there have not been many applications of it. This being said, it does not mean that there is insufficient research/developed consumer products. In fact, it appears that the interest in this field of study is peaking once again, probably stimulated by the increased availability and reliability of auxiliary technology. This is all caused by growth of computational power provided, keeping up with the pace defined Moore's Law [46].

In this manuscript, an overview of the SoA in Holography is revealed, as well as the prior works which used holographic input for interactive means. Lastly, a difference between AR, MR, VR is outlined and a proposal for the definition of Holographic Reality is depicted.

In table 1, an overview of some holographic technologies is provided, summarizing their attributes including the methods, interactivity and the cost. As it can be assessed, these products are either mostly high cost, or don't even have their prices displayed at all. This poses a potential to prototype such environments with a significantly lower cost.

2.1 State of the Art in Holography

Nowadays, a clear and subtle example of a mainstream usage of holographic technology are the anti-forgery mechanisms found in banknotes[7], passports, ID cards, as well as other important items susceptible to counterfeiting, due to the difficulty demanded to its replication, since they cannot be scanned or copied[8], without the necessary equipment. This system was first introduced in circulating bills (Figure 2) in 1988, and ever since, it has been adopted in over 300 denominations of 97 currencies worldwide[9]. This type of hologram is clearly visible in figure 2, which demonstrates a 5€ banknote specimen. However, this particular implementation, remains static, with no interaction, and serves no other purpose than anti-forgery.

In contrast, the most simple method to create a quasi-holographic illusion is to use an optical effect dubbed Pepper's Ghost. This optical illusion was firstly introduced in a theater context, by Professor John Pepper, to simulate a ghost appearing on stage [10]. This Victorian Era method used a spotlight to lit an actor, who was hidden bellow the stage, in a dark room, to minimize the impact caused by external light sources. The actor's image was then reflected by a mirror onto an angled glass, where the audience would then see it as a ghost [10] (figure 1).

[7]European Central Bank (`https://www.ecb.europa.eu/euro/banknotes/denominations/html/index.en.html`)

[8]Sapling (https://www.sapling.com/5724023/hologram-credit-cards-used-for)

[9]Giesecke+Devrient (`https://www.gi-de.com/en/cn/currency-technology/trends/banknote-security/30-years-holograms-on-banknotes/`)

Table 1. State of the Art for Holographic Technology

Dimensions	Company	Product	Method	Interactivy	Cost (EUR)
2D	PM Screen	1, 3 or 4 Sided Display	Pepper's Ghost	Requires a sensor package	1481.73 - 6588.30
	Virtual On	Holographic Displays	Pepper's Ghost	None	568 - 37368
		Virtual Mannequin	Transparent Screen Projection	Requires a touch screen	5586
		Holographic LED Fan	Rotating LED Fan	None	511 - 1914
		Holographic Projection Screen	Transparent Screen Projection	Can be turned into a touchscreen	N.A.
	HYPERVSN	HYPERVSN Wall	Rotating LED Fan	Through SDK	N.A.
	Kaleida	Holonet	Transparent Screen Projection	None	N.A.
3D	Holokit	Holokit1	Pepper's Ghost	Software supported	30.36
	Aryzon	Aryzon Original	Pepper's Ghost	Software supported	30
		Aryzon Pop-up	Pepper's Ghost	Software supported	15
	Microsoft	Hololens	Projection-based	Gesture, voice and gaze recognition	3159
	Magic Leap	Magic Leap 1	Projection-based	Dedicated remote, together with head, hand and eye tracking	1940.59
	Holoxica	Segmented Holographic Display	Hologram Flip-Motion	None	N.A.
		Planar Interactive HUD	Free-space Optics	Enabled through Kinect motionsensor	N.A.
		Looking Glass	Lenticular Array	Supported by compatible software (Blender, Unity, etc)	601 - 3358
		HoloVizio	Light Field Projection	Software supported	N.A.
	Voxon	VX1	3D Volumetric Display	Software supported	8092
		Z3D	3D Volumetric Display	Incorporated Arcade Controls	N.A.

Fig. 1. Victorian Era Pepper's Ghost[10]

To take advantage of this effect, the modern procedure, which is replicated by PM Screen's[11] products, is to use a reflective surface to reflect an image from a screen, which gives out a 3D effect, since the image appears to be floating in mid-air (see Figure 3).

Fig. 2. Banknote with holographic security measure[12]

[10] Adapted from https://magic-holo.com/en/peppers-ghost-the-innovation-from-the-19th-century/, retrieved on 6th March 2020

[11] PM Screen (`https://pmscreen.com/`)

[12] Provided by ECB (https://www.ecb.europa.eu/euro/banknotes/images/html/index.en.html, retrieved on 20th December 2019)

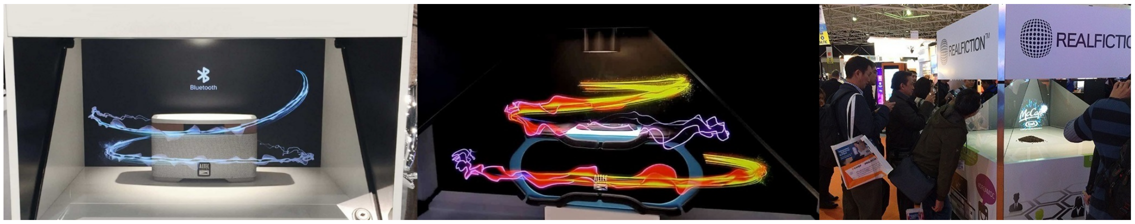

Fig. 3. PMScreen's 1, 3 and 4 sided displays [13]

Most companies use fully developed and on-market holographic technologies, focusing solely on their employment in marketing and exhibition displays, as is the case of Virtual On[14]. This group "offers a wide variety of Mixed Reality exhibition display stands", which includes, among others, Holographic Displays, as well as virtual and augmented reality solutions, all of which are destined for product/brand promotion, customer assistance and/or exhibition purposes. Some examples of their implementations are again, simple Pepper's Ghost [10] projections and transparent projection screens (with multiple available sizes, some of which can be combined with real objects), as well as life-size holographic mannequins that can communicate and attend to customers, and provide interactive features to some extent. One of their most simple albeit innovative solutions is the Hologram Projector LED Fan[15]. This device produces the illusion of a hologram floating in the air through the continuous high speed rotation of one or more LED light bars, whose image is created by synchronizing this rotation with quick changes of the LED output. This apparatus results in a cost-effective, easy to transport and easy to assemble product, capable of producing a holographic effect (see Figure 4). HYPERVSN[16] is another company which develops holographic solutions for advertising, also commercialized a similar, fan-like holographic system, however going one step further, by combining and synchronizing multiple rotating LED fans, greatly increasing the magnitude of the projection (see Figure 5).

Fig. 4. Products from Virtual On's catalog[17]

[13] Adapted from `https://pmscreen.com/`, retrieved on 20th December 2019
[14] Virtual On (`https://virtualongroup.com/`)
[15] From https://virtualongroup.com/3d-holographic-led-fan-display-projection-air/
[16] HYPERVSN (`https://hypervsn.com/`)
[17] Adapted from https://virtualongroup.com, retrieved on 20th December 2019

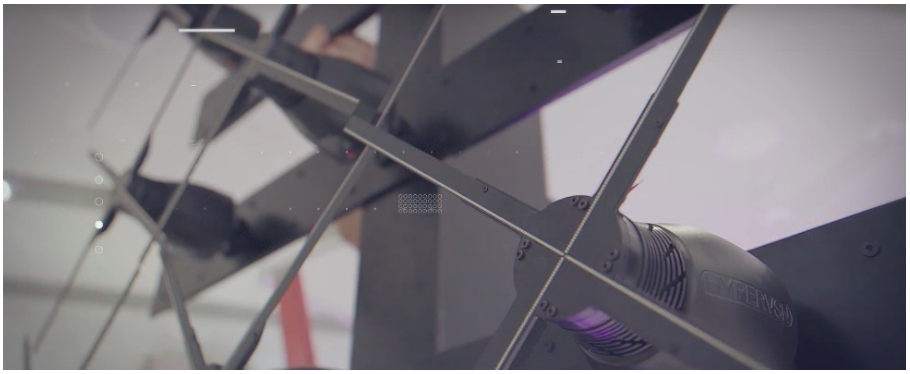

Fig. 5. HYPERVSN Wall[18]

Holoxica Limited [19], on the other hand, is a company whose focus is to leverage holographic technology, not for publicity, but for other purposes, such as Medicine, Simulations, Engineering, Architecture, Cartography, Military, etc. To fulfill this objective, they partnered with multiple companies and institutions to develop and resell holographic displays and exhibitions. Their first generation prototype, the Segmented Holographic Display, simply used a fixed number of static holographic images, who were sampled and interwoven into the screen. This device produced "flip motion" style animations, to give the impression of a 3D movement, and ultimately only allowed for simple applications (clocks, simple signs or icons, etc). For the second generation, the Planar Interactive HUD Display was developed, building upon its ancestor, introducing real-time changing images, as well as a Kinect motion sensor to enable interactivity with a number of apps that were purposely developed for this system. The third generation, the Volumetric Display, is still in development, and it will employ voxel technology[20]. As for the Looking Glass Factory (see Figure 7), it is a light field display that can actually showcase full-color 3D animations, with no requirements for dedicated glasses/headsets. The combination of an LCD screen, lenticular array (see figure 6) and a perspex block[21] allow it to display the animation with a parallax effect within a field-of-view of 50 degrees, and also, through the dedicated graphics processing unit, support multiple software frameworks, such as Unity and Unreal Engine, along with the native Holoviewer application[22]. Another way of using screen arrays has been seen in HoloVizio Light Field Display[23], composed of a large projector array driven by a high performance GPU cluster, responsible for generating a dense light field, projected onto a horizontal parallax display. The result is a full-colour real-time 3D display that does not require any headset whatsoever. Also noteworthy is their Digital Holo-Printing device, a printer for static holographic images.

[18] Adapted from https://hypervsn.com/store/hypervsn-wall/, retrieved on 20th December 2019

[19] Holoxica (`https://www.holoxica.com/`)

[20] A voxel is the 3D equivalent of a pixel, and relates to an elementary volume unit. Typically has a square base. [5]

[21] A perspex block is a transparent acrilic solid.

[22] An overview is provided in https://www.holoxica.com/holoviewer

[23] Specifications available in https://www.holoxica.com/holovizio

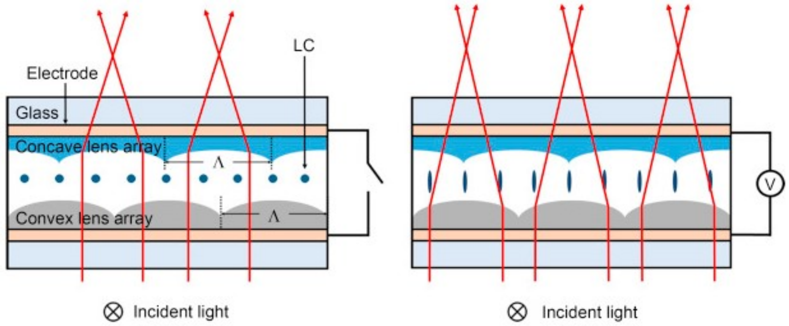

Fig. 6. Example of a Lenticular lens array[24]

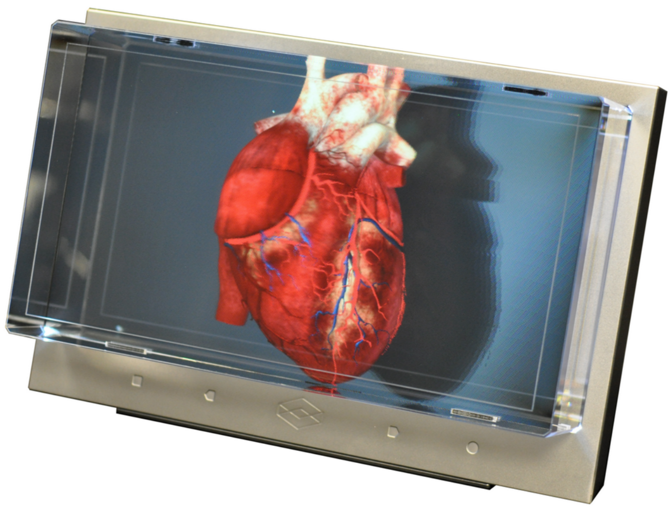

Fig. 7. Looking Glass, from Holoxica[25]

There are also other methods to implement holographic displays, e.g., Kaleida[26] strives to develop holographic systems, but also interactive and other visual experiences. For this purpose, the company has produced the 3D Holonet (see Figure 8), a gauze screen for front projection holograms, containing silver to reflect part of the projected image, successfully creating 3D images with holographic effects. With correct lighting, the remainder of the screen becomes imperceptible to the human eye, further contributing to the 3D holographic illusion. A similar solution is also provided by RealFiction's DeepFrame[27], which also projects images onto a transparent screen, along with other Pepper's Ghost like products.

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[24] Adapted from [38], retrieved on 28th January 2020

[25] Adapted from `https://www.holoxica.com/`, retrieved on 20th December 2019

[26] Kaleida (`https://www.wearekaleida.com/`)

[27] RealFiction (`https://www.realfiction.com/solutions/deepframe`)

Fig. 8. Kaleida's Holonet[28]

Voxon's[29] systems can also display a 3D holographic projection, however their approach displays a real-time, high definition, interactive hologram which can be viewed from any direction, without head-worn apparatus. The Voxon VX1, unlike the Pepper's Ghost [10] illusion and fan-like devices, does not generate a 3D holographic illusion, moreover it is a full fledged 3D volumetric display[30]. The projection itself is divided into multiple layers, before being projected onto a high speed reciprocating screen, which diffuses the photons and forms a cross section of the model. The human eye then blends these layers, forming a true 3D object. An alternative version to this device, the Voxon Z3D, was developed for entertainment purposes, with adequate controls (see Figure 9).

Fig. 9. Voxon VX1 and Z3D[31]

A head-mounted/wearable approach is also something to consider, in interactive holography. In spite of being classified as AR/MR, low-end devices such as the ones produced by Holokit (Holokit 1)[32] and Aryzon (Aryzon Original/Pop-up)[33], and high-end devices such as Microsoft's Hololens[34] and Magic Leap 1[35], can also be considered holographic, at least to some extent, due

[28] Adapted from https://www.wearekaleida.com/netflix, retrieved on 20th December 2019
[29] Voxon Photonics (`https://voxon.co/products`)
[30] This is achieved through a dedicated high-speed rendering engine, combined with their proprietary hardware, making it capable of projecting over half a billion points of light every second.
[31] Adapted from https://voxon.co/products/, retrieved on 20th December 2019
[32] Available in https://holokit.io/
[33] Available in https://www.aryzon.com/
[34] Available in https://www.microsoft.com/en-us/hololens
[35] https://www.magicleap.com/en-us

to the fact these head mounted displays are based on Pepper's Ghost like illusions and/or other optical effects.

Fig. 10. Head mounted holographic displays[36]

As it can be assessed from these examples, holographic technologies remain mostly expensive, lack application in educational settings, and/or are prone to large amount of supported equipment such as screens, cables, power supplies, etc. The strengths and weaknesses reported in these research studies and consumer products were, therefore, considered for the development of the studies described in this manuscript, favoring systems with mostly simple and low cost features, in order to achieve the objectives and correspond to this project's philosophy. In the next section, the manuscript will discriminate the previously existent artificial reality technology [21], which is an alternative to holography.

2.2 Artificial Reality

In general, there are other digital environments that can be considered an alternative to holography, including Augmented, Virtual or Mixed Reality. In the table below, a brief definition of existing digital environments is provided, comparing AR, VR, MR and proposing Holographic Reality as a new setting, which can also be considered as new branch of artificial reality [21], just like its counterparts.

Virtual reality, for example, replaces the users' physical surroundings with a virtual computer generated scene [35], by placing a screen in front of their eyes and headphones/speakers with surround-sound effects. The goal of VR is to completely immerse and allow users to interact with the artificial world [9]. Some released VR devices are, for example, the Oculus Rift, Google Cardboard and PlayStation VR (see Figure 11) [9]. This technology is the most successful in terms

[36]Adapted from https://holokit.io/, https://www.aryzon.com/, https://phys.org/news/2016-04-microsoft-hololens-glimpse-holographic-future.html and https://hothardware.com/news/magic-leap-is-a-heap, retrieved on 25th November 2020

[37]Can also be classified as MR, depending on the content developed and the tools (SDK's, API's, etc) that are integrated with it.

Table 2. Artifical Reality Branches(Definitions and Examples)

Technology	Description	Company	Product	Cost (EUR)
VR	Replaces the users' surroundings with a virtual computer generated world.[35]	Oculus	Rift S	330
			Quest 2	247
		Google	Cardboard	5 - 62
		Playstation	PS VR	300
		VIVE	Cosmos	577
			Cosmos Elite	742
			Cosmos Elite (Headset only)	453
AR	Allows the user to perceive the physical world with overlaid virtual elements.[2]	Google	ARCore[37]	N.A.
		Holokit	Holokit 1[37]	30.36
		Aryzon	Aryzon Original[37]	30
			Aryzon Pop-up[37]	15
		Euclideon	Hologram Table	N.A.
MR	Combines elements from both VR and AR to allow the user to perceive both real objects, and virtual objects which respond to and interact with the real world. [30]	Microsoft	Hololens	3159
		Magic Leap	Magic Leap 1	1940.59
		Google	Glass	1182.96
HR	Allows the user to perceive the physical world with overlaid virtual elements, by means of optical effects/illusions	N.A.	N.A.	N.A.

of creating an immersive experience for its users, which can attributed to its ability to direct sensory focus from the real world to the artificial realm [66]. In turn, an immersive experience is then more enjoyable, meaningful and stimulating to the user. This limited interaction with the real world does, however, come with its drawbacks, mostly inherent social interaction issues [47], and the requirement for the experience to occur in a safe and relatively open environment, otherwise it becomes prone to accidents. Issues such as hardware cost/quality ratio, excessive cabling and motion sickness, caused by sensory overload are also prevalent [14].

Fig. 11. VR game, Beat Saber[38]

Another possible alternative is Augmented Reality technology, which allows the user to see the physical world with overlaid virtual elements [2], and is currently used by several mobile applications (Pokémon GO (figure 12), Snapchat, Yelp, etc), through smartphone cameras [9]. This technology's biggest strength is its capability of augmenting and expanding what is possible to do in the real world. By keeping the user in touch with "real reality", it allows for the development of more engaging and social experiences [49], which VR cannot match. It is also the most readily available artificial reality technology, since most users already have an AR-capable device, which they use on a daily-basis [6]. However, this technology does suffer from limited immersion that can lead to potential interruptions and loss of focus and low tech maturity [65].

Fig. 12. Pokémon GO[39]

Mixed Reality is an attempt to combine both VR and AR elements, in order to allow the user to perceive both real objects and believable, virtual objects which respond to and interact with the real world [30]. The main difference between MR and AR, is the addition of the perception of depth and perspective (a virtual chair would be partly hidden beneath a real table, a virtual agent would avoid real obstacles). The Microsoft HoloLens (see Figure 13) is a clear application of this technology [9]. Due to its close proximity to AR, MR possesses similar strength's and weaknesses, however mixed reality does manage to outperform, due to the extra layer of immersion provided, in terms of its capability for the artificial reality to react to and interact with the real world [9]. This does, however, also add an additional layer of system complexity and greater hardware demands [63] [42].

[38] Adapted from https://www.engadget.com/2019/02/12/beat-saber-players-too-fast-for-steam-vr/, retrieved on 20th December 2019

[39] Adapted from https://www.slashgear.com/pokemon-go-ar-plus-apple-arkit-augmented-reality-game-update-20512429/, retrieved on 29th January 2020

Fig. 13. Microsoft HoloLens[40]

In this manuscript, the definition of Holographic Reality is proposed, as an interactive experience with similar features to the ones AR, VR and MR offer, in the sense that it also brings virtual elements to the real world. However, it accomplishes this by means of optical effects/illusions. Following this rationale, Microsoft Hololens, Aryzon Original and other similar devices, can be shifted into this category, due to the fact that they also employ an optical effect to bring virtual objects to the physical world. However, Hololens in particular is better categorized as Holographic Mixed Reality, since it also allows the physical and virtual elements to interact with each other. Furthermore, this classification allows Holographic Reality to be placed, together with its counterparts (AR, VR and MR), into the Milgram Reality-Virtuality Continuum [48], ranking it in the middle of the spectrum.

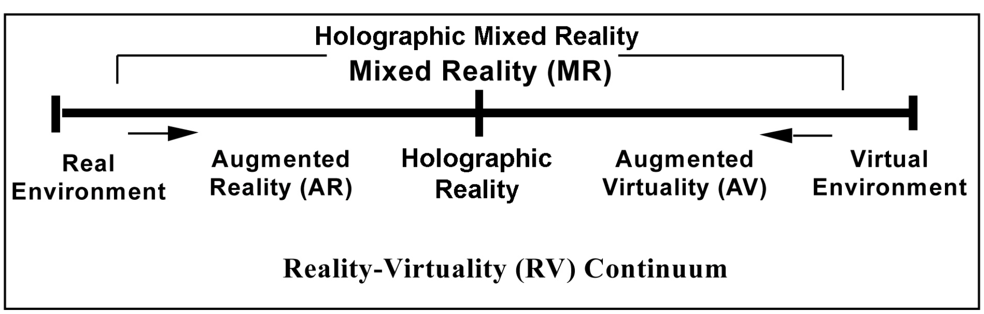

Fig. 14. Milgram Reality-Virtuality Continuum, adapted to fit Holographic Reality

[40]Adapted from https://www.microsoft.com/en-us/hololens, retrieved on 20th December 2019

Fig. 15. Example of Holographic Mixed Reality[41]

2.3 Prior Research

In this chapter, manuscript outlines some of the discriminating aspects and previous academic works and publications in holography exploring stereoscopy, depth, interactivity, embodiment, geospatial, etc.

2.3.1 Stereoscopy and Depth in Holography

TeleHuman2(see figure 16), a hologramatic teleconferencing system enabled life-size 3D human telepresence, built by Gotsch et al. [27], who build upon the first TeleHuman, designed by Kim et al. [40], by removing the requirement for a head tracking system[42] or other similar apparatus in order to generate parallax effect and stereoscopic illusion. Moreover, an alternate telepresence system based on VR/MR technology is presented in subsection 2.3.6.

State of the art equipment remains mostly expensive, and this is possible to observe in the TeleHuman2 study [43]. Due to the high-end hardware requirements and budget constraints, the authors limited the system to a 59° field of view. Their user studies consisted of asking 2 participants to perform a collaborative task, where each was given a Bluetooth remote that controlled an arrow in the room. In one condition, the arrow was rendered on the TeleHuman2, whereas in the

[41] Adapted from https://codebrave.files.wordpress.com/2016/08/tony-stark-hologram.jpg, retrieved on 15th January 2020

[42] HMD - Head-worn realtime 3D interactive display devices in the line of sight of a user, allowing for full body mobility [58]

[43] To provide full 360° of parallax, it required a 195cm cylindrical acrylic display, 275 laser projectors, each connected to an Odroid C1+ (Single board computer, specifications available on https://www.odroid.co.uk/hardkernel-odroid-c1) board functioning as a rendering engine, and an array of 5 speakers and microphones to provide surround sound. The image itself was captured through 9 2x2K ZED cameras, connected to an Intel i5 computer with one NVidia GTX1080 graphics card per camera.

second condition it was physically present in the room. The task, in both conditions, consisted of asking the left participant to point the arrow at itself, and then at the right participant, who was also asked to do the same. After this, a live remote human was projected onto the cylinder, and the participants were asked to rate their stereoscopic perception, walk around the 59^{o} projection and rate the experience. The procedure was repeated 3m away from the center and the participants were asked for general comments. Their results showed that the mean error in pointing the arrow was less than 1^{o}, yielding that there were no meaningful differences between the conditions, and the same was true between pointing at self and pointing at another. After this task, the users performed a Likert scale questionnaire, with the statements *I am experiencing an accurate three dimensional image of a person.* and *I am experiencing an accurate rendition of motion around a person.*. This scale showed insignificant differences in rankings for stereoscopy between 1.8m and 3m, however the same was not true for motion parallax. Overall, they concluded that the participants were able to perform the tasks accurately, to within 1^{o} of arc, which is better than the angular resolution of the system. Authors concluded that the system provided acceptable stereoscopy and parallax effects for multiple users, however loosing the quality the bigger the distance between itself and the user.

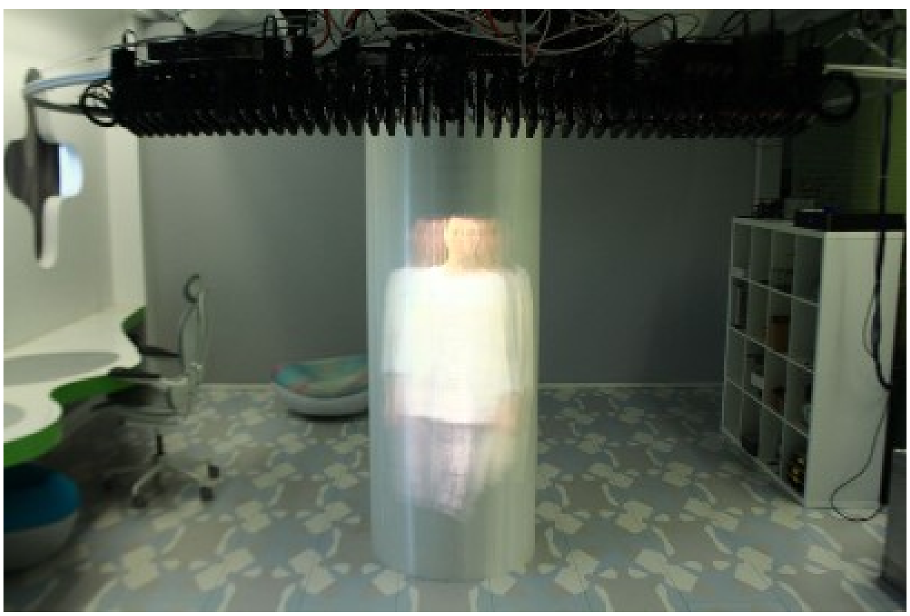

Fig. 16. Gotsch's TeleHuman2[44]

In contrast to expensive holograms, a similar, albeit cheaper solution was proposed by Ito et al. [32], whose approach also employed a cylindrical hologram with a 360^{o} degree view of a static light field (see figure 17). Ito described multiple methods to achieve this, all of which use a laser beam for recording. They developed a printer for a Computer Generated Cylindrical Hologram, consisting of a laser beam, an x-y stage to restrict motion, and liquid crystal on silicon. A fractional part of the hologram is displayed in the silicon, and a reduced image is recorded on a holographic plate. The plate is then translated by the x-y stage to be printed to the next part of the hologram.

[44]Adapted from [27], retrieved on 16th January 2020

The printer obtained an average number of 20.000 object points, throughout the course of 30h with multiple computers, and 150h with a single machine.

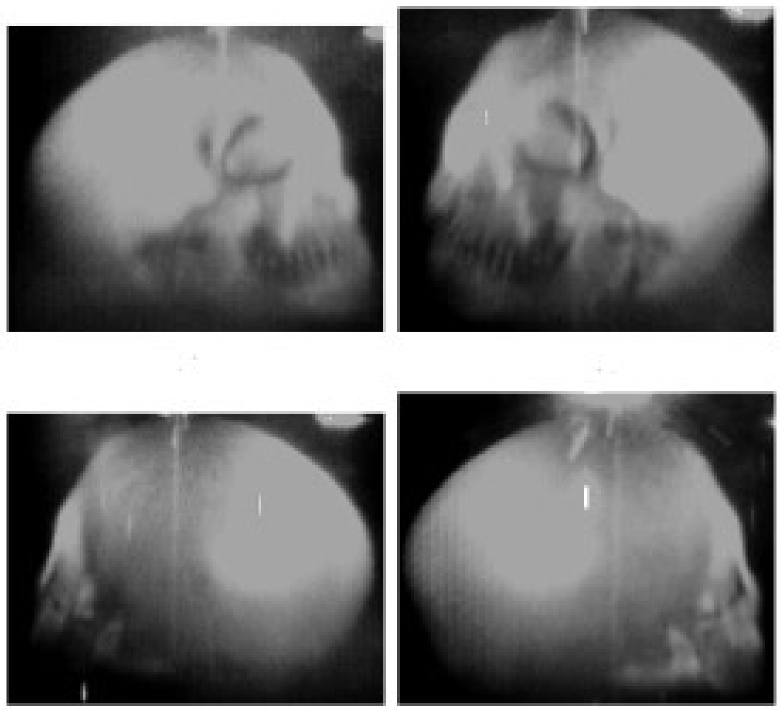

Fig. 17. Cylindrical Hologram obtained through Ito's method[45]

2.3.2 Interactive Holography

Current holographic systems are mostly static or video-based imagery, proving no source of dynamism or interaction. Taking this issue into consideration, one can consider there's a need to turn this technology interactive, to further improve immersion during interaction with virtual objects/environments.

Following this line of thought, the previous work reported by Dalvi et al. [15], authors followed a simple approach that, again, takes advantage of the Pepper's Ghost [10] illusion to simulate a 3D hologram (see figure 18). The system only requires a computing device with a screen, a hand gesture system for interaction, and a transparent truncated pyramid. The hand gesture system detects the position of the hand through infrared radiation, and uses it to map the rotation of the displayed hologram. The hologram itself is rendered on the computer using a game engine, with 4 cameras placed at specific angles and positions, in order to capture different views of the 3D object. Once this is displayed on the monitor, it is placed on top of the pyramid to project the different views. Kim et al.'s [41] Sense of the Deep is actually very similar, apart from the user interface, where you can interact with a gelatinous substance and witness changes to the displayed hologram that mirror their movements(see figure 19). The objective of their study is to

[45]Adapted from [32], retrieved on 16th January 2020

propose an alternative and immersive interface that bridges the gap between the visual and tactile sensory inputs, while simultaneously alluding to amoebic deep sea creatures. The interaction itself is interpreted by Arduino microcontrollers.

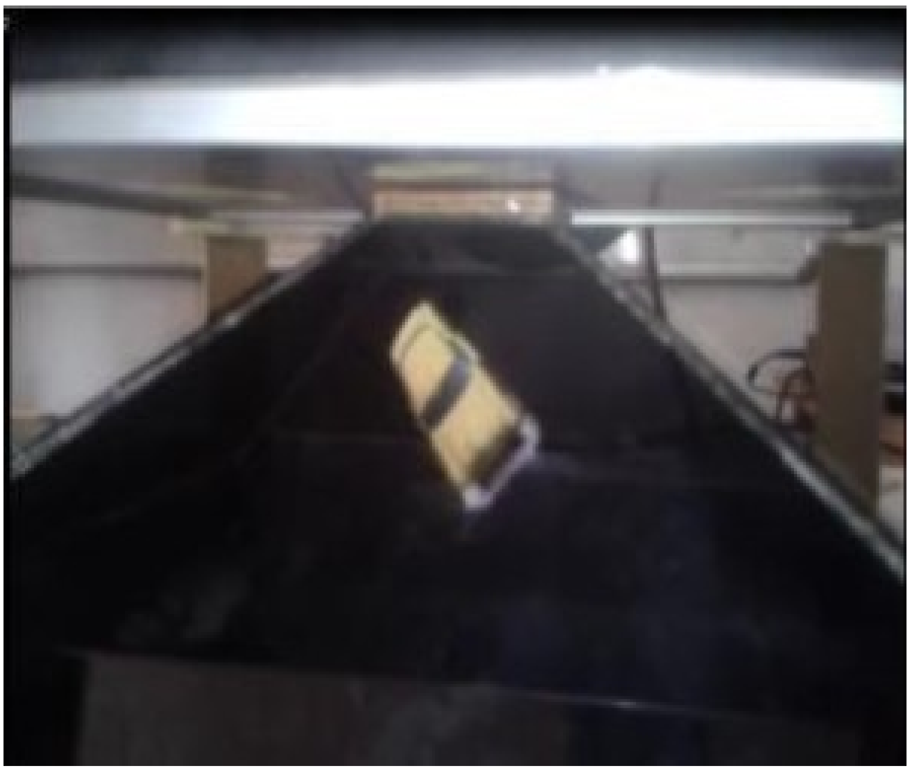

Fig. 18. Dalvi's pyramidal hologram[46]

[46]Adapted from [15], retrieved on 16th January 2020

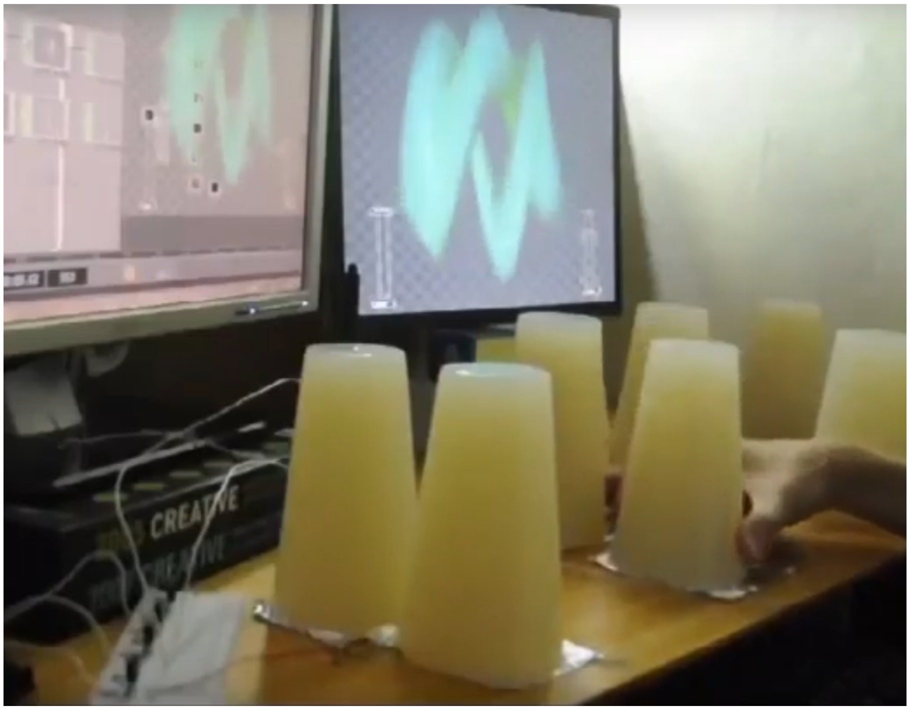

Fig. 19. Kim's proposed method for holographic interaction[47]

Conversely, Kervegant et al. [36] created a touch "hologram" through an Augmented/Mixed Reality device, Microsoft Hololens[48] (see figure 20). Their biggest contribution, however is its combination with a touch development kit from Ultrahaptics[49], mixing Augmented Reality with an array of ultrasonic transducers, coupling it with a tangible feedback, enhanced the immersion and presence of the virtual object and gave a spatial reference to the user. In order to obtain this, the Ultrahaptics device enabled the production of focal points that tracked the hands of the users which, is this specific case, invited them to rotate a virtual sphere around its center of gravity. Using 40 points per hand, when a collision was detected, the algorithm computed an input to the haptic device. For the system to remain consistent throughout the experience, a client-server connection was established, to ensure real time interaction. The server itself broadcasted the position and orientation of the hologram via Wi-Fi, after which the HoloLens interpreted the features, and used them for the graphical rendering. This turns out to be a singular experience that enhanced the interaction with the holographic projection, giving it a physical presence.

[47] Adapted from [41], retrieved on 18th December 2020
[48] Available in https://www.microsoft.com/en-us/hololens
[49] Available in https://www.ultraleap.com/haptics/

Fig. 20. Kervegant's solution, combining HoloLens with Ultrahaptics[50]

Also, Leuski et al. [43] took the hologram concept and developed Sergeant Blackwell (see figure 21), a holographic character designed to serve as an interface for exhibitions and kiosks. Blackwell is a 3D model rendered by a high-quality computer, projected onto a transparent optical film, and animated to provide a life-presence effect. A user can actually communicate with the sergeant through a head mounted microphone, whose speech is then converted to text using an automatic speech recognition system. Blackwell responds with pre-recorded lines automatically transcribed to generate lip movement animations, accompanied by a variety of gestures and body movements.

The studies described in this manuscript draw inspiration and build upon the transparent screen projections and pyramidal Pepper's Ghost like approaches described by Dalvi et.al., Kim et.al. and Leuski et.al., due to their inherent characteristics such as simplicity and affordability.

[50]Adapted from [36], retrieved on 16th January 2020

Fig. 21. Leuski's Sergeant Blackwell[51]

2.3.3 Perception, Interaction and Embodiment in Holography

Holography provides multiple advantages over standard virtual experiences and personal devices, enabling more natural interactions than those provided by 2D screens.

Moreover, Bach et al. [3] study benefits the immersed tangible with 3D visualizations interface, whilst comparing the Hololens to a traditional desktop and a tablet, in terms of 3D perception, interaction and embodiment (see figure 22). These criteria where chosen since they represented characteristics considered to have a greater influence on task performance in a 3D environment.

[51] Adapted from [43], retrieved on 16th January 2020

In what perception is concerned, the Hololens enabled a stable view of a 3D object with a stereoscopic sensation, providing the users with free movement around the hologram, in Bach's study. This resulted in far higher 3D perception than the desktop or tablet, both of which provide a simple flat screen with no stereoscopic view whatsoever. As for user interaction, the benefit of the Hololens is that it allows for the tracking of the position and orientation of tangible fiducial markers, similar to AR applications on a tablet/mobile phone. This enables a higher degree of interaction when comparing to a desktop environment. Therefore, a significant part of it is the embodiment, which, the extent to which the users movements are visually and spatially coordinated. The Hololens itself gives users the ability to "touch" the hologram which, given the appropriate tracking technology, allows its manipulation. In contrast, the very same manipulations in a desktop are constrained to user by the mouse movement on the screen.

Multiple controlled user studies were performed, the first of which consisting of a standard desktop environment, where participants where asked to use a standard mouse for interaction with a perspective projection. In the second experiment, the environment featured a handheld tablet, filming fiducil markers in a cardboard, used to render the visualization, through the Vuforia toolkit[52]. The participants where then able to interact with the cardboard, that propagated their movements to the visualization. The third and final environment was setup for the Microsoft Hololens, where, for interaction, the users were given the Hololens clicker. Since the Hololens continuously tracks movement, it allowed for a stable hologram that the participants could walk around. For every trial, a set of 4 tasks were given, that were representative of 3D exploration. To limit number of conditions and the effort, the displayed 3D object was a simple point cloud. Firstly, the users were asked what was the closest point pair, between two colored options, then they were asked the minimum number of clusters they could count from multiple directions, following by quick selection of every red dots. As a final task, the users had to place a cutting plane in order to intersect three red clusters. On average, every participant required 1.5 hours to complete all three environments, resulting on 270 recorded trials (15 participants x 6 trials x 3 environments). Their study findings demonstrated that interaction through tangible markers outperformed the remaining devices for tasks that required coordination between perception and interaction, whilst the Hololens dominated when high requirements for manipulation were needed. The tablet environment led to the highest number of errors.

[52]Available in https://developer.vuforia.com/

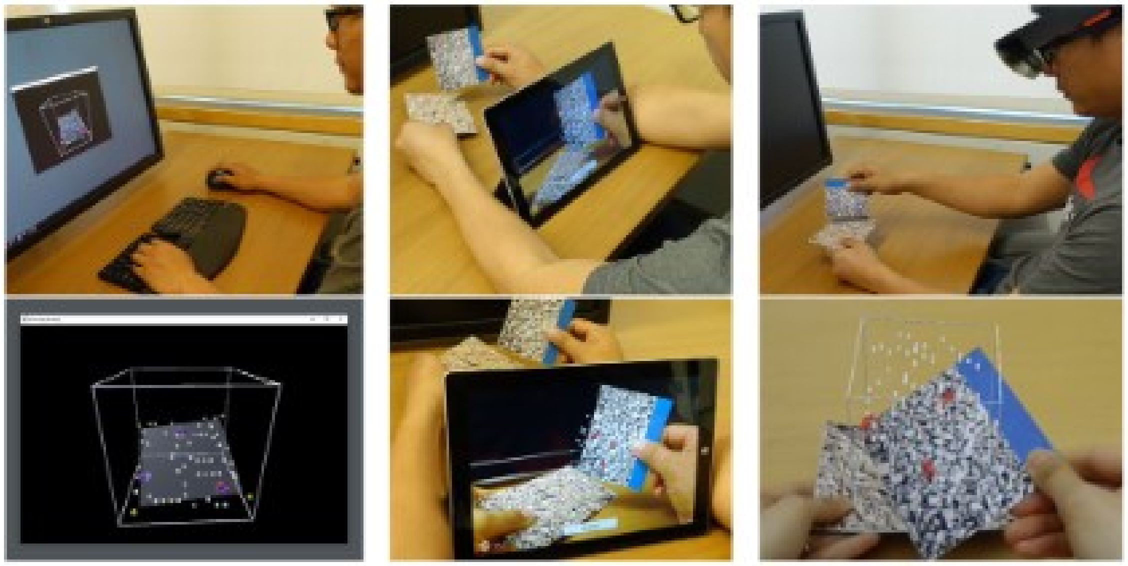

Fig. 22. Multiple 3D environments. From left to right, computer, tablet and HoloLens[53]

In this manuscript, a study for a head mounted holographic experience is described, such as in the previous article. However, it is implemented by a low-cost device coupled with a standard smartphone, making it accessible and available to the average user, hindering the usage of the high cost Hololens approach.

2.3.4 Holography and Computer Graphics

In order to achieve interactivity through static holograms, these can also be combined with other graphical elements, such as real world objects, or computer generated 3D graphics.

Bimber [7] attempts to combine holograms with other elements. In this particular case, he merges optical holograms with 3D computer graphics to provide an acceptable tradeoff between high-quality static holograms and interactivity provided by additional graphical information that is generated, inserted, modified and animated. He also describes multiplex holograms, that are an apparent exception to static holograms that lack interactivity. Multiplex holograms are built from multiple vertical strip holograms that contain multiple static recordings of the same scene at varied time intervals, allowing for the observation of a motion by either moving around the holographic projection, or spinning it around its axis. Multiplex holograms, however are not interactive, despite their semi-dynamic nature. It is for this fact that Bimber combines them with 3D computer graphics with stereoscopic elements to provide a full-fledged interaction. He also establishes a comparison between digital and electroholography, where digital holography requires holographic printers to expose a photometric emulsion to computer generated imagery, which results in conventional holograms that display noninteractive holographic views. On the other hand, electroholography displays holograms in real time, that can be computed by rendering multiple perspective views and combining them, or by simulating and calculating the optical interference pattern. This requires the computation, transmission and storage of a massive amount of data

[53] Adapted from [3], retrieved on 16th January 2020

that simply puts a significant amount of strain in today's computer, establishing limits to electro-holography. To overcome this difficulty, researchers developed advanced compression algorithms that, although useful, produce small, low resolution holograms. He states that, technically, optical combiners such as beam splitters or semi-transparent screens can successfully overlay the rendered output over a holographic plate, resulting in an interference between the reconstructed light of the hologram and the overlaid light of the rendered graphics. As a solution, there's a possibility to solely reconstruct the object's wave partially, in order to leave gaps where the rendered graphical elements are placed, requiring a point light source, such as conventional projectors, capable of selectively emitting light in multiple directions, with the added advantage of the brightness produced by today's high-intensity discharge lamps. If this is combined with parallax displays capable of rendering 3D graphics, both the holographic and graphical contents appear three dimensional. To prove this concept, a hologram of a dinosaur skull was recorded and underwent this procedure.

Fig. 23. Combination between a static 3D hologram and computer graphics[54]

Just like the apparatus' proposed in this manuscript, this study outlines a solution for an interactive hologram. This a relevant system, however, its complexity is far higher than those of the proposed studies.

2.3.5 Applications of Holography

This type of technology has a great deal of potential to be applied in a broad range of areas. This chapter outlines several application areas which can be distinguished, ranging from cartography, education, air-traffic control, gaming, data storage, and others.

Cartography

Like Leuski's Sgt. Blackwell, Interactive Holography has the potential to greatly influence both academic research and the consumer market through its application in the design of immersive 3D tools. Another possible application is the one described by Fuhrmann et al. [25], whose main

[54] Adapted from [7], retrieved on 16th January 2020

objective is to aid and improve geospatial decision-making, providing a meaningful impact in time critical missions, tactical planning, navigation and route planning. These goals are achieved through true 3D representations able to extend traditional 2D/3D map properties, affordances and cartographic methods, rendered by interactive geospatial holograms of natural or artificial environments. However, despite the increased benefits in rescue and military scenarios, traditional holography still faces some limitations concerning real time content, regarding the time frames of holographic production processes being too long for mission success requirements. Tactical planning is often influenced by massive amounts of data such as line-of-sight analysis, air space status, satellite feed, terrain, structures and other metadata that needs to be provided and updated on a realtime basis. These dynamic changes can be overlayed in 2D onto existing holograms by using a video projector, which also allows for decision makers to interact with this data. These augmented holograms are, therefore, an intermediate step towards fully dynamic and interactive holography with a full parallax with no eyewear apparatus, and the ability to use streaming video and geometry together with static content. A prototype dubbed ZScape Motion Display (ZMD, see figure 24) was actually developed by Fuhrmann et al. with all these characteristics, enabling 3D geovisualization of topographic and other critical data by up to 20 simultaneous users, and supporting immediate and accurate collaboration. The ZMD also offers many opportunistic applications for medicine, education, environmental catastrophe response, urban search and rescue and disaster management.

Fig. 24. Overview of the ZMD device[55]

Education

As stated by Hacket [28], another possible and useful application for this technology would be in

[55] Adapted from [25], retrieved on 16th January 2020

the fields of medicine and education. Recent studies suggested that the incorporation of simulation training improves outcomes, and an increasing number of medical schools are making simulation a core component of their curriculum. One particular area of medical education which would benefit from new technologies is anatomical training, a highly complex task that requires the memorization of a broad range of anatomical structures with complex nomenclature. The students are also required to expend a great mental effort to understand the complex structure and spatial orientation of the human body. The application and generation of 3D anatomical models has the potential to facilitate the learning of anatomy and improve student interest and so he extends these findings and examines the benefits of 3D holographic models in anatomy training, through the measurement of cognitive load. Hacket's experimental procedure divided the participants into two groups, one being a control group with 9 participants, taught using standard anatomical handouts, and a treatment group with 10 subjects, which received medical holograms. Both the handouts and the hologram presented 4 distinct views of the heart, with the hologram having the added advantage of rotation to move between views. Each subject conducted a pre-questionnaire on cardiac anatomy before the test, and were later given the medical content in an isolated room with the task of studying it. After five minutes, the participants conducted a post-test with the same questions as the pre-test. To finalize the experiment, the subjects reported their perceived cognitive load on a nine point rating scale ranging from "very very low mental effort" to "very very high mental effort". The experimental results demonstrated a similar performance for both groups on the pre-test, with an insignificant difference, which indicates a similar amount of previous knowledge in cardiac anatomy. As for the post-test, the control group demonstrated a significant improvement between pre and post-test results, being, however, overshadowed by the performance of the hologram group. As for the cognitive load index, the holograms showed a significant decrease in mental effort. He states this an be due to the novelty of the technology, which is a step-up from standard textbooks, or even a cause of imagery learning strategy. The results, overall, indicate the medical holograms may turn out to be, as excepted a beneficial tool in medical education.

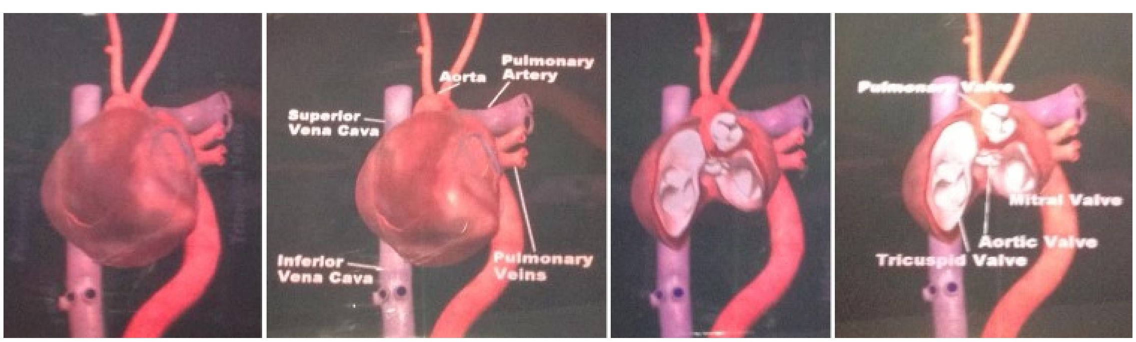

Fig. 25. 3D Anatomical model of the human heart[56]

Figueiredo et al. [23] employ holography in an educational context as well. Their work takes advantage of Augmented Reality applications available for mobile devices to provide Mechanical Engineering students with an educational system for the visualization of 3D models of mechanical parts. To complement the study, a low cost holographic prototype supported by a tablet, the

[56]Adapted from [28], retrieved on 16th January 2020

EducHolo, was also developed. This research stems both from the increasing availability of mobile devices, mainly tablets, and the initial difficulty mechanical engineering students demonstrate in understanding and drawing 3D objects from 2D representations, and to draw 2D representations of 3D objects, that occurs when these students learn the basic concepts and techniques of technical drawing. The augmented reality app running on a mobile device is triggered by a QR code. This app gives the students free range to view the object from multiple orientations, whilst providing free and rapid access to multiple educational materials, removing the constraints posed by physical 2D images. As for their implementation of the holographic method, like other previous studies, their hologram is produced through the Pepper's Ghost [10] illusion, a transparent polyester film placed at 45°, and a mobile device (see figure 26). To improve the 3D illusion, the background behind the film should be dark. Overall, these systems resulted in a low cost implementation of 3D environments, able to improve the users' comprehension of a 3D object.

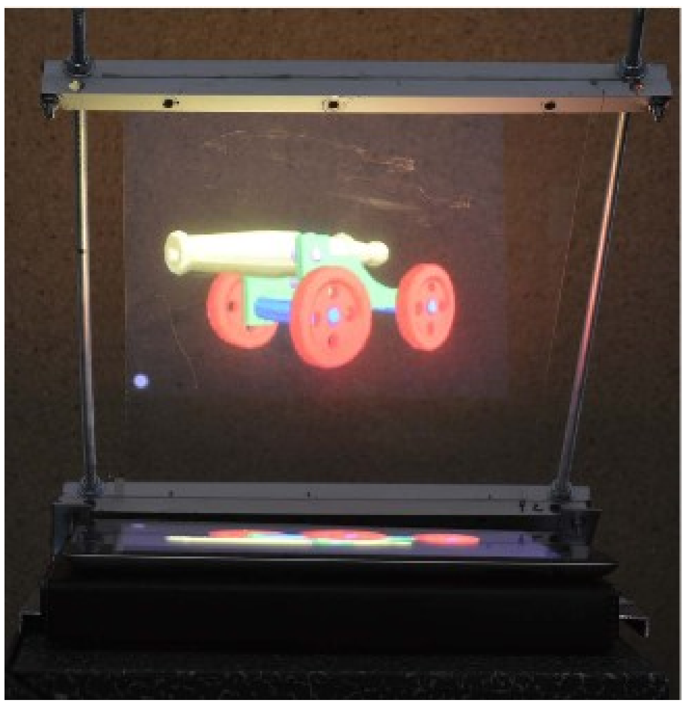

Fig. 26. Figueiredo's Pepper's Ghost Hologram[57]

Air-Traffic Control

3D holography has proven its usefulness in a multitude of situations, otherwise constrained by non-stereoscopic 2D/3D views displayed in flat screens. According to Robin et al. [57], air traffic control can also benefit from this technology, since the current paradigm is dominated by the use of rudimentary 2D radars, that fail to provide the controllers the correct altitude of each specific airplane. Air traffic control is a very high risk and highly demanding career in terms of focus and concentration, where human errors are inevitable, which, in the worst scenario, may be the trigger

[57]Adapted from [23], retrieved on 16th January 2020

of an otherwise avoidable collision/accident. In a mainstream 2D radar, the location of a specific aircraft is displayed by a small dot with written information such as its call sign, altitude and speed, making it more cumbersome and requiring more concentration to extract the vital data. The introduction of a third dimension through holography provides the controller with a much needed decrease in work load.

This system is very advantageous, since it has the potential to greatly reduce aircraft collisions, holding times for takeoff/landing, significantly increase air travel safety and, overall, make air traffic management more efficient. An example is provided in figure 27.

Fig. 27. 3D radar view of an airplane[58]

Gaming

Holography can also provide opportunities to the gaming industry, through its implementation into home entertainment systems. For instance, Bala et al. [4] developed Keyewai: Last Meal, a game system that combines eye tracking devices, gamepad controllers and a holographic projection screen to provide a unique social experience to its users (see figure 28). They took advantage of the fact that the users were placed front to front to explore game mechanics that motivated the players to cooperate, communicate and interact. The game's objective is for the two players to assume the role of a couple stranded on a remote island, searching for radio pieces to contact the outside world, all while evading cannibals. Each avatar is controlled by the gamepad controller, and is also given a flashlight controlled by the gaze, since the player has a limited view of the world.

However, one the issues they faced was caused by the transparent nature of screen, resulting in problematic text representation. Their solution was to use this to their advantage, and further promote cooperation between the users, by reversing portions of the instructions, making them readable only to the corresponding user. The game was tested by 21 players, who all filled an

[58]Adapted from [57], retrieved on 16th January 2020

anonymous questionnaire. The overall reaction to the system was positive, and the use of eye tracking was one of the most enjoyable aspect to the users. The cooperation feature was also well received, even though the familiarity between became a decisive factor, since players who knew each other "were more verbal, willing to share items and more protective of each other", when comparing to players who weren't familiar with one another.

Fig. 28. Last Meal gameplay[59]

Holographic Data Storage Drive
Psaltis et al. [56] provide an overview of an ingenious, albeit unorthodox employment of this technology. They provide a review on the application of the holographic method as a data storage medium, and compare it to traditional systems. Their research stems from the continuously growing demand of memory capacity, who, so far, has been successfully satisfied by the standard products available in the market. However, these devices use 2D surface storage, and these limits are rapidly being approached, creating a need for a device capable of 3D data storage, whose recent developments were discussed in this article. The data itself is encoded and retrieved as 2D pixelated images, with each pixel representing a standard bit, resulting in fast readout rates, due to the inherent parallelism, while achieving an output data rate up to 1 Gbit per second. Regarding surface density, holographic memories have been experimentally demonstrated to possess 100 bits per square micron in a 1mm thick material, far exceeding this value when the thickness is increased. As for a DVD disk, the surface density is merely 20 bits per square micron, and a magnetic disk, a measly 4 bits. A hologram recording uses two light beams, a reference, and an object beam, whose interference pattern is recorded (see figure 29). To use holography as a memory storage method, the digital data is imprinted onto the object beam, and then retrieved from the reconstructed beam during readout. A planar array of pixels called spatial light modulator (SLM) is used as an input device, able to either block or pass light to the holographic storage,

[59] Adapted from [4], retrieved on 16th January 2020

who is then diffracted and read by the output device, a similar array of light detector pixels such as a charged-coupled device camera or a CMOS pixel array. To enable read/write operations, the hologram is composed of inorganic photorefractive crystals doped with transition metals or rare-earth ions. These specific materials react to light and dark regions of the interference pattern by trapping electrons, resulting in a correspondence between the light intensity in the interference pattern and the variations of the refraction index. This trapped charge can then be rearranged by illumination, which allows the erasure and replacement of data, though leading to gradual deletion of stored data during the read operations, due to charge re-excitation. In the dark, the trapped charge slowly escapes, establishing the data lifetime from months to years.
These issues, however, can be solved through thermal or electronic processes, with the counterpart that the data becomes permanent and cannot be erased or replaced. This type of system is also susceptible to errors caused by detector changes, variations in readout, alignment problems, excess lighting or brightness variations. Despite, holographic storage is still a promising technology, whose next step is to become cost competitive and employ more suitable materials.

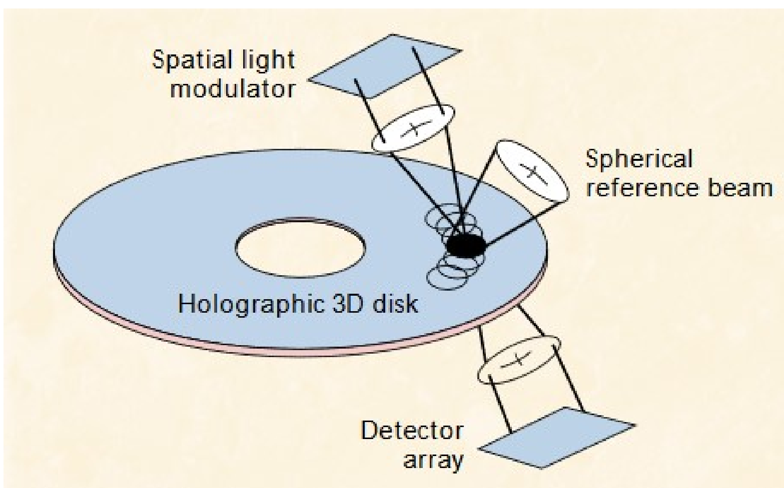

Fig. 29. Recording process for holographic data storage[60]

This subsection outlined multiple possible applications of Interactive Holographic Technology, however this can be further expanded to accommodate other prominent industries and/or fields of study such as Architecture, Media, Physics and Chemistry. The studies described in this manuscript can be considered as contributions for Environmental Education and Gaming, by employing Interactive Artificial Reality experiences, in order to draw attention to current environmental concerns. The systems proposed by Figueiredo et.al.[23] and Bala et.al.[4] are both used as inspiration for the those same studies, by building upon the usage of Pepper's Ghost illusions, and tangible controllers, respectively.

2.3.6 Holographic Reality: Alternative Artificial Reality

Interactive Holographic technology can be considered as a sub-branch to Artificial Reality, and can and should be compared to its counterparts, AR, VR and MR. This section summarizes previous

[60] Adapted from [56], retrieved on 16th January 2020

research that was conducted in the field of Artificial Reality, mainly alternatives to the focus of this manuscript, Interactive Holography.

Simulation Training and Education

The most obvious application for this type of technology is its usage for entertainment and/or gaming purposes [70] [39] [68], regardless if it is developed in industry or academia. A similar employment, albeit with an educational purpose, is using it for simulation training of potential dangerous or complex situations, or as a learning tool in a classroom environment. Aslandere et. al. [1], for instance, used virtual reality as a means to develop a standardized low-cost flight simulator and facilitate pilot training, aircraft design and development. This approach presents a solution to the problems of the current paradigm in that field, which is plagued by high-cost complex full-scale simulators, whose constraints are further aggravated by the need to adjust the hardware and controls to be compatible with every individual aircraft type. Zhang et. al. [75] compare different types of VR technology, currently in use as teaching mechanisms for trainees to simulate drilling in underground mines. They conclude head-mount displays, together with a leap motion[61] input device creates the better system, on which the users can feel full immersion, however they also state the current training system lacks high quality content. In a more educational context, Liang et. al. [45] propose leveraging Augmented/Mixed Reality for healthcare professionals' clinical training, in this case in a stroke assessment simulation. The developed simulation projects a human face displaying stroke symptoms onto a computerized training mannequin, on which the nursing students would have to perform an assessment to identify the symptoms and act accordingly. Their results demonstrate most students enjoyed the simulation and felt the system had potential as a useful educational tool for healthcare.

Medicine and Psychology

Artificial Reality also demonstrates a great potential for clinical treatment applications, aside from healthcare professional training. Salisbury et. al. [61] presents an attempt to facilitate post-stroke upper limb rehabilitation at home through VR, without requiring constant assistance from a trained professional. A therapeutic gaming system is developed to encourage task-oriented movement, and placed in a stroke survivor's home, who utilized it over several months. The patient is placed into an immersive world where therapeutic tasks generate and dynamically adapt to the user. Data analysis suggests the user showed significant improvements regarding movement smoothness by providing a "feasible, well-tolerated and engaging" experience. De Bruin et. al. [16] describe how VR can be used to enhance quality of life for the elderly, as a technique for training motor control. They state virtual, interactive environments provide the means to improve postural control, balance, orientation and stepping patterns, through dance pad games with repetitive movement. Hoffman [31] also enumerates how VR can be applied to medical treatments, as a tool for treatment of pain, wounds, phobia, PTSD, anxiety disorders and burn injuries.

Computer Aided Design

Virtual reality, in specific, can be considered a useful complement to CAD, just as proposed by Friedrich et. al. [24]. They state this design technique is a time-consuming complex task with a

[61] Available in https://developer.leapmotion.com/

steep learning curve, which can be simplified by a prototype VR system of their design, combined with a hand gesture and voice-based interface for 3D modelling. Furthermore, they reveal the hand tracking feature was "sufficiently robust and precise", in spite of occasional tracking issues occurring without an apparent motive. However, the participants were able to quickly gain insights into the interaction flow, with a flat learning curve, revealing the potential of the proposed system.

Artificial Reality Telepresence

Continuing from subsection 2.3.1, Fadzli et. al. [22] described an alternative to remote telepresence, based on VR/MR technology. They classify remote 3D telepresence in Artificial Reality as a challenge, since both users at each end of the remote collaboration need to have the same system to obtain a successful communication pipeline. Furthermore, creating a full realistic 3D representation of the human body requires a complex reconstruction method to achieve teleportation, further described in this study. This specific approach supports both MR and VR through the Project NorthStar and the Oculus Rift, respectively. Users were able to successfully cooperate remotely to complete a given urban planning task, with some degree of issues in network connection delay/stability.

Tourism and Culture

Touristic and cultural activities can also leverage and benefit from Artificial Reality. More specifically, for the purpose of motivating, persuading and drawing both tourists and locals to culturally significant sites, such as museums. Khan et. al. [37], for example use augmented reality with this objective, as an attempt to enrich the tour experience in the Taxila Museum, in Pakistan. The AR solution utilizes smartphones as means to recognize artifacts, through Deep Learning, to retrieve relevant multimedia information for the users. This system was further evaluated by relevant scales and tests, showing a significant experience and engagement enhancement over traditional tours. Yovcheva et. al. [74] further outline an overview of the usefulness and relevance of AR based applications for tourists, by providing access to location based information, enabling access to updated content, their flexibility in terms of provided media and interactive annotations integrated with map services. They also list design guidelines that can be used to improve and develop context-aware smartphone AR.

Persuasive Technology for Environmental Concerns

This technology also the potential to be used as a means to persuade its users and direct them into following desired behaviours [53] [13]. More specifically, as was demonstrated by Santos et. al. [62], AR systems can be used to raise awareness to ongoing sustainability issues, of which a significant portion of the population is still not aware of. In their study, eVision is described as an environmental scanner, aimed at combining AR with environmental data to allow users to search for pollution sources in their surroundings. eVision then allows them to virtually eliminate them, acting as a means to persuade users into pursuing eco-friendly habits, through a reward system and positive reinforcement. Similarly, Ducasse [19] explored other various AR research prototypes able to enhance environmental education in public spaces. Such prototypes ranged from 'Environmental Detectives' for ground water contaminants, 'EcoMOBILE Water Quality' for water quality and 'Mystery at the Lake' for teaching the audience about lake ecosystems.

Their study also analyzed how digital augmentations may be used to portrait different times, scales and levels of analysis of the environment. Another similar apparatus is the one described by Goldsmith et. al. [26]. SensAR is a prototype AR system on which the user can visualize environmental data, represented graphically as 3D objects. However, at the time of the study, the device had yet to be tested and evaluated by users.

2.4 Summary of the Related Work

As it can be seen in analyzing the state of the art and prior research, there are existing technologies and extensive prior work in holography, which is depicted in tables 3 and 4. However, it is possible to assess that these holographic technologies remain expensive and mostly provide a complex setup. Moreover, not all works provided are interactive, which is at the core of this manuscript. Conversely, as for the selected theme, no prior work explored the aquatic setting, therefore this manuscript will explore how to leverage interactive holography to increase marine conservation awareness, and to which extent it manages to persuade its users into pursuing more eco-friendly habits.

All of the studies previously described where considered when designing and implementing the interactive experiences proposed by this manuscript. However systems with features such as simplicity, affordability, eco-friendliness and usability where greatly emphasized, in order to comply with the project's *ethos*.

Table 3. Overview of Prior Research

Author	Project	Interactivity	Imagery	Complexity
Gotsch et al	TeleHuman2: A Cylindrical Light Field Teleconferencing System for Life-size 3D Human Telepresence	No	Realtime Video	High
Ito et al	High resolution computer-generated cylindrical hologram	No	Static Hologram	High
Dalvi et al	3D holographic projections using prism and hand gesture recognition	Yes	3D model	Low
Kim et al	Sense of the Deep	Yes	Dynamic Pepper's Ghost	Medium
Kervegant et al	Touch hologram in mid-air	Yes	Mixed Reality	Low
Leuski et al	How to talk to a hologram	Yes	Transparent Screen Projection	High
Bach et al	The hologram in my hand: How effective is interactive exploration of 3D visualizations in immersive tangible augmented reality?	Yes	Mixed Reality Compared to Flat Screen Devices	Low
Bimber et al	Combining optical holograms with interactive computer graphics	Yes	Holograms combined with 3D computer generated graphics	High
Fuhrmann et al	Developing interactive geospatial holograms for spatial decision-making	Yes	Dynamic content projected onto holograms via video projector	High
Hacket	Medical holography for basic anatomy training	No	Static Hologram	Low
Figueiredo et al	Augmented reality and holograms for the visualization of mechanical engineering parts	Only AR	Augmented Reality and Pepper's Ghost	Low
Robin et al	Holographic InfraRed Air Traffic Control	No	Dynamic Holographic Projection	High
Bala et al	Keyewai: Looking at Cooperation in a Holographic Projection Screen	Yes	Transparent Screen Projection	Low
Psaltis et al	Holographic data storage	No	N.A.	High

Table 4. Overview of Prior Research (Continuation)

Author	Project	Interactivity	Imagery	Complexity
Aslandere et.al.	A generic virtual reality flight simulator	Yes	Virtual Reality	Medium
Zhang et.al.	Head-mounted display-based intuitive virtual reality training system for the mining industry	Yes	Virtual Reality	Medium
Liang et.al.	Enhancing stroke assessment simulation experience in clinical training using augmented reality	Yes	Augmented/Mixed Reality	Low
Salisbury et.al.	At-home self-administration of an immersive virtual reality therapeutic game for post-stroke upper limb rehabilitation	Yes	Virtual Reality	Low
De Bruin et.al.	Use of virtual reality technique for the training of motor control in the elderly	Yes	Virtual Reality	Low
Hoffman	Virtual-reality therapy	Yes	Virtual Reality	Low
Friedrich et.al.	Combining gesture and voice control for mid-air manipulation of cad models in vr environments	Yes	Virtual Reality	Medium
Fadzli et.al.	3d telepresence for remote collaboration in extended reality (xr) application	Yes	Virtual/Mixed Reality	Medium
Khan et.al.	Using augmented reality and deep learning to enhance taxila museum experience	Yes	Augmented Reality	Low
Yovcheva et. al.	Smartphone augmented reality applications for tourism	Yes	Augmented Reality	Low
Santos et.al.	evision: a mobile game to improve environmental awareness	Yes	Augmented Reality	Low
Ducasse	Augmented reality for outdoor environmental education	Yes	Augmented Reality	Low
Goldsmith et.al.	Augmented reality environmental monitoring using wireless sensor network	Yes	Augmented Reality	Low

3 Methodology

This section thoroughly describes the both conducted studies, using Tangible User Interface (TUI) and Head-Mounted Display (HMD) for Holographic Reality (HR) apparatus' structure, behaviour and architecture, as well as the experimental procedure followed in order to obtain quantifiable metrics, required for the classification and evaluation of multiple parameters related to the study, such as Usability, User Experience, Emotional State and Ecological Perception, through Interactive Holography and other Artificial Reality experiences.

3.1 Baseline Prototype and Experimental Setup

This section describes, in detail, the baseline study, which will be used as a means of comparison to the posterior prototypes. This apparatus is composed by an (i) **Interactive Hologram**, a low-cost 5-sided Pepper's Ghost illusion, placed inside a (ii) **Geodesic Structure**, whose main function is to create an immersive environment with characteristics suitable for the holographic display.

3.1.1 Interactive Hologram

The holographic display itself is based on a Pepper's Ghost optical illusion [10]. A 5-sided transparent acrylic display was built, in order to match the geodesic structure's geometry, resulting in an overall more natural composition between both elements, as well as to portray one more view of the 3D object, when comparing to other Pepper's Ghost holograms, possessing 4 or less views [15,23].

The image, regardless of its source, is generated by a micro projector, directed downwards, onto 5 angled mirrors, which, in turn, reflect it back up, until it hits a white projection screen, bellow the users' eye level. The acrylic display then reflects this projection, and generates the hologram through a Pepper's Ghost illusion. The apparatus is built this way, in order to double the distance between the projector and the projection sheet, resulting in an increase of the image's scale, whilst maintaining the device as compact as possible. As for the interaction aspect, it is conducted via a tangible interface.

3.1.2 Geodesic Dome

Pepper's Ghost holography can easily by interfered by external light sources, which is why the apparatus requires a sufficiently dark environment, on which the user can successfully interact and simultaneously, be provided with an immersive, albeit slightly constrained experience. For this motive, a geodesic dome was built to house the holographic projection. Taking into consideration current environmental issues, the structure was built, in its entirety, using recycled materials, whilst meeting ease of assembly, disassembly and transportation requirements. Furthermore, the geodesic structure can also be built upon, to serve additional functions, that provide a more intimate and immersive *interaquatic* space.

The structure was based on 2V Fuller Geodesic Domes [73], resulting in a self sustaining structure without any frame or external support, and an inner space with 6m diameter and 3m height, comfortable enough to accommodate up to 5 people and the holographic display, in the center.

3.2 Experimental Protocol

The experimental protocol itself was defined in order to verify if the evaluated apparatus meets all the established requirements, through the collection of quantifiable and comparable data.

Prior to the experiment, the user is provided with a short questionnaire, to assess its current emotional state and ecological perception, as well as its demographics (gender, age, nationality) and previous experience with the baseline technology of the system under evaluation.

After the experiment, a post-study inquiry was also conducted, to evaluate a total of 4 parameters, all of which determined by the collection of data by employed a corresponding 5 point Likert scale [34], in which a score of 5 is the optimal classification, in addition to the questionnaire conducted before the experience. In this questionnaire, two parameters are repeated from the pre-study questionnaire, in order to determine if the system has a meaningful impact in those aspects.

Summarizing, the following parameters were evaluated:

A. **User Experience**
Intrinsic Motivation Inventory - Assess' participants' interest/enjoyment [71] (Post-study)
- Interest/Enjoyment (EN)
- Perceived Competence (CO)
- Effort (EF)
- Pressure/Tension (TE)
- Perceived Choice (CH)
- Relatedness (RE)
- Value/Usefulness (US)

B. **Usability - System Usability Scale - Scores the system's overall usability [44]** (Post-study)

C. **Emotional State**
Self-Assessment Manikin - Measures the users' affective reaction to the experience [8] (Pre/Post-study)
- Pleasure (P)
- Arousal (A)
- Dominance (D)

D. **Ecological Perception**
New Environmental Paradigm - Determines the environmental awareness of the subjects [29] (Pre/Post-study)
- Reality of limits to growth (GR)
- Possibility of an eco-crisis (CR)
- Rejection of exceptionalism (EX)
- Fragility of Nature (FR)
- Antianthropocentrism (AN)

4 Conducted studies

A prologue study was conducted, which describes the development and evaluation of a prototype based on interactive holography. Its purpose was to determine how the users interacted with and responded to this technology.

Then, several similar prototypes were built, following a custom Agile Development Model [67] and based on the same baseline experience. This new experience was designed taking into consideration what was learned in the prologue study. The model itself was adapted in order to suit an incremental development of systems targeted for multiple platforms, conducted by a small team. As per usual, in the early stages, the overall experience was planned and designed. The development of the first subsystem was then performed, with the particularity of the implementation being conducted by an inner development/testing loop, meaning the subsystem was developed and then tested, one mechanic/feature at a time. For each iteration of this inner loop, it was decided if the current requirement needed more time being developed, or if it could advance to next feature. Upon completion of the requirement list, the subsystem was then deployed to be tested with real users, and subsequently reviewed. After this stage, user feedback and collected data was considered, to determine if the system required improvements, on which it would reiterate into the development/test stages, or if it could be launched. Furthermore, development of the next subsystem would initiate, by returning to the design stage, where the requirements would be adjusted to fit the constraints of the new target platform. This cycle is repeated until all the planned subsystems are completed.

Furthermore, all experiences were developed through Unity Game Engine and, consequently, C# programming language. However, other development tools were also employed for the development of auxiliary systems, including Python, LoPy Dev Board and Node.JS. Pre-existing Unity packages were also leveraged, such as ARCore[62], Multiplayer HLAPI[63], XR Legacy Input Helpers[63], XR Plugin Management[63], Android Logcat and Post Processing.

[62] Quickstart guide available at https://developers.google.com/ar/develop/unity/quickstart-android
[63] May vary depending on Unity version.

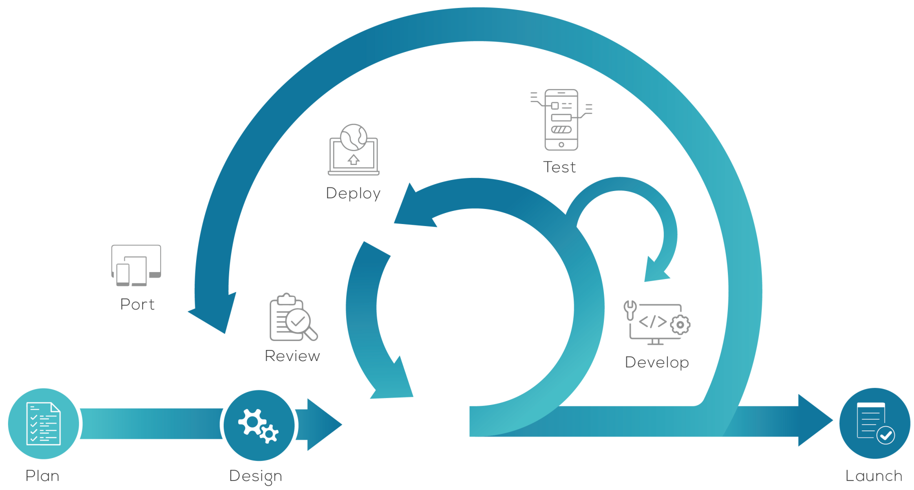

Fig. 30. Custom Agile Development Model, followed for the development of all subsystems

4.1 Study 1 - TUI Holographic Reality

Herman Melville's novel, *Moby Dick*, tells the story of Captain Ahab's quest for vengeance, to hunt the legendary white sperm whale, which ultimately ends in disaster as the protagonist is dragged to the depths by his sworn enemy. This tale can be considered an allegory warning us about human destructive behaviour, eventually becoming the cause of our own downfall. Inspired by the allegoric nature of Melville's masterpiece, this study's main objective is to raise awareness to the preservation of these marine behemoths, given their importance to the ecosystem and our planet's future, further supported by the emergence of recent evidence [11].

Great whales capture large amounts of living biomass, in order to sustain their own body mass, forcing them to adapt and develop a low metabolic rate. For this motive, these animals have become highly efficient carbon absorbers, when comparing to other smaller creatures, turning them into living vectors for the transfer of carbon and nutrients, in the world's oceans. On a global scale, whales are able to transfer these elements from their polar feeding territories to the warmer breading waters, closer to the equator, and, on a more local scale, between the surface and deep ocean waters, through the release of fecal plumes and urine, feeding, metabolization, breathing and resting in these areas [59]. This "whale pump" effect is vital to the increase of phytoplankton productivity, responsible for the production of as much as 50% of the oxygen in our atmosphere, together with the capture of an estimated 40% of the released $CO2$ [18].

This particular study describes a novel interactive experience, designed for the depiction of sperm whales and the transmission of relevant knowledge to the user, regarding their life cycle (sleeping habits [50], diet [60], echolocation and prey capture [51]). The implementation combines a standard Pepper's Ghost Hologram for the display, with a purposely built "underwater flashlight" for the interaction, and a geodesic structure, whose purpose is to create a dark enclosed environment, to further increase the hologram's quality and immersion. The holographic display itself is based on a Pepper's Ghost optical illusion [10], as was previously mentioned in section 3.1.1.

Furthermore, the structure has been designed and built taking into consideration current environmental issues, by being built, in its entirety, using recycled/recyclable materials, whilst meeting ease of assembly/disassembly and transportation requirements. It was based on 2V Fuller Geodesic Domes [73], resulting in a self sustaining structure without any frame or external support, and an inner space with 6m diameter and 3m height, comfortable enough to accommodate up to 5 people and the holographic display, in the center.

In more detail, the flashlight, nicknamed Whalelight, is responsible for the interaction between the user and the apparatus. It is a hollow container, prototyped from MDF, that stores a microcontroller. This microcontroller retrieves data from an acceleromenter sensor, which is then mapped to the displayed 3D object's orientation, giving the user a tool for the exploration in the holographic projection. The interaction begins when the user presses the switch, giving a signal to the system, to start collecting the data. This data is then forwarded via Wi-Fi, to a Node.JS server, whose main function is to re-route it to the Unity application[64]. The Unity application then filters the data, before mapping it to the whale's rotation (see figure 39)[65].

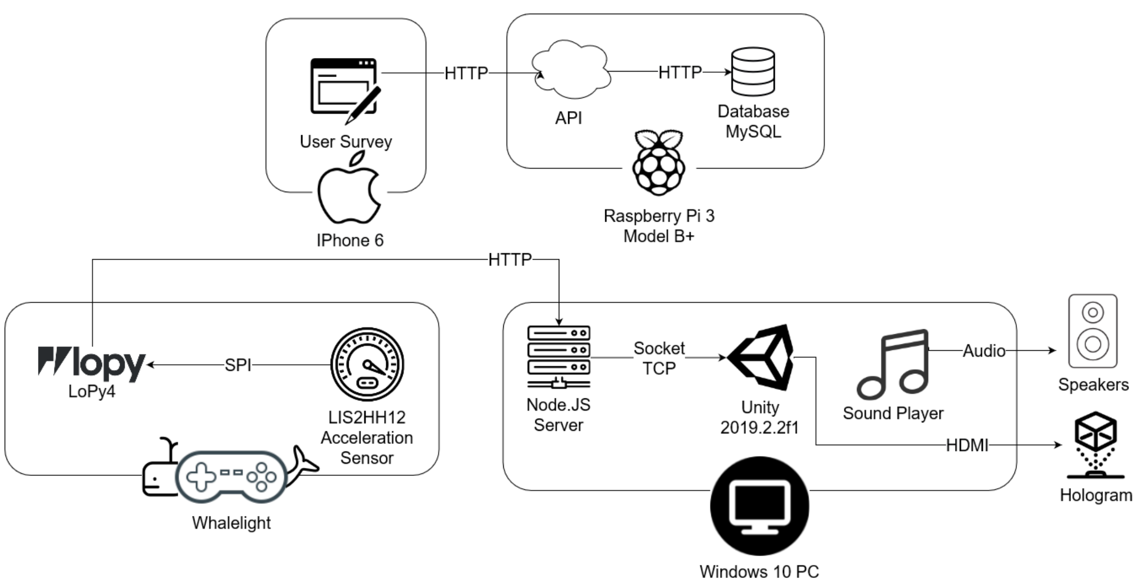

Fig. 31. System Architecture of the first study

[64]This middleware was implemented with the to increase scalability and modifiability aspects of the apparatus (ex.: Saving rotation values to database, replacing the Unity application for a similar system, etc). However, this module does incur in noticeable delays, regarding data transmission, and introduces both a bottleneck and an additional failure point.

[65]The User Survey, API, Database and Accelerometer Data Collection systems had been previously implemented by other contributors of the larger project this study is inserted into. The Node.JS server, HTTP connection between the LoPy and the server, and the Unity application were newly developed.

The experiment begins when the user is provided with the Whalelight. No mention to its function was given, with the objective of observing and reporting their natural reaction and interaction with the apparatus. The participant then enters the dark environment, and starts the experience by pressing the physical on/off switch in the Whalelight. This switch triggers the appearance of the specimen, in this case a sperm whale, in the holographic display, showcasing the animal awakening, diving, foraging and returning to sleep. The Whalelight gives the user the opportunity to inspect the whale and explore its details, allowing a 360deg view of the 3D animation[66], throughout all sides of the projection. The experience finished after two minutes, after which the participant was provided with the post-study inquiry, and their feedback was also collected.

Fig. 32. Geodesic structure used to create the required environmental features for the hologram

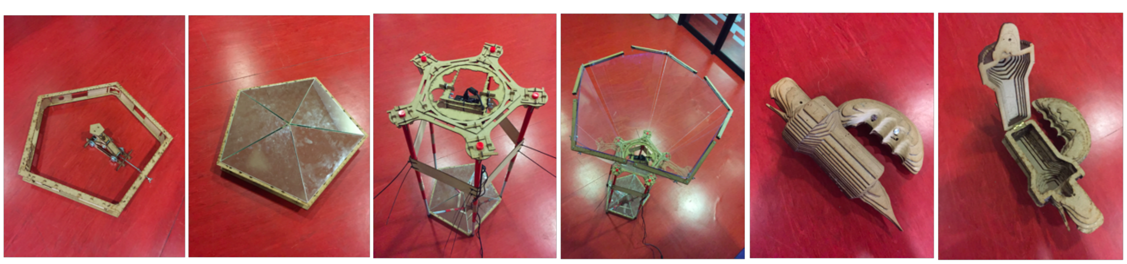

Fig. 33. Assembly of the holographic apparatus, and the Whalelight TUI device

[66]For this particular study, the user was able to change pitch and roll rotation values, and was prevented from altering yaw.

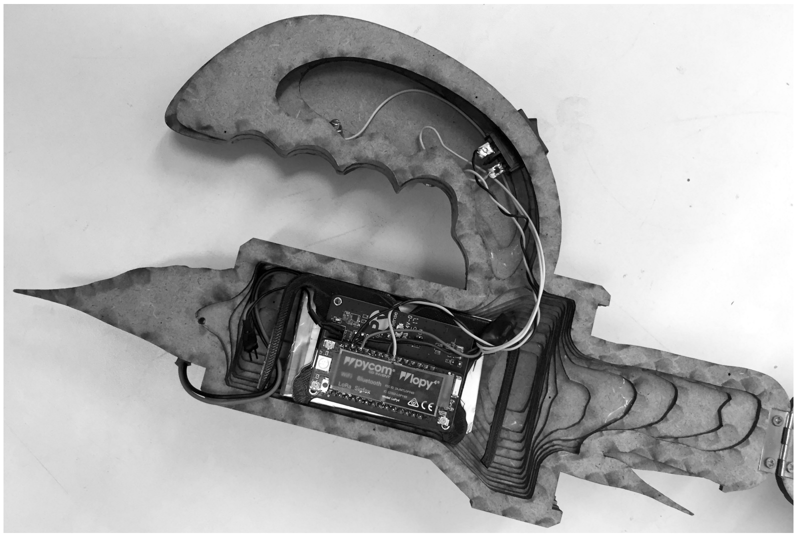

Fig. 34. TUI device, in detail

4.1.1 Research Questions

Great whales are very illusive and difficult to encounter, even during dedicated whale watching trips. Even if these creatures are successfully encountered, there is a minimum distance that should be respected, in order to not disturb the animals and maintain the safety of everyone on board of the vessel. Due to this factor, the whales are only partially visible, for a limited amount of time, which is why the developed holographic interface supports close-up interaction and manipulation of the animal, creating an experience rarely available, even in a museum context.

The main goal of this study is to raise awareness to the lifestyle and preservation of a major whale specie, and to obtain a baseline comparison for future iterations of this device. To fulfill this objective, this study attempts to explore two distinct research questions:

- **[RQ1] - Is interactive holography an effective method to raise awareness for the preservation of marine species such as great whales?**
  The low-cost geodesic dome, coupled with the Pepper's Ghost illusion is used to portray scientific facts about the sperm whales. User studies are performed using diverse scales, measuring usability, user experience, emotion and ecological perception, to obtain a quantifiable baseline study for *interaquatic* experiences, and to determine how successful the desired message was communicated. This particular research question is the adaption of the thesis' **RQ3** for this individual study, and its context.
- **[RQ2] - How do users interact with holographic information inside a geodesic dome?**
  The user's behaviour is studied, and how they interact with the holographic information. The data is displayed through a 3D animation running on Unity Game Engine, depicting a sperm whale's sleep, diet and hunting habits. Fields observations and user feedback are reported. This research questions is, therefore, related to the dissertation's **RQ1**, since it relates to a particular implementation of an interactive holographic experience.

4.1.2 Data Inquiry

The backend portion of the system uses a REST API and a MySQL database, both hosted in a Raspberry Pi 3B microcomputer, to allow the transmission of HTTP requests by any device, in order to read/write information to the database. The main function of this subsystem is to store the answers provided by the users during the pre and post-study questionnaires, and make them accessible for statistical treatment later on. The surveys were conducted through a purposefully developed mobile application. The measured scales were mentioned previously, in section 3.2. Moreover, to complement user inquiries and feedback, a researcher was always present during the experience, to monitor and report the users' behaviour. As for the context-related questionnaire, the users were asked the following questions, in this study:

1. **What depth can a sperm whale reach, in meters?**

   Possible answers were: $<$10, 10-49, 50-99, 100-1000, $>$1000. The final choice was the correct answer [72].

2. **In what position does a sperm whale sleep?**

   Possible answers were: horizontal, upwards vertical, downwards vertical, does not sleep. The second choice was correct [50].

3. **What type of sounds do sperm whales emit?**

   Possible answers were: clicks, moans, no sound. The first one was correct [51].

4.1.3 Location of Study/Sample Size

The sample size (N=20) included testers from Portugal(16), Canada(1), Italy(1), Spain(1) and Slovenia(1). 50% of the participants identified themselves as female, with a relatively young age (M=32, SD=6.52). None of the users was given any incentive for participating in the study. The study was performed indoors, at the University campus.

4.2 Study 2 - HMD Holographic Reality

Climate change is still a heavily disputed topic, in spite of the numerous evidence supporting its existence [20,17,54,12], as well as the urgent need to take action in order to prevent it. However, without demeaning this issue's importance, it has somewhat overshadowed other concerns, in terms of overall environmental literacy, more concretely regarding the pervasive pollution of marine ecosystems, and the subsequent endangerment of the species relying on those same ecosystems [64].

Fig. 35. User testing the mobile application, with the Aryzon holographic device

Fig. 36. Stereo image displayed on the screen. The Aryzon device then combines both views into a 3D effect

The objective of this study is to draw users' attention to these very same ecological concerns, by leveraging Interactive Holographic Technology. This artificial reality experience is based on an Android OS mobile application, and was implemented through Google's ARCore SDK for Unity[67]. This system was developed by leveraging AR Core's Surface Tracking feature, rather than traditional Image Augmentation. Furthermore, a stereo camera was implemented, in order to allow the user to experience both traditional AR and Holographic Reality, in the same application, however only the holographic mode is evaluated thoroughly in this study. The stereo camera should

[67] Overview and Quickstart guide available in https://developers.google.com/ar/develop/unity

be used together with a low cost holographic display, such as the Aryzon Original[68], which was also utilized in this study. Moreover, user data for the AR version was also collected, in order to obtain a means of comparison to an already existent and more mature artificial reality technology.

The experience itself depicts a cave like environment filled inside with rocks, corals, fishes and scattered marine litter, and an entangled anthropomorphic turtle outside. The experience begins in an initial Menu screen, where the users can get familiar with the project, receive statistical information regarding marine littering and entanglement, be instructed on how the GUI functions, or press Play to change to the next window. After pressing Play, the users are asked to scan the ground surface in front of them, and simply tap the screen to place the environment. However, they allowed to reset the scene and redo tracking/placement at any point during the experience, in case any error has occurred. After correct placement, the user can then switch to stereo mode, and place the smartphone into the Aryzon display, to view and interact with the application in holographic mode. If everything was performed correctly, the 3D cave will be anchored to the tracked surface, with the virtual entangled turtle standing next to it, asking the user to aid it in collecting the marine litter scattered inside the cave. The turtle itself is interactive, meaning if the user looks at it, this action will trigger a struggling animation and a painful shout.

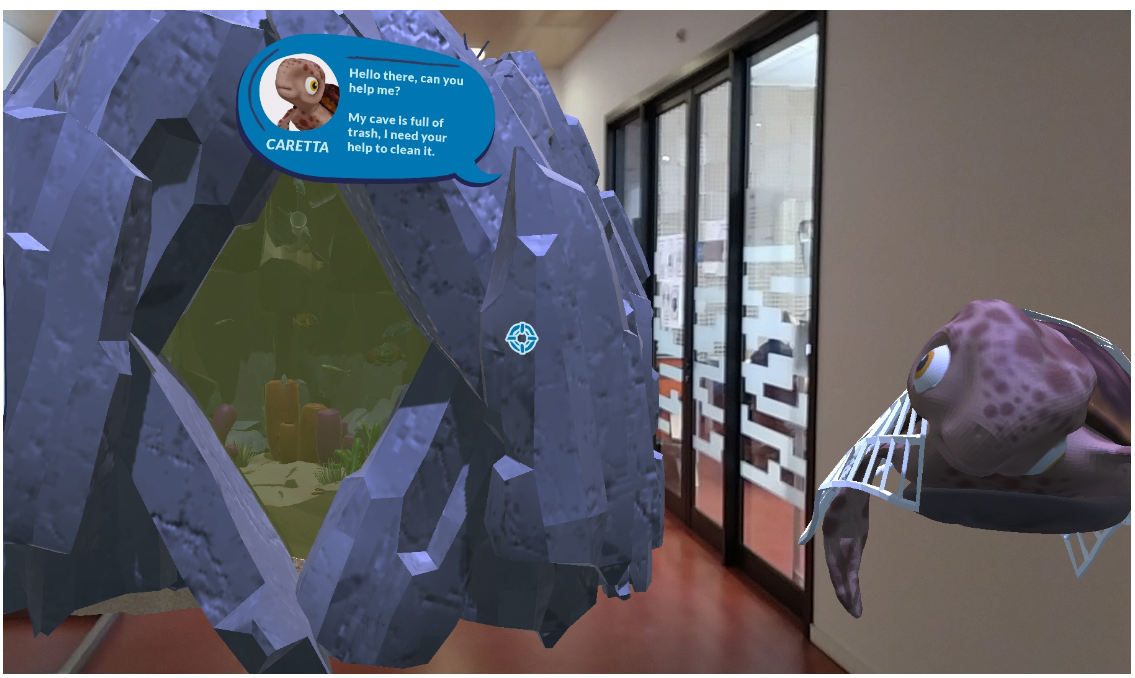

Fig. 37. User view outside the virtual cave

[68]Available in https://www.aryzon.com/

Fig. 38. Inside view of the virtual cave

Afterwards, by stepping into the cave, the users see themselves surrounded by an underwater environment filled with fauna, flora and marine litter, with two openings, the front entrance and the top water surface, allowing them to keep in contact and visualize, to some extent, the real world. Additionally, the action of stepping inside the cave triggers environmental audio (water currents, fish motion, etc...). The users may then spot the litter items (bags, plastic cups, bottles, etc...) scattered in the environment, slowly free falling towards the seabed, a bar in the GUI indicating there's 10 litter items to be collected and an aim marker in the center. By pointing this marker to any litter item, it glows red, serving as the indicator the object is in focus and being collected. When all marine litter objects are collected, a popup message invites the user to exit the virtual cave, where it is surprised by the turtle freed from the fishing net, thanking the user for making a difference. The users can then interact with the turtle once more, in the same previous manner, this time triggering a vigorous motion and an excitement/happiness sound, symbolizing the turtle greeting the user, before it swims away, terminating the experience. Furthermore, experience and user data was collected[69], and saved to a database hosted on a server, for future analysis.

[69]Collected data included experience duration, user GPS coordinates, device ID and amount of trash collected.

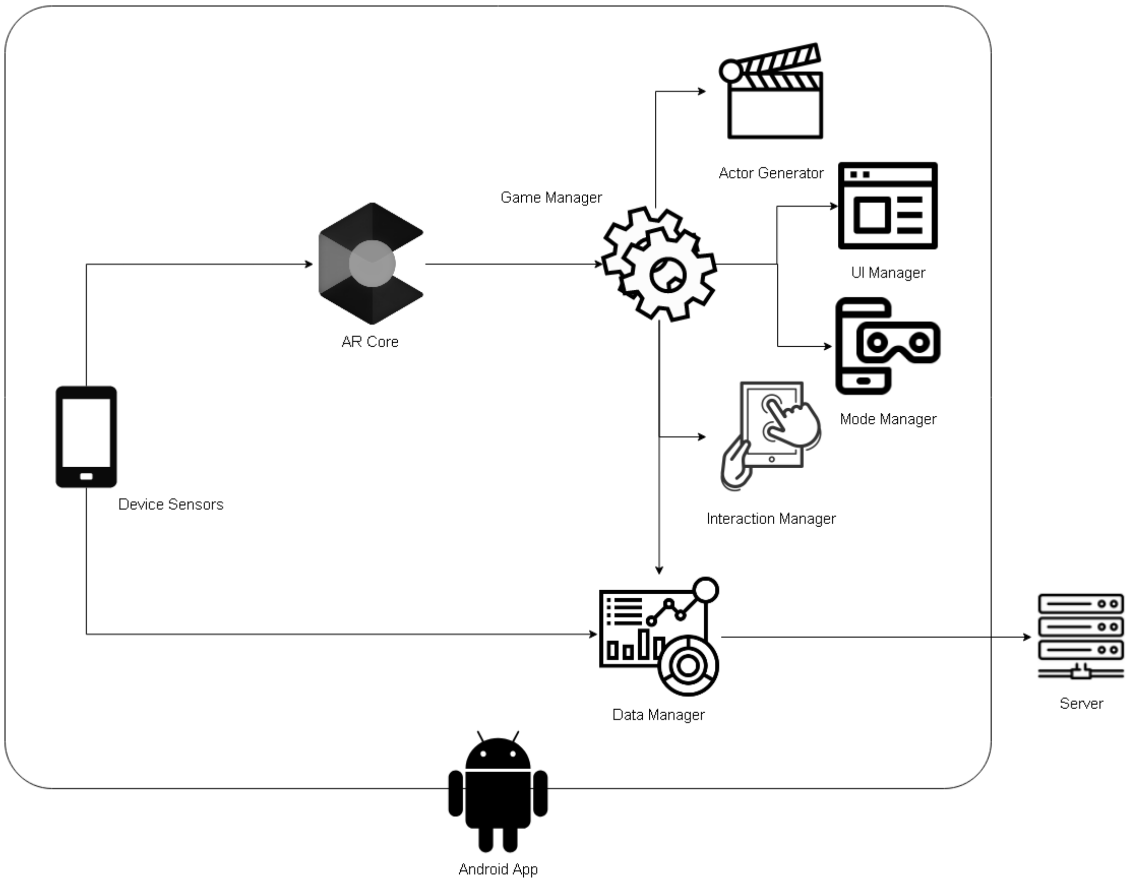

Fig. 39. System Architecture of the second study

4.2.1 Research Questions

Similarly to the prior study, this experiment focused on depicting the two main research questions:

1. **[RQ1] - Is interactive holography an effective method to raise awareness for the preservation of marine species such as sea turtles?**
   Similarly to the previous study, thesis explored the bonding with the other marine megafauna protagonists. Similar low-cost version of the apparatus is described. This research question also relates to the overall thesis' **RQ3**, because it relates to the issue of increasing ecological awareness, albeit in a more specific scope.
2. **[RQ2] - How do users interact with holographic information in a head mounted holographic display?**
   Compared to the previous study, this dissertation analyzed the perception of interactive holography with no hand held tangible user interfaces (TUI). Using the stereoscopic view in Unity Game Engine, a scene is constructed where the person enters into the underwater environment using see-through HMD. Similarly to the previous study, relates to the **RQ1** of the thesis itself, because it describes a possible solution for a low-cost interactive holographic display.

4.2.2 Data Inquiry

The conducted experiments included a pre-study questionnaire, participation in the experience, post-study questionnaire, collection of user feedback and field observations. No incentives were given throughout the study, and all participants voluntarily contributed to the experiment when they were invited to participate. Multiple methods for assessing user experience, system usability, user emotional state and environmental mindset were employed:

- **Pre-study (Baseline): Demographics, Previous Tech Experience, Emotional State and Environmental Perception** - After inviting the users to participate in the study, they were then briefed about the project and its end purpose, and given the pre-study form to be filled, where they inserted their demographic data (age, gender, nationality), prior experience with similar technologies (overall tech-savyness, AR/ARCore experience, experience with Holographic technology), and evaluate their emotional state and ecological perception, through SAM and NEP [8] [29], correspondingly.

- **Experience** - The users were given an Android smartphone with the installed application. The subjects were invited to relocate to the reference point by themselves. Furthermore, if required, they were briefed/assisted on how to follow the instructions from the app, and explore interactions with and within the virtual underwater environment, as well as the turtle protagonist, inspired by similar interactions [52]. During the experience, both field observations and imagery of the interaction between the subjects and the experience were collected. Upon completion of the experience, the subjects were also asked to share their opinions regarding their experience, which were, in turn, manually noted.

- **Post-study: Emotional State, Environmental Perception, Usability, UX and Litter Activity** - In the post-study stage, the SAM and NEP [8] [29] were collected again, in order to obtain comparisons before and after the experience, understanding whether there was any meaningful impact to emotional bonding or environmental perception, caused during the interaction. Additionally, the System Usability Scale (SUS) was used to assess the potential flaws within the application [44]. Subsequently, in order to measure their overall user experience, the Intrinsic Motivation Inventory(IMI) [71] was used to understand how immersive the experimental apparatus was. At the end of the data inquiry. Users were also asked how much virtual trash they collected, in order to determine what they experienced.

4.2.3 Location of Study/Sample Size

The sample size (N=20) was solely comprised of Portuguese testers, with 55% of them identifying themselves as male, while the remainder were female. None of the users was given any incentive for participating in the study, which was performed indoors, in the University campus, in a purposefully chosen room with a suitable dim environment. The average declared age of the participants was 28.95 (SD=5.43), and they classified their tech-savyness to be an average of 3.95 (SD=0.60). Regarding previous experience with AR, most participants had used this technology occasionally (Experience resulted in: I have never used(0), I have used once(3), I have used sometimes(14), I use on a regular basis(2), I have developed AR apps(1) and I don't know(0)), and, more specifically with AR Core, most also stated to have had occasionally experienced it (I have never used(3), I have used once(1), I have used sometimes(10), I use on a regular basis(4), I have developed AR apps through AR Core(2) and I don't know(0)). Regarding previous experience with Holography, most participants had little to no experience, resulting in: I have never used(4), I have used once(9), I have used sometimes(5), I use on a regular basis(0), I have developed AR apps(1) and I don't know(1).

5 Results

This section depicts the results of the conducted studies, obtained through the measurement scales. The results obtained for these measuring scales are included in User Experience, Usability, Emotional State, Ecological Perception parameters, furthermore, all scales measure their corresponding parameters through a Likert classification between 1 and 5, 5 being the optimal score. Every employed scale is further divided into its corresponding subscales and/or individual questions.

5.1 Study 1 - TUI Holographic Reality

This study can be seen as a prologue to future studies. Its main purpose was to evaluate and determine how the users responded and interacted with it. This subsection reports the results extracted from all the measurement scales. Furthermore, the compiled data can be visualized in figure 40. In this study, data was also collected to measure the Again-Again, AttraktDiff, Smileometer and Panksepp scales, together with the scales previously mentioned in the standard study protocol, all of which were collected solely in a post-study stage. In addition, the only data collected both in pre and post-study stages was a context-related inquiry, performed with the purpose of determining if the system could also educate the users, and increase their marine literacy.

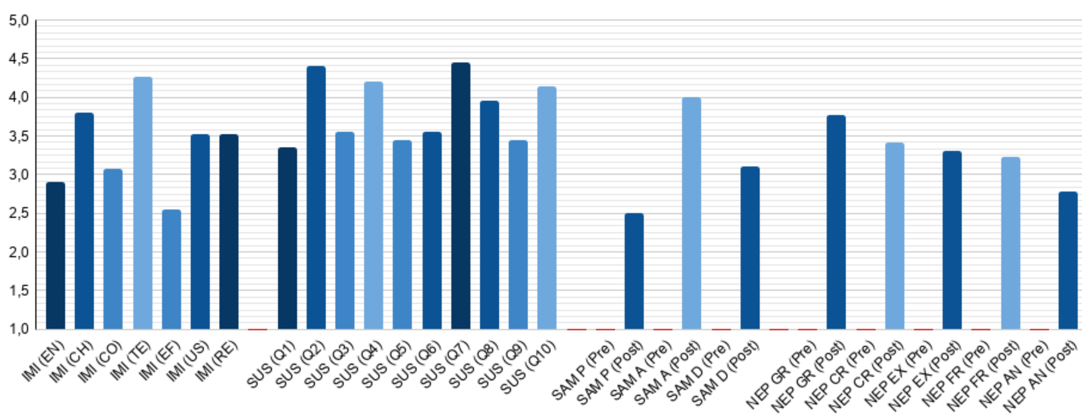

Fig. 40. System Sorted mean values of the 5 point Likert scales of the TUI, clustered into their respective measured attribute. From left to right, User Experience, Usability, Emotion and Ecological Perception.

5.1.1 User Experience

For the User Experience aspect of the system, in table 5, the concrete results are depicted, for each scale/subscale. For the IMI scale in particular, the EN subscale obtained a mean value of 2.91 (SD = 0.30), CH's mean classification was 3.81 (SD = 0.50), CO received a mean value of 3.08 (SD = 0.90), TE received an average classification of 4.27 (SD = 0.62), EF had a mean 2.55 classification (SD = 0.91), US was given an average 3.53 score (SD = 0.91) and RE was classified with an average of 3.52 (SD = 0.52). As for the Again-Again scale, the mean obtained score was 3.75 (SD = 0.91).

Table 5. Results obtained post data treatment for the User Experience scales employed in Ahab's Ghost

User Experience				
IMI			Again-Again	
Subscale	M	σ	M	σ
EN	2.91	0.30	3.75	0.91
CH	3.81	0.50		
CO	3.08	0.90		
TE	4.27	0.62		
EF	2.55	0.91		
US	3.53	0.52		
RE	3.52	0.52		

5.1.2 Usability

Regarding the classification of the system's Usability, quantifiable data was also obtained, which can be visualized in table 6. In detail, the mean obtained score for the SUS was 3.86 (SD = 0.97). As for the AttraktDiff scale, the results, again are subdivided into its subscales, whereas PQ obtained an average score of 3.40 (SD = 0.44), HQ received a mean classification of 3.75 (SD = 0.46) and GB received an average value of 2.93 (SD = 0.46).

Table 6. Results obtained post data treatment for the Usability scales employed in Ahab's Ghost

Usability				
SUS		Short AttraktDiff		
M	SD	Subscale	M	SD
3.86	0.97	PQ	3.40	0.44
		HQ	3.75	0.46
		GB	2.93	0.46

5.1.3 Emotional State

Table 7. Results obtained post data treatment for the Emotional State measurement scales employed in Ahab's Ghost

Emotional State							
Sam			Smileometer		Panksepp		
Subscale	M	SD	M	SD	Seeking	Play	Care
P	2.50	0.76	3.65	0.88	4	13	3
A	4.00	1.52					
D	3.10	1.15					

The Emotional State of the users was also evaluated, through multiple methods. One of these scales was the SAM scale, which itself possessed 3 subscales, P, obtaining an average classification of 2.50 (SD = 0.76), A obtained a mean score of 4.00 (SD = 1.52), and D received an average score of 3.10 (SD = 1.15). As for the Smileometer, the average score obtained was 3.65 (SD =

0.88). Regarding the Panksepp scale, 4 users rated the feelings induced by the apparatus with the words **Seeking**(4), **Play**(13) and **Care**(3). This data can be further visualized in table 7.

5.1.4 Ecological Perception

The users Ecological Perception was collected, through the usage of the NEP scale, with 5 distinct subscales, further detailed in table 8. GR obtained a mean score of 3.77 (SD = 0.65), CR received an average score of 3.42 (SD = 0.37), EX obtained a mean classification of 3.30 (SD = 0.72), FR obtained a mean value of 3.23 (SD = 0.53) and AN received a mean value of 2.78 (SD = 0.53).

Table 8. Results obtained post data treatment for the Ecological Perception scale employed in Ahab's Ghost

Ecological Perception		
NEP		
Subscale	M	SD
GR	3.77	0.65
CR	3.42	0.37
EX	3.30	0.72
FR	3.23	0.53
AN	2.78	0.53

5.1.5 Context-Related Questionnaire

Table 9. Results obtained post data treatment for the Context-Related Questionnaire employed in Ahab's Ghost

Context-Related Questionnaire			
Questions	**Prior Study**	**Post Study**	**Variation**
Max Depth	12	10	-2
Sleeping Habits	6	6	0
Emitted Sounds	2	4	2

Concerning the context-related questionnaire, as mentioned, the users were queried in the prior and post-study stages. In the prior stage, for the max depth question, as much as 12 correct answers were provided, 6 correct for the sleeping habits question, and 2 correct ones for the emitted sounds. As for the post stage, 10 correct answers were collected for the first question (max depth), 6 for the second question (sleeping habits) and 4 correct in the third (emitted sounds). The summarized results can be seen in table 9.

5.2 Study 2 - HMD Holographic Reality

Every participant managed to successfully complete the full evaluation process (pre-study, interactive holographic experience and post-study), including interaction with the 3D protagonist and collection of the virtual litter objects. This section describes the obtained values for every measured aspect. Summarized data can be further seen in figure 41.

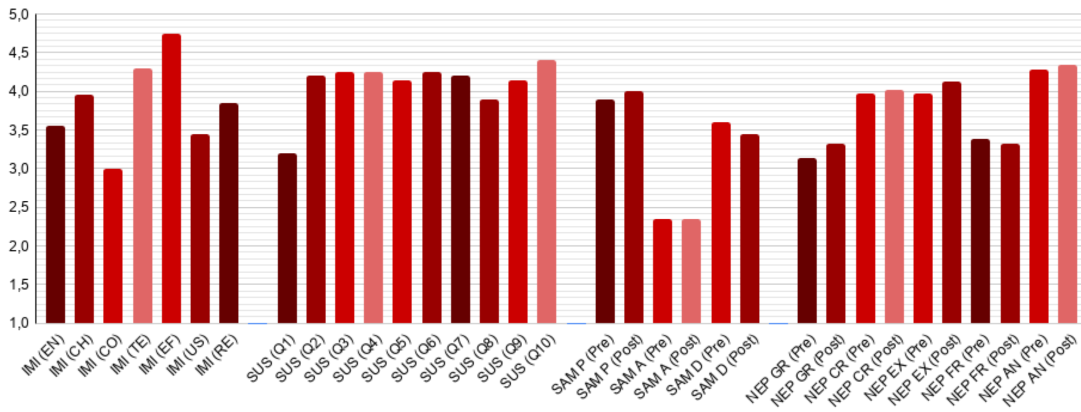

Fig. 41. System Sorted mean values of the 5 point Likert scales of the HMD, clustered into their respective measured attribute. From left to right, User Experience, Usability, Emotion and Ecological Perception.

5.2.1 User Experience

For the User Experience aspect of this system, valid results were obtained for the IMI scale, which received an average classification of 3.55 (SD=1.36) for the EN subscale, an average of 3.95 (SD=0.76) for the CH subscale, an average of 3.00 (SD=1.34) for the CO subscale, an average of 4.30 (SD=1.38) for the TE subscale, an average of 4.75 (SD=0.64) for the EF subscale, an average of 3.45 (SD=1.23) for the US subscale, and an average of 3.85 (SD=1.39) for the RE subscale. These values can also be viewed in table 10. Moreover, the total average classification for the system's User Experience parameter was 3.84/5.00 (SD=1.28).

Table 10. Results obtained for IMI scale, post-study stage

IMI		
Subscale	M	SD
EN	3.55	1.36
CH	3.95	0.76
CO	3.00	1.34
TE	4.30	1.38
EF	4.75	0.64
US	3.45	1.23
RE	3.85	1.39

5.2.2 Usability

The Usability aspect of the apparatus was also evaluated, through the SUS scale, as was previously mentioned. The detailed results for each question can also be seen in table 11. Furthermore, total average obtained score for Usability was 4.10/5.00 (SD=0.98).

Table 11. Results obtained for SUS scale, post-study stage

SUS		
Question	M	SD
Q1	3.20	1.06
Q2	4.20	1.11
Q3	4.25	0.79
Q4	4.25	0.91
Q5	4.15	0.99
Q6	4.25	0.97
Q7	4.20	0.95
Q8	3.90	0.97
Q9	4.15	0.88
Q10	4.40	0.82

5.2.3 Emotional State

Data was collected to evaluate the user Emotional State parameter, through the SAM scale. In this particular study, SAM was evaluated before and after the experience, in order to better determine to what extent it influenced the user's emotions. In the pre-study stage, the P subscale received a mean value of 3.90 (SD=0.64), the A subscale received a mean value of 2.35 (SD=1.14) and D received an average classification of 3.60 (SD=1.14). As for the post-study stage, these values became 4.00 (SD=0.73), 2.35 (SD=1.09) and 3.45 (SD=1.27), correspondingly. The detailed values are visible in table 12. This yields a total variation of +0.10 for P, 0.00 for A and -0.15 for D.

Table 12. Results obtained for SAM scale, pre and post-study stages

SAM				
Subscale	Pre		Post	
	M	SD	M	SD
P	3.90	0.64	4.00	0.73
A	2.35	1.14	2.35	1.09
D	3.60	1.14	3.45	1.27

5.2.4 Ecological Perception

Similarly to the Emotional State, NEP data was collected both before and after the experience, whose variation determines whether the system had any meaningful impact into the participants' Environmental Perception. In the pre-study stage, obtained average values were 3.13 (SD=1.28) for GR, 3.97 (SD=1.01) for CR, 3.97 (SD=0.83) for EX, 3.83 for FR (SD=1.11) and 4.28 (SD=0.76) for AN. In comparison, in the post-study stage, these changed to 3.32 (SD=1.30) for GR, 4.02 (SD=1.16) for CR, 4.13 (SD=0.93) for EX, 3.32 (SD=1.17) for FR and 4.35 (SD=0.86) for AN. Furthermore, the total average is 3.75 (SD=1.09) in the pre-study, and 3.83 (SD=1.17) in the post-study, yielding a total variation of +0.08.

Table 13. Results obtained for NEP scale, pre and post-study stages

NEP				
Subscale	Pre-Study		Post-Study	
	M	SD	M	SD
GR	3.13	1.28	3.32	1.30
CR	3.97	1.01	4.02	1.16
EX	3.97	0.82	4.13	0.93
FR	3.38	1.11	3.32	1.17
AN	4.28	0.76	4.35	0.86

5.3 Overall

A chart is show in figure 42, which displays, summarizes and allows for data comparison, from both studies. As can be seen, the HMD solution is overall, the highest scoring apparatus, demonstrating a greater difference in more specific aspects, such as IMI(EF), SUS(Q3), SUS(Q5), SUS(Q6), SUS(Q9), SAM(A), NEP(EX) and NEP(AN). A third apparatus is also displayed, which demonstrates the obtained values for the same experience as the HMD study, but in its Augmented Reality version.

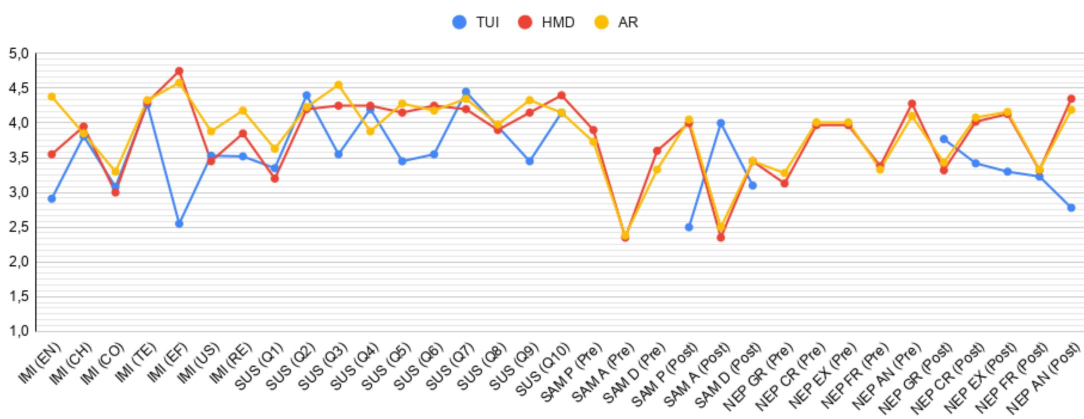

Fig. 42. System Sorted mean values of the 5 point Likert scales common to the two studies, clustered into their respective measured attribute. From left to right, User Experience, Usability, Emotion and Ecological Perception.

6 Discussion

In this section, the collected and processed data from each study is discussed and complemented by the field observations and user feedback. Furthermore, the studies' contributions are outlined, together with the experience's limitations, required future work and overall conclusions.

6.1 Study 1 - TUI Holographic Reality

Using the Tangible User Interface (TUI), this apparatus has made contributions in interactive holography for environmental awareness, outlining several key aspects on which future studies should and will be based upon. The classification of this apparatus is reported in this subsection, through the extracted and processed data, obtained from the measurement scales.

6.1.1 Result Analysis

User Experience. It is possible to ascertain from the results obtained off the IMI scale, that the developed system rated above average both in the CH and RE scores, ranking as much as 3.81/5.00, which is a good indicator to the users' motivation and overall value of the experience. However, the EF and TE subscales reveal some inherent flaws to the apparatus, concerning the effort required for the users' engagement, as well as the pressure they felt, both being aspects in need of improvement. All of the previous characteristics are supported by user feedback and other reported data, during the experiment (ex: confusion regarding the manipulation of the 3D model using the flashlight). The participants willingness to repeat the experience is also noteworthy.

Usability. The system also ranked medium to high, regarding usability, suggesting the testers managed to successfully interact with the apparatus, and achieving a meaningful experience, however, only to a certain degree, due to several constraints. The AttraktDiff measurement scale, in particular, received a medium score and, by reviewing its subscales (PQ, HQ and GB), it is possible to conclude the system has some issues in terms of simplicity and/ or structure, and lacks captivating features, despite possessing a multitude of aesthetic elements that are very appealing.

Emotional State. The SAM scale succeeded in the extraction of relevant data, concerning users' emotions. It reveals the system failed to create an exciting experience to the testers. In contrast, it also demonstrates its attractiveness, beauty and somewhat sense of control it gave them. These findings are confirmed by the Smileometer, which reveals the users also had an engaging and immersive experience, as well as the Panksepp scale, where their emotions were mostly connected to the word PLAY.

Ecological Perception. The data provided by the scales in this category demonstrate the users possess an intermediate pro-environmental attitude. The GR subscale, in particular, reveals they are aware of the existence of limits to the growth of humanity, as a specie, and, as supported by the CR subscale, they are also aware that surpassing these limits may lead to an imminent ecological catastrophe. The remaining subscales (EX, FR and AN) demonstrate the notion of human exceptionalism is, indeed, decreasing, even though both antianthropocentrism and nature's fragile balance are concepts that have yet to become major concerns. It is however, difficult to determine if the results were in any way influenced by the experience, since it was only employed in the end of the experience.

Context-Related Questionnaire. Obtained data for this questionnaire, both on pre and post-study stages, demonstrates a decrease in the knowledge related to the maximum depth sperm whales can reach (-2), a neutral variation to the perception of their sleeping habits (0) and an increase in the vocal calls perception (+2). It is then safe to assume the participants' overall knowledge about the habits and life of the displayed marine specie remained constant, suggesting the apparatus failed to successfully transmit information, through interaction with the holographic experience. Further detailing, the maximum depth question may have had a negative variation since this data was not explicitly portrayed, and the interaction with the Whalelight caused the users to lose orientation, at times. Regarding the sleeping pattern question, the correct answer value remained constant, also probably relating to the interference caused by the Whalelight in the perception of motion and position. Regarding vocal calls, since the sounds in the experience were synthesized, as opposed to real recordings, it may have been a detriment to the obtained results. In spite of this constraint, the results demonstrate a positive, albeit minimal variation.

6.1.2 Field Observations

Most testers managed to quickly comprehend how to interact with the experience, by rotating the Whalelight (90%), but 75% of the users believe a variation in the distance between themselves and the apparatus would correspond to a variation in the 3D object's scale, a feature that has not been implemented, due to hardware/sensor constraints. Some users did experience system faults, related to sudden movements in the hologram, that did to correspond to their respective input.

Furthermore, it was also noted 15% of the users attempted to use the Whalelight as an actual flashlight, and also pointing it around, inside the dome, in an attempt to uncover hidden features, before actually discovering its true functionality. This may be influenced by the high luminosity contrast between the outer/inner dome environments, causing the users' vision to be affected by this sudden change of brightness. It is also relevant to note several curious interactions that have occurred, for example, some participants attempted to place the Whalelight over the hologram, others, instead, payed more attention to the image projected onto the sheet, as opposed to the actual hologram, and, lastly, some users tried to actually touch the hologram.

The field observations also allowed to clearly perceive some frustration when the testers explored the 3D animation, caused by conflicts between the user input and the animation itself. This statement is also supported by the results obtained in the SUS and AttraktDiff scales.

6.1.3 Participant Feedback

As was previously mentioned, the participants were requested to provide some feedback regarding their overall experience, as well as its strengths and weaknesses.

35% of the users agreed the Whalelight was the source of some issues, mostly due to its bulkiness and weight, which caused it to become cumbersome to use during an extended period of time. Furthermore, this tangible interface was designed only taking into consideration right-handed individuals, but, curiously enough, the only left-handed user disagreed, and believed this subsystem was actually comfortable to use. Also supported by the field observations, some users mentioned the Whalelight afforded its usage as a standard flashlight, however in a sense that it would reveal hidden creatures within the environment on which they were immersed.

Furthermore, 50% of the testers expected zoom and translation functions to have been implemented through the tangible interface, since they were natural features that seemed to be implied. Also, and according to 45% of the users, the mapping between their input and the displayed output in the holographic projection was confusion and unnatural. This was a consequence of conflicts between their movements, the 3D animation and erratic data, obtained from inherent sensor flaws. One particular user also mentioned the existence of brightness and control differences between the multiple holographic views, as well as lack of synchronization between the sound and the whale movements. It is also worth to note two of the users desired to actually communicate with the whale through any means.

The users also complimented the beauty and the aesthetics of the apparatus, the overall system, and the combination of acoustics with the immersive environment provided by the geodesic structure. Despite these positive markers, 35% of the users had expected a bigger hologram, able to contest with the real animals. They also recommend the implementation of a more meaningful interaction, the addition of graphical elements that complement the hologram, and the gamification of the system.

6.1.4 Research Contributions

This study successfully delivers a substantial contribution to HCI, through multiple distinct aspects: **(i)**A system able to facilitate interaction between a user and an underwater virtual creature, whilst also transmitting knowledge about itself, was developed. **(ii)**As opposed to the majority of prior conducted research, the resulting apparatus can be categorized as low-cost, environmental-friendly holographic experience, which is also reusable, upcycled, fairly straightforward and available for replication by any individual, either for future research or citizen science. **(iii)**A quantifiable baseline was established from data collected by every measuring scale, and is suitable for comparison with data obtained in future studies, by any researcher.

6.1.5 Research Questions

Meaningful data was extracted from the user studies, allowing to answer the proposed Research Questions:

- **[RQ1] - Is interactive holography an effective method to raise awareness for the preservation of marine species such as great whales? -** According to the results obtained from the measurement scales, mostly relating to the NEP scale, it is possible to conclude the users have some degree of environmental concern, however, since the this scale was only measured in a post-study phase, it is not possible to measure the extent on which it influenced their mindset.
- **[RQ2] - How do users interact with holographic information inside a geodesic dome? -** The collected Field Observations, complemented by the User Feedback and the Context-Related Questionnaire, reveals how the users interacted with the apparatus, and to what extend the displayed information has been transmitted to them. They reveal the users managed to understand how to control the apparatus, as well as some inherent usability and design issues.

6.1.6 Limitations of Study and Future Work

This study provides a thorough insight on how to be built upon, in order to construct a more robust and perfected immersive *interaquatic* experience. Taking this objective into consideration, it should be mentioned the usefulness of retrieving data from emotional and environmental awareness scales, not only in the post-study, but also in the pre-study stages, to determine if the system actually motivated the users to pursue a more eco-friendly mindset.

As for the size of the displayed specimen, the apparatus' employment of low-cost materials/hardware and sustainable design became a constraint for this aspect. For instance, the pico-projector that was used possessed less capabilities than other standard, higher-cost devices, hence the need to increase the size of the projection through external means (mirrors). Nevertheless, it should be considered the usage of increasingly expensive hardware, or non-sustainable materials would go against the project's *ethos*.

The end results provide a quantifiable baseline, whose data depicts a control group to be used to classify the performance of *interaquatic* systems with similar content, regardless of their classification (Holographic, Virtual or Augmented/Mixed Reality). Additional behaviour change and persuasive computation research should be conducted to determine which type of artificial reality experience has the most significant impact in boosting environmental support, and the increase in awareness of eco-concerns.

Through sustainable design practices, this study sought to produce a system based on interactive holography or other artificial reality experiences, able to depict and provide an interaction with a large scale marine specie, otherwise inaccessible to land-based audiences. The TUI has successfully expanded the state of the art and prior work in HCI, and should be considered for future studies which employ interactive holography and/or attempt to reach a wide audience, with the end goal of increasing their marine literacy and eco-friendly habits.

6.2 Study 2 - HMD Holographic Reality

In this setting, Head-Mounted Display (HMD) was used to leverage hands-free interactions. This apparatus has further made contributions in interactive holography and HCI for environmental concerns. The classification of this apparatus is reported in this subsection, through the extracted and processed data, obtained from the measurement scales.

6.2.1 Result Analysis

User Experience. The IMI results classified the system in the mid to high tiers, a good indicator to the users' motivation and their success in achieving a meaningful experience. The system does show flaws, more specifically in the CO, TE and US subscales, meaning the users didn't feel completely comfortable and dominant, and have minor issues in taking benefit from it. On the other hand, this scale also demonstrates they felt they were pretty good at using the system, and that it was an enjoyable experience they would like to repeat.

Usability. The average SUS values determines the system the system is well classified in terms of Usability, ranking medium to high. This suggests the users managed to successfully interact with the experience, albeit suffering from some minor constraints, caused by inherent flaws in the used device, Aryzon, which is susceptible to luminosity, and may cause interference with the screen projection, and tracking issues that occurred, caused by the tracked surfaces. This aspect also demonstrates they would like to use it somewhat regularly, in the future. In terms of complexity, integration and consistency, the data reveals only minor issues, most likely caused by the previously mentioned constraint.

Emotional State. In terms of emotional impact, the A subscale had a null variation, but P reveals the users' emotional state slightly shifted from Unhappy to Happy, perhaps due to the sense of fulfilled duty the experience provides them. Similarly, the D subscale also suffered a variation, indicating a shift from an "In Control" emotional state to a feeling of being controlled, probably caused by the mentioned illumination issues which constrained their experience.

Ecological Perception. The NEP data demonstrates a minimal variation between the pre and post-study stages, meaning, overall, the system didn't manage to significantly impact the participants' environmental awareness, in any way. However, a more thorough insight into these results, demonstrates most subscales were positively influenced, apart from the FR scale.

6.2.2 Field Observations

Every user managed to reach the end and fully experience this Holographic Reality Interface, quickly discovering how to interact with the system.

Moreover, 70% of the users had issues resuming the experience after losing tracking of the 3D objects, which was caused by the above mentioned constraints. This caused some frustration, and, consequently, may have caused the scale values to become lower than the system's full potential. These same constraints also caused one user to trip in a pre-existing floor outlet, since the 3D objects and light interference caused it to become confused. It is noteworthy to mention this specific user had eyeglasses.

30% of the users had initial interaction difficulties, or some sort of issue finding the virtual trash objects. These constraints might have been caused by the implemented method for interaction and/or the display luminosity problems.

Some curious interactions also occurred, for example, two users closed one eye at a time, to perceive the different views of each eye, another user held the Aryzon device further away from its face than the other participants.

6.2.3 Participant Feedback

The participants were requested to provide some feedback regarding their overall experience, just as the TUI study.

The users enjoyed the overall experience, the system was mentioned to be "very good, easy to use and fun", "an excellent idea" and "felt very immersive".

The previous lighting constraints were brought up in this stage, since the users mentioned it made the headset hard to use, due to the difficulty in differentiating trash from other objects, and could also cause minor accidents, if the space wasn't appropriate. The experience felt immersive, but some users had troubles and experienced some confusion, mostly in the beginning. Furthermore, the "fear of disconnecting", or, in other words, lose tracking, made some users fell weary and cautious, which, as previously mentioned, may have harmed the user experience.

It was also suggested to tailor the apparatus and appeal to a younger audience, mostly children, due to the simplistic and "cartoony" nature of the experience. This specific feedback supports the obtained results for the SUS question 1, "I would like to use this system frequently."

6.2.4 Research Contributions

This apparatus successfully contributes to the fields of HCI and Interactive Holography, by: **(i)**Enabling interaction with an endangered aquatic animal, and aiding it, whilst also drawing attention to a pervasive ecological concern. **(ii)** Unlike most previous research, this study delivers a low-cost solution to a meaningful holographic experience, and, just as the TUI study, it is also reusable, recyclable, straightforward and easy to replicate.

6.2.5 Research Questions

From the data obtained off the user studies, it was, therefore, possible to extract data relevant to the proposed Research Questions:

- **[RQ1] - Is interactive holography an effective method to raise awareness for the preservation of marine species such as sea turtles?** - In accordance with the obtained results, mostly relating to the NEP scale, it is possible to conclude the apparatus had a minimal positive impact in the users' environmental concern awareness.
- **[RQ2] - How do users interact with holographic information in a head mounted holographic display?** - The Usability and User Experience scales, together with the collected Field Observations and User Feedback. These values demonstrate the users successfully managed to interact with the apparatus, as well as some minor issues with the apparatus, and environmental constraints.

6.2.6 Limitations of Study and Future Work

This study has successfully achieved its goal, of developing an interactive low-cost holographic experience, by building upon the previous baseline study's strengths and weaknesses.

However, light interference and, consequently, the requirement for a suitable environment, is a pervasive issue that plagues Pepper's Ghost like holography. As was shown, underestimating this problem as revealed itself as a common pitfall that should always be addressed for similar future studies. Alternative solutions to consider, would be to either use expensive technology that has already solved this issue, which would go against the objectives of the project, or develop a new low-cost portable/semi-portable device that creates a suitable micro-environment.

User interaction and interface are aspects that can also improve. Future work should consider other possible methods for achieving the most natural interaction possible, while keeping the number of UI elements to a minimum. Possible alternatives can be, for example, voice commands, gesture recognition or embodied interfaces.

Aside from detected weaknesses, this system has managed to expand the state of the art and prior work in the related fields of study, and should be considered for similar future studies.

6.3 Overall Comparison

Since both studies are closely related and extract data from similar sources, obtained results can be further compared and analyzed.

As can be seen in figure 42, previously mentioned in the Results section, the HMD solution, overall, scores substantially higher, when comparing with the TUI approach. In contrast, the TUI approach does surpass it in specific subscales, more specifically, in the SUS scale questions 1, 2 and 7, to how frequently they would like to use the system, its overall complexity, and how quickly the users become familiar/prominent with the experience. All these aspects may have been caused to the unfamiliar interaction that was implemented in the HMD study, since a tangible interface can enhance and make the overall experience feel more natural. Another two subscales, one from SAM and another from NEP, also surpass the HMD results. Both these measurements may be a result of the TUI study's strengths, mostly relating to the displayed content and environment immersiveness, however, this can also closely relate to the sample's emotional and ecological awareness states, prior to the experience. Also noteworthy is the steep descent in the IMI(EF), relating to how the users were willing to participate in the experience in the first place. The obtained result for this parameter cannot, however, be fully explained due to the fact it is most likely related to factors external to the experience itself.

Furthermore, the HMD study outlines similar results between the Holographic and Augmented versions. In spite of the AR version slightly surpassing in most parameters, it should be considered this branch of Artificial Reality is relatively more mature than Holography Reality, which, in comparison, is still in its infancy. Moreover, the HR version received a greater score in the evaluation of the IMI(CH), IMI(EF), SUS(Q4), SUS(Q6) and SUS(Q10) subscales, revealing user experience and usability advantages over traditional AR. Regarding user experience, these parameters determine how good the users feel they are at using the system, how willing they were to try the experience, and, in usability, the SUS subscales demonstrate if they required/would require assistance, the system's consistency and complexity.

7 Conclusion

In this dissertation, Holographic Reality (HR) is proposed as an alternative artificial reality setting, which leverages optical illusions/effects in order to bring virtual objects into the real world. Two studies were implemented using a TUI HR interface and a HMD HR interface, studying and evaluating how the audience interacts with such interfaces, with and without handheld devices. In all studies, scales were used to measure user experience, usability, emotional state and ecological perception were obtained, providing meaningful and relevant data, in order to obtain a means of comparison for all the developed systems.

Obtained findings from conducted studies indicate that the proposed concept of Holographic Reality (HR) may be considered as an artificial reality branch, that can further expand the state of the art in this field of study, as studies were performed with (TUI) and without hand-held devices (HMD) as an interface for HCI. Comparisons of these same studies indicate HMD HR to be the more immersive holographic experience, most likely due to the hands-free interaction, combined with the see-through augmented underwater environment. While case study of the proposed tool has been provided, indeed, such system advances the literature in holography, artificial realities and HCI, providing an affordable tool able to raise awareness for ongoing ecological concerns, whilst successfully delivering a meaningful interactive experience for its users.

7.1 Research Questions

In relation to the proposed RQ's, it can be concluded all three were successfully answered in the following manner:

- **[RQ1]. How to design low-cost interactive holographic experiences for an aquatic setting?**
  By drawing inspiration and building upon previous literature's strengths and weaknesses, two distinct approaches are proposed, a TUI-based and an HMD-based apparatus. It is concluded the HMD system achieved a higher classification, however both systems have their strong points, and can be further built upon and combined, possibly resulting in an even better and more immersive system, also capable of supporting interactive aquatic and non-aquatic experiences. Regarding cost, the first solution was mostly based on recycled materials, however it did require a computer and a micro-projector, which did indeed raise the price to some extent. The second solution was, by far, the most accessible, only requiring the purchase of a low cost holographic display, since the common user already has access to a smartphone that supports the Android application used in the experience.
- **[RQ2]. How does the same interactive experience compare when it's developed for Holographic Reality and other Artificial Reality branches?**
  For the HMD study, the apparatus was subdivided into two subsystems, a head-mounted holographic display and a traditional smartphone based AR application. From obtained results, in spite of being in its infancy, the HR subsystem managed to obtain an overall lower score, only by a minimal margin, even surpassing AR, an already relatively mature and available technology, in some parameters, demonstrating the cheer potential Holographic Reality possesses.

- **[RQ3]. How is such an apparatus effective in increasing awareness of current marine ecological concerns?**
  The implemented Interactive Holographic systems managed to slightly increase the users' ecological perception, according to NEP scale. However, this increase is minimal and cannot be considered significant, meaning the apparatus, and, therefore, Holographic technology, in general, need to be built upon and be allowed to mature, before any meaningful impact is observed.

7.2 Comparison with Previous Literature

In this subsection, a comparison is outlined between the state of the art research previously referred in the Related Work section, and the conducted studies.

Both studies are based on Pepper's Ghost holography, just as the solutions proposed by Dalvi et.al.[15], Kim et.al.[41] and Figueiredo et.al.[23]. This approach was chosen due to its simplicity and low-cost features, unobtainable by the solutions proposed by Gotsch et.al.[27] and Bimber et.al.[7]. In more detail, the HMD study managed to successfully produce a holographic head mounted display, at a very low-cost, in comparison to the study's performed by Kervegant et.al.[36], Bach et.al.[3] and Fadzli et.al.[22], all of which utilize an expensive approach, based on Hololens or similar devices, or even Gotsch et.al.'s[27] highly complex TeleHuman apparatus.

The developed interaction method for the TUI study was derived from the apparatus proposed by Bala et.al.[4], supported by a traditional game controller. The TUI device, however, was a customized controller, with only one button and an incorporated accelerometer sensor, to facilitate its embodiment and seem more intuitive to the user. As for the HMD study, its rationale followed a hands-free philosophy, similarly to Kervegant et.al.[36], Bach et.al.[3] and Furhmann et.al.[25], in spite of pursuing a different method to these approaches.

The proposed systems serve an educational purpose, similarly to Hacket[28] and Figueiredo et.al.[23]. This purpose, however, isn't served in a classroom/university context, instead offering a means to appeal to a greater audience and raising awareness to environmental concerns, just as the augmented reality solutions developed by Santos et.al.[62], Ducasse[19] and Goldsmith et.al.[26].

7.3 Limitations and Future Work

This section outlines the implemented systems limitations and future work, required in order to properly advance the conducted research and the outlined contributions that were provided.

As was previously stated in both studies, the requirement for a suitable environment greatly influences the quality of Pepper's Ghost like holographic experiences, and the subsequent obtained results for their evaluation. This is a common pitfall, which was successfully addressed in the TUI study, through the construction of the geodesic structure, however this does also pose a limitation, since the common user won't always have access to such a structure or an alternate low-light environment. In an attempt to resolve this constraint, an HMD portable holographic display was employed in the second study, however the light interference issue remained prevalent and was only partly solved, probably causing a decrease in regards to its potential score in the measured parameters. In contrast, this inherent flaw can be overcome by encasing the holographic display in a case, creating a dark micro-environment, or employing non-Pepper's Ghost solutions such as

Hololens, rotating LED fans or other systems, previously described in the Related Work section. Despite their advantages, these solutions also pose their own problems, such as lack of portability for the holographic case, high-cost for Hololens, and an additional layer of complexity required for the synchronization of the rotational motion with LED output, in the case of LED fans.

Regarding the method for interaction, other approaches should also be considered, without disregarding the strengths of the methods outlined in this manuscript. The TUI approach, by retrieving and processing data from an accelerometer sensor, revealed itself to be intuitive to the users, however its weight and bulkiness constrained proper wrist motion and, according to the participants, felt unnatural. In the HMD study, an attempt was made to turn the interaction hands free, by pointing your head, in an effort to resolve this. In contrast, and according to the users feedback, this fixed the bulkiness issue, but aggravated the naturalness of the interaction. This would, of course, be reliant on which solution is implemented to obtain the holographic effect, but possible alternatives include voice commands, gesture recognition or other embodied alternatives. Furthermore, as is prevalent in VR applications, the amount of GUI elements should either kept to a minimum, ideally, be non-existent, or blend in with the virtual elements.

In order to complement this manuscript, and other previous literature, whilst also advancing the state of the art even more, future studies should also port and adapt the HMD experience to other artificial reality settings, more specifically VR and MR, to further determine how this new concept stands in regards to its counterparts. The measured parameters should also be the same, to obtain a quantifiable and reliable means of comparison between all systems. This comparison can also be performed through other experiences, with added focus to replay-ability, which also appeal more to and impact the users' emotional state.

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