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Review

The Usage of Virtual and Augmented Reality in Underwater Archeology

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Featured Application: Improvement in VR/AR solutions for application in cultural heritage.

Abstract: Currently, virtual and augmented reality (VR and AR) technologies are becoming more and more widely used in various fields of human activity, including archeology. The aim of this article is to analyze the possibilities of using VR and AR technologies in broadly understood activities related to underwater archeology. This work is a review and presents current applications of VR and AR in underwater archeology based on case studies. This paper presents the development of VR and AR technologies, including in the field of underwater archaeology, and generally describes the process of creating VR and AR applications for underwater archeology purposes, with particular emphasis on data collection methods. Then, the areas of application of these technologies in underwater archeology and related areas were generally presented and the barriers to their use were discussed. The most important part of the work is a discussion of the use of VR and AR in underwater archeology based on the selected case studies. The article ends with a summary of the current state and a discussion of the possibilities of developing virtual technologies in the applications of underwater archeology.

Keywords: virtual reality; augmented reality; underwater archeology

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1. Introduction

Underwater cultural heritage is an immeasurable historical and archaeological resource, with many diverse archaeological sites, such as sunken cities, shipwrecks, prehistoric sunken landscapes, sacrificial sites, and the remains of ancient fishing installations and ports, scattered around the world. Underwater archeology includes the study of sites that come from different periods and are located in various locations, including those not only in seas and oceans, but also in lakes, rivers, and swampy areas [1–3]. Specialists in the field of underwater archeology indicate that there is much more heritage underwater today than it might seem [4,5]. However, this heritage is often underestimated and destroyed, both by the activities of nature—strong currents, biodegradation, such as borers' activity, etc., as well as through human activities, for example, deep-water trawling or treasure hunting [4,6,7].

Underwater cultural heritage is also usually less accessible to the average citizen than archaeological sites located on land. Access to these sites is difficult due to a number of restrictions imposed by the underwater environment or legal framework [4,8]. For this reason, the potential of underwater cultural heritage, in particular in relation to maritime and coastal tourism, is only considered to be exploited to a very small degree [9]. Therefore, in the case of this field of science, it is particularly important to develop technologies and tools that will, on the one hand, allow the preservation of sites for future research purposes, while making them available to the widest possible group of specialists, and, on the other hand, they will make it possible to make the results of work available in an attractive way to a wide audience [4,6]. Virtual and augmented reality (VR and AR) technologies can help in achieving these tasks and can contribute to increasing the exploitation of underwater archaeological sites, in a way that is both sustainable and accessible to large-scale tourism [9,10].

Broadly speaking, VR technology can be defined as a fully artificial environment (usually a simulation of physical reality) in which a person can freely look around (and even move) and establish various types of interactions with it or have the ability to interact with it [11–13]. The definition of this concept is important due to the fact that in the field of archeology, it is very often used to represent almost anything that contains 3D visualisations [14,15]. In turn, the term AR means an environment in which computer-generated elements are artificially superimposed on the real image [12,16]. It is worth noting, taking into account the development of current technologies, that specialists in the field distinguish more forms than just VR and AR. In the literature, it is possible to encounter other concepts, such as augmented virtuality (AV) or mixed reality (MR), in which virtual reality is enriched with elements from the real world [17,18]. However, for the purposes of this article, only two basic concepts will be used—VR and AR—due to the lack of a clear dividing line between AR and MR [18].

The thesis of this work is the statement that VR and AR technologies can provide significant support for underwater archeology activities, both at the research and educational levels, and are a useful tool in popularizing the topic of underwater research. The idea behind the use of these technologies is to offer both archaeologists and the wider public a new perspective on reconstructed archaeological sites, which enables archaeologists to analyze material obtained directly from the reconstructed site—a virtual site, and at the same time allows the wider public to "immerse" themselves in a realistic exploration of selected archaeological sites. These technologies are particularly useful in hard-to-reach places, such as the deep sea, where time and skills play a significant role in reaching a given object. The literature review also shows a small amount of research in the area of usage of VR and AR in underwater applications; in particular, there is a lack of reviews in this area. This article's ambition is to fill this gap. The aim of this article is to analyze the possibilities of using VR and AR in broadly understood activities related to underwater archaeology. This work is a review and presents the current applications of VR and AR in underwater archeology, based on case studies. The research issues undertaken were based on a review of the world literature and Internet sources. Due to the subject matter, this work concerns activities that are carried out all over the world and are related to various archaeological periods. This article presents the development of VR and AR technologies, in the field of underwater archaeology; the process of creating VR or AR reality applications for underwater archeology is generally described, with particular emphasis on the data collection methods. Then, the use of these technologies in underwater archeology and related areas is presented in general and the barriers to their use are discussed. The most important part of this work is a discussion of the applications of VR and AR in underwater archeology, based on selected case studies. The work ends with a summary of the current state and shows the possibilities of developing virtual technologies in the applications of underwater archeology.

2. Methodology

The main research method used in this article is a critical analysis of the literature sources by review. This critical review evaluates the possibilities and problems in the usage of VR and AR technologies in underwater archeology. It is focused on the content of the presented works. It not only describes and analyzes the existing works, but also shows some common points and their importance in the wider context.

The review was designed around a defined literature base. The starting point for the search was the Scopus literature database, where a combination of the keywords "underwater archeology" with the terms "virtual reality" or "augmented reality" was used. The search phrase: "((TITLE-ABS-KEY (archaeology)) AND (underwater)) AND ((vr) OR (ar))" allowed for obtaining about 120 items connected with the current literature (search results), mainly chapters in monographs and scientific articles. All of them were analyzed, in the first step, and about 80% were involved in the final publication. There are relatively few studies on the applications of VR and AR in underwater archeology. Further analysis of the material showed that most of these items are case studies for individual projects. There are no reviews or summaries of the current state of knowledge on this topic. The search showed a significant increase in publications on the subject of the query after 2014; this is related to the popularization of VR technology. The dominant countries from which the authors of the publications came were the United States and Italy. A large number of publications from Italy were related to numerous projects involving the use of VR and AR in underwater archeology, carried out with the participation of this country.

Not all articles indicated by the Scopus database turned out to be useful for the purposes of this work. However, they constituted the basis for further analysis and finding information on activities carried out in this area. In the second step, the Google Scholar database was also used for analysis and the database of projects co-financed by the European Union—CORDIS. Due to its specificity, the article also refers to numerous online sources, which contain information about projects related to the development of VR/AR and its applications, including in the field of underwater archaeology. This part was necessary for the proper analysis of the presented case studies based on primary sources published directly by authors of particular software. In some cases, the authors also downloaded and tested VR/AR applications to form their own opinion; this was possible for the current project.

3. Virtual and Augmented Reality Technologies

3.1. Development of Technology, Including Underwater Archeology

The invention of stereoscopic devices by Sir Charles Wheatstone in 1838 can be considered the first step in the development of VR and its accompanying devices [19,20]. These devices were the prototype of today's 3D goggles. They created depth in the presented image through a pair of mirrors positioned at a 45-degree angle to the user's eyes. Since these devices were created before photography, they used drawings [20]. The next step in technological development was the first flight simulator called "Link trainer" (also described as "Blue Box" and "Pilot Trainer"). This simulator was built in 1929 by Edwin Albert Link at Link Aviation Devices [19]. The system was the world's first commercially built flight simulator and was used to train pilots during World War II [20].

The concept of modern VR emerged almost 100 years later. It was first described in a science fiction story called "Pygmalion's Spectacles" in 1935. In this story, Stanley G. Weinbaum describes a device equipped with lenses and a cable that transports the user to another dimension [20].

An important person in the development of VR and AR was Morton Heilig. In 1952, he published a short article entitled "Experience Theater", where he presented the concept of a VR machine. Along with the article, he began work on creating a prototype of the device [19,21]. The effects of this work were two inventions, important from the point of view of the development of VR technology. The first of them is the "Telesphere" mask with a headset, developed in 1960. It provided a wide-vision image with stereoscopic 3D and stereo sound through the earbuds. This mask was also the first head-mounted display. The second project is "Sensorama", patented in 1962. The device was a combination of a 3D screen, stereo speakers, scents, vibrations, and atmospheric effects such as wind. It was intended to engage all the viewer's senses during the projection of the image. The creator considered "Sensorama" to be "the future of cinema", but the device was not widely used due to its high cost [16,22].

At the same time, i.e., in 1961, Comeau and Bryan, two engineers from Philco Corporation, developed the so-called head-mounted display technology—HMD (from helmet-mounted display or head-mounted display). The device, called "Headsight", was equipped not only with depth-of-view solutions, but also with a magnetic tracking device that allowed the remote camera to be moved, which in turn gave the user the ability to look around the environment without physically being there [23,24].

Another important date for the development of VR and AR is 1965, in which a new prototype of a virtual helmet was developed by Ivan Sutherland, a professor at Harvard University [16,22]. Work on this topic continued, resulting in a device developed by Ivan Sutherland in cooperation with his student Bob Sproul called the "Sword of Damocles". Many people consider this invention to be the first AR and VR equipment. Compared to the previous model, it included additional features such as graphics generation and computer integration [18,20]. The main barrier to the wider application of this invention was the excessive weight of the device [22].

In the 1970s, a noteworthy system was developed by MIT in 1978, a virtual map of the city of Aspen— the "Aspen Movie Map". The system used photos taken from a car in Aspen, Colorado, which were used to simulate driving on the streets in one of three modes: summer, winter, and polygons, from a first-person perspective. The system can be considered a prototype for Google's later VR application "Street View" [23,24].

In the 1980s, new possibilities for using VR and AR appeared. Aviation-related projects are worth mentioning, as well as astronautics. In 1981, NASA's "Virtual Interface Environment Workstation" (VIEW) project began. The project concerned the creation of an inexpensive pilot training system for manned space missions. It was to combine computer graphics and video imaging, 3D sound, voice recognition and synthesis, and a HMD display. The project significantly improved VR technology [20].

It is also worth mentioning that in the 1980s, considerations began on the digitization of cultural goods, including archaeological resources, and the creation of the so-called digital cultural goods [14]. The consequence of this was subsequent experiments with 3D modeling techniques in archeology, in terms of the possibility of using this visualization technology to study ancient sites [15,25] and tools for presenting various types of data for effective communication of the obtained research results [12,15]. These were primarily the first "virtual reconstructions" in the 1990s—interactive three-dimensional computer visualizations that provide the viewer with freedom of movement and navigation from a first-person perspective [15]. The topic was continued with a "discussion" on "virtual museums" and the potential of using them to attractively convey underwater archeology discoveries, which has appeared in the specialist literature since 1998 [26].

During this period, probably in 1987, the term "virtual reality" was also invented and popularized. Jaron Lanier, the founder of VPL Research, is considered its creator [20,24]. It is worth noting, however, that during the same period, the term also began to be used by Tom Caudell and David Mizell, workers at Boeing on systems that were used to train pilots [27].

The year 1991 was important for the popularization of VR technology. This year, the so-called "Virtuality Group" created slot machines with AR sets and a multiplayer game called "Virtuality 1000" [28]. In the same year, SEGA's first mass-produced VR system appeared. It consisted of both a set of goggles and a set of gloves. However, it was not widely disseminated due to the high cost of the kit [19,28]. Continuation of work on this topic allowed the presentation of a prototype of an improved system in 1993 at the "Consumer Electronics Show" called SEGA VR. The improved prototype of the VR device had wrap-around goggles (allowing free viewing in different directions), a head-tracking system, stereo sound, and LCD screens [19,20]. In 1994, SEGA released a motion simulator arcade game with 3D polygonal graphics in stereoscopic 3D—"SEGA VR-1". In response to the ongoing technological development in the area of virtual technologies, Nintendo released a handheld console for 3D video games in 1995 called "Virtual Boy" [20,24]. In 1997, VR also found applications outside the entertainment industry. Scientists from Georgia Tech and Emory University joined forces to create an application called "Virtual Vietnam", an application that used VR to simulate war zones to help treat veterans suffering from post-traumatic stress disorder after the Vietnam War [19,24].

Since 1992, next to the term "virtual reality", the term "augmented reality" has been used, and these two types of activities have been distinguished [29]. Thomas P. Caudell is considered the creator of the term AR, who described a set that could be used by Boeing factory employees for training purposes—to visualize production instructions [18,28]. While VR was developed during this period mainly for entertainment purposes—computer games, for example—AR began to have a practical dimension. An example is an application developed in 1992 by Louis Rosenberg called "Virtual Fixtures", which was intended to increase the efficiency of air force operators in remote locations [18,28]. Another practical application of AR was the "KARMA" system developed in 1993 by Steve Feiner and a team of Columbia University students. This system was used to convey instructions on repair and maintenance procedures [18].

In 1996, "CyberCode", the first AR system using 2D markers, was created. It is a prototype for future tag-based systems. In 1998, engineer Stan Honey and his Sportvision team developed the so-called yellow line technique, demonstrated during sports competitions. The full development of markup technology occurred in 1999, when Hirokazu Kato of the Nara Institute of Science and Technology developed the first cross-platform library based on open-source computer code called "ARToolKit". It enables the recognition of square markers in real time, which makes it possible to track the user's point of view [18,30]. A year later, the first AR game—"ARQuake"—was released. It was created by Bruce Thomas of the Wearable Computer Lab and was an extension of the popular computer game "Quake".

From the point of view of the use of VR and AR in underwater archeology, it is worth noting that in 1997 the premiere of the game "Treasures of the Deep" on the Play Station took place. It was focused on plot, and the depiction of wrecks and other underwater places (not necessarily of an archaeological nature) was not very realistic. However, this game was the first step in using VR for educational and entertainment purposes [31].

At the beginning of the 21st century, as the performance of personal computers increases, the development of VR and AR also accelerates significantly. New areas involving their application are also emerging, while the general public's interest in these technologies is growing. Among the more important events during this period, it is worth noting the presentation of the first hand-held AR system on a "personal digital assistant". This system was developed in 2003 by Wagner and Schmalstieg and over the following few years, it led to the development of VR on smart devices [24,28]. During this time, programming languages were also developed. The beginnings of the VRML (Virtual Reality Modeling Language), currently one of the most popular languages for describing VR, date back to 2004 [32]. The purpose of this language was to enable the enrichment of the website with elements of VR using predefined 3D elements that enable the rapid creation of interactive content [32]. Another important event was the development of the "Street View" system by Google and Immersive Media in 2007. Initially, the technology only allowed users to view five mapped cities, but it was consistently developed. Three years later, stereoscopic 3D was introduced to "Street View" [24].

In underwater archaeology, the beginning of the 21st century was associated with the improvement in data collection technologies and the development of 3D modeling methods, including methods for examining various marine sites and artifacts. An example of the activities carried out during this period is the use of the "FaroArm 3D" digitizer to research the wood of the Viking ship Roskilde I, excavated in the port of Roskilde in Denmark, or the use of multi-beam sonars to create accurate bathymetric maps and 3D terrain models, including the visualization of wrecks by Woods Hole Oceano graphic Institution in Woods Hole, MA, USA [15].

Since 2009, there has been a paradigm shift in archeology, from recording techniques and interpretation of 2D images, to 3D images and records, which is particularly visible in the scientific publications on underwater archeology [33]. During this period, more advanced projects in underwater archeology also appeared, including the VENUS project [15,34], which will be discussed in detail later in this article.

The year 2010 is considered a breakthrough for the development of HMD equipment. It was then that Palmer Luckey designed a prototype of lightweight goggles— the "Oculus Rift", with a 90° field of view. The prototype was used in later years to prepare subsequent versions of the goggles and bring them to market [20,24]. In 2011, we saw the first ad in AR. It was an advertisement in the form of a game, created by Blippar for the Cadbury chocolate brand. In 2013, there was another progression in VR—Valve Corporation developed a way to display content in VR without delays. A year later, the previously mentioned company Blippar created a new platform that allowed programmers to create games using image-tracking technology implemented by the user's eye movement [24,35]. At the same time, Sony developed a new PS4 game console, where it introduced elements of VR, and Google released the so-called "Google Cardboard"—a cheap version of a VR headset. In response to the dynamic market development, in 2015 Samsung released a set that is compatible only with Samsung smartphones, called "Samsung Gear VR", and in 2016, HTC released advanced "VIVE VR" goggles [24,28]. In 2016, we also saw the premiere of the game "Pokémon Go", published by Niantic. The popularity that the game gained was important in terms of increasing the use of AR [36].

During this period, the market development was very dynamic, as well as the development of applications of VR and AR in underwater archaeology. In 2014, full-scale underwater archeology projects began to be implemented using VR and AR. These were primarily the VISAS and iMARECULTURE projects, where underwater tablets with AR functions were used for the first time [9,37].

Various types of games based on VR, i.e., "Ocean Rift", developed in 2014–2019, also contributed to popularizing the topic of underwater archeology. The game was developed by a team from Bangor University, and one of the game's elements is a virtual dive into the Zenobia wreck [31]. It should be noted, however, that apart from popularizing the topic, the game does not contribute much to the development of underwater archeology in terms of science or education, due to the fact that it is not based on thorough archaeological research [31].

In terms of technology development, in the context of potential applications in underwater archaeology, and in particular in education in the field of underwater work, the "Amphibian" project launched in 2016 is also worth a brief mention. It is a 3D scuba diving simulator using a motion platform [38]. Full "immersion" in VR is provided to users by a platform on which they lie on their torso with their arms and legs placed on a suspended harness, which is intended to provide a movement experience similar to that of a real dive. VR equipment, in the form of "Oculus Rift" goggles, provides them with appropriate visual and auditory experiences. Additionally, the device also simulates buoyancy, drag, and temperature changes through various sensors [38,39].

Following the development of VR and AR and their application in underwater archeology (Figure 1), one can notice the relatively early use of modern technologies in this field.

Nowadays, VR and AR technologies are still used in underwater archeology for both research purposes and the popularization of underwater cultural heritage. They are also being used more and more often in education at all its levels [40,41].

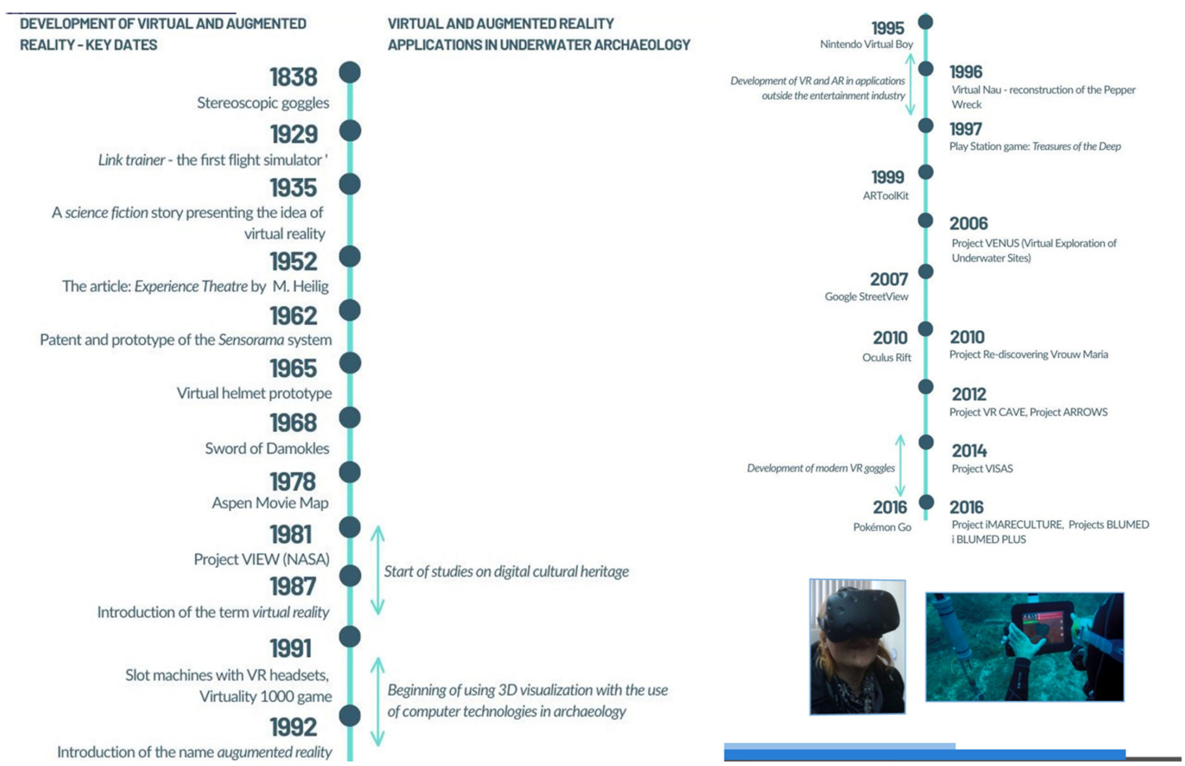


Figure 1. The history of the development of VR/AR and their application in underwater archaeology.

3.2. Creating Virtual or Augmented Reality Applications for Underwater Archeology

The process of creating applications in the field of underwater archeology, unlike other applications, is based on specific methods of collecting scientific data using methods specific to underwater research. Creating an application consists of many tasks. Generally, the entire process can be divided into three stages (Figure 2). These are the following:

1. Collecting information about an object, where an object will be both a single artifact, e.g., a shipwreck, and the entire archaeological site from which we will process data in order to obtain a 3D visualization. Additionally, at this stage, additional information should be defined, i.e., the group of recipients that may influence the technologies used.
2. Processing the data into a three-dimensional reconstruction of an archaeological site and/or set of artifacts. Objects can be described using a set of points in three-dimensional space, a map of normal vectors describing the object, as well as a map of surface gradients obtained in the shape reconstruction process. The third technique has the widest application [32].
3. Preparing an appropriate form of information transfer using AR or VR, e.g., in the form of an application containing elements of AR.

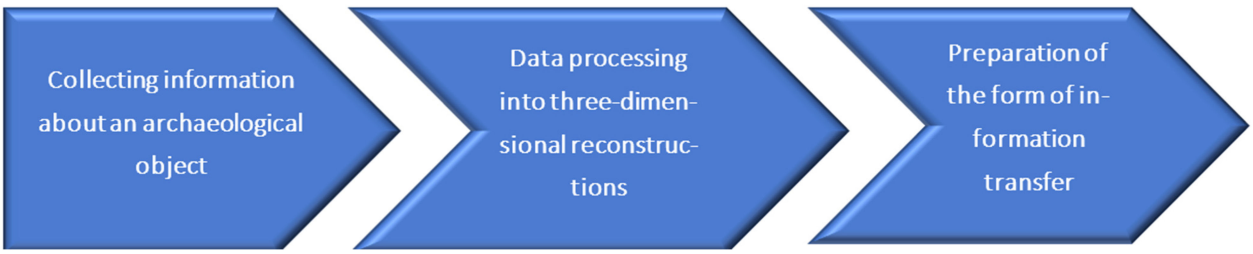


Figure 2. Diagram of the process of creating virtual and augmented reality applications.

The first stage is usually collecting information about the facility, which most often begins with obtaining general information, followed by collecting detailed data and carrying out measurements. The first data point about the archaeological sites may come both from regular surveys and from reports by amateur divers or local people [26]. After confirming the reliability of the information, preliminary research is usually carried out at a given site in order to confirm the credibility of the reports and confirm the archaeological character of the site. Only then are fundamental works planned to collect information about the archaeological site and document it. Broadly speaking, the methods used at this stage can be divided into two groups—visual methods and acoustic (hydroacoustic) methods. Additionally, in this division, we can distinguish a third group of other methods that do not fit into any of the above groups (Figure 3).

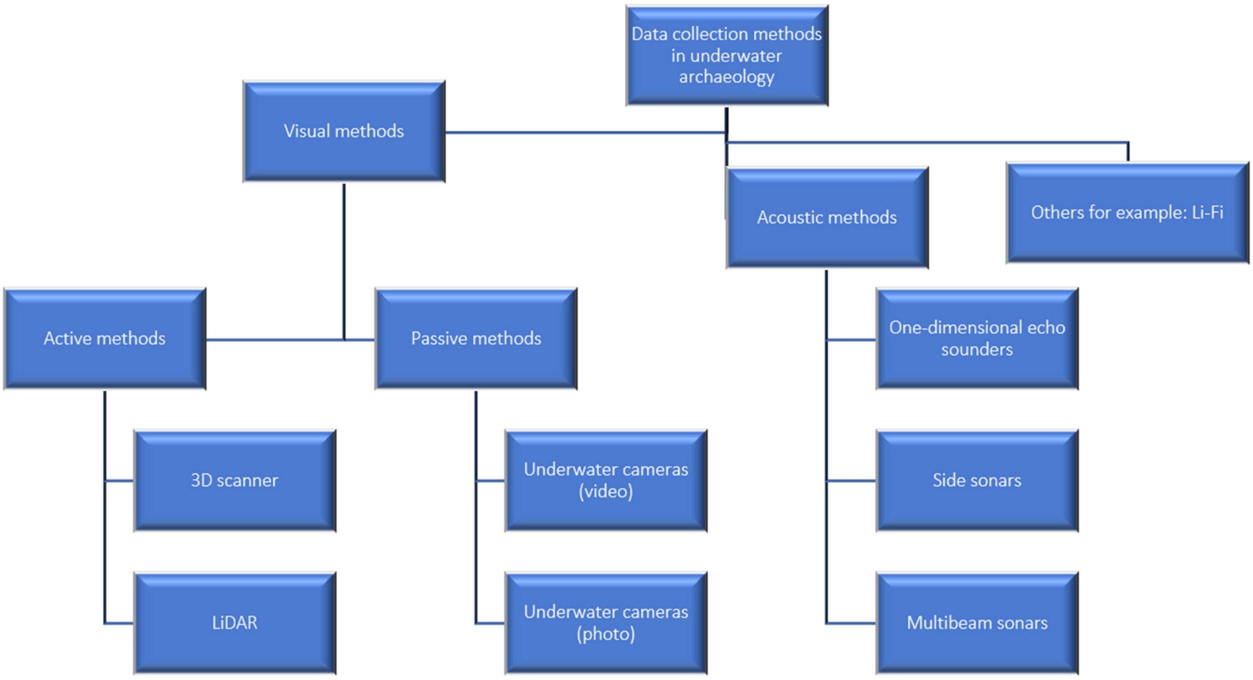


Figure 3. The general division of data collection methods in underwater archeology.

Methods based on acoustics include the following: one-beam echosounders, side-scan sonars, and multi-beam sonars [32]. Among hydroacoustic methods, side sonars and multi-beam probes are most often used for the accurate reconstruction of archaeological sites due to the fact that they allow for observing of the bottom of the site with high resolution and for obtaining image quality similar to photography [32]. In the case of multi-beam equipment, the software attached to the device often has the ability to visualize the obtained image in three-dimensions. Measurements with multi-beam probes are used, among others, for making detailed profiles of the seabed and support research in the field of underwater archaeology. They were used, among others, at an underwater archaeological site in the Gulf of Pozzuoli (Naples, Italy), allowing to obtain additional information about archaeological sites, i.e., Secca delle Fumose and Villa dei Pisoni [42]. In images obtained from side measurements, we most often receive two-dimensional data that resemble black-and-white photos. These data require the use of various image analysis methods, which then allow for obtaining three-dimensional visualization [32]. Side-scan sonar research combined with other methods has been used, among others, in work on the documentation of the Roman port of Nisida, the Roman port of Marechiaro, and the remains of the Rosebery villa [43]. It is worth noting that in turbid waters, hydroacoustic methods have an advantage over visual methods because they are not sensitive to the degree of water transparency [32,44].

Hydroacoustic devices used for research are usually mounted under the ship's hull using, e.g., mobile platforms. Less often, they are towed by a vessel or mounted to remotely operated underwater vehicles—ROV (Remotely Operated Vehicle) or autonomous units AUV (Autonomous Underwater Vehicle). When using remote vehicles, detection devices are often used, i.e., side sonars or the so-called subbottom profiler—a low-frequency echo sounder [4,45].

Among the visual methods, we can distinguish between active and passive methods. Active methods are most often based on devices with built-in optical sensor systems. An example of such a method is, among others, a 3D scanner. Scanners are currently primarily used for the 3D reconstruction of artifacts pulled from underwater and their documentation, and sometimes for reconstruction for museum purposes [4,46]. Their main advantage is the lack of a need for direct interaction with the scanned object [47]. Another example is the LiDAR system, i.e., the use of laser measurements. LiDAR-type systems are used, in particular, for bathymetric mapping. They use a blue-green laser light wave [4]. These types of measurement systems are usually mounted on flying units (planes or drones) and provide continuous coverage of the entire imaging area between land and sea, which ensures the ability to observe the entire coastal zone and allows for its 3D modeling [4,5,48]. The group of passive methods is most commonly used for the purpose of documentation of sites; in addition to photographs and films, it also includes traditional forms of documentation, i.e., precise drawings, general sketches, or even a series of measurements taken at the site, etc. All these techniques require conversion from a 2D image, or a set of dimensions, to 3D models (solids, editable polygons, or meshes with unique coordinates for each point), i.e., processing into a 3D reconstruction [15,49]. One of the specific methods used in this field is photogrammetry, which is widespread in underwater archeology [46].

Photogrammetry offers a realistic visualization of an object or place in its current form [26,50,51]. Its definite advantage is the fact that models can even be created with images that are not from professional cameras, but from data collected using sports cameras [46,52]. However, the state of preservation of the underwater object is a separate problem. Photogrammetry brings the best results in the case of well-preserved objects not covered with a bottom layer. An example of this type of facility that has been reconstructed using photogrammetry is the wreck of the Swedish ship Mars from the 16th century [26,53]. Additionally, this reconstruction also shows the effectiveness of the method for objects of large dimensions, because the mentioned ship at the time of its sinking, i.e., in 1564, was considered to be one of the largest ships in the world [53]. However, it should be noted that such an object, especially in the aquatic environment, may be damaged, e.g., by bioerosion processes or even largely destroyed, which makes the documentation process difficult. In this case, it may be beneficial to recreate it using VR methods [51].

Visual data are collected depending on the underwater archaeological site—either using trained divers or autonomous vehicles. ROV and AUV systems are particularly used in hard-to-reach places, including those located at considerable depth. These vehicles can perform most of the tasks needed for photogrammetric purposes, reducing the need for the services of specialized technical divers, which proves to be a more cost-effective solution [4,54].

It is worth noting that in extensive archaeological research, the possibility of combining visual and acoustic systems is increasingly used due to the advantages of both systems [4,44,48].

Other data collection methods include magnetic methods or Li-Fi (equivalent to terrestrial Wi-Fi). These methods, however, are not very popular in underwater archeology and serve rather auxiliary functions. For example, electrical resistivity tomography (ERT), which is based on measuring the differences in the electrical properties of the medium, was used, among other methods, to collect measurements of a barge called Crowie, located in the town of Morgan on the Murray River in southern Australia, in order to create its 3D visualization [49]. This method is rarely used in underwater archaeology.

In the second stage, various techniques are used to recreate the shape and build models for later use in a virtual application [55,56]. The most frequently used methods in this area include the following [32]:

- Shape from texture (SfT)—the source of information is photos of objects that are processed by algorithms analyzing the textures covering the objects.
- Shape from focus and defocus—this method involves extracting depth from many photos taken with different focal lengths. Algorithms analyze both the shape and brightness of the object.
- Shape from motion (SfM)—the shape of an object is recreated using its motion recorded by a camera. Currently, this is probably the most frequently used method in underwater archeology to create a three-dimensional visualization of objects [47].
- Shape mapping from shades of gray (shape from shading, SfS), known as photoclinometry—algorithms reproduce the shape using the degree of shading of various parts of the object in a two-dimensional image, taking into account the direction of incidence of light. This is also one of the most commonly used methods today.

The next step after building a three-dimensional computer model of an object is to select the output formats available for viewing the results. These may include the following, among others: animations; 3D graphics using applications such as AutoCad or 3D studio; panoramas and three-dimensional photos, e.g., using the QTVR format (QuickTime dedicated to VR); VR simulators, e.g., using the VRML programming language; and finally, applications in online gaming environments, e.g., Unity3D [57]. The selected output format will depend on the purpose of use of the resulting images, their recipient, and the equipment and display software to which we want to dedicate the results of the visualization [15,32].

At the stage of preparing an appropriate form of information transfer using VR or AR, the choice of content display technology is equally important. Most devices available on the market offer only visual and auditory simulations. The most popular VR solutions can be divided into two groups: head-mounted displays, the so-called HMD; or the so-called environment CAVE, which is implemented on the scale of a room or part of it [51,57]. In both cases, it is possible to stimulate other senses, e.g., smell or touch, but they are relatively rarely used and usually require more expensive solutions [57]. In the field of AR and MR, mobile devices are used in many cases to superimpose a virtual simulation on the real world [57].

4. Virtual and Augmented Reality Technologies in Underwater Archeology

4.1. Application Areas

Currently, VR and AR have found applications in many fields, both for entertainment purposes and as a tool supporting scientific research or specialized work [57–59]. These applications include medicine [60,61], construction and architecture [62–64], the machinery industry [65,66], production management [67] or education [16,68,69], and even sports training [70,71] and religious education [72]. The chapter discusses several exemplary applications of VR and AR, which, on the one hand, show the spectrum of its possibilities and, on the other hand, are directly related to the subject of underwater archeology. The main areas of application of VR/AR in underwater archeology are presented in Figure 4.

VR, or, if we are talking about applications in the field of history and archaeology, increasingly mixed reality, is used as an educational and entertainment method. The use of mixed reality most often involves spatial visualization of the environment using VR, which allows users to move around three-dimensional space as if they were playing a game. AR, in turn, is used to add computer-generated information to physical places and objects [73]. When applied to historical or archaeological sites, mixed reality applications usually fulfill many functions. First of all, they are intended to teach, but at the same time, they also have entertainment value; at the same time they constitute a research area with an increased amount of information for interactive development [3,12]. It is also worth noting that VR can be used as a pedagogical tool supporting so-called historical empathy, i.e., for various types of activities that allow us to better understand the motives behind the actions of people from the past, even if they now seem unreasonable to someone in the present [73]. Emotional immersion is achieved through the user's contact with content, e.g., archaeological content, through the convergence of technologies [12]. In particular, it is possible to use VR tools for detailed and realistic visualizations and the discovery of historical and archaeological spaces, which in turn allows the study of its details in historically significant periods, as well as a reflection on how this space has changed over time [73–75].

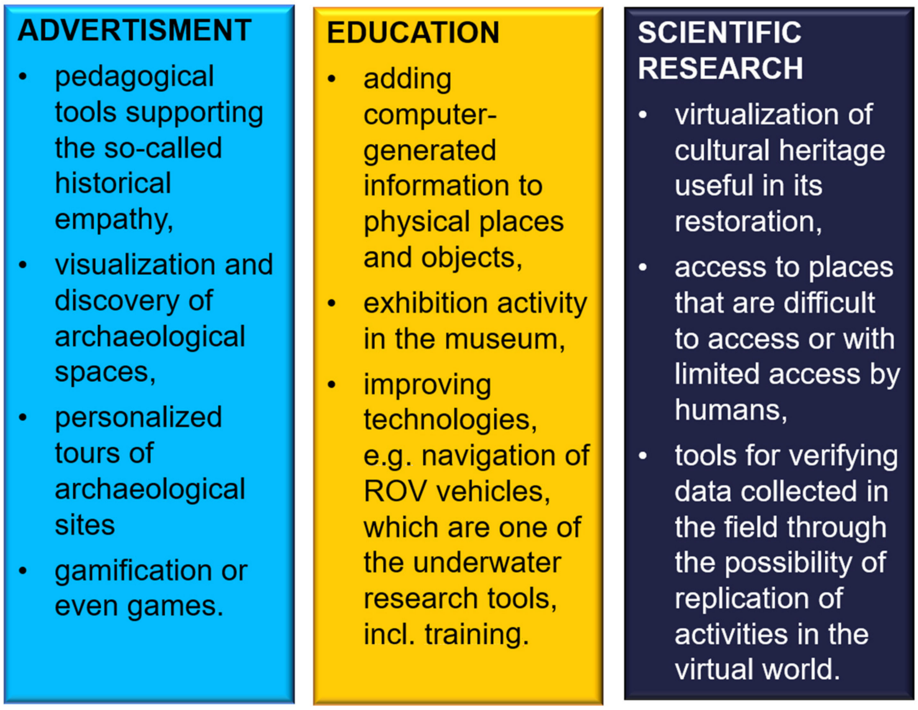


Figure 4. VR/AR and their application in underwater archaeology.

It is worth noting, however, that most applications using VR or AR and offering visualizations of archaeological objects are dedicated to increasing interest in tourism in a given area, and the analyses carried out show that this type of activity gives positive results [76,77]. An example of one of the first applications of this type is "Archeoguide", which offers personalized tours of archaeological sites in AR [1,78]. The application uses the location of the mobile device, 3D visualization, and AR techniques to make the presentation of archaeological information more attractive by enabling the viewing of a virtual reconstruction of a given object [1,78]. Other systems also work on a similar principle, i.e., "KorfuAR", which works based on AR and in historically significant tourist attractions, where information about the sites is presented. This system also provides personalized recommendations about further monuments worth seeing in the region [1,79]. A project involving an AR system in the city of Chania in Crete, Greece took this a step further, where it is possible not only to obtain information and watch the reconstruction of monuments, but the so-called element of "gamification" was also implemented, i.e., the intentional implementation of game features in contexts that are not usually associated with games [80]. A similar idea has been proposed for the partially submerged fortifications of the Halai acropolis in eastern Lokris, Greece [10]. As part of the idea of "Smart Cultural Heritage" services (SCHaaS), a system was designed that would use AR on mobile devices to create a coastal path that would allow users to obtain various pieces of information about archaeological sites in this area [10]. Tourism applications also include virtual systems enabling visits to a created aquatic environment, promoting both touristic and ecological aspects [81–83].

An equally important area of application of VR and AR is education in the field of archeology and other useful skills in this field, such as photogrammetry [1,2,51]. In this regard, the use of virtual technologies in the area of virtualization of cultural heritage and its renovation is worth mentioning. An exemplary system was developed by Pontificia Universidad Católica del Perú, where the combination of new technologies and management methods, i.e., Lean Construction (LC) and Building Information Modeling (BIM), with VR was used to plan structural interventions in cultural heritage sites [84]. The first step in the creation of AR was the use of drones to record the spatial image of real objects and their measurements, including the use of laser measurement. The next step was digital and computer processing (using photogrammetric methods). The correctly processed image could be seen both on the monitor screen and through special goggles [84]. The system enables spatial observation of a historical object and conducting simulations. The system is currently used for both research and educating students, in particular in master's and doctoral studies. Examples of objects on which work was carried out using this methodology include St. Jerome Hall in the Church of the Nativity in Bethlehem, Palestine, and the baroque church of San Pedro Apostol of Andahuaylillas in Peru [84,85].

It is worth noting that some VR solutions cannot be clearly classified into only one field. For example, the theoretical model being developed, the so-called "smart ticket", is a combination of audiovisual learning and archeology with user interactions, for cultural heritage dedicated to both tourism and educational purposes. Additionally, the system provides the user with the ability to interact with 3D animation information using interactive buttons and games, which further introduces a ludic element [12]. A similar approach in educational games created on the basis of archaeological sites combines entertainment elements and educational, including in the field of underwater archeology [31].

In the entertainment and educational aspects, it should be noted that computer games using VR are becoming more and more popular [75]. The trends in this area are different—they include both the use of archaeological reconstructions as elements of popular games and the creation of the so-called "serious games" that are based on archaeological realities. The plot in these games is only an addition that is intended to make education more interesting and effective through user involvement or the previously mentioned introduction of gamification elements to virtual applications [75,86].

In the first case, an example is the previously mentioned Play Station game "Treasures of the Deep", which featured unrealistic representations of wrecks [31,86]. However, there are many such games. Among the most popular, it is worth mentioning "Discovery Tour of Origins" and "Odyssey", chapters of the "Assassin's Creed" saga produced by Ubisoft Entertainment, which carefully recreated historical places in consultation with historians and archaeologists. Additionally, "Discovery Tour of Origins" is a game mode focused on education. This game mode allows users to interact with recreated historical sites [75]. In the second case, the so-called "serious game" VR applications are characterized by an accurate historical background and a confirmed 3D reconstruction based on archaeological research [75,87]. An exemplary solution in the field of "serious games" is described by Ferdani et al. [75]. They describe a game about Roman times aimed at familiarizing the user with historical and archaeological knowledge related to the Forum of Augustus in Rome [75] or the virtual application "Titanic VR" [26].

In terms of education and entertainment, the use of VR elements has also been used in the plots of films and series. Here, it is worth mentioning the documentary series entitled "Drain the Oceans" from 2018, based on virtual reconstructions based on archaeological research [88]. It showed the exploration of shipwrecks and other sunken archaeological sites underwater, including cities, using an underwater scanning system.

VR and AR are also finding wider applications in scientific research. Thanks to the use of these technologies, it becomes possible to access places that are difficult to access or have limited human accessibility, as well as their reconstruction and critical analysis from a scientific perspective [12,73,89]. The element of visualization of archaeological sites is particularly useful. Visualizing both the elements and the larger whole is often a fundamental part of the research process, as it is used to understand, interpret, and discover relationships [90]. Additionally, it is worth noting that VR can provide scientists with a new tool for verifying data collected in the field by replicating activities in the virtual world [90], including 3D documentation archeological sites [91]. An example is the archaeological research conducted in the volcanic area of Campi Flegari, where 3D visualizations were prepared based on barometric data obtained from the probe and visual data, which allowed to confirm research on the flooded area that was urbanized in the Roman period [43]. The presented work used computer simulations and concerned, in particular, the occurrence of land subsidence, which over the last 2300 years resulted in the complete submergence of the coastal belt in this area [43]. There are also useful tools for bioarcheological investigations [92].

Another application of VR that is becoming more and more popular is exhibition activities conducted in various institutions. In this respect, technology can be used both at the planning stage of the entire exhibition and its fragment [12,93]. Two of the exemplary applications of visualization of objects related to underwater archeology are the 3D and 4D simulators that are part of the exhibition at the Chinese Maritime Museum in Shanghai [94]. The 3D technologies used in the exhibition include both a 3D cinema and various sailing simulators during a storm or snowstorm [94]. Another possibility for enriching the exhibition is the use of gamification elements, including the use of elements typical of games, especially computer games, as a reference to the interactive experience [51]. This approach directs users' interest to the content of the application and thus increases the attention devoted to cultural exhibits [12,95,96]. Such a reaction may refer, for example, to kinesthetic experiences. An example is a program that places the user in the role of an ancient craftsman, creating Cycladic sculptures in a simplified virtual environment using appropriate movements and gestures [97].

VR is also used to improve technologies, e.g., navigation of an ROV vehicle, which is one of the tools used for underwater research, especially in situations where wrecks are located at considerable depths [98]. In this case, VR helps visualize the ROV's behavior in various situations and allows it to be tested. VR allows for simulating most situations that an ROV may face in the real world, including various types of interactions with objects and the environment [98].

4.2. Advantages of Virtual and Augmented Reality Technology

Due to the potential benefits they bring, VR and AR technologies are currently gaining popularity, also in the field of underwater archaeology. Their main advantage is their cost-effectiveness in many areas, including education and research in the field of archaeology, especially underwater. Conducting a simulation is usually much cheaper than taking action in the real world [99]. An example here is underwater work, the costs of which are usually very high and can reach up to several thousand dollars a day [8].

Additionally, it is worth paying attention to the aspect of risk, which is significantly lower in "dry diving" using VR applications than in real underwater work [100]. It is worth noting that although virtual training will not replace realistic training, in the first stage of an archaeological diver's preparation, it could be a good alternative when introducing basic underwater work techniques or even specialized training [98]. Experience from other fields shows that VR and AR can play an important role in emergency training. These types of simulation provide more realistic experiences than "false alarms" and "role-play" studies, e.g., in the situation of evacuation from a building, and also help to better design situations for other people [101].

Another important element, from the point of view of underwater archeology, is the user's involvement and complete "immersion" in a "different dimension". This has the advantages of both in terms of training and research, as well as in presenting the results of work to a wider audience. In the first case, it allows the user to focus on training tasks by eliminating disturbing factors. This allows to shorten the training time and increase its effects [102]. The use of new teaching tools, i.e., VR, often arouses the interest of learners, thereby strengthening the teaching effect. In the case of archaeology, virtual reconstruction improves cognitive processes by making historical–archaeological data easily understandable to any user [75]. Additionally, the cognitive process can be enhanced by the so-called storytelling, i.e., an engaging story played out most often in the first perspective, and learning by doing [75].

Additionally, if the user has difficulty mastering a specific skill, the program allows the user to repeat the task many times until satisfactory results are achieved [103]. In the case of underwater archeology students, it is also important that technology allows not only to improve technical skills but can also be used to effectively improve visual thinking skills, which may be useful in future research work, including understanding ship construction, maritime reconstruction, or infrastructure in a given cultural context [15,104].

From the point of view of scientific analysis, VR offers new ways to both visualize problems and interact with the environment in order to effectively analyze them, discover new relationships, understand objects and events, and solve research problems [13,103]. These methods usually increase the researcher's participation and help in understanding complex situations [15]. Additionally, creating virtual research allows for the verification of data obtained in the field (testing research hypotheses) and their re-analysis, and facilitates the exploration of various perspectives, also by researchers who do not have diving skills [13,31,90]. It may help also in collecting appropriate documentation [15]. The method of 3D visualization very often helps to look at the research site from a new perspective, which contributes to asking new questions about existing data and also leads to new and unexpected insights, sometimes challenging traditional interpretations based on 2D documentation [15]. In the case of underwater archeology sites, this aspect seems to be particularly important due to various factors operating underwater and impeding access to archaeological objects or causing their rapid destruction.

Underwater sites may be inaccessible to researchers due to difficult conditions, i.e., depth or currents, or for conservation reasons or legal reasons [12,73,100,105]. They may also have not been preserved in their previous form because all physical artifacts were permanently removed from their original position and context, e.g., due to the threat of destruction or looting [13]. In such cases, virtual reconstruction based on previous mapping and data registration may be the only option for repeated analysis [13]. It is also worth noting that even if an underwater site is available for another visit, this visit, unlike land-based excavations, is most often associated with additional preparations and most often with difficulties and limited time [15].

VR and AR technologies can also increase interest in learning from both students and the wider public. Unlike land areas, underwater archaeological sites and the monuments they contain, e.g., ancient ports or shipwrecks, are usually not accessible to the general public due to the specialized diving skills required to view them. Most often, photos or individual artifacts exhibited in maritime museums provide only fragmentary access to these cultural goods [31,105]. In this case, the use of VR technology seems to be particularly desirable, because it will play an important role in the dissemination of cultural heritage and not only provide access to a given archaeological site, but also create a unique experience related to it [106]. These activities will take place without any associated risks with exploration of the underwater world [100]. An additional advantage may be the availability of this type of station without distance or time limits, if they are designed to be used also outside the walls of the museum, e.g., as mobile AR applications [105]. It is worth noting that these types of activities, apart from being "spiritual", also have a material dimension. Public access to underwater and marine cultural heritage has been proven to have a very positive impact on the local economy [76].

4.3. Barriers to the Use of Virtual and Augmented Reality

In addition to their significant advantages, VR and AR technologies also have limitations. One of the most obvious is the need to have appropriate hardware and software to reproduce the content [107,108]. This limitation applies to both normal users and cultural institutions that want to use virtual elements during their exhibitions. Designed virtual applications sometimes require the use of dedicated solutions, which are not cheap and require a significant amount of time for their preparation [13]. When designing virtual applications, many creators face the dilemma of whether to design a solution for specific goggles, where it will work almost flawlessly, or to expand the software capabilities (which also involves additional costs) for various devices and risk software bugs also appearing. In turn, designing software for one type of device may make it completely impossible to play it on other devices, which from the user's point of view would require doubling the existing hardware. This type of limitation is primarily related to the dynamic development of the VR and AR market and the lack of well-established standards for this type of solution. A partial solution to this problem is both VR and AR applications dedicated to mobile devices [105]. However, here too we may encounter a lack of software compatibility with our equipment. Moreover, this solution does not provide a full sense of "immersion" in VR.

It is also worth noting that each visualization, even the best one, will impose certain limitations, which are most often related to the quality of the input data [15,109]. When creating a computer application, you cannot omit selected elements of the entire station that are not sufficiently documented from an archaeological point of view. Therefore, this type of reconstruction always includes a risk of error [109]. A similar problem may also occur in the educational field, where on the one hand the archaeological reconstruction should be a faithful reflection of the research work carried out, and on the other hand the application should be engaging for the user. Maintaining fidelity to the source material most often imposes certain restrictions on planned virtual applications, the so-called "serious game", while in video game design, there are no limits to the imagination and the scenario that is created according to the needs of the game [75]. Another disadvantage of creating a virtual application for educational purposes may be its costs. Virtual reconstruction of the past imposes many limitations and requires great effort to ensure the consistency and credibility of the reconstruction hypothesis, which often includes the need to employ additional people to ensure the coherence of the presented objects and scenario with historical realities [75].

Another limitation is that the user has appropriate knowledge or training in using the program or devices [110]. Potential users, including guests of cultural institutions, do not always have the appropriate knowledge to fully use the possibilities offered by virtual technologies [26,110]. For this reason, developers of VR programs sometimes choose to limit program features and "full immersion" experiences in favor of simple and intuitive application operations [26].

Education using VR and AR, apart from emphasizing its advantages, also meets some criticism. A debatable issue may be the acquisition of equivalent skills in virtual training compared to training conducted on real equipment, in particular this issue concerns motor skills [16,27]. For related issues with underwater archeology, these issues are particularly important in terms of training from photogrammetry or controlling remote vehicles when examining underwater sites [98]. Although research indicates that virtual training is sufficient for this type of skill in these matters, there are still doubts as to whether in the case of virtual training the student will approach it seriously enough. Due to the form of teaching, the student may have the impression that he or she is playing a video game and downplay certain underwater phenomena. This type of training may lack a real sense of responsibility for the assigned equipment or due attention to safety issues [107].

The most important advantages and disadvantages connected with using AR/VR in underwater archeology are summarized in Table 1.

Table 1. Advantages and disadvantages connected with using AR/VR in underwater archeology.

No.	Advantages	Disadvantages
1	Cost-effectiveness in many areas.	Input data quality constraints.
2	Minimalization of risk connected with underwater activity.	The need to have the appropriate hardware and software to play the content.
3	Shortening the training time and increasing its effects—virtual reconstruction improves cognitive processes and learning by doing.	The acquiring of equivalent skills—motor skills are not clearly proven (e.g., lack of responsibility for ROV).
4	The program allows you to repeat the task many times until satisfactory results are achieved.	The user should have appropriate knowledge or training in the use of the program or devices.
5	Visualization of problems as well as interaction with the environment for their effective analysis.	Lack of a real sense of responsibility for the entrusted equipment or due attention to safety issues.
6	Availability of underwater archeology positions without distance or time restrictions.	

5. Use of Augmented and Virtual Reality in Underwater Archeology—Example Solutions

5.1. Virtual Science

The modeling of the interior of the "Pepper Wreck" took place mainly in the period 1996–2000 (Castro 2008). This wreck was a Portuguese merchant ship that sank at the mouth of the Tagus River in September 1606. It was named because of the amount of pepper found in its hull. The wreck currently lies at a depth of 9 m [15,111].

The main recipients of the created virtual application were scientists. The app was supposed to help in understanding how the internal space of this ship was arranged and used, particularly in terms of the likely configuration of the cargo carried [15]. It helped in understanding a complex environment that was very difficult to study using conventional 2D imaging techniques. The visualization helped to obtain data that are much closer to reality and allowed users to examine the reconstructed artifact. The resulting environment dramatically improved the ability to understand spatial relationships, including cargo distribution and nuances of rigging, as well as other ship elements [15,111]. The created application could be used on a specially designed simulation station equipped with large screens. This was similar to the idea in the CAVE configuration [15]. After testing by scientists, the system was also made available for educational purposes [15].

5.2. VENUS Project

The VENUS project (full name: "Virtual Exploration of Underwater Sites") was implemented in 2006–2009 by a multidisciplinary team of 11 European institutions [15,112]. The consortium's goal was to increase the accessibility of underwater archaeological sites for both archaeologists and the general public by generating accurate, comprehensive 3D records for virtual exploration. The activities carried out were primarily of a scientific nature and were based on the best practices available at that time. The research was carried out using AUV and ROV, which were equipped with the latest sonar and devices necessary to prepare photogrammetric documentation of archaeological sites and objects [112]. The work focused primarily on the exploration of "deep" archaeological sites and other inaccessible underwater locations [15].

The created application was dedicated primarily as an interactive application available via websites; additionally, access to the application using HMD devices was also provided [34]. The content of the application was dedicated both to experts in the field of archeology as research material, and to a wider audience, mainly for educational purposes in the presentation of underwater cultural heritage [112]. It is because of this second target group that elements of seabed visualization were added to the created application, including fauna and flora, as well as underwater lighting effects [112].

As part of the VENUS project, data were made available on the archaeological site, which is also a diving site related to the remains of the cargo of the merchant ship Pianosa [112]. The site is located near the island of Scoglio della Scola off the coast of Tuscany, Italy. There is a cluster of amphorae (about 100) discovered in 1989 by divers Giuseppe Adriani and Paolo Vaccari. The site is located at a depth of 35 m. It was explored by divers and ROVs using multi-beam sonars and photography. It is dated to the period between the 1st century BC and the 3rd century AD [15,112].

As part of the project, a visualization of the archaeological site and individual artifacts was created. Additionally, an application called "Venus-PD" ("Virtual Exploration of Underwater Sites—Public Demonstrator"), which allows the user to pilot a virtual underwater vehicle and use it to visit an archaeological site [112]. At specific moments in the designed scenario, the application displays additional information to the user about the history of the wreck and the artifacts currently located at the archaeological site [34].

5.3. Re-Discovering Project—Vrouw Maria

Re-discovering Vrouw Maria is a gesture-based, interactive VR simulation that allows visitors to explore a cultural heritage site and underwater archaeological site, the wreck of Vrouw Maria [106]. Vrouw Maria is a Dutch cargo ship from the 17th century that sank off the coast of Finland, near Nauvo, in 1771 on its way to St. Petersburg [14,106]. It was rediscovered in 1999, at a depth of 41 m near the coast of Finland [14,106]. Its state of preservation is assessed as very good due to the conditions in the Baltic Sea [106]. Apart from the depth, the second factor that makes access to the wreck difficult for the general public is its location in a nature reserve. The developed site is a VR representation of the wreck, which is still located at the site of the sinking [14].

The project related to the development of the virtual site was carried out in the years 2009–2012 by the Department of Media at Aalto University School of Arts, Design and Architecture and the Maritime Archeology Unit operating within the National Board of Antiquities of Finland [106]. The result of the work was an application using VR developed in April 2012, which presented a museum object at the Maritime Museum of Finland in Kotka, Finland. The application has an intuitive interface that was based on simple human gestures and actions thanks to the use of a motion sensor—the Microsoft Kinect sensor and gesture recognition technologies—which was an innovative solution at that time. The application allows real-time simulations to be performed in a virtual 3D environment, without any additional hardware required from the user [106].

The developed application presents the Vrouw Maria wreck on a stereoscopic large screen with a surround sound system. At the beginning of the simulation, visitors can watch a short animated sequence presenting historical information about the object and the probable events that led to its sinking [106]. Next, the user goes to VR, where he can move in 3D in the underwater landscape. Visitors can also gain knowledge about various aspects of the area through information points in the surroundings [106]. All this results in a significantly better and more complete perception of the archaeological site, which, thanks to virtual reconstruction, ensures the greater involvement of the recipient and a more interesting presentation in a museum setting [14].

In the created application, the main area of interest is the wreck, including the recreated one in the virtual environment, the deck, and two holds, which are accessible through small hatches on the deck. Users can explore both the external environment and the interior of the wreck, including the holds and the kitchen, as well as the underwater landscape around the wreck, including natural habitats, i.e., schools of several species of fish, colonies of edible mussels and algae typical of the Baltic Sea [106]. The exterior of the wreck model was created based on a laser-scanned physical model of the wreck. The interior of the wreck is modeled in 3D, based on technical drawings and photos; records from multi-beam sonar scanning were used to recreate the underwater landscape [106]. The above activities were intended to provide a holistic image of the site and its surroundings in the form of designing the so-called immersive installation [14].

5.4. VR CAVE

Work under the project titled "A State-of-the-Art VR CAVE facility for the Advancement of Multi-Disciplinary Research & Development in Cyprus" was carried out in 2012–2014 and financed by the Cyprus Foundation for the Promotion of Research using EU structural funds [113]. The project aimed to use VR in various aspects, including underwater archeology [113].

In terms of underwater archaeology, the project focused on the Mazotos wreck, which dates back to the 4th century BC [13]. Currently, the archaeological site is only an outline of the wreck and the amphorae collected there. Data for the project were obtained on the basis of previously conducted archaeological works. The VR site itself was developed to make the interpretation and analysis of the wreck easier and more effective. The created application was intended to serve as a scientific tool for underwater archeology [113].

The project's application was designed to provide an intuitive work environment for users and enable researchers to easily interact with archaeological data, which required a high level of accuracy and authenticity in the reflection of the wreck [13]. It was intended not only to enable the simultaneous and easy to manage viewing and comparison of the results of the documentation process of an underwater archaeological site, but also to introduce a virtual environment in which spatial analysis can be performed in three dimensions. Such a visualization allows one to see the relationship between artifacts and the surrounding environment and thus enable the exploration of alternative perspectives and interpretations [13]. An additional feature of the application was that it must also enable the addition of new information from future research work carried out at the site and the updating of existing data [13].

The created VR CAVE station consisted of four projection screens (three projections on the walls and one on the floor), which allowed the use of stereo projection technology. Additionally, the tracking of the user's head movement was used to enable interaction with the virtual environment [13]. Stereoscopic glasses were used to ensure the proper perception of 3D images. An Xbox controller was used as an interaction device in the VR CAVE application, which allowed for great freedom in navigation control when using the application, including manipulating virtual objects [13]. The application interface consists of menus, icons and information panels through which the user can load various data and supporting materials into the virtual environment, e.g., photos corresponding to each artifact [13]. The application also has the potential to be used as an educational tool, in particular for training archeology students [13].

5.5. ARROWS Project

The ARROWS project ("ARchaeological RObot systems for the World's Seas") was implemented in the years 2012–2015 under the 7th Framework Programme. The project was financed by the European Commission [114]. The project was implemented by an international consortium consisting of 10 organizations from 6 countries—Italy, Estonia, Scotland, Turkey, Spain, and England (http://www.arrowsproject.eu/, accessed on 1 August 2024). The main objectives of the ARROWS project were related to the development and integration of advanced technologies for use in underwater and coastal archaeological sites, including tools for mapping, diagnosis, and securing these sites [114].

Research conducted as part of the project focused primarily on automated vehicles dedicated to underwater archaeological work, but also developed auxiliary technologies [115,116]. One of the technologies developed was a virtual environment enabling the presentation of all available data collected in various formats, in an interactive form and in three-dimensional space. The system was dedicated both to experts, for research purposes, and to the general public, including for educational and information dissemination purposes in the field of underwater archeology [114].

The Unity platform was used for visualization, and the "Oculus Rift" goggles and a gesture-responsive interface, "Leap Motion", were used as peripheral devices [114]. As part of the developed system, the user could interact with various objects and obtain additional information about them, i.e., 3D mesh reconstruction for a given object which was possible to be viewed from various perspectives, videos recorded from places where diving took place, raw data from measuring devices and other supporting information [114]. Tests of these technologies were carried out in the Mediterranean Sea at the archaeological site of Cala Minnola and in conditions similar to those in the Baltic Sea—in the Rummu quarry, Estonia [116].

5.6. VISAS Project

The VISAS project ("Virtual and augmented exploitation of Submerged Archaeological Sites") was carried out between 2014 and 2016. It was financed by the Italian Ministry of Education [9,87]. The main goal of the project was to create a system based on VR and AR technologies allowing for the enrichment of the cultural and tourist activities offered in relation to underwater archaeological sites, for scuba divers and non-diving tourists. Thanks to the use of a modern form of communication, the cultural and educational experience could be more engaging for the viewer and could additionally attract new tourists and increase revenues from the tourism industry in a given region [9,117].

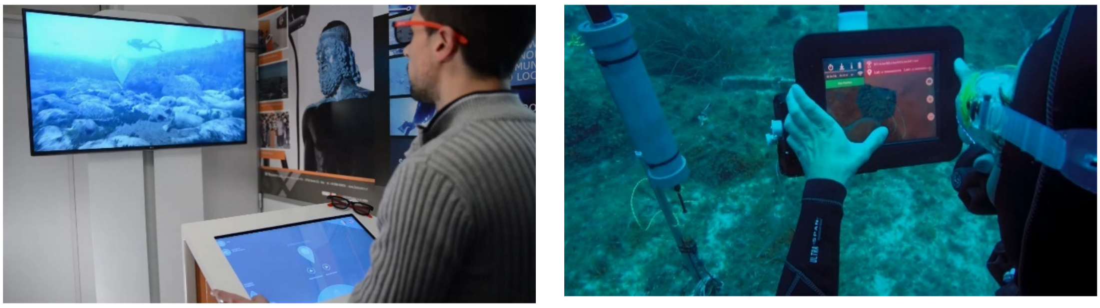
The project was implemented at two underwater archaeological sites. The first of them was Punta Scifo D located on the eastern coast of Calabria, 10 km from Crotone. The underwater site contains underwater artifacts, mainly raw materials and semi-finished marble products that were transported by Roman cargo ships. The site is located at a depth of 7 m [9]. The second site is Cala Minnola; it is located on the eastern coast of the island of Levanzo in the Aegadian archipelago, a few kilometers from the western coast of Sicily. The wreck was discovered in 1970. The main element of the underwater archaeological site is the wreck of a Roman cargo ship that was carrying a cargo of amphorae with wine. The ship sank around the 1st century BC and currently lies at a depth of 25 to 30 m [87,118].

The first stage of the work was to collect data from selected archaeological sites by employing divers and remotely operated underwater vehicles (ROV). The second stage of work included collecting accurate measurements using a multi-beam sonar system mounted on the bottom of the ship from the selected location [9]. The next stage was 3D optoacoustic reconstruction (both visual and acoustic data were used for the reconstruction), from which textured 3D models of underwater archaeological sites were generated. These models were made available to divers and non-diving tourists using VR and AR tools [9]. The VR station is based on five elements: a database, a website, a scene editor module, an interaction module, and a controller. The Unity system was used to create appropriate modules [119].

In this case, VR allows users not only to view underwater archaeological sites and acquaint themselves with their 3D reconstructions, but also to receive information about specific sites in the historical context and information about submerged exhibits [117]. The application also included information about local flora and fauna, with a particular emphasis on their impact on submerged artifacts [9,118]. As an additional benefit for the divers who will use the system, it may be used as an underwater route planning tool [37]. VR can be explored both using a stand with an HD monitor (Figure 5a), as well as using a VR set, e.g., "VIVE HTC" [119].

AR was implemented in the project using an underwater tablet equipped with a positioning and orientation system—Figure 5b [9]. The positioning and orientation system operates using an acoustic modem and stationary transmitters placed on the seabed (LBL—Long Base Line technique). The tablet was also equipped with an inertial platform, and a depth sensor guides divers during a diving session, and at the same time provides information about the archaeological artifacts found [9,87].

It is worth noting that the virtual application, apart from archaeological education, can also be used by archaeological divers to plan dives at archaeological sites. It allows for the planning of work, taking into account field conditions and changing environmental conditions, e.g., water transparency [87].



(a) (b)

Figure 5. VISAS project (selected shots from promotional materials): (**a**) use of virtual reality—a stand allowing a "visit" to Cala Minnola, (**b**) use of augmented reality underwater.

5.7. Mercurio Shipwreck

Activities related to the creation of a VR application based on the archaeological site—the Mercurio wreck, were carried out in 2016–2017 as part of the project entitled "Restituzione 3D di Relitti Antichi Sommersi finalizzata alla realizzazione di Musei virtuali con realtà immersiva e aumentatä". This initiative was implemented thanks to the European Social Fund, with financial resources from the Veneto region, Italy [100].

The 19th century brig Mercurio was sunk during the Battle of Grado in 1812. It currently lies at a depth of 17 m in the northern Adriatic Sea. Artifacts found during research on the wreck were recovered and are currently exhibited in the Maritime Museum of Caorle (Museo Nazionale di Archeologia del Mare of Caorle, near Venice), where a multimedia station has also been installed to make the exhibition there more attractive [100]. The application has been available to visitors since July 2018. The created virtual application uses HMD display technologies (the "Oculus Rift" model was selected) and is integrated with other multimedia applications and displays available in this museum [100].

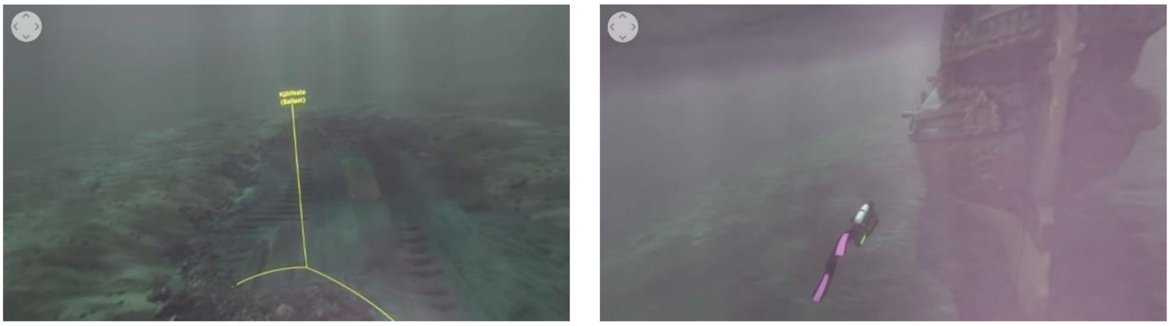
The application allows you to virtually visit the shipwreck in the condition it was in at the end of the excavations. Currently, the underwater site has been protected against corrosion processes in the sea using a geotextile, which makes access to it impossible in reality. Therefore, a virtual tour is de facto the only possibility to see the wreck [100]. The virtual application, in addition to a realistic reconstruction of the wreck, also contains elements of the seabed and artificially generated elements of flora and fauna, e.g., eels, shells, and seagrass [100]. Additional elements have also been added, such as a decrease in water transparency, a decrease in the amount of light with depth, and a dirty mask simulation, which are intended to achieve a realistic virtual underwater scenario [100]. Moreover, selected artifacts from the wreck, i.e., a cannon and a gun, contain additional information that can be reproduced during a virtual dive [100].

5.8. Melckmeyt Shipwreck

An unusual VR project is the reconstruction of the Melckmeyt wreck. This Dutch ship sank in 1659 off the coast of Iceland, near Flatey Island in Breiðafjörður [26]. It was discovered in 1992 by local divers Erlendur Guðmundsson and Sævar Árnason [26]. Currently, the wreck is at a depth of 12 m. The Melckmeyta wreck survey was carried out between 2016 and 2019 and was financed mainly by the Government of Iceland, with additional funding from the Netherlands (including the Embassy of the Kingdom of the Netherlands in Canberra, Australia) [26].

The goal of the project was to create an immersive and realistic virtual experience from diving the wreck, and at the same time use the possibilities of 3D modeling to provide as much archaeological information as possible in a short time [26]. This was due to the preparation of the virtual application for exhibition purposes, which forced the duration of the virtual experience to be limited to a maximum of several minutes. The authors of the application assumed that an interactive game that was too long would be impractical for use in public places, and that additional extensive functions could be difficult for people with less computer knowledge [26]. The application created in this way was described as 2.5D VR, which means that it has only certain VR functions, and its essential part is an animated 360° panoramic film [26]. In this solution, the user has limited interactivity with the scene and can only control the viewing direction [26]. This approach also has other advantages beyond ease of use. This type of virtual experience can be more easily directed by developers who are confident that key archaeological information will be communicated in a timely manner. Additionally, the technology itself does not focus the user's attention, so he or she can focus on the content being conveyed [26]. A "guided tour" causes the user to follow subsequent parts of the wreck, while at the same time limiting the user's involvement time—this is particularly important for use in cultural institutions, where it allows more people to participate in the experience [26].

The entire application consists of two parts of similar duration. In the first part, the user sails over a wreck mapped on the basis of data from photogrammetric measurements, where the most important objects and elements of the wreck are marked and additional information about them is included (Figure 6a). In this part, the seabed and environmental background are also visualized, including seaweed and jellyfish, as well as a diving partner, which also promotes elements of good diving practices [26,120]. In the second part of the virtual experience, the user explores the wreck and is exposed to its hypothetical reconstruction (Figure 6b). Contemporary models of a similar type of ship were used to create an authentic reconstruction [26].



(a) (b)

Figure 6. Visualizations from the virtual experience (selected shots from the promotion materials): (**a**) a view of the photogrammetric reconstruction of the wreck—the first from the second part of the animation; (**b**) a hypothetical reconstruction of the wreck—a shot from the second part of the animation. Based on [120].

The created virtual experience was originally presented at the Maritime Museum in Reykjavik, Iceland (June 2018–December 2019) at the exhibition entitled "Melckmeyt 1659". For this purpose, the museum purchased ten VR sets—"Samsung Gear" [26].

5.9. *iMARECULTURE Project*

The iMARECULTURE project ("Advanced VR, iMmersive serious games and Augmented REality as tools to raise awareness and access to European underwater CULTURal heritage") received funding from the EU Horizon 2020 research program. It was implemented in 2016–2020. The consortium included 11 organizations from the Czech Republic, Canada, Bosnia and Herzegovina, France, Cyprus, Italy, Portugal, and Hungary, https://imareculture.eu/ (accessed on 1 August 2024) [121,122].

The project aimed to raise European identity by increasing society's interaction with marine and underwater cultural heritage in the Mediterranean [37]. As part of the project, two multimedia applications in the form of games were created. The first of them uses geospatial technologies enabling the development of a game about sailing in the Mediterranean in ancient times [123]. The second one is related to the exploration of underwater archaeological sites [37]. In addition to elements closely related to archaeological sites, the game also educates on the research methods used in underwater work [86].

The project included three archaeological sites. The first of them is the wreck of the Phoenician ship Xlendi, which dates back to the 7th century BC. It lies at a depth of 110 m. It sank off the coast of Gozo, Malta [37,122]. In this case, due to the significant depth of the wreck, the application creators used an underwater vehicle equipped with reflectors as a virtual exploration tool. Additionally, the application included information about the wreck, its discovery and underwater work, including interviews with experts in this field [37].

The second archaeological site is the villa with a vestibule ("Villa con ingresso a protiro"), dating back to the first half of the 19th century. The site itself dates back to the 2nd century AD, and is part of the ruins of the Roman city of Baiae, located near Naples, Italy [124–126]. The current archaeological site was a vacation spot in the past, appreciated by the Roman aristocracy. As a result of volcanic activity (tectonic movements), a significant part of the settlement was below sea level around the 4th/5th century AD [124,126]. In the case of this archaeological site, the virtual application allows users to interact with the current state of the ruins of the sunken city and its hypothetical 3D reconstruction. Additionally, the application introduces a narrative that deepens the historical and archaeological understanding and provides additional knowledge about sunken artifacts—Figure 7 [124,125].

(**a**) (**b**)

Figure 7. Visualizations from the dry visit—dive into underwater archaeological sites—iMARECulture application (selected shots from promotional materials): (**a**) view of the ruins of the Roman city of Baiae from the perspective of a diver—representation of the actual state of the site; (**b**) narrative module.

Moreover, in the case of this archaeological site, an AR system analogous to the systems used in the VISAS project was prepared [125]. An application on a tablet adapted for underwater use allows divers to explore selected underwater routes and obtain additional information about the found artifacts [1,122,125].

The third archaeological site is the Mazotos shipwreck in Cyprus, or rather its outline, which was recorded in the cargo being transported. The archaeological site is located 44 m underwater, 14 nautical miles southwest of Larnaca, 1.5 miles from the shore [31]. It consists of a cluster of amphorae measuring 17.5 × 8 m, located on a sandy, almost flat area of the seabed. It has the form of a ship and contains 500–800 Chian amphorae, partially or fully visible, dating to the mid-4th century BC [31,127]. This position is inaccessible to most people due to its depth and conservation considerations. In order to make it more widely available for both research and entertainment purposes, it was decided to realistically model and map this archaeological site using visual data, and then create an application based on VR enabling underwater exploration of the Mazotos shipwreck.

Images from multiple uncalibrated underwater cameras processed using the structure-from-motion (SfM) pipeline and Dense Image Matching (DIM) were used to model and 3D map the wreck. The processed 3D visualizations were used to create a feasible application in VR, for an application requiring VR goggles (e.g., "HTC VIVE"). The purpose of the application was mainly archaeological visualization, including enabling the exploration of underwater archaeological sites related to the wreck [31]. Additionally, in order to make the application more attractive to a wider audience, randomly appearing elements of the seabed, i.e., plants, fish, stones, etc., have been added. The application has also been enriched with historical data, including information about the shipwreck and its cargo (i.e., text descriptions, videos, and sounds), which uses archaeological knowledge and raises the cultural awareness of the recipient [31,86].

The limitation of the created application is its compatibility with only one virtual reality headset—the "HTC VIVE". Another objection to the application may be the fact that a significant part of the VR, i.e., the placement of amphorae, wood, rocks, and vegetation, is procedurally generated using a stochastic approach, which means that it does not faithfully reflect the conditions underwater. It is estimated that 60% of the virtual environment is not an accurate reconstruction of an archaeological site [119].

It is also worth mentioning that the project also prepared auxiliary tools that were aimed at educating people in the field of the photogrammetry method. The target group of this application was archeology students [51].

5.10. BLUMED and BLUMED PLUS Projects

The projects are a continuation and extension of the VENUS project [119]. The BLUMED project was implemented in the years 2016–2021 by a consortium consisting of 14 organizations from the following countries: Italy, Cyprus, Spain, France, Greece, Croatia, Malta, Portugal, and Slovenia [128]. The projects did not create new virtual solutions, but previously developed solutions were implemented in new places, including archaeological sites. The focal points of the BLUMED project were as follows [128]:

- Underwater archaeological park—Baiae, Italy, where existing VR solutions have been improved;
- Marine protected area—Capo Rizzuto, Italy, including the underwater archaeological site of Punto Scifo D, where existing VR solutions have been improved and stands in the local museum have been additionally adapted to allow the introduction of VR systems as exhibition elements;
- Underwater museum—Alonissos/Sporades, Greece, where a VR site was created allowing for diving to the Peristera wreck (a wreck dating back to the 5th century BC);
- The Underwater Museum of Western Pagasetic Gulf, Greece, where virtual sites were created for the Kikinthos, Akra Glaros and Telegrafos shipwrecks;
- Underwater archaeological sites of Cavtat, Croatia, where VR systems have been implemented for the local archaeological site.

In this case, virtual applications were only aimed at increasing the tourist attractiveness of selected places, using existing underwater archaeological sites for this purpose. The system did not develop original solutions in this area, but used applications developed as part of other projects, adapting them to the needs of the given archaeological sites [128].

5.11. MeDryDive Project

"Dive in the Past" is an educational game that allows you to simulate a virtual dive in the Mediterranean Sea and explore accurate 3D reconstructions of underwater archaeological sites. On the one hand, the application aims to engage divers and non-diving tourists in the virtual exploration of underwater archaeological sites through digital storytelling and in-game challenges, and on the other hand increase cultural awareness and archaeological knowledge of the heritage of the Mediterranean [105]. The game was developed as part of the MeDryDive project (COSME program), in which seven institutions from five European countries were involved: Italy, Greece, Croatia, Montenegro, and Albania. The project was implemented in 2019–2022 [129]. Unlike most applications of this type, the project focused on providing a faithful and complete reconstruction of submerged archaeological sites, rather than on the entertainment side [105].

The application offers four archaeological sites for virtual exploration:

- The World War II wreck Oreste was sunk by a mine in 1942 in Trsteno Bay, near Montenegro. The wreck lies in two parts at approximately 32 m [105].
- The 16th-century wreck of Gnalić, sunk in 1583 near Biograd Na Moru, Croatia. The ship transported goods from Venice to Constantinople. Currently, the wreck lies at a depth of between 23 and 27 m [105].
- Ruins of the Roman city of Baiae, located near Naples, Italy. The site is a flooded area of 177 ha, with a wide range of diverse architectural structures located up to 15 m below sea level. These are facilities such as fishing and port infrastructure, thermal baths, residential buildings and villas. The project focused on the complex "Villa con ingresso a protiro-Villa with vestibule" (Figure 8), which was also an object in underwater works carried out as part of the iMARECULTURE project, and the Sunken Nymphaeum of Claudius [105,124].
- The ancient wreck of the merchant ship Parister, which sank in the 5th century AD and was carrying a large cargo of amphorae. The wreck is located near the island of Alonissos, Greece. Currently, the wreck lies at a depth of between 22 and 28 m [105].

(**a**) (**b**)

Figure 8. Visualizations from the game Dive in the Past (selected shots from promotional materials): (**a**) view of the ruins of the Roman city of Baiae from a diver's perspective—a representation of the real state of the site; (**b**) a reconstruction of the archaeological site made in the game.

All four underwater archaeological sites included in the game are realistic 3D reconstructions. When visiting them, the user must conduct a kind of treasure hunt and at the same time get to know each of these objects in detail [105]. The game's time sequence follows the reverse chronological order of dating the archaeological sites. By visiting each of them, the user advances to subsequent levels of the game and at the same time gains historical, archaeological, and cultural information about underwater archaeological sites and the artifacts found there [105].

Additionally, the application, which has a plot and game scenarios, has been enriched with additional quizzes and mini-games that increase its educational value [105,129]. The use of an appropriate narrative in the game increases user engagement and strengthens the educational message [26,105]. "Dive in the Past" has been developed for both Android and iOS platforms, which allow users to play the game on smartphones and tablets. Additionally, it is also available in full VR technology, e.g., the "Oculus Quest" goggles [105].

6. Summary of the Current State and Possibilities of Development of Virtual Technologies in Underwater Archeology Applications

Table 2 summarizes the most important virtual applications that have been developed for underwater archeology sites to date. It is worth noting that this is not a complete list, but projects were only selected if they were either pioneering or included all the functions that allow a given reconstruction to be considered a full VR or AR, along with interactive functions typical of these applications.

Table 2. A list of the most important virtual applications in the field of underwater archeology.

No	Project	Archeological Site	Depth [m]	Years of Project	Application VR/AR	Aim of Application	Sources
1	Virtual Nau	Pepper Wreck	9	1996–2000	3D modeling of the wreck and virtual reconstruction of the ship's interior	CAVE environment allowing for scientific research	[15,111]
2	VENUS	Pianosa	35	2006–2009	Modeling of archaeological sites and artifacts	Interactive application available via websites; underwater vehicle piloting application	[15,34,112]
3	Re-discovering Vrouw Maria	Vrouw Maria wreck	41	2009–2012	VR system based on motion sensors	Interactive museum stand	[14,106]
4	VR CAVE	Mazotos wreck	44	2012–2014	3D visualizations with elements of a VR system	An interactive research station, visualizations of artifacts	[13,113]
5	ARROWS	Cala Minnola	25–30	2012 -2015	VR application that collects data and enables its visualization	An interactive station for research and education	[114,116]
6	ARROWS	Rummu, Estonia	Lack of data	2012–2015	VR application that collects data and enables its visualization	An interactive station for research and education	[114,116]
7	VISAS	Punta Scifo	7	2014–2016	VR application and underwater AR system for navigation	Interactive station and information provided during diving	[9]
8	VISAS	Cala Minnola	25–30	2014–2016	VR application and underwater AR system for navigation	Interactive station and information provided during diving	[118]
9	Melckmeyt wreck	Melckmeyt wreck	12	2016–2018	Visualization with interactive elements	Enrichment of the museum exhibition	[26]
10	Mercurio wreck	Mercurio wreck	17	2016–2017	VR application, a reconstruction of an archaeological site	Museum stand, providing data about a wreck that is inaccessible to divers	[100]
11	iMARECULTURE	Xlendi wreck	110	2016–2020	Reconstruction of the site in its current state, visualization of the past, VR application	Increasing user involvement in raising cultural awareness—an educational game	[37,121]

Table 2. *Cont.*

No	Project	Archeological Site	Depth [m]	Years of Project	Application VR/AR	Aim of Application	Sources
12	iMARECULTURE	Baiae city	Up to 15	2016–2020	Reconstruction of the site in its current state, visualization of the past, VR application and underwater AR system for navigation	Increasing user involvement in raising cultural awareness—an educational game	[37,121]
13	iMARECULTURE	Mazotos wreck	44	2016–2020	Reconstruction of the site in its current state, visualization of the past, VR application	Increasing user involvement in raising cultural awareness—an educational game	[37,121]
14	BLUEMED	VR improvements for 5 different sites	---	2016–2021	Application of existing virtual applications to new positions	Making museum exhibitions more attractive	[128]
15	MeDryDive	Oreste wreck	32	2019–2022	Reconstruction of the site in its current state, visualization of the past	An application using VR, including for mobile devices—an educational game	[105,129]
16	MeDryDive	Gnalić wreck	23–27	2019–2022	Reconstruction of the site in its current state, visualization of the past	An application using VR, including for mobile devices—an educational game	[105,129]
17	MeDryDive	Baiae city	Up to 15	2019–2022	Reconstruction of the site in its current state, visualization of the past	An application using VR, including for mobile devices—an educational game	[105,129]
18	MeDryDive	Paristera wreck	22–28	2019–2022	Reconstruction of the site in its current state, visualization of the past	An application using VR, including for mobile devices—an educational game	[105,129]

--- Not applied.

AR and VR solutions for underwater archeology currently use the best available practices at a global level, but are still implemented in a few places, while their "sharing" between different cultural centers should be possible. This is particularly important for popularizing the topic of preserving underwater cultural heritage. VR and AR solutions provide new opportunities, including the dissemination of the results of archaeological work [33], including the possibility of a simple "exchange" of this type of application between cultural units. For now, however, this opportunity is not widely taken.

The aspects that are highlighted as prospective for VR and AR applications are their personalization and design aimed at the needs of a specific group of recipients [130,131]. Currently, VR applications related to underwater archeology are not personalized. Perhaps this trend will appear in the future. AR applications are partially personalized or dedicated to a specific group of users. The first archaeological applications that have been personalized to a given person's tourist interests are already appearing, but for now, they concern "land" archeology [79,131]. An example of an application related to underwater archeology dedicated to the specific needs of users is the use of underwater tablets navigating around a specific underwater archaeological site [87].

Another trend in designing VR and AR applications is the creation in the so-called participatory approach, i.e., with the participation of target users [130,132]. This trend is partially visible in underwater archeology applications, where it is practically impossible to develop an application without one of the target groups—scientists. To have educational and scientific value, these applications must be based on data from archaeological research, and experts in this field are necessary to process them. The involvement of this target group therefore increases the quality of the final product through cooperation with professionals [133,134]. Here, a careful approach to the existing archaeological documentation may also be important for the development of systems, e.g., clear marking of fragments of wrecks created as part of data collection and those that were added to the composition in order to complement the 3D image of a given object, which may help in research work carried out on virtual models also by other researchers. However, the participatory approach in this area is not limited to professional users. VR programs intended for a wider population are also very often tested on a pilot group and as a result of this research, changes are introduced to the application [87,105].

Another interesting perspective in specialists' predictions is the increase in the inclusion of human factors in the application, including, among others, social relations [130,135]. In this respect, VR and AR applications do not have advanced solutions implemented, but they seem relatively easy to implement, taking into account their development in other areas.

Another broad issue is the development of equipment enabling the use of VR and AR. In this respect, the importance of applications dedicated to mobile devices is expected to increase. Currently, however, only a few applications related to underwater archeology offer such capabilities [105], and the vast majority require specialized equipment. Technological development also extends the spectrum of applications of virtual technologies in underwater archaeology. Applications in deep-sea archeology are also a promising direction of development for virtual technologies [8]. However, due to the costs, research on deep-sea sites is still not a standard task performed by archaeological institutions [8]. Another option is the integration of existing systems. Caspari and Crespo point to one of the possibilities for the development of archaeological systems as a combination of satellite systems with neural networks trained to search for potential archaeological sites [136]. It seems that similar prospects for the use of such technologies are promising for underwater archeology sites. On the one hand, it would be possible to combine neural networks with sonar, which would allow for searching large areas of the bottom of the ocean and identifying areas requiring further search. Such activities could be carried out using remote systems. On the other hand, it would allow the most promising of these places to be reproduced in VR and identify potential areas of interest for underwater archaeological work.

It should be noted that future potential applications of VR and AR technologies in underwater archeology depend solely on the imagination. It is worth noting that in the long term, it is very difficult to predict the development of the capabilities of a technology that did not even exist 50 years ago.

7. Conclusions

The analysis carried out as part of the article showed that VR and AR technologies are used in underwater archeology for various purposes. They are both research tools dedicated to professional applications and support the educational process at various levels, including educating students. These technologies are also eagerly used as a tool for popularizing and disseminating research results in the field of underwater archeology. In the latter respect, they are eagerly used by museum institutions as a tool to enrich exhibitions. Such use also stimulates the development of tourism in coastal areas.

The analyzed application examples confirmed that VR and AR technologies can provide significant support for underwater archeology activities, both at the research and educational levels, and are useful tools in popularizing the topic of underwater research. VR and AR help document cultural heritage and conservation work and increase its accessibility to audiences. The idea behind the use of these technologies is to offer both archaeologists and the wider public a new perspective on reconstructed archaeological sites, which enables archaeologists to analyze material obtained directly from the reconstructed site using a virtual site, and at the same time allows the wider audience to "immerse" themselves in a realistic exploration of selected archaeological sites. The main findings show that these technologies are particularly useful in hard-to-reach places, such as the deep sea, where time and skills play a significant role in reaching a given object. Additionally, it is worth noting that the use of these technologies in underwater archeology is carried out in accordance with market directions and expected future trends in technology development, including the use of a participatory approach and the design of user-oriented applications.

The further direction of development of VR and AR in underwater archeology depends solely on the imagination. However, it seems that this technology will be extended in three parallel directions: science, education, and entertainment. All of them can also be integrated into new technological trends, such as artificial intelligence. This kind of software could be used for supporting archeological database analysis (image processing) or for providing better interaction with users in education and entertainment.

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References

1. Čejka, J.; Zsíros, A.; Liarokapis, F. A Hybrid Augmented Reality Guide for Underwater Cultural Heritage Sites. *Pers. Ubiquitous Comput.* **2020**, *24*, 815–828. [CrossRef]
2. Jiménez Fernández-Palacios, B.; Morabito, D.; Remondino, F. Access to Complex Reality-Based 3D Models Using Virtual Reality Solutions. *J. Cult. Herit.* **2017**, *23*, 40–48. [CrossRef]
3. Liritzis, I.; Korka, E. Archaeometry's Role in Cultural Heritage Sustainability and Development. *Sustainability* **2019**, *11*, 1972. [CrossRef]
4. Menna, F.; Agrafiotis, P.; Georgopoulos, A. State of the Art and Applications in Archaeological Underwater 3D Recording and Mapping. *J. Cult. Herit.* **2018**, *33*, 231–248. [CrossRef]
5. Benjamin, J.; O'Leary, M.; McDonald, J.; Wiseman, C.; McCarthy, J.; Beckett, E.; Morrison, P.; Stankiewicz, F.; Leach, J.; Hacker, J.; et al. Correction: Aboriginal Artefacts on the Continental Shelf Reveal Ancient Drowned Cultural Landscapes in Northwest Australia. *PLoS ONE* **2023**, *18*, e0287490. [CrossRef] [PubMed]
6. Gregory, D.J. Development of Tools and Techniques to Survey, Assess, Stabilise, Monitor and Preserve Underwater Archaeological Sites: SASMAP. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Bethesda, MD, USA, 2015; Volume 40, pp. 173–177. [CrossRef]
7. Sturt, F.; Flemming, N.C.; Carabias, D.; Jöns, H.; Adams, J. The next Frontiers in Research on Submerged Prehistoric Sites and Landscapes on the Continental Shelf. *Proc. Geol. Assoc.* **2018**, *129*, 654–683. [CrossRef]
8. Søreide, F. Cost-Effective Deep Water Archaeology: Preliminary Investigations in Trondheim Harbour. *Int. J. Naut. Archaeol.* **2000**, *29*, 284–293. [CrossRef]
9. Bruno, F.; Lagudi, A.; Barbieri, L.; Muzzupappa, M.; Ritacco, G.; Cozza, A.; Cozza, M.; Peluso, R.; Lupia, M.; Cario, G. Virtual and Augmented Reality Tools to Improve the Exploitation of Underwater Archaeological Sites by Diver and Non-Diver Tourists. In *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*; Ioannides, M., Fink, E., Moropoulou, A., Hagedorn-Saupe, M., Fresa, A., Liestøl, G., Rajcic, V., Grussenmeyer, P., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, Switzerland, 2016; Volume 10058, pp. 269–280. ISBN 978-3-319-48495-2.
10. Malliri, A.; Siountri, K.; Skondras, E.; Vergados, D.D.; Anagnostopoulos, C.-N. The enhancement of underwater cultural heritage assets using augmented reality (AR). In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Bethesda, MD, USA, 2019; Volume 42, pp. 119–125. [CrossRef]

11. Zhang, J.; Wan Yahaya, W.A.J.; Sanmugam, M. The Impact of Immersive Technologies on Cultural Heritage: A Bibliometric Study of VR, AR, and MR Applications. *Sustainability* **2024**, *16*, 6446. [CrossRef]
12. Panagiotakopoulos, D.; Dimitrantzou, K. Intelligent Ticket with Augmented Reality Applications for Archaeological Sites. In *Strategic Innovative Marketing and Tourism*; Kavoura, A., Kefallonitis, E., Theodoridis, P., Eds.; Springer Proceedings in Business and Economics; Springer International Publishing: Cham, Switzerland, 2020; pp. 41–49. ISBN 978-3-030-36125-9.
13. Katsouri, I.; Tzanavari, A.; Herakleous, K.; Poullis, C. Visualizing and Assessing Hypotheses for Marine Archaeology in a VR CAVE Environment. *J. Comput. Cult. Herit.* **2015**, *8*, 1–18. [CrossRef]
14. Reunanen, M.; Díaz, L.; Horttana, T. A Holistic User-Centered Approach to Immersive Digital Cultural Heritage Installations: Case Vrouw Maria. *J. Comput. Cult. Herit.* **2015**, *7*, 1–16. [CrossRef]
15. Catsambis, A.; Ford, B.; Hamilton, D.L. (Eds.) *The Oxford Handbook of Maritime Archaeology*; First issued as an Oxford University Press paperback; Oxford University Press: Oxford, UK; New York, NY, USA; Auckland, New Zealand; Cape Town, South Africa, 2014; ISBN 978-0-19-933600-5.
16. Korniejenko, K. Wykorzystanie wirtualnej rzeczywistości jako nowoczesnego narzędzia wsparcia w kształceniu inżynierów. *Zesz. Nauk. Wydziału Elektrotechniki Autom. Politech. Gdańskiej* **2018**, *58*, 37–40.
17. Lee, L.-K.; Wei, X.; Chui, K.T.; Cheung, S.K.S.; Wang, F.L.; Fung, Y.-C.; Lu, A.; Hui, Y.K.; Hao, T.; U, L.H.; et al. A Systematic Review of the Design of Serious Games for Innovative Learning: Augmented Reality, Virtual Reality, or Mixed Reality? *Electronics* **2024**, *13*, 890. [CrossRef]
18. Arena, F.; Collotta, M.; Pau, G.; Termine, F. An Overview of Augmented Reality. *Computers* **2022**, *11*, 28. [CrossRef]
19. KnowledgeNile. Virtual Reality History: Complete Timeline Explained. Available online: https://www.knowledgenile.com/blogs/virtual-reality-history-complete-timeline-explained (accessed on 5 August 2024).
20. iB Cricket. The Story of Virtual Reality. Available online: https://ib.cricket/the-story-of-virtual-reality/ (accessed on 5 August 2024).
21. Berkman, M.I. History of Virtual Reality. In *Encyclopedia of Computer Graphics and Games*; Lee, N., Ed.; Springer International Publishing: Cham, Switzerland, 2024; pp. 873–881. ISBN 978-3-031-23159-9.
22. Carmigniani, J.; Furht, B. Augmented Reality: An Overview. In *Handbook of Augmented Reality*; Furht, B., Ed.; Springer: New York, NY, USA, 2011; pp. 3–46. ISBN 978-1-4614-0063-9.
23. Schuster, C.M.; Moloney, M.J. The Future of Virtual Reality in Education. In Proceedings of the 13th International Conference on Education Technology and Computers, Wuhan, China, 22–25 October 2021; pp. 85–89.
24. Virtual Reality Society. History of Virtual Reality. Available online: https://www.vrs.org.uk/virtual-reality/history.html (accessed on 5 August 2024).
25. Richards, J.D. Recent Trends in Computer Applications in Archaeology. *J. Archaeol. Res.* **1998**, *6*, 331–382. [CrossRef]
26. McCarthy, J.; Martin, K. Virtual Reality for Maritime Archaeology in 2.5D: A Virtual Dive on a Flute Wreck of 1659 in Iceland. In Proceedings of the 2019 23rd International Conference in Information Visualization—Part II, Adelaide, Australia, 16–19 July 2019; pp. 104–109.
27. Akçayır, M.; Akçayır, G.; Pektaş, H.M.; Ocak, M.A. Augmented Reality in Science Laboratories: The Effects of Augmented Reality on University Students' Laboratory Skills and Attitudes toward Science Laboratories. *Comput. Hum. Behav.* **2016**, *57*, 334–342. [CrossRef]
28. Oppermann, L.; Prinz, W. Introduction to This Special Issue on Smart Glasses. *i-com* **2016**, *15*, 123–132. [CrossRef]
29. Li, X.; Yi, W.; Chi, H.-L.; Wang, X.; Chan, A.P.C. A Critical Review of Virtual and Augmented Reality (VR/AR) Applications in Construction Safety. *Autom. Constr.* **2018**, *86*, 150–162. [CrossRef]
30. Rekimoto, J.; Ayatsuka, Y. CyberCode: Designing Augmented Reality Environments with Visual Tags. In Proceedings of the DARE 2000 on Designing Augmented Reality Environments, Elsinore, Denmark, 12–14 April 2000; pp. 1–10.
31. Liarokapis, F.; Kouřil, P.; Agrafiotis, P.; Demesticha, S.; Chmelík, J.; Skarlatos, D. 3D modelling and mapping for virtual exploration of underwater archaeology assets. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Bethesda, MD, USA, 2017; Volume 42, pp. 425–431. [CrossRef]
32. Bikonis, K. Algorytmy Rekonstrukcji Kształtu dna Morskiego i Trójwymiarowa Wizualizacja Obiektów Podwodnych. Ph.D. Thesis, Politechnika Gdańska, Gdansk, Poland, 2007.
33. McCarthy, J.; Benjamin, J.; Winton, T.; Van Duivenvoorde, W. The Rise of 3D in Maritime Archaeology. In *3D Recording and Interpretation for Maritime Archaeology*; McCarthy, J.K., Benjamin, J., Winton, T., Van Duivenvoorde, W., Eds.; Coastal Research Library; Springer International Publishing: Cham, Switzerland, 2019; Volume 31, pp. 1–10. ISBN 978-3-030-03634-8.
34. Haydar, M.; Roussel, D.; Maïdi, M.; Otmane, S.; Mallem, M. Virtual and Augmented Reality for Cultural Computing and Heritage: A Case Study of Virtual Exploration of Underwater Archaeological Sites (Preprint). *Virtual Real.* **2011**, *15*, 311–327. [CrossRef]
35. Bekler, M.; Yilmaz, M.; Ilgın, H.E. Assessing Feature Importance in Eye-Tracking Data within Virtual Reality Using Explainable Artificial Intelligence Techniques. *Appl. Sci.* **2024**, *14*, 6042. [CrossRef]
36. Usidus Mirosław Rozkwit Techniki Pokazywania Więcej niż w Rzeczywistości. Młody Tech. 2021. Available online: https://mlodytechnik.pl/technika/30486-rozkwit-techniki-pokazywania-wiecej-niz-w-rzeczywistosci (accessed on 1 August 2024).
37. Skarlatos, D.; Agrafiotis, P.; Balogh, T.; Bruno, F.; Castro, F.; Petriaggi, B.D.; Demesticha, S.; Doulamis, A.; Drap, P.; Georgopoulos, A.; et al. Project iMARECULTURE: Advanced VR, iMmersive Serious Games and Augmented REality as Tools to Raise Awareness and Access to European Underwater CULTURal heritagE. In *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*; Ioannides, M., Fink, E., Moropoulou, A., Hagedorn-Saupe, M., Fresa, A., Liestøl, G., Rajcic, V., Grussenmeyer, P., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, Switzerland, 2016; Volume 10058, pp. 805–813. ISBN 978-3-319-48495-2.

38. Jain, D.; Sra, M.; Guo, J.; Marques, R.; Wu, R.; Chiu, J.; Schmandt, C. Immersive Terrestrial Scuba Diving Using Virtual Reality. In Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems, San Jose, CA, USA, 7–12 May 2016; pp. 1563–1569.
39. Amfibian Amfibian Scuba VR. VR Simulator to Experience Scuba Diving Virtually in a Terrestrial Setting. Available online: https://sites.cs.ucsb.edu/~sra/amphibian.html (accessed on 5 August 2024).
40. Plecher, D.A.; Keil, L.; Kost, G.; Fiederling, M.; Eichhorn, C.; Klinker, G. Exploring Underwater Archaeology Findings with a Diving Simulator in Virtual Reality. *Front. Virtual Real.* **2022**, *3*, 901335. [CrossRef]
41. Corrales-Serrano, M.; Merchán, P.; Merchán, M.J.; Pérez, E. Virtual Reality Applied to Heritage in Higher Education—Validation of a Questionnaire to Evaluate Usability, Learning, and Emotions. *Heritage* **2024**, *7*, 2792–2810. [CrossRef]
42. Passaro, S.; Barra, M.; Saggiomo, R.; Di Giacomo, S.; Leotta, A.; Uhlen, H.; Mazzola, S. Multi-Resolution Morpho-Bathymetric Survey Results at the Pozzuoli–Baia Underwater Archaeological Site (Naples, Italy). *J. Archaeol. Sci.* **2013**, *40*, 1268–1278. [CrossRef]
43. Aucelli, P.P.C.; Mattei, G.; Caporizzo, C.; Cinque, A.; Amato, L.; Stefanile, M.; Pappone, G. Multi-Proxy Analysis of Relative Sea-Level and Paleoshoreline Changes during the Last 2300 Years in the Campi Flegrei Caldera, Southern Italy. *Quat. Int.* **2021**, *602*, 110–130. [CrossRef]
44. Ferreira, F.; Machado, D.; Ferri, G.; Dugelay, S.; Potter, J. Underwater Optical and Acoustic Imaging: A Time for Fusion? A Brief Overview of the State-of-the-Art. In Proceedings of the OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, USA, 19–23 September 2016; pp. 1–6.
45. Polymenis, I.; Haroutunian, M.; Norman, R.; Trodden, D. Virtual Underwater Datasets for Autonomous Inspections. *J. Mar. Sci. Eng.* **2022**, *10*, 1289. [CrossRef]
46. González-Merino, R.; Sánchez-López, E.; Romero, P.E.; Rodero, J.; Hidalgo-Fernández, R.E. Low-Cost Prototype to Automate the 3D Digitization of Pieces: An Application Example and Comparison. *Sensors* **2021**, *21*, 2580. [CrossRef]
47. Costa, E. The progress of survey techniques in underwater sites: The case study of cape stoba shipwreck. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Bethesda, MD, USA, 2019; Volume 42, pp. 69–75. [CrossRef]
48. Aucelli, P.; Cinque, A.; Mattei, G.; Pappone, G.; Rizzo, A. Studying Relative Sea Level Change and Correlative Adaptation of Coastal Structures on Submerged Roman Time Ruins Nearby Naples (Southern Italy). *Quat. Int.* **2019**, *501*, 328–348. [CrossRef]
49. Simyrdanis, K.; Bailey, M.; Moffat, I.; Roberts, A.; Van Duivenvoorde, W.; Savvidis, A.; Cantoro, G.; Bennett, K.; Kowlessar, J. Resolving Dimensions: A Comparison Between ERT Imaging and 3D Modelling of the Barge Crowie, South Australia. In *3D Recording and Interpretation for Maritime Archaeology*; McCarthy, J.K., Benjamin, J., Winton, T., Van Duivenvoorde, W., Eds.; Coastal Research Library; Springer International Publishing: Cham, Switzerland, 2019; Volume 31, pp. 175–186. ISBN 978-3-030-03634-8.
50. Calantropio, A.; Chiabrando, F.; Auriemma, R. Photogrammetric underwater and uas surveys of archaeological sites: The case study of the roman shipwreck of torre santa sabina. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Bethesda, MD, USA, 2021; Volume 43, pp. 643–650. [CrossRef]
51. Doležal, M.; Vlachos, M.; Secci, M.; Demesticha, S.; Skarlatos, D.; Liarokapis, F. Understanding underwater photogrammetry for maritime archaeology through immersive virtual reality. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Bethesda, MD, USA, 2019; Volume 42, pp. 85–91. [CrossRef]
52. Ballarin, M.; Balletti, C.; Guerra, F. *Action Cameras and Low-Cost Aerial Vehicles in Archaeology*; Remondino, F., Shortis, M.R., Eds.; The International Society for Optical Engineering: Munich, Germany, 2015; p. 952813.
53. Eriksson, N.; Rönnby, J. *Mars* (1564): The Initial Archaeological Investigations of a Great 16th-Century Swedish Warship. *Int. J. Naut. Archaeol.* **2017**, *46*, 92–107. [CrossRef]
54. Royal, J.G.; McManamon Sj, J.M. At the Transition from Late Medieval to Early Modern: The Archaeology of Three Wrecks from Turkey: The archaeology of three wrecks from turkey. *Int. J. Naut. Archaeol.* **2010**, *39*, 327–344. [CrossRef]
55. Giatsiatsou, P. Predictive Modelling in Underwater Archaeology. A Case Based on Mesolithic Coastal Settlements in Denmark. *Acta Archaeol.* **2024**, *94*, 3–11. [CrossRef]
56. Nawaf, M.; Drap, P.; Ben-Ellefi, M.; Nocerino, E.; Chemisky, B.; Chassaing, T.; Colpani, A.; Noumossie, V.; Hyttinen, K.; Wood, J.; et al. Using virtual or augmented reality for the time-based study of complex underwater archaeological excavations. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *8*, 117–124. [CrossRef]
57. Walcutt, N.L.; Knörlein, B.; Sgouros, T.; Cetinić, I.; Omand, M.M. Virtual Reality and Oceanography: Overview, Applications, and Perspective. *Front. Mar. Sci.* **2019**, *6*, 644. [CrossRef]
58. Scollen, R.; Mason, A. Shark Dive and Hologram Zoo: Two Case Studies of Virtual Animal Encounters as Possible Models for Sustainable Wildlife Tourism. *Animals* **2024**, *14*, 926. [CrossRef] [PubMed]
59. Ujkani, A.; Hohnrath, P.; Grundmann, R.; Burmeister, H.-C. Enhancing Maritime Navigation with Mixed Reality: Assessing Remote Pilotage Concepts and Technologies by In Situ Testing. *J. Mar. Sci. Eng.* **2024**, *12*, 1084. [CrossRef]
60. Quan, W.; Liu, S.; Cao, M.; Zhao, J. A Comprehensive Review of Virtual Reality Technology for Cognitive Rehabilitation in Patients with Neurological Conditions. *Appl. Sci.* **2024**, *14*, 6285. [CrossRef]

61. Singh, R.P.; Javaid, M.; Kataria, R.; Tyagi, M.; Haleem, A.; Suman, R. Significant Applications of Virtual Reality for COVID-19 Pandemic. *Diabetes Metab. Syndr. Clin. Res. Rev.* **2020**, *14*, 661–664. [CrossRef]
62. Aguilar, R.; Montesinos, M.; Uceda, S. Mechanical Characterization of the Structural Components of Pre-Columbian Earthen Monuments: Analysis of Bricks and Mortar from Huaca de La Luna in Perú. *Case Stud. Constr. Mater.* **2017**, *6*, 16–28. [CrossRef]
63. Tini, M.A.; Forte, A.; Girelli, V.A.; Lambertini, A.; Roggio, D.S.; Bitelli, G.; Vittuari, L. Scan-to-HBIM-to-VR: An Integrated Approach for the Documentation of an Industrial Archaeology Building. *Remote Sens.* **2024**, *16*, 2859. [CrossRef]
64. Andalib, S.Y.; Monsur, M. Co-Created Virtual Reality (VR) Modules in Landscape Architecture Education: A Mixed Methods Study Investigating the Pedagogical Effectiveness of VR. *Educ. Sci.* **2024**, *14*, 553. [CrossRef]
65. Alam, M.F.; Katsikas, S.; Beltramello, O.; Hadjiefthymiades, S. Augmented and Virtual Reality Based Monitoring and Safety System: A Prototype IoT Platform. *J. Netw. Comput. Appl.* **2017**, *89*, 109–119. [CrossRef]
66. De Souza Cardoso, L.F.; Mariano, F.C.M.Q.; Zorzal, E.R. A Survey of Industrial Augmented Reality. *Comput. Ind. Eng.* **2020**, *139*, 106159. [CrossRef]
67. Tatić, D.; Tešić, B. The Application of Augmented Reality Technologies for the Improvement of Occupational Safety in an Industrial Environment. *Comput. Ind.* **2017**, *85*, 1–10. [CrossRef]
68. Dordio, A.; Lancho, E.; Merchán, M.J.; Merchán, P. Cultural Heritage as a Didactic Resource through Extended Reality: A Systematic Review of the Literature. *Multimodal Technol. Interact.* **2024**, *8*, 58. [CrossRef]
69. Van Der Want, A.C.; Visscher, A.J. Virtual Reality in Preservice Teacher Education: Core Features, Advantages and Effects. *Educ. Sci.* **2024**, *14*, 635. [CrossRef]
70. Ahir, K.; Govani, K.; Gajera, R.; Shah, M. Application on Virtual Reality for Enhanced Education Learning, Military Training and Sports. *Augment. Hum. Res.* **2020**, *5*, 7. [CrossRef]
71. Demeco, A.; Salerno, A.; Gusai, M.; Vignali, B.; Gramigna, V.; Palumbo, A.; Corradi, A.; Mickeviciute, G.C.; Costantino, C. The Role of Virtual Reality in the Management of Football Injuries. *Medicina* **2024**, *60*, 1000. [CrossRef]
72. Andriyandi, A.P.; Darmalaksana, W.; Maylawati, D.S.; Irwansyah, F.S.; Mantoro, T.; Ramdhani, M.A. Augmented Reality Using Features Accelerated Segment Test for Learning Tajweed. *TELKOMNIKA* **2020**, *18*, 208. [CrossRef]
73. Sweeney, S.K.; Newbill, P.; Ogle, T.; Terry, K. Using Augmented Reality and Virtual Environments in Historic Places to Scaffold Historical Empathy. *TechTrends* **2018**, *62*, 114–118. [CrossRef]
74. Marques, C.G.; Pedro, J.P.; Araújo, I. A Systematic Literature Review of Gamification in/for Cultural Heritage: Leveling up, Going Beyond. *Heritage* **2023**, *6*, 5935–5951. [CrossRef]
75. Ferdani, D.; Fanini, B.; Piccioli, M.C.; Carboni, F.; Vigliarolo, P. 3D Reconstruction and Validation of Historical Background for Immersive VR Applications and Games: The Case Study of the Forum of Augustus in Rome. *J. Cult. Herit.* **2020**, *43*, 129–143. [CrossRef]
76. Pérez-Reverte Mañas, C.; Cerezo Andreo, F.; López Osorio, P.; González Gallero, R.; Mariscal Rico, L.; Arévalo González, A. Underwater Cultural Heritage as an Engine for Social, Economic and Cultural Development. State of Research at the University of Cadiz (Andalusia, Spain). *Heritage* **2021**, *4*, 2676–2690. [CrossRef]
77. Iacono, S.; Scaramuzzino, M.; Martini, L.; Panelli, C.; Zolezzi, D.; Perotti, M.; Traverso, A.; Vercelli, G.V. Virtual Reality in Cultural Heritage: A Setup for Balzi Rossi Museum. *Appl. Sci.* **2024**, *14*, 3562. [CrossRef]
78. Vlahakis, V.; Ioannidis, M.; Karigiannis, J.; Tsotros, M.; Gounaris, M.; Stricker, D.; Gleue, T.; Daehne, P.; Almeida, L. Archeoguide: An Augmented Reality Guide for Archaeological Sites. *IEEE Comput. Graph. Appl.* **2002**, *22*, 52–60. [CrossRef]
79. Kourouthanassis, P.; Boletsis, C.; Bardaki, C.; Chasanidou, D. Tourists Responses to Mobile Augmented Reality Travel Guides: The Role of Emotions on Adoption Behavior. *Pervasive Mob. Comput.* **2015**, *18*, 71–87. [CrossRef]
80. Panou, C.; Ragia, L.; Dimelli, D.; Mania, K. An Architecture for Mobile Outdoors Augmented Reality for Cultural Heritage. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 463. [CrossRef]
81. Dantes, G.R.; Suputra, P.H.; Sudarma, I.K.; Suwastini, N.K.A.; Dantes, K.R. Evaluating and Redesigning Virtual Reality "underwater Tourism" Application Based on Heuristic Method. *Int. J. Bus. Inf. Syst.* **2020**, *35*, 225. [CrossRef]
82. Pehlivanides, G.; Monastiridis, K.; Tourtas, A.; Karyati, E.; Ioannidis, G.; Bejelou, K.; Antoniou, V.; Nomikou, P. The VIRTUALDiver Project. Making Greece's Underwater Cultural Heritage Accessible to the Public. *Appl. Sci.* **2020**, *10*, 8172. [CrossRef]
83. Liestøl, G.; Bendon, M.; Hadjidaki-Marder, E. Augmented Reality Storytelling Submerged. Dry Diving to a World War II Wreck at Ancient Phalasarna, Crete. *Heritage* **2021**, *4*, 4647–4664. [CrossRef]
84. Brioso, X.; Calderón, C.; Aguilar, R.; Pando, M.A. Preliminary Methodology for the Integration of Lean Construction, BIM and Virtual Reality in the Planning Phase of Structural Intervention in Heritage Structures. In *Structural Analysis of Historical Constructions*; Aguilar, R., Torrealva, D., Moreira, S., Pando, M.A., Ramos, L.F., Eds.; RILEM Bookseries; Springer International Publishing: Cham, Switzerland, 2019; Volume 18, pp. 484–492. ISBN 978-3-319-99440-6.
85. Burgos, M.; Castaneda, B.; Aguilar, R. Virtual Reality for the Enhancement of Structural Health Monitoring Experiences in Historical Constructions. In *Structural Analysis of Historical Constructions*; Aguilar, R., Torrealva, D., Moreira, S., Pando, M.A., Ramos, L.F., Eds.; RILEM Bookseries; Springer International Publishing: Cham, Switzerland, 2019; Volume 18, pp. 429–436. ISBN 978-3-319-99440-6.

86. Liarokapis, F.; Vidová, I.; Rizvić, S.; Demesticha, S.; Skarlatos, D. Underwater Search and Discovery: From Serious Games to Virtual Reality. In *HCI International 2020—Late Breaking Papers: Virtual and Augmented Reality*; Stephanidis, C., Chen, J.Y.C., Fragomeni, G., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, Switzerland, 2020; Volume 12428, pp. 178–197. ISBN 978-3-030-59989-8.
87. Bruno, F.; Barbieri, L.; Muzzupappa, M.; Tusa, S.; Fresina, A.; Oliveri, F.; Lagudi, A.; Cozza, A.; Peluso, R. Enhancing Learning and Access to Underwater Cultural Heritage through Digital Technologies: The Case Study of the "Cala Minnola" Shipwreck Site. *Digit. Appl. Archaeol. Cult. Herit.* **2019**, *13*, e00103. [CrossRef]
88. NatGeoTV. National Geographic—Drain the Ocean: Deep Sea Mysteries. Available online: https://www.natgeotv.com/pl/programy/natgeo/wyprawa-na-dno#opis (accessed on 5 August 2024).
89. Chen, G.; Yang, R.; Lu, P.; Chen, P.; Gu, W.; Wang, X.; Hu, Y.; Zhang, J. How Can We Understand the Past from Now On? Three-Dimensional Modelling and Landscape Reconstruction of the Shuanghuaishu Site in the Central Plains of China. *Remote Sens.* **2022**, *14*, 1233. [CrossRef]
90. Mel, K.; Luca, B.; Fabio, V.; Varvara, A.; Ugo, B.; Elena, R.; Fabio, M.; Luca, F.; Paraskevi, N.; Martin, K.; et al. Workflows for Virtual Reality Visualisation and Navigation Scenarios in Earth Sciences. In *Proceedings of the 5th International Conference on Geographical Information Systems Theory, Applications and Management*; Heraklion, Greece, 3–5 May 2019, Science and Technology Publications; SciTePress: Setúbal, Portugal, 2019; pp. 297–304.
91. Lin, G.; Li, G.; Giordano, A.; Sang, K.; Stendardo, L.; Yang, X. Three-Dimensional Documentation and Reconversion of Architectural Heritage by UAV and HBIM: A Study of Santo Stefano Church in Italy. *Drones* **2024**, *8*, 250. [CrossRef]
92. Manzollino, R.; Chellini, G.; La Torre, P.; Malatesta, S.G.; Marini, M.R.; Moricca, C. Archaeobotany and Bioanthropology: The Potential of VR and 3D Printing in the Enhancement of Archaeological Organic Remains. In Proceedings of the Una Quantum, Rome, Italy, 15–16 December 2022; p. 15.
93. Lin, C.-L.; Chen, S.-J.; Lin, R. Efficacy of Virtual Reality in Painting Art Exhibitions Appreciation. *Appl. Sci.* **2020**, *10*, 3012. [CrossRef]
94. Domżał, R. MUZEALNICTWO MORSKIE I OCHRONA ZABYTKÓW W CHINACH. *Muzealnictwo* **2016**, *2016*, 47–58. [CrossRef]
95. Chernbumroong, S.; Ariya, P.; Yolthasart, S.; Wongwan, N.; Intawong, K.; Puritat, K. Comparing the Impact of Non-Gamified and Gamified Virtual Reality in Digital Twin Virtual Museum Environments: A Case Study of Wieng Yong House Museum, Thailand. *Heritage* **2024**, *7*, 1870–1892. [CrossRef]
96. Anastasovitis, E.; Georgiou, G.; Matinopoulou, E.; Nikolopoulos, S.; Kompatsiaris, I.; Roumeliotis, M. Enhanced Inclusion through Advanced Immersion in Cultural Heritage: A Holistic Framework in Virtual Museology. *Electronics* **2024**, *13*, 1396. [CrossRef]
97. Koutsabasis, P.; Vosinakis, S. Kinesthetic Interactions in Museums: Conveying Cultural Heritage by Making Use of Ancient Tools and (Re-) Constructing Artworks. *Virtual Real.* **2018**, *22*, 103–118. [CrossRef]
98. Khadhraoui, A.; Beji, L.; Otmane, S.; Abichou, A. Stabilizing Control and Human Scale Simulation of a Submarine ROV Navigation. *Ocean Eng.* **2016**, *114*, 66–78. [CrossRef]
99. Dücker, J.; Häfner, P.; Ovtcharova, J. Methodology for Efficiency Analysis of VR Environments for Industrial Applications. In *Augmented Reality, Virtual Reality, and Computer Graphics*; De Paolis, L.T., Mongelli, A., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, Switzerland, 2016; Volume 9768, pp. 72–88. ISBN 978-3-319-40620-6.
100. Secci, M.; Beltrame, C.; Manfio, S.; Guerra, F. Virtual Reality in Maritime Archaeology Legacy Data for a Virtual Diving on the Shipwreck of the Mercurio (1812). *J. Cult. Herit.* **2019**, *40*, 169–176. [CrossRef]
101. Nourbakhsh, S.; Rehman, U.S.A.; Carbonneau, H.; Archambault, P.S. Development and Validation of Virtual Reality Scenarios to Improve Disability Awareness among Museum Employees. *Disabilities* **2024**, *4*, 525–538. [CrossRef]
102. Radianti, J.; Majchrzak, T.A.; Fromm, J.; Wohlgenannt, I. A Systematic Review of Immersive Virtual Reality Applications for Higher Education: Design Elements, Lessons Learned, and Research Agenda. *Comput. Educ.* **2020**, *147*, 103778. [CrossRef]
103. Cheng, J.; Wang, Y.; Tjondronegoro, D.; Song, W. Construction of Interactive Teaching System for Course of Mechanical Drawing Based on Mobile Augmented Reality Technology. *Int. J. Emerg. Technol. Learn.* **2018**, *13*, 126. [CrossRef]
104. Bursali, H.; Yilmaz, R.M. Effect of Augmented Reality Applications on Secondary School Students' Reading Comprehension and Learning Permanency. *Comput. Hum. Behav.* **2019**, *95*, 126–135. [CrossRef]
105. Cozza, M.; Isabella, S.; Di Cuia, P.; Cozza, A.; Peluso, R.; Cosentino, V.; Barbieri, L.; Muzzupappa, M.; Bruno, F. Dive in the Past: A Serious Game to Promote the Underwater Cultural Heritage of the Mediterranean Sea. *Heritage* **2021**, *4*, 4001–4016. [CrossRef]
106. Sen, F.; Diaz, L.; Horttana, T. A Novel Gesture-Based Interface for a VR Simulation: Re-Discovering Vrouw Maria. In Proceedings of the 2012 18th International Conference on Virtual Systems and Multimedia, Milan, Italy, 2–5 September 2012; pp. 323–330.
107. Potkonjak, V.; Gardner, M.; Callaghan, V.; Mattila, P.; Guetl, C.; Petrović, V.M.; Jovanović, K. Virtual Laboratories for Education in Science, Technology, and Engineering: A Review. *Comput. Educ.* **2016**, *95*, 309–327. [CrossRef]
108. Hornsey, R.L.; Hibbard, P.B. Current Perceptions of Virtual Reality Technology. *Appl. Sci.* **2024**, *14*, 4222. [CrossRef]
109. Osiadacz, M. The Virtual Reconstruction of an Early Medieval Folded Sickle from Nasielsk. *Przegląd Archeol.* **2020**, *68*, 187–198. [CrossRef]
110. Derboven, J.; Geerts, D.; De Grooff, D. Appropriating Virtual Learning Environments: A Study of Teacher Tactics. *J. Vis. Lang. Comput.* **2017**, *40*, 20–35. [CrossRef]
111. Castro, F.; Fonseca, N.; Wells, A. Outfitting the Pepper Wreck. *Hist. Archaeol.* **2010**, *44*, 14–34. [CrossRef]
112. Chapman, P.; Bale, K.; Drap, P. We All Live in a Virtual Submarine. *IEEE Comput. Grap. Appl.* **2010**, *30*, 85–89. [CrossRef]

113. VR CAVE. VR CAVE About. Available online: https://vrcave.com.cy/about/ (accessed on 5 August 2024).
114. Magrini, M.; Moroni, D.; Pascali, M.A.; Reggiannini, M.; Salvetti, O.; Tampucci, M. Virtual Environment as a Tool to Access the Marine Abysses. In Proceedings of the OCEANS 2015, Genova, Italy, 18–21 May 2015; pp. 1–5.
115. Preston, V.; Salumäe, T.; Kruusmaa, M. Underwater Confined Space Mapping by Resource-constrained Autonomous Vehicle. *J. Field Robot.* **2018**, *35*, 1122–1148. [CrossRef]
116. Allotta, B.; Costanzi, R.; Ridolfi, A.; Salvetti, O.; Reggiannini, M.; Kruusmaa, M.; Salumae, T.; Lane, D.M.; Frost, G.; Tsiogkas, N.; et al. The ARROWS Project: Robotic Technologies for Underwater Archaeology. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *364*, 012088. [CrossRef]
117. Bruno, F.; Lagudi, A.; Barbieri, L.; Muzzupappa, M.; Mangeruga, M.; Cozza, M.; Cozza, A.; Ritacco, G.; Peluso, R. Virtual Reality Technologies for the Exploitation of Underwater Cultural Heritage. In *Latest Developments in Reality-Based 3D Surveying and Modelling*; MDPI: Basel, Switzerland, 2018; ISBN 978-3-03842-685-1.
118. Bruno, F.; Lagudi, A.; Barbieri, L.; Muzzupappa, M.; Mangeruga, M.; Pupo, F.; Cozza, M.; Cozza, A.; Ritacco, G.; Peluso, R.; et al. Virtual diving in the underwater archaeological siteof cala minnola. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; International Society for Photogrammetry and Remote Sensing: Bethesda, MD, USA, 2017; Volume 42, pp. 121–126. [CrossRef]
119. Bruno, F.; Barbieri, L.; Lagudi, A.; Cozza, M.; Cozza, A.; Peluso, R.; Muzzupappa, M. Virtual Dives into the Underwater Archaeological Treasures of South Italy. *Virtual Real.* **2018**, *22*, 91–102. [CrossRef]
120. McCarthy, J. Virtual Dive on the Wreck of the Melckmeyt (1659), Iceland's Oldest Identified Shipwreck. Available online: https://www.youtube.com/watch?v=hovKu1bi7kA (accessed on 1 August 2024).
121. CORDIS. Advanced VR, iMmersive Serious Games and Augmented REality as Tools to Raise Awareness and Access to European Underwater CULTURal heritagE. Available online: https://cordis.europa.eu/project/id/727153 (accessed on 5 August 2024).
122. Bruno, F.; Lagudi, A.; Ritacco, G.; Agrafiotis, P.; Skarlatos, D.; Cejka, J.; Kouril, P.; Liarokapis, F.; Philpin-Briscoe, O.; Poullis, C.; et al. Development and Integration of Digital Technologies Addressed to Raise Awareness and Access to European Underwater Cultural Heritage. An Overview of the H2020 i-MARECULTURE Project. In Proceedings of the OCEANS 2017, Aberdeen, UK, 19–22 June 2017; pp. 1–10.
123. Poullis, C.; Kersten-Oertel, M.; Benjamin, J.P.; Philbin-Briscoe, O.; Simon, B.; Perissiou, D.; Demesticha, S.; Markou, E.; Frentzos, E.; Kyriakidis, P.; et al. Evaluation of "The Seafarers": A Serious Game on Seaborne Trade in the Mediterranean Sea during the Classical Period. *Digit. Appl. Archaeol. Cult. Herit.* **2019**, *12*, e00090. [CrossRef]
124. Bruno, F.; Lagudi, A.; Barbieri, L.; Cozza, M.; Cozza, A.; Peluso, R.; Davidde Petriaggi, B.; Petriaggi, R.; Rizvic, S.; Skarlatos, D. Virtual tour IN the sunken "villa con ingresso a protiro" within the underwater archaeological park of baiae. *ISPRS J. Photogramm. Remote Sens.* **2019**, *42*, 45–51. [CrossRef]
125. Bruno, F.; Barbieri, L.; Mangeruga, M.; Cozza, M.; Lagudi, A.; Čejka, J.; Liarokapis, F.; Skarlatos, D. Underwater Augmented Reality for Improving the Diving Experience in Submerged Archaeological Sites. *Ocean Eng.* **2019**, *190*, 106487. [CrossRef]
126. Petriaggi, B.D.; Petriaggi, R.; Bruno, F.; Lagudi, A.; Peluso, R.; Passaro, S. A Digital Reconstruction of the Sunken "Villa Con Ingresso a Protiro" in the Underwater Archaeological Site of Baiae. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *364*, 012013. [CrossRef]
127. Demesticha, S.; Skarlatos, D.; Neophytou, A. The 4th-Century B.C. Shipwreck at Mazotos, Cyprus: New Techniques and Methodologies in the 3D Mapping of Shipwreck Excavations. *J. Field Archaeol.* **2014**, *39*, 134–150. [CrossRef]
128. CORDIS BLUMED. Available online: https://cordis.europa.eu/project/id/727453 (accessed on 8 August 2024).
129. MyDryDive. MyDryDive Project. Available online: https://medrydive.eu/ (accessed on 8 August 2024).
130. Zhang, Y.; Liu, H.; Kang, S.-C.; Al-Hussein, M. Virtual Reality Applications for the Built Environment: Research Trends and Opportunities. *Autom. Constr.* **2020**, *118*, 103311. [CrossRef]
131. Kontogiorgakis, E.; Zidianakis, E.; Kontaki, E.; Partarakis, N.; Manoli, C.; Ntoa, S.; Stephanidis, C. Gamified VR Storytelling for Cultural Tourism Using 3D Reconstructions, Virtual Humans, and 360° Videos. *Technologies* **2024**, *12*, 73. [CrossRef]
132. Zhao, Q. The Application of Augmented Reality Visual Communication in Network Teaching. *Int. J. Emerg. Technol. Learn.* **2018**, *13*, 57. [CrossRef]
133. Zhou, L.; Wu, G.; Zuo, Y.; Chen, X.; Hu, H. A Comprehensive Review of Vision-Based 3D Reconstruction Methods. *Sensors* **2024**, *24*, 2314. [CrossRef]
134. Mak, S.L.; Tang, F.W.F.; Li, C.H.; Lee, G.T.W.; Chiu, W.H. A Review on Development and Application of Virtual Reality (VR) Training Platform for Testing, Inspection and Certification Industry. *Int. J. Inf. Educ. Technol.* **2020**, *10*, 926–931. [CrossRef]
135. Cruz, M.; Oliveira, A. Unravelling Virtual Realities—Gamers' Perceptions of the Metaverse. *Electronics* **2024**, *13*, 2491. [CrossRef]
136. Caspari, G.; Crespo, P. Convolutional Neural Networks for Archaeological Site Detection—Finding "Princely" Tombs. *J. Archaeol. Sci.* **2019**, *110*, 104998. [CrossRef]