Personal and Ubiquitous Computing
https://doi.org/10.1007/s00779-019-01354-6

ORIGINAL ARTICLE

A hybrid augmented reality guide for underwater cultural heritage sites

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Received: 6 August 2019 / Accepted: 29 November 2019

Abstract
Modern technologies allow us to experience cultural heritage sites in new and exciting ways. Recent improvements in mobile computing provide tools capable of running augmented reality in real-time performance. Augmented reality is the perfect medium for visualizing and interacting with cultural heritage sites including both buildings and artefacts. Currently, this is possible on land, but sites located in the sea under water are hard to access and present many challenges. In this paper, we present a novel augmented reality guide for divers to present ancient lost buildings at underwater archeological sites. The prototype system runs on a smartphone sealed in a waterproof case and uses a hybrid approach (markers and inertial sensors) to localize the diver on the site. Accuracy of the tracker is measured in a laboratory in a simulated underwater environment. The application was experimentally evaluated at an underwater archeological site in Italy in Baiae. A pilot study with ten expert divers was performed, and their feedback, obtained directly in water, showed that this new experience significantly enhances user experience in underwater archeological sites.

Keywords Augmented reality · Cultural heritage · Underwater · User experience

1 Introduction

Historical sites represent an essential element of the cultural heritage of nations. Modern technologies give people new opportunities to experience these sites, people enjoy learning important facts with serious games [23], they are offered virtual visits of historical places in museums or their homes using head-mounted displays (HMD) for virtual reality (VR), and see missing buildings at their original location with augmented reality (AR) [4]. AR technology can also help the tourists with navigation at the site and provide information about objects they see.

Many cultural heritage sites and historical objects are not on land but in the sea. These sites include cities that submerged under water due to volcanic activity, earthquakes, or tsunami waves, and merchant ships that sunk in a storm whose cargo can still be found on the bottom of the sea. One of the most interesting underwater sites is the city of Baiae, located in Italy near Naples. In the ancient times, this town was famous for its luxurious villas, imperial houses, spas, and thermae, but during the last two thousand years, it partially submerged due to the volcanic activity of near Vesuvius. Remains of many buildings are still present here, and since they are a few meters under water, they are easily accessible. One of such buildings is Villa con ingresso a protiro with a characteristic black-and-white mosaic in one of its rooms.

Unfortunately, such sites are difficult to access not only for underwater archeologists that study and preserve them but also for the general public that would like to visit them. Additionally, underwater marine locations represent a harsh environment for augmented reality systems in general, since they limit the methods of tracking and interaction. Positioning systems based on technologies like GPS of Wi-Fi are not available [26], and visual conditions under water in the sea are degraded by turbidity and small floating particles, limiting the visibility to just a few meters [34]. The devices must be protected from the water in waterproof housing, which often interferes with their controls.

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In this paper, we address these issues and present a novel system that uses augmented reality to enhance the user experience of divers visiting underwater archeological sites. This system uses artificial markers to specify important points of interest, which are tracked with a mobile device sealed in a waterproof housing held by the diver. The system is autonomous, and the localization requires only visual input obtained by the camera and internal measurement unit (IMU) of the device. To our knowledge, this is the first autonomous underwater system for augmented reality running in the harsh sea environment, which do not require any additional devices apart of a smartphone.

Our system is based on a solution presented by Neunert et al. [19], a marker-based system that is designed for clear visibility conditions and runs on a personal computer. We tested this solution in a laboratory in simulated underwater conditions, identified its weaknesses, and improved it to run on a smartphone, and handle the conditions of the sea.

The final system was tested in simulated underwater conditions, and then deployed at the location of the room with the mosaic of Villa con ingresso a protiro and evaluated by ten expert divers by analyzing their personal opinion and by using a questionnaire, which was filled immediately after the experience under water. Another novelty of this work is the data collection process, which was done underwater. Results of this evaluation indicate that the expert divers rated their interaction as natural and they enjoyed the whole experience. They also valued the easiness of the installation, and they expect that the system will be used in practice for touristic purposes in the near future.

This paper is organized as follows. After presenting the state of the art in the field of systems utilizing augmented reality in Section 2, Section 3 evaluates an existing tracking system designed for clear conditions in a simulated underwater environment, Section 4 adapts this system to work under water on mobile devices, Section 5 proposes an experiment to test this system on an underwater cultural heritage site, and Section 6 presents the results of this experiment. Finally, Section 7 concludes this paper.

2 State of the art

In the past two decades, augmented and virtual reality was successfully applied to enhance the user experience from archeological sites on land. Guttentag [9] presents a survey on using VR in tourism, focusing on various aspects of tourism, including preservation of cultural heritage, and discussing possible complications. Sylaiou et al. [30] and [29] provide surveys in terms of virtual and augmented reality museums for land application. Archeoguide [35] is one of the first mobile systems providing additional information about historical sites to tourists. This system consists of a mobile unit (laptop, tablet, head-mounted display) and an on-site server connected with the mobile unit using a wireless LAN. User position is obtained by the GPS and further refined by matching images. Seo et al. [27] discuss problems with tracking on various types of cultural heritage sites and proposes a tracking framework that is adaptable to different environments. Their solution is using a laptop and a USB camera. With advances in computation power of smartphones, latest solutions do not require a computer and a dedicated camera. CityViewAR [15] is a system for presenting 3D virtual models of non-existing building in augmented reality, with a focus on modern buildings lost in earthquakes. It uses the GPS and inertial sensors to track the position of users and runs on mobile devices supporting the Android operating system. CorfuAR [12] is a web-based system with optimized user interface presenting only textual information and icons superimposed using AR at proper locations in the real image. The system focuses on providing personalized recommendations for tourists that visit historical sites. Similarly, a system presented by Panou et al. [22] aims at improving the user experience from visiting cultural heritage places. This system uses gamification and adds components that reward users exploring various points of interest. KnossosAR [7] is a mobile AR system providing guided tours for secondary school students. It addresses the problems of navigation between points of interest, interaction with the system, occlusion of virtual an real objects, and engagement of the participants. Bjørkli et al. [2] present a system that uses AR to show a variation of the sea level in the last 10,000 years. Tscheu and Buhalis [32] focus on factors affecting the value of the virtual environments in cultural heritage applications. Jung et al. [11] investigate an impact of differences between cultures on perceived usefulness, enjoyment, and ease of use of AR applications.

AR under water is more complicated than on land. GPS, Wi-Fi, or Bluetooth signal is absorbed in water in distances greater than tens of centimeters [26], so the localization is limited on using cameras, inertial measurement units, sonars, and specialized hardware [8]. Construction of devices for displaying virtual content is also tricky since they are required to be resistant to underwater conditions. Morales et al. [18] present one of the first examples of systems that use augmented reality underwater and discusses its benefits in displaying visual cues and artificial horizons. Von Lukas et al. [17] provide a survey and typical use cases of AR and VR solutions underwater. Yamashita et al. [37] adapt CAVE systems for virtual reality to work with displays placed around a small pool with water, addressing problems with tracking and with reflections and distortions of presented images. Hatsushika et al. [10] proposes an HMD for underwater VR in swimming pools, which based on the existing solution for VR on land and can be used in depths of about 4 m. The system must be connected wich a wire to a VR-ready laptop that is running the application. Osone et al. [21] focus on a problem with the buoyancy of watertight underwater HMDs caused by air inside these devices and designs a specific case for HMDs that is partially filled with water to reduce this problem.

Regarding applications for underwater environments, Oppermann et al. [20] present a multiplayer underwater AR game for kids in swimming pools that uses markers to localize the points of interests. The system uses Wi-Fi to communicate with devices that are out of water. DOLPHYN [1] is a mobile and autonomous device providing an AR experience for divers in swimming pools. It also uses markers to localize underwater. Quarles [24] presents a virtual reality game for aquatic rehabilitation of injured or disabled people. Since the motion of the patient is limited, his system uses a simplified tracking solely based on inertial sensors. Bruno et al. [3] introduced a set of tools to show underwater cultural heritage sites for users on land using VR and for divers in the sea using AR and acoustic sonars.

The immersive underwater VR environment of the Mazotos shipwreck site [16] was designed to raise users' archeological knowledge by merging the digital model of the underwater archeological site with a procedurally generated environment composed by amphorae, wood, rocks, and vegetation. Moreover, an immersive VR application was developed to teach the basics of underwater excavation to future marine archeologists [13]. Finally, another educational VR application assists maritime archaeology students to learn basic photogrammetry techniques [5] and preliminary results indicated that the VR photogrammetry gamification techniques allow the creation of accurate measurements to be taken.

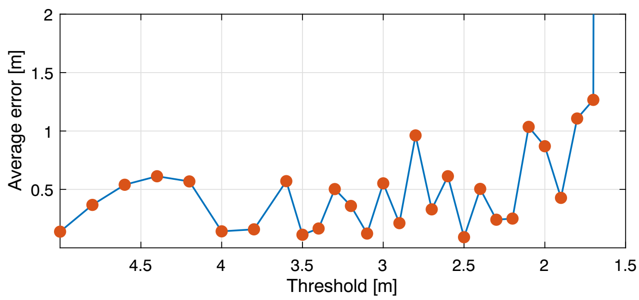
3 Existing tracking systems in simulated underwater environments

Precise tracking is a fundamental part of AR systems as they require to accurately place virtual objects at their positions. Neunert et al. [19] present an autonomous tracking system called RCARS that uses only a set of markers and inertial sensors to track the position of a moving robot. This system represents a possible candidate for tracking divers underwater, as it requires only a visual and inertial input. This section evaluates the system in a simulated underwater environment to assess its performance in poor visibility conditions in the sea.

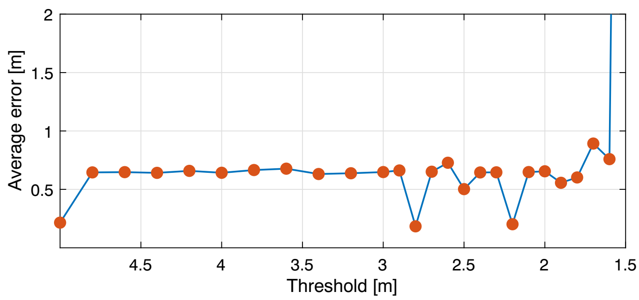
RCARS system uses the Robot Operating System (ROS) and runs on a PC with the Ubuntu operating system. It tracks markers with a highly accurate but slow AprilTag library [36]. The evaluation uses 27 markers distributed in a room of area of 5.4 m $\times$ 6.6 m, see Fig. 1, and recorded with a OnePlus 6 smartphone during three types of motion: clockwise circular motion around the room, counterclockwise circular motion around the room, and random motion around the room. The recorded data consisted of a stream of an uncompressed video in the resolution of 1280 $\times$ 720 pixels synchronized with the data from the inertial unit (accelerometer and gyroscope) sampled at 200 Hz. The smartphone was tracked with OptiTrack motion capture system to obtain its ground-truth position.

The video data were post-processed to imitate underwater environment. First, we simulated low visibility conditions by removing markers that were beyond a threshold representing the maximum visibility. Figure 2 shows the average error per frame at various visibility levels. As long

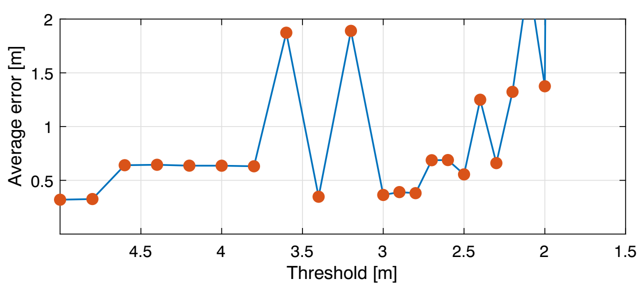
Fig. 1 Distribution of AprilTag markers



(a) Clockwise circular motion around the room



(b) Counterclockwise circular motion around the room



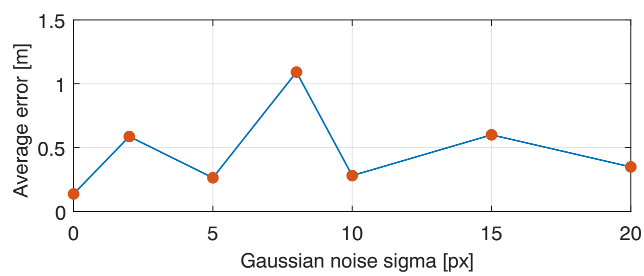
(c) Random motion around the room

Fig. 2 Average per frame errors in estimated position at various maximum visibility thresholds, when performing circular (**a**, **b**) or random (**c**) motions in the testing room. The error is below 2 m (often less than 1 m) until a certain threshold is reached. When the visibility is below this threshold, the tracking is lost and the error in tracking gets extremely high

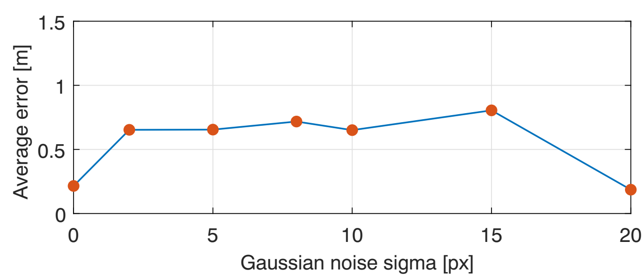
as the visibility is higher than a distance of approximately 2 m, the error lies within a reasonable range, but rises very high after exceeding this distance. Further investigation revealed that as long as the system sees at least a single marker, it uses its position to correct errors obtained by integrating results from the accelerometer. However, when the visibility is very low and no marker is visible, the position is derived only from sensors and the error gets extremely high.

We also performed another experiment to assess the effect of various levels of turbidity on the precision of the tracking. The simulation added a noise in the visual data, which increases due to the presence of small particles floating in the water, low contrast of images, and low intensities of incoming light. The corners of detected markers were displaced with a small Gaussian noise, which increased when decreasing the quality of the simulated environment. The results are presented in Fig. 3 and demonstrate that the system is much more robust to errors in the position of markers than in the previous experiment.

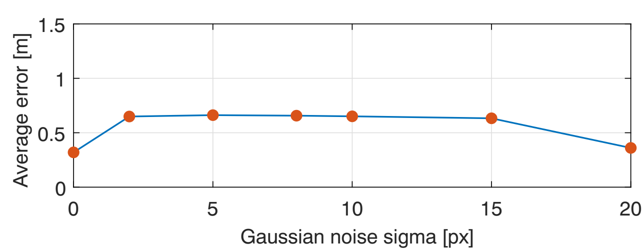
This evaluation showed that this system is a viable solution for tracking position of a diver underwater. It is robust to noise in input images and works even with a low number of visible markers. However, the system needs some improvements for mobile underwater augmented reality applications. Namely, the implementation must run fast on smartphones, and the error in the position must be kept in reasonable values even if all markers are lost.



(a) Clockwise circular motion around the room



(b) Counterclockwise circular motion around the room



(c) Random motion around the room

Fig. 3 Average per frame errors in position at various intensities of the Gaussian noise, when performing circular (**a**, **b**) or random (**c**) motions in the testing room. Although the error increases when displacing the corners with a small noise, it stays within reasonable values even when the displacement is large

4 Underwater augmented reality system for cultural heritage

The AR system for underwater application was based on the results of the RCARS system. Its general structure is presented in Fig. 4. Like RCARS, the system searches the recorded images for markers, fuses their positions with the data from inertial sensors using the Kalman filter, and uses the filtered position of the diver to place virtual objects at their proper positions. It also stores the data from the camera and sensors in the memory for further offline processing. Unlike RCARS, it uses a faster but less robust ARUco3 library for detecting markers, faster and simplified version of the Kalman filter, and it is more robust to a loss of the detected markers.

4.1 Detection of markers

The system uses the ARUco3 library [25] to detect markers in images. This library is faster than AprilTag, but is less robust to bad visibility conditions [33]. As the AprilTag library, it uses square markers containing a pattern resembling a 6 × 6 black-and-white matrix to distinguish between individual markers. In our system, a pair of these markers defines an anchor connecting a position in the real world with the corresponding position in the virtual model. The first marker of the pair defines the position of the anchor and must be placed at the proper position in the real world (e.g., in the corner of the room). The other marker defines the orientation of the anchor and is placed in a specific direction (e.g., along a wall), approximately 70 cm from the first marker. We estimate that this solution allows our system to compute the orientation of the anchor more precisely when compared to systems that use only a single marker for the anchor. The size of our whole anchor is larger, which makes it more robust to errors in positioning the markers under water. Additionally, the orientation of individual markers is irrelevant, which eases their installation on the site. The up-down direction of the virtual model is derived from the gravity vector that is estimated with the Kalman filter from the data of the internal accelerometer. An illustration of an anchor is depicted in Fig. 5.

We used 10 markers of size 20 cm × 20 cm and printed them on 25 cm × 25 cm Dibond sheet of thickness 3 mm. Weight of one marker was 230 g on land, but it decreased to approximately 24 g in water, due to buoyancy. The anchors were placed at four corners of the room and in the center of the mosaic.

4.2 Sensor–vision fusion

Our AR system uses the extended Kalman filter to fuse the position of each marker and the data from the gyroscope and the accelerometer. It computes the pose of the device with respect to each anchor. The Kalman filter is based on the work of Neunert et al. [19] and Solá [28], but is simplified as follows.

Unlike the Kalman filter used in RCARS system, the sensors are modeled with no bias, using equations:

$$a_s = a + w_a \tag{1}$$

$$\omega_s = \omega + w_\omega \tag{2}$$

where a_s and ω_s are current acceleration and angular velocity measured by accelerometer and gyroscope, a and ω are real acceleration and angular velocity of the device, and w_a and w_ω represent Gaussian noise that is present when reading a data from the sensors. This simplified model is preferred to models with biases because the Android operating system preprocesses the sensor data, estimates the biases, and provides the values with no (or negligible) bias.

Internal state of the Kalman filter x consists of position p, velocity v, and orientation q of the inertial measurement unit (IMU) of device, direction of gravity vector g, and position p_M and orientation q_M of each marker M. All these variables are expressed in the world coordinate frame. Additionally, the Kalman filter operates with relative pose between the camera and the IMU, and intrinsic and distortion parameters of the camera. Unlike other systems, in our system, these parameters are constant during the

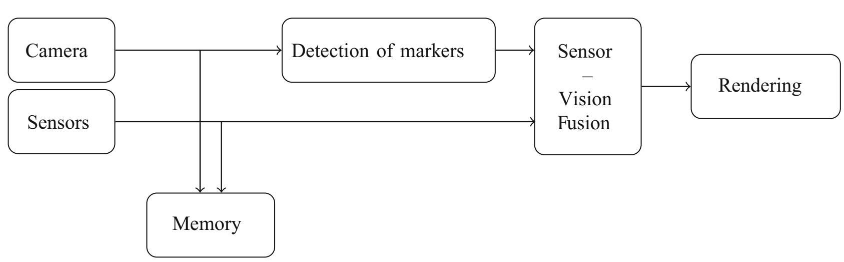


Fig. 4 Overview of hybrid underwater augmented reality system architecture

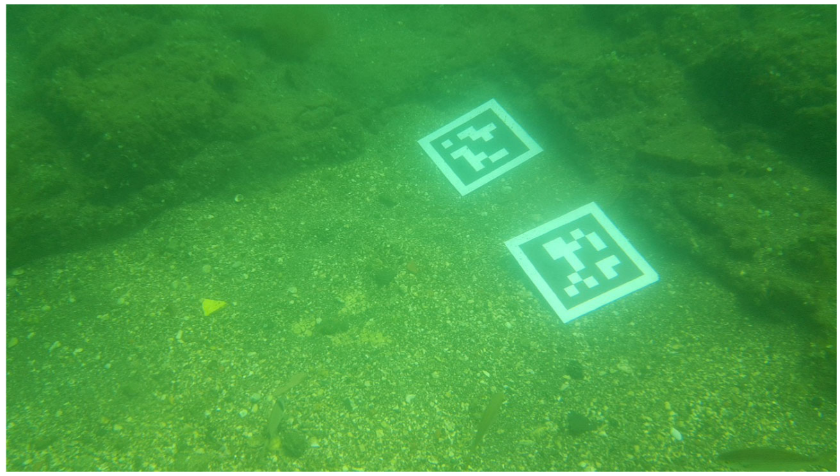


Fig. 5 A pair of ARUco3 markers defining an anchor placed at the remains of a corner of the room. The upper marker is placed at the corner and defines anchor position. The other marker defines the orientation of the anchor and is placed approximately 70 cm along the wall

computation and are obtained by calibrating the device before the experiment.

Internal state x_0 is initialized when the first marker is detected. Initializing procedure sets position of IMU p_0 to zero, orientation q_0 to identity, and position and orientation of the marker p_{M0} and q_{P0} to values obtained by the marker detecting algorithm. Gravity vector g_0 is derived from a measured acceleration, and initial velocity v_0 is set to zero. Covariant matrix of the Kalman filter is set to very high values, so that the real value of the velocity is derived by the filter very quickly during the first frames of the simulation. In rare cases, the velocity and the gravity are initialized incorrectly, and the virtual scene flies away. These situations are detected, and the internal state is reset and initialized again.

New estimated state x_t is derived from previous estimate x_{t-1}, and is updated when a new acceleration or angular velocity is measured by the sensors, using the following equations:

$$p_t = p_{t-1} + v_{t-1}\Delta t + 1/2\Delta t^2(R_{t-1}a_s + g_{t-1}) \quad (3)$$

$$v_t = v_{t-1} + \Delta t(R_{t-1}a_s + g_{t-1}) \quad (4)$$

$$q_t = q_{t-1} * Q(\omega_s, \Delta t) \quad (5)$$

$$g_t = g_{t-1} \quad (6)$$

$$p_{Mt} = p_{Mt-1} \quad (7)$$

$$q_{Mt} = q_{Mt-1} \quad (8)$$

where Δt is the elapsed time from the previous measurement, R_{t-1} is a rotation matrix that corresponds to rotation q_{t-1}, $Q(\omega_s, \Delta t)$ is a quaternion that corresponds to the rotation of the object with angular velocity ωs over time Δt, and an $*$ represents quaternion multiplication.

The Kalman filter performs the update step when the system detects markers in a new image. The innovation term is based on a difference between the measured position of marker corners and the estimated position of those corners transformed by current values of the internal state. Since the camera records images at a lower frequency than the frequency of the inertial sensors, the system usually runs several estimation steps per one update step.

The system reacts on the loss of all markers in the following way. When there are more than 5 consecutive frames with no detected markers, the filter switches to a *no-marker state*, in which it updates only the rotation using (5). This avoids enormous errors in the position that appear due to imprecise estimates of device acceleration and their integration when computing the position and the velocity of the device. The errors in orientation caused by integrating estimates of the angular velocity are much smaller and are not noticed for several minutes of the simulation. This allows the filter to update the orientation of the virtual model and keep the loss of markers not apparent to the user. When some markers are detected again, the system resets its position p and orientation q to the values derived from the last p_M and q_M and switches back from the no-marker state to the normal state.

The final camera pose is averaged from poses of all anchors that are not in the no-marker state. If all anchors are in the no-marker state, the system takes the pose from the last anchor with a detected marker. Updates of the final camera pose are limited by a maximum velocity and maximum angular velocity to avoid abrupt changes in positions, which happen when the diver moves from one anchor to another.

4.3 Rendering

The system renders the scene with OpenGL. The virtual model of the villa consists of the room with the mosaic, a room that is visible through an opened door, a cabinet, a chest, and a small table. The objects were represented with 275,000 triangles and 20 textures. Due to the visibility conditions underwater that are similar to foggy weather, there is no intense main light in the scene, and the whole scene is lit by an ambient light. For this reason, the objects are not rendered with lighting. The real environment and the virtual scene are depicted in Fig. 6.

4.4 Recording of data

Application stores the data of the camera and sensors for further offline processing, e.g., to optimize the system. Images are recorded and stored in YUV420 format, which is the native format of the camera data of the Android operating system. This format consists of a luminance channel Y (which is used for detecting markers), and subsampled color channels U and V. Regarding sensors, the application stores the data of the accelerometer, gyroscope, and magnetometer. The system also stores the time stamps of the data to be matched together for offline processing.

The application splits the stream of the data from the camera into two streams: one that stores the data into an external SD card and another one that stores the data into the internal memory. The internal memory of the smartphone is fast, but with limited storage. On the other hand, the capacity of the external memory is much higher, but its writing speed is lower. Both streams contain a queue for approximately one second of frames waiting to be stored into the corresponding storage. The application prefers the stream that writes the data into an external SD card, and if the writing speed is not sufficient and the queue gets full, it writes the frames into the queue for writing into the internal memory. After the system stores the data into the external SD card, the queue becomes empty and the application again stores frames into this queue.

Fig. 6 Remains of the villa underwater with an anchor placed the corner of the room (top), and the virtual model of the room superimposed at the location of the anchor (bottom)

4.5 Hardware and user interface

The system was implemented and tested on a Samsung S8 smartphone and a Diveshot housing (see Fig. 7). Diveshot housing [6] is a housing for smartphones of various models and allows them to operate in depths of up to 60 m. It contains five optical buttons that are pressed by covering the corresponding sensor with a finger, and sends the click events to the smartphone using Bluetooth, behaving like an external Bluetooth keyboard.

The user interface of the application is designed to operate only with these five buttons, because the housing prevents divers from controlling the smartphone directly by touching its surface. The screen is divided into two parts: a left part dedicated for the application and a right part containing a visual representation of the buttons. Most of the left part is occupied by the camera image and maintains its aspect ratio; the size of the right part adapts according.

The screen of smartphones is very small, so the user interface contains only a few controls to avoid user overloading. The function and labels of the buttons change to match the needs of the application. When a button is not required, it disappears, but the position of other buttons is kept the same (see Fig. 8). This makes the interface consistent and avoids confusion of the users.

Samsung S8 contained 64 GB of the internal memory, and additional 128 GB of memory was available on the external SD card. The writing speed of the SD card was about 40 MB/s, which was sufficient for writing a video in a resolution of up to 1280 × 720, but not sufficient for writing a video in the resolution of 1920 × 1080. The writing speed

Fig. 7 Hardware used for testing: Samsung S8 smartphone placed in Diveshot housing

Fig. 8 Buttons of the housing (left) and the corresponding buttons in the application (right). The bottom-most button is not used

of the internal memory was more than 200 MB/s, which is enough even for storing uncompressed Full HD videos.

4.6 Subapplications

The housing disallows a diver to change the active application, so all functionality must be incorporated into a single application. For this reason, the main application is separated into four subapplications for various tasks underwater: observing underwater site in augmented reality (subapplication iMare AR), recording the data in a higher resolution for offline tests (subapplication Recorder), calibrating the camera under water (subapplication Calibration), and filling a questionnaire after a dive (subapplication Questionnaire). All subapplications are presented in Fig. 9.

Subapplication iMare AR is the most crucial part of the system. It records the data from the camera and sensors, detects the markers, computes the position of the camera, and renders the virtual model at the proper position. Its structure was described in details in the previous sections. It records and stores images in resolution 1280×720 since images in higher resolutions could not be searched for markers in the real time. Its user interface consists of a clock, a text with information about the site displayed over the AR content, and the recording status of camera and sensors streams.

Subapplication Recorder is a simplified version of subapplication iMare AR. It does not detect markers or render a virtual scene, it only records the data in a higher quality for further offline tests. This simplified structure allows the camera stream to be recorded in a Full HD resolution. Its interface is simpler when compared to iMare AR subapplication, it contains only a label indicating whether the application is recording or not, and graphs showing the occupancy of the memory and SD card.

The device is calibrated with subapplication Calibration. It computes the intrinsic and distortion parameters of the camera using procedures of OpenCV that calibrates the camera with a calibration board. It works with the same resolution of the camera as the AR application. The user interface is similar to iMare AR subapplication, but instead of the information text, it shows the instructions of the current calibration step.

The last subapplication Questionnaire was developed to allow the diver to fill the answers immediately after finishing the experiment. To our knowledge, this is the first time that questionnaires are filled in such conditions. Typing in the conventional way is not possible, so an alternative way was implemented. The user interface consists of a black screen with no images from the camera, and contains only the question and several answers. These answers are picked by an arrow, which is controlled by tilting the device. Thanks to this, the number of answers is not limited by the number of buttons, and the answer can be selected quickly by tilting the device and pressing a button (see Fig. 10). This method of user input was highly appreciated by the divers because it is a convenient and easy way to collect feedback. The application does not record any images from the camera, it only uses input from inertial sensors.

5 Methodology of the system evaluation

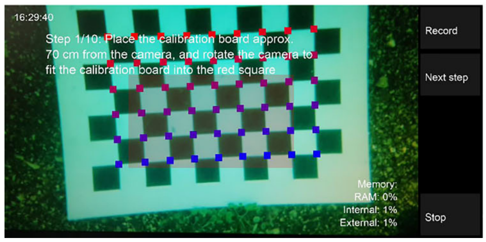
Our system was evaluated in Baiae, Italy, at the location of ancient Villa con ingresso a protiro. The evaluation was restricted to only one room, the room with the black-and-white mosaic. This pilot study was focused on evaluating user experience of divers when using augmented reality to see a virtual reconstruction of the villa in real time.

The evaluation was done within three dives in a period of 2 days. The first dive was focused on preparing the site and the device. During this dive, the site was checked to see the current status of the remains of the villa, the vegetation, and the visibility conditions, and the device was calibrated using Calibration subapplication. This calibration is required to be done under water since optical conditions in the water are different from those in air [14], but they remain the same between experiments, up to a small negligible error. The calibration was followed by an initial run of the AR application to tune the experiment. The markers were placed in their final configuration, and the number of questions was decreased to reduce the time required to fill the questionnaire.

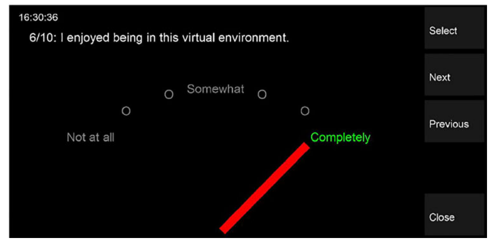
The divers performed the actual evaluation in the second day during the second and the third dive. The application

(a) iMare AR subapplication

(b) Recorder subapplication



(c) Calibration subapplication



(d) Questionnaire subapplication

Fig. 9 Subapplication of the system for four typical use cases. Subapplication iMare AR (**a**) displays AR content, subapplication Recorder (**b**) records the data in a higher quality for offline processing, subapplication Calibration (**c**) calibrates the camera, and subapplication Questionnaire (**d**) records the answers to several questions about the user experience under water

was started on the boat before the device was sealed in the waterproof housing. Each dive started with placing markers at their proper location and with a brief check to assure that all markers are detectable. Seven divers evaluated the system during the second dive and three divers during the third dive. They were asked to swim around the site and observe the virtual model of the room in augmented reality. Particularly, the application suggested to observe the frescoes on the walls. Then, they swam into the center of the room and observed an emblem in the center of the mosaic. Description of the tasks was shown on the display of the device (see Fig. 11). The divers were not discouraged from observing other parts of the room or punished for doing so. At the end of each dive, the markers were collected back to leave the place clean.

5.1 Questionnaire

User experience was evaluated using a questionnaire consisting of ten questions selected from a questionnaire from Tcha-Tokey et al. [31]. Expert divers (including maritime archeologists and photogrammeters) filled the questionnaire directly in water immediately after the experiment to avoid their user experience from being altered due to a time delay between the experiment and a return to the surface. All questions were answered by selecting a number in the range from 1, Not at all; through 4, Somewhat; to 7, Completely.

6 Results

The divers not only filled the questionnaire but also provided their personal opinion on the application. Additionally, the data recorded by the application during the experiment were processed to obtain a map of virtual places and objects that the divers found the most interesting. Two divers did not fully understand the questionnaire, and for this reason, they did not answer the questions. However, the data recorded during their dives are still included in the map of the most interesting places and objects.

6.1 Heat map of objects of interest

The data recorded during the experiment were processed offline to acquire the points of interest where the users looked, computed as intersections of the walls of the room and the direction of view. The computation ignored the

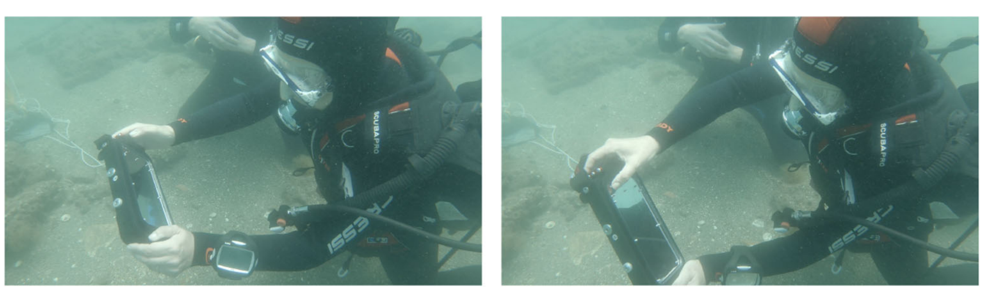
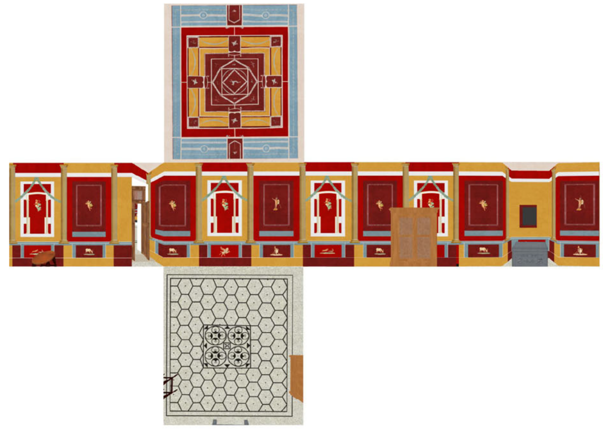


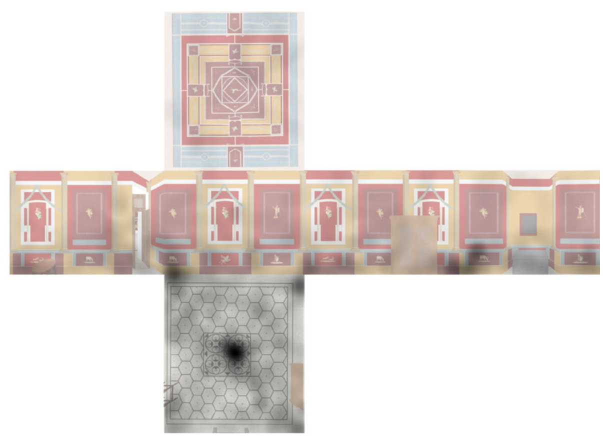
Fig. 10 Diver filling the questionnaire under water: reading a question (left) and tilting the device to choose an answer (right)

Fig. 11 Two tasks presented to the divers (top, middle) and a request to fill the questionnaire (bottom)



(a) Room with a mosaic on floor, frescos on walls and on ceiling, a cabinet, a chest, and a small table.

(b) A map with points where divers looked. It clearly shows that divers observed each wall, the floor, and the ceiling.



(c) A heat map of points where divers looked. Darker colors indicate places, which divers spent more time with observing. It shows that the most interesting parts were the center of the mosaic and the corners of the room.

Fig. 12 Places which divers observed under water. (**a**) Room with a mosaic on floor, frescos on walls and on ceiling, a cabinet, a chest, and a small table. (**b**) A map with points where divers looked. It clearly shows that divers observed each wall, the floor, and the ceiling. (**c**) A heat map of points where divers looked. Darker colors indicate places, which divers spent more time with observing. It shows that the most interesting parts were the center of the mosaic and the corners of the room

objects inside the room because they were located near the walls.

The results are in Fig. 12. Figure 12a represents six sides of the room, rendered from the center of the room. Apart from the illustration on the walls, this image also shows the positions of three objects in the room (the cabinet, the chest, and the small table). Figure 12b shows the points at which the divers looked. It shows that they were interested more in the floor of the room and on the lower parts of walls, and less in the ceiling. Figure 12c also shows the parts of the room where the divers looked, but instead of using a black dot, it uses darker colors to indicate places, which divers spent more time with observing. This figure indicates that the divers looked at the center and at the corners, which are the places with markers, so the divers kept tracking the markers even though the application did not require them to do so, because the virtual model is displayed even when the markers are out of the field of view.

The heat map clearly shows that the divers observed objects that were located below them. This may not be caused only by the necessity of tracking markers located on the ground but also because the remains of the room were very small, so there were no real observable objects at the level of the diver or higher. Also, it is much easier for divers swimming underwater to look below them than to look up, due to the general orientation of their body.

6.2 Questionnaire

The questionnaire was filled underwater by eight divers. Table 1 presents the mean values and their standard variations, and Fig. 13 shows a histogram of answers to individual questions. Results indicate that the users rated their interaction with the augmented reality environment mostly as natural (Q1, mean 5.625; std. dev. 1.111), they enjoyed being in the augmented reality environment (Q6, mean, 6.5; std. dev. 1.0), and they did not feel nervous in this environment (Q7, mean 1.750; std. dev. 1.299). Many divers also agreed that they could somewhat examine objects closely (Q4, mean 4.375; std. dev. 1.409), and that the environment is not confusing (Q9, mean 2.250; std. dev. 1.561). The divers did not agree on whether they could actively survey the AR environment using vision (Q2, mean 5.0; std. dev. 1.871), whether the sense of moving around inside the environment was compelling (Q3, mean 4.5; std. dev. 1.803), whether the augmented reality environment is practical (Q8, mean 4.75; std. dev. 1.714), and whether they suffered from fatigue during their interaction with the virtual environment (Q10, mean 2.250; std. dev. 1.639). Regarding question Q5 asking whether they became so involved in the augmented reality environment that they lost all track of time, the divers mostly split into two groups, a group in which they did lose all track of time and a group in which they did not (mean 4.25; std. dev. 2.332).

6.3 Qualitative results

Divers provided their personal opinion on the application after they returned on the land. They valued the easiness of the installation at the site and they expect that the system will be used in practice for touristic purposes in the near future. They could see the virtual scene very clearly and agreed that they felt completely immersed in the virtual environment and stopped paying attention to their surrounding. This high level of immersion, however, raised some concerns. Although some divers highly appreciated this, others were worried, since divers must be aware of the situation underwater. This can lead to problems, especially if the diving happens in greater depths. However, none of the divers reported any accidents that would be caused by their inattention during their dive. They were able to stay oriented on the site and keep their buoyancy.

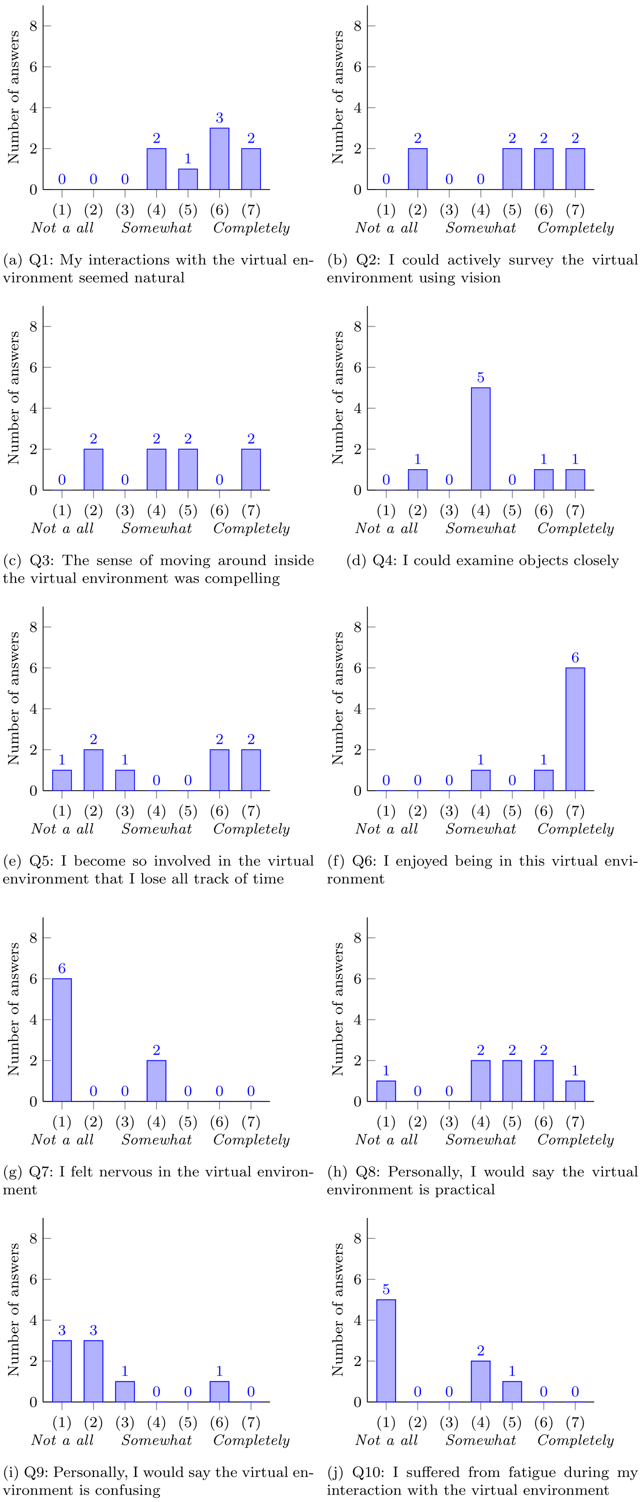
Some divers complained that due to their complete immersion, they lost the feeling of actual diving, which was substituted by their impression of the virtual experience. The reason was that this was their first experience with augmented reality underwater, which captivated them so much that they forgot about diving. They agreed that if they had more experience with augmented reality, this would not happen and they would enjoy both diving and the virtual visit.

One diver argued that his experience was influenced by the fact that the virtual model was misaligned with the real environment at one anchor. This misalignment was caused

Table 1 The mean and the standard variation of answers of the questionnaire

Question	Mean	Std. var.
Q1: My interactions with the virtual environment seemed natural.	5.625	1.111
Q2: I could actively survey the virtual environment using vision.	5.000	1.871
Q3: The sense of moving around inside the virtual environment was compelling.	4.500	1.803
Q4: I could examine objects closely.	4.375	1.409
Q5: I become so involved in the virtual environment that I lose all track of time.	4.250	2.332
Q6: I enjoyed being in this virtual environment.	6.500	1.000
Q7: I felt nervous in the virtual environment.	1.750	1.299
Q8: Personally, I would say the virtual environment is practical.	4.750	1.714
Q9: Personally, I would say the virtual environment is confusing.	2.250	1.561
Q10: I suffered from fatigue during my interaction with the virtual environment.	2.250	1.639

Range of answers: 1—Not a all, 4—Somewhat, 7—Completely



(a) Q1: My interactions with the virtual environment seemed natural

(b) Q2: I could actively survey the virtual environment using vision

(c) Q3: The sense of moving around inside the virtual environment was compelling

(d) Q4: I could examine objects closely

(e) Q5: I become so involved in the virtual environment that I lose all track of time

(f) Q6: I enjoyed being in this virtual environment

(g) Q7: I felt nervous in the virtual environment

(h) Q8: Personally, I would say the virtual environment is practical

(i) Q9: Personally, I would say the virtual environment is confusing

(j) Q10: I suffered from fatigue during my interaction with the virtual environment

Fig. 13 Histogram of answers to individual questions

by one marker, which another diver accidentally moved from its original position during the experiment. Despite this, his opinion on the application was a positive and enjoyable experience.

7 Conclusion

This paper presented a novel AR system that improves the user experience of divers visiting ancient underwater cultural heritage sites. For localization, this system uses a hybrid approach (markers and inertial sensors) tested in a laboratory in simulated underwater conditions. It superimposes virtual objects into the real images on the screen of a mobile device directly at the archeological place. The application was installed and evaluated at the location of Villa con ingresso a protiro, an ancient villa that is currently submerged about 5 m underwater. The methodology of the evaluation allowed the divers to record their feedback underwater and fill the questionnaires under water immediately after observing the site in AR. The results showed that the system provided an unique and enjoyable experience.

The future work is aimed at improving the tracking of the device by utilizing natural features and ensuring a proper functionality when markers are not visible. This will allow the system to operate in larger areas while requiring less amount of markers. Also, the system can be extended with algorithms that improve detection of markers in the sea [33] to increase the distance at which these markers are detected. With this, the system will be capable of working in other parts of Villa con ingresso a protiro and other villas at the underwater archeological site. Finally, the application will be tested with non-expert users that will come to visit the site for touristic purposes.

Funding information This research is a part of the i-MareCulture project (Advanced VR, iMmersive Serious Games and Augmented REality as Tools to Raise Awareness and Access to European Underwater CULTURal heritagE, Digital Heritage) that has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 727153.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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