IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 27, 2021, accepted February 6, 2021, date of publication February 16, 2021, date of current version March 26, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3059978

Evaluating the Potential of Augmented Reality Interfaces for Exploring Underwater Historical Sites

JAN ČEJKA[1], MARINO MANGERUGA[2], FABIO BRUNO[2], DIMITRIOS SKARLATOS[3], AND FOTIS LIAROKAPIS[4,5], (Member, IEEE)

[1]Human Computer Interaction Laboratory, Faculty of Informatics, Masaryk University, 602 00 Brno, Czech Republic
[2]3D Research s.r.l.—University of Calabria, 87036 Rende, Italy
[3]Photogrammetric Vision Laboratory, Department of Civil Engineering and Geomatics, Cyprus University of Technology, 3036 Limassol, Cyprus
[4]Research Centre on Interactive Media, Smart Systems, and Emerging Technologies, 1011 Nicosia, Cyprus
[5]Faculty of Engineering and Technology, Cyprus University of Technology, 3036 Limassol, Cyprus

Corresponding author: Jan Čejka (xcejka2@fi.muni.cz)

This work was supported in part by 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) from the European Union's Horizon 2020 Research and Innovation Programme under Grant 727153, in part by the European Union's Horizon 2020 Research and Innovation Programme (RISE–Call: H2020-WIDESPREAD-01-2016-2017-TeamingPhase2) under Grant 739578, and in part by the Government of the Republic of Cyprus through the Directorate General for European Programmes, Coordination, and Development.

ABSTRACT Underwater cultural heritage sites represent an attractive and exciting experience for diving tourists, even if often it is complicated for them to understand the significance and value of the remains that are usually strongly damaged and covered by the marine organisms. Thanks to the recent advancements in technologies that overcome these problems, augmented reality is nowadays possible even in such harsh conditions, opening new possibilities for enhancing the diver's experience. However, no user study has formally evaluated the usefulness and usability of augmented reality in open sea underwater environments. This paper presents two novel solutions for underwater augmented reality: a compact marker-based system for small areas, and a complex acoustic system for large areas. Both of them were deployed at an underwater cultural heritage site and evaluated by ten divers in experiments analyzing their perception and remembrance, interests, and user experience. For comparison, the same study was also performed with non-divers assessing the marker-based system on land. Results show that both systems allow divers to encounter new and exciting moments and provide valuable insights for underwater augmented reality applications.

INDEX TERMS Augmented reality, cultural heritage, sensor fusion, underwater, user experience, user testing.

I. INTRODUCTION

Cultural heritage sites are spread not only on land, but also underwater. Places of great historical importance include submerged buildings, sunken ships, or ports [11]. Such sites are of interest to historians, archaeologists, tourists, and enthusiastic divers due to better accessibility of the sites and increased diving equipment availability in recent years. Although augmented reality (AR) systems help with presenting similar on-land sites to the general public for a long time [54], applying AR on underwater cultural heritage sites is still very challenging. The main reasons are bad visibility conditions [50] and unavailability of localization tools like Global Navigation Satellite System (GNSS) [46]. The underwater environment also impedes diver's movements and requires electronic devices to be covered from water, which causes difficulties when operating the equipment. Because of the above, we have limited knowledge about user experiences in underwater AR environments.

This paper presents the final prototypes of two novel hybrid systems for underwater AR presented by Čejka *et al.* [53] and Bruno *et al.* [9]. The first one is designed for smartphones and uses visual-inertial tracking. It obtains the diver's absolute position from a set of markers placed predefined locations, and represents a compact solution for small areas. The system is also equipped with an image-enhancing part to improve

The associate editor coordinating the review of this manuscript and approving it for publication was Chao Tan.

the performance of the marker tracking technique operating underwater in bad visibility conditions. The second one is designed for tablets. It also utilizes inertial tracking, but the absolute position is obtained by acoustic localization (which does not depend on the visibility) although its accuracy and update rate is lower. This system represents a complex solution that can span large area underwater sites. Both systems include optimised user interfaces specifically designed for underwater environments and were evaluated with ten users at an underwater cultural heritage site assessing their user experience and perceived cognitive workload.

This paper also explores how divers perceive virtual objects underwater. Although past research has been done for virtual scenes on land [34], to our knowledge, this is the first perception study performed in underwater conditions. After the participants explored the underwater site, they were asked about the details they remembered about the site. Their answers were compared with the ones of another group of participants performing the same test on land. Additionally, the paper explores the similarities and differences in objects that are observed by divers in water and non-divers on land.

The main contributions of this paper are:

- Description of improvements in two novel systems localizing divers at underwater sites designed for underwater AR and utilizing on marker-based tracking, markerless tracking, inertial sensors, and acoustic tracking. The systems extend the previous versions with markerless tracking and support for new housing. They also include new methods for interaction with smartphones using tilting and with tablets using a five-button interface of the new underwater housing.
- An evaluation of user experience, perceived workload, and perception of virtual scenes of both systems in real-world conditions of an underwater cultural heritage site.
- An extension of the comparison of image-enhancing algorithms for AR performed by Čejka *et al.* [50] based on the data collected in real use case scenarios.

Both applications are available for the general public and can be downloaded at https://imareculture.eu/downloads/project-tools/ar-underwater.

A. RELATED WORK

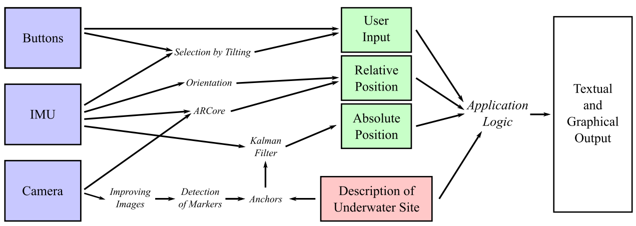
There are several systems that present information about cultural heritage using AR [2]. Archeoguide [54] was one of the first systems that displayed virtual objects in AR at historical sites and provided information about cultural heritage objects. CityViewAR [30] focused on buildings in modern cities lost during earthquakes, and KnossosAR [18] addressed the problems of interaction, navigation, and occlusion in the virtual scene. Web-based systems were explored by Kourouthanassis *et al.* [28]. User experiences in a mobile AR tourist guide were also recently examined [47].

Underwater AR is mostly an unexplored area. We found only a very few solutions, most of them for controlled environments like swimming pools. One of the first underwater AR solutions was proposed in 1999 by Gallagher [19] for military purposes. It consisted of an underwater head-mounted display (HMD) that improved the view of Navy divers. Morales *et al.* [35] proposed a more recent solution, which implemented a system composed of a see-through HMD with a webcam in front of it, integrated into a waterproof housing, and placed over the diving mask. This system aimed to increase the awareness and safety of the diving operations by providing the diver with additional elements in his visual field. Brown and Wang [8] presented an underwater AR system intended to support both recreational and commercial divers during navigation and provide also a fish identification scheme. Other AR systems were limited only to swimming pools [4], [38], [39]. Bruno *et al.* [10] presented a novel system that integrates an underwater tablet with an acoustic localization system with a Long BaseLine (LBL) configuration to enable a diver to locate itself through a map of the underwater site. It was not an underwater AR system because it did not deliver any AR visualization through a hypothetical reconstruction.

Many AR systems track objects with markers, which are artificial targets that are easy to recognize. Real-time applications often use square markers [20], [24], [43], [55], elliptic markers [6], [27], [37], or markers of irregular shapes [5]. Robust markers for bad visibility conditions also exist [49], [56]; however, their detection is very slow. Enhancing the contrast of underwater images can improve detection [50], [52]. Tracking can also be done without markers by tracking natural features [26], [36], or directly by comparing image intensities [17], [45]. Systems for tracking the position of the viewer are incorporated into modern mobile operating systems [3], [21].

Perception and user experience in mixed reality environments have been evaluated in many occasions. Albert *et al.* [1] examined participant's ability to recall objects in a virtual reality scenario and studied the dynamics of their gaze behavior and fixation of their eyes on individual virtual objects. Rietzler *et al.* [42] focused on perceiving time and explored the impact of its acceleration and deceleration on users. Keil *et al.* [25] investigated the user's perception of space and measured the effect of guides and virtual grids on assessing the distances between real objects. The effect of AR on attention, accuracy, and recognition was studied by Dixon *et al.* [14] on surgeons performing endoscopic operations and by Rusch *et al.* [44] on car drivers traveling long distances in simulated environments.

In terms of user experience, Greenfeld *et al.* [22] compared the impression of users on five methods providing mixed reality experience: head-mounted displays, large-scale immersive displays, AR see-through displays, smartphone virtual reality, and tablets. Differences in engagement between a real and simulated walk in nature were examined by Calogiuri *et al.* [12]. Still, none of this research explored user experience in underwater marine virtual environments, though an AR game for children in swimming pools was designed and tested by Oppermann *et al.* [39].



(a) The architecture of the marker-based AR system. The system uses three hardware sources of data (blue boxes), and with the knowledge about the description of the site (red box), it computes the derived data (green boxes) and passes it to the application logic, which updates the textual and graphical output to the diver.

(b) The marker-based AR system runs on a Samsung S8 sealed in Diveshot, a waterproof housing from Easydive. Divers operate the lower four buttons that correspond to the four buttons of the application, and the fifth, top-most button is used by the supervisor to access and change the application settings.

FIGURE 1. **Architecture (a) and hardware (b) of the marker-based AR system.**

II. MARKER-BASED VISUAL-INERTIAL SOLUTION FOR SMARTPHONES

The marker-based visual-inertial system represents a compact and affordable solution for underwater localization, whose price compensates the necessity of populating the area with markers. It is composed of a smartphone, a waterproof housing, and a set of markers. The architecture of the system is based on the work of Čejka *et al.* [53] and is depicted in Figure 1a. The system processes the data from the smartphone's camera and its inertial measurement unit (IMU) and computes the diver's absolute location using the information about markers distributed over the underwater site at known positions. User interaction is realized with the buttons of the housing and with the smartphone's accelerometer that allows divers to tilt the device to write texts or choose from a list of options. The input is processed by the application and presented as a textual and graphical output on the screen.

The system is designed to run on a general smartphone, which usually cannot operate under water and must be protected. Our experiments were performed using a Samsung S8 smartphone sealed in a Diveshot housing from Easydive [15], see Figure 1b. This housing completely covers the smartphone and prevents the divers from controlling it by accessing its screen. The only way to operate the smartphone is with five optical buttons located at the right part of the housing.

The camera images are first improved by the MBUWWB algorithm [52] and then searched for markers in the subsequent step with the ARUco3 algorithm [43]. Black-and-white markers of size 20×20 cm are printed on 20×20 cm Dibond sheets of thickness 3 mm; each marker contains a 6×6 binary matrix with its identification. Additional weight was added to the markers to avoid them moving around. Pairs of markers are grouped into anchors that define reference points with a known absolute position at the site, see the left part of Figure 2.

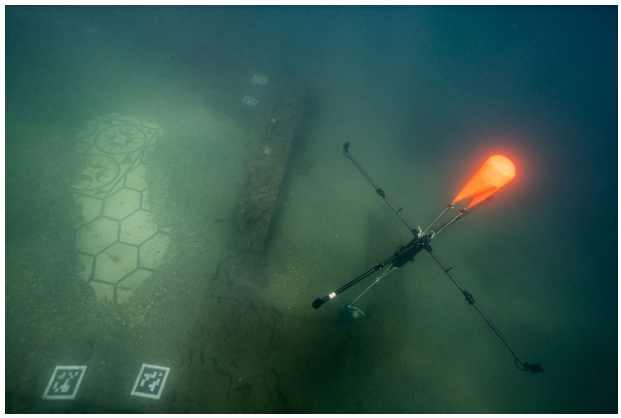
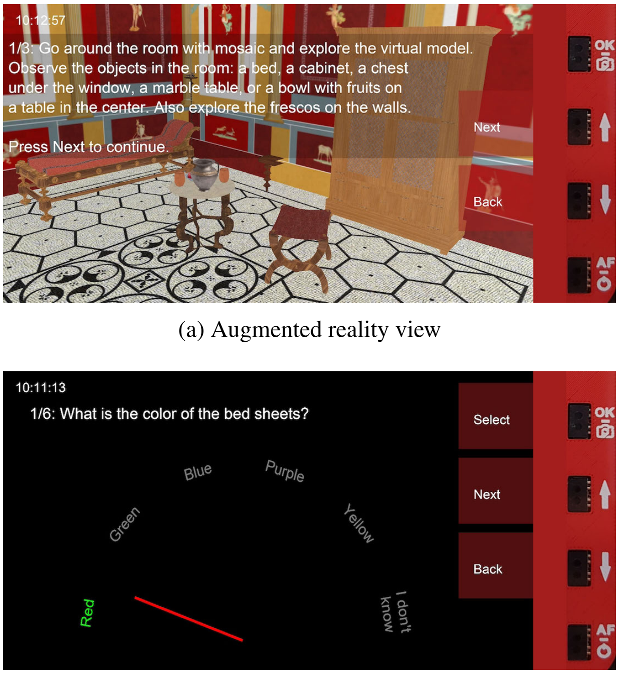


FIGURE 2. **Underwater site after the setup of both the systems. Notice two pairs of markers representing two anchors located in corners of the room in the left part of the image, and the base of the acoustic localization system in the right part of the image.**

Our system also incorporates the ARCore library [21]. This library is a standard component of the Android operating system and provides a marker-less tracking based on the IMU and the natural features detected in the camera stream. It gradually builds an internal map of the area and computes the diver's position on this map, relative to the last known point. When combined with anchors' position, it updates the absolute location of divers, and thus it can provide the position even when they travel between anchors and no marker can be detected.

Two main activities are supported: observing the underwater site augmented with virtual objects (see Figure 3a), and filling a questionnaire underwater (see Figure 3b). For the first activity, the system improves recorded images, searches for markers, and renders the virtual content on the screen. The questionnaire activity obtains feedback from the diver; it asks for their name or other identification and gives them a set of questions with predefined answers. Other supported functionalities are a calibration tool, and a recorder tool. The calibration tool computes the camera's intrinsic and extrinsic parameters under water, because the parameters are different from those obtained on land [29]. The recorder tool stores the



(a) Augmented reality view

(b) Questionnaire, a user selects an answer

FIGURE 3. Two main activities provided by the system: AR view on the underwater site (a) and answering a questionnaire (b).

incoming uncompressed visual and inertial data for further offline processing and system evaluation.

User interaction is supported based on tilting the device underwater as described by Čejka *et al.* [51]. It operates by reading the accelerometer data, then derives a device inclination, and transforms it into a position of an arrow on the screen. Divers use this arrow to select an answer from a list of predefined choices or write their name (or other identification) to match their performance with other data collected during the experiment, see Figure 3b.

The five housing buttons are operated as follows. Two of the buttons express a transition between *previous* and *next* actions (e.g., steps of the experiment, or questions of the questionnaire), one button selects an option highlighted by tilting, and one button switches between activities, i.e., between viewing the AR scene and filling the questionnaire. The last button of the housing is left without any specified action; the system hides this button from users and gives it to the operators to access the system setup and parameters.

III. ACOUSTIC VISUAL-INERTIAL SOLUTION FOR TABLETS

A markerless underwater AR technology integrates acoustic localization systems and visual-inertial odometry techniques. This technology has been implemented through an application running on a commercial tablet housed in a waterproof case. This application provides the user with different features: a map of the underwater site that allows the diver to know his position within the submerged site; additional information about specific points of interest (POI); and an enhanced diving experience through an on-site augmented visualization of a 3D hypothetical reconstruction that shows to the diver as the actual ruins should appear in the past.

FIGURE 4. The redesigned user interface of the application running on the underwater tablet.

The information about the diver localization has to be provided to the system with high precision and at a high update rate to deliver a consistent and smooth AR visualization. Unfortunately, the acoustic localization systems suffer from low update rate and low accuracy, and cannot be employed alone for the AR purpose. Then, to overcome this limitation, a hybrid tracking system has been specifically developed by integrating acoustic localization and visual-inertial odometry to enable a consistently high frame rate and improve the performance of the proposed underwater AR technology. The hybrid tracking system merges positioning data, generated by the acoustic system, with data coming from a visual inertial-odometry framework. In particular, given the low update rate of the acoustic system, it has been implemented a data fusion strategy aimed to fill the gaps between two consecutive acoustic positioning data.

This system has been introduced in a previous work [9], and since then, it has been further improved. The tablet was enclosed in a waterproof case that should preserve all the touchscreen functionalities thanks to a pressure management system that ensures the presence of an air gap between the tablet display and the housing membrane. However, this case proved ineffective in real use due to the different problems from which it suffers. Therefore, a new underwater case produced by EasyDive [16] that is more affordable and easier to use has been adopted. The housing is made from a solid block of anodized aluminium for maximum resistance over time against wear and saltiness. The tablet can be controlled using a Bluetooth keyboard composed of five buttons equipped with optical sensors and placed on the right side of the case, under the housing glass.

The user interface has been mostly redesigned (Figure 4) to fit the layout of the new underwater case grouping all the interaction buttons on the right side of the screen,

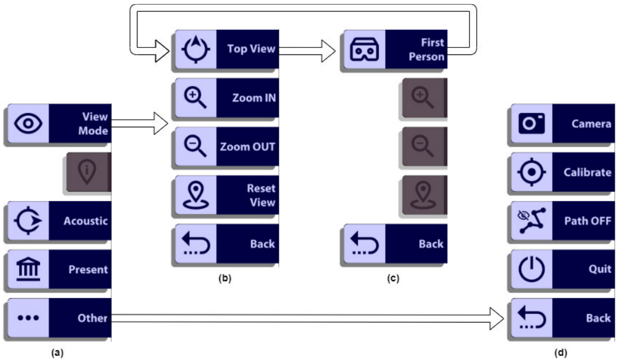


FIGURE 5. Five-button menu hierarchy.

in correspondence with the five physical buttons. This allows the diver to access all the features of the application with just one hand. These buttons can be triggered both through the touchscreen when the tablet is outside the case, and through the Bluetooth keyboard integrated into the underwater case.

Each of the five buttons is composed of an icon and a label representing the button's actual function. Indeed, the buttons are dynamic and can represent different functions in the app lifecycle, as illustrated in Figure 5. The main menu (a) enables the user to access the major features of the system. The first button permits to switch the view modality between a top view (b) of the underwater archaeological site and a first-person view (c). The latter is particularly useful to visualize the hypothetical reconstruction of the structures and artefacts superimposed on the present status of the underwater archaeological site. This feature is precisely accessible through the fourth button that enables the user to switch the visualization through the present and the past status. Whenever the visualization is in "top view" modality, some additional features are accessible to the user (b), such as the zoom and reset of the viewing. The second button of the main menu (a) is enabled only when there is a POI nearby the diver and permits to show additional information about this POI. The fifth button opens a menu (d) that enables the user to access additional features such as the camera function that permits to shot geo-localized pictures. Besides, through this menu, a calibration feature is accessible, which is mostly a debug feature not intended for the final users.

Since the presentation of the previous work [9], the acoustic localization system has been substituted with a Short Base-Line positioning system provided by AppliCon Srl and described by Cario *et al.* [13]. This system consists of a base with four transmitters and one or more underwater receivers. The underwater receiver is intended to be coupled with the tablet; therefore, it was also conformed to the new underwater case and designed to be compact (Figure 6). Through this localization system, the tablet can know its positions to the base and, if the latter is geo-localized, it can know its absolute geographical position. During the test in the archaeological site of Baiae, it has been evaluated that the tablet could operate within a maximum range from the base around 70 meters

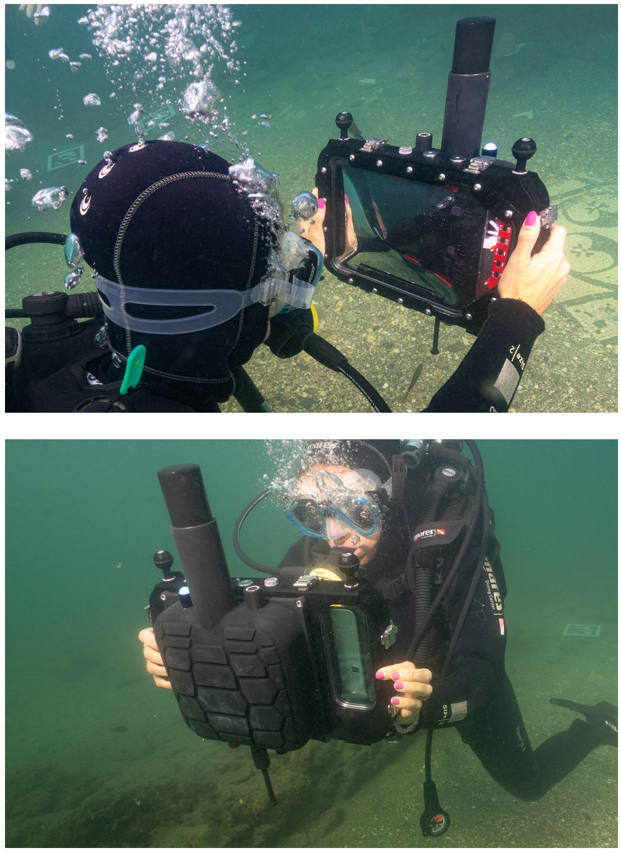


FIGURE 6. The new underwater case coupled with the acoustic localization system.

and can receive localization data at an update rate of 1 Hz. A detailed analysis of precision and accuracy has not yet been done, but a study about the error sources is reported by Cario *et al.* [13].

IV. METHODOLOGY

Both AR systems were deployed on the site of submerged ancient roman Villa con ingresso a protiro in Baiae, Italy. The three-dimensional (3D) hypothetical reconstruction of this Villa has been achieved under the direction of Barbara Davidde Petriaggi and Roberto Petriaggi following a theoretical and multidisciplinary scientific approach [40]. The 3D reconstruction process started from the data collection focused on the acquisition of historical documentation, scientific literature, and geometric data. Its aim was to collect all the information needed to create a hypothetical reconstruction of the archaeological remains with a high level of consistency. Several experts were involved in order to discuss different interpretation hypotheses. The architectural remains have been modelled and validated according to the interpretation provided by the experts. These phases of technical reconstruction and critical revision by the experts were interleaved in order to generate a feedback process that was repeated as many times as needed.

The 3D modelling of the hypothetical reconstruction was realized through the 3D creation suite Blender [7]. High-resolution 3D data have been exploited together with drawings and other historical and archaeological information to build a suggestive and consistent digital reconstruction of the underwater architectures that, unfortunately, does not exist anymore. The AR systems were evaluated by ten divers (seven males, three females; one in age category 18–25, one in category 34–41, five in category 42–49, and three older than 50; eight right-handed and two left-handed; various diving skills from beginners to instructors; see Table 1). The marker-based approach was tested in a room with a characteristic mosaic and a great hall next to that room. The area was populated with ten markers creating five anchors with known location: four anchors were placed at the corners of the room, and a single anchor was placed in the center of the hall. The test of the markerless approach was conducted in the entire Villa, since this system easily covered the whole area.

TABLE 1. Participants testing the systems on land and under water.

		Divers	Non-divers
Gender	Male	7	7
	Female	3	3
Age category	18–25	1	4
	26–33	0	6
	34–41	1	0
	42–49	5	0
	>50	3	0
Dominant hand	Right	8	10
	Left	2	0

Participants that tested the marker-based system were given three tasks: to swim around and look around the room, move into the great hall, and look around the hall. They were instructed to explore the virtual objects in the room, specifically mentioning a bed, a cabinet, a chest under room window, a marble table, a bowl with fruits on a table in the center of the room, and the frescos on the walls. They were also asked to look around the great hall without mentioning any specific objects to observe. After that, they filled a questionnaire inquiring about what they noticed. The questionnaire was answered directly in the water right after the experiment to avoid a time gap caused by arriving at the surface. The application also recorded the diver's location and the direction in which they looked to reconstruct later a map of the most interesting objects. The divers were not limited by time and were not penalized for spending too much time on the place. They spent approximately 5 – 10 minutes on completing all tasks.

The same experiment was repeated with other ten participants on land (seven males, three females; four in age category 18–25 and six in age category 26–33; all right-handed; see Table 1) to obtain differences in behavior between underwater and on-land participants. The test was performed in an empty hall with markers distributes at places corresponding to the locations of markers under water. Although performed on land, the smartphone was sealed in the housing to provide the same method of interaction to the users.

The acoustic localization system has been deployed on the underwater site before the test. This operation is straightforward; it needs to set the base extending and locking the arm support of each four transducers and power on the system. After a little time that the unit needs to lock the GPS signal to synchronize its internal clock, the unit has been deployed, mooring it on the seafloor with a little lifting bag. This is illustrated in Figure 2.

FIGURE 7. Two divers testing the markerless UWAR application through the tablet.

During the test of this system, three tablets were available to be used simultaneously by three different users, see Figure 7. The system has been explained to the users before the dive and each of them had the opportunity to interact with the tablet for a couple of minutes to explore the different features and become familiar with the user interface. Due to the nature of underwater AR application, that was designed to help divers to freely explore the surrounding area getting information on their position and the interesting spots of the site, no precise tasks have been assigned to users. The test has been carried out in this way to evaluate the system in the most common use case: tourist divers exploring an underwater archaeological site. Each of them tested the system freely and without limitations for about fifteen minutes. The only indication they received was to test both the main visualization modalities that the system deliver to the user: the top view visualization of the map that enables the users to locate themselves in the underwater sites quickly and the first person AR visualization that allows them to observe the hypothetical reconstruction of the Villa. They could focus on the spots that they felt more interesting with the possibility to visualize also additional textual information related to some POIs.

This test also enabled us to investigate how comfortable it is for a diver to bring with him such a big system composed by the tablet and the acoustic modem. The underwater site was perfect for this kind of test because of the low visibility that forced the divers to use the tablet to locate themselves to understand where they are and what they observe. Even with low visibility, the shallow depth of 5 meters and constant observation of the users by the organizers of the tests have guaranteed the maximum safety of the operations.

After the diving sessions, the participants were asked to provide personal feedback and fill an additional questionnaire about both systems designed by Tcha-Tokey *et al.* [48]. The number of questions was reduced to the following fifteen questions to decrease the time to fill all answers and prevent the exhaustion of participants after the dive:

1) My interactions with the augmented environment seemed natural.
2) The visual aspects of the augmented environment involved me.
3) I could actively survey the augmented environment using vision.
4) I could examine objects closely.
5) I was involved in the augmented environment experience.
6) I felt stimulated by the augmented environment.
7) I become so involved in the augmented environment that I was not aware of things happening around me.
8) I become so involved in the augmented environment that I lose all track of time.
9) I felt I was experiencing an exciting moment.
10) I enjoyed being in this augmented environment.
11) I felt nervous in the augmented environment.
12) Personally, I would say the augmented environment is practical.
13) Personally, I would say the augmented environment is confusing.
14) I found that this augmented environment is likeable.
15) I suffered from fatigue during my interaction with the augmented environment.

They also filled the NASA TLX questionnaire [23] inquiring the following questions:

1) Mental Demand: How mentally demanding was the task?
2) Physical Demand: How physically demanding was the task?
3) Temporal Demand: How hurried or rushed was the pace of the task?
4) Performance: How successful were you in accomplishing what you were asked to do?
5) Effort: How hard did you have to work to accomplish your level of performance?
6) Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

The answers were obtained from all three groups of participants (divers testing the marker-based system in water, divers testing the acoustic-based system in water, and non-divers testing the marker-based system on land). The divers filled these questionnaires once they returned to the diving center.

V. RESULTS

Four sets of results were obtained from the tests. A perception study performed by the divers working with the marker-based system investigated which virtual objects they notice. The second study focused on objects divers found the most interesting and matched it with participants doing the same test on land. The user feedback found the pros and cons of both systems, and finally, an additional evaluation of several image-enhancing algorithms, similar to a comparison presented by Čejka *et al.* [50], measured their performance in a real-world scenario.

A. PERCEPTION STUDY

Divers working with the marker-based smartphone solution filled a questionnaire with six questions regarding objects they could notice in the rooms. Each question had five possible answers and an additional option *I don't know* to express they do not remember the fact, which reduced the number of incorrect answers obtained by guessing. They were explicitly told that there is no penalty for choosing this answer. The questionnaire contained the following questions about objects depicted in Figure 8 (the correct answer is emphasized in boldface, and the number of answers is in parentheses representing answers of divers / non-diver participants on land):

- Question: What is the color of the bed sheets?
  Answers: **Red (6/8)**; Green (0/0); Blue (0/1); Purple (1/0); Yellow (0/1); I don't know (3/0).

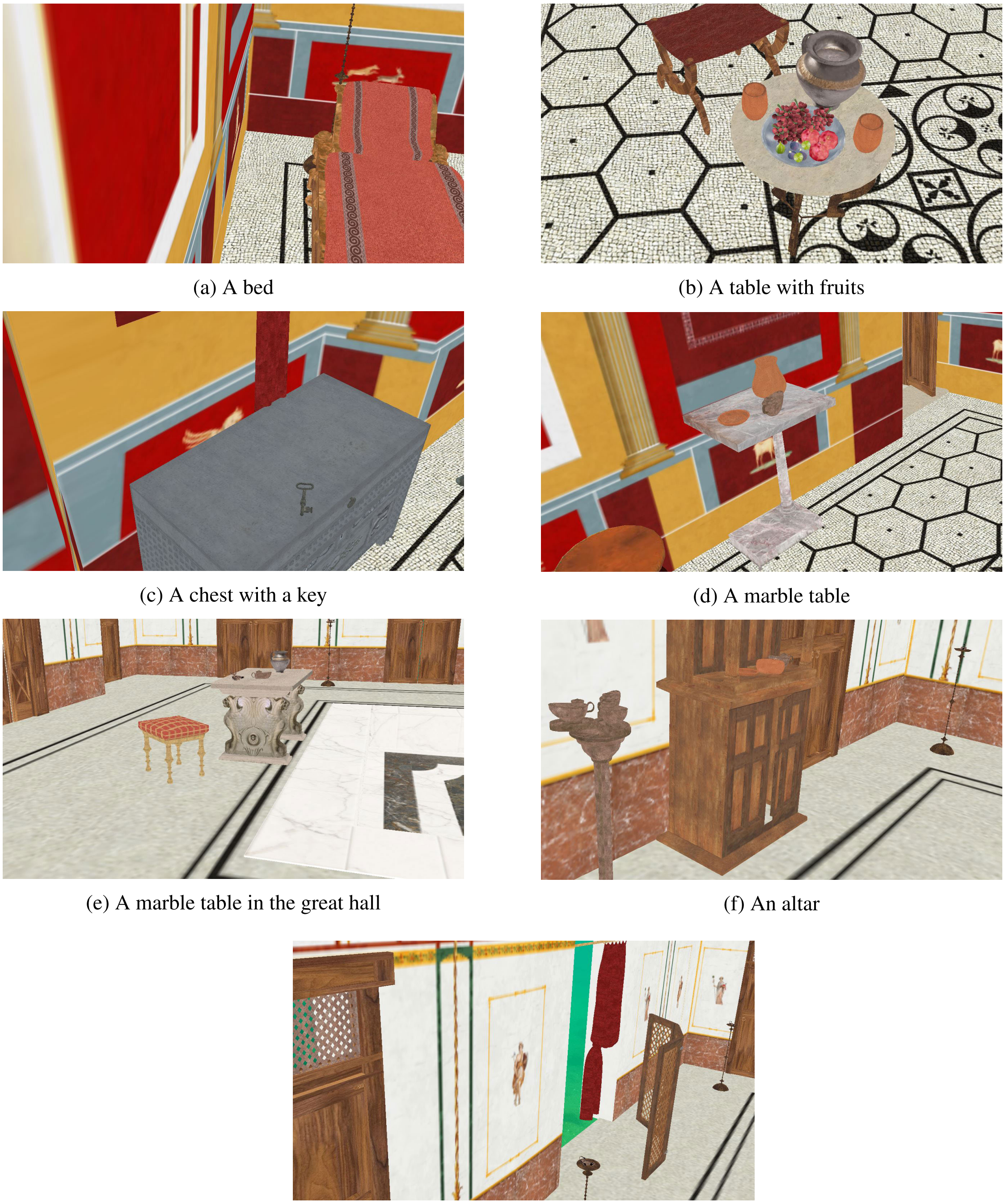
The first question targeted a bed placed in the room, see Figure 8a. The bed was large when compared to other objects in the room, and was quite recognizable. The results show that this was one of the easier questions as six divers and eight non-divers correctly remembered the color. Only one diver and two non-divers chose a wrong color, and three divers could not remember the color.

- Question: How many cups are on the table in the center of the room?
  Answers: 0 cups (0/1); 1 cup (2/4); **2 cups (5/2)**; 3 cups (1/2); 4 cups (0/0); I don't know (2/1).

The second question was focused on a table with fruits, see Figure 8b. The table was small compared to other objects, but it was located in the center of the room and was very exposed. The results show that this was one of the more problematic questions since five divers correctly remembered the number of cups, but only two non-divers chose the correct answer. On the other hand, eight divers and the same number of non-divers missed the correct number by up to one.

- Question: Where is the key of the chest?
  Answers: On the bed (0/0); On the table in the center of the room (1/0); On the marble table at room's wall (2/1); **On the chest (2/5)**; None of the answers (2/1); I don't know (3/3).

The difficulty of the third question was similar. It targeted a chest placed in the room and its key placed on the chest, see Figure 8c. The key was very distinguishable, but it could have been easily missed if the participants did not move around. Five non-divers and only two divers chose the correct option, whereas three divers chose an incorrect location.



(a) A bed

(b) A table with fruits

(c) A chest with a key

(d) A marble table

(e) A marble table in the great hall

(f) An altar

(g) A screen

FIGURE 8. **Objects in the room and the great hall. objects in the room: (a) a bed, (b) a table with fruits, (c) a chest with a key, (d) a marble table. objects in the hall: (e) a marble table, (f) an altar, (g) a screen.**

- Question: How many objects are on the marble table at room's wall?
  Answers: 1 object (0/2); 2 objects (0/1); **3 objects (2/0)**; 4 objects (1/5); 5 objects (4/0); I don't know (3/2).

The fourth question was focused at a marble table placed at one of the room walls, see Figure 8d. The table was not as exposed as the table in the center and the objects were not as distinguishable as the key of the chest. The results show that this was one of the hardest questions because only two divers and no non-diver remembered the number of objects, and most participants chose an incorrect answer.

- Question: What kind of fruit is NOT on the table in the room?
  Answers: Figs (0/0); **Lemons (4/8)**; Grapes (1/0); Pomegranates (1/0); All of them are present (2/0); I don't know (2/2).

The fifth and the sixth question were targeted at remembering which objects did not appear in the scene. The fifth question returned to the table in the center of the room and inquired about the fruits on it, see Figure 8b. Although it could be hard to recognize the individual types of fruits here, it was supposed to be easy to remember that there is no yellow fruit resembling a lemon, especially since there were no objects of bright yellow color in the whole scene. Four divers correctly remembered that there were no lemons on the table, two divers chose a different fruit, and two divers thought there were all mentioned kinds of fruit. Regarding the non-divers, eight chose the correct option, with non of them choosing an incorrect option. Two divers and two non-divers admitted they could not remember.

- Question: What object is NOT it the hall?
  Answers: A marble table (0/0); **A statue (1/6)**; A screen (1/1); An altar (3/1); All of them are present (3/1); I don't know (2/1).

The last question was targeted at the great hall, see Figure 8e, Figure 8f, and Figure 8g. The marble table that was present in the center of the hall was remembered by all users. However, other objects were not as easy to recognize. The screen was shading one of the entrances into the room but could be confused with a door, similarly as the altar placed at one of the walls and may have been confused with a cabinet. Nevertheless, there was no statue in the room and no object resembling a statue, although there were figures painted on the walls. This question was much harder for divers since only one of them correctly remembered that there was no statue. It was much easier for non-divers, as six of them selected the correct option. Four divers and two non-divers chose a different object, and three and one thought that all mentioned objects were present. Two divers and one non-diver could not remember the correct answer.

The participants remembered the color of the bed sheets and fruits on the table at the room's center. This could have been caused by the fact that the bed was one of the more prominent objects in the room, and the table was in the middle of the room. They had some problems with less recognizable and less emphasized objects in the room and in the hall, these objects were placed at the walls, the users paid little attention to them, or they missed them completely.

B. OBJECTS OF INTEREST

The application recorded the position and orientation of participants in the virtual scene. During the evaluation, these data served as a position and direction of a ray cast into a simplified scene with two boxes in place of both rooms, and the resulting intersections represented points where the participants looked and which they found interesting.

Figure 9 illustrates the objects of participants' interest. The first two figures 9a and 9f depict clear views around the room and the hall with no overlaid results. The following four figures 9b, 9g, 9c, and 9h depicts points at which the participants looked with an opaque black dot at the intersections of participants' view. These figures show that the participants were more interested in the lower parts of the room and the hall than in the ceiling, observed by a very few people. Non-divers were focused more on the walls than on the mosaic, which indicates that they were able to follow the instructions better (to walk around the room), or that divers tend to observe the floor, which corresponds to their body posture when diving.

The points of interest illustrate objects of attention, but they cannot show the duration and reveal the most interesting parts. This is solved by heatmaps, as presented in Figures 9d, 9i, 9e, and 9j. The heatmaps accumulate the number of intersections at each point, normalize it, and represent the areas with more attention with darker colors. The images of both the room and the hall show that the participants spent most of the time around the walls, as in the case of points of interest. Figure 9d contains dark colors at the corners of the room at places where the markers were located, which indicates that the markers drew divers' attention.

Similar behavior can be observed with non-divers, as illustrated in Figure 9e, although it is less prominent. Figure 9e shows an interesting detail that many non-divers looked out of the window of the room and observed the objects outside of the room. This is surprising, because the application displayed no virtual objects outside the room, so the participants saw the rest of the hall where the experiment was performed.

This experiment revealed two significant aspects. First, all participants, both on land and in water, focused very little on the ceiling and observed the walls and the floor instead. Second, the markers attract the users' attention even though they do not represent locations of specific virtual objects. This might be considered as a disadvantage compared to the acoustic tracking AR solution.

C. USER FEEDBACK AND COMPARISON OF BOTH SYSTEMS

The following tables combine the recorded feedback of all participants testing both systems in water and on land. Table 2 shows the answers to the selected fifteen questions of the Tcha-Tokey questionnaire. Participants found the interaction natural and the visual aspects involved them, which is very positive. In particular, they could actively survey the environment and examine the objects closely. Another positive point is that they were involved in the experience and felt stimulated. They reported that they enjoyed being in the environment and found the environment practical and likeable.

Surprisingly, participants did not feel nervous and did not find the environment confusing. Most importantly they did not suffer from fatigue even if this is common issue diving. Furthermore, they stated immersion was low and did not lose track of space and time. This is a positive outcome, since the divers should be only partially involved in the environment because they must be constantly aware of things happening around them. The acoustic solution showed slightly better results than the marker-based solution tested by divers. Similarly, the non-divers rated the marker-based system better

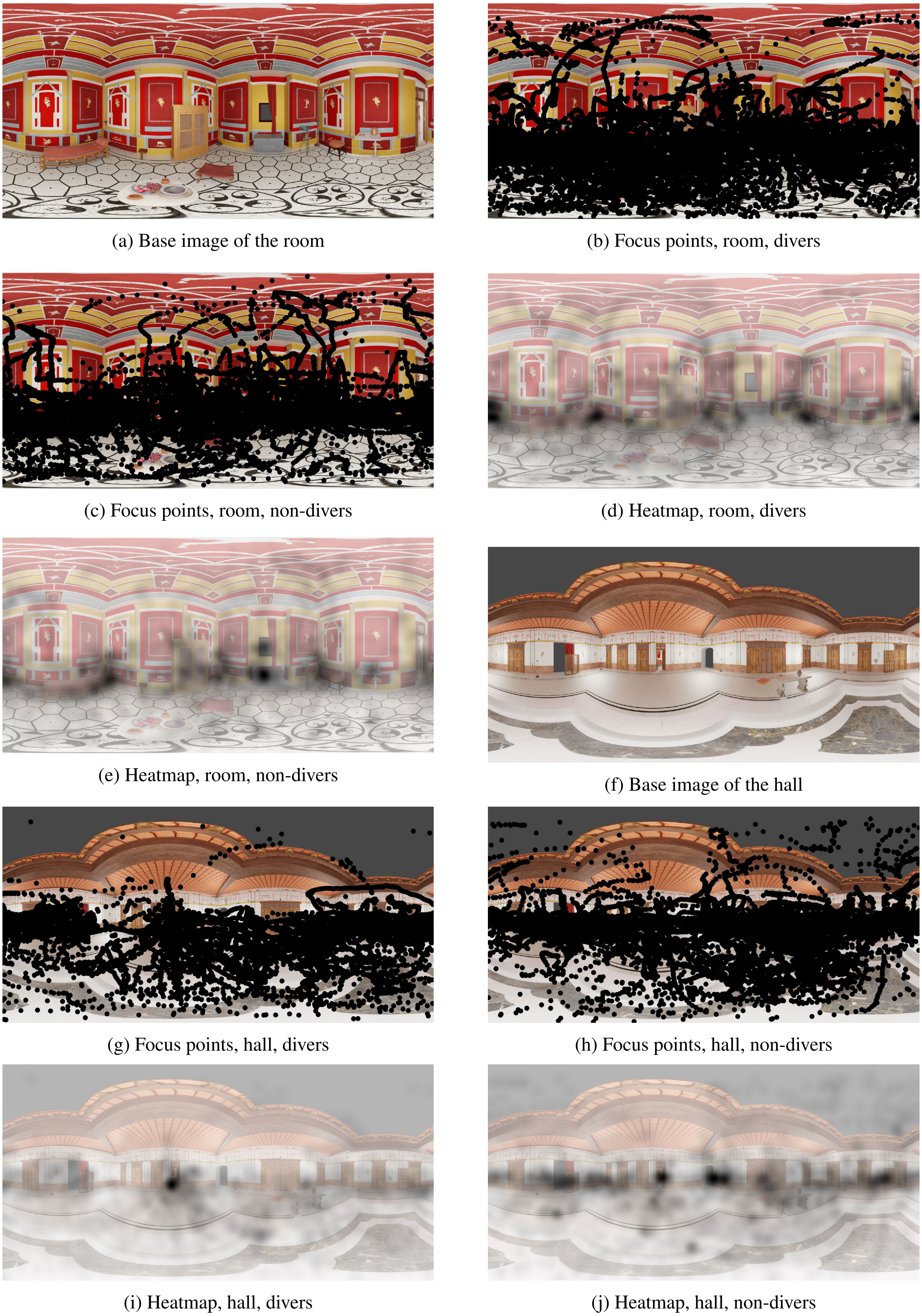


FIGURE 9. Focus points and heatmaps of objects of interest.

TABLE 2. Feedback of participants to the user experience; the full text of the questions is in section IV. Red represents the marker-based system tested by divers, green represents the acoustic system, and blue represents the marker-based system tested by non-divers.

Question	Marker-based system Divers	Acoustic system Divers	Marker-based system On land
1) My interactions (...)	4.9 ($\sigma = 1.969$)	4.5 ($\sigma = 1.900$)	5.6 ($\sigma = 1.350$)
2) The visual aspects (...)	5.5 ($\sigma = 1.581$)	6.0 ($\sigma = 0.816$)	5.4 ($\sigma = 1.265$)
3) I could actively (...) vision.	5.1 ($\sigma = 1.969$)	5.6 ($\sigma = 1.350$)	6.3 ($\sigma = 0.949$)
4) I could examine objects closely.	5.0 ($\sigma = 1.491$)	5.7 ($\sigma = 1.160$)	6.1 ($\sigma = 1.370$)
5) I was involved (...)	5.8 ($\sigma = 1.549$)	6.5 ($\sigma = 0.527$)	5.6 ($\sigma = 1.075$)
6) I felt stimulated (...)	5.3 ($\sigma = 1.703$)	6.5 ($\sigma = 0.527$)	5.5 ($\sigma = 1.269$)
7) (...) things happening around me.	2.4 ($\sigma = 2.119$)	4.3 ($\sigma = 2.111$)	3.4 ($\sigma = 2.066$)
8) (...) I lose all track of time.	3.0 ($\sigma = 2.160$)	3.8 ($\sigma = 2.150$)	3.5 ($\sigma = 1.780$)
9) (...) exciting moment.	4.3 ($\sigma = 2.163$)	4.8 ($\sigma = 1.317$)	4.8 ($\sigma = 1.874$)
10) I enjoyed (...)	5.6 ($\sigma = 2.011$)	6.6 ($\sigma = 0.516$)	5.8 ($\sigma = 1.135$)
11) I felt nervous (...)	1.1 ($\sigma = 0.316$)	1.2 ($\sigma = 0.422$)	1.1 ($\sigma = 0.316$)
12) (...) environment is practical.	5.3 ($\sigma = 1.418$)	5.6 ($\sigma = 1.174$)	5.7 ($\sigma = 1.059$)
13) (...) environment is confusing.	2.1 ($\sigma = 2.079$)	1.6 ($\sigma = 0.966$)	2.1 ($\sigma = 1.101$)
14) (...) environment is likeable.	5.7 ($\sigma = 1.494$)	6.5 ($\sigma = 0.707$)	5.5 ($\sigma = 1.179$)
15) I suffered from fatigue (...)	1.2 ($\sigma = 0.421$)	1.2 ($\sigma = 0.422$)	1.2 ($\sigma = 0.422$)

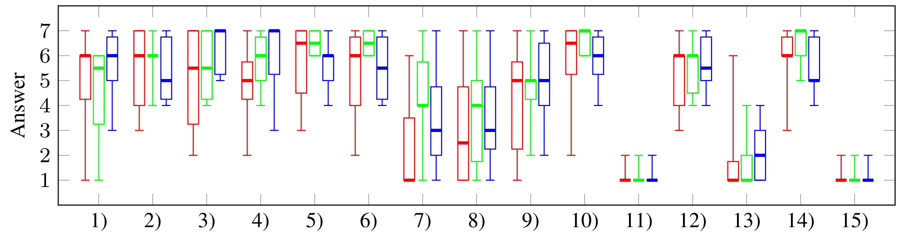
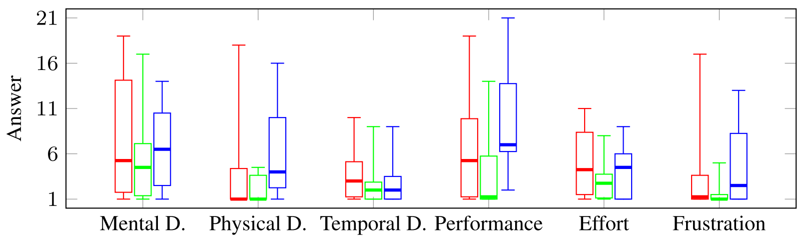


TABLE 3. Feedback obtained with the NASA TLX questionnaire, lower is better. Red represents the marker-based system tested by divers, green represents the acoustic system, and blue represents the marker-based system tested by non-divers.

Aspect	Marker-based system Divers	Acoustic system Divers	Marker-based system On land
Mental Demand	7.8 ($\sigma = 7.025$)	5.5 ($\sigma = 5.044$)	6.8 ($\sigma = 4.849$)
Physical Demand	3.8 ($\sigma = 5.293$)	2.1 ($\sigma = 1.506$)	6.4 ($\sigma = 5.680$)
Temporal Demand	3.9 ($\sigma = 3.187$)	2.7 ($\sigma = 2.486$)	3.1 ($\sigma = 2.998$)
Performance	6.6 ($\sigma = 6.208$)	4.0 ($\sigma = 4.428$)	9.3 ($\sigma = 5.982$)
Effort	5.3 ($\sigma = 4.036$)	3.0 ($\sigma = 2.224$)	4.1 ($\sigma = 3.035$)
Frustration	3.8 ($\sigma = 5.143$)	1.9 ($\sigma = 1.647$)	4.8 ($\sigma = 4.638$)



than divers, which indicates that the underwater environment negatively influences the user experience.

Table 3 shows encouraging results in all aspects of the NASA TLX questionnaire with the acoustic tablet solution being better than the two other solutions. An interesting point was that non-divers found the tasks more mental and physically demanding, they reported lower performance and high levels of frustration. We believe that the main reason for that is that the application was mainly designed for AR diving. Even if it works perfectly well for land, according to the results the divers enjoyed the diving part of the test very much, which increased their rating.

In terms of the qualitative feedback, all divers found both systems practical, engaging, and useful tools for diving and archaeology, and they enjoyed the experience. They appreciated the compact size of the marker-based system for smartphones and its ability to track the device's orientation, but the text was small and covered the AR view on the site. The acoustic system for tablets was valued for its ability to localize the diver on site and for its ability to transit between viewing modes, but many divers complained about occasional inaccuracies in diver's position. They also criticized the reflections of the sun on the screen of the tablet, which occur mostly in shallow depths of the sea and disappear as the diver descent deeper. This was faced by modifying the screen shape to minimise this problem.

One user noted that the hardware is not designed well for left-handed people, one found the tablet bulky, but another one mentioned it is easy to use. In general, the divers were especially excited and suggested many more features to include in future prototypes such as: a preview of locations, more information about POIs, a sound, a checklist of POIs, an ability to take pictures in the AR environment, or a confirmation window when answering the questionnaire. Both systems were easy to handle even for divers with the first level diving certificate because the weight of both systems in water is almost zero (due to buoyancy).

The non-divers testing the marker-based system for smartphones also enjoyed the experiment. Some participants mentioned problems with tracking, but others were surprised by its precision. Several users complained about the poor quality of 3D models and textures, mainly when they observed the frescos. Although there are photorealistic techniques for games and virtual environments, we had to take into consideration the rendering capabilities of mobile devices. Finally, one participant found the housing heavy, but this was expected since the hardware is designed for underwater environments.

D. IMPROVING UNDERWATER IMAGES

Our system also recorded an uncompressed video during the experiment with divers. This allowed us to compare additional image-improving and marker-detecting algorithms as was done by Čejka *et al.* [50], but unlike them, who recorded the videos during a controlled experiment, we obtained the results during a user study. Thus, our results provide an invaluable source of information to choose the proper combination of algorithms for systems when designing a system for other cultural heritage locations. We compared four marker detecting algorithms (ARUco, two versions of ARUco3, and UWARUco) and three image improving algorithms (CLAHE, white balancing, and marker-based underwater white balancing).

ARUco [20] is a real-time algorithm for the detection of square markers, uses an adaptive thresholding algorithm, and is robust to various lighting conditions. ARUco3 [43] is the newest version of the ARUco project. Its implementation is a part of open-source library OpenCV and exists in three variants. A variant that uses an adaptive thresholding algorithm is not tested here since Čejka *et al.* [50] compared it to other solutions and showed that its performance is deficient. The other two variants use a constant threshold and trade the robustness for increased processing speed. The Fast version of this algorithm, denoted in this paper only as *ARUco3*, uses the data from the previous frame to choose a proper threshold in the next frame. The Video-Fast version, denoted as *ARUco3 VF*, performs additional optimizations to decrease the processing time further. UWARUco [50] is another marker-detecting algorithm based on ARUco that is optimized for the detection of markers under water.

TABLE 4. Results of various image improving and marker detecting algorithms, sorted by the processing time.

Combination of algorithms	Detected markers	Processing time (ms)
ARUco3 VF + Original	13990	8.11
ARUco3 + Original	16927	8.25
ARUco3 + MBUWWB	18518	18.60
ARUco3 + WB	17605	19.40
ARUco3 + CLAHE	19041	19.52
ARUco + Original	20396	22.88
UWARUco + Original	25440	35.01
ARUco + MBUWWB	23486	40.32
ARUco + WB	22721	46.25
ARUco + CLAHE	23765	51.51

Contrast-limited adaptive histogram equalization (CLAHE) [41] is an image-improving algorithm based on standard histogram equalization, and changes the color of pixels using the data of neighbor pixels. Mangeruga *et al.* [32], [33] evaluated the performances of different underwater image enhancement algorithms and found that the CLAHE algorithm works reasonably well in different environmental conditions and maintains an acceptable computational cost. White balancing algorithm shifts the colors of the image to look more natural; we used an algorithm by Limare *et al.* [31], the same as Čejka *et al.* [50] did in their tests. Marker-based underwater white balancing (MBUWWB) [52] is an adaptation of the previous white-balancing algorithm, which uses black-and-white markers in images to choose the black and white points for the white-balancing algorithm.

This comparison was made offline after the test on a desktop PC with Intel Core i5 760 processor, 8 GB of operating memory, and Windows 10. We measured the average time required to process a frame (the sum of the time required to improve the image and detect the markers) and the number of detected markers in 56766 recorded frames. The results are presented in Table 4 and demonstrate that ARUco3 and ARUco3 VF algorithms with no image improvements are the fastest solutions of detecting markers, with ARUco3 detecting approximately 21 % more markers than ARUco3 VF. ARUco3 combined with MBUWWB (the combination chosen for the marker-based system) or combined with CLAHE and ARUco without any image improvement provide more detected markers than a sole ARUco3 at the cost of increased processing time. UWARUco obtains the highest number of detected markers. The other tested combinations (ARUco3+WB, ARUco+MBUWWB, ARUco+WB, and ARUco+CLAHE) were found less optimal since there were combinations that detected more markers in less time.

The impact of the increase of detected markers on the tracking cannot be adequately measured since the ARCore library does not provide an offline mode that would allow us to record the data and compare the results of the whole tracking system. Based on our results, we estimate that the best tracking results are obtained with combinations of a sole ARUco3, ARUco3+CLAHE, ARUco3+MBUWWB, and UWARUco. The optimal choice depends on the visibility conditions and available processing capacity.

VI. CONCLUSION

This paper presented two different solutions enabling divers to experience AR in underwater cultural heritage sites. The systems were designed for smartphones and tablets and supported a real-time localization obtained by various techniques. The system for smartphones was compact and used a set of markers combined with the state-of-the-art visual-inertial ARCore library, whereas the other system for tablets utilized an acoustic technology to localize users over vast areas. The systems also incorporated new underwater interaction methods when the divers had no access to the touchscreen. They are required only to tilt the device to choose an option on the screen and confirm the choice by pressing a single button, and thanks to it, they were able to provide answers directly in the water right after the test.

Both systems were successfully evaluated at an underwater cultural heritage site. Ten divers participated in a user study that evaluated their perception of virtual objects under water and user experience, and the results were compared with participants testing on land. Results showed that divers noticed details about large and more exposed objects and were less aware of details about objects located at the walls of the virtual room. They also enjoyed their time and claimed that the technology had great potential in underwater archaeology and tourism. The data recorded during the user study were used for offline evaluation of four marker-detecting and three image-improving algorithms in real environments, which showed that the combination of algorithms used in the system is a viable real-time solution.

There are several aspects that can be further improved. Rendering can be redesigned concerning the underwater environment to avoid the virtual objects being overlooked. Its visual quality will also be improved, but it must still reflect the limits of the hardware and should not suppress the feel of the dive. Future work will also include a performance evaluation of both tracking systems in terms of accuracy and precision. This task requires the setup of a precise and big enough ground truth to record the divers' movement along this path and measure the errors of the localization techniques. New hardware features should also be investigated; newer smartphones incorporate depth sensors which help ARCore to reduce the time of initialization, but their performance in underwater environments is unknown. Finally, the tracking components of both systems could be merged together to leverage the benefits of both, i.e., to combine the large-scale tracking of the acoustic solution, and the higher precision of the marker-based solution.

ACKNOWLEDGMENT

The authors would like to thank the Parco Archeologico dei Campi Flegrei for the permission to conduct the tests in the Marine Protected Area - Underwater Park of Baiae; the Istituto Centrale per il Restauro for the valuable support and collaboration; Roberto Petriaggi for the supervision of the hypothetical reconstruction and his valuable suggestions; the underwater unit of Carabinieri for the kind participation in the testing; Matteo Collina for the pictures included in this paper; and all participants performing the test on land.

REFERENCES

[1] G. Albert, P. Renaud, S. Chartier, L. Renaud, L. Sauvé, and S. Bouchard, ''Scene perception, gaze behavior, and perceptual learning in virtual environments,'' *Cyberpsychol. Behav.*, vol. 8, no. 6, pp. 592–600, 2005.

[2] E. F. Anderson, L. McLoughlin, F. Liarokapis, C. Peters, P. Petridis, and S. de Freitas, ''Developing serious games for cultural heritage: A state-of-the-art review,'' *Virtual Reality*, vol. 14, no. 4, pp. 255–275, Dec. 2010.

[3] Apple. (2019). *ARKit3—Augmented Reality—Apple Developer*. [Online]. Available: https://developer.apple.com/augmented-reality/arkit/

[4] A. Bellarbi, C. Domingues, S. Otmane, S. Benbelkacem, and A. Dinis, ''Augmented reality for underwater activities with the use of the DOLPHYN,'' in *Proc. 10th IEEE Int. Conf. Netw., Sens. CONTROL (ICNSC)*, Apr. 2013, pp. 409–412.

[5] R. Bencina, M. Kaltenbrunner, and S. Jorda, ''Improved topological fiducial tracking in the reactivision system,'' in *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit. (CVPR) Workshops*, 2005, p. 99.

[6] F. Bergamasco, A. Albarelli, L. Cosmo, E. Rodola, and A. Torsello, ''An accurate and robust artificial marker based on cyclic codes,'' *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 38, no. 12, pp. 2359–2373, Dec. 2016.

[7] Blender Foundation. (2020). *Blender.org—Home of the Blender Project—Free and Open 3D Creation Software*. [Online]. Available: https://www.blender.org

[8] H. C. Brown and H. Wang, ''Underwater augmented reality: Navigation and identification,'' in *Proc. OCEANS San Diego*, Sep. 2013, pp. 1–5.

[9] F. Bruno, L. Barbieri, M. Mangeruga, M. Cozza, A. Lagudi, J. Čejka, F. Liarokapis, and D. Skarlatos, ''Underwater augmented reality for improving the diving experience in submerged archaeological sites,'' *Ocean Eng.*, vol. 190, Oct. 2019, Art. no. 106487.

[10] F. Bruno, A. Lagudi, L. Barbieri, M. Muzzupappa, G. Ritacco, A. Cozza, M. Cozza, R. Peluso, M. Lupia, and G. Cario, ''Virtual and augmented reality tools to improve the exploitation of underwater archaeological sites by diver and non-diver tourists,'' in *Proc. 6th Int. Conf., Digit. Heritage. Prog. Cultural Heritage, Document., Preservation, Protection, EuroMed*. Cham, Switzerland: Springer, 2016, pp. 269–280.

[11] F. Bruno, A. Lagudi, G. Ritacco, P. Agrafiotis, D. Skarlatos, J. Cejka, P. Kouril, F. Liarokapis, O. Philpin-Briscoe, C. Poullis, S. Mudur, and B. Simon, ''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 *Proc. OCEANS Aberdeen*, Jun. 2017, pp. 1–10.

[12] G. Calogiuri, S. Litleskare, K. A. Fagerheim, T. L. Rydgren, E. Brambilla, and M. Thurston, ''Experiencing nature through immersive virtual environments: Environmental perceptions, physical engagement, and affective responses during a simulated nature walk,'' *Frontiers Psychol.*, vol. 8, p. 2321, Jan. 2018.

[13] G. Cario, A. Casavola, G. Gagliardi, M. Lupia, U. Severino, and F. Bruno, ''Analysis of error sources in underwater localization systems,'' in *Proc. OCEANS Marseille*, Jun. 2019, pp. 1–6.

[14] B. J. Dixon, M. J. Daly, H. Chan, A. D. Vescan, I. J. Witterick, and J. C. Irish, ''Surgeons blinded by enhanced navigation: The effect of augmented reality on attention,'' *Surgical Endoscopy*, vol. 27, no. 2, pp. 454–461, Feb. 2013.

[15] Easydive. (2019). *Diveshot*. Accessed: Sep. 8, 2019. [Online]. Available: https://www.easydive.it/en/underwater-housing/smartphone/diveshot.384.html

[16] Easydive. (2020). *DivePad—Universal Underwater Housing for Tablets*. [Online]. Available: https://www.easydive.it/en/underwater-housing/tablet/divepad.722.html

[17] J. Engel, T. Schöps, and D. Cremers, ''LSD-SLAM: Large-scale direct monocular SLAM,'' in *Computer Vision—ECCV*, D. Fleet, T. Pajdla, B. Schiele, and T. Tuytelaars, Eds. Cham, Switzerland: Springer, 2014, pp. 834–849.

[18] P. Galatis, D. Gavalas, V. Kasapakis, G. Pantziou, and C. Zaroliagis, ''Mobile augmented reality guides in cultural heritage,'' in *Proc. 8th EAI Int. Conf. Mobile Comput., Appl. Services*, 2016, pp. 11–19.

[19] D. G. Gallagher, ''Development of miniature, head-mounted, virtual image displays for navy divers,'' in *Proc. Oceans 99. MTS/IEEE. Riding Crest 21st Century. Conf. Exhib. Conf.*, Sep. 1999, pp. 1098–1104.

[20] S. Garrido-Jurado, R. Muñoz-Salinas, F. J. Madrid-Cuevas, and M. J. Marín-Jiménez, "Automatic generation and detection of highly reliable fiducial markers under occlusion," *Pattern Recognit.*, vol. 47, no. 6, pp. 2280–2292, Jun. 2014.
[21] Google. (2019). *ARCore—Google Developers*. [Online]. Available: https://developers.google.com/ar
[22] A. Greenfeld, A. Lugmayr, and W. Lamont, "Comparative reality: Measuring user experience and emotion in immersive virtual environments," in *Proc. IEEE Int. Conf. Artif. Intell. Virtual Reality (AIVR)*, Dec. 2018, pp. 204–209.
[23] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (task load index): Results of empirical and theoretical research," in *Advances in Psychology* (Human Mental Workload), vol. 52, P. A. Hancock and N. Meshkati, Eds. Haarlem The Netherlands: North-Holland, Jan. 1988, pp. 139–183.
[24] H. Kato and M. Billinghurst, "Marker tracking and HMD calibration for a video-based augmented reality conferencing system," in *Proc. 2nd IEEE ACM Int. Workshop Augmented Reality (IWAR99)*, Oct. 1999, pp. 85–94.
[25] J. Keil, A. Korte, A. Ratmer, D. Edler, and F. Dickmann, "Augmented reality (AR) and spatial cognition: Effects of holographic grids on distance estimation and location memory in a 3D indoor scenario," *PFG J. Photogramm., Remote Sens. Geoinf. Sci.*, vol. 88, no. 2, pp. 165–172, Apr. 2020.
[26] G. Klein and D. Murray, "Parallel tracking and mapping for small AR workspaces," in *Proc. 6th IEEE ACM Int. Symp. Mixed Augmented Reality*, Nov. 2007, pp. 225–234.
[27] J. Köhler, A. Pagani, and D. Stricker, "Robust detection and identification of partially occluded circular markers," in *Proc. VISAPP 5th Int. Conf. Comput. Vis. Theory Appl.*, May 2010, pp. 387–392.
[28] P. Kourouthanassis, C. Boletsis, C. Bardaki, and D. Chasanidou, "Tourists responses to mobile augmented reality travel guides: The role of emotions on adoption behavior," *Pervas. Mobile Comput.*, vol. 18, pp. 71–87, Apr. 2015.
[29] J. M. Lavest, G. Rives, and J. T. Lapresté, "Dry camera calibration for underwater applications," *Mach. Vis. Appl.*, vol. 13, nos. 5–6, pp. 245–253, Mar. 2003.
[30] G. A. Lee, A. Dunser, S. Kim, and M. Billinghurst, "CityViewAR: A mobile outdoor AR application for city visualization," in *Proc. IEEE Int. Symp. Mixed Augmented Reality Arts, Media, Humanities (ISMAR-AMH)*, Nov. 2012, pp. 57–64.
[31] N. Limare, J.-L. Lisani, J.-M. Morel, A. B. Petro, and C. Sbert, "Simplest color balance," *Image Process. Line*, vol. 1, pp. 297–315, Oct. 2011.
[32] M. Mangeruga, F. Bruno, M. Cozza, P. Agrafiotis, and D. Skarlatos, "Guidelines for underwater image enhancement based on benchmarking of different methods," *Remote Sens.*, vol. 10, no. 10, p. 1652, Oct. 2018.
[33] M. Mangeruga, M. Cozza, and F. Bruno, "Evaluation of underwater image enhancement algorithms under different environmental conditions," *J. Mar. Sci. Eng.*, vol. 6, no. 1, p. 10, Jan. 2018.
[34] K. Mania and A. Chalmers, "The effects of levels of immersion on memory and presence in virtual environments: A reality centered approach," *Cyberpsychol. Behav.*, vol. 4, no. 2, pp. 247–264, Apr. 2001.
[35] R. Morales, P. Keitler, P. Maier, and G. Klinker, "An underwater augmented reality system for commercial diving operations," in *Proc. OCEANS*, Oct. 2009, pp. 1–8.
[36] R. Mur-Artal, J. M. M. Montiel, and J. D. Tardos, "ORB-SLAM: A versatile and accurate monocular SLAM system," *IEEE Trans. Robot.*, vol. 31, no. 5, pp. 1147–1163, Oct. 2015.
[37] L. Naimark and E. Foxlin, "Circular data matrix fiducial system and robust image processing for a wearable vision-inertial self-tracker," in *Proc. Int. Symp. Mixed Augmented Reality*, Oct. 2002, pp. 27–36.
[38] L. Oppermann, L. Blum, J.-Y. Lee, and J.-H. Seo, "AREEF multi-player underwater augmented reality experience," in *Proc. IEEE Int. Games Innov. Conf. (IGIC)*, Sep. 2013, pp. 199–202.
[39] L. Oppermann, L. Blum, and M. Shekow, "Playing on AREEF: Evaluation of an underwater augmented reality game for kids," in *Proc. 18th Int. Conf. Hum.-Comput. Interact. Mobile Devices Services*, Sep. 2016, pp. 330–340.
[40] B. D. Petriaggi, R. Petriaggi, F. Bruno, A. Lagudi, R. Peluso, and S. Passaro, "A digital reconstruction of the sunken 'villa con ingresso a protiro' in the underwater archaeological site of baiae," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 364, Jun. 2018, Art. no. 012013.
[41] S. M. Pizer, E. P. Amburn, J. D. Austin, R. Cromartie, A. Geselowitz, T. Greer, B. T. H. Romeny, and J. B. Zimmerman, "Adaptive histogram equalization and its variations," *Comput. Vis., Graph., Image Process.*, vol. 39, no. 3, pp. 355–368, 1987.
[42] M. Rietzler, F. Geiselhart, and E. Rukzio, "The Matrix has you: Realizing slow motion in full-body virtual reality," in *Proc. 23rd ACM Symp. Virtual Reality Softw. Technol. VRST*. New York, NY, USA: Association for Computing Machinery, 2017, pp. 1–10.
[43] F. J. Romero-Ramirez, R. Muñoz-Salinas, and R. Medina-Carnicer, "Speeded up detection of squared fiducial markers," *Image Vis. Comput.*, vol. 76, pp. 38–47, Aug. 2018.
[44] M. L. Rusch, M. C. Schall, P. Gavin, J. D. Lee, J. D. Dawson, S. Vecera, and M. Rizzo, "Directing driver attention with augmented reality cues," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 16, pp. 127–137, Jan. 2013.
[45] T. Schops, J. Engel, and D. Cremers, "Semi-dense visual odometry for AR on a smartphone," in *Proc. IEEE Int. Symp. Mixed Augmented Reality (ISMAR)*, Sep. 2014, pp. 145–150.
[46] S. Sendra, J. Lloret, J. J. P. C. Rodrigues, and J. M. Aguiar, "Underwater wireless communications in freshwater at 2.4 GHz," *IEEE Commun. Lett.*, vol. 17, no. 9, pp. 1794–1797, Sep. 2013.
[47] D. Stáelák, F. Škola, and F. Liarokapis, "Examining user experiences in a mobile augmented reality tourist guide," in *Proc. 9th ACM Int. Conf. Pervas. Technol. Rel. Assistive Environ.*, Jun. 2016, p. 19.
[48] K. Tcha-Tokey, O. Christmann, E. Loup-Escande, and S. Richir, "Proposition and validation of a questionnaire to measure the user experience in immersive virtual environments," *Int. J. Virtual Reality*, vol. 16, no. 1, pp. 33–48, Jan. 2016.
[49] M. Toyoura, H. Aruga, M. Turk, and X. Mao, "Detecting markers in blurred and defocused images," in *Proc. Int. Conf. Cyberworlds*, Oct. 2013, pp. 183–190.
[50] J. Čejka, F. Bruno, D. Skarlatos, and F. Liarokapis, "Detecting square markers in underwater environments," *Remote Sens.*, vol. 11, no. 4, p. 459, Feb. 2019. [Online]. Available: https://www.mdpi.com/2072-4292/11/4/459
[51] J. Čejka, J. Chmelík, and F. Liarokapis, "Exploring tilting methods for typing under water," *Multimedia Tools Appl.*, vol. 79, pp. 1–19, Aug. 2020.
[52] J. Čejka, M. Žuži, P. Agrafiotis, D. Skarlatos, F. Bruno, and F. Liarokapis, "Improving marker-based tracking for augmented reality in underwater environments," in *Proc. Eurographics Workshop Graph. Cultural Heritage*, R. Sablatnig and M. Wimmer, Eds. Vienna, Austria: Eurographics Association, 2018, pp. 21–30.
[53] J. Čejka, A. Zsíros, and F. Liarokapis, "A hybrid augmented reality guide for underwater cultural heritage sites," *Pers. Ubiquitous Comput.*, vol. 24, no. 6, pp. 815–828, Dec. 2020.
[54] V. Vlahakis, M. Ioannidis, J. Karigiannis, M. Tsotros, M. Gounaris, D. Stricker, T. Gleue, P. Daehne, and L. Almeida, "Archeoguide: An augmented reality guide for archaeological sites," *IEEE Comput. Graph. Appl.*, vol. 22, no. 5, pp. 52–60, Sep. 2002.
[55] J. Wang and E. Olson, "AprilTag 2: Efficient and robust fiducial detection," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2016, pp. 4193–4198.
[56] A. Xu and G. Dudek, "Fourier tag: A smoothly degradable fiducial marker system with configurable payload capacity," in *Proc. Can. Conf. Comput. Robot Vis.*, May 2011, pp. 40–47.

JAN ČEJKA was born in Brno, Czech Republic, in 1989. He received the B.S. and M.S. degrees in computer graphics from Masaryk University, Brno, in 2011 and 2013, respectively, where he is currently pursuing the Ph.D. degree. From 2017 to 2020, he has participated in the iMARECULTURE Project as a Researcher in augmented reality. His research interests include image processing and recognition of objects, underwater interaction, and rendering. During this time, he also taught the computer graphics and real-time rendering at Masaryk University.

MARINO MANGERUGA received the master's degree in computer engineering from the University of Calabria, in 2016, with a thesis entitled A pathfinding algorithm in a navigation system with decompression constraint and its implementation on an underwater tablet with acoustic positioning. He is currently a Researcher and a Software Engineer with 3D Research, and he has a Ph.D. in ICT in progress with the DIMES, University of Calabria. His research interests include the study of underwater image enhancement methods and the exploitation of new technologies for underwater geo-localization and path planning. He has experience in design and development of VR, AR, and mobile applications. He has been involved in some research projects: H2020 iMareCulture (Immersive Serious Games and Augmented Reality as tools to raise awareness and access to European Underwater Culture), Lab4Dive (the Mobile Smart Lab for Augmented Archaeological Dives), DiveSafe (Integrated System for scientific and environmental underwater surveys with advanced health and safety features), MOLUX (the MObile Lab for Underwater eXploration). He is a coauthor of several scientific articles and publications. In 2017, he has gained the diving certification PADI Open Water.

FABIO BRUNO is currently an Associate Professor of design and methods of industrial engineering with the Department of Mechanical, Energy, and Management Engineering (DIMEG), University of Calabria. His research interests include virtual and augmented reality (VR&AR) techniques and their application in Industrial Design and Cultural Heritage, underwater mechatronic systems and 3D reconstruction techniques. He is also a founding member of two Spin-Offs of the University of Calabria, and he has been the Scientific Coordinator of working groups in various national and European research projects targeted at the development of underwater technologies.

DIMITRIOS SKARLATOS is currently an Associate Professor of geoinformatics with the Department of Civil Engineering and Geomatics, Cyprus University of Technology (CUT). He also serves as the Vice Dean of the School of Engineering and Technology. He has coordinated iMARECULTURE a H2020 Research and Innovation Project about AR and VR museums in underwater Cultural Heritage sites. His research interests and publication record include UAV mapping, optical bathymetry of coastal areas, underwater 3D modeling, CH applications of the afore mentioned topics, mobile mapping, and use of small ROVs for 3D recording. He has been the academic representative of Cyprus in EuroSDR, since 2010, and the Co-Chair of International Society of Photogrammetry and Remote Sensing, Commission II, since 2016, Working Group 9, about underwater photogrammetry. He has the Chair of the organizing committee for the Underwater 3D Recording and Modeling Workshop, organized in Limassol, Cyprus, in May 2019, under ISPRS and CIPA auspices. He has also served as member for board in Hellenic Society of Photogrammetry and Remote Sensing, from 2003 to 2019, and the Vice President of Cypriot Association of Rural and Surveying Engineers for one term, from 2014 to 2016.

FOTIS LIAROKAPIS (Member, IEEE) received the D.Phil. degree from the University of Sussex, U.K. He has worked as a Research Fellow with City University, London, U.K., Coventry University, U.K., and most recently at Masaryk University, Czech Republic, where he was an Associate Professor and the Director of the HCI Laboratory. He is currently a Senior Researcher with the Research Centre on Interactive Media, Smart Systems, and Emerging Technologies, Nicosia, Cyprus, and the Cyprus University of Technology, Limassol, Cyprus. He has published more than 130 peer-reviewed articles in journals and international conferences on virtual reality, augmented reality, computer graphics, brain–computer interfaces, and serious games. He has organized multiple conferences and workshops, and he is the Co-Founder of the International Conference on Virtual Worlds and Games for Serious Applications (VS-Games).