

An Underwater Augmented Reality System for Commercial Diving Operations

R. Morales*, P. Keitler†, P. Maier†, G. Klinker†

†Technische Universität München - Institut für Informatik
Boltzmannstr. 3, D-85747 Garching, Germany

*rogelio.rmoral@gmail.com, †keitler@in.tum.de, †maierp@in.tum.de, †klinker@in.tum.de

Abstract- This paper describes the implementation of a novel prototypical Underwater Augmented Reality (UWAR) system that provides visual aids to increase commercial divers' capability to detect, perceive, and understand elements in underwater environments.

During underwater operations, a great amount of stress is imposed on divers by environmental and working conditions such as pressure, visibility, weightlessness, current, etc. Those factors cause a restriction in divers' sensory inputs, cognition and memory, which are essentials for locating within the surroundings and performing their task effectively. The focus of this research was to improve some of those conditions by adding elements in divers' views in order to increase awareness and safety in commercial diving operations.

We accomplished our goal by assisting divers in locating the work site, keeping informed about orientation and position (constantly), and providing a 3D virtual model for an assembling task. The system consisted of a video see-through head mounted display (HMD) with a webcam in front of it, protected by a custom waterproof housing placed over the diving mask. As a very first step, optical square-markers were used for positioning and orientation tracking purposes (POSE). The tracking was implemented with a ubiquitous-tracking software (Ubitrack). Finally, we discuss the possible implications of a diver-machine synergy.

I. INTRODUCTION

Today, commercial divers compromise their integrity in an effort to support offshore and inland industries related with underwater activities. They perform daily operations below the surface that are highly demanding and hazardous, having an important physiological and psychological impact on them, not to mention the challenges for their visual system [1][2][3][4][5]. Some manifestations of these activities appear in divers' lack of spatial positioning and orientation awareness, reduced cognition, and memory disorders [3][4][6]. These limitations compromise divers' confidence and safety, and consequently, expose them to a great amount of stress that negatively affects performance, and could even develop in panic [3][7][8][9].

Despite these facts, divers are unique in their capabilities of executing complex tasks (both mentally and manually), and

performing a high level of adaptable and flexible thinking required in major underwater operations [4][10][11].

At the moment, those capabilities cannot be matched by robotic systems, for instance, Remote Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) or manned platforms, like Atmospheric Diving Suits (ADS) and submersibles (Fig. 1) [12][13][14][15][16].

These platforms, however, have been increasingly assigned to low and middle-level tasks, where the advantages of artificial intelligence (AI) and robotics are remarkably useful in repetitive and endurance missions, supporting diving operations, and as a diver replacement in high-risk sites [11][12]. But divers' importance persists, and has not been overtaken yet [4][10][11].

This paper describes the effects that aquatic environments have in divers' physical and mental conditions, and how those conditions jeopardize divers' integrity. At the same time, we present in detail a technology known as Augmented Reality or AR ([17]), which could bring for divers an important advantage in overcoming some of the difficulties that exist in underwater operations, by improving performance and safety. The Underwater Augmented Reality system is also described in detail.

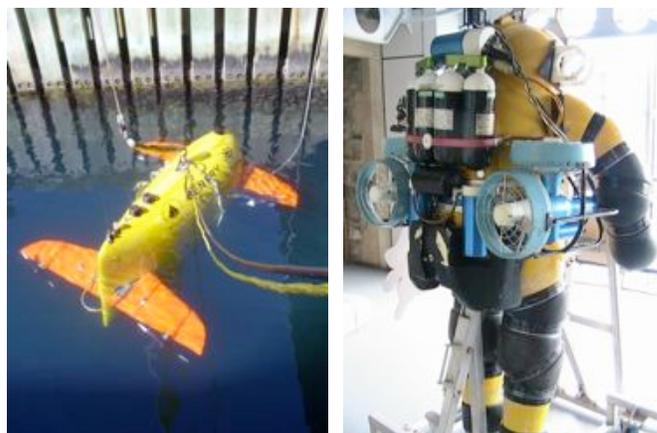


Fig. 1. (Left) *SENTRY*, an Autonomous Underwater Vehicle for exploration and oceanographic research (Woods Hole Oceanographic Institution). (Right) *Newt Suit*, an Atmospheric Diving Suit for industrial underwater operations (Aberdeen Maritime Museum).

This *diver-machine* synergy could upgrade divers to a new level, in which they will perform beyond their actual

capacities and abilities, making them *Augmented Performance Divers (AP-Divers)*. A concept that in addition to the cognitive side (approached in this research) could include physical augmentation, which is the amplification of human endurance and strength [18].

Previous works in underwater Augmented Reality focused on industrial and military applications. Fusiello & Murino for example, integrated virtual models into the video stream of an ROV operator. To register the virtual data to the real images, they rely on optical and acoustic sensors. They derived the vehicle POSE and superimposed virtual objects upon actual images; and as a result, they generated an augmented-reality representation of the environment. Their main goal was to produce an output that is readily understandable by an ROV operator [19].

In 1999, Gallagher ([20]) explained the development of a Head Mounted Display (HMD) for Navy divers. He describes why such a display is required for divers to interpret and make use of this enhanced information (video images, graphics and alphanumeric data). Furthermore, he describes different display technologies and compares them with respect to their ability to augment the diver's view with virtual information in military operations, especially under poor visibility conditions. However, this is not Augmented Reality in a strict sense, since the virtual information presented is not registered with the user's 3D perception of the real world [17].

These previous works show the potential applications for UWAR. Our goal is to provide visual cues to divers to compensate sensory impairment and cognitive changes, such as lack of orientation, position awareness, and memory disorders, in order to keep divers calm within acceptable levels of stress, and hoping to improve diver performance and safety.

II. UNDERWATER OPERATIONAL ASPECTS

The underwater industry consisted of an enormous and diverse range of operations, such as construction, inspection, repairs, maintenance, surveys, etc. All those operations share the same unavoidable difficulties of aquatic environments, being dangerous and variable. Those difficulties compromise in many occasions the success of an underwater operation that normally requires complex logistics, large amount of resources (vessels, cranes, etc.) and budget, in which any delay or reschedule could increase operational costs [11].

To minimize those difficulties, in the past few years the industry developed technologies (besides using divers), that can work in many operational conditions nonviable and hazardous for humans, or because represent a better cost/value option. Platforms like ROVs (surveys, inspections, pipelines connections, etc.), AUVs (surveys, seafloor mapping) and Atmospheric Diving Suits (oilfield operations) are widely used worldwide in underwater operations [11][12][14].

Divers on the other hand, are more involved with repairs and construction activities, where their proven manual dexterity and mental capacities are crucial to accomplish

complex projects [4][11]. One example of this critical ability is underwater construction, concerned with the process of building and assembling structures in underwater or marine sites. Installation of marine structures (e.g. oil platform), pipeline projects (rerouting, abandonment and repair), hot tapping (the connection of a new pipeline while the pipeline remains in service), marine risers (installation and repair) and civil projects (e.g. concrete mats setting, bridge scour remediation) are examples of those activities (Fig. 2) [11].

In underwater construction and in many other activities, divers' manual dexterity and mental capacities are essential and valuable [3][4]. But environment and task challenge divers' capacities (physical and physiological) and jeopardize operation effectiveness [1][3].

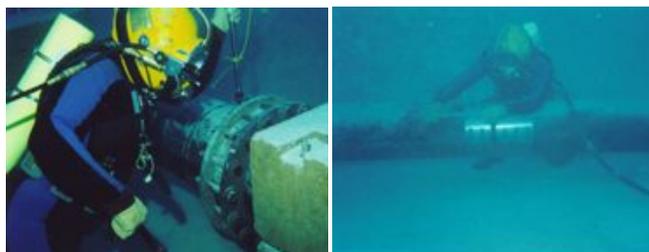


Fig. 2. Different underwater activities that involve divers mental skills and manual dexterity. (Left) Pipeline connection. (Right) Pipeline repair.

III. DIVING PHYSIOLOGICAL EFFECTS

Physiologically, divers suffer the consequences of remaining in an environment where the pressure is significantly high compared with surface (e.g. about 31atm at 300m during saturation diving) [1][2]. As a consequence, some critical medical conditions appear, such as Nitrogen Narcosis, Central Nervous System (CNS) and Pulmonary Oxygen Toxicity, Decompression Sickness (DCS), Arterial Gas Embolism (AGE), Hypothermia, Barotraumas, etc. All those well studied [1][2][3].

The tactile-kinesthetic and vestibular systems are also affected. These systems (in coordination with other senses) give divers information about their location, orientation and movement. Tactile-kinesthetic information is affected by cold, weightlessness and water drag. Alternobaric vertigo affects the vestibular system due to the effects of breathing at depth. Also, the perception of gravitational vertical is reduced underwater as a consequence of deteriorated visual and somesthetic information. [3][4][6].

Therefore, in weightless condition with low or zero visibility, the knowledge of orientation tends to be much poorer than on land (particularly when inverted), and divers tend to have no sense of position relative to any other surface or object (loss of reference planes) [3][4]. Divers have some difficulties knowing how far they have swum, their actual depth, and if they maintain a straight line or not. Without vision or navigational aid, large errors occur and divers have a tendency to underestimate the distance they have traveled [4].

However, they do retain an accurate understanding of their own body (according to proprioceptive cues), and a good

understanding of the 3D structure of their environment. What is lost, is their clear understanding of their own position and orientation within this environment. That is why in the absence of visual cues and normal patterns of vestibular cues, divers have to rely on tactile cues (haptic) that could be misleading [3][4].

The viscosity (friction) and buoyancy of the water restrict mobility and the capacity of exerting an effective force against any object underwater. Therefore, divers require to expend more time and effort to accomplish any task underwater, not to mention the effort of breathing at depth. This causes an increase of divers' metabolism, pulmonary ventilation and heart rate. In rest condition (on surface), the energy expenditure is 1.2-1.5 kcal/min; during an underwater task, this parameter increases to a value that is approximately 3-6 kcal/min. Physical fatigue is normally a consequence of this effort, and could develop faster with stress [4][7][8][9].

Another environmental factor is water temperature. In cold water, the body's core temperature drops. As a result, the cognitive functioning of the brain slows down and perceptual capabilities are narrowed, with consequences to divers' performance and safety. This is especially critical in deep diving, and when diving in Arctic or Subarctic areas. On the contrary, in warm water there is a sharp drop-off in endurance around 37.3°C for body overheating reasons [1][3][21][22].

Hearing is also compromised underwater. The density of water causes losses and distortions in the auditory system because of the high impedance of water when it fills the auditory canal. The human ear functions poorly in water, with a loss of sensitivity between 30-60 dB compared with air [1][3][4].

Directional sensitivity and localization ability are reduced underwater, partly, to a loss in intensity difference between the two ears (one of the main binocular cues). Under water, the intensity of sound is not much absorbed by the diver's head. Thus it is approximately the same at both ears, regardless of the angle of incidence [4][6].

Sound travels faster in water than in air (at the sea level at 20°C, 343 m/s in air and 1.482 m/s in water, almost five times faster.) The interaural temporal difference (ITD, another binocular cue) is reduced accordingly, and cannot help divers to orient themselves according to location of sounds they hear [4][6].

Other environmental factors such as currents and waves are also hazardous since they can sweep divers away from their original location. In summary, divers are exposed to demanding physiological circumstances, which eventually, will have a significant impact in behavior and mental processing of divers.

III. VISUAL PERCEPTION DIFFICULTIES

Visual perception difficulties below the surface, are due to subtle changes in factors such as water temperature, light absorption, reflection, turbidity, illumination, index of

refraction, etc., all play a role in how a scene is perceived [3][4][23].

The most important reason for the low visibility in water is the weakening of the refraction capability of human eyes. In this case, light is only slightly refracted and the image is formed far beyond the retina, corresponding to a loss of focusing power of about 45 diopters. This is overcome by using diving masks or diver helmets. However, this reduces divers' peripheral vision and depth perception [3][4][6].

In diving, both the facemask and the diver helmet introduce a distortion due to the refraction of light at the interface between air (diver's face mask or helmet), glass, and water. The refracted image of an underwater object causes an angular enlargement of about 4/3, and a reduction in the image distance to about 3/4 of the physical distance. At greater distances, however, distant objects appear farther away than they actually are. This judgment of depth effects increases with water turbidity. Angular eccentricity is increased as well, such that the perceived angular orientation of objects that are not in the center of the field of view is mistaken [4][6].

Light is absorbed and scattered by the particles in the water, thus reducing the quality of the visual image. As a result, visual acuity and luminance contrast are reduced under water and objects are hard to detect [4][5][6][23].

Absorption and scattering systematically alter the received color image data, affecting detectability of the presence of colored objects, and their color appearance. Absolute color recognition improves when extra color cues from familiar objects are available and the best results are achieved for distant objects. This suggests that the observers are more likely to rely on cognitive cues to target color when visual cues are reduced or distorted, as they are over long viewing distances underwater [4][5]. It is important to realize that poor visibility makes divers anxious, has a direct effect on their kinesthetic and vestibular systems, and eventually, compromises diver's confidence.

IV. DIVING PSYCHOLOGICAL EFFECTS

Pressure, weightlessness, and senses degradation have a psychological impact on divers, affecting them socially, emotionally and cognitively. Below the surface, "stress" (either mental or physical) and the way divers manage it, will define their psychological integrity. Mental stress could be the consequence of divers' lack of confidence in their ability to perform well, their equipment, surface support, or work-site location. Physical stress could be the result of cold, fatigue, narcosis, limited breathing-gas supply, currents, sensory deprivation and confined spaces. When stress is not controlled or cannot be suppressed, a condition known as anxiety is developed [3][7][8][9].

(a) Anxiety

Anxiety is a common place for divers. Even before a dive, the anxiety as a product of fear is always present in divers' minds. The trigger for anxiety is hidden behind divers' stressful environmental and working conditions. The main

problem is that anxiety, in many ways, affects divers' performance and safety [3][4][8][9].

Manual dexterity is one of the diver's abilities affected by anxiety when performing a task underwater. Under water, manual dexterity is more sensitive to anxiety effects than an equivalent task performed on land. The reason is that motor skills are susceptible to anxiety effects in terms of their direct action on muscular control. As a result, divers may tremble and thereby lose the fine motor skills that are required to fulfill their manual tasks. Additionally, concentration that is a critical factor for manual activities is also affected by anxiety [4][7][8].

Anxiety impairs short-term memory as well perceptual narrowing. One of the major ways that anxiety affects performance may be through worry where the diver may be distracted from performance on the cognitive task by the thought of potential threats. This is likely to produce a general impairment in a range of tasks. A study of performance in dangerous environments describes the relationship between arousal and performance is described as an inverted U-curve: when arousal is at a moderate level, performance is at high level, but when arousal is at a high level, performance drops [3].

Physiological effects of anxiety are expressed in a heart rate increment of approximately 50%, and an increment in pulmonary ventilation of 200% compared with resting condition [7].

(b) *Panic*

Evoking or anticipating events that the diver feels unable to handle can produce a gradual accumulation of anxiety that could lead to panic. Panic can be defined as a sudden fear, which dominates or replaces thinking [9].

According to some diving psychologists, such as Bachrach and Egstrom (1987), panic is the leading cause of diving fatalities [9].

Panic prevents divers from thinking in a cool, rational way. For example, it can prevent divers to deal properly with equipment malfunction [9]. When a diver is experiencing weightlessness and isolation (e.g. while working on a task alone), a psychological reaction can be caused (blue dome syndrome), which increases over time the more the diver becomes aware of his lonely situation. This may panic the diver and produce a rapid ascend which may lead to a decompression sickness (DCS) or a pulmonary overinflation [1][3].

(c) *Memory Disorders*

All thinking skills are inextricably tied to the ability to remember, and this ability is tied to the senses that provide information. These senses are under considerable stress in water and can be degraded in some cases, and redundant in others. These conditions affect sensory memory, working memory and long-term memory. The sensory memory is vital in the determination of working memory, long-term memory and related conditions, such as context-dependent memory.

This suggests that stressed senses have a negative impact on memory, and will inevitably affect performance [3].

In this research, we considered the context-dependent memory to be relevant. If something has been learned in some context, it is best remembered in that context. By creating the conditions for recall (memory cues) through the reinstatement of the original context of learning, it is possible that divers can perform better [3][24][25].

V. UNDERWATER AUGMENTED REALITY (UWAR)

One way to preserve divers' integrity would be changing underwater conditions (pressure, visibility, current, etc.), but normally, this cannot be accomplished. The other possibility would be to adapt divers to those severe conditions. This would require technologies that allow divers to overcome the difficulties imposed by the environment, improving or augmenting their suppressed capabilities (physical, sensory and cognitive) to properly perform below the surface. This is possible with *human augmentation technologies*, which by definition are the attempt to overcome, temporally or permanently, the current limitations of the human body through natural or artificial means [18].

Augmented Reality (AR) is a technology that allows users to blend, within their field of view, synthetic information into the physical world, in which reality plays a dominant role. The information about the reality (e.g. underwater environment) is displayed usually as 3D graphical elements, that keep a spatial-relation link with the reality (registration). This understanding about the underwater environment is what could make AR remarkably useful, since that information normally comes from our senses, and they are partially disabled underwater. Investigations have shown that the human perceptual system can adapt to various types of optical stimulation. Thus, if it was possible to provide visual-spatial sketchpads directly to divers' eyes by means of the generation of visual images (in our case Augmented Reality), divers could have a better interpretation and understanding of the environment [3].

We think that AR could help to overcome diver cognition and perception impairment, and consequently, reduce anxiety and its negative effects. Our approach intends to incorporate virtual elements (e.g. environmental and task information) in divers' view, in order to improve visual cues, and therefore, surroundings understanding. The aim is to keep divers calm and oriented, performing well and within acceptable levels of stress, obtaining as much as possible the level of performance that is achievable on surface.

We approached those goals by providing information that is relevant to divers (Fig. 3) as follows:

1) *Orientation and position awareness.* A visualization of an artificial horizon (red grid) to increase position awareness within the environment and work-site.

2) *Navigation Aids.* A guidance to the work-site implemented with a virtual red arrow sign pointing to the task location. Designed to show a diver's course constantly, and a yellow line that links the arrow with the target position.

3) *Context-dependent memory*. A 3D model of an assembling task or project planned, intended to reduce mental workload and compensate any memory disorder [24][25].

We hope that those visualizations will reduce the factors that trigger anxiety.

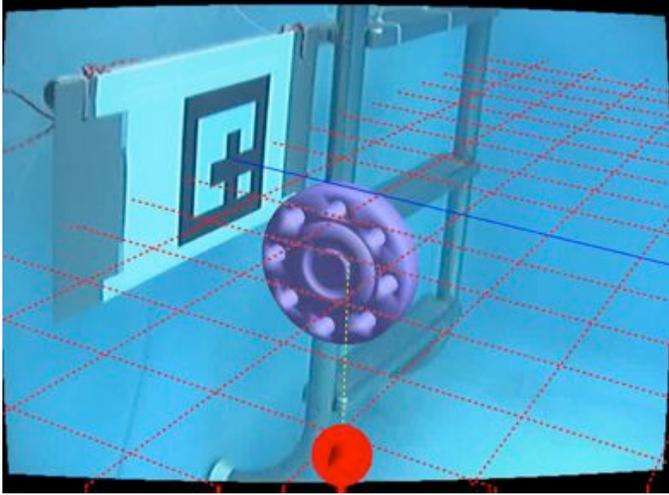


Fig 3. The image shows features of the visualization. A navigation aid (virtual red arrow) that points to the work-site and a yellow line that connects the arrow tip with the location of the target (constantly). An artificial horizon (red grid) to aware divers of their orientation related with horizon. A 3D model of an assembling task (flange).

VI. EVALUATION SYSTEM

To demonstrate the concept, we implemented an AR system for being used in underwater conditions. Tests were conducted in swimming pools in favorable water conditions (visibility and lighting).

(a) Hardware

The hardware setup consists of an eMagin Z800 3D Visor head mounted display and an off-the-shelf Logitech Quickcam Pro 4000. The camera is mounted in front of the display (a Head-Mounted Display, HMD) and provides a live video of the scene to be rendered in the display. This video is also for tracking the POSE of the HMD with respect to the scene. Both components have been disassembled and integrated into a watertight custom acrylic-housing. The latter is intended to be mounted in front of a commercially available diving mask. The prototype was designed to fit directly against the diver's facemask just few millimeters away (Fig. 4). For diver comfort, HMD brightness levels and resolution can be adjusted from surface.



Fig 4. Hardware configuration of the UWAR system used in the experiments. (Top) Diver wearing the UWAR system. (Left-Bottom) Watertight housing for Logitech Quickcam Pro 4000 and eMagin Z800 3D Visor HMD. (Right-bottom) HMD driver and umbilical connections to surface.

(b) Tracking and Rendering

In order to render virtual content on top of the real image, it is necessary to track the position and orientation (POSE) of the HMD in real-time. Our evaluation system is based on the Ubitrack tracking framework [26]. It is open source and incorporates many different drivers for sensor hardware that is commonly used for tracking. The dataflow engine allows for efficient processing of the sensor data, including sensor fusion. Furthermore, it contains algorithms to solve common registration tasks [27]. For the system described in this paper, we use an optical square-marker tracking algorithm similar to AR Toolkit [28], which is also contained in Ubitrack. Mathematically, the system consists of two cameras (webcam and OpenGL virtual camera), which are both approximated by a pinhole model. Radial undistortion is applied on the webcam image before they are used for tracking and rendering. To align the diver's eyes within the display system, a SPAAM calibration has to be performed once under water before the system can be used [29]. For this, several 3D-2D correspondences have to be collected semi-interactively by manually aligning points on the display with points in the scene. The calibration remains valid as long as the optical refraction properties of the water (e.g. salinity and temperature) remain constant (Fig. 5).

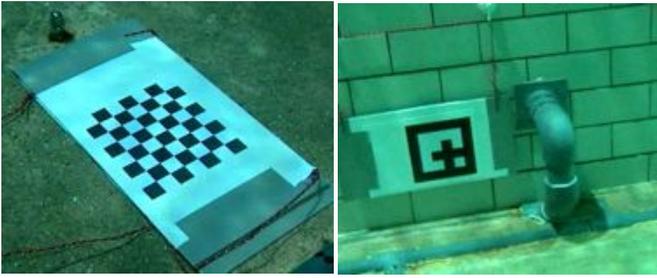


Fig. 5. (Left) Calibration grid for camera calibration. (Right) Optical square-marker for rendering. In both cases visibility, contrast and water parameter challenge the Augmented Reality implementation.

(c) System Considerations

The chosen layout is suitable for an evaluation of the visual aids described above, under the conditions of good visibility and illumination. Under more hostile conditions (such as described in chapters 3 and 4), it might make sense to use an optical see-through display instead, mainly for two reasons. Firstly, under bad lighting conditions, the video will further degrade the already weak visual perception of reality, which might contribute to an increase instead of a decrease in the diver's stress level. If the AR system fails, a video see-through system might even become dangerous because such an incident would deprive the user of all visual perception [20]. With an optical see-through device, the diver could still perceive the real world, as without using the AR system. Secondly, in our target environment, other tracking modalities will be used, so that the camera becomes superfluous for tracking, too.

VIII. RESULTS AND DISCUSSION

This was our first attempt with an Underwater Augmented Reality (UWAR) system, therefore, many problems and considerations were found during the experiment process.

We found the expected differences in focal length and in the field of view (FOV) between water and air [4][6]. Corrections regarding these differences were made during the calibration process. The default calibration available in Ubitrack did not work well. Instead, we used manual calibration. The visual optical square-markers were not robust enough for tracking and POSE underwater. Good tracking in these conditions requires optimum water visibility and good illumination. But even in those conditions (visibility greater than 6m), it was necessary to adjust camera parameters to accomplish tracking and rendering.

Most videos captured with augmentations were from the diver's egocentric point of view. Nevertheless, extra material was captured without augmentation (exocentric and egocentric views) with the purpose of having additional material available for further visualizations development.

We positioned the artificial horizon at different heights (e.g. 0.0m, 0.5m, 1.0m, 1.5m) in which the optical square-marker corresponds to 0.0m height reference. This positioning of horizon was intended to test any relationship between diver's comfort and horizon height. The artificial horizon (red grid)

was fixed to end in the optical square-marker, improving work-site understanding, and avoiding cognitive conflict. Being red a non-common color underwater due to absorption reasons, we chose this color for the artificial horizon, to provide a better contrast with the surroundings. The navigation aids (red arrow and yellow line) provided an effective sense of positioning and orientation. However, more testing is needed to find the right location of the navigation aids) within the diver's FOV (Fig. 6).

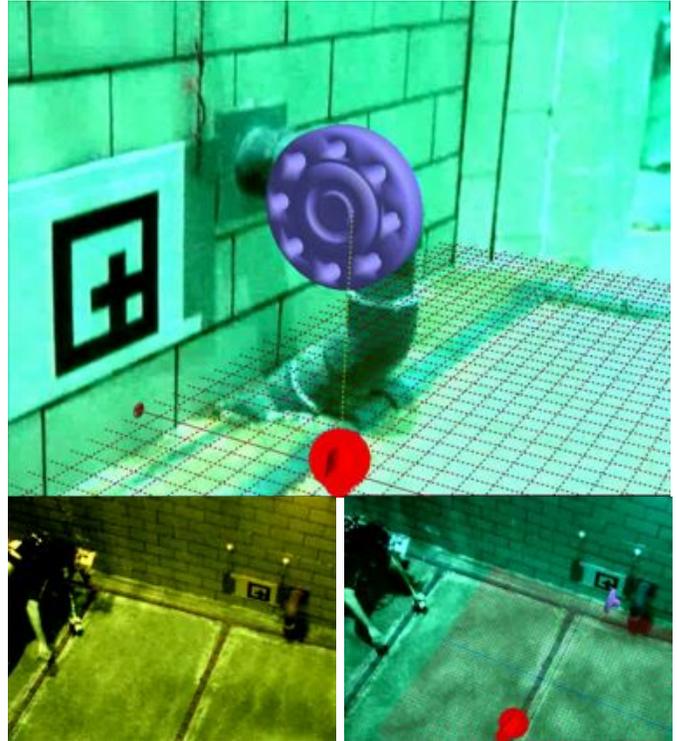


Fig. 6. (Top) Image shows the visualization implemented, virtual arrow and yellow line for navigation, artificial horizon (red grid) for orientation, and 3D model for an assembling task (flange). (Bottom left) Exocentric view without augmentation. (Bottom right) Exocentric view with augmentation.

The housing was designed to be almost neutrally buoyant. It provided a better head mobility (horizontally and vertically), a smoother survey of the work-site, and a more comfortable experience. It is necessary a more compact-housing to reduce drag, and a better sealing (vacuum) to avoid condensation problems.

The camera field of view did not match the diver's FOV. This produced sometimes an unpleasant experience. Despite this fact, the HMD displayed realistic images. We were able to control HMD parameters from the surface. Additionally, the HMD display presented a small-delay. We do not know if this delay can seriously affect diver's mobility and dexterity. It is possible that the limited mobility experienced underwater could reduce the impact of this effect.

To experiment with other kinds of commercial diving activities, we also implemented the visualization of a vessel (3D submarine model) for survey purposes (Fig. 7).

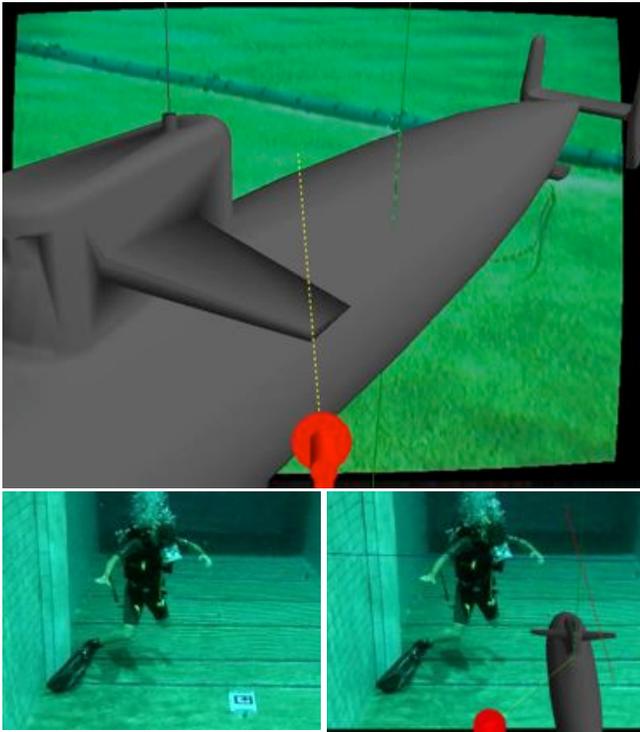


Fig. 7. Simulation of a vessel inspection (3D submarine model). (Top) Diver's egocentric view with the augmentation. (Bottom left). Exocentric view with augmentation. (Bottom right) Diver's exocentric view with the augmentation.

IX. CONCLUSION AND FURTHER DEVELOPMENTS

In the present research we were able to implement a basic augmented reality system for underwater applications. We accomplished an effective camera calibration that was a critical element for rendering the visualizations proposed initially. The information displayed, navigation aid to reach the work-site, artificial horizon for diver awareness of orientation and positioning, and the memory clues for executing an assembling task and an inspection survey were accomplished. These aids were thought to compensate the difficulties described by bibliography that affects divers effectiveness and safety in underwater operations. And at the same time we intended to increase divers' spectrum of capabilities in commercial operations.

The tracking of the optical square-marker to render the visualization was, mainly, to prove the concept of UWAR. Since this approach can not yet be expected to be reliable for a wide spectrum of adverse water conditions, a more reliable and robust technology for tracking should be implemented by using an underwater acoustic tracking system (e.g. Multi-User Long Base Line or MULBL), which is perhaps a better underwater solution [30]. However, optical square-markers are a useful start for developing and testing the visualizations, software, and system robustness.

The artificial horizon (from below the grid and from above of it) gives divers an important understanding of position, orientation, and proximity to the horizon. Further user studies

are required to know what is the proper horizon height with respect to the diver, and how this affects a diver's comfort. This includes the implementation of the system in a commercial diving operation, in order to test it in real conditions.

The HMD used (eMagin Z800) allows further system improvements, for example, stereoscopic visualizations. Other issues, such as better camera resolution, greater field of view, and better speed connections are required to enhance the diver's experience. In addition, a better HMD design that includes high strength, compact and easy to access watertight-housing is necessary. The design should include a quick release mechanism that allows the entire system to be quickly attached or removed from the mask, as an essential safety feature [20]. All the previous features are intended to do more tests and gain more experience.

Mixed Reality (MR) could also open new opportunities for UWAR development. For example, the visualization of hidden objects that due water conditions can only be observed by acoustic systems (e.g. Blue View or DIDSON) [31][32].

In this research we did not approach a panic control system. We were more concerned with anxiety and a cognitive solution to keep divers calm and focused. However, further work could include the implementation of an "alert mode" that detects diver's stress level and acts accordingly. This could be achieved by observing signs of stress, such as the eyes' pupils, the pulse, and the breathing rates. We think that any system intended to assist divers should be designed as a human-centered system, and should also consider other fields of science and engineering involved in overcome human challenges below the waterline, for instance, physics (e.g. optics), image processing, visual psychophysics, ergonomic, cognitive science, etc [33].

In the present work we showed the possibilities of augmented reality (AR) as one of the ways to improve the effectivity of commercial diving operations. However, more it has to be done in order to make the system more reliable, robust and ergonomically faultless.

The challenge is to implement technologies that are currently available or being developed in the industry, to upgrade divers' potentialities, establishing the concept of an *Augmented Performance Diver (AP-Diver)*. Investigating how the environment and working conditions affect divers performance, the mechanisms by which they operate, and the solutions to compensate or avoid those effects, will open vast possibilities for humans in the exploration and understanding of oceans.

ACKNOWLEDGMENT

We would like to thank the people of the Fachgebiet Augmented Reality (FAR) for their outstanding support, especially Marcus Tönnis, Björn Schwerdtfeger, Christian Waechter, Florian Ehtler, Manuel Huber, Marina Plavsic and Martin Horn. Also, the Maier family, the first author's brother Alexander Morales, his mother Manuelita García, his cousin Eduardo González and Mr. Richard Haensch.

REFERENCES

- [1] United States Navy, *United States Navy Diving Manual*, 6th ed., 2008.
- [2] James T. Joiner, *NOAA Diving Manual: Diving for Science and Technology*, 4th ed., February 2001.
- [3] Stanley, J.V. Scott, C., "The effects of the underwater environment on perception, cognition and memory," vol. 3, pp. 1539-1548 [*OCEANS '95. MTS/IEEE, Challenges of Our Changing Global Environment Conference Proceedings*].
- [4] H.E. Ross, "Perceptual and motor skills of divers under water," *International Reviews of Ergonomics*, vol. 2, 155-181, 1989.
- [5] S. Ma and P. Milgram, "Investigation of potential benefits of stereoscopic video for visual detection in turbid underwater environments," *SPIE*, vol. 4297, pp. 22-33, 2001.
- [6] H.E. Ross, "Orientation and movement in divers," in *The Perception and Control of Self Motion*, R. Warren and A.H. Wertheim, Eds. Hillsdale: Lawrence Erlbaum Associates, 1990, pp. 463-486.
- [7] E. Toscano, E. Fubini and E. Gaia, "Microgravity simulation: physical and psychological workload evaluation test in an underwater environment," *Applied Ergonomics*, vol. 35, n°4, pp. 383-391, 2004.
- [8] A. Baddeley and C. Idzikowski "Anxiety, manual dexterity and diver performance," *Ergonomics*, vol. 28, iss. 10, pp. 1475-1482, October 1985.
- [9] A.J. Bachrach and G.H. Egstrom, *Stress and Performance in Diving*, Best Pub Co., p. 183, 1987.
- [10] A. Murata, "Ergonomics and cognitive engineering for robot-human cooperation," *Robot and Human Interactive Communication*, pp. 206-211, 2000 [*9th IEEE International Workshop*].
- [11] B. C. Gerwick Jr., *Construction of Marine and Offshore Structures*, CRC Press, 3rd ed., p. 840, March 2007.
- [12] R. D. Christ, R. L. Wernli Sr., *The ROV Manual: A User Guide for Observation Class Remotely Operated Vehicles*, Butterworth-Heinemann, p. 320, Aug. 2007.
- [13] B. Fletcher, C. Young, J. Buescher, L. L. Whitcomb, A. Bowen, R. McCabe and D. R. Yoerger, "Proof of concept demonstration of the hybrid remotely operated vehicle (HROV) light fiber tether system," *Proc. of the 2008 IEEE/MTS Oceans Conf.*, Quebec City, Canada, Sep. 2008.
- [14] M. Thornton, R. Randall and K. Albaugh, "Then and now: atmospheric diving suits," *Underwater Magazine*, Doyle Publishing Company, Inc., April/March 2001.
- [15] S. Carnevale and B. Robison, "Scientific research with atmospheric diving suits," *OCEANS*, vol. 15, pp. 479-482, Aug. 1983.
- [16] W. Greenert, "Navy's deep ocean technology project evolution and progress," *OCEANS*, vol. 3, pp. 50-53, Sep. 1971.
- [17] O. Bimber and R. Raskar, *Spatial Augmented Reality: Merging Real and Virtual Worlds*, A. K. Peters, Ltd., p. 392, Jul. 2005.
- [18] U.S. Army Research Institute for the Behavioral and Social Sciences, *Human-System Integration for Future Command and Control: Identifying Research Issues and Approaches*, Research Report 1792, Jul. 2002.
- [19] A. Fusiello and V. Murino, "Augmented scene modeling and visualization by optical and acoustic sensor integration," *IEEE Transactions on Visualization and Computer Graphics*, vol. 10, iss. 6, pp. 625-636, Nov.-Dec. 2004.
- [20] D.G. Gallagher; "Development of miniature, head-mounted, virtual image display for navy divers," *OCEANS '99, MTS/IEEE Riding the Crest into the 21st Century*, vol. 3, pp. 1098-1104, Sep. 1999.
- [21] R. G. Hoffman, "Chapter 12 Human Psychological Performance in Cold Environments," *Medical Aspects of Harsh Environments*, vol. 1, p. 384.
- [22] E.T. Long, "Warm water diving: physiological effects as a function of body temperature," vol.2, pp. 905-910, 2001 [*OCEANS, 2001. MTS/IEEE Conference and Exhibition*].
- [23] T. N. Cornsweet, *Visual Perception*, Academic Press, 1971.
- [24] Smith, S.M., "Theoretical principles of context-dependent memory," in P. Morris and M. Gruneberg, *Aspect of memory: Theoretical aspects*, 2nd ed., Routledge Press, pp. 168-195, 1994.
- [25] K. M. Martin and J. P. Aggleton, "Contextual Effects on the Ability of Divers to use Decompression Tables," *Applied Cognitive Psychology*, vol. 7, iss. 4, pp. 311-316, February 2006.
- [26] M. Huber, D. Pustka, P. Keitler, F. Echter and G. Klinker, "A System Architecture for Ubiquitous Tracking Environments," *Proceedings of the 6th International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 211-214, Nov. 2007.
- [27] D. Pustka, M. Huber, M. Bauer and G. Klinker, "Spatial Relationship Patterns: Elements of Reusable Tracking and Calibration Systems," *Proc. IEEE International Symposium on Mixed and Augmented Reality (ISMAR'06)*, pp. 88-97, October 2006.
- [28] H. Kato and M. Billinghurst, "Optical square-marker tracking and HMD Calibration for a video-based Augmented Reality Conferencing System," October 1999, *Proceedings of the 2nd International Workshop on Augmented Reality (IWAR 99)*, San Francisco, USA.
- [29] T. Mihran, G. Yakup and N. Nassir, "Single-point active alignment method (SPAAM) for optical see-through HMD calibration for augmented reality," *Presence: Teleoperators and Virtual Environments*, June 2002, vol. 11, iss. 3, pp. 259-276.
- [30] D. Newborough and B. Woodward, "Diver navigation and tracking system," *OCEANS '99 MTS/IEEE. Riding the Crest into the 21st Century*, vol. 3, pp. 1581-1586, 1999.
- [31] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *EICE Transactions on Information Systems*, vol. E77-D, No. 12, December 1994.
- [32] E. O. Belcher, "Thin, acoustic lenses applied in a 64-beam, 750-kHz diver-held sonar," *OCEANS '97. MTS/IEEE Conference Proceedings*, vol. 1, pp. 451-456, Oct. 1997.
- [33] M. A. Blumentberg, *Human Factor in Diving*, California Univ. Berkeley, Dec. 1996.