Towards building a diving simulator for organizing dives in real conditions

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ABSTRACT

We present a prototype of a diving simulator system that can be used for organizing dives in real conditions. Our simulator comprises of (a) an accurate visualization of a real wreck site in Mediterranean sea, Zenobia Cyprus, one of the most well-known wrecks worldwide and (b) visualization of marine life based on the real types of species that are gathering near the wreck. Moreover, a first attempt of integrating an existing diving computation algorithm has been made. The simulator's purpose, in its complete framework, is to be used by divers to organize their dives in advance at the specific wreck and moreover to be used as a tool to promote diving tourism. The diving computation part of the simulator has been validated according to the Professional Association of Diving Instructor's data, while the complete prototype of the system has been evaluated by expert users (divers) denoting the importance of the specific simulator.

Keywords

diving simulator, dive computations, wreck 3D reconstruction, marine life, diving tourism.

1 INTRODUCTION

The recreational scuba diving, in recent years, has been developed into the most popular water sport worldwide. This is a highly enjoyable and entertaining activity for many millions of people around the world who have discovered and appreciate the beauty, tranquillity and richness of the underwater world. According to the international diving training organization PADI (Professional Association of Diving Instructors), - which currently owns 70 % of the world's diving market - more than one million people every year, obtain diving degrees from the aforementioned organization [PADI14a].

In addition, virtual replicas of real world sites became increasingly common over the past few years used in a variety of applications. The invasion of this new form of media, changed the way we look and understand the world, influencing among others, architecture, archaeology, medicine, science. Nowadays, the phrase "a picture is worth a thousand of words" can not really describe the amount of information one can perceive, when a 3D interactive visualization is used. 3D representations of entire cities, archaeological places, museums, are among others, parts of virtual worlds which allow interactive visits [Yar08a]. As a response of the technological achievements and the increasing number of divers, a new type of software applications developed targeting them. Digital representations of wrecks or variety of dive sites, virtual environments where divers can practice diving, video games with underwater theme, and dive simulations with 3D graphics, are examples of migrating scuba diving into this new digital era.

In this paper we present the methodology and the implementation for a virtual reconstruction of a dive destination, the Zenobia wreck. The real underwater environment is transferred into a virtual environment from the perspective of scuba diving, taking into consideration the effects that a human body has when it is exposed to underwater depth. This application is designed to target potential scuba divers of the specific destination. It employs the principles of scuba diving, underwater physics and decompression theory, aiming to be used as a tool for organizing better a physical dive. Finally, we examine the acceptance of such an application by

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the diving community, since there is no data recorded in the known literature about users' opinion for diving simulators.

2 RELATED WORK

Virtual Underwater Environments

The underwater environment is hazardous and in most of the cases it's very expensive to perform underwater activities either for pleasure or to gain scientific knowledge. These characteristics show the necessity of the virtual representation of the underwater environment, usually integrated with Virtual Reality systems.

Examples of applications of such 3D representations, include robotic testings, such as testing of Autonomous Underwater Vehicles (AUV). In such applications, the virtual world is reconstructed from the viewing perspective of the robot, enabling realistic AUV evaluation and allowing testing in the laboratory [Bru94a].

Virtual Reality applications are also used at the underwater archaeology field. For example the VENUS project (Virtual ExploratioN of Underwater Sites) survey's shipwrecks at various depths and explore advanced methods and techniques of data acquisition through autonomous or remotely operated unmanned vehicles. Innovative sonar and photogrammetry equipment are used, in order to develop virtual reality and augmented reality tools for the immersive visualization and interaction with a digital model of an underwater site. Underwater archaeological sites within a VR framework, can be used for digital preservation and for demonstrating new facilities for the exploration of the underwater site, in a safe, cost-effective and pedagogical environment [Cha06a].

In the field of water sports, Drvis et al. [Drv06a] demonstrate a swimming simulator in a virtual reality ocean environment using a hand gliding and leg harness with pulleys and ropes in swimming apparatus. A deep-sea apnoea diving simulator is demonstrated at [Fel05a]. It integrates a virtual undersea environment and a mechanical structure that helps divers descent and ascend. Moreover, there exist dive simulations which allow beginners scuba divers to experience the effect of buoyancy control mechanisms before actually entering the water, making the training less stressful and safer for all participants [Kor03a].

Dives Planning

Since the 1920s, the community of the diving sport, has seen drastically changes, in set of rules, especially in the field of computing the absorption of inert gasses in the diver's body. The study and the modelling of the spread of inert gas from breathing gases to the lungs and then to the tissues of the diver and back, is described in the Decompression theory [Yar08a]. The results of the Decompression theory, have been recorded on dive tables that are used by divers still today. Later, they have been integrated into dive computers that model absorption of inert gasses 'on the fly' during a divers dive [eDiv14a]. Recently, it has become common the usage of software tools for organizing a dive and making a dive plan following the motto "Plan your dive, and dive your plan". These tools, mainly show to the user indicative information for a number of deco stops, i.e. possible stops of diver, in several depths, while ascending in order to gradually decompress. The number and the duration of each deco stop for a specific dive profile is gained by calculating the absorption and discharge of inert gasses during the dive [SL14a].

Dive Simulations

In the recent years, with the increasingly available computer power, as well as the increasing number of certified scuba divers, a new form of dive planners came into play: the dive simulations with 3D graphics. There are several dive simulations available at the moment, but only few are implementing the Decompression theory for diving into real dive sites' virtual representations. Some of the simulators emphasis on education, others on promoting diving tourism, other attempt to recreate the peaceful feeling of being in the underworld while users are asked to complete specific tasks, while only few simulate a dive into real diving destinations.

At eDiving [eDiv14a], an integrated learning system, the user can practice diving online, visit virtual representations of real dive sites, plan his next diving expedition, find and interact with others to conduct a joint dive, and share experiences and photos through a forum. In Second Life [SL14a], there is Suboceana Scuba Diving environment, where users can find educational information for the marine environment and perform virtual diving.

The Infinite Scuba [Inf14a] is a collaborative effort of a number of companies and organizations included the Cascade Game Foundry (a computer games production company), the PADI, the Mission Blue, the DEMA (Diving Equipment Manufacturers Association) and other companies producing diving equipment. The game is based on real data. The user is trained in diving and exploring exotic places that exist in the real world. The developers aim is to increase the awareness of the public for the diving sport and encourage people to start diving into the natural world. Another interesting game which has been released recently is the multiplayer diving game World of Diving [WoD14a]. The game is providing the possibility of using the virtual reality headset Oculus Rift to maximize the immersion in the marine environment. It begins with a diving site at Caribbean, while the developers of the game are promising more sites that exist in the real world with Real biological and geographical data.

Among all the previously mentioned dive simulations, only eDiving [eDiv14a] combines a dive computer implementation in a reconstruction of real dive sites. However, the integration of a dive computer in eDiving, has as purpose to advertise dive computers that exist in the trade market and teach divers how to use a specific dive computer model.

3 DIVING SIMULATOR SYSTEM

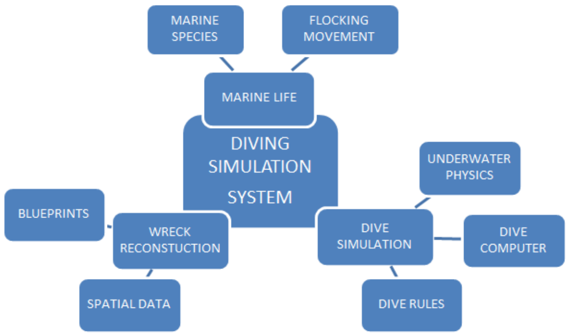

Figure 1: Main components of the designed diving simulator.

We designed and implemented our diving simulator with a component basis approach. As shown in the Figure 1 the three basic components of the simulator are:

- Reconstruction of a real underwater scene; the wreck Zenobia
- Representation of marine life based on real data
- Dive simulation that allows divers to plan their dive

The decomposition of the complete simulator in different parts gives the flexibility of the substitution of one component with a different implementation while reusing the rest of the components. This makes our simulator easily extensible and reusable. For example the same simulator can be used for organizing dives in a different wreck (and not only at Zenobia wreck) providing the reconstruction and integration of that other wreck while the rest of the components can be reused as they have already been implemented.

The three main components of the simulator are explained in detail in the following sections.

Real Wreck's Digital Reconstruction

The Zenobia wreck has been selected to be reconstructed digitally, since it is one of the top dive destinations in the world [Eco07a]. The MS Zenobia was a Swedish built Challenger-class RO-RO ferry launched in 1979 that capsized and sank close to Larnaca, Cyprus, in June 1980 [HHV14a].

In order to create a 3D model of the Zenobia wreck, we examined the different options suitable for underwater environments reconstruction. The old fashion way (used even today) was the entirely manual mapping of the wreck using tape measures, measurement frameworks, drawing tablets and pens. Another option was using remote sensing methods deploying sonar, radar or magneto metric devices. However, these devices are not accurate enough and usually they are very expensive. Computer vision offers promising technologies to build 3D models of an environment from two-dimensional images. The state of the art techniques have enabled high-quality digital reconstruction of large-scale structures, even in the underwater environment [Eri12a]. However, reconstructing using computer vision methods require involvement of many divers in order to capture real underwater photographs of the wreck, increasing drastically the cost of the virtual reconstruction.

At the end, we took advantage of the fact that the wreck is inducted as a structure and use the 2D model blueprints to recreate the ship in 3D, as shown in the Figure 2. In order to locate the position and orientation of the shipwreck on the seabed, we used data from the official accident report of the Swedish authorities who carried out the investigation of the cause of the wreck in October 1981 [Mou96a]. Moreover, exact information were used for smaller parts of the ship such as for the bridge and propellers.

Marine Life Representation

For the marine life representation we took into account two parameters: (a) species of marine life surround the real wreck, and (b) real movements of marine life. In order to create the dive site in a realistic way we used real biological data for that specific wreck.

A previous study at the Zenobia wreck [Ari09a] recorded the number of marine species and their allocation. The wreck has been divided into four sections. The division was based on the difference of lighting conditions in each one of the sections, since the distribution of marine species is highly affected by the existance of the light. In each of the four sections, data about the numbers of each one of the marine species were recorded.

In the four examined areas of the wreck, there were 85 species of organisms of which 24 were fish. Most of the fishes where benthic (living near the seabed or hard surfaces). According to the same study, there was a frequency indicator for the appearance of each fish. This indicator was used to spawn species in realistic populations in several areas of the wreck, as shown in the Figure 3. To achieve the fish movement in groups, we used the well-know flocking algorithm of Reynolds [Rey14a]. The algorithm is based on three simple steering behaviors (separation, cohesion, alignment) which describe how an individual boid (fish) maneuvers based on the positions and velocities of its nearby flockmates (school of fish).

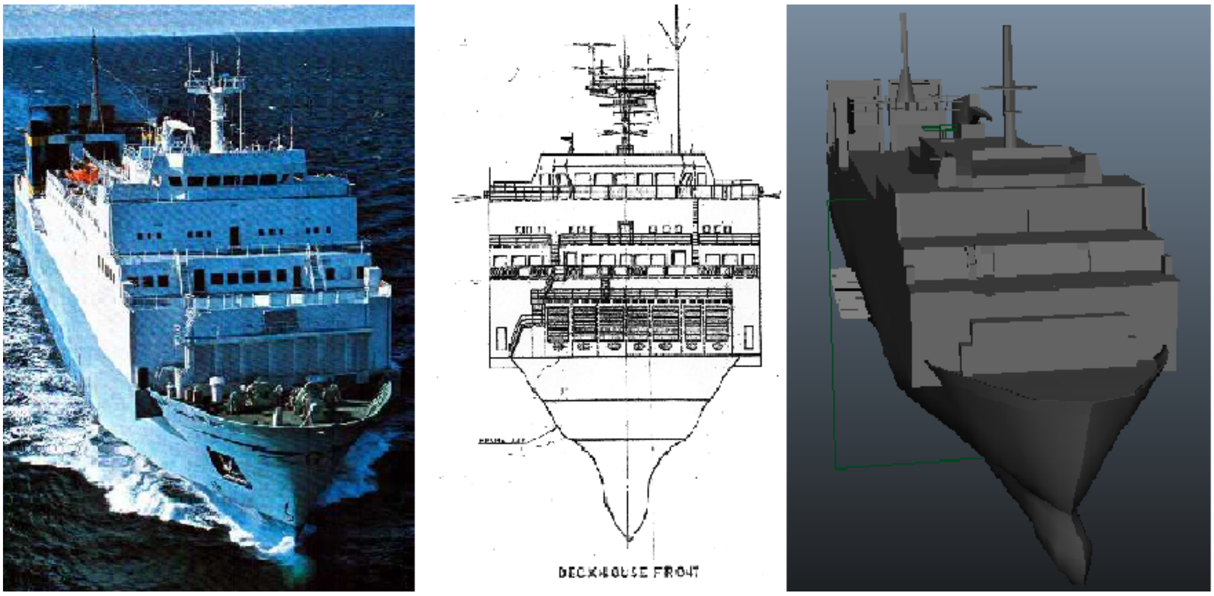

Figure 2: The Zenobia ship (left) has been digitally 3D reconstructed (right) based on blueprints (middle).

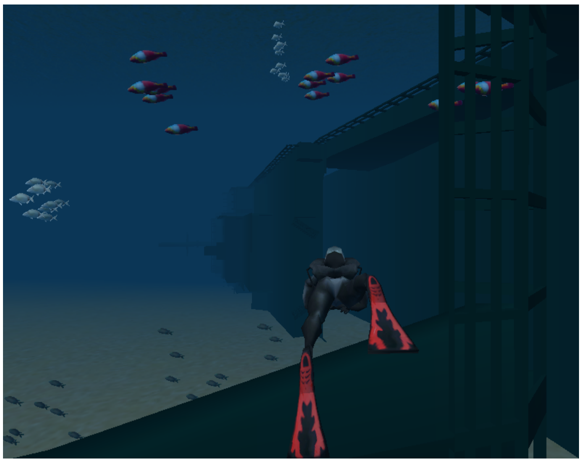

Figure 3: Marine life representation based on real biological data.

Dive Simulation

The Dive Simulation component is the core of the Diving System. In this work in progress, we make a first attempt to cover this component. Below, we present the parameters that are taken into consideration during the virtual dive that is performed by the user. They can be summarized to parameters related to:

- Remaining gas status
- No-Decompression Limit (NDL)
- Ascending speed

The above are used to provide the user with crucial information indicating drowning, occurring by the first one, or decompression sickness, occurring by the last two. The aim of this prototype of the diving simulator is to integrate existing models addressing these three issues, and not propose new models, thus we provide below only the basic concepts behind them. A more in depth explanation of the related mathematical backgrounds can be found in [Phy14a], [Bad11a] and [Mou96a].

Remaining Gas Status

In order to avoid drowning, the diver should always has gas in his tank. The remaining gas calculation depends on the absolute pressure, the tank capacity, the tank pressure, and the diver's breathing rate.

While the user dives virtually, we track the diver's position and based on his current depth, we calculate the absolute ambient pressure based on physical lows given at [Phy14a]. The ambient pressure affects the breathing rhythm of the diver.

Taking into account the tank capacity and the tank pressure, the remaining gas in the tank is calculated. Based on diver's breathing rhythm and the remaining gas, the available time that the diver is allowed to stay in the water, can be computed.

Moreover, in scuba diving there are rules about actions that should be taken by the diver, given the tank's pressure status. For example if the tank's pressure reaches 100 bars the diver should start returning to his boat, or if the tank pressure reaches 50 bars, he should be at ascending mode (in the case of recreational diver). We are taking into consideration these divings rules and thus our simulator provides the user with this feedback according to his tank's pressure status.

No Decompression Limit

In scuba diving, apart from the remaining gas that controls the duration of a dive, there is also another parameter: the No-Decompression Limit (NDL). The NDL is the maximum amount of time that a diver is allowed to stay at a specific depth, in order to avoid the decompression sickness.

No Deco Limits vary from dive to dive. In physical dives the diver can track his NDL in two ways: (a) by using a waterproof dive table that provides a set of NDL time for several depths, accompanying with a watch to track the time he stayed in that depth, and (b) by using a dive computer, that is a type of a watch that tracks depth and does all the calculations giving to the diver feedback about the NDL.

Both dive tables and dive computers NDL feedback based on a mathematical theory, the Classical decompression theory, first developed by J. S. Haldane. The theory describes the diffusion of Nitrogen in the diver's body by dividing the human body into several independent compartments that load and discharge inert gas with different rates [Bad11a], [Sch06a].

In our simulator, in order to provide the user with NDL information we implemented an algorithm that is based on Classical decompression theory. The NDL is computed on what is proposed at [Bak] using the Equation 1.

$$NDL = -\frac{1}{k} * \ln[\frac{P_{no\_deco} - P_{alv}}{P_t - P_{alv}}] \quad (1)$$

where:
k is a constant, different for each type of tissue ($\frac{1}{min}$),
P_{no_deco} is the Nitrogen partial pressure value where diver should start ascending (bar),
P_{alv}: is the Nitrogen partial pressure in diver's lungs (bar),
P_t is the current Nitrogen pressure in each compartment (bar).

The simulator updates at each second, as it is also done in dive computers, the information about:

1. the charge of Nitrogen in the different compartments
2. the prediction of surface Nitrogen partial pressure in the different compartments if the diver starts assenting that very moment
3. the NDL according to the prediction of surface Nitrogen partial pressure

based on virtual diver's position and route.

Whenever NDL reaches zero, means the diver is obligated to perform decompression in order to eliminate the risk of getting the decompression sickness.

Ascending Speed

Decompression sickness can be also occur even in cases where the diver complies with NDLs, but he operates a rapid ascent. Its a common functionality of dive computers to track diver's position in every second and check if the diver is near to exceed a specific ascent speed. In our simulation we are taking into consideration the maximum speed allowed to avoid decompression sickness, when a diver is ascending vertically, as many international dive organizations suggest ($9\frac{m}{min}$) [Mou96a], [Pal97a], [TDI10a]. We track the diver's position every second and we calculate his ascending speed, providing feedback to the user in cases he reaches the maximum allowed speed.

Dive Site Specific

In order to be dive site specific we do the calculations for NDL based on the location of the specific wreck reconstructed for this simulator.

We calculate the NDL according to the time a diver needs to swim from his/hers current position, to the spot where his boat is located. To achieve this we use real spatial data. Above the Zenobia wreck, there is a buoy in a fixed position where all the boats fasten. Below the buoy there is a rope that leads to the wreck. Usually, the last point that a diver visits at Zenovia wreck is where the rope is attached on the wreck (Figure 4, B), about 17 meters in depth, while after that the diver starts ascending until he reaches the buoy at sea level (Figure 4, C).

Based on the above, at each second we calculate the time needed to return at the sea level from diver's current position (Figure 4, A. In this calculations we take into consideration: (a) the maximum speed allowed to avoid decompression sickness, when a diver is ascending vertically ($9\frac{m}{min}$), (b) the reported divers' average speed ($15\frac{m}{min}$) when swimming horizontally and (c) No Deco Limits at depths (A) and (B).

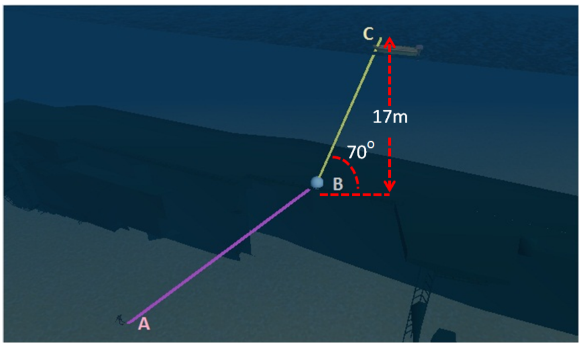

Figure 4: The calculations that are performed to avoid decompression sickness are done using the specific dive site parameters.

4 RESULTS

In this section we present the results of evaluation for our diving simulator system. Firstly the system was validated for its accuracy regarding the information that provides to the participants (competent divers) and then the system was evaluated for its usability and usefulness among experts divers. Finally we demonstrate the strengths and weakness of our simulator comparing to other systems.

Validation

The component of the system that needs validation is the numerical computation of the No Deco Limit time. The outputs of this component were validated according to data provided by the Professional Association of Diving Instructors (PADI). PADI provides this data in the form of tables computed using the DSAT Recreational Dive Planner model [Sch06a].

The comparison between the two; our system's results and PADI's tables is shown in the Figures 5 and 6.

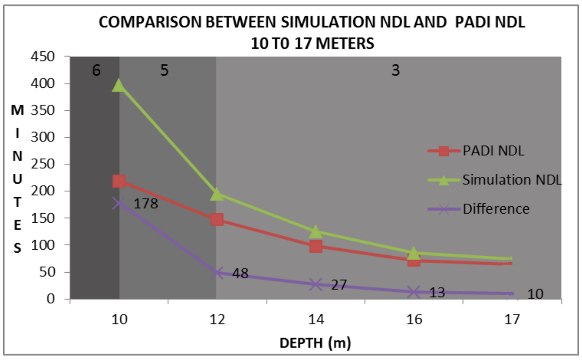

Figure 5: Validation of our simulator with data provided by Professional Association of Diving Instructors (PADI) for depth between 10 to 17 meters.

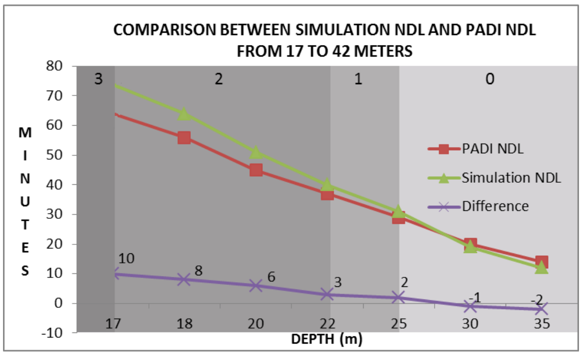

Figure 6: Validation of our simulator with data provided by Professional Association f Diving Instructors (PADI) for depth between 17 to 42 meters.

The Zenobia wreck can be found from 17 meters to 42, so we split the results of validation in two parts according to the depth that Zenobia wreck position. Figure 5 illustrates that the simulation NDL differs from PADI's NDL. Figure 6 depicts that simulation NDL for depths greater than 18 meters, where is the Zenobia wreck, becomes more accurate. In bigger depths, where the danger is higher, we observe better accuracy. However in shallow depths there is a difference between the two.

This can be explained, considering the Equation 1 that has been used for NDL compuation, In cases where the fraction is less than or equal than zero, the *ln* is not defined. The cases where this happens are when the diver is in shallow depths, mostly at the beginning of the dive, where the partial pressure of Nitrogen in the breathing gas is more that the partial pressure of the Nitrogen loaded at the hypothetical compartments. This is the case when we have many missing compartments, marked with dark gray color at the graph in Figure 5.

Evaluation by Expert Divers

A meeting was held with seven divers. The majority of them where very experienced divers, with an average number of 154 logged dives. All were Cypriot residents and six of them visited several times the Zenobia wreck. They were asked to use the application based on a common frame. They had to descend to 40 meters, explore the wreck, stay long enough without exceeding the NDL, not overcome the maximum ascent rate or run out off the air. Divers where not informed that the presented wreck was the Zenobia wreck in order to examine how convincing was the three-dimensional representation, and also to speculate if the application teases them to travel, even outside their country, in order to achieve a physical dive. During the application use, experts were commenting and indicating problem areas. However, the main objective of this evaluation was to speculate whether the concept of this application is something useful, and if there is audience among the diving community that would support such applications. For this reason, we conducted a questionnaire of closed type, which experts were asked to answer after contacting with the particular application. Finally, the user evaluation closed with a group discussion where the main subject was what they would prefer to see in such a simulation and what not.

Regarding the experts opinion about the dive simulations, we recorded that dive simulations and dive planning software are not very popular among the divers, but divers are positive in using them for planning their dives at specific dive destinations. We asked divers if they were willing to pay an amount of money in order to have a similar product and the majority of them where positive (five of seven). A crucial question was if they can trust this kind of simulations for organizing their physical dives. All except one, stated that they can trust a dive site specific simulation for planning a real dive. We wanted to find out which components of the dive simulation divers think are important. So we gave to divers a list with four different components that appear in a dive simulation (Marine Life, Dive Computer, Realistic underwater environment, Digital shipwreck representation and real dive site bathymetry) and we ask them to rank these components to what they think is important and what is not, with the freedom to give the same rating to more than one part of a hypothetical wreck simulation. The vast majority of users depicted that the most important part of a simulation is the dive computer where user responses were nearly unanimous. According to international statistics [Sto07a], the most important factor for a diver to visit a dive site is the rich marine life. In contrast with that, the majority of the users were apathetic to the virtual marine life in a simulation. Additionally, we wanted to record the experience from this simulation and to verify whether if triggers the divers to do something else other than continue using it, stop using it, or making them to go for a dive. We gave the divers three options as an answer: (a) to stop using the application, (b) to continue using the application, and (c) to go for a physical dive. We gave the option to the participants to select more than one possible answer. 5 participants choose to go for a physical dive, 5 choose to continue using the application and none choose to stop using it. We could say that generally the application gave a positive impression since none of the users wanted to stop using the application. Finally we wanted to investigate if a dive simulation could be used as a tool to promote diving tourism in a country. In order to capture as clearly as possible a reliable trend, during the evaluation with experts, we intentionally we did not mention that the diving simulation was at the Zenobia wreck. We told experts that the simulation was in a wreck located in the European region and asked them if they would be willing to travel outside their country to see the shipwreck. All responded positively. However, it should be noted here that the divers who performed the physical dive at the Zenobia wreck (6 out of 7), immediately recognized the wreck and knew that this wreck is in the region of their country of residence. This does not make it reasonable to conclude that such simulations would lead to diving tourism, but also reveals that the 3D modeling of the wreck, although not done in detail, was convincing.

The evaluation closed with a discussion about what the divers would prefer to see on a diving simulation. Among the comments was that they would like to have the ability to change parameters in the application depending on their personal profile. For example, they would like to have an option to change the respiration rate (in the simulation the rate was 20 litres per minute at the surface) and put their own breathing rate. They stated that it would be better to choose the type of bottles between 15 litres, 18 litres, or a specific set of twin bottles, and the estimations of remaining air inside the bottle to be based on their choice(in the simulation the divers used a 12 Lt tank at 200 bar pressure). They also stated that they would like to have the ability to choose the oxygen fraction containing respiratory mixture, enabling with this calculations for NITROX dives (dives with more than 21% oxygen in the breathing gas). Some would like to have the opportunity to create their own avatar by choosing themselves the appearance of the diver. Divers were asked whether the swimming speed of the virtual diver should correspond to the real underwater swimming speed or a higher speed. Referring to speed, divers stated that it is better to have both options, with the decompression algorithm working in both cases relatively with the speed and time.

Comparison with Existing Systems

In this subsection we make a comparison of our diving simulator with other existing systems. The comparison is conducted in the scope of scuba diving, so we ignored any other components that may appear in an interactive environment such as multiple players, avatar creation etc. In Table 1 we present a summary of component features that build up a diving simulator. It is clear that none of the dive simulations implements all of the components. The novel point of our simulation when comparing with the other systems is the implementation of a dive site specific simulation that calculates the NDL according to the distance that the diver has to cover in the horizontal and vertical axis for returning not just to the surface, but to a specific boat located in the water surface. However, this feature is optional with the user making the final decision.

Components	e-Diving	Infinity Scuba	Sub-oceana	World of Diving	This Work
Real Marine Life	N/A	N/A	N/A	Yes	Yes
Real underwater scene	Yes	Yes	No	Yes	Yes
Diving rules	No	No	No	No	Yes
Dive site specific	No	No	No	No	Yes

Table 1: Comparison between existing diving systems and our work.

5 CONCLUSIONS

We demonstrated the methodology for implementing a prototype of a complete diving simulator. The proposed diving simulator can be used for promoting tourism diving in Zenobia wreck, one of the top ten dive sites world wide. The simulator is a standalone application and can run on a desktop computer.

For our simulator we used real data for both, reconstruction of the wreck and the representation of the marine life surrounding the wreck. Moreover, a diving computation algorithm has been integrated as a first attempt towards using the simulator for organizing dives and having indications for decompression sickness and danger of drowning.

We compared our simulator with existing systems. To the best of our knowledge, it's the only simulator that is site specific while it also integrates the aforementioned components. Moreover we evaluated our simulator based on expert divers' opinions and based on recorded data for the computations performed.

A more in depth and formal evaluation is needed to be done [Bow02a], [Dys03a], having more participants. Moreover, the simulator should be evaluated by non divers participants, to demonstrate whether it can be used for training purposes and for encouraging people to become divers.

As far as it concerns the diving computation component, further investigation is needed for the algorithm to be used for the integration in order to give more accurate and conservative results in all depths. A bigger number of marine life species can be used in the simulator based on provided biological data while more details on the wreck can be also modelled and textured based on real underwater photographs. An extended version of the simulator can be also provide the option to the user to choose at which wreck would like to run a virtual dive. This implies the virtual reconstruction of other wrecks as well.

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