HYPERBARIC PLANT SIMULATION FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

Several industrials sectors require to extend underwater capabilities by adopting alternative and multiple solutions both involving human divers as well as robotic technologies such as ROVs & AUVs. In general the main mandate is to improve performance reducing costs and risks. On the other side, new technologies and advancements are enabling to further develop the potential of the above mentioned solutions; for instance the authors propose a new generation of computer based Hyperbaric Plant Simulators that are pretty promising for improving training & education without rising costs of underwater man based operations. This paper proposes an innovative approach in M&S for the Hyperbaric Plants devoted to support training and certification of Life Support Supervisors (LSS) as well as other operators active into diving activities.

Keywords: Hyperbaric Chamber Simulation, Underwater Operations, Life Support Supervisor

1 INTRODUCTION

Underwater activities carried out by humans or robotic systems are very important for many sectors especially Oil and Gas Industry; in facts there is an emergent request to carry out many activities such as maintenance and service of underwater installations, cables, pipelines in addition to marine salvage and rescue operations. The difficulties and risks associated to the underwater operations for human divers promoted the introduction of robotic solutions since almost 70 years, even if the performance of such systems were originally pretty limited and evolved drastically along last decades (Rebikoff 1954; Graczyk et al. 1970; Martin 2013). Despite the big advances offered by the new robotics systems, humans are still much more flexible in underwater operations where they could be active due to physiological limitations; indeed they provide higher productivity and they are still irreplaceable for completing some specific tasks; so due to these reasons the human divers are still in use along the years and their range of operations has been extended up to 250-300m (Naquet & Rostain 1988).

Therefore, the high deep operations are still very dangerous since are performed in an hostile environment for human health, characterized by high pressure, no breathable atmosphere, low temperature and total darkness. Due to these reasons very special equipment and pretty well trained personnel result fundamental for completing successful each mission. Indeed training plays a very important role in this sector, both for operations performed by human divers as well as for missions carried out by Remotely Operated underwater Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) supervised by humans.

The training of new personnel is very critical because real operations are costly and dangerous, due to the risk of accidents, errors and mistakes of inexperienced people; in this context small errors involve big risks for human life, while the cost of carrying out the training at sea and/or by using real equipment is very expensive.

So, it is clear that modern M&S (Modeling and Simulation) could be very useful to support training activities, reduce costs and risks by substituting the real plant or equipment with a properly verified and validated simulator (Amico et al.2000). Currently the authors are involved in developing different simulators for this sector of applications, therefore in our paper the focus is on the creation of a simulation environment devoted specifically to train personnel involved in diving operations where the human intervention is required.

2 UNDERWATER OPERATIONS AND HYPERBARIC CHAMBERS

One of common techniques used in diving is Self-Contained Underwater Breathing Apparatus (SCUBA), which utilizes a breathing equipment carried entirely by a diver, however its application field is limited to shallow water, while in case of a deep waters, the saturation diving technique has to be applied (Department of the Navy 2005). Indeed, saturation diving is a technique that allows divers to stay and work at great depths for long periods of time; the term "saturation" refers to the fact that the diver's tissues are saturated with helium or other inert gas at the pressure of the surrounding water. In both civil and military fields a special hyperbaric chamber is necessary to perform all activities required by saturation diving techniques, which allows to extend the achievable deepness down to 300m, which represent the maximum depth safely affordable for human body.

In facts as the depth increases, it becomes necessary to use special breathing mixture due to the oxygen toxicity at high pressure. In general, it is necessary to replace the normal atmosphere composition with a special mixture consisting of an inert gas with reduced oxygen concentration respect to normal values.

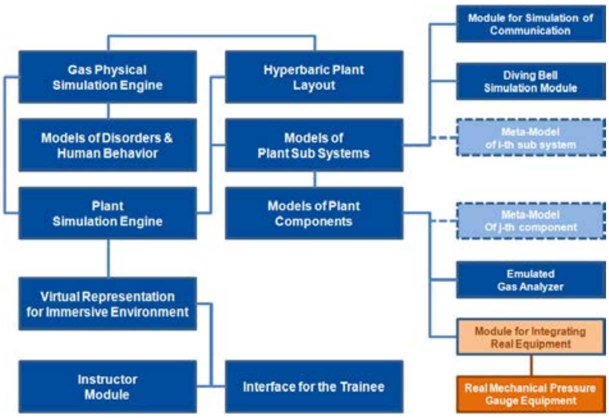


Figure 1 – General Architecture for Hyperbaric Chamber Simulation

Due to restrictions related to human body physiology, just for the decompression cycle, several days are required. This means that in Oil & Gas operations in deep waters, the hyperbaric chamber is part of a real plant that need to support the operations by covering many different aspects; for instance it is required a diving bell, plus pressure and gas mix control systems; in addition, due to normal operation requirements and economic consideration, the hyperbaric plant need to conduct long sessions lasting for weeks; indeed it is necessary to include within the hyperbaric plant all facilities and systems to provide life support, to host and to react to any possible crisis along its deployment on a ship or off-shore platform. In facts the hyperbaric chamber host normally multiple diver teams (often 3 teams of 2 people each) operating 24/7 (3 time shifts, with each team spending 8 hours underwater on the diving bell with each member having 4 hours in the bell and 4 hours out on water connected by an umbilical cable to it). As anticipated, these operations last usually for 4 weeks, forcing the personnel to live for the whole period in pressure inside the plant and its modules.

In facts the hyperbaric plant consists usually of several modules and hyperbaric chambers are based on interconnected pressurized tank containers that are able to guarantee safety and support living conditions. Indeed the different chambers are connected each other by clamps for guaranteeing the control of internal pressure. A normal hyperbaric plant, for industrial applications, includes life-support systems, submersible decompression chamber, rescue chamber, plus several auxiliary systems. The whole plant is typically containerized and installed on vessels, barges or Off-Shore Platform. Due to the risks for human life, to operate and control this plant, high professional skills are required. Indeed, these systems must be controlled by qualified operators, named Life-Support Supervisor (LSS).

Such operators are certified through their professional experiences as well as specific training programs, test and assessments; this process could be completed on real plants or on simulators.

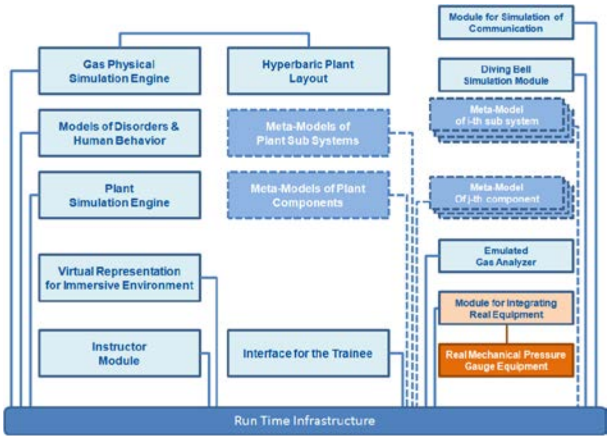


Figure 2 –Hyperbaric Chamber Simulation in HLA

In facts, the LSS figure is required to control directly the chamber internal pressure, and the other vital parameters for the divers like temperature, humidity and breathing gas composition.

In addition all the other parameters have to be monitored and controlled, like for example the temperature, the gas storage system through additional pressure regulators, back-up power supply and control of bell's position; it is also required to guarantee continuous communications between LSS and divers as well as other technical and operational staff (e.g. officer at ship bridge for positioning of the vessel carrying the plant; off-shore control room operators) to address the different critical issues.

3 TRAINING AND SIMULATION

In the past, the training for divers was almost based on the use of the real equipment, and just few simulators, mostly physical ones, have been developed and adopted. The majority of them is not still operational today. However there are several hyperbaric and hypobaric chambers which are used to prepare personnel to harsh ambient conditions, and some of them are used for training the divers. Examples of hyperbaric chambers are HYDRA and MEDUSA developed by HAUX, that allows to achieve 16 bar pressure (equivalent to 160 meters depth), while examples of hypobaric chambers, used for pilots is Falcon Altitude Chamber produced by ETC. Training for Life Support Supervisor (LSS) is also a necessity in space operations that have a similar complexity level of deep diving operations; for example V-HAB (Virtual Habitat) project was created to simulate the LSS of the International Space Station. In this case the simulator was based on Matlab and resulted totally virtual and able to simulate atmospheric conditions, water and food consumptions as several other factors (Czupalla 2005; Zhukov et al. 2010; Czupalla 2011).

Despite the increasing interest on computer simulation in diving operations (IMCA 2015) there are still few information about existing training solution for diving sector and, we are aware of the existence of just one commercial tool devoted to simulate an hyperbaric chamber control system (CKAS Mechatronics, Australia) able to achieve IMCA certification (International Marine Contractors Association) for training purposes. Hence, the solution by the authors is based on modern interoperable M&S (Modeling and Simulation) and combines different models, being expected to be adopted for the development of the first simulator certified in Europe for LSS training. As mentioned above at this moment, the training of LSS is usually performed by using real chambers; therefore such operation obviously have limitations and problems; for instance, during operations on a real plant, it's almost impossible to experience and test emergency situations; at the same time, inexperienced personnel could damage the equipment, while training on the job is not possible being very dangerous for divers.

These elements as well as the necessity to supervise around the clock the deep divers in operations reduce drastically the efficiency in using real hyperbaric chambers for trainings. Due to these reasons the introduction of simulation-based training results very efficient for improving safety, reducing costs and increasing the training opportunities as it is already common in many other industrial sectors as well as in military domain. The benefits of a simulation-based training equipment devoted to test and assess LSS are evident, in facts the simulator results much more available respect to a real plant (saturated by real operations and often located overseas on the fields) and it guarantees the possibility to reproduce emergency situations. In facts existing international organizations such as IMCA (IMCA, 2015, 2016) are evaluating the advantage of simulation respect real equipment training and, in some case, they are counting one hour of training on a certified simulator double compared to an hours of work on a real plant; so training course could be shorter and cheaper; obviously the simulator costs are even lower than using real equipment.

Another benefit of simulation is the possibility to support virtual prototyping of new equipment considering not only engineering, but also operational issues. Indeed the simulation allows to replicate predefined scenarios and to repeat already performed exercises recording in an exhaustive and synchronized way the operation log for correcting wrong behaviors and systematic errors.

For these reasons the use of simulation in this field is expected to be quite preferable and it make sense to develop new solutions able to combine the plant processes and physics with the operational issues as well as with human behavioral and physiological models to deal even with this critical aspects that usually are the cause of accidents.

4 SIMULATION MODELS

The proposed architecture developed by the authors is summarized in figure 1 and includes the different main component; originally the authors have considered to support the interoperability among the different models, simulators and real equipment by adopting High Level Architecture standard.

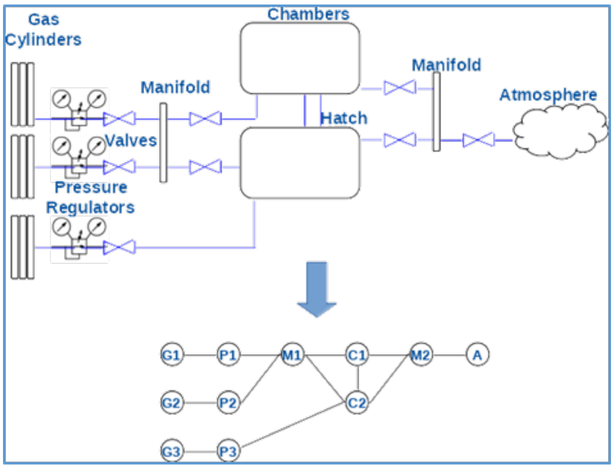


Figure 3. Gas Distribution Model

Indeed this approach is the most open and generic and could lead to significant benefits in further extensions, therefore the same architecture could be based also on different technological interoperability approaches (Kuhl et al.1999). In this case, the overall simulation turns to be based on a federation of models as proposed in figure 2, simulators and real equipment that operates as federates and are interconnected through a Run Tim Infrastructure; in this case it is possible to use meta-models to cover elements of the original systems that does not require very high detailed simulation (Kleijnen et al.2000).

This paper focuses mostly on two main aspects to be covered within the whole simulation these two models corresponds respectively to the plant processes dealing with gas physics and the human physiology and disorder modeling. The physical models of the gases have to address, for the training purposes, their dynamics and mixture considering the pressure regulators, gas cylinders, piping systems, valves, chambers, control systems, gas recuperation system as well as on-going operations and human activities. Obviously, such type of plant requires effective and redundant control system; in facts, due to safety reasons it's necessary to have more than one instrument capable to measure key parameters of the atmosphere inside, for example pressure is measured simultaneously by pressure gauges connected directly to different sections of the plant and by gas analyzers using special sensors. For these reasons, one of the need of the simulation is to cover all the equipment, devices and components present in a real plant in order to be able to be certified and to handle LSS training as it happen on real plant. Furthermore, the simulators used for training purposes need to appear pretty similar to real systems to increase immersion of the trainee during the exercises and consequently to improve the quality of learning process. As anticipated, one of the simulation key elements is the gas distribution model which reproduces all the atmospheric conditions in every part of the plant.

This model should be able to reproduce all the plant different components; in the proposed model two main objects are introduced able to couple all the plant components: Node and Arc.

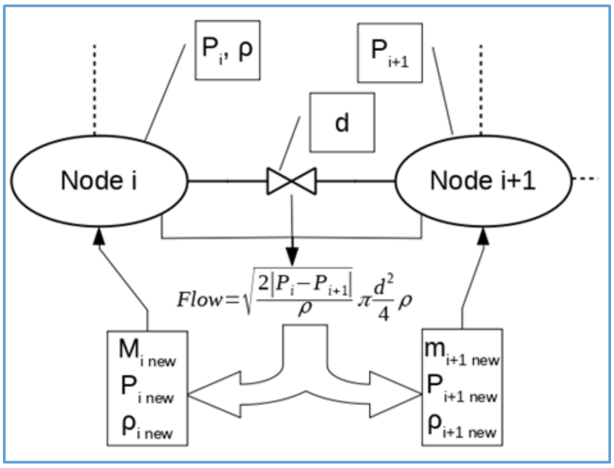


Figure 4. Calculation Process over all the Nodes

Nodes are used to model parts of the plant where parameters of gas mixture could change such as, for example, pressure regulators, manifolds, chambers and pipes' connections while Arcs are used to represent the connections among the Nodes.

This approach allows to represent the entire system as mathematical graph as proposed in figure 2.

As anticipated, the author are currently developing preliminary models to finalize the creation of new distributed simulation solutions for this context; the final goal is to create an open and interoperable environment therefore the specific characteristics of this application area require to develop tailored models and simulation engines. The development of models related to human behavior inside the hyperbaric plants represents a specific innovative components that could further improve training in this sector and it demonstrates the potential of new generation of simulators. The created physical model of the plants is based on a non-oriented graph G, composed by a N nodes and A Arc . As anticipated, each object have been modeled by means of a node, while each connection is represented by an arc.

$$G=(N,A) \qquad (1)$$

For instance, i node could represent a chamber, a pressure regulator, a manifold, a gas cylinder or a long pipeline and it characterized by several variables:

$V_i(t)$ = Volume of i node at t time
$T_i(t)$ = Temperature of i node
$P_{x,i}$(t) = Partial Pressure of x gas in the $i$node
$M_{x,i}$ = Mass of x gas in the i node

ML
P = 11.682 MSW
O2 = 218.2 mbar
CO2 = .06 mbar
t = 25.0 °C

TUP
P = .000 MSW
O2 = 207.3 mbar
CO2 = .00 mbar
t = 25.0 °C

SDC
P = .000 MSW
O2 = 207.1 mbar
CO2 = .11 mbar
t = 25.0 °C

CO2
74.0 ppm
ML

Bombole
Mix A: 57.9 bar
Mix B: 60.0 bar
O2: 60.0 bar
Mix A SDC: 60.0 bar
Mix B SDC: 60.0 bar
Mix SDC: 60.0 bar

Riduttrici
Mix A: 18.0 bar
Mix B: .0 bar
O2: .0 bar
Mix A SDC: 20.0 bar
Mix B SDC: 20.0 bar
Mix SDC: 20.0 bar

O2 Metabolic
ML 0.0 g/s
EL 0.0 g/s
TUP 0.0 g/s
HRC 0.0 g/s

Figure 5. Control panel GUI

Each i Volume is governed by the Boyle's Law and simulated through dynamic integration of Bernoulli equation as proposed in figure 4.

With the P_i total pressure of the atmosphere mix, in the i node, resulting from the sum of the $P_{x,i}$ partial pressure of each gas component; steady state conditions could be computed based on the Dalton's law with n representing the number of moles and R the Gas Constant (8.3144598 kg m^2 s^{-2} K^{-1} mol^{-1}).

$$n_i = \sum_{x=1}^{j} n_{x,i} \qquad (2)$$

$$P_i = \frac{(R \cdot n_i \cdot t_{i,})}{V_i(t)} \qquad (3)$$

In facts, the Pipelines could be considered as nodes if their volume is significant, while the Arc are representing the logic connections among the different elements; in case a pipeline length and dimension is negligible it could be possible to use directly an Arc to model it as an approximation; in facts, this approach allows to simplify calculation of gas transfer in case this hypothesis is valid because only one step is required to estimate the flow between two connected Nodes.

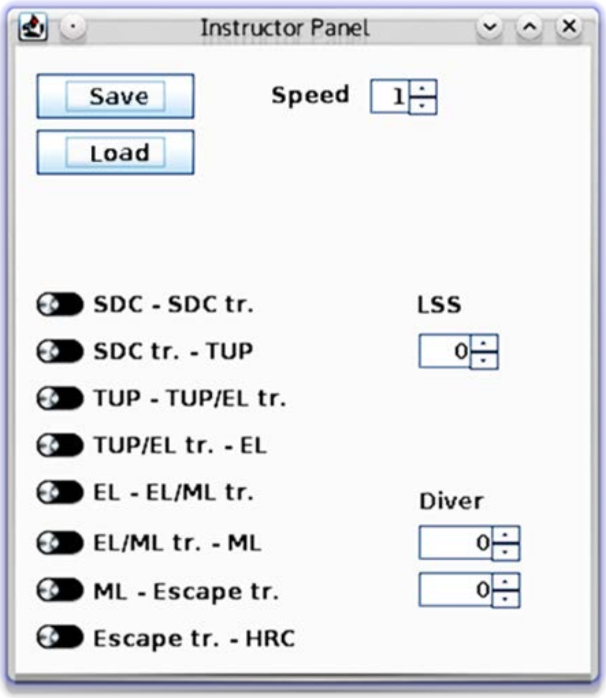
As anticipated, the proposed model allows to optimize in terms of efficiency the calculation sequence presented in figure 4 in order to guarantee high performance even on basic hardware solutions.

This aspect from Education and Training point of view it is pretty important due to the nature of hyperbaric plant; currently some operations are proceeding pretty slowly in terms of solar time (e.g. hours). In facts often just crucial moments are tested on the field on the real equipment training in order to reduce the time for completing the assessment of the trainees as well as the instruction time. Vice versa, by simulation this limitation could be overridden especially, for education, by running a fast time simulation execution; therefore this requires to be able to reproduce the whole plant physical evolution of gases very fast.

The proposed model allows to achieve very satisfactory results even in the case of a large hyperbaric complex by continuous simulation on the Bernoulli equations for each pipeline (Arc) and module (Node), based on Runge Kutta integration technique; for the training purposes this result able to recalculate completely the plant states quickly and quite precisely.

In facts these implementation aspects have been investigated during the conceptual modeling to check the capability to achieve this objective; the authors completed an implementation in Java of the conceptual model and added also for validation and verification purposes a specific simple GUI (Graphic User Interface) based on Swing toolkit.

Obviously the final training equipment should adopt a specific interface that result graphically similar to the real ones eventually using virtual reality, physical mock up, real equipment, interactive screen, etc.



Speed 1

LSS 0

Diver 0 0

Figure 5. Instruction Panel to override Controls

Therefore also the development framework created by the authors provides an interface that reproduce in simplified way the several panels, similar to presented in the real plant for being reviewed by Subject Matter Experts (SME), such as control panel (fig. 4), and panel with valves and pressure regulators, with additional separate control panel for instructor.

In addition to these aspect, several crucial components of the hyperbaric plant need to be simulated. In facts the real control panel contains several types of elements and these devices are often characterized by different nature and/or on diverse physical principles. In some case for training it could enough just to use virtual models, therefore for other purposes or for high fidelity simulation real equipment needs to be part of the loop.

In this case, it is proposed an architecture open to support both approach; for instance the gas analyzers are digital and could make sense to use virtual models to reproduce their behavior; so it is possible to use specific federates, within the overall federation, to reproduce these elements by specific simulators or emulators. For instance, it could be integrated in the whole simulation network a single-board computer with touch screens that share objects and data with core simulation engine over a LAN (Local Area Network).

Contrary, the pressure gauges are analogous and it could be possible that is required to include the real ones into the simulation to provide the trainee with a very realistic interface able to take care of parallax, gauge oscillations and inertia affecting measure readiness. In this case it required to adopt an hardware in the loop paradigm that could be achieved by proposed architecture by creating a specific federate digital module controlling the stepper motor that moves the pointer of the gauge.

Among other subsystems of the plant, a very important one is the reproduction of communication between LSS and other personnel such as divers, technicians, officers, control room operators, etc. In this case an hard integration with simulation is not strongly necessary therefore the possibility to have a federate devoted to this aspect could provide significant benefits considering the possibility to couple voice message with events. For this purpose is suggested to use recorded messages in addition to instructor voice communications and the development of a specific module to manage this aspect. In facts due to absence of all mentioned staff during the training sessions, the only real human the LSS could interact is instructor; therefore in real plants divers are breathing special gas compositions at high pressure, which creates significant voice distortion, hence to create realistic training environment plausible voice distortion for messages arriving from 'divers' must be introduced.

5 MODELING OPERATION EFFECTS ON HUMANS WITHIN THE SIMULATION

As was mentioned, in many cases, simulation allows to significantly improve human safety, in facts to maximize its positive effect, influence of LSS's decisions on divers' health could be considered. Obviously the quantity of physiological factors which could cause effects on diver is enormous and their implementation could require a lot of resources, while most of them have very limited effect or rare impact considering that the divers are selected people with excellent health. In addition some pathologies require detailed interaction with Medical Doctors and it is not required to train the LSS on such issues. So it's necessary to choose several most important factors considering field of application of a simulator and real effects on quality of training. Based on this consideration it is useful to refer to main analyses of different phenomena and effects available in technical and scientific literature (US Navy, 2008; Evan, 2016; Fisher, 2011; Bosco).

The authors posed special attention to US Navy Diving Manual that is a reference document for the whole sector; in facts, health and safety are main issues for training of LSS and LST (Life-Support Technicians), and this manual contains a lot of information regarding underwater physiology and describes situations and symptoms of different diving disorders.

After analysis the different health care cases the following main elements were identified to be modeled for the simulation: barotraumas, hypoxia, hyperoxia, carbon dioxide poisoning, nitrogen narcosis, hypothermia, hyperthermia and various problems caused by contamination.

These disorders, which are summarized in table 1, are caused by atmosphere composition, temperature and pressure change rate, hence during simulation health indexes of every diver are calculated using data about current and previous states of the plant, for example concentration of oxygen in last 10 minutes, so the temporal evolution of state variables is very important.

Table 1. Principal Disorders included in the Simulation

Disorder and Sickness	*Cause based on Simulated parameters*	*Effects and Symptoms presented by virtual simulation*
Barotrauma	Pressure variation in time	Ear pain; Pain in front or cheekbones
Vertigo	Pressure variation in time	Vertigo Nausea
Hyperoxia	Oxygen concentration	Uncontrolled movements
CO2 poisoning	CO2 concentration	Breathing difficulties Respiratory spasms Loss of consciousness
Hypoxia	Oxygen concentration	Shortness of breath
Narcosis	Inert gas concentration (Nitrogen, Hydrogen)	Small tics and convulsive phenomena
Hypothermia	Temperature	Shivering
Hyperthermia		Sweating

From this point of view virtual humans driven by agents could be used to reproduce pathology evolution (Bruzzone et al. 2012).
In facts, it could be interesting in the proposed approach to adopt the MS2G paradigm (Modeling, interoperable Simulation and Serious Game) where a virtual environment is used to maximize the effectiveness of training by presenting through audio and/or video effects the impact of the disorders on the people (Bruzzone et al.2014). From this point of view, it should be outlined that in some cases it's difficult to provide enough data to decide if certain medical condition should be applied; for instance, hypoxia could be caused by stratification of atmosphere inside the chamber in case of low gas circulation rate. Another example is contamination which could be caused by different agents placed inside the chamber, usually transported from out of the plant after the completion of an underwater work shift. For these reasons, it could be more effective to generate, some of these disorders, manually by direct commands from the instructor's control panel. For instance, he could inject within a simulated virtual diver the symptoms of hypoxia to check trainee reaction. However, it's important to distinguish events generated automatically from these introduced by the instructor; from this point of view is useful to block inconsistent situation, for example, to avoid that a simulated diver presents barotrauma symptoms while there is no any pressure change in that zone. Currently the training courses are performed mostly by using real hyperbaric chambers without leaving personnel inside; in these case the trainee could understand if system's parameters and pressure dynamics respect safety limits only by instructor feedback or by comparison of the instrument measures respect table values. For instance the maximum compression rate depends on depth (pressure inside) and could be compared with expected trends on tables. Furthermore, the traditional approach does not exclude human error and misses completely some aspects of life support, such as the control of carbon dioxide concentration, so it cannot guarantee that training is really performed correctly; obviously these aspects are compensated by the experience and skill of the instructors that pose questions to the trainees to verify their preparation and understanding. Therefore, these considerations make it evident the big potential of new simulations able to consider human behavior and physiological modeling to improve safety in this field.

CONCLUSIONS

The model developed by the authors as well as its preliminary implementation allows to simulate the training environment for LSS as it is experienced from the real control panel of hyperbaric chambers.
The simulation is open to include all the functionalities required for supporting the instructor in injecting and controlling the exercises. In facts, the resulting simulator is scalable and it allows to reconfigure the hyperbaric plant in an easy way in case of the necessity to adapt it to specific installations or training courses. At the same time the architecture is open to integrated further models in order to extend the training equipment functionalities and/or the scope of this virtual framework. Currently, further investigations are ongoing for finalizing all models definition of a case study related to an existing hyperbaric plant that will be used to finalize the Verification, Validation and Accreditation (VV&A).

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