A Multi-Sensor Fusion Framework for Improving Situational Awareness in Demanding Maritime Training

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Abstract

Real offshore operational scenarios can involve a considerable amount of risk. Sophisticated training programmes involving specially designed simulator environments constitute a promising approach for improving an individual's perception and assessment of dangerous situations in real applications. One of the world's most advanced providers of simulators for such demanding offshore operations is the Offshore Simulator Centre AS (OSC). However, even though the OSC provides powerful simulation tools, techniques for visualising operational procedures that can be used to further improve Situational awareness (SA), are still lacking.

Providing the OSC with an integrated multi-sensor fusion framework is the goal of this work. The proposed framework is designed to improve planning, execution and assessment of demanding maritime operations by adopting newly-designed risk-evaluation tools. Different information from the simulator scene and from the real world can be collected, such as audio, video, bio-metric data from eye-trackers, other sensor data and annotations. This integration is the base for research on novel SA assessment methodologies. This will serve the industry for the purpose of improving operational effectiveness and safety through the use of simulators.

In this work, a training methodology based on the concept of briefing/debriefing is adopted based on previous literature. By using this methodology borrowed from similarly demanding applications, the efficiency of the proposed framework is validated in a conceptual case study. In particular, the training procedure, which was previously performed by Statoil and partners, for the world's first sub-sea gas compression plant, in Aasgard, Norway, is considered and reviewed highlighting the potentials of the proposed framework.

Keywords: Maritime Operations, Situational Awareness, Offshore Simulator

1. Introduction

Nowadays, increasingly demanding maritime operations are at the heart of the maritime industrial cluster. Such operations are usually conducted in a dynamic environment in which technical, human and organisational malfunctions may cause accidents. Under such circumstances, situational awareness (SA) for the

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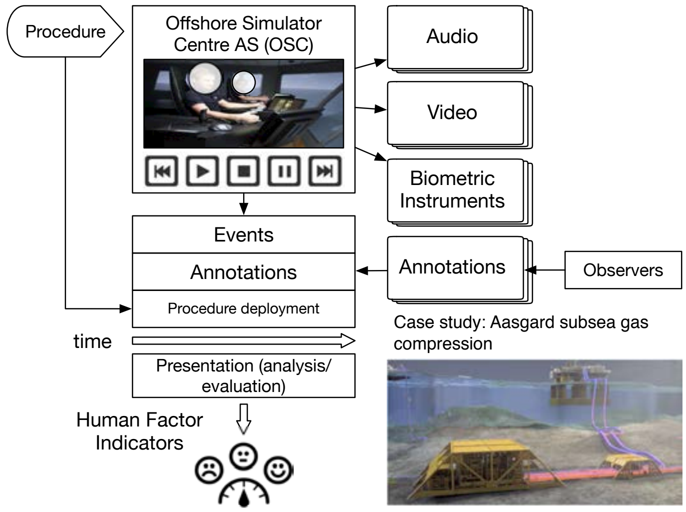


Figure 1: The underlying idea of developing an integrated multi-sensor fusion framework for planning, executing and assessing demanding maritime operations. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

operators plays a crucial role in effective risk reduction [1]. Executing and assessing demanding maritime operations is a vital issue for the European as well as for the entire world economy as reported in several risk governance gap analyses [2].

The classic methodology for risk estimation is generally adopted as an accepted practice to improve safety of offshore installations. Experts commonly define risk as the danger unwanted events may have on human, environmental, and economic values [3]. Operators must respect the regulations defined by the Offshore Safety Case for identifying the major hazards and to reduce risks to As Low As is Reasonably Practicable (ALARP) [4]. Quantitative Risk Assessments (QRA) must be used when preparing the Safety Case, as stated by the regulations [5]. Risk is evaluated within the framework of the Formal Safety Assessment (FSA), introduced by the International Maritime Organization [6]. However, this formal risk estimation does not necessarily correspond with individual risk perception. Taking this into account, improving the user's risk perception becomes of crucial importance. There is an urgent need to develop faster methods and tools that enhance SA on board a vessel so that accidents can be avoided.

Developing and testing such methods in a real set-up environment is very difficult because of the challenging operational workspace of maritime installations. Due to the demanding operational scenario in real applications, a promising approach consists in using sophisticated training programmes within specifically designed simulator environments. Training programmes have been succesfully adopted to reduce risk and to improve efficiency of maritime operations. Training personnel in simulators makes it possible to improve the overall understanding of different operations to be performed [7, 8, 9].

In this perspective, the Offshore Simulator Centre AS (OSC) [10] is one of the the world's most advanced provider of simulators for demanding offshore operations. Together with the Norwegian University of Science and Technology (NTNU) in Aalesund (the former Aalesund University College), the OSC has implemented a highly regarded and sophisticated team-training concept for offshore crews, both for crane operations, anchor handling, and platform supply vessel operations. However, even though the OSC provides very powerful simulation tools, effective techniques to visualise and analyse operational procedures that can be used to further improve SA are still lacking, though. This lack is especially noticeable when unique operations have to be performed. For instance, this is the case of one of the most technologically demanding projects that was recently developed in Norway by Statoil. This project concerned the deployment of the world's first subsea gas compression facility at Aasgard, in the Norwegian Sea [11]. To cope with the uniqueness of this challenging operation, the full subsea installation and the entire procedural training was simulated in the world's first integrated Subsea Simulator, developed by the OSC. This experience highlighted the need for developing instrumentation and methods for improving SA as an integrated component of simulation training.

In this work, a multi-layer and multi-sensor fusion framework is integrated with the OSC simulator for planning, executing and assessing demanding maritime operations and procedures by adopting newly designed risk-evaluation tools that take human factors into consideration and focus on SA. The underlying idea is shown in Fig. 1. The proposed integrated framework allows for collecting different information from the simulator scene, such as audio, video, bio-metric data from various sensors and annotations. Annotations can be added during the training phase by different observers such as researchers, supervisors, instructors and other participants. A specifically designed time-line allows for playing back the collected historical data and to present them for analysis and evaluation studies. Different human factors indicator can be obtained. This integration establishes the base for the research of novel methodologies for training and for assessing SA. Operational effectiveness and safety, an industry priority, can be improved through the use of simulator technology and facilities. In this study, a briefing/debriefing model [12] is adopted as training methodology. Based on this method, the training procedure that was performed for the Statoil Aasgard subsea gas compression plant is reviewed and analysed as a conceptual case study to highlight the potentials of the proposed framework. The information used in this paper concerning the Statoil Aasgard subsea gas compression is of public domain as it is available on several newspaper pages, websites [11, 13] and articles [14].

The paper is organised as follows. A review of the related research work is given in Sect. 2. In Sect. 3, the OSC facilities are first described, then the focus is on the description of the selected training methodology. The developed framework architecture is then presented together with the constituting components and the adopted multi-layer and multi-sensor organisation. A review of the unique training procedure for the Statoil Aasgard subsea gas compression plant is presented in Sect. 4 as a conceptual case study. In Sect. 5, a discussion regarding the validation of the proposed framework is outlined. Finally, conclusions and future works are outlined in Sect. 6.

2. Related Research Work

In existing literature, not much work has been done to develop specifically designed tools for assessing SA during maritime training operations. In order to understand SA within maritime applications, several examples of similarly demanding applications can be considered as sources of inspiration. For instance, in the last years, the performance assessment was successfully combined with a psycho-physiological approach for the objective assessment of the levels of physiological arousal and psychological load. This approach was validated and tested in simulators for civil airlines and space applications [15].

A key aspect of demanding maritime operations is the interaction between humans and machines. When considering human-machine interactions, human operators have to be considered in the centre of the loop. Considering this aspect, again space research can provide solid directions. The National Aeronautics and Space Administration (NASA) is a worldwide leading institution in redesigning novel methodologies as well as tools for complex distributed systems [16] by keeping human in the centre of the loop. In programmes established or supported by NASA and other research institutes [17], human error analysis due to procedures, operations, design or personnel stress have been addressed by adopting structured approaches. These methods may be adapted for similar analysis in the maritime domain.

Making decisions and managing competences in complex systems is a challenging task to accomplish. In this perspective, another significant example that can be taken as a source of inspiration comes from the process industry. For instance, the *Plant Simulator* (PS) is the expression coined in [18] for chemical production sites, to address something that is in analogy with the flight simulator paradigm. The PS is an information technology (IT) infrastructure created to replicate the exact plant conditions and to enable both expertise and field operators to cooperate as they would do in reality, i.e. as a team. The PS allows expertise and field operators for experiencing both rationally and emotionally the same situations they would live in reality in terms of process behaviour and consequences originated by either nominal or abnormal operating conditions. The PS can be surely taken as an example, however several elements would need to be adapted to the different domain of offshore applications.

Demanding offshore operations place workers in dynamic, rapidly changing conditions, which impose the need for effective teamwork among crew members to successfully achieve the desired tasks. Under such conditions, learning to work effectively in a team environment is challenging. Several factors need to be taken into account, such as emergency response as a team, crew resource and crisis management. In this perspective, applying simulation to team-training may be beneficial to better assess these factors and to improve safety and security in maritime operations [19]. Based on this idea, an enhanced simulation-based team-training approach is presented in [20]. According to the authors, an effective way for the crew team to gain experience and achieve corresponding skills consists in iterating several team-training sections on specially designed simulators that realistically represent complex conditions on-board vessels, following emergency alerts. The article introduces the concept of a safety and security training simulator and describes the research work related to the implementation of a learning objective-oriented development of simulation training scenarios and the pedagogic value added by simulation to maritime education and training (MET). To support this study, the authors present results of a simulation case study. These results highlight the potential of applying simulation to team-training for improving efficiency and safety of maritime operations.

To understand and monitor human factors during maritime training operations, it is necessary to transforms the simulators into research laboratories by instrumenting them with sensors for studying complex biological and socio-technical relationships. Even though independent sensor information is conducive to revealing an overview of the considered operation to some extent, a comprehensive multi-parameter sensing model is more effective for analysis and evaluation of potential operational risks. To the best of our knowledge, multi-sensor fusion is one of the most suitable technologies to use when dealing with data from disparate sources [21]. Concerning the possibility of improving maritime SA by adopting an infrormation-fusion or a sensor-fusion approach, various studies have been presented by different authors. For instance, a combined methodology of data visualization, interaction and mining techniques that allows for establishing individual or collective maritime SA by building a model over normal behavior from which the user can detect deviations was presented in [22]. The methodology includes a set of interactive visual representations that support the insertion of the user's knowledge and experience in the creation, validation and continuous update of the normal model. In [23], a system that aim to improve SA and threat detection capabilities in maritime scenarios by combining sensor-based information with context information and intelligence from various sources was developed.

The problem of identification and isolation of dangerous zones in offshore installations by using a

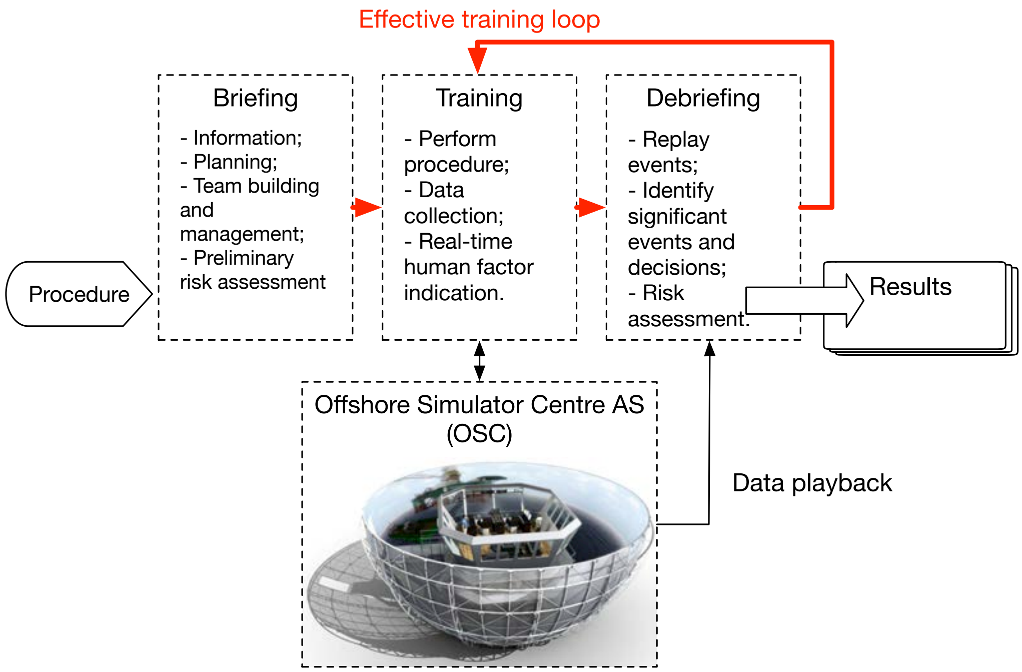


Figure 2: The adopted training methodology. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC).

sensor-fusion approach was investigated by our research group in [24]. In particular, this approach is based on a node positioning algorithm that allows for tracking and identifying the operational movements on board the vessel. In [25], our research group successively presented a wearable integrated health-monitoring system that can be used for maritime applications. The system is based on a multi-sensor fusion approach. It consists of a chest-worn device that embeds a controller board, an electrocardiogram (ECG) sensor, a temperature sensor, an accelerometer, a vibration motor, a colour-changing light-emitting diode (LED) and a push-button. This multi-sensor device allows for performing bio-metric and health monitoring of offshore operators.

It should be noted that most of the currently available systems based on sensor-fusion technology have exclusively been employed to monitor real applications. However, to the best of our knowledge, no integrated systems for planning, executing and assessing SA in demanding maritime operations exist as a built-in part of simulation training facilities. The main contribution of this paper is to propose such integrated framework.

3. Framework Architecture

In this section, the Offshore Simulator Centre AS (OSC) facilities are first presented. Then, the adopted training methodology is illustrated. Afterwards, the design guidelines of the framework are presented. Successively, the selected architecture technology is described.

3.1. Offshore Simulator Centre AS (OSC)

The Offshore Simulator Centre AS (OSC) [10] is designed for optimal training and education of offshore operation personnel. Based on advanced simulation and visualisation technology, the simulator can be configured in a number of ways, regarding hardware set-up, display solution, and software setup. It is possible to select different types of vessels, cranes/lifting objects, remotely operated underwater vehicle (ROV) systems and training scenarios [8]. The main components of the OSC simulator are:

- OSC Offshore Simulator Software. It includes all the simulation functionality;
- Instructor Station. It is an additional component that allows instructors and expertise to supervise the training operations;
- Deck Personnel functionality. It allows for including personnel such as a banksman, a slingerman or a signalman;
- Training scenarios and cases. It is possible to select different cases and operation scenarios;
- Crane Simulator hardware. The hardware set-up can be customised according to the desired need;
- ROV Simulator hardware. The hardware set-up can be customised according to the desired need;
- Virtual World and 3D Graphics. The simulated environment can be customised according to the desired application;
- Crane driver chair with armrest, joysticks, buttons and touch screens;
- Display Solution options. Different solutions can be used for visualisation.

The most realistic set-up uses an array of projectors to visualise the simulated environment on the inner surface of a "dome", as shown in Fig. 2. Advanced software algorithms are used to align the different components of the scene and to avoid any kind of distortion.

The OSC simulator is a provider of state-of-the-art commercial training courses. However the OSC actively participates in collaborative research projects with the Norwegian University of Science and Technology (NTNU) and other research partners both from the industry and from the academic world. In particular, NTNU is the main official partner regarding research and development.

Even though, the OSC Crane Simulator provides such advanced simulation facilities, the main drawback is that effective techniques and tools to visualise and analyse operational procedures, which can be used to further improve SA, are still lacking. The main contribution of this work is to integrate this missing technology with the OSC.

3.2. Training methodology

The adopted training methodology is based on previous literature. In particular, the briefing/debriefing model [12] is adopted as training methodology. The choice is motivated by the fact that this team-based, reflexive organisational model borrowed from the military was proved to be very effective in several group psychological interventions under acute stressor situations. When considering offshore training operations, for instance, this method was successfully applied to improve safety in maritime crane and lifting operations [26].

The selected training methodology is described in Fig. 2. Each session comprehends three different phases: briefing, training and debriefing. These phases are described in the following. The training and debriefing phases are iterated to achieve an effective training loop.

Briefing

during this phase, all personnel is thoroughly briefed on the purpose of an operation prior to participating in it. The time available for briefing may vary, depending on the circumstances. Briefings are structured according to the specific needs of the operation. Borrowing the main concepts from the "Information, Intention, Method, Administration, Risk Assessment, Communications, Human rights and other legal issues" (IIMARCH) model [27], which is adopted for the briefing of other similar acute stressor situations such as police operations, the briefing phase may be structured in the following steps:

- information: during this initial step, the preliminary schedule for the selected procedure to be performed is analysed. Similar cases are discussed if applicable;
- planning: at this stage, a tactical plan is discussed according to the available resources and with respect to the selected policies. Possible contingency plans are also identified;
- team building and management: during this step, personnel rules, duties and responsibilities are defined. Duty times and locations are assigned accordingly. At this stage, it is very important to quickly establish synergies between the team members;
- preliminary risk assessment: it consists in an individual as well as an overall assessment of all relevant risks.

By the end of this phase, it is necessary to check whether all the briefing objectives are achieved. In particular, although personal briefing styles may vary greatly, every briefing must satisfy certain key objectives in order to ensure that:

- relevant information has been communicated clearly and thoroughly (this can be confirmed by randomly checking team members to see if they understand completely);
- roles and responsibilities are understood for the assigned tasks;
- there are sufficient resources for performing these tasks (including situations where only self-briefing is possible, for example at remote stations).

Once the briefing phase is terminated, the training loop iteration starts alternating training and debriefing sections.

Training

the training phase is the key stage of the adopted methodology. During this phase, personnel get a first-hand experience within a simulated operation scenarios that is as close to reality as possible. This phase can be efficiently performed within the training facilities provided by the OSC simulator. The OSC simulator is designed for optimal training and education of maritime operation personnel. Based on advanced simulation and visualization technology, the simulator can be configured in a number of ways, regarding hardware setup, display solution, and software setup (including all the required modules such as the type of crane, types of vessels/lifting objects and training scenarios).

The training phase may be structured in the following steps:

- perform procedure: the planned procedure is executed in the simulation environment. The OSC simulator facilities allow the entire team to be trained together in rigorous real-life exercises. This training concept gives all team members the advantage of working together to avoid operational mistakes and misunderstandings and to increase safety on the real job. This way of learning builds very effective teams. The OSC offshore simulator software includes different simulation functionality. For instance, instructor stations can be setup to allow instructors to supervise the training operations. Different deck personnel functionality can be operated allowing for including personnel such as a banksman, a slingerman, or a signalman. It is possible to select different cases and operation scenarios. The OSC hardware setup can be customised according to the desired need. For instance, crane driver chairs can be provided with armrest, joysticks, buttons, and touch screens. Different solutions can be used for visualisation. The most realistic setup uses an array of projectors to visualize the simulated environment on the inner surface of a "dome", as shown in Fig. 2. Advanced software algorithms are used to align the different components of the scene and to avoid any kind of distortion. It should be noted that since the OSC simulator is a commercial product, internal implementation details cannot be provided;

- data collection: during the training phase it is essential to collect data concerning both the real scene as well as the simulated world. Concerning the simulator real scene, different information such as audio, video and bio-metric data from various sensors must be collected. In addition, possible annotations may be added during the training phase by different observers such as researchers, supervisors, instructors and other participants. Concerning the simulator virtual scene, it must be possible to store important information that may be played back at a later stage according to the certain time reference settings. This data collection is of crucial importance for the purpose of improving operational effectiveness and safety through the use of simulator facilities. All the collected data is relevant for the subsequent phase of debriefing;

- real-time human factor indication: during the training phase it is also important to provide personnel with tools that can improve their perception and SA of the ongoing simulated operational procedure. For instance, real-time visual indicators highlighting some estimated stress parameters may certainly improve the training experience. A real-time human factor indication may be achieved by interpreting data coming from different bio-metric sensors. These data may be processed in real-time by adopting proper methods based on a multi-sensor fusion concept.

It should be noted that the first of these steps can be easily achieved by using the tools originally provided by the OSC since the main objective of such an advanced simulator is to provide a realistic training environment. However, the steps concerning data collection and real-time human factor indication cannot be originally performed since the OSC does not naturally offer any integrated and flexible method for these purposes. The integration with the proposed framework makes these steps possible.

Debriefing

the purpose of debriefing is to identify good practice and areas for improvement, which could include organisational learning. Effective debriefing leads to many positive outcomes. The evaluation of the outcomes and processes of operations enhances team knowledge and develops the expertise of staff involved. Personnel can gain a better understanding of their roles in the selected procedure and how they can contribute to performance. More useful information can be collected, which in turn may be relevant for future operational decisions. The debriefing phase is structured in a way that it is possible to achieve the following steps:

- replay events: different events can be played back and discussed openly. An open discussion is established as an opportunity for all personnel involved to understand and share what went well during the training phase and to identify areas for development;
- identify significant events and decisions: potential issues can be identified. Significantly stressful decision can be highlighted. These events can be marked as critical and carefully considered in the next following loop iteration;
- risk assessment: this step aims to ensure that the deployed procedure is performed with a valid method of psychological management and that it can be delivered in a reliable manner. Effective management strategies can be planned accordingly.

It should be noted that none of these steps can be originally performed within the training facilities provided by the OSC simulator. The integration with the proposed framework makes these steps possible.

3.3. Design guidelines

The design of the proposed framework architecture is intended to allow the application of the previously introduced training methodology and it is based on the following guidelines:

- flexibility: the system must offer the possibility of collecting different training information from both the simulated scene as well as from the real scene. Different data such as audio, video and bio-metric data from eye-trackers and other sensor data must be gathered and integrated;
- reliability: as a research tool, the system must be easy to maintain, modify and expand by adding new components and features;
- integrability: the system must transparently be integrated with the existing framework provided by the OSC.

3.4. Architecture Technology

The adopted architecture technology is presented in the following. The reader is referred to Fig. 3. In particular, a client-server pattern is adopted. In the following, the key elements of the system are presented.

Server

The server is designed to collect data from the following different sources:

- cameras and microphones: video and audio sources can be collected from the real scene of the different simulator stations. Concerning the video information, several internet protocol (IP) cameras can be installed at strategic locations within the different simulator stations. A video surveillance software system, such as Milestone [28] or other similar programs, can be adopted to monitor the different scenes of all simulator stations. Each IP camera can also be accessed separately through a specific streaming source address. By accessing the different streaming sources, the server receives the video streaming from the cameras. Concerning the audio data collection, various microphones are located at the different simulator stations. These different audio sources can be first collected by using an audio mixer device and then streamed to the server in a similar way as it is done for the videos;

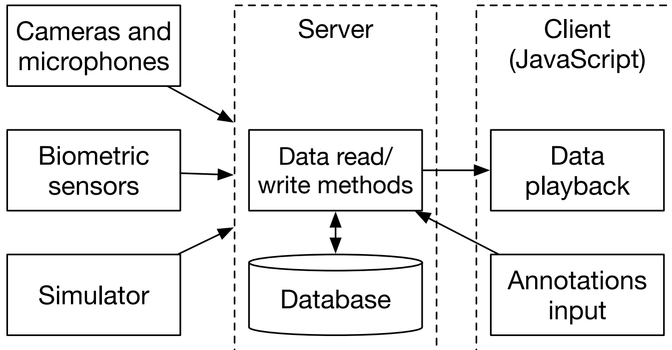


Figure 3: The proposed framework architecture.

- bio-metric sensors: different data from various sensors, such as eye-trackers, ECG sensors or other bio-metric sensors, can be collected. These data may provide very valuable information for both the training phase as well for the debriefing phase. For instance, a Tobii Pro Glasses 2 eye-tracker [29] was employed in this initial study to track eye-tracking data of the personnel while training. Some results are reported in Sect. 4. Thanks to the modular design of the proposed framework, support for other kind of bio-metric sensors can be easily added at a later stage;

- simulator: data from the simulator are collected regarding both the simulated physics and scenes. To realise this feature, both the physics systems and the scenes are stored in specifically designed cache memories. The physics systems have cache length settings independent of the scene frame range. This approach allows for selecting various simulation states and variables that can be made available for recording and playback. Additionally, different recording properties can be specified for each separate simulation object, which allows for increasing the playback fidelity or to minimize the memory usage for recording. It should be noted that this feature is still in a very preliminary design stage.

On the server side, the collected data are logically organised according to a multi-layer configuration, as shown in Fig. 4. This particular multi-layer configuration allows for overlapping different data according to a multiple information stack and a modular approach. The stack includes the simulated scene layer, the real scene layer, the bio-metric data layer and the annotations layer. This design approach allows for selecting and isolating only the desired data that are considered relevant for a particular series of events during the training and debriefing phases. For instance, eye-trackers may be used for tracking the personnel eye positions and eye movements, while ECG sensors can be employed to monitor the personnel health state and finally visual sensors can be adopted to monitor the personnel facial expressions.

By using specifically designed data read/write methods, the collected data are simultaneously being streamed from the server to the client in real-time and together being stored in a database on the server side. The data that are being streamed to the client in real-time can be used during the training phase for realising the real-time human factor indication feature. Instead, the data that are being stored on the database can be played back during the debriefing phase for achieving the possibility of replaying the most significant events of the training. It should be noted that some of the presented features for the server are currently under developing.

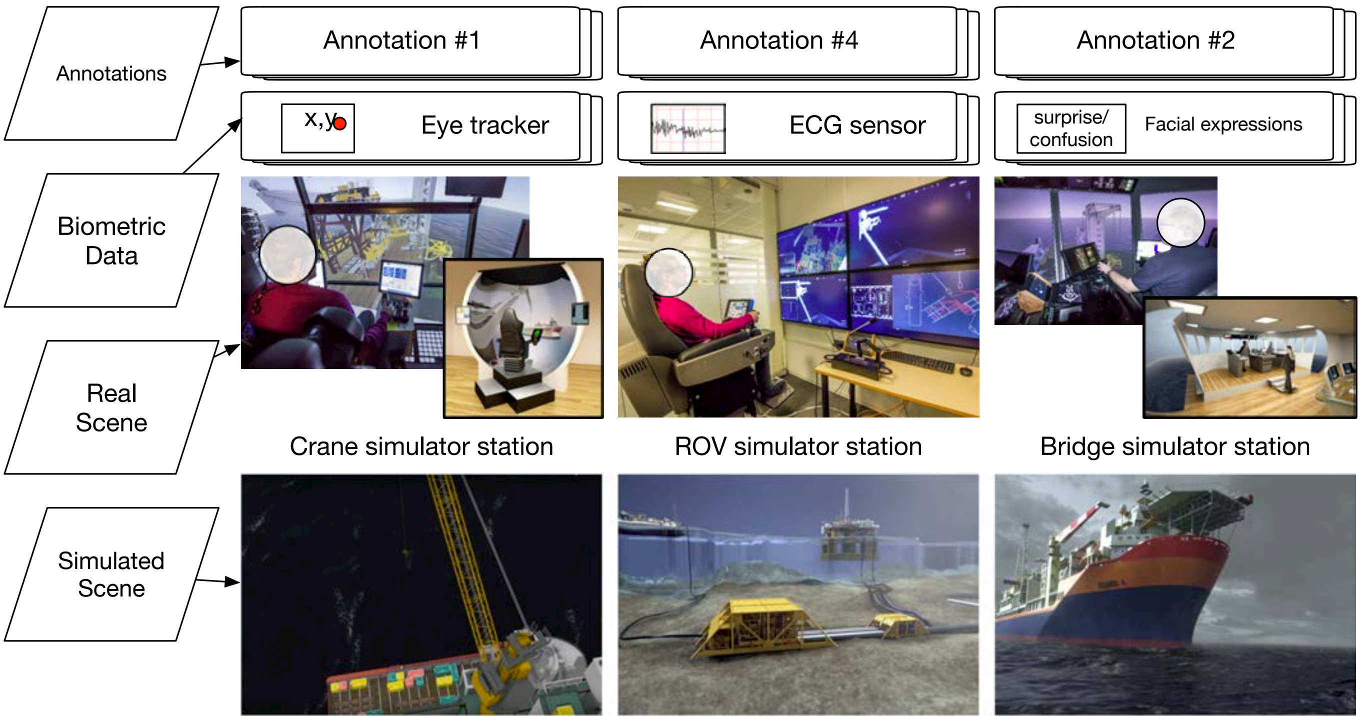


Figure 4: The proposed concept for the multi-layer and multi-sensor fusion framework. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

Client

The client application is designed to realise the following features:

- to visualise in real-time or to playback the collected data;
- to allow for adding annotations;
- to visualise human factor indicators.

These features are intended to be used during both the training phase as well as the debriefing phase. During the former phase data are visualised in real-time, while during the subsequent phase data are played back on demand.

The client software is designed as a multi-platform application that can be used on different operating systems. To make this possible, the client application is implemented as a web browser application. This design choice allows to fully exploit the ubiquity of web browsers, and the convenience of using a web browser as a client to update and maintain the proposed application without distributing and installing software on a considerable number of client computers. The client application is, in fact, intended to be used by all the different participants to the training procedure. Each participant can run the client application on a tablet device while participating in the training.

An interactive user interface is proposed for the client, as shown in Fig. 5. The standard HyperText Markup Language version 5 (HTML5) [30] and the JavaScript (JS) [31] high-level, dynamic, untyped, and interpreted programming language are adopted for structuring and presenting the content in a flexible yet

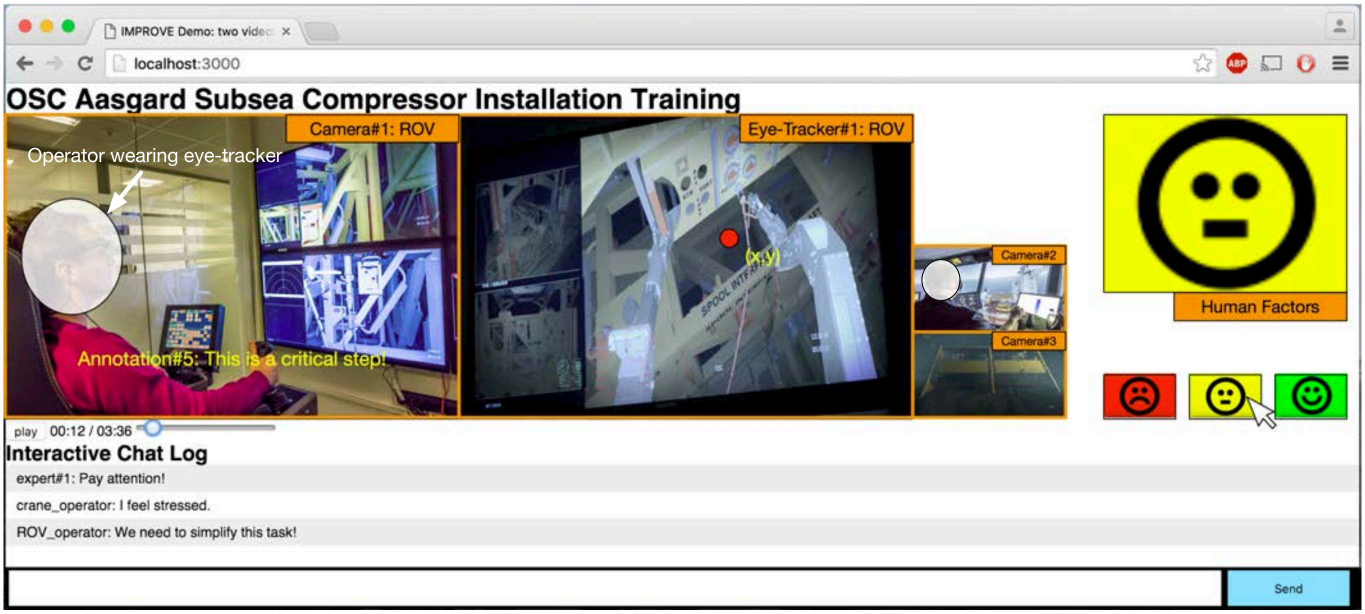


Figure 5: The proposed interactive user interface for the client. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

effective way. In particular, different video sources coming either from the simulated scene or from the real scene can be simultaneously visualised on the top panel. The different video sources can be dynamically selected and arranged according to the current need. Sensor data are overlapped and synchronised on top of the videos. For instance, a circular marker (superimposed on the video) is used to indicate the gaze data point collected by an eye-tracker, as shown in Fig. 5. Annotations are visualised on another overlapping layer on top of the previous ones. To keep the annotations synchronised with the other data, the *Popcorn.js* library [32] is adopted as a specific software library. *Popcorn.js* is a Mozilla's HTML5 video and media library. This library has been adopted as it helps simplifying media application program interface (API) and implementation differences between browsers and includes a powerful event system and a rich plugin architecture and plugins.

An interactive chat log is provided in the lower panel of the proposed interface. New annotations can be typed through a specific text input field and send to the server to be shared with all the participants of the ongoing training procedure.

Simple and yet effective input buttons representing emoticons are visualised on the right panel of the developed interface symbolising human factor indicators. In this initial study, according to an individual estimation of the current training situation, each participant can click on the corresponding emoticon button. As a result of a collective estimation given by different participants, a corresponding emoticon is shown.

A common slider make it possible to control the time-line and allows for synchronously playing the data and for displaying annotations in chronological order. By moving the slider is possible to play data back and forward and to review particularly significant events of the selected training procedure.

It should be noted that, as at the time of writing, the entire framework implementation is still in a prototype stage and the complete integration with the OSC simulator is currently an undergoing process.

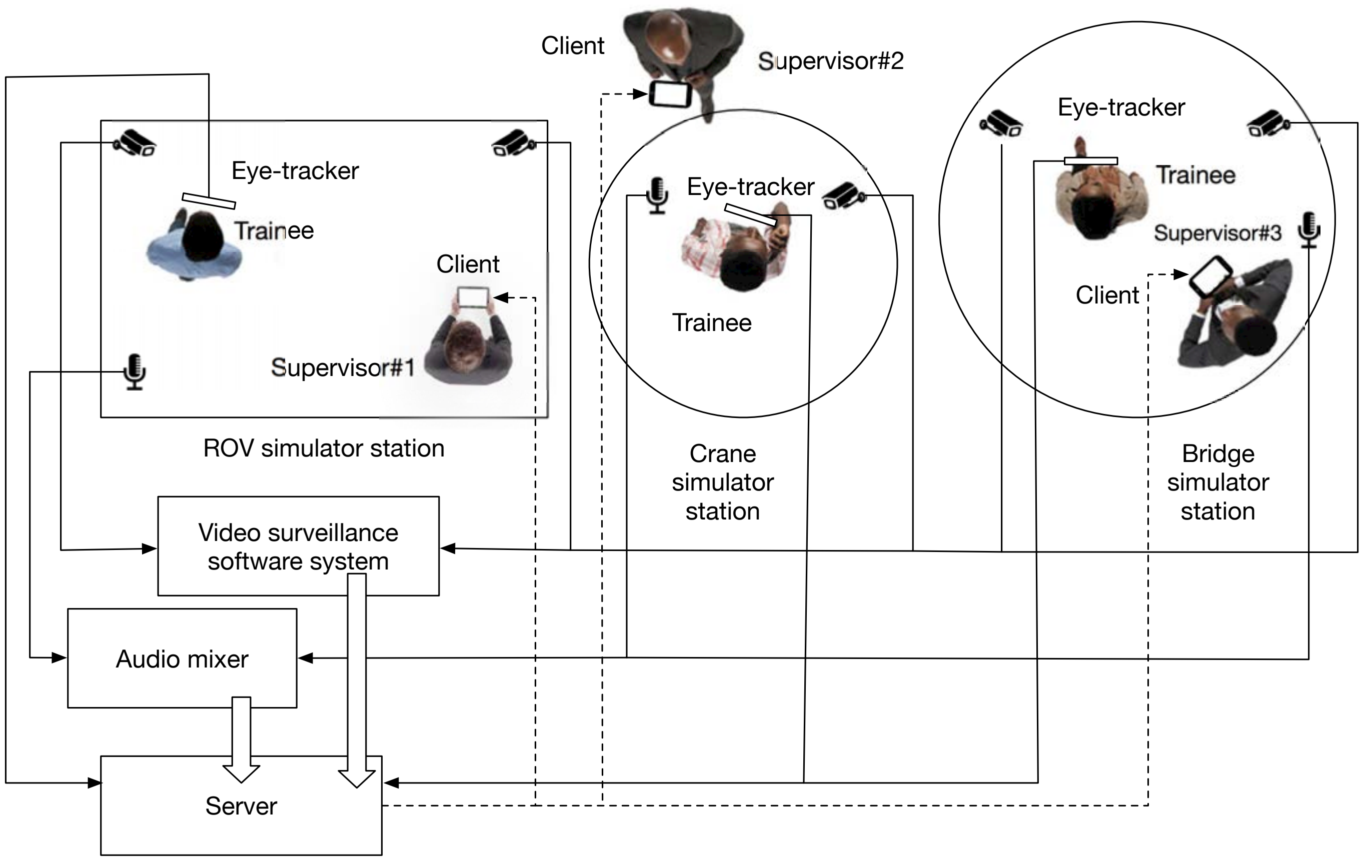


Figure 6: The considered conceptual case study and the different simulator stations. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC). Any person depicted in the image is being used for illustrative purposes only.

4. Conceptual Case Study

In this section, a conceptual case study is presented. In particular, the training procedure that was previously performed for the Statoil Aasgard subsea gas compression plant [11] is considered. The information related to the Statoil Aasgard subsea gas compression is of public domain as it is available on several newspaper pages, websites [11, 13] and articles [14]. This information is only intended to contextualise the selected case study. Based on this information, the selected training procedure is hereafter reviewed and analysed according to the proposed framework. It should be noted that, to the best of our knowledge, no bio-metric data was collected during the original training procedure performed for Statoil and partners. In this conceptual case study, some steps of the considered training procedure have been repeated in order to collect some meaningful data.

The considered case is probably one of the most unique and technologically demanding maritime projects that was recently developed in Norway. Ranking among the largest developments on the Norwegian continental shelf, the Statoil Aasgard field lies on the Halten Bank in the Norwegian Sea, about 200 kilometers off Norway. The Aasgard subsea gas compression facility is the world's first project of its kind. Using new technology, the compression process enables the gas to gain sufficient additional pressure for it to be transported through the pipeline to the platform. This helps boosting the recovery factor and producing life for gas fields. The Aasgard subsea gas compression facility is built by using a modular design approach where different interfaces are adopted including a spool interface, a scrubber and a compressor. A more detailed description of the Aasgard subsea gas compression facility is reported in [33]. The deployment and installations of the facility building modules required a coordinated team work involving different maritime expertise and devices. For this purpose, Statoil also involved the expertise provided by Technip [13] and other partners.

To exploit the uniqueness of this demanding procedure, the world's first integrated Subsea Simulator was developed by the OSC to make it possible the simulation of the entire procedural training. OSC simulated the full subsea installation including the following modules:

- the North Sea Giant vessel [34];
- the crane system that has been modified to incorporate a so-called special handling system (SHS) [35];
- two remotely operated underwater vehicle (ROV) systems;
- one observation-class ROV and the instructors station.

A simplified schematic representation of the OSC Subsea Simulator is shown in Fig. 6. Referring to Fig. 6, the two ROVs, the observation-class ROV and the instructors station can be simulated within the ROV simulator station. The modified SHS crane system can be simulated within the crane simulator station. Finally, the North Sea Giant vessel can be simulated in the bridge simulator station. Each simulator station is equipped with different IP cameras and microphones. The various IP cameras stream the recorded videos to the video surveillance software system (or alternatively straight to the server), while the audio information collected by the different microphones is sent to an audio mixer. Both audio and video data can then be forward to the proposed server. Different supervisors can follow the training procedure by using the client browser application running on their portable devices.

From a methodology point of view, this unique training procedure may be conducted by first organising the trainees in two different teams. This approach makes it possible to stimulate teamwork skills and critical thinking abilities. From a social point of view, group dynamics are also relevant. The teams must be assembled together by considering the necessary competences to accomplish the selected training. The two teams can participate together to the previously introduced effective training loop, which is shown in Fig. 2. However, during the training phase, the two teams must be alternating each other in such a way that when one team is performing the other team is observing. This approach can effectively improve operational effectiveness and SA.

A schematic time-line overview of the selected training procedure is shown in Fig. 7. It includes the deployment and installation of a spool interface, the deployment and installation of a scrubber and the deployment and installation of a compressor. It should be noted, that this is a clear simplification of the actual training procedure that was performed for Statoil and partners. This schematic time-line is only intended to contextualise the selected case study.

In this conceptual case study, some steps of the considered training procedure have been repeated in order to collect some meaningful data. In particular, eye-trackers were used to collect eye-tracking data from personnel while training, as shown in Fig. 6. In particular, a Tobii Pro Glasses 2 eye-tracker [29] was employed for this purpose. The Tobii Pro Glasses 2 eye-tracker is a wearable eye-tracker with wireless live view function for insights in any real-world environment. These features make the device very suitable for

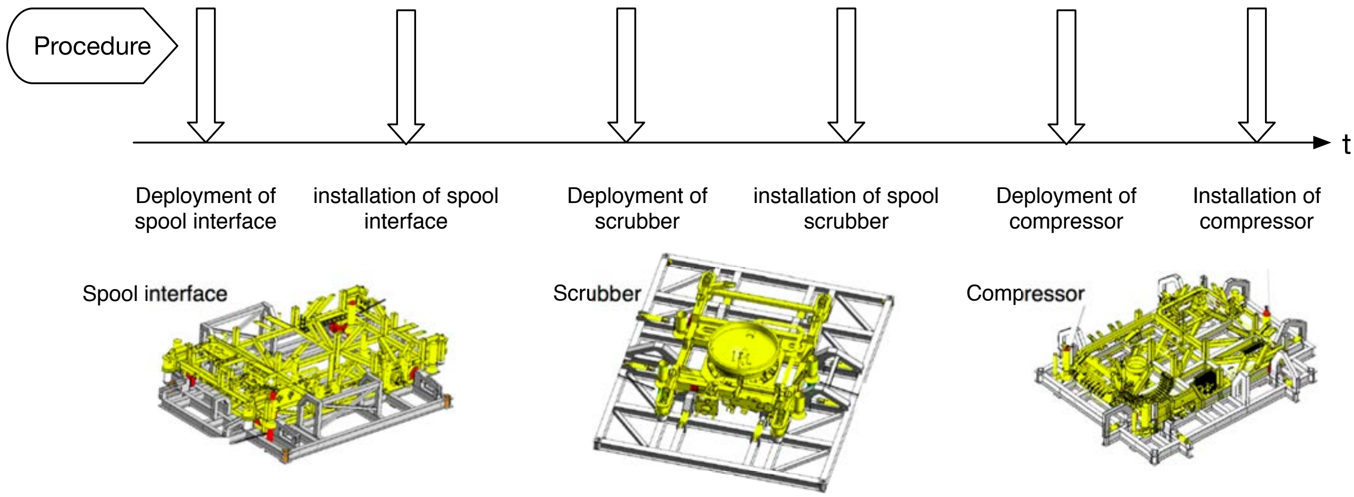


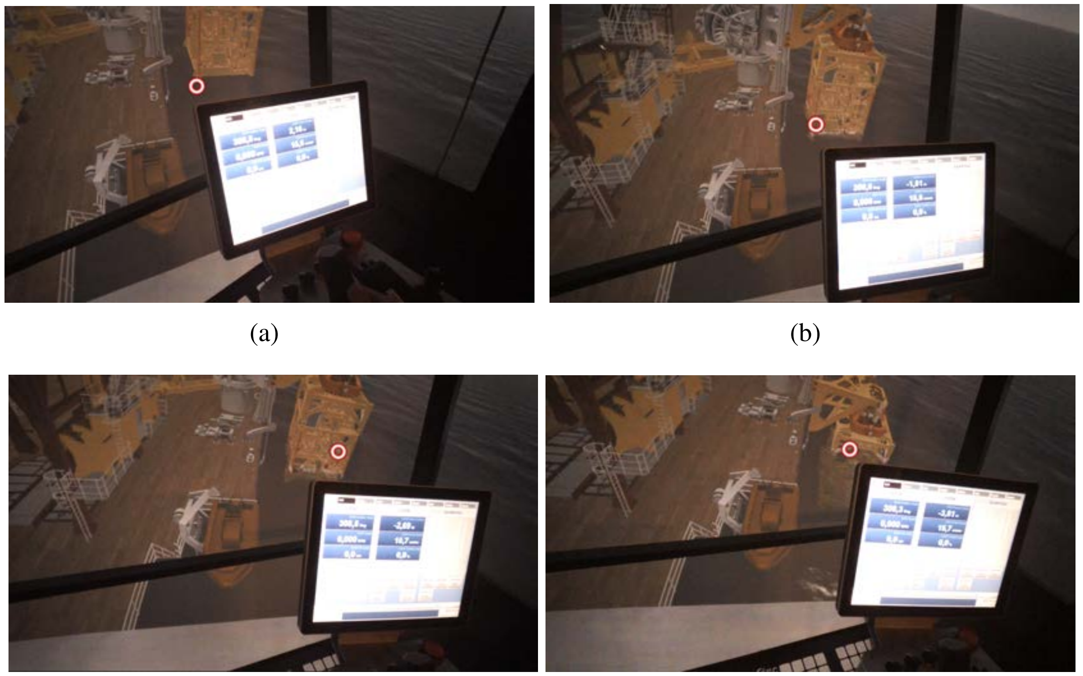
Figure 7: A schematic time-line overview of the selected training procedure. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC) [14], to Statoil and partners. These elements are for illustrative purposes only.

collecting valuable data that can be used for both the training phase as well as for the debriefing phase. Some results are reported in the following.

Concerning the training phase, the data collected from the Tobii Pro Glasses 2 eye-tracker can be directly streamed to the client. This functionality can be achieved by using the Tobii Pro software development kit (SDK) APIs. On the client user interface, these data can be visualised according to the adopted multiple information stack protocol, as shown in Fig. 5. It should be mentioned that this feature is still under developing. It should be noted that, because of the strict real-time constraint that is required during the training phase, only the raw data (corresponding to the x and y coordinates) coming from the Tobii Pro Glasses 2 eye-tracker are visualised and synchronised with the other data on the user interface. Even tough the information carried by the raw data is relatively simple, it is still significantly relevant for estimating the level of attention of a trainee wearing the eye-tracker while performing demanding procedures.

For instance, lifting or lowering loads through the splash zone is a very challenging procedure to be accomplished for a crane operator. To successfully perform this procedure, several elements need to be taken into account such as slamming forces, added mass and drag of the lifted object, which can increase the forces transferred to the crane and the object by many times the weight of the object. In addition, snap loads caused by wave or boom-tip motion may be very large. A sequence of consecutive screenshots taken from the OSC crane simulator station demonstrating the execution of a similar routine is shown in Fig. 8. In this particular case, the deployment of a module is performed as a sub-routine of the selected training procedure (the reader is referred to the time-line shown in Fig. 7). Real-time eye-tracking data are combined with the visual information. A circular marker (superimposed on the video) is used to indicate the gaze data point. The positions of the markers highlight the fact that the operator's gaze point is gradually following the module entering through the splash zone.

Concerning the debriefing phase, a more accurate analysis of the collected data can be conducted. In particualr, the Tobii Pro Glasses Analyzer software [29] can be used for post-analysis and visualization of data from the Tobii Pro Glasses 2 eye-tracker. This software make it possible to replay eye-tracking videos, aggregate data, visualize the results and calculate statistics. In particular, the raw data points are further processed into attentional eye movements to better visualize and interpret the information. To efficiently



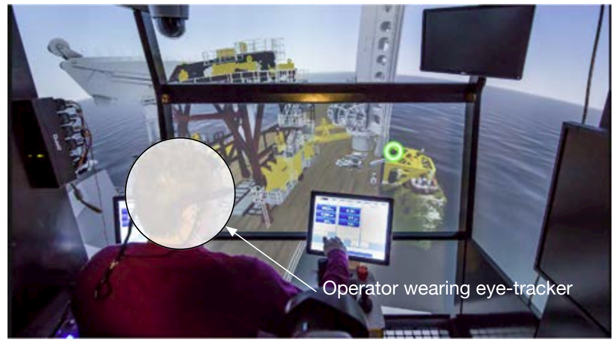
(a) (b) (c) (d)

Figure 8: (a), (b), (c), (d) A sequence of consecutive screenshots taken from the OSC crane simulator station demonstrating the deployment of a module through the splash zone. Real-time eye-tracking data are combined with the visual information. A circular marker (superimposed on the video) is used to indicate the gaze data point. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners.

achieve this, data points are first aggregated into relevant eye movements so that it is possible to significantly reduce the amount of eye-tracking data to process. Successively, different filters can be applied. For instance, the sample point validity can be checked in order to discard points with no eye position data or incomplete data. One example of such occurrences could be when only one eye has been recorded without identifying if it is the left or right eye and therefore a final gaze point cannot be estimated.

Considering the previously mentioned sub-routine used for the deployment of a module through the splash zone, different post-analysis results can be obtained. In particular, the raw data are first mapped onto a snapshot taken from the real scene to make data aggregation feasible. The result of this mapping is shown in Fig. 9. It should be noted that the gaze data point (red marker superimposed on the video, as shown in Fig. 9-a) and the corresponding location on the snapshot image (green marker superimposed on the snapshot, as shown in Fig. 9-b) are precisely mapped. Based on this mapping, a heat map can be produced as shown in Fig. 10. A heat map is a gaze data visualization on top of a snapshot image that uses colors to represent how much the participants gazed on (attended to) different areas of an object or an environment. In this case, the crane operator gazed more on the crane control interface and on the module to be deployed. Based on the same snapshot, a gaze plot can be also obtained as shown in Fig. 11. A gaze plot is another interesting mapping that shows the sequence and position of fixations (dots) of the operator. Gaze plots can be used to illustrate the gaze pattern of a single test participant throughout the entire eye-tracking session. The numbers and the connecting lines shown in Fig. 11 are used to highlight the time sequence concerning this particular case.

(a)



(b)

Figure 9: The raw data of the sub-routine used for the deployment of a module through the splash zone (a) are mapped onto a snapshot taken from the real scene (b) to make data aggregation feasible. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

Additionally, to better analyse the considered sub-routine, an area of interest (AOI) can be defined to study the region of the scene where the module is being deployed through the splash zone, as shown in Fig. 12-a. Defining an AOI allows for performing numerical/statistical analyses. For instance, the data coming from the gyroscope and accelerometer built into the Tobii Pro Glasses 2 eye-tracker can be retrieved to accurately tracking the operator's head movements in time within the selected AOI. The corresponding result are shown in Fig. 12-b. Is it possible to notice that the operator's head follows the movement of the deployed module through the splash zone. Another possible analysis concerns the 3D gaze information that can be gathered from the collected data. A scene-centric attention analysis can be performed for the selected sub-routine showing the operator's gaze position in the 3D space of the surrounding scene. The results of this analysis are shown in Fig. 12-c. It is possible to notice that the 3D gaze points are more concentrated in the region corresponding to the direction of the splash zone. It is also possible to notice that the operator makes smaller and repeated gaze movements when approaching the splash zone direction. These results are consistent with the fact that the operator pays more attention when approaching the splash zone. Note that a low-pass filter is applied to reduce the noise from all the collected data.

By using the previously described approach, additional data can be collected from the ROV simulator station. For instance, a sub-routine can be considered where the operator is manoeuvring the ROV and performing some grasping tasks. After performing an accurate analysis of the collected data, the heat map for this sub-routine can be obtained as shown in Fig. 13. To highlight the time sequence concerning this particular sub-routine, a gaze plot can be also used as shown in Fig. 14. These results show the fact that the operator pays attention to the ROV control interface and to the some relevant regions of the simulated scene.

Analogously, a similar analysis can be performed for the bridge simulator station. For instance, a sub-routine can be considered where the operator is manoeuvring the vessel. After post-processing the raw data, the heat map for this particular sub-routine can be obtained as shown in Fig. 15. Additionally a gaze plot can be also used as shown in Fig. 16. These results show the fact that the operator pays attention to the bridge control interface and to the some relevant regions of the simulated scene.

Concerning the considered case study, a comprehensive demo video is available on-line at: `https://youtu.be/2xl7vFV3vE8`.

Figure 10: A heat map of the sub-routine used for the deployment of a module through the splash zone. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

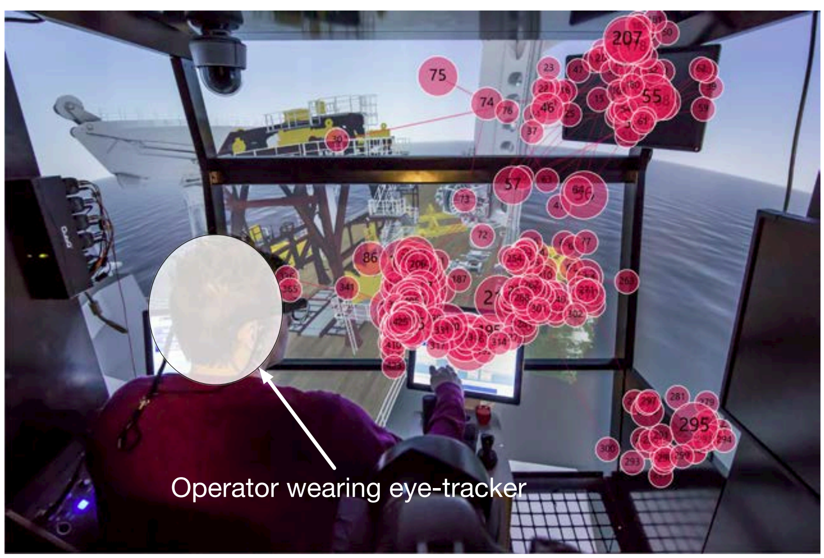
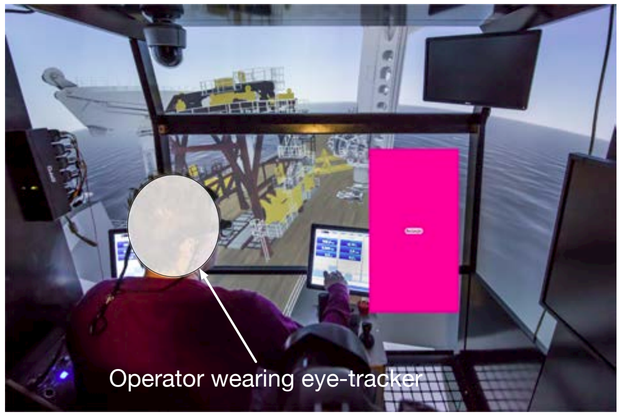
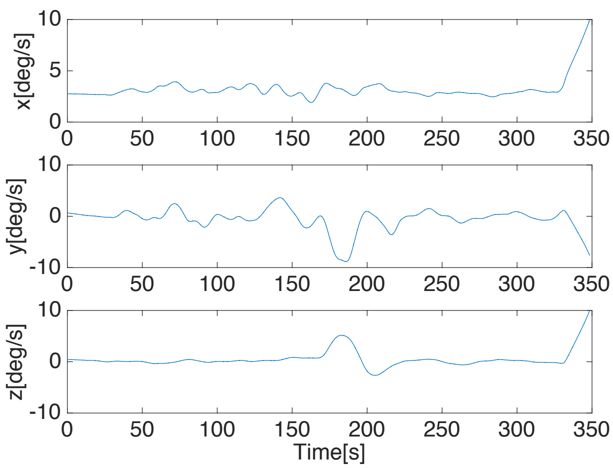


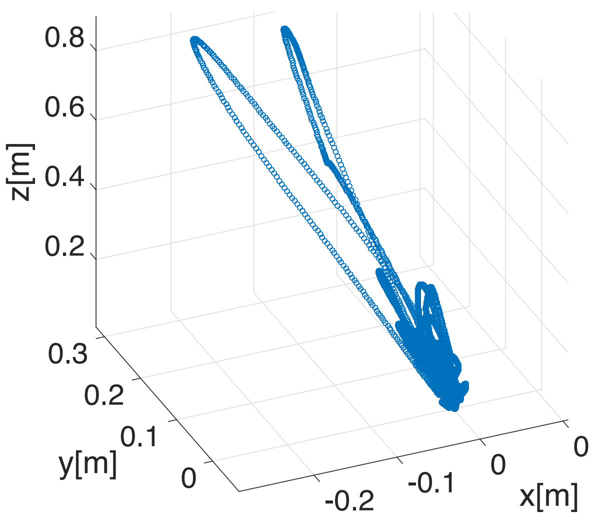
Figure 11: A gaze plot of the sub-routine used for the deployment of a module through the splash zone. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.



(a)



(b)



(c)

Figure 12: (a) The definition of a specific AOI into a snapshot of the scene; (b) a plot showing the tracking of the operator's head movements; (c) a plot showing the operator's 3D gaze combined points. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

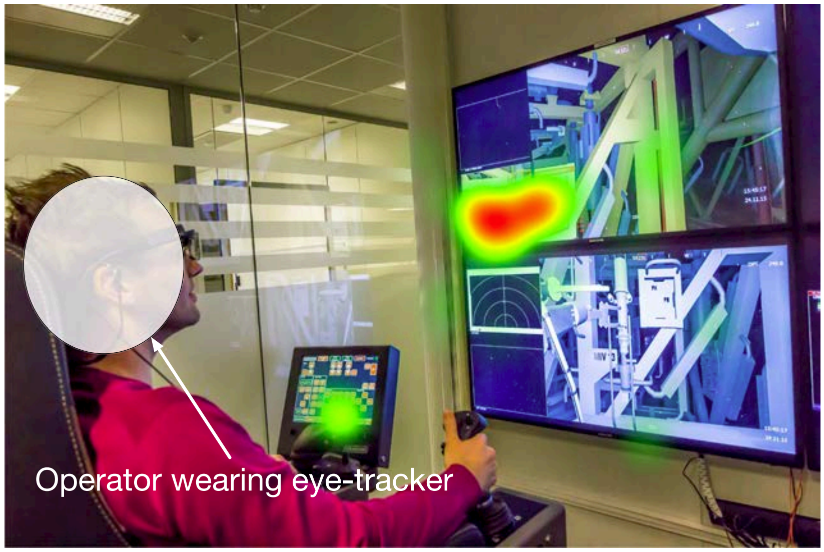


Figure 13: A heat map of the sub-routine performed in the ROV simulator station. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

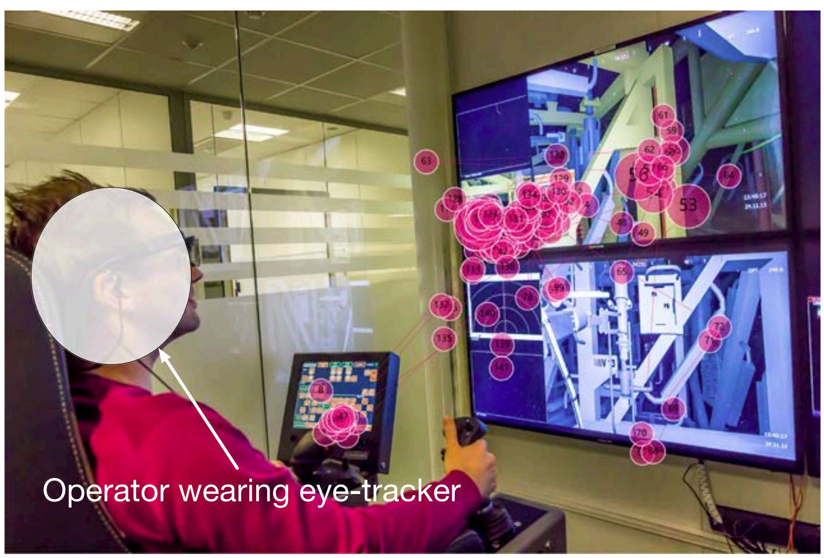


Figure 14: A gaze plot of the sub-routine performed in the ROV simulator station. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

Figure 15: A heat map of the sub-routine performed in the bridge simulator station. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

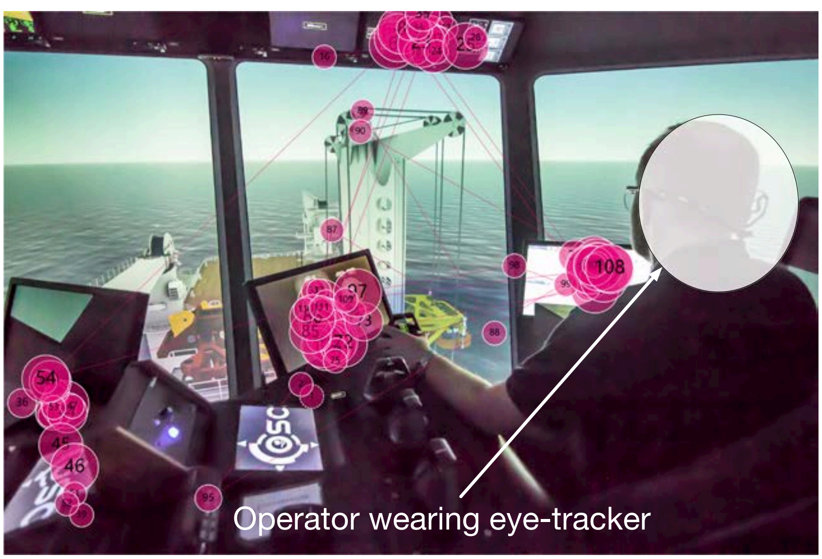


Figure 16: A gaze plot of the sub-routine performed in the bridge simulator station. Some elements of this figure are credit to the Offshore Simulator Centre AS (OSC), to Statoil and partners. Any person depicted in the image is being used for illustrative purposes only. People's faces are obscured for privacy concerns.

5. Discussion

The integration of the selected training methodology with the proposed framework enables trainees to familiarise themselves with different operational scenarios. This is the first step towards achieving an effective risk reduction from both an individual as well as an overall evaluation of the potential harm in real offshore operations. Preliminary tests of the proposed framework highlight its potentials. However, an extensive validation test is needed in order to assess the effectiveness of the proposed technology. In this perspective, similarly demanding applications can be considered as sources of inspiration to design the appropriate validation methodology.

For instance, considering the field of process industry as a source of inspiration, the results of the experiment campaign performed in the so-called *Plant Simulator* (PS) [18, 36] can be considered as guidelines to be followed. Indeed, the experiments conducted in [18, 36], highlight the efficacy of using immersive simulators both to make decisions and to train teams (not just single operators). The example provided by the concept of the PS can be useful when considering how the assessment of the proposed framework can be performed. In particular, very good guidelines are provided in [18, 36] regarding:

- the experiment design;
- the people profiling and selection;
- the scenario and implementation in the *Plant Simulator* (PS);
- a specific assessment algorithm shared with domain experts and process owners.

Obviously, these elements would need to be adapted to the different domain of offshore applications but they represent a very promising starting point for the assessment of both subjective as well as objective factors.

The process of validation require an extensive effort including a broad field test with a sufficiently large group of trainers for comparison. To undertake such a major field test, several instrumentation set-ups are currently underway at the OSC simulator facilities. This necessary but extensive validation process is therefore left as future work.

6. Conclusion and Future Work

In this paper, a framework for improving SA in demanding maritime training has been proposed based on a multi-layer and multi-sensor fusion design approach. The proposed framework is integrated with the Subsea Simulator developed by the OSC. This integration takes full advantage of the OSC domain-consistent simulation tools. Different information from the simulator scene and from the real world can be collected, such as audio, video, bio-metric data from eye-trackers and other sensor data. In this perspective, this integration represents the base for research on novel SA assessment methodologies. Based on previous literature, a promising training methodology has also been discussed [12]. The choice is motivated by the fact that this team-based, reflexive organisational model borrowed from the military was proved to be very effective in several group psychological interventions under acute stressor situations. When considering offshore training operations, for instance, this method was successfully applied to improve safety in maritime crane and lifting operations [26]. This methodology is based on the concept of briefing/debriefing and on an interactive and effective training loop. The contribution of this work is the integration of this methodology with the proposed framework. This will gradually meet the the industry needs for the purpose of improving operational effectiveness and safety through the use of simulator facilities.

Even tough some of the presented system features are currently under development, several advantages can be highlighted. In terms of user experience, trainees can familiarise themselves with different operational scenarios. This is the first step towards achieving an effective risk reduction from both an individual as well as an overall evaluation of the potential harm in real offshore operations. In addition, from a research point of view, different methodologies can be also developed for assessing SA by using the proposed framework as a research tool. To highlight the potentials of the proposed framework, a conceptual case study has been also presented. In particular, the training procedure performed for the world's first sub-sea gas compression plant, in Aasgard, Norway, has been analysed and reviewed. For this conceptual case study, eye-trackers were used to collect eye-tracking data from personnel while training and repeating some steps of the considered procedure. Related results have been reported.

These preliminary testing of the proposed framework highlights its potential, however, in order to validate its efficiency in effective risk reduction, the system must be run through an extensive field test with a sufficiently large group of trainers for comparison with a control group. To undertake such an extensive field test, several instrumentation set-ups are currently underway. This necessary but extensive validation process is left as future work.

As future work, it would be interesting to implement different methods for assessment SA and approaches that consider human factors like the ones presented in [37] or in [23]. A set of routine tests, different techniques and metrics may be added to the proposed framework, taking into account several factors, including fatigue, stress, health, teamwork, decision-making, communication, automation, and safety culture. Different common key areas may be investigated such as common themes of accidents, the influence of human error, and interventions to make maritime operations safer. More sophisticated methods for an automatic trigger and verification of events may be also implemented. This will allow for a more accurate and effective verification of deadlines during the deployment of procedures.

One more possible future work that is under consideration is the possibility of using the proposed framework as a tool to develop new training programmes for unique operational procedures. Starting from a preliminary procedural plan, the entire operational procedure may be developed by using the proposed training iteration loop and based on the concept of briefing/debriefing.

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