Human Reliability and the Impact of Control Function Allocation in the Design of Dynamic Positioning Systems

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Abstract: The design and function allocation of control in complex technological systems have mainly been technology driven, resulting in increased automation. A human or user perspective is rarely taken in the technological development. The pertaining attitude seems to be that increased automation will reduce the occurrence of human error and thereby ensure safer design and operation. Increased levels of automation, however, may come with a cost of reduced situation awareness for the human operator. This is also the case in the design of the dynamic positioning (DP) system for vessels. Accident statistics show that the frequency of collisions in certain DP operations is above the acceptance criteria and that a combination of technical and human failures were the main causes in nearly all accidents. This article underlines the importance of considering the role of the human operator and human reliability in the design and operation of DP systems. It presents a functional model of the DP system, and discusses current function allocation of control and its impact on operators' situation awareness and performance. This article concludes with recommendations regarding function allocation of control and visualization of operational risk to enhance operator performance and reliability.
Keywords: Human Reliability, Automation, Dynamic Positioning (DP), Control Function Allocation, Situation Awareness.

1. INTRODUCTION

The design and function allocation for control of complex technologies have mainly been driven by technology (meaning that the capabilities of the technology were central in its development), resulting in systems with increased automation. The term automation has several definitions. This article uses Sheridan's definition [1]: "Automation refers to the mechanization and integration of the sensing of environmental variables (by artificial sensors), data processing and decision making (by computers), and mechanical action (by motors or devices that can apply forces on the environment or by communicating information to the environment)". The term automation utilized in this article to represent the execution of a function by a machine that was previously performed by a human [2]. A human or user perspective is rarely adopted in the design phase of an advanced technological system [3]. The pertaining attitude seems to be that more automation will reduce the occurrence of human error and thereby ensure safer design and operation [4]. The increasing levels of automation, however, may come at a cost.

A dynamic positioning (DP) system is an example of a complex and advanced technology. The International Maritime Organization (IMO) had defined a DP vessel as a vessel that is able to maintain its position and heading, and to maneuver slowly along a predefined course, solely by means of its thrusters. The DP system consists of all the systems necessary to enable position-keeping, which include the DP computer control system (DPCCS), the thruster system and the power system [5].

A DP vessel relies on a computer system to interpret signals from reference systems, wind and motion sensors to maintain position and heading or to follow a preset course. Maintaining position or following a preset course is accomplished by adjusting the direction and force of the thrusters of the vessel. DP is used for a variety of operations. Within the offshore oil and gas industry it is, for example, used for offloading, drilling, diving, subsea intervention, seismic and construction operations [6].

IMO [5] has defined three DP classes. The basis of the classification is the worst case single failure modes.

- Equipment class 1: Loss of position may occur after a single failure,

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- Equipment class 2: Loss of position should not occur after a single failure of an active component,
- Equipment class 3: Loss of position should not occur from any single failure (including flooded watertight component and fire in subdivision.

DP class 2 and 3 systems are considered to be highly reliable due to the requirements for redundancy [7]. DP class 2 and 3 vessels are mostly used in the oil and gas industry in Norway.

The general advantages of automation are considered manifold [8]. It enables higher information processing and movement speed, it can assert greater mechanical power, it can execute certain operations with greater accuracy and precision. Automation has also enabled increased duration of operations, and more robustness to environmental conditions. In some cases, automation also has a higher reliability than human operators. Finally, the cost of automation can be substantially lower than of human operators [8].

Nevertheless, accident statistics show that the frequency of collisions of DP vessels (for example, floating production storage and offloading (FPSO) - shuttle tanker (ST) collision) is above the general 10^{-4} per year acceptance criteria. Collisions are considered one of the defined safety hazard and accident (DSHA) by the Norwegian oil and gas industry. Collisions could damage structural integrities and cause hydrocarbon releases which could result in injuries or loss of life. Detailed analysis of this type of accident has revealed that a combination of technical and human failures was the main immediate cause in nearly all accidents that happened between 1995 and 2015 [9, 10].

All DP operations are inherently threatened by loss of position, and operators often only have a short response time in which to correct or mitigate such a loss [11]. Operating conditions for DP are often characterized by a limited time window in which to recover position or steer the vessel into a safe zone in case of loss of vessel position. The complexity, the high technical reliability of the system, and the reactive relationship of operating the system leads to reduced situation awareness and system understanding among operators. This results in operating conditions that can be described as 99% boredom and 1% panic [11].

In this article, we present a method that can be used to ensure that the design of DP systems, and their human-machine interface (HMI) in particular, will facilitate high human operator reliability during DP operations. The method combines an analysis of function allocation for system control with human reliability analysis. Using this method, we study the interactions between automation and the human operator during DP operations in the oil and gas industry on the Norwegian Continental Shelf (NCS), in order to evaluate the human operator safety performance and reliability during DP operation.

In the following sections, a functional model of the DP system is presented with the current function allocation of control. The impact on operator's situation awareness and the reliability of performance is discussed, as well as the risk associated with the current design. The paper concludes with recommendations regarding function allocation of control, the HMI and visualization of operational risk to enhance operator performance and reliability.

2. AUTOMATION AND SITUATION AWARENESS

The DP computer control system (DPCCS) consists of several sensors, decision elements, and actuators. The various motion and wind sensors provide input to the DPCCS, which transfers the input through a vessel observer, (e.g., a Kalman filter). This filters away the noise and wave frequency motion of position and heading sensor readings, and produces filtered estimates on actual position, heading and velocities. Based on the offset between these estimates, and the desired motion states, the controller allocates force and direction to the thrusters. The systems are spread throughout the vessel and mutually interactive; it includes wind sensors all the way on the rooftop as well as the thrusters down in the water. The communication between the components might be varying in speed and a decision element might control multiple actuators, such as the DPCCS. The system is built on interactions between different components. While most of these interactions are designed, some unintended interactions can arise due to the dynamic nature of the system. Due to the coupling and feedback loops in the systems, some actuators may inadvertently affect sensors, decision elements or other actuators. For example, based on differences between estimated and measured motion states, the DPCCS can decide to reject input from certain sensors or position reference systems. These unintended interactions make the system complex, and understanding and foreseeing all interactions is nearly impossible [1].

Automation in aircraft and plant operation can involve long periods of boredom interrupted by sudden bursts of activity. The same can be said about the monitoring of DP operations. Sudden transients in workload are a considerable threat and may increase the probability of human error and misjudgment [3, 1]. Such sudden transients are often combined with an information overload, which could result in operators bypassing quantitative input channels and generating an overview of the situation from ad hoc qualitative channels, which may not be reliable.

A balance must be struck between automation and the situation awareness of the operators. Situation awareness is knowing what is happening around you and understanding what this means to your situation now and in the future. Situation awareness has been classified into three levels: the perception of elements in the current situation, comprehension of the current situation, and projection of future status [3]. These perceptions comprehensions and projections are continuously tested on the current mental model of the operator. The external cues that are perceived are interpreted based on the current mental model of the operator; the mental model helps the operator comprehend the current situation, and helps formulate expectations of the future. A mental model is a systematic understanding of how something works. For example, the mental model of traffic flow tells you that when a driver in front of you signals with a turn signal, you expect him or her turn off the road. Knowing this lets you adapt your driving accordingly. A well-developed mental model supports situation awareness by dynamically directing attention toward critical cues from the environment. The mental model further supports situation awareness with an expectation of the results of any given situation based on the projection mechanism of the mental model. The mental model also includes pre-learned typical actions facilitating the decision process of selecting the appropriate action [3].

A common but unjustified belief is that increased automation reduces the need for situation awareness [3, 1]. However, situation awareness is considered equally as important in automated systems as when operating without automation. One could even argue that the need for situation awareness increases when automated systems are part of the operation, because the operator needs to be aware of all basic input as well as what is happening in the automated system. Decision making capabilities are gradually transferred from the human operator to the system with the implementation of more automation and autonomous functionality [12].

The increasing complexity of automated systems and operations, combined with poor human machine interfaces and inadequate training, have led to reduced system understanding. The operator is “out-of-the-loop”. This significantly affects the situation awareness level 2 and 3: comprehension of the current situation and projection of what will happen in future [3].

Situation awareness can be improved by keeping the number of different performance modes to a minimum, providing automation transparency, making modes and system states clear, and enforcing automation consistency (a consistent way of presenting information from the system to the operator) [3]. This can be supported by the use of ecological displays. Ecological displays are designed based on the notion that constraints should be evident and convey the correct response in a natural way [13]. Ecological interface design (EID) is one approach that has been shown to have considerable success in supporting problem-solving activities in process control situations [14]. EID encourages the use of skill-based and rule-based behaviour, and supports knowledge-based behaviour. Knowledge-based behaviour is often linked to the ability to handle unforeseen situations. One of the design principles for EID dictates that the work domain should act as an externalized mental model of the situation to support the operator in decision-making for events that require knowledge-based behaviour [15].
Burns [14] conducted a study of a large process system presented in three different types of ecological displays, differing in space and time integration. She found that scan patterns, emerged from the operator monitoring the displays to gather separated information which improved performance [14]. In general,

EID results in an interface with several levels of information beyond equipment settings and values. This additional information can help the user solve the problems and takes advantage of a reasoning path from that visualizes how the intended purpose is achieved. This can strengthen the system understanding and the mental model of operators [3].

Currently, for most DP operations, the operator is tasked with passively monitoring system performance. In general, there are four aspects of tasks that can be automated during station keeping on DP: monitoring, generating options or strategies for achieving goals, deciding what option to deploy, and implementing actions [1]. Each of these aspects can be allocated to a human, a computer, or a combination of the two. Based on a literature review of all levels of automation from the 1950s up to the present, Vagia, Transeth and Fjerdingen [16] propose eight levels of autonomy (see Table 1). They have chosen to define levels of autonomy instead of automation, because autonomy specifies that the system has the possibility to decide by itself (deliberate control), instead of being solely preprogrammed as a reactive control system. Even though the distinction between the terms automation and autonomy is somewhat blurred, it is becoming more relevant with recent and potential future developments, for example, in the field of artificial intelligence [16, 12]. However, as mentioned earlier, in this article we use the broader term levels of automation, the execution of a function by a machine that was previously performed by a human [2], which can also include autonomy.

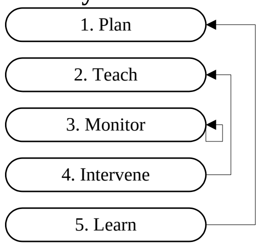
Table 1: Levels of autonomy [16]

Level of autonomy	Stage	Description
Level 1	Manual control	Computer offers no assistance
Level 2	Decision proposal stage	The computer offers some decisions to the operator. The operator is responsible to decide and execute.
Level 3	Human decision select stage	The human selects one decision and the computer executes.
Level 4	Computer decision select stage	The computer selects one decision and executes with human approval
Level 5	Computer execution and human information stage	The computer executes the selected decision and informs the human
Level 6	Computer execution and on call human information stage	The computer executes the selected decision and informs the human only if asked
Level 7	Computer execution and voluntarily information stage	The computer executes the selected decision and informs the human only if it decides to
Level 8	Autonomous control stage	The computer does everything without human notification, except if an error that is not into the specifications arrives. In that case the computer needs to inform the operator.

These levels could differ for the four aspects of a task and the levels of autonomy presented above should be adapted to better describe the system that is evaluated. Nevertheless, the current DP system is generally automated at level 5 (although development is taking place to increase the level of autonomy for some vessels). Most things are executed automatically; however, the human operator is always informed of the actions. For example, automation disables a position reference sensor (e.g., a Differential GPS) because the system believes it is unreliable. The operator is informed, although the operator might have to click through a few screens to get the information, for example when a sensor is automatically deselected. The thrust command is always visible on the HMI for the DPO.

The control the human operator wields over DP systems is best described as supervisory control. The supervising human operator plans, teaches, monitors, intervenes (if necessary), and learns from the DP operation (see Figure 1) [1].

Figure 1: Supervisory control functions/phases [1]



During the planning phase, the human supervisor decides the limits and parameters in which the DP system can operate. To do so correctly, the mental model of the operator needs to be complete and correct. The operator must understand how input values will affect the system. The operator needs to understand not only how the DP system will respond under normal conditions, but also under abnormal conditions. The DP system functions and DP operating limits need to be further planned with regard to other operating constraints, such as fuel, available power, time, etc. These plans then need to be verified against the ultimate goal of the operation [1]. In the teaching phase, the operator needs to translate the plans into a format that can be understood by the system. This is done by configuring settings and parameters, or other forms of programming.

Once the system is configured and the automation activated, the human supervisor enters the monitoring phase. Monitoring means observing a set of variables and keeping a look-out for abnormalities or failures. In this article's case; signs of loss of position. If the supervisor is responsible for observing multiple variables then attention must be divided. Humans are somewhat poor at rapidly shifting attention, and this phase is highly dependent on situation awareness. The following phase of operation, intervention, is also dependent on situation awareness. The decision of when, where, and how to intervene is critical. The longer the supervisor waits to intervene, the more information the supervisor has available to base the decision on, but by the time the supervisor has enough information it might be too late to intervene. Consequences due to a late response can be severe.
The desired action selected during the intervention phase can, in some cases, also be taught to the system. During the last phase, learning, experience from the human supervisor is taken into account for the next planning phase. This could also be applicable for self-learning automated systems, or the operator could improve the model/software performance. For example, the mental model of the supervisor might have changed based on experiences with system behavior [1].

3. METHOD - ALLOCATION OF FUNCTION ANALYSIS

The method that has been chosen to review the current design of the DP system and to evaluate the interaction between the operator and the automation in the system, is allocation of function analysis [17]. Allocation of function analysis is used to allocate jobs, tasks, and responsibilities to either a human operator, a system operator (computer), or a combination of the two, during the design process [17]. The analysis consider each task and the advantages and disadvantages of the task being performed by either a human or a system operator. The analysis is especially important when automation is considered. Steps in an allocation of function analysis are:

1. Identify tasks for analysis
2. Conduct a task analysis
3. Conduct a stakeholder analysis
4. Consider human and computer capabilities
5. Evaluate impact of allocation of function on performance and job satisfaction

For step 4, the consideration of human and computer capabilities, a list developed by Fitts [18] is often used. This list compares what humans are better at to what machines are better at and it is a well-known basis for the allocation of function analysis. The list should not, however, be applied directly in analyses. Considerations should be made of the context in which the system will be used, advances in the development of technology, and the consequences for the situation awareness of the operator if control is allocated to the computer. Fitts' list has been criticized for being outdated in light of recent advances in technological development [19]. De Winter and Hancock [19] surveyed ca. 3,200 people in 103 countries to see whether humans surpassed machines or machines surpassed humans on the 11 statements of the Fitts' list. Their study concluded that machines surpass humans in detection, perception, and long-term memory (4, 5, and 6 respectively in Table 2). In 1951, when Fitts' list was published, these changes were already anticipated [19]. This article will utilize the updated Fitts' list (see Table 2) in the analysis of function allocation to help determine the effects of the current function allocation for the different tasks associated with maintaining position for DP operations.

Table 2: Capabilities related to humans and machines. Adapted Fitts' list [18] based on research from de Winter and Hancock [19]

Humans Are Better At	Machines Are Better At
1. Ability to improvise and use flexible procedures (improvisation)	4. Ability to detect a small amount of visual or acoustic energy (detection)
2. Ability to reason inductively (induction)	5. Ability to perceive patterns of light or sound (perception)
3. Ability to exercise judgment (judgement)	6. Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time (long term memory)
	7. Ability to respond quickly to control signals and to apply great force smoothly and precisely (speed & power)
	8. Ability to perform repetitive, routine tasks (replication)
	9. Ability to store information briefly and then to erase it completely (short term memory)
	10. Ability to reason deductively, including computational ability (computation)
	11. Ability to handle highly complex operations, i.e., to do many different things at once (simultaneous operations)

For step 5, the evaluation of the impact of the function allocation on performance and job satisfaction variety of methods could be applied. It depends on the context of the system which method is most appropriate. In the case of this article the focus is on DP operations and the performance of the DP operator. Therefore, to evaluate the impact of the function allocation on the human operator performance the article utilizes a human reliability analysis (HRA). Further details on this can be found in section 4.4.

Furthermore, when deciding how to allocate functions of a system, it is important to consider the completion time and the task complexity. For simple tasks that take little time, manual control (low level of autonomy) might be preferred over supervisory control. For example writing a note on a pad contra using a writing software program on a computer. However, if the task is very complex then it might not be possible to develop a software program, or it might be prohibitively resource demanding. In these situations, manual control might also be preferred over supervisory control. For all tasks between these two extremes, supervisory control might be preferred. However, factors such as repetition of the task could also influence the decision for allocation of control [1].

According to Sheridan [1], humans are poor monitors of automation. Humans' psychological needs, such as the need for variation, make it nearly impossible for us to continuously monitor a system. If the automation functions as planned, the human becomes bored, inattentive, and can fall asleep. When the human is surprised by the failure of a complex automated system he or she may become overloaded with information, and the human operator has to cope with the crisis. Despite these risks, humans are inevitably put in the role of monitoring and are meant to increase the robustness of the system. Although humans are prone to making errors, they are also good at discovering and recovering from system malfunctions under the right circumstances [1].

4. RESULTS

This article identifies the tasks related to the main function of the DP system, which is to maintain vessel position. The task analysis is presented in Section 4.2. The article does not include a stakeholder analysis as part of the allocation of function analysis for the DP system, because the results are meant to be discussed at a more general level and stakeholders were not involved in this phase of the study. The tasks identified in the task analysis are categorized based on the updated Fitts' list (see Table 2) in Section 4.3. In addition to an evaluation of allocation based on capabilities, the consequences for human performance have been analyzed using a human reliability analysis (HRA) especially adapted for the oil and gas industry (Petro-HRA), which is presented in Section 4.4. Finally, some considerations based on job satisfaction are discussed in Section 5.

The analyses are based on a document review of the DP manual of the most frequently used DP supplier on the NCS [20], as well as several interviews with DP operators or persons with DP experience and observations of DP operations in simulators.

Four interviewees are selected for this study based on their long and broad experience with DP operations. All interviewees had several years of experience (two with more than 20 years, two with 15 years' experience) operating DP systems on a variety of DP vessels and a variety of DP operations, including subsea, anchor handling, supply, construction, drilling, diving, and shuttle tanker offloading operations. Moreover, most interviewees had held several positions on board the DP vessels with varying levels of responsibility regarding the DP operations. Positions held included DPO, first officer, captain, and OIM. The interviews are either conducted via video conference or face-to-face. Each interview lasts one hour, and is conducted with only the interviewee and interviewer present. The semi-structured interview guide contained open-ended questions that allowed for an open discussion related to the context of DP operations on the NCS.

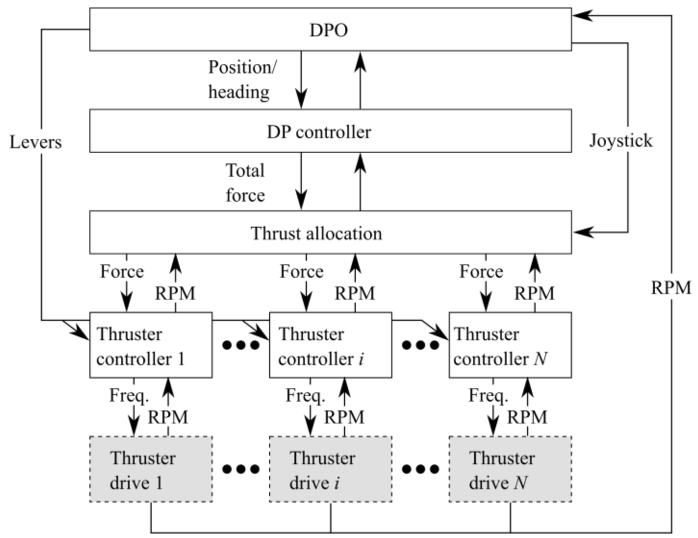
4.1 Step 1 - Identification of tasks for analysis

Figure 2 depicts the controllers within the DP system. The DP operator (DPO) is at the head of the DP system, and instructs and monitors the system. The DPO also has the possibility to intervene, as shown in the hierarchical task analysis in Figure 3. The DP controller has the main control within the DP system and is responsible for computing a suitable total thrust force vector. Other controllers in the system are the thrust allocation, and thruster controllers that control the electrical drives of each thruster. Commands from the DP controller trickle down, and is translated into new signals and actions. A more detailed description of the controllers illustrated in Figure 2 is given below. The power system and the power management system (PMS), which are also part of the DP-system, have not been included in the figure. They are, however, also described below.

The DPO instructs the DP controller on the desired position and heading. The DP controller then calculates and estimates the expected total force needed to maintain that position and heading, and gives this command to the thrust allocation controller. This controller then instructs each thruster controller on desired force and direction, which the thruster controller translates into the required frequency for the thruster drives. This information flows top down, but feedback also flows bottom up through the system.

The system includes back-up solutions, i.e., different DP modes that have varying levels of automation, that are to be used in situations where it is not desirable to allocate control with the automation at the highest level.

Figure 2: Controllers within the DP system and thruster drive (actuator)



The role of the human

The DPO is responsible for developing the operating strategy and translating this into parameters, which are to be entered into the HMI to instruct the automation (DP system) how to operate. Once this is done and the DP mode, station keeping, has been activated, the DPO monitors the HMI and any other physical indicators for abnormalities and failures of the DP system. The DPO can also reconfigure the settings of the DP system based on changes in operational conditions. If any such abnormalities or failures are detected, the DPO has to decide whether to intervene. The DPO can either make changes in the parameters or settings using the HMI, or take over control from the DP mode.

The DPO can also take over control on different levels as depicted in Figure 2; by selecting Joystick or Manual mode the DPO can directly control thrust allocation, bypassing the DP controller. If the DPO decides to use the Levers mode, the DPO directly controls the thruster controller, bypassing both the DP controller and the thrust allocation. The levers or joystick (in the case of Azimuth thrusters) are hardwired to the thrusters and there is one lever for each thruster. The DPO can then control direction (in the case of Azimuth thrusters or similar) and thrust of each single thruster.

The role of automation

The function of the DPCCS is to provide each active thruster with control signals that will result in position keeping. For the thrusters to be able to follow these control signals, sufficient amounts of power must be available. Most DP vessels are equipped with diesel-electric power systems [21], where diesel generators feed electrical power to an electrical bus that distributes the power to thrusters and other vessel consumers. A PMS is responsible for overall control of the power generation, and a particular responsibility is to ensure that sufficient amounts of power is available for the thruster system.

The DPCCS consists of a DP controller, a position reference system module and thrust allocation module. The function of the DP controller is to calculate thrust vector command in surge, sway and yaw (i.e., the necessary forces in forward and sideways direction and a torque about the vertical axis) [22]. To calculate the thrust vector command, the DP controller compares estimates of the actual motion states to desired motion states, such as position and heading. The position reference system is responsible for providing motion state feedback through sensors and signal treatment modules. The thrust vector command is allocated to individual thrusters in the thrust allocation.

4.2 Step 2 – Conduct task analysis

The actions for maintaining position of the vessel and preventing loss of position, were identified using a behavioral model that also includes cognitive elements [23]. This model is a linear task success/failure sequence consisting of cognitive considerations and manual actions required for responding to an alarm (or a similar cue). It includes one success pathway and four potential failures, failure to detect, failure to diagnose, failure to decide, and failure to act in time. This method has been selected because it facilitates the identification of potential human failure events and assessing human reliability [23].

The hierarchical task analysis (see Figure 3 and Table 3) can be divided into two phases: normal and abnormal operations. The first branch allocates thruster force, and its subsequent branches are considered normal operations, and the other branches are considered actions to recover from an abnormality.

Figure 3: Hierarchical Task Analysis DP operations

*PMS = Power Management System

4.3 Step 4 - Consider human and computer capabilities

Not including step 3 (the stakeholder analysis) in the allocation of function analysis, step 4 is based on the task analysis performed under step 2. The task analysis (see Table 3) has been limited to the tasks, which are currently allocated to the system, during normal operations. The recovery tasks are in current practice allocated to the human operator. In most cases, the DP system has not been able to respond appropriately or has failed in some way when there is a need for recovery actions. This means that the integrity of the system might be compromised and that the decision making of the system can no longer be trusted. In some cases, a loss of position is initiated by human error, and in these cases, the human reliability probability of the recovery actions is also compromised [4].

The task analysis has further limited itself to the allocation of function and characteristics of the tasks, based on the updated Fitts' list in Table 2. As can be seen, the tasks during normal operations have been allocated to automation.

Table 3: Task Analysis of DP control system

#	Task	Task resp.	Updated Fitts' list (humans are better at – machines are better at)	Equipment used	Information required
1.	Maintain position and heading	DP controller	perception, speed & power, computation	Sensors, DP console, reference systems, communication wires to thrust allocation controller	Environmental forces, current position, expected position, desired position
1.1	Control thrust	DP controller and thrust controller	judgement, speed & power, replication, computation	DP model	Direction of environmental forces, desired heading and position, direction other thrusters
1.1.1	Calculate total thrust vector	DP controller	speed & power, computation	DP model, sensors	Environmental forces, current power/thrust usage
1.1.2	Allocate total thrust vector	Thrust allocation	speed & power, replication, computation	Switchboard, generators, thrusters	Number of thrusters available, amount of power that needs to be distributed
1.1.2.1	Find suitable/ optimal direction and force for each available thruster	Thruster allocation	speed & power, replication, computation	DP model	Direction of environmental forces, desired heading and position, direction other thrusters
1.1.3	Generate thrust	Thruster controller	speed & power, replication	Thruster drive	Required thrust, available power, current RPMs
1.1.4	Direct available thruster in correct direction	Thruster controller	speed & power, replication	Thrusters	Calculated optimal direction of thrusters
1.2	Ensure necessary available power for each thruster	PMS	judgement, speed & power	Generators, thrusters, switchboards	Required thrust, available power
1.2.1	Activate generators	PMS	judgement, speed & power	Generators, (remote) control console	Number of required generators
1.2.2	Configure switchboard	PMS	judgement, speed & power	Switchboard, (remote) control console	Preferred switchboard configuration

2.	Detect change in position	DPO/DP controller	detection	DP console	Sensory information, environmental indicators, position settings
2.1	Detect visual/audio alarms	DPO	detection		Colour of alarm, location of alarm, source of alarm, type of alarm, severity of alarm
2.2	Detect loss of function	DPO/DP controller	detection	DP console, PMS console	Degree of loss of function, what equipment is affected, what are the consequences for the system, what are the consequences for the operation
2.3	Detect movement relative to surroundings	DPO/DP controller	detection	Position reference systems	Position settings, reference points, distance to reference points
2.4	Detect unexpected increase/decrease in thruster power	DPO/DP controller	detection	DP console, PMS console	Amount of unexpected increase/decrease in power, effect on position and potential for worsening of position
2.5	Detect physical movement	DPO	detection		Direction of movement, does the movement lead to a loss of position
2.6	Detect changes in weather	DPO/DP controller	detection	DP console	Do the weather changes affect position keeping abilities
2.7	Detect difference on independent position reference systems	DPO/DP controller	detection	Position reference systems, DP console	Size of the difference, which reference system is most likely providing faulty information, how many reference systems are affected
3.	Diagnose situation	DPO			
3.1	Call in for advisory meeting	DPO	judgement	Telephone	Captain/OIM, first officer available, how do they diagnose the situation and how do they think the scenario will progress and what actions should be taken
3.2	Determine cause of failure (within control system/PMS)	DPO	computation	DP console, PMS console, local consoles, local equipment	What has failed, how has it failed, can it be fixed, how fast
3.3	Determine drift off/drive off occurring	DPO	judgement	DP console	Thruster capacity, number of available thrusters, weather and current state
3.4	Determine weather state and changes in	DPO	judgement	DP console	Future weather, wind, current, etc. state and

	current, wind, etc. that could cause further worsening of position				their effect on the current position keeping capabilities
4.	Decide on intervening action	DPO	judgement, improvisation	Operating guideline	
4.1	Determine potential consequences	DPO	judgement		Potential collision risk, risk of damages to hydrocarbon containment capabilities or other underwater structures, risk for death, injuries, or damages to underwater activities
4.2	Decide if it is necessary to stop operations	DPO	judgement, improvisation	Operating guideline	Does the scenario exceed any of the limits set by the operating guideline
4.3	Decide if system override is necessary based on operating guideline parameters	DPO	judgement, improvisation	Operating guideline	Does the situation warrant a system override according to the operating guideline
5.	Execute intervening action	DPO	speed&power	DP console	
5.1	Select system override mode	DPO	speed&power	DP console	What system override mode should be used, is this functionality available
5.2	Confirm and execute system override	DPO	speed&power	DP console	Is the functionality available and functional
5.3	Move vessel to safe zone, if indicated by operating guideline	DPO/DP controller	speed&power	DP console	Does the situation warrant a move of the vessel to the safe zone according to the operating guideline, location of safe zone

4.4 Step 5 - Evaluate impact of current allocation of function on performance

The impact of the current allocation of function on performance can be considered to be represented by the accident frequency of DP operations, which for FPSO-ST is above the acceptance criteria of 10^{-4} per year, and statistics from 1993-2009 show a frequency of loss of position of 2.9E-05 per DP hour for DP 2 and 3 Classed vessels [24]. However, to evaluate how the current allocation of function impacts the performance and reliability of the human operator, this article is utilizing a human reliability analysis (HRA).

An HRA is a structured identification and evaluation of critical human errors. The analysis can be either quantitative or qualitative. When quantitative, the analysis assesses the human error probability (HEP). The HEP can be assessed by evaluating the performance shaping factors (PSFs) that influence the task and multiplying the effects with a nominal or basic probability for error of the task [25]. However, a quantitative analysis builds upon many qualitative analysis such as a task analysis and human error identification. A HRA method especially adapted for the oil and gas industry, Petro-HRA [26], is used to evaluate the implications of the current allocation of function between the DP system and human operator. The Petro-HRA is based on the well-known SPAR-H method, and although the list of performance shaping factors (PSFs) that is utilized by the method is not exhaustive it is considered a representative selection of factors for the oil and gas industry, which would include the type of DP operations that this article is considering.

As mentioned previously, all DP operations are inherently threatened by a loss of position, therefore failing to prevent loss of position is selected as the human failure event (HFE). Other HFE could occur during any other of the supervisory control phases: plan, teach, monitor, intervene, and learn. The HFE selected in this article focuses on the monitoring and intervention phase. However, human failure in the planning phase can result in the selection of wrong system parameters for the DP system, which in turn may result in loss of position. A potential human failure in the teaching phase can be a maintenance or setup error in one of the DP related systems. Finally, a failure to learn from system or environmental behaviour may lead to the operator selecting the wrong systems parameters for the next operation.

The HFE to prevent loss of position also includes failure to recover loss of position. These HFE assumes a failure in task 1: maintain position and heading (as per task analysis presented in Figure 3), then the human operator has the opportunity to recover loss of position in tasks 2-5: detect change in position, diagnose situation, decide on intervening action, and execute intervening action, but if the operator fails a safe position cannot be maintained. Task 1 is currently mainly allocated to the DP system, however the DPO still has to monitor the system and the situation and should be able intervene at an early stage, preventing a loss of position. A failure in one of these five tasks can ultimately result in a loss of position and possibly a collision or damages to hydrocarbon containment. This scenario is assumed to take place within a 500-meter zone on the NCS. The task analysis in table 3 is the foundation for the HRA. It identifies all tasks necessary to avoid a loss of position. The most critical tasks will be analysed in the HRA and the information gathered in the task analysis is important input to the analysis.

To ensure that the analysis is relevant for various DP operations and DP vessels, it has been conducted on a high level, not specifying the cause for the vessel to lose position and mainly focusing on a qualitative evaluation of the PSFs. Petro-HRA includes the following PSFs: time, threat stress, task complexity, experience/training, procedures, HMI, attitudes to safety, work and management support, teamwork and external working environment [26]. The HEP for each critical task part of the HFE is calculated by the nominal HEP; 0.01 x the multiplier of each PSF as per method Petro-HRA (see example below). The nominal HEP is a value of human error probability that is supposed to contain all small influences that can contribute to task errors that are not covered by the PSFs. The nominal HEP in Petro-HRA is 0.01 for all task types [26].

The HEP of failure to prevent a loss of position is determined by the evaluation of these PSFs which have categories with associated multipliers. An evaluation of the PSFs is presented below and are based on typical DP2 and DP3 operations and vessels.

Time

As mentioned previously, DP operations often have a narrow footprint for movement and a loss of position can already occur if the vessels move just a few meters, for example, for supply or lifting operations. This leaves the operator with only a few seconds to intervene. Other operations like drilling, ST offloading and flotel operations, are characterized by distances of ca. 40-100 meters before impact or well damage occurs. This often leaves the operator with 30-60 seconds response time [11], depending on the speed of the vessel, to intervene before impacts or damage becomes unavoidable. The operator will within this time window need to detect and correctly diagnose the situation and decide if a system override is required, and if so, how best to do this. In situations where the vessel has built up a high speed a collision or damage to subsea structures might be unavoidable, and the HEP consequently should be considered to be equal to 1. These cases might be considered extreme, but could nevertheless occur. Other loss positions scenarios that have a lower speed also put the operator in a challenging condition. The time PSF will, in most cases, increase the HEP with a multiplier of 10 or 50 in accordance with the Petro-HRA method [26].

Threat stress

Threat stress; stress related to damage to self, others, or reputation, in DP operations could be posed by the possible collision in cases where the DP vessels is nearby other structures, or by damaging subsea structures which could lead to blow outs and potential explosions or fires, or by divers that could be severed from the life support functions by a loss of position. Depending on the scenario, the threat stress multiplier will increase the HEP with a multiplier of 5 or 25 (according to Petro-HRA [26]), since there is an (immediate) threat on person's, own or others, life in most cases. In cases where the loss of position cannot lead to a collision, because the vessel is moving away from the collision object, the failure is still evaluated to evoke threat stress to the self-esteem of the operator and the professional status since an incident in the 500-meter zone is still quite serious.

Task complexity
In most cases, the task complexity of preventing loss of position is not high. There are several cues that warn an operator that a loss of position is about to take place: alarms, changes in thruster force or power required/available, patterns in vessel movement, physical cues, etc. However, the automation might obscure some relevant cues by responding automatically, for example in case of a drifting sensor or a reference system that is deselected by the automation. Once a (near) loss of position is detected and diagnosed, the operator has to decide either to relocate to the safe zone or try to stop the movement of the vessel (this is often quite clear from the specific scenario), and then to execute the action based on the decision. The action often consists of several steps, which might take some time, but are not overly complex. Please note that some differences might exist between operations and companies. On average, the HEP for the PSF task complexity for this HFE is considered nominal with a multiplier of 1 in accordance with Petro-HRA [26].

Experience/training
All DP operators on the NCS have to be certified to be able to work. However, the certificate is universal for all DP operations, despite there being significant differences between them, especially regarding the risk picture of the entire operation. Most companies have additional requirements for experience before they allow DPOs to work unsupervised, but these requirements can be flexible under significant time or financial pressures. There are no official requirements for retraining from the authorities. However, some companies do set such requirements. Quality of training conducted on board on the different scenarios which might lead to a loss of position varies. Common practice is to have table top exercises. They contribute to making the operator more risk aware, but they are not very realistic and do not allow for hands on experience. Furthermore, not all operators have experienced a loss of position. Realistic training, with for example a simulator, could improve operators to detect loss of position earlier, diagnose it correctly and improve decision making by strengthening the mental model that operators have of the DP system and DP operations. Since there is quite a bit of variance in the levels of experience and training, the HEP for the PSF is evaluated to have a low to moderate negative effect on performance and is based on the minimum requirements for experience and training of DPOs, with a multiplier of 5 or 15 respectively, in accordance with Petro-HRA [26].

Procedures
Since there is not much time available to the operator to intervene in case of a potential loss of position scenarios a very schematic procedure is used for most DP operations, the operating guidelines. These guidelines are operation, vessel, and field specific, and can be used as a decision support tool. Predefined parameters indicate which actions to take based on the status of the operation, vessel, or environmental forces. A risk analysis should be at the foundation of the operating guidelines and set parameters. These guidelines are also integrated in the training of the DP operators. Not all DP operations have or utilise these guidelines. The HEP multiplier for this PSF is therefore overall evaluated to be 1, in accordance with Petro-HRA [26], the quality of the procedures is adequate and they are followed.

Human machine interface
The HMI of the operators could be considered flawed in some ways. There are often problems with alarms, alarm floods and alarm lists. As a consequence, critical information can get buried by consequence alarms making it very difficult to diagnose the situation. In some cases, the DPCCS makes wrong decisions based on wrong input information or is not able to process information input and the causes and consequences of this might be difficult to infer from the HMI. These problems could have even bigger consequence if higher levels of automation are introduced. Then the operator is even more

reliant on the information she/he is able to gather from the HMI to diagnose the situation and decide on a course of action. In emergency situations where the operator is trying to prevent a loss of position it is important that the most critical information is easily available, based on the current HMI the operator has to, in some cases, navigate through several pages to obtain the necessary information. These characteristics are considered by the Petro-HRA method [26] to have a very high negative effect on the HEP, with a multiplier of 50.

Attitudes to safety, work and management support

On the NCS there is generally a positive attitude towards safety, work and there is management support, as well. Also on the NCS there are financial and time pressures that take the focus away from safety. In the current cost cutting climate the time and financial pressures are increasing. Also, some tensions exist between contractors and subcontractors about priorities, where subcontractors are pressured to do things quickly which might lead to some corners being cut. These are of course general evaluations and exceptions might exist. On average therefore the PSF is evaluated to have a moderate negative effect on the HEP, with a multiplier of 10, in accordance with Petro-HRA [26].

Teamwork

For most DP operations on the NCS within the 500-meter safety zone, there are at least two operators on the bridge or central control room, where the DP control system is located. In case of abnormal situations, the two operators are able to support each other and diagnose the situation together, as well as deciding on how to intervene. If there is sufficient time available they will call in extra support from a first officer or the captain, if they are not already present. Teamwork can generally be considered adequate or even very good. This PSF would therefore be considered nominal and have no effect or even a decreasing effect on the HEP, with a multiplier of 1 (nominal) or 0.5 low positive effect on performance, in accordance with Petro-HRA [26].

External working environment

The direct working environment of the operator on the bridge or central control room on vessels operating on the NCS is generally good and does not influence performance of the operator. The multiplier for the PSF is therefore evaluated as nominal (= 1), in accordance with Petro-HRA [26].

Conclusion

The conservative HEP is

$$HFE_{loss\ of\ position} = 0.01\ x\ 50\ (PSF_{time})x\ 25(PSF_{threat\ stress})x\ 1\ \left(PSF_{task\ complexity}\right)x\ 15\ \left(PSF_{experience/training}\right)x\ 1\ \left(PSF_{procedures}\right)x\ 50\ (PSF_{hmi})x\ 10\ (PSF_{attitudes})x\ 0.5\ (PSF_{teamwork})x\ 1\ \left(PSF_{external\ working\ environment}\right) = 46875$$

The above results, which obviously is>1, implies that a human operator cannot be seen as a barrier to prevent or recover a loss of position, i.e., low human reliability, because the error probability is 1.

Even though the HEP for the HFE to prevent loss of position is very conservative and only considered on a general industry level and a thorough analysis of a specific case could yield more detailed results, some trends can be seen in the PSFs affecting the HEP. The HEP is mainly affected by time, threat stress, experience/training, HMI and attitudes towards safety, work and management support. These PSFs have high multipliers that have a negative effect on the human reliability during DP operations. The PSF teamwork has a moderately positive effect on the human reliability. Furthermore, the PSFs task complexity, procedures, and external working environment have a nominal effect. The results of the HRA in this article are mainly qualitative, however, they do shed light on the problems that may have arisen due to the current allocation of function, for example, time available, experience and training and HMI. Also, the HEP values help prioritize the importance of the different PSFs and give an indication of the potential average HEP for s loss of position event within the oil and gas industry on the NCS.

Time available for the operator to respond is determined by the level of automation. The system is supposed to maintain position, until due to circumstances it no longer can. This leaves an operator with very little time to respond. Due to the reliability of the system not all operators have experience with handling a drive off or drift off scenario and with the lack of realistic training they also do not have the opportunity to practice these scenarios in a safe setting. The HMI does not support the operator because the automation has become too much of a black box, so there is insufficient flow and transparent information presented to the operator to be able to monitor the situation optimally. Furthermore, the HRA and identified PSFs also can help identify ways to improve human reliability.

5. DISCUSSION

5.1 Automation vs. human operator performance

The current allocation of function and control in a DP system has had several consequences for the operation and performance of the operator. The tasks allocated to machines are considered to be predominately better performed by machines than humans. The perception, speed and power, replication, and computation required for the tasks of maintaining position are generally performed better by machines. However, they are also characterized by the need for judgement, which is typically better performed by humans. The system addresses judgement with predetermined logic. Sometimes this logic falls short, because the situation has not been anticipated by the designer, and this is why there is a DPO in the first place. The DPO forms a last barrier to prevent a loss of position or to mitigate the consequences of a loss of position. Based on the evaluation of tasks with the updated Fitts' list it appears that the allocation utilizes the strengths of the chosen controller, human and/or computer. However, safety and reliability are never just the sum of its components. It should be viewed in a system setting, which is evident from the results from the Petro-HRA study conducted in this article and the accident statistics from the industry.

5.2 Human error probability in DP operations

Based on the analysis, the HEP of the performance of the DPO is mainly negatively affected by the time available to the operator to respond, the perceived threat stress of the situation, the experience level and quality of training of the operators, the quality of the HMI, and the attitudes towards safety, work and management support. The time available for the operators is reduced by the level of automation, as well as the operational use of the technology. The operator is necessary to handle situations that are too complex to be anticipated or modelled by designers and is designated as a barrier to prevent serious accidents with major consequences from happening. These situational factors impact the reliability of the performance of the operator by inducing extra stress. Furthermore, there are few prescriptive regulations and standards that address requirements for training, experience and HMI. The few that do exist are either not mandatory to follow or seems insufficient to support reliable performance of the operators. The industry is currently really feeling the economic pressures and that affects the attitudes towards safety, work and management support.

Another PSF that is identified in this article to have a high HEP for the HFE loss of position is time available. Some operations require position keeping with very narrow footprints. If the DP system is compromised or the environmental conditions are more severe than expected, the DPO has only seconds to respond to the emergency. Operating conditions should be reconsidered, it cannot be expected from a human operator to respond that quickly. This article therefore recommends to either refrain from DP operations where inhuman response times are expected, or additional technological measures should be implemented in terms of automated responses to drift off and drive off scenarios.

5.3 Allocation of function and control – impact on current operations

Nonetheless, the current allocation of function and control has enabled operations in more challenging environments where anchor line mooring is not an option or not economical. A DPO would also not be able to maintain position with the same level of precision, or over long periods of time if directly steering the thrusters. Since the DP operation is relying on automation to execute the function of maintaining position, constant judgements and corrections to position need to be made by the system. The DPO is still in place to monitor the performance of the system and make changes in the set-up where and when necessary and intervene when the system is no longer performing according to the operating limits. This makes the role of the DPO passive and in absence of disturbances or need for changes, as is characteristic of the DP system, it is boring. Often, one person is dedicated to monitoring the DP system and does that, with few additional tasks, typically for six hours straight, or even for an entire twelve-hour shift. Depending on the type of vessel, size of the crew, and shift arrangements, the DPO may have other tasks after those six hours, either on the bridge or on other areas of the vessel. This, combined with the required vigilance over longer periods of time, makes the job monotonically, but demanding. Especially, since the DPO needs to be able to respond to abnormal situations in a matter of minutes or even seconds. Judging whether this job is satisfying will differ from person to person, but what is clear is that this job is not for everyone.

As Endsley and Jones [3] pointed out, automation can lead to boredom and the operator may be “out-of-the-loop” when they have to respond to emergency situations. The change in workload from low to high makes the operator more error-prone. Especially, when this is combined with information overload, which is characteristic for emergency situations where several alarms tend to go off at the same time. The human operator has been given the job of monitoring and responding to abnormal system states with little time available, information overload, and high consequences which humans are known to be bad at. Initiatives are being developed by the industry to address the information overload by extracting the most relevant alarms and presenting them separately to the operators [27].

Failure scenarios where loss of position occurs, are characterised by being unexpected, because they have not been foreseen by the designers of the automation. Moreover, the DP systems is reliable, which tends to make operators trusting and over-reliant on the system [28, 29]. A certain level of trust is necessary for the automation and technology to be accepted by operators [2]. However, when the automation brings about levels of trust, which are undeserved this can lead to complacency and a degraded monitoring performance [29, 2]. This reduces their system understanding and makes them often even more “out-of-the-loop” [30]. This is further effected by the complexity of the automated system [3]. The human reliability for these emergency actions is therefore relatively low, due to the already limited time available to respond and the perceived threat stress.

5.4 Function allocation and impact on future HMI designs

Despite the challenges with the balance between automation and operator control, the current allocation of function and control with the automation is necessary for the vessels to operate in certain environments. The reliability of the DP system is high. Statistics from 1993-2009 show a frequency of loss of position of 2.9E-05 per DP hour for DP 2 and 3 Classed vessels [24]. However, some DP operations, for example FPSO-ST operations, are reported to have accident and incident frequencies that exceed the acceptance criteria [9, 10]. The causes of these accidents and incidents were found to be a combination of human and technical failure, meaning, in some cases, that operators were not able to recover the situation when position was lost. To enable the operators to better respond to these types of events, the situation awareness of operators needs to be increased and they need to be kept “in-the-loop”, enabling them to detect potential loss of position scenarios earlier and to respond faster. Currently, the DP system is perceived by operators too much as a black-box, where the DPCCS transforms a lot of the input data so that it is not always possible for the DPO to anticipate how the system will respond to changes in settings or environment. In other words, their mental model is incomplete.

The existing literature proposes several ways to combat the loss of situation awareness during monitoring of automated systems. Ecological interface design, as mentioned earlier, has had positive results in improving performance of operators handling unforeseen and unanticipated situations. Ecological displays enable operators to become active problem solvers instead of passive monitors [31]. An ecological interaction design could support the mental model of the DPO by providing information on the system states more clearly, making knowledge-based behaviour easier. For example, clearly indicated operating guideline limits for the most important operational parameters on the HMI, clear information on system state, clear and easily available information on alarm state and alarm history, risk trends to help predict the development of the situation. Another example of such a suggestion is adaptive automation. Adaptive automation allocates control from the computer back to the human operator based on a predetermined factor, such as time interval, occurrence of critical events or physiological parameters. The intention of adaptive automation is to reduce complacency and improve monitoring performance [32, 33]. Studies on the effects of adaptive automation on situation awareness and workload have been positive [34, 35]. The DPO already has the possibility to take back control of function by selecting a different DP mode. However, in common practice this change is mainly warranted by the DP system not being able to maintain position, and not by other parameters, such as time intervals or physiological indicators (e.g., heart rate, pupil dilation).

5.5 Human reliability analysis – the impact on human factors engineering and design

Furthermore, it is paramount that human reliability is considered during the design of the level of automation of the DP system. This is especially true taking into consideration developments within the maritime industry with unmanned automated vessels. The results from the Petro-HRA have shown serious concerns regarding the HMI of the DP system, with often having to click through several screens to get relevant information and alarm floods that make it very difficult to diagnose a potential emergency situation correctly. Possible ways to address these issues are user centred design and an alarm review.

An HRA can give essential insights into potential operational challenges for human factors engineering and engineering in general at an early stage. The current study has shown existing issues within the industry with available time, threat stress, experience/training, HMI, and attitudes towards safety, work and support from management. Some of these issues are more easily addressed than others, more realistic training and stricter requirements for experience levels could be realised with simulator training and changes in company practices. Others require more time, and perhaps even further advances in technology. However, it is clear that the strengths and limitations of operators, either present on the vessel or on a remote location, need to be taken into account during the design and planning phase so automation best supports overall reliability of the operation, not just the system.

5.6 Limitations of the study

The allocation of function study in this article has mainly focused on the thruster system within the DP system, although parts of the other systems were also mentioned. As a consequence of this limitation findings from the study cannot be directly generalized to the system as a whole. Furthermore, the study is limited by considering DP operations in general and some specifics regarding certain DP operations could influence the results. The assumptions made in this analysis needs to be tested for specific cases, and results cannot be directly transferred. As mentioned previously, a stakeholder analysis was not included as part of the allocation of function analysis; adding this element could provide a more holistic insight into the requirements for the allocation of function within the DP system. The HRA performed for this study has focused on the HFE loss of position, and used information from the oil and gas industry on the NCS in general. For more detailed results an HRA should be performed for a specific case. Then the HEP can provide even more insights into the human contribution to the total risk picture.

6. CONCLUSION

This article presents a method that can be used to facilitate high human operator reliability during DP operations, combining an analysis of function allocation for system control with human reliability analysis. In the current allocation of function and control of the DP system, the situation awareness and system understanding of the DPO is compromised. The DPO is tasked with monitoring a highly automated and complex system which leaves the DPO "out-of-the-loop". Yet, the operator is asked to intervene when the DP system is failing in ways unforeseen by designers often with little time available. These contextual factors compromise human reliability and increase the risk of human error.

To improve the situation awareness of the DPOs, this article suggests making the logic behind the DPCSS more transparent utilizing ecological-interface design, and to visualise the risk trends more clearly during operations. These measures should support the operator in detecting deviations early on and give them more time to prevent loss of position. This could be part of the online risk framework, as proposed by Vinnem, Utne and Schjølberg [10]. Future work should also focus on visualising risk trends of DP operations and making the workings of the DPCCS more transparent to the DPOs.

List of abbreviations

DP	Dynamic Positioning
DPCCS	Dynamic Positioning Computer Control System
DPO	Dynamic Positioning Operator
DSHA	Defined Situation, Hazard and Accident
EID	Ecological Interface Design
FPSO	Floating Production, Storage and Offloading
GPS	Global Positioning System
HEP	Human Error Probability
HFE	Human Failure Event
HMI	Human Machine Interface
HRA	Human Reliability Analysis
IMO	International Maritime Organization
NCS	Norwegian Continental Shelf
OIM	Offshore Installation Manager
PMS	Power Management System
PSF	Performance Shaping Factor
RPM	Rates per Minute
ST	Shuttle Tanker

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