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**RISK**

# Safety of Dynamic Positioning Operation on Mobile Offshore Drilling Units

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## ABSTRACT

Safety of dynamic positioning operation on mobile offshore drilling units is characterized by two key parameters, namely, the resistance to loss of position, and the robustness of recovery. Both parameters should be evaluated in order to identify effective ways to further improve the safety. The failure modes, applicable frequencies, and probabilistic modeling for both loss of position and recovery are discussed in this paper. Influencing factors to the resistance and robustness parameters are identified respectively. The results contribute to the further development of the safety assessment methodology for DP operation on drilling units. Areas that need further development of modeling approach and analyses are pointed out.

## ABBREVIATIONS

| | |
|---|---|
| ALARP | As Low As Reasonably Practicable |
| BOP | Blowout Preventer |
| DP | Dynamic Positioning |
| ECR | Engine Control Room |
| EQD | Emergency Quick Disconnect |
| FMEA | Failure Modes and Effect Analysis |
| HMI | Human-Machine Interface |
| IMCA | International Marine Contractor Association |
| IMO | International Maritime Organization |
| LMRP | Lower Marine Riser Package |
| MODU | Mobile Offshore Drilling Units |
| NCS | Norwegian Continental Shelf |
| NPD | Norwegian Petroleum Directorate |
| NTNU | Norwegian University of Science and Technology |
| OIM | Offshore Installation Manager |
| QRA | Quantitative Risk Assessment |

## 1 INTRODUCTION

With more and more oil and gas fields developed in deep and harsh waters, safe and reliable positioning operations on floating offshore installations become more and more important. The dynamic positioning operation on mobile offshore drilling units, which is termed as DP drilling operation in this paper, is a typical example. Basically, the dynamic positioning operation for a DP drilling unit in harsh waters is demanding. In an event of loss of position, a DP drilling unit must be able to shut in the well and disconnect the riser in time. Failure to disconnect may result in damaged riser, wellhead or BOP, and in worst case an uncontrolled subsea blowout. Collisions with other installations in the vicinity may also be applicable if in congested waters.

The Norwegian Petroleum Directorate (NPD) published a study of the risk level development on the Norwegian Continental Shelf (NCS) [1]. One of the recommendations from the report to the offshore industry is to improve the safety of dynamic positioning (DP) operations, and especially the DP drilling operations.

The DP operation generally involves a human-machine system, including at least the following: DP control system, reference system, power system, thruster system, and DP key personnel (see Figure 1). To improve the safety of DP operation thus requires that all major elements in this human-machine system be taken into account. This requires that safety modeling and analyses should include not only technical system failures (e.g. covered by DP system FMEA studies), but also human operational failures, and interactions between these two types of failures.

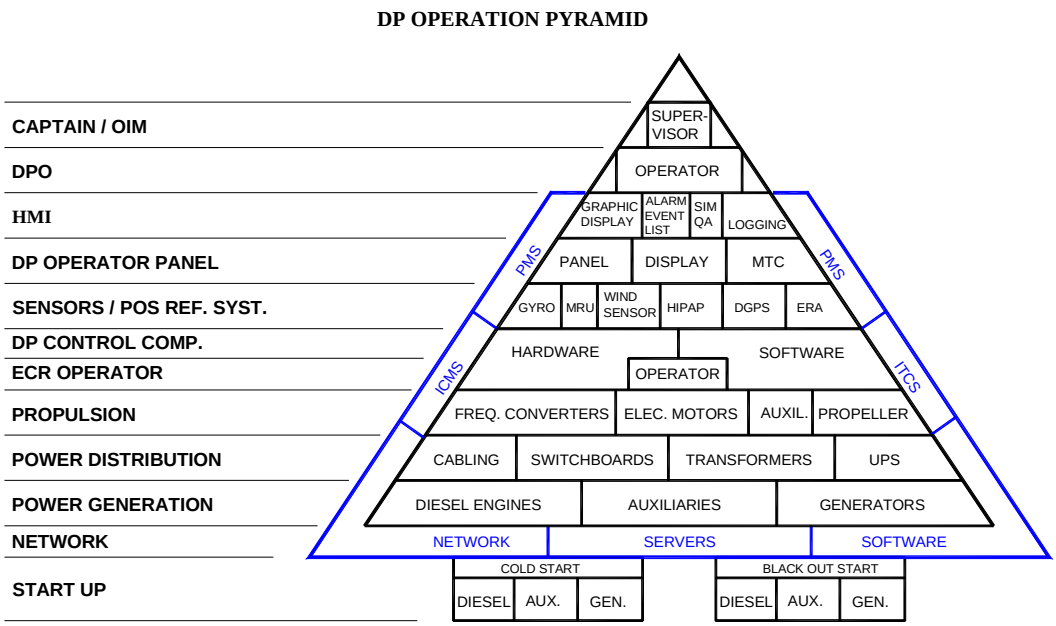


Figure 1: Major Elements in DP Operation

There has been limited risk modeling work carried out to meet the above requirement. Most studies on the safety of DP operation have been concentrated on DP technical system failures. Consequently, risk control and reduction measures address mainly the technological improvements. This may be effective at one time, but given the significant improvement of DP technology in recent years, there is a need to search potential improvements from a broader perspective, which particularly should take human and organizational contributions into account.

The operational facts tell us that DP vessels loss of position during operation is not rare. The IMCA DP incident data suggest a frequency of loss of position in the order of 10-5 per DP hour, or 10-1 - 10-2 per vessel year [2]. In addition, DP operators, and recently DP computers, are seen on top of the primary cause list. We have to note that the above frequency represents DP vessels in general, and it may not be fully applicable to a DP class 3 drilling units. However, the data nonetheless demonstrate that the safety of DP operation generally deserves concern, and human (and organizational) contributions are important. These will be particularly true for the DP drilling units, given the potential serious consequences from failure of DP operation.

A research study on the safety of DP operation has been initiated by the Centre for Ships and Ocean Structures at NTNU since August 2003. In the meantime, the Norwegian Shipowners' Association's group of drilling contractors have also initiated efforts on improving the safety of DP drilling operation since September 2003. The two initiatives were united in November 2003 into a joint research study. The objectives of this joint research study are to:

- Develop an applicable operational safety modeling methodology for DP drilling operation.
- Collect operational data and perform case studies by the proposed methodology.
- Identify feasible and effective measures to further improve the safety of DP drilling operation on the NCS.

This paper presents the results focusing on the methodology development in this research study. The contents are structured as follows.

A probabilistic model for analyzing failure of DP drilling operation is presented in Chapter 2. In the light of this model, the research work is focused on the two key parameters that characterize the safety of DP drilling operation, i.e. resistance to loss of position, and robustness of recovery. The resistance to loss of position for DP drilling units is discussed in Chapter 3. The loss of position incidents are modeled in a human machine interaction perspective. Factors that influence the resistance to loss of position are identified and discussed. The robustness of recovery during loss of position for DP drilling units is discussed in Chapter 4. In most cases recovery efforts are carried out by human operators. Actual recovery actions are identified, and failure of recovery is discussed. Factors that influence the robustness of recovery are identified. In the end, conclusions and future work are summarized in Chapter 5.

## 2 METHODOLOGY

A probabilistic model for safety of DP drilling operation is proposed. This model is largely adapted from the previous model used in the DP shuttle tanker tandem loading study [3]. The model is presented in Eq. 1 below.

$$P(\text{Accident}) = P(\text{Failure of Recovery} \mid \text{LOP}) \times P(\text{LOP}) \quad (1)$$

where:

$P(\text{Accident})$ is the probability of accident. This is operational specific in DP drilling operation. Loss of rig position may lead to disconnection of the LMRP and loss of time, or damage of marine riser, or a blowout in the worst case. Collision with other installations in the vicinity may also be possible in congested waters.

$P(\text{LOP})$ is the probability of a DP drilling unit loss of position. There are three basic types of DP vessel loss of position, namely drive-off, drift-off and force-off.

$P(\text{Failure of Recovery} \mid \text{LOP})$ is the probability of failure of recovery given loss of position. When a DP drilling unit loses its position, there will be DP key personnel together with drillers, or some automatic devices (e.g. Auto EQD), that take actions to prevent damage of well.

The analytical steps according to the above model are explained below. The work starts with the identification of various loss of position scenario. For each scenario, analyses are carried out in the following two stages:

- the initiating stage
- the recovery stage

In the initiating stage, cause analysis of the identified scenarios is carried out. The loss of position may be initiated from external condition, e.g. excessive weather, or various technical and operational failures. The event paths that may lead to the scenario are modeled and the probability of the scenario is quantified. The results from analyses in the initiating stage may be represented by a parameter called Resistance to Loss of Position. It characterizes the capability of a DP vessel to resist the occurrence of position loss.

In the recovery stage, recovery analysis is carried out to model the development of scenarios and assess the system's recovery ability. The successful recovery will depend on operators, technical system, and the field configuration, e.g. the water depth (which influences how much recovery time the operators will

have). The results from analyses in the recovery stage may be represented by a parameter called Robustness of Recovery. It characterizes the capability of the joint human-machine system on a DP drilling unit to successfully avoid accidents given loss of position scenarios.

After completing the analyses, the safety of DP drilling operation, which is characterized by the two fore-mentioned parameters, can be illustrated by a diagram as shown in Figure 2. The similar principle has been applied for evaluating the safety of tandem offloading operation by DP shuttle tankers [4]. The safety levels of various DP rigs are exemplified in the figure.

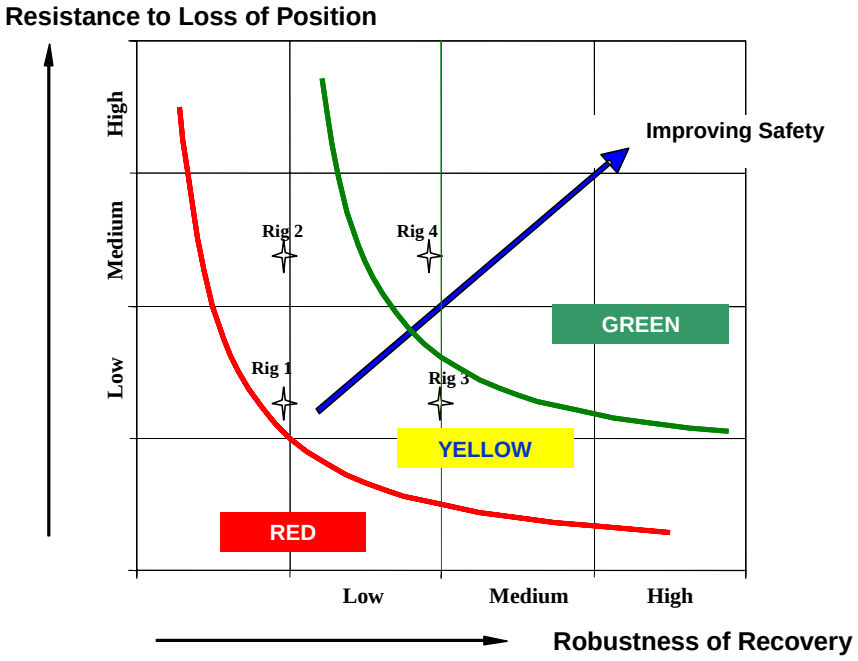


Figure 2: DP Drilling Operational Safety Diagram

The safety diagram has two limit curves indicating the acceptable and preferable safety levels of DP drilling operation. The curves are theoretically determined based on Eq. 1. Each curve indicates the same safety level along itself. The low, medium and high values of "resistance to loss of position" and "robustness of recovery" are determined by taking into account of a number of influencing factors. These factors are discussed in detail in Ch. 3 and Ch. 4.

The safety diagram is able to indicate the safety level variations for the same DP drilling vessel/rig. Change of operational condition, change of competent crew, install new technical equipment, etc., all may have positive or negative influence on the safety level. For example, when the rig moves from deep water to shallow water, the time for successful manual EQD will be significant constrained. Given the same crew competence, robustness of recovery is degraded which ultimately reduces the safety level.

The safety diagram can also be used to assess and compare the safety level among various DP drilling vessel/rigs. The safety level of DP drilling operation by rig which is located in the RED region (area between two axes and red hyperbola) may be viewed as not acceptable. Similarly, the YELLOW region (area between red and green hyperbola) in the figure may indicate that safety level should be further improved in an ALARP context. The GREEN region in the figure implies that the safety level of DP drilling operation is satisfactory.

The safety diagram will help to identify the most effective ways to improve the safety of DP drilling operation. This is exemplified in the figure from Rig 1 to Rig 4 by improving both parameters. For Rig 2, measures to increase the robustness of recovery will be the most effective. Similarly for Rig 3, efforts should target on increasing the resistance to loss of position. Risk reduction measures can be identified and evaluated during the detailed modeling and analyses of the resistance and robustness parameters.

## 3 RESISTANCE TO LOSS OF POSITION

### 3.1 Failure Modes and Frequencies

There are three basic failure modes of loss of position, namely drive-off, drift-off, and force-off. The definitions are given below.

Drive-off: Failures onboard of MODU resulting in active thruster forces driving the MODU away from its target position. The drive-off may involve, false position information, DP control failures, thruster failures, and operator errors as primary or secondary causes.

Drift-off: Failures onboard of MODU resulting in deficiency of thruster forces in relation to the environmental forces, e.g. partly or total blackout. The MODU is drifted off position due to insufficient thruster forces.

Force-off: No failures onboard of MODU, but due to sudden change in environmental conditions, the MODU is operating outside its capability envelope and is forced off position due to insufficient thruster forces.

In 1998, Deegan [5] stated that “The frequency (of loss of position) is one of the areas of the greatest uncertainty because of the lack of good quality data associated with DP drilling vessels”. This problem remains now.

The IMCA DP incident database is by far the most completed one to the industry. Relatively high frequencies of loss of position per DP vessel year are observed. However we may also note that the majority of DP vessels in the database are not related to DP drilling operation. For example, the DP drilling units account for only 5% of DP vessel population in the database in year 2001 [2]. If the IMCA data are used for assessing the historical frequency of loss of position for DP drilling units, the applicable incident numbers and exposure time have to be derived. These are not available from the database at present.

Further data collection work is needed in order to derive the historical frequencies of loss of position for DP drilling units. One of the tasks in this research project is to collect the exposure time and incident records for each DP drilling unit on the NCS (or those that had once been operated in this region). However at the time of writing this paper, these results are not yet available.

### 3.2 Probabilistic Modeling

Given the human-machine interaction nature, to effectively increase the resistance to loss of position, a broad range of preventive measures, which target on, for example, hardware, software, operational procedures, and other individual or organizational factors, should be considered. To identify these measures requires that a model of loss of position should be set up. The model has to be made as complete as possible. This is because we will not be able to identify measures to increase the resistance to loss of position in those areas that are basically excluded in the modeling.

Attempt has been made to set up a probabilistic model for loss of position. This model is discussed below. Assume $P(TF_j)$ is the probability of technical failure event j. The possible technical failure events in the model may cover, for example, failure of the following main systems and their sub-systems:

- power and electrical systems
- thruster system
- DP software, hardware and data network
- position reference system and vessel sensors

This is the area where modeling has been extensively developed, e.g. in offshore QRA or FMEA studies. The human actions and their interaction with technical failure events, based on occurred DP incidents, can be categorized into the following three categories:

1. Initiating action - an action itself is able to initiate vessel loss of position.
2. Response action - an action responds to meet system demands, typically under technical failure events or special external situations. It may save or worsen the situation or cause a transition to another event.
3. Latent action – an action influences (but does not directly initiate) the technical failure and the above two types of human actions.

Assume $P(AI_i)$ is the probability of human initiating action i, which can directly initiate a loss of position scenario. It is modeled by $P(LOP_1)$ in Eq.2. Similarly, $P(AR_k \mid TF_j)$ is the probability of human response action k conditioned on technical failure j. Its contribution to a loss of position scenario is modeled by $P(LOP_2)$ in Eq. 2.

In DP FMEA analysis, the human operator is not addressed [6]. Some of the human actions may be modeled in offshore QRA studies. For example, by setting the node such as "operator error causing loss of position" in fault tree and quantifying its frequency. However, the modeling of human actions in general is not mature, and has not been carried out systematically in the light of Eq. 2. And moreover, Eq. 2 is not yet a complete model, since the latent human action has not been included.

$$P(LOP_1) = \sum_i P(LOP \mid AI_i) \times P(AI_i)$$
$$P(LOP_2) = \sum_j \sum_k P(LOP \mid AR_k, TF_j) \times P(AR_k \mid TF_j) \times P(TF_j) \qquad (2)$$

where:

$P(LOP \mid AI_i)$ is the probability of loss of position conditioned on human initiating action i.

$P(LOP \mid AR_k, TF_j)$ is the probability of loss of position conditioned on human response action k and technical failure j.

The latent human action has a vast span in terms of time and contents. It may occur in design, construction, installation, operation and/or maintenance. It may interact not only with technical failure, but also with the other two types of human actions. In isolation, it may not be enough to initiate an event, and subsequently it can lie in the system for a long time before it strikes. Modeling of the latent action therefore has to include the organization, i.e. we have to not only consider front-line operators, but also include maintenance personnel, management teams, company safety culture, and so on.

Further work is needed to set up a complete probabilistic model which includes latent human actions. Other modeling approach, i.e. risk influence analysis [7], will also be evaluated in this study. The goal after modeling and analyses is to obtain the following results:

- factors that influence the resistance to loss of position and their contributions
- measures to improve the resistance to loss of position and their gains.

## 3.3 Influencing Factors

Based on the current incomplete modeling, attempt has been made to identify the factors that somehow reflect the status of resistance to loss of position, or have certain influence on. These factors are grouped into the following three categories. Efforts to improve the resistance to loss of position should consider at least these factors.

- Environmental conditions
- DP system
- DP key personnel

Environmental Condition

Environmental condition, i.e. wind, wave, and current, directly influences DP vessels' resistance to loss of position. Severity of the weather (wind speed, significant wave height), possibility of sudden change of wind/current direction, possibility of certain atmospheric condition that influence GPS (scintillation phenomena), these are at least the factors to evaluate.

DP System

The primary factor within the DP system that influences or represents a DP vessel's resistance to loss of position is the DP class. According to the IMO DP equipment class [8], it states:

| | |
|---|---|
| Equipment class 1 | loss of position may occur in the event of a single fault. |
| Equipment class 2 | loss of position should not occur from a single fault of an active component or system, including a single inadvertent human action. |
| Equipment class 3 | loss of position should not occur from any single fault of an active component or system, any single failure of a static component, any single inadvertent act, fire in any one fire sub-division or flooding of any one watertight compartment. |

Given similar conditions of environment and DP key personnel, a DP class 3 vessel has better resistance to loss of position than a DP class 1 or 2 vessel. Note that the DP class 3 is a mandatory requirement from NPD for DP drilling and well activities on the NCS [9]. This implies that it is the DP class 3 units (with open bus-bar) that are considered in this study.

The DP vessel's station-keeping capability is another influence factor. This factor is reflected by:

- DP capability plots
- Power generation and consumption
- Thruster output.

Concerning the loss of position scenarios, the characteristics of DP control system, and status of position reference systems have dominant contributions. The status of vessel sensors is also relevant. The influencing factors are:

- DP control system (including DP software, hardware, and data network)
- Position reference systems
- Vessel sensors

DP Key Personnel

Human actions from DP key personnel may directly initiate a loss of position scenario, or interact with technical failure events which then contribute to a loss of position scenario. The following factors are considered to have influence on these two types of human actions.

Competence
- Training
- Certification
- Operational experience
- Knowledge about system onboard

Attention level
- Job attitude
- External/internal distractions

Communication and team work

Lack of competence, or lack of knowledge about system onboard, may lead to operator a) acts with wrong expectation of technical system function, or b) improper use of technical system, e.g. erroneous selection of position reference, or c) makes wrong assessment of internal and external situation, e.g. weather criteria and vessel positioning capability.

If operator is distracted, or have a bad job attitude, he may temporarily lack attention. For example, a DP operator was distracted when operating the vessel in joystick mode, and loss of position was resulted.
The communication and team work among DP key personnel belong to the organizational level, and their influence is more on latent human action. Further work is needed to model the latent human action and identify influencing factors.

## 4 ROBUSTNESS OF RECOVERY

### 4.1 Probabilistic Modeling

The recovery is, in most cases, the response actions taken by the DP operator in a loss of position scenario. The probabilistic model involving recovery can in principle be written as:

$$P(\text{Accident}) = \sum_i \sum_j P(\text{Accident} \mid AR_j, LOP_i) \times P(AR_j \mid LOP_i) \times P(LOP_i) \qquad (3)$$

where:

$P(LOP_i)$ is the probability of a loss of position scenario i.

$P(AR_j \mid LOP_i)$ is the probability of operator's recovery action j which is time dependent, and it is conditioned on loss of position scenario i.

$P(\text{Accident} \mid AR_j,\ LOP_i)$ is the probability of accident (e.g. blowout, collision) conditioned on loss of position scenario i and operator's recovery action j

To assess the failure of recovery, the following two questions need to be answered:

1. What are the possible recovery actions in loss of position scenarios, i.e. $P(AR_j \mid LOP_i)$?
2. What is the likelihood that these actions prevent accident, i.e. $P(\text{Accident} \mid AR_j,\ LOP_i)$?

If there is an automatic technical system to perform the recovery action, then the failure probability of recovery will consist of only one term, which is the probability of this automatic technical system failure

on demand. The robustness of recovery will then depend on the reliability of this automatic technical system, which further depends on the design, commission, testing, maintenance, and other possible factors.

The following discussions are concentrated on the recovery that human operators are involved. This is after all the majority case, and for some recovery actions such as maneuvering the vessel to avoid collision targets, apparently no technical system can replace the human operator during the recovery.

## 4.2 Recovery Actions

When a DP vessel/rig loses its position and moves away from the desired position, the riser angles at the bottom and at the moon pool will increase. At some point, usually 8-10°, the lower or up flex joints can not rotate any further. Then, as the vessel/rig continues to move away, the riser or BOP may be damaged; the riser may fail, or the wellhead may be pulled over.

To ensure the safety of the well and equipment, the well must be shut in and the riser must be disconnected in the time it takes for the vessel/rig to move from its normal operating position to the offset at which damage may occur [10]. The recovery in this perspective is to initiate the Emergency Quick Disconnect (EQD) within the allowable offset (or equivalently the allowable time).

Automatic technical system, i.e. Auto EQD triggered by the DP system upon loss of position, has been implemented for a DP rig in shallow water drilling operation on the NCS. However, on other DP drilling units worldwide, EQD is initiated by driller upon receiving red status alarm from DP operator, i.e. manual EQD by driller and DP operator.

A DP drilling unit in loss of position scenarios may pose collision threat to other installations in the vicinity, or the LMRP underneath may collide with subsea equipment or sea bottom. The recovery in this perspective is to avoid surface and/or subsea collisions. The actual recovery efforts vary among various loss of position scenarios. For example, efforts to stop the vessel or steer it away from the potential collision target may be carried out in a drive-off scenario. While efforts to re-gain vessel propulsion power, or to set up emergency towing may be carried out in a drift-off scenario. It appears that no automatic technical system can handle this type of recovery. DP key personnel are supposed to carry out the recovery actions.

Note that the recovery to avoid collision is not applicable to the case where there is no collision target. While to initiate EQD in time is generically applicable and in most cases more failure critical. The following evaluations are therefore concentrated on the failure of initiating EQD.

## 4.3 Failure of Recovery

The allowable time to initiate EQD is often very short. The time relationship may be expressed as:

$$\underline{\text{Total available time}} = \underline{\text{Time allowable to initiate EQD}} + \underline{\text{Time need for EQD process}} \quad (4)$$

The total available time is determined by the allowable offset and the speed of vessel/rig in loss of position scenarios.

The allowable offset is determined by water depth and riser lower/upper flex joint angle limitation. Shallow water (below 400-500 m) will have an allowable offset which is much smaller than deep water. As an example, a standard drilling BOP and riser system may require that disconnect to be completed

before lower flex joint angle reaches 8°. Assume a linear relation (crude assumption) to the water depth 500 m, this gives a maximum 70 m allowable offset.

DP drilling units are typically designed with large capacity of propulsion. This implies that the vessel/rig will have high acceleration and high speed given a worst case scenario (e.g. a 100% drive-off). As an example based on Scandpower's in- house project experience, it may take a DP vessel about 70 s in average to move 70 m, given a 100 % drive-off condition.

We may assume that the time needed for the EQD process is within 30 s. Consequently, the allowable time; for DP operator to assess the situation and initiate red status alarm, and afterwards driller pushes EQD buttons, will be around 40 s.

Given the significant time pressure, the failure of recovery should firstly be addressed from the human action-time perspective[1].

There is basically little statistical data for human reaction time in this specific operational context. Literature survey found only one reference in [11], it states that it is generally assumed that it takes between 10 s and 72 s for the operator to be aware of the problem and start to take action.

The evaluation has often to be based on the expert judgment, which directly gives the probability of operator failure, e.g. 10%. The expert judgment makes the quantification of risk model possible. However, this approach may have the problem of consistency among different groups of experts. Further, quantification in the above manner provides limited information of where further risk reduction efforts should be targeted on.

Further work in this research project is to be based on a model of DP operator reaction in loss of position scenarios. The model is presented in Figure 3, and has been applied to analyze shuttle tanker DP operator reaction in drive-off scenarios during tandem offloading operation [3].

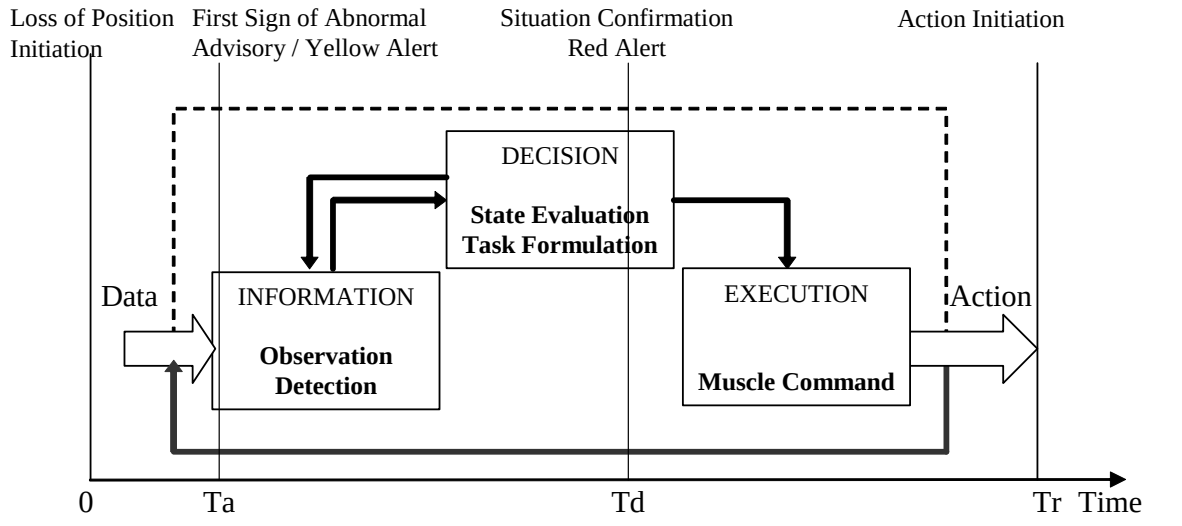


Figure 3: DP Operator Reaction Model in Loss of Position Scenarios

[1] Note that in deep and ultra-deep water, the allowable time may not be so critically short, i.e. in a range of minutes. In such case, there is generally enough time for operators to initiate EQD. The failure of recovery should therefore also be addressed from the human error perspective

Analyses based on this model will quantify the human reaction time, and identify a number of measures, e.g. alarm design, training, procedure, crew resource management, etc., to a) improve early detection and b) effectively reduce operator's time in diagnosis and situation awareness. These measures will ultimately improve the robustness of recovery.

### 4.4 Influencing Factors

Based on the above discussions of failure of recovery, factors that influence the robustness of recovery are identified. These factors are grouped into the following two categories. Efforts to improve the robustness of recovery should be targeted on these factors.

- Factors influence the allowable time for initiating EQD
- Factors influence the operator reaction time

Allowable Time

Factors that influence the allowable time to initiate EQD are listed below.

Total allowable offset
- Water depth
- Lower/up flex joint angle limitation

Offset-time relation - rig movement behavior
- Environmental condition (wind, wave, current)
- Failure modes of loss of position
- Rig propulsion characteristics
- Initial rig position and velocity when loss of position happens
- Any action from operator to change rig movement behavior

Time needed for EQD process

Operator Reaction Time

The operator reaction time is determined mainly by two time intervals, i.e. time used for detection, and time used for diagnosis and achieving situation awareness. A range of technical, human and organizational factors may influence.

Technical factors
- alarm designs, commissioning, and alarm limits setting in the operation
- human-machine interface design (i.e. whether relevant information concerning the state of the operation is made easily available to the operator)

Human factors
- attention level
- knowledge about system onboard
- competence, especially the ability to intervene emergency situations

Organizational factors
- emergency procedures
- communication and team work

## 5 CONCLUSIONS AND FUTURE WORK

A probabilistic model for safety of DP drilling operation is proposed. This model indicates that to effectively improve the safety of DP drilling operation, efforts should be targeted on the improvement of the two key parameters, i.e. resistance to loss of position, and robustness of recovery.

Drive-off, drift-off, and force-off are three basic failure modes for DP vessel loss of position. Though statistics imply relatively high frequencies of loss of position for DP vessels in general, it is found that

applicable frequencies for DP drilling operation need to be derived. Attempt has been made to model the loss of position in a human-machine interaction perspective. Through the incomplete model at present, factors that influence/indicate the resistance to loss of position are identified. Efforts to model and improve the resistance to loss of position should at least consider these factors.

Given vessel/rig loss of position, the recovery in DP drilling operation is, in the first place, to initiate the Emergency Quick Disconnect (EQD) within the allowable offset. The shallow water significantly limits the allowable offset, which poses significant time pressure on DP operator and driller, if the automatic EQD system is not in place. The failure of recovery is therefore mainly addressed in the human action-time perspective. Factors that influence the robustness of recovery are identified. Efforts to improve the robustness of recovery should be focused on these factors.

The research work presented in this paper is mainly on the development of safety assessment methodology for DP drilling operation. The results have provided a good starting point for further modeling and analyses, via which we will be able to identify feasible and effective measures to improve the safety of DP drilling operation on the NCS.

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