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Operational failure assessment of Remotely Operated Vehicle (ROV) in harsh offshore environments

Samson Nitonye[1], Sidum Adumene[2], Charles Ugochukwu Orji[1], Anietie Effiong Udo[3]

[1] Department of Marine Engineering, Rivers State University, Nkpolu-Oroworukwo PMB 5080 Port Harcourt, Nigeria, e-mail: nitonyesamson@ust.edu.ng
[2] Faculty of Engineering & Applied Science, Memorial University of Newfoundland, St. John's NL, Canada A1B 3X5
[3] Department of Marine Engineering and Naval Architecture, Akwa Ibom State University, PMB 1167 Uyo, Nigeria

ABSTRACT

For an effective integrity assessment of marine robotic in offshore environments, the elements' failure characteristics need to be understood. A structured probabilistic methodology is proposed for the operational failure assessment (OFA) characteristics of ROV. The first step is to assess the likely failure mode of the ROV system and its support systems. This captures the interaction and failure induced events during operation. The identified potential failure modes are further developed into logical connectivity based on the cause-effect relationship. The logical framework is modeled using the fault tree analysis technique to predict the ROV operational failure probability in an uncertain harsh environment. The fault tree analysis captured the logical relationship between the primary, intermediate, and top events probability. The importance measure criteria were adopted to identify the most probable events, links, and their importance on the failure propagation. The model was demonstrated with an ROV for deep arctic water subsea operations. The result identified the control system, communication linkages, human factor, among others, as most critical in the ROV operational failure. The methodology's application provides core information on the Mean time between failure (MTBF) of the ROV system that could aid integrity management and provides a guide on early remedial action against total failure.

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1 Introduction

The increasing oil and gas exploration in the remote harsh environment present safety challenges, such as frequent oil spills, system failure, and environmental toxification. Human and engineering systems performance in such terrain is limited due to harsh environmental factors. These factors include iceberg, extreme depth, extremely low temperature, geo-hazard, and remoteness. The limitations caused by extreme environmental factors have enhanced the development/application of robotic (ROV) technology for offshore operations in harsh environments, especially in the integrity management of critical subsea infrastructures.

The ROV technology has promoted research and safer conditioning monitoring of underwater and subsea facilities. For inspection-class ROV, which is commonly used for offshore facilities integrity management, it uses a surface user via an umbilical system [1]. This aid in providing feedback based on the video signal and transmits scientific data/information to the operator [2]. The operations of the vehicles are influenced by size. For instance, a larger ROV requires a Launching and Recovery System (LARS) and extra sensor. These additional elements may increase the cost and management of the vehicle. The sensor performance and the inspection ROVs' navigational ability play a critical role in the accuracy of the data gathering on the said infrastructure [3]. Research showed that the medium ROV had demonstrated accuracy in navigation and resolution imagining in subsea pipeline inspections [1], [4]. This was demonstrated in underwater mapping and geological surveys.

Further classification of the ROVs can be grouped into five classes, namely class I to class V, that differ by their specific operation. Offshore systems maintenance and repairs operations also employ the ROVs. They are complex systems incorporating electrical and mechanical assemblies, computing equipment and their associated systems, and various off-the-shelf components and accessories [5]. ROVs are controlled and monitored by an operator on board a surface ship or on a shore ground station (SGS). The control is sent through series of communication links called tether/ cable. Oftentimes reliability of the ROVs' communication systems is doubted [6],[5]. This is often experienced by the poor performance of the instructions given by the operator or through loss of signal from the ROV. Hence, it becomes imperative for a proper OFA of ROVs to ensure maximum productivity and service life prediction.

There are multifarious functions that enable the efficient and effective performance of ROV for maritime/ offshore operations which include the control system, coupling issues, under-actuated condition, pose recovery or station keeping, and communication linkages [6]. When any of the enablers is not functioning according to design conditions due to a harsh environment or system error, the functionality of ROV is diminished and cannot be relied upon. The consideration of the reliability factor of the design of the affected function(s) associated with the use of the communication between an ROV and an operator is known to be one of the main considerations in the design of ROV. The communication system performance is a core function for high efficiency and effective ROV operation in harsh offshore environments. The communication system deals with the rendering of video recording and pictures capturing, collecting environmental data, controlling the ROV motion, and performing tasks in the ocean environment. Mostly, loss of signal is one of the challenges accrued to ROVs maneuverability in deeper water operations. This has necessitated recent research works into improving the design and operational integrity of the ROV communication system. This improvement could be achieved through a risk-based assessment of critical subelements in the design of ROVs communication and operational systems. The need to ascertain the probability of failure on demand is vital in the risk-based design analysis of complex systems, such as the ROV [1],[3],[6],[7]. The ROV design's associated complexity needs to be understood and capture the interactions among subsystems further and identify common cause failure elements in the ROV structure. Chowdhury et al. [8] carried out a fractographic study of the ROV fastener and its effect on the system performance in harsh environment. Critical failure characteristics based on the material microstructure were established. Further subsystems failure analysis for ROV operations are detailed in the reference literature [4,9,10]. There is no comprehensive study that captured the interaction effects among the ROV's key elements for OFA in an extremely harsh environment. The cause-effect analysis could provide key information that will aid condition monitoring and integrity management of the ROV subsystems. Also, the need to understand the performance of the sensors and their survivability under harsh environments is pivotal to a holistic risk-based analysis. It is necessary to develop a robust probabilistic framework to investigate the failure of the ROV operations considering cause-effect relationships via a logical formalism.

The present study presents the application of a deductive graphical probabilistic model for the operational failure analysis of ROV in a harsh offshore environment. The model captures the underlying technical failure initiating events and their propagation to the complex system's total breakdown. To develop the logical framework, cause-effect assessments of the ROV subsystems and their interconnectivity is carried out to establish a robust methodology for failure probability prediction. Furthermore, the critical failure events of the ROV are identified via the importance measure analysis (IMA). The IMA employed the Birnbaum and Fussell-Vesely (BAF) measure based on the component performance at a set time and the characterized minimal cut sets. These measures help to identify the weak link and the probable failure of common causative factors in the complex ROV structure. The methodology provides key information on the failure characteristics and critical failure events of the ROV for integrity-related decision making.

2 Overview of ROV failure assessment

The complexity in the design and operation of the ROVs required a comprehensive understanding of the subsystems' state-of-the-art performance. Several approaches for failure assessment of ROV based on the subsystem's performance have been proposed. Generically, this is based on either a qualitative or quantitative analysis methodology or framework. Among the common approaches, the application of the Failure modes and Effects Analysis (FMEA), Failure modes Effects and Criticality Analysis (FMECA), Reliability Block Diagram (RBD), and fault tree has been highlighted in the literature [1],[3],[5],[7],[11],[12],[13]. For instance, Hu et al. [12] analyzed an autonomous underwater vehicle's reliability based on the FMEA and FMECA frameworks. The authors identify leakage, deformation, and brokenness as common failure modes and integrate the identified failure modes into a graphical structure for failure prediction using the fault tree mechanism. The likely failure influencing factors and their severity on the overall vehicle failure was captured.

Dickson [5] proposed the use of a design verification and product quantification performance (DV&PQP) tool for subsystems performance assurance criteria. The approach will aid in the FMEA based analysis from the design perspective. A proper diagnosis of the likely failure characteristic of the ROV subsystems from the design point will provide a significant advantage in the FMEA framework application in operation. For instance, the hydraulic pump design can be optimized via the multiple values configurations to aid recoverable failure modes at the design stage of the ROV. The applicability of the DV&PQP tool will help to determine the technical, quality, delivery capability, and failure of the ROV from design [5],[6]. Azis et al. [6] further identified critical failure modes and categorized them into control system failure, underactuated conditions, station keeping failure, coupling, and communication issues. The complexity of the non-linear hydrodynamic effects on the ROV operation complicates the control system of ROV, especially in a harsh ocean environment. The application of controllers to minimize the non-linear hydrodynamic impacts has not yielded much performance because of the environmental dynamics. A simple linear Quadratic Gaussian controller and complex control techniques have recently been integrated for control system failure mitigation. This includes the Simple Input Fuzzy Logic Controller (SIFLC) [6],[14]. The SIFLC has shown capacity against the modeling of the complex hydrodynamic of the vehicle in operation.

Furthermore, Lachaud et al. [15] highlighted the failure challenges of deploying the ROV from unmanned surface vessels (USV) for harsh offshore operations. The authors identified communication and control system failure as critical challenges in such offshore operations. It was observed that mitigating against bandwidth restriction could aid the communication link and physical effect on the vehicle's performance and sensitivity [15]. A simulation conducted by [15] for ROV operations at targeted subsea interventions shows interactions in the various communication between the ROV and USV. The interaction could enhance more accurate data acquisition and interpretation for reliability assessment. Such operational data could be used to manipulate the ROV interaction with the subsea hardware, especially for inspection and repairs.

Vedachalam et al. [18] proposed a quantitative assessment model for risk and safety modeling of a ROSUB 6000 (that is a deepwater work class ROV; an unmanned, free swimming underwater vehicle that has six degrees of freedom) operation. The approach classified the likely safety integrity levels of the ROV subsystems based on the probability of failure on demand. The authors identified seven core failure events that determine the safety integrity level for the ROV operations. Among the core factors, the com-

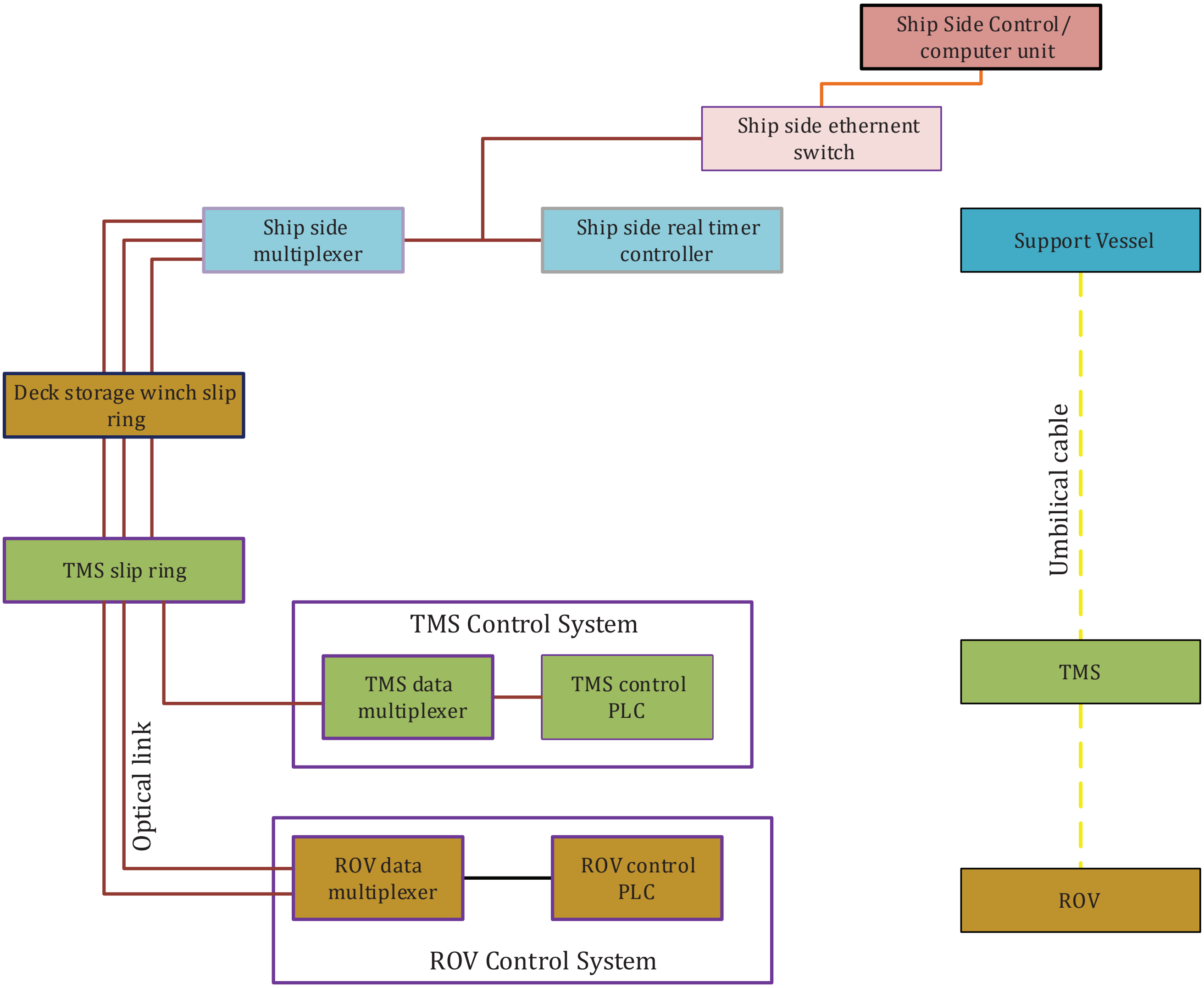

Figure 1 Schematic of the ROV-TMS-Support vessel operation/communication interfaces [7]

munication link between the tether management system (TMS) and the LARS are fundamental to the operation and failure of the ROV. The probabilistic framework captures the core failure events for risk assessment of the ROV system.

The reviewed literature has shown critical failure events that characterized ROV operations. However, there is limited knowledge to represent the identified failure modes for failure prediction graphically considering interconnectivity among common cause failure under different operational scenarios. Furthermore, an importance measure tool is needed for critical failure link identification and performance prediction. This could be integrated into the probabilistic framework.

3 Methodology

3.1 Operational failure analysis framework for ROV

The proposed OFA approach utilizes the fault tree analysis (FTA) technique. The FTA is a graphical deductive tool for complex systems which has shown a capacity to analyze complex engineering system to obtain failure probability model [16]. It has the capacity for failure probability prediction based on the logic gates (AND/OR gates) inferred from the interdependence relationship among the variables (subsystems). The model captures a cause-effect relationship based on the assigned logical gates. For example, the OR gates characterize the interaction among components connected in series, while the AND gates represent the interaction among parallelly connected subsystems. As shown in Figure 1, the interaction among the sub-nodes during the ROV operation is described.

Given the complex interactions in ROV operations and the likely failure modes, a robust failure assessment methodology is proposed. This describes the top event as the major failure consideration in ROV operation with a downward representation of a structural visualization of the associated subsystems malfunction effect on the top event performance. Figure 2 shows the algorithm for the proposed probabilistic approach. The following steps describe the procedure for the model application.

Step 1. ROV is a complex system with multiple design configurations based on performance and targeted tasks. It has a wide range of application which must be clearly defined. The characteristic features of the study ROV must be understood, and the subsystems' performance based

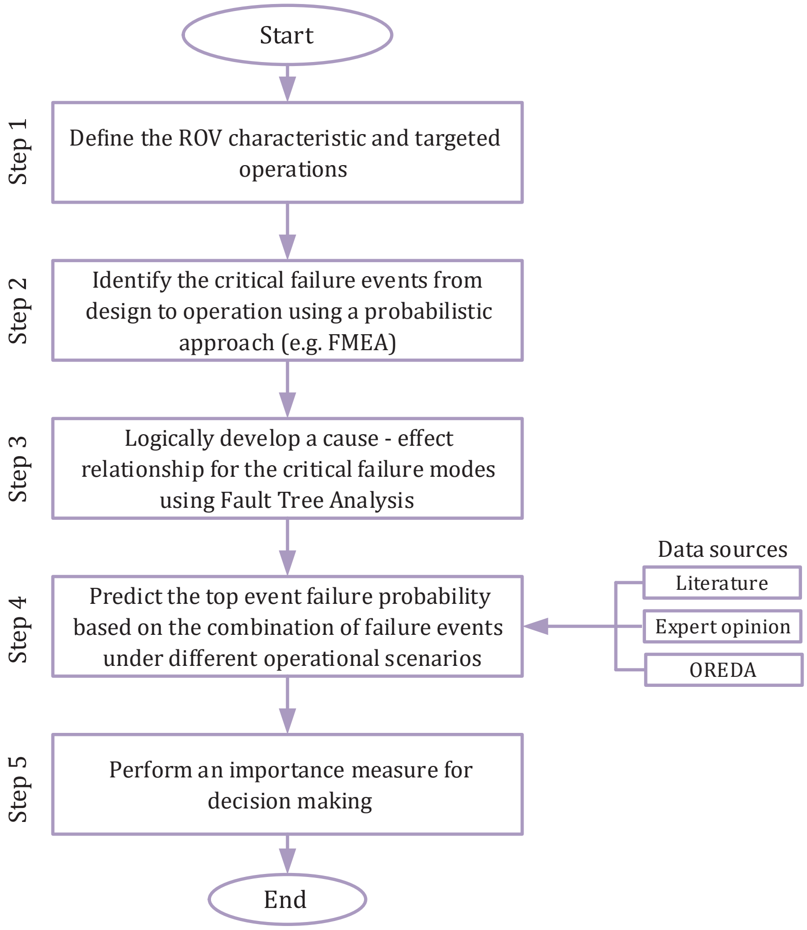

Figure 2 An algorithm for failure assessment of ROV operations

Source: Authors

on their safety integrity level (SIL) should be defined. The nature of the marine operation for the deployment of the ROV must be well understood. Various marine operations present different risk criteria and environmental constraints, such as in inspection, subsea assets repair & maintenance, valve operations, hotslab insertion, inteligent fish ethology research, beacons installation, geotechnical research, etc. Comprehensive knowledge of the targeted operations/mission will help in the operational failure analysis and predictions.

Step 2. In this step, the potential failure modes from design to operation are assessed using the FMEA. For the ROV operation, critical failure predisposing factors have been identified and grouped under their subsystems. These include the control system, underactuated condition, station keeping, coupling, and communication linkages. The characterized ROV operating environment coupled with the vehicle dynamics affect the performance of the pilot controllers. The effect of this dynamic interaction may yield disappointing responses on command. The hydrodynamic nonlinearities, inertial nonlinearities, modeling uncertainties, and the coupling effect due to vehicle degree of freedom (DOF) also affect the control system's safety level. The vehicle's failure in actuation as per direction and depth during operation falls under the underactuated failure event. This may be due to the failure of one or more thrusters. The dynamic thruster behavior could affect the ROV dynamics by restricting the maximum closed-loop bandwidth and create a limiting cycle during operation. This is fundamental to the station keeping/safe positioning of the vehicle on target mission. The coupling of the tether and umbilical cable with the body of the ROV enhances stability. However, the operating environment's sensitivity and vehicle dynamics could be affected and result in failure events. Failure in communication linkages affects the ROV operations. The ROV tracking and operations use multi-sensors-based cameras and a doppler velocity log (DVL). This helps in the manipulator operations, tracking, and targeted mission accomplishment. The vision-based system needs a consistent reference frame for signal transmission and management. Failure of the sensors on demand due to nonlinearities could affect the ROV operations. Although the implementation of a Sigma-Point Kalman Filter (SPKF) has shown promise to handle nonlinearity, signal uncertainty is still a challenge.

Step 3. The identified failure modes are further represented using a logical cause-effect relationship. The fault tree analysis (FTA) technique is adopted to model the operational failure logical diagram for the ROV. The logical connection is used to describe the event occurrence in a system as a result of the failure of subsystems down to individual elements. These elements are called basic events, while the combination of failure elements results in intermediate events based on their logical gates. The gates play a key role in the process of failure evolution over time. The FTA results show the effect of the combination of failure elements on the system failure for the ROV case study.

Step 4. In this step, failure probability is assigned to the basic events for the system's quantitative failure prediction. The fault tree structure, which is built based on the available data, is used for the analysis. For complex systems such as the ROV, the probability of failure of the system in series (top event) can be calculated using Equation (1) [12]. Configuration that are parallel (AND gate) equation 2 is used to predict the top event failure probability.

$$P_f(t) = F_s(t) = \sum_{j=1}^{N_k}\left(\prod_{i\in K_j} F_i\,(t)\right) \tag{1}$$

$$P_f(t) = F_s(t) = \sum_{j=1}^{N_k}\left(\prod_{i\in K_j}(1 - F_i\,(t))\right) \tag{2}$$

where $P_f(t)$ is the top event probability, $F_s(t)$; $F_i(t)$ is the probability of the *ith* bottom event in the *jth* minimal cut set at the time of t; K_j is the *jth* minimal cut set; N_k is the number of minimal cut sets.

For the ROV failure predictions, data from the literature, expert opinion, and the Offshore and Onshore Reliability Data (OREDA) could be used in the modeling depending on the system's characteristic features and the formulated logical diagram. Different operational scenarios are analyzed due to the complex configuration of the ROV system.

Step 5. To establish the critical components in the logical diagram, the fault tree can be reduced to minimal cut set (MCSs). These are a disjointed sum of products consisting of the smallest combination of the system's basic elements that is critical to cause the top event. Upon establishing the failure links, quantitative reliability indexes such as the importance measure (IMs) are predicted. The essence of understanding the system reliability via the subsystems' performance and the elements with the highest IMs values required critical intervention. For the IMs, the BAF measure is applied as shown in Equation (3) and Equation (4) [17] respectively. Birnbaum's measure is expressed as a partial differential of the system reliability with respect to the element's reliability. The decision of the elements' importance is dependent on the $I_B(i|t)$ values. The Fussell-Vesely's measure placed importance on the least minimal cut set that contain the failure elements as the system fails in a given time.

$$I_B(i|t) = \frac{\partial h(t)}{\partial P_i(t)} \qquad (1 \le i \le n) \tag{3}$$

where $h(t)$ is the system reliability, $P_i(t)$ is the reliability of the element *i*

$$I_{FV}(i|t) = \frac{P_r[D_i(t)]}{P_r[C(t)]} \qquad (1 \le i \le n) \tag{4}$$

where $D_i(t)$ define that at least one minimal cut set which contains element i is failed at the time, t. $C(t)$ denotes that the system is failed at the time, t.

Such elements' performance state is crucial to the ROV operation's reliability, especially in the harsh offshore environment. The importance measures result in critical decision-making to aid inspection, repair, maintenance, and integrity management strategy.

3.2 Application

The OFA approach is demonstrated with an electric work class, Remotely Operated Vehicle ROSUB 6000 [7],[18]. The system is assumed to be operating in a deep water arctic subsea environment. The region has a high harshness index and critical iceberg, strong wind, and wave challenges. The ROSUB configuration comprises the ROV, TMS, LARS, Support Vessel, and Control console. The

Table 1 Principal events of ROV operational failure in harsh environment

Logic gates	Basic events	Failure rate (week^{-1})
Control system failure	Manipulator operation failure	1.63E-03
ROV-TMS Docking failure	Pump operation failure Operator error	1.00E-04
Communication failure	Manipulator operation video failure	8.40E-03
Human failure	Path planning flaws	1.80E-04
	Waypoint generator & flaws	1.67E-03
	Obstacle detector failure	2.32E-03
	Failure in interfaces among MGNC	6.21E-04
	Referencing model failure	3.40E-03
	Navigation system failure	5.21E-04
	Observer module fault	2.17E-04
	Faulty DP control	2.14E-03
	Hardware component failures	3.61E-04
	Signal process module	2.10E-03
	Thrust allocation module fault	2.89E-04
	Failures to sending/receiving signals	7.08E-03
	Acoustic interference	4.23E-02
	Soft panel control failure	1.17E-02
	Controller operation failure	2.12E-02
	Tether cable twist information failure	2.14E-03
	ROV maneuvering for docking operation failure	5.85E-04
	Twist feedback failure to pilot/co-pilot plasma	4.32E-03
	TMS winch winding/unwinding operation failure using hard/soft switch	1.28E-04
	TMS winch A pump operation failure	3.67E-04
	TMS winch B pump operation failure	3.67E-03
	TMS docking vision support failure	6.5E-04
	Black dock enabling system failure	2.11E-03
	Maneuvering errors	3.56E-04
	Poor tether management	1.21E-03
	Slips and lapses	2.01E-04
	Pilot-induced oscillation	3.21E-03
	Wrong mission command	6.80E-05
	Wrong configuration setting	7.32E-04
	Erroneous override	5.46E-05
	Failure to intervene in a timely manner	4.11E-04
	Wrong input parameters	2.31E-04
	Wrongful signal interpretation	1.11E-04
	Wrong interference	1.54E-03
	Too early/too late to change control mode	4.21E-04

Source: Authors

ROSUB is a robust vehicle for critical deep-water operations. The interaction in the configuration is captured for the OFA of the ROSUB. However, the associated complexity poses multiphase operational challenges. For the failure analysis, additional probability information and data for the basic events are extracted from the referenced literature and expert opinion [6],[12],[19],[20],[21]. The data used for the probabilistic analysis is shown in Table 1. For this analysis, a graphical probabilistic approach considers the interaction of the other subsystems in the operational framework for the study ROV, as shown in Figure 1 is presented.

4 Analysis of results

The research's main objective is to apply a graphical probabilistic methodology for the OFA of an ROV in a harsh offshore environment. The analysis probabilistically assessed the ROV subsystems and identified likely failure modes via the FMEA, considering the operating environment. The environmental factors critical in station keeping and the target mission in ROV operations were captured for a robust graphical approach. The interconnectivity of the basic failure induced events/actions were logically represent based on the gates. The logical gates define the interaction/combination of these events to cause the top event's failure (ROV operational failure). The critical failure modes/factors are identified, classified, and represented by Figure 3. This represents the intermediate events which are subsequently developed into the basic events downward, as shown in Figure 4-7.

4.1 Communication System

The ROV communication system is complex, with multiple signal transmitters. These elements (such as a sensor for video, data transfer, and Global positioning system (GPS) are fundamental in inspection, monitoring, and video transmission operation in ROV target mission. However, underwater wireless communication may face challenges due to limited distance for video streaming and transmission at high frequency. It has been reported that in deep water operation, the GPS receiver strength drop at a position greater than 8 cm deep underwater [6]. Besides the information transmission elements performance, the acoustic interference and the twist feedback system failure affect the communication linkages in ROV operations (see Figure 1). The communication linkages between the TMS, support vessel, and ROV provides necessary information for the ROV operation and performance. The events resulting from the communication failure can be represented using the OR gate, as shown in Figure 4.

The communication failure can be predicted for a known probability of failure on demand for the communication link elements and for a series system, the failure of one component of the structure results in the top event's failure. Equation (1) is used to predict the top event failure likelihood based on the probability data in Table 1. The FTA for the prediction of the failure event probability is based on a week operation.

4.2 ROV-TMS docking

The operation and interactions of the ROV-TMS are crucial for its underwater mission/performance. The most common failure is the docking failure and tether cable damage. Severe safety instrumented function (SIF) is implemented to achieve the required SIL levels. These elements are used to detect unsafe low insulation conditions and for pressure maintenance. For water tightness integrity, the O-rings are used, and their performances

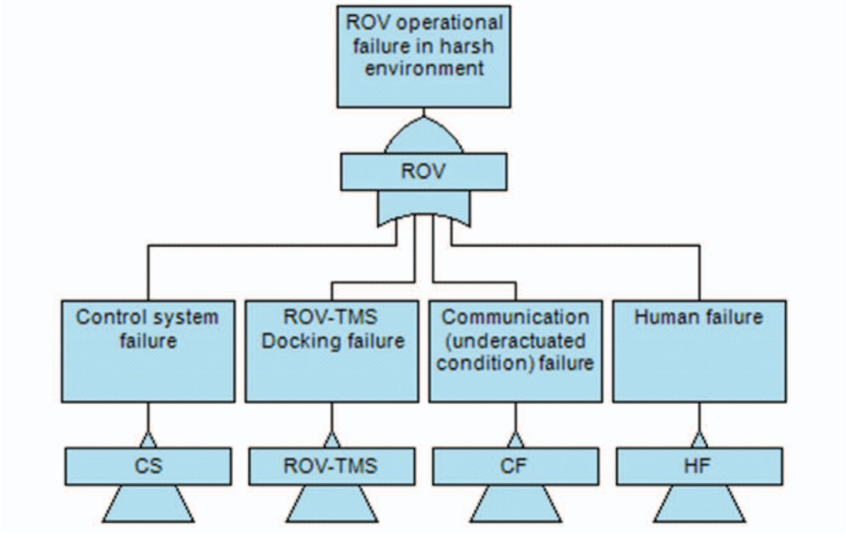

Figure 3 First stage failure mode for ROV operational failure in harsh environment

Source: Authors

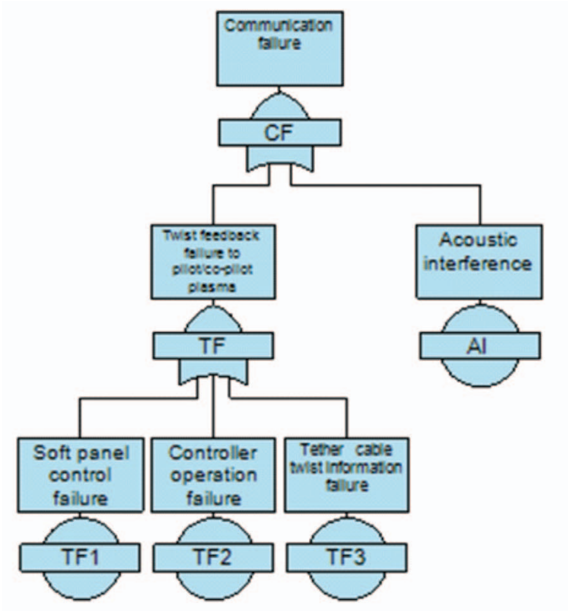

Figure 4 Fault tree of communication system failure

Source: Authors

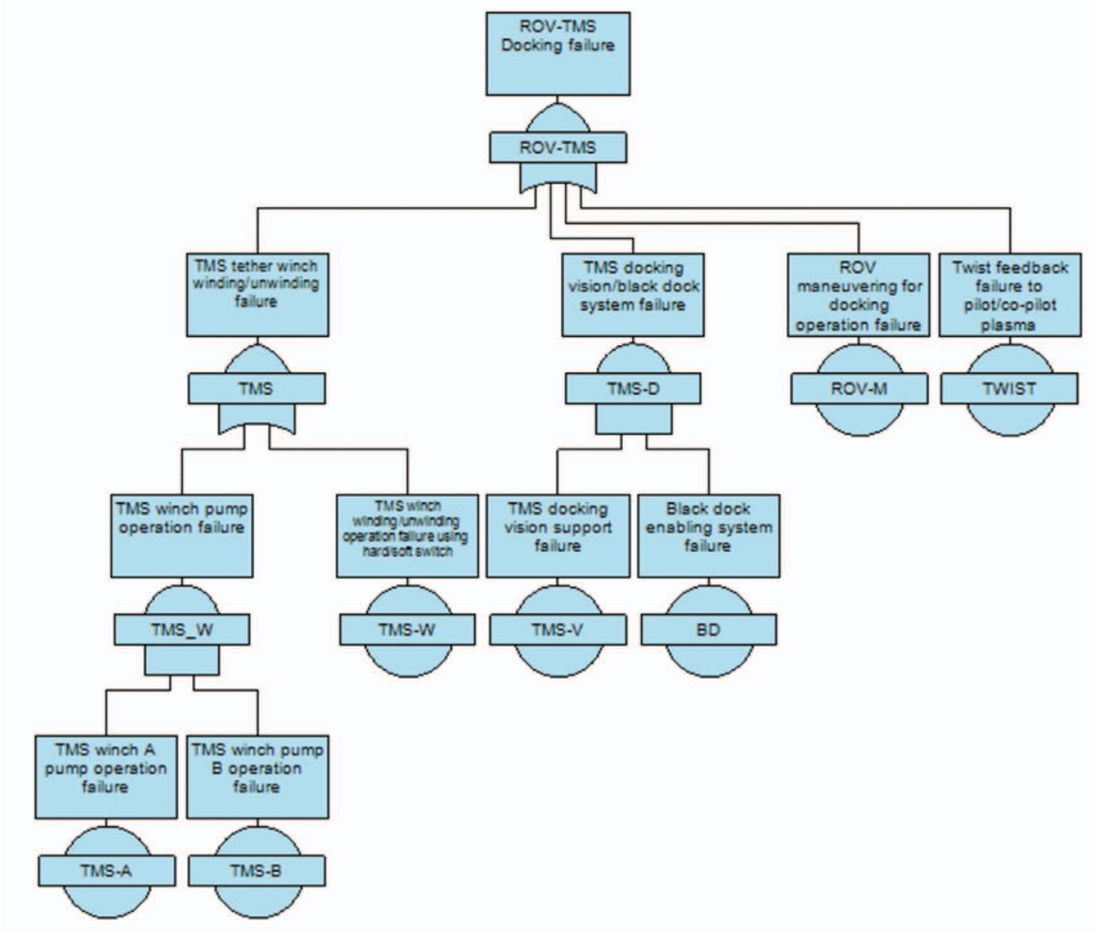

Figure 5 Fault tree of ROV-TMS Docking system failure

Source: Authors

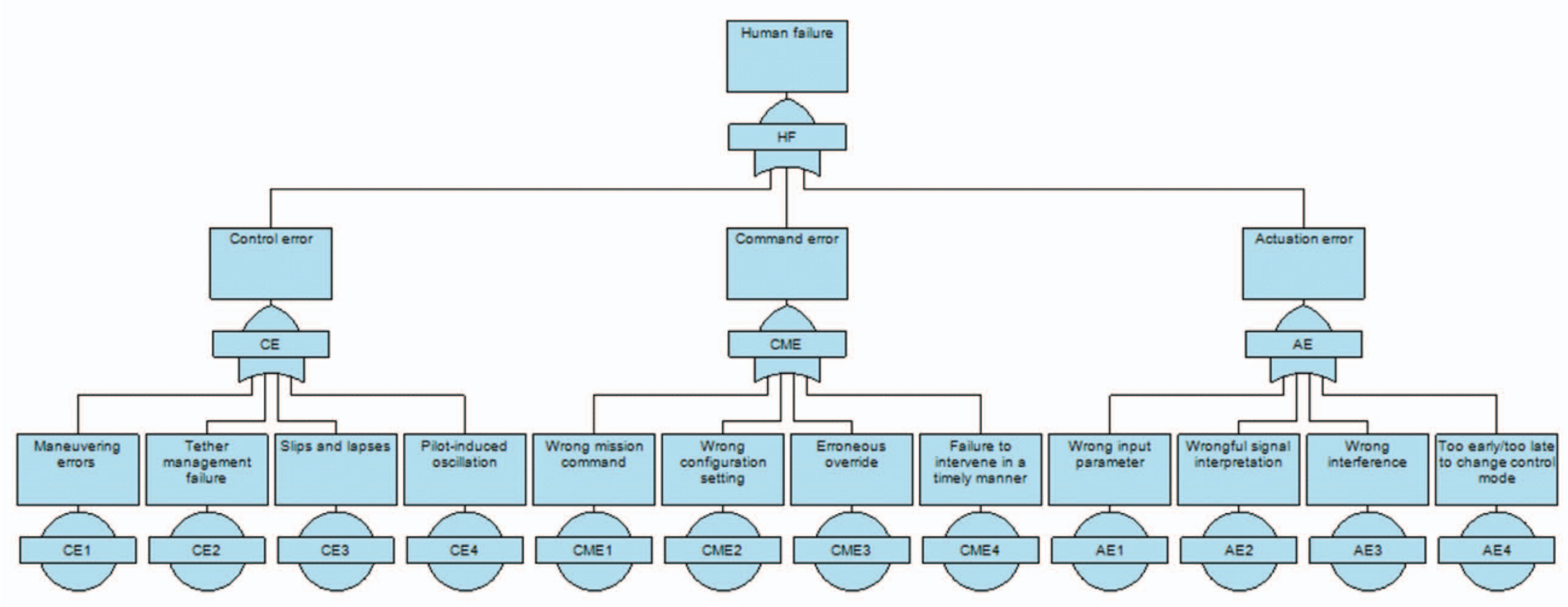

Figure 6 Fault tree of Human failure in ROV operations

Source: Authors

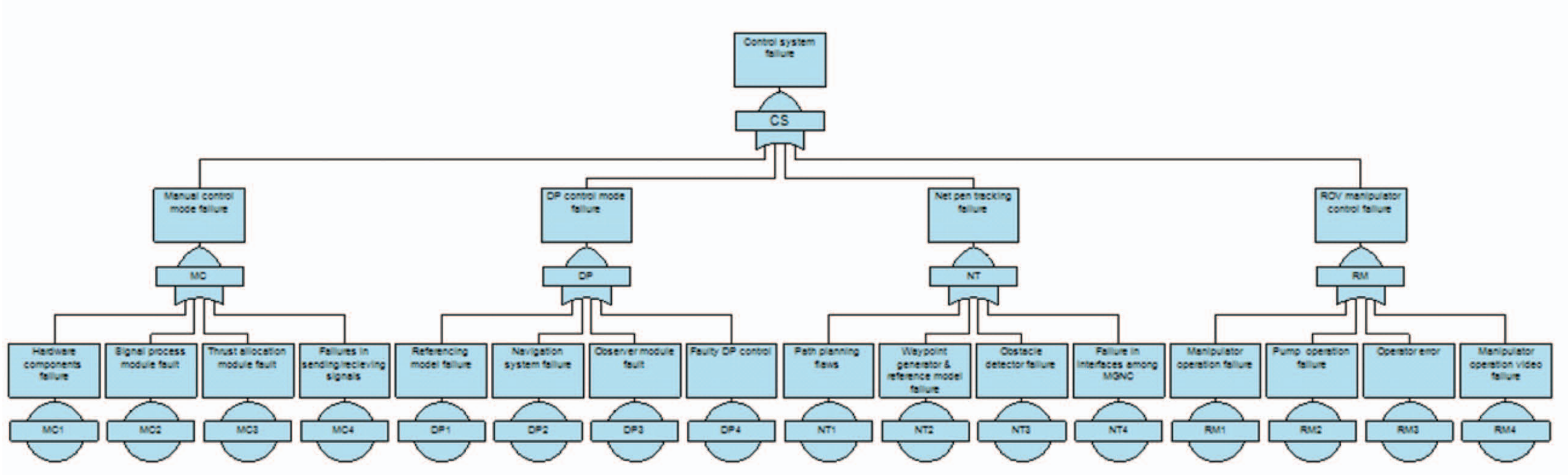

Figure 7 Fault tree of control system failure in ROV operations

Source: Authors

are dependent on the operating stresses. Figure 5 shows the likely failure event during ROV-TMS docking operations. The LARS and the Umbilical storage support the interaction between these two systems. This operation is winched driven to locate the ROV at the targeted location. Upon the ROV positioning, the ROV is unlocked from the TMS and piloted from the deployment vessel. The twisting process and heading change during these ROV operations could result in over twist/cable damage or failure, especially in harsh offshore operations. For this research, the critical failure events for the docking and unlocking are group into TMS tether winch winding/unwinding failure, ROV maneuvering for docking operation failure, TMS docking vision/black dock system failure, and twist feedback failure to pilot/co-pilot plasma. Given the elements' failure probability as shown in Table 1, the effect of ROV-TMS docking failure on the overall operation is predicted.

4.3 Human failure

Human factor/performance is crucial in the launching, unlocking, subsea and docking operations of ROV. Human actions range from command, control, and actuation. For switch-off operation, in case of unsafe event detection, the thruster and pump may be commanded by the operator to request the TMS controller to open the Motor Vessel (MV) switch. These actions require an interaction between the control system and communication interfaces. Similar interactive activities are required if water is detected in the TMS telemetry pressure case. In the present study, the various human failures are shown in Figure 6.

In every unsafe action during ROV operations, the effect of human-machine-environmental interactions is key. In most cases, human intervention or error through a wrong command or signal interpretation are primary causes of ROV operational failure. ROV docking and deployment could result in hard-hitting of the vehicle on the seabed. The maneuvering of the ROV by the pilot in the absence of an altitude-guided system/information may result in unsafe conditions. In a similar manner, the tether cable may be subjected to over twisting during undocking operation. The failure that results due to cable over twist is due to pilot error. The actuation or position-keeping actions are dependent on sensor signals and human interpretation. Wrong reading or interpretation of signals could result in the wrong command that affects the ROV operation failure.

The classified basic events and their likelihood of occurrence are used as the input data for modeling the human failure probability for the given operational scenario, as shown in Figure 5.

4.4 Control system

The ROV is a complex system, and their interaction with critical subsea infrastructures could complicate their control operations. The associated complexity in ROV operation is due to their operations' sensitivity, multipurpose sensors, controller, and subsystems interactions. The control system performance is key in the targeted mission, monitoring, and process of the ROV. The control elements facilitate the information logging operations in the pilot computer console and the necessary feedback to the supporting vessel from the ROV. The interaction between human action and control elements is depicted in the manipulator operations. The manipulator, in most cases, is equipped with vision systems to provide real video feedback to the operators. In multi-task subsea operations such as pipeline valve operations, pipeline sacrificial anode fixing, wet mate connector, there may be complex interconnectivity across the task that could increase the manipulator control failure risk. The manipulator system's failure could result in potentially unsafe scenarios that could cause catastrophic damage to subsea oil and gas wellheads and manifolds. As shown in Figure 7, four core failure events that result to control system failure are represented. These events are further developed into basic events based on a logical relationship. The SIL of the control elements will guide the performance of the elements and predict the probability of failure on demand during operation. In most configurations, the redundant setup could enhance the system's reliability as a means for risk mitigation measures during operations.

4.5 ROV performance

The overall results analysis show that the ROV operational failure could be predicted for a known probability of failure for the basic events. For the period of a week operation, the likelihood of operational failure is 2.245E-04, and the failure rate of 8.451E-04 per hour, indicating that the MTBF is 1183 hours. The result suggests the need for a proactive maintenance plan for a 55days period of operation. The most failure events magnitude is around E-04 and E-06. The merit of the presented approach is to quantitatively predict the likely failure bound for the ROV operations in the harsh enviornments in comparison to the referenced work [12].

Further analysis based on the importance measure is presented to capture the critical event's critical failure mode. The control systems and the communication linkage's failure modes show criticality to the sustainable operation of the ROV. The application of the Fussell-Vesely criteria on the control system depicts the degree of importance of the basic events. The result of the analysis is shown in Figure 8. Among the basic causative events, the hardware component failures, such as sensors, GPS, camera, thruster, joysticks, show great importance on the control failure mode for the ROV operational failure. This accounts for about 45% impact based on the Fussell-Vesely importance measure criteria.

The result further reflects the contribution of the other elements/action on the control system failure. The signal processor module fault, navigation system failure, Dynamic Positioning (DP) control failure, and waypoint

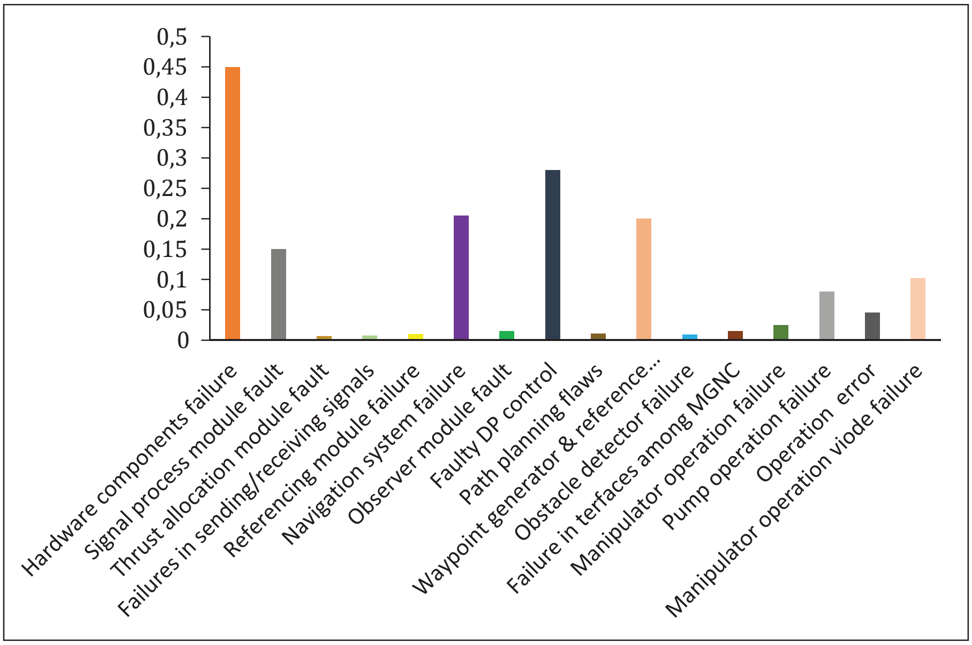

Figure 8 Fussell-Vesely of control system failure basic events

Source: Authors

generator accounted for 15%, 20%, 30%, and 18%, respectively. The result reflects the likely dependencies and interaction among the subsystems for multi-task operations. The communication controllers and sensors function in the most subsystem of the ROV. Actuation, which is critical in the station keeping and thruster support operations through referencing modeling, exhibits non-linear dependencies. These dependencies could inform stochastic failure characteristics that may complicate the failure predictions. However, this concept is out of the scope of the present study. It could be considered in further studies. The other failure modes' critical basic events could be predicted similarly based on the Fussell-Vesely criteria as illustrated for the control system failure.

The overall probabilistic analysis provides a vital parametric assessment framework for the likely failure causative factors/actions for the ROV operational failure. The environment influences the failure characteristics of the elements via the failure rate. This is reflected in the probability data used in the analysis. The result analysis agrees with previous research findings on the critical ROV failure influencing factors [14],[15],[18]. Nevertheless, the presented structure is inexhaustive, and the analysis may present some limitations due to subjectivity in the data and the cause-effect connectivity.

5 Conclusions

The present study demonstrates the application of a logical probabilistic methodology for the OFA of the ROV and the support systems. The model captures the cause-effect relationship and their propagation to the top event's failure (ROV operation). The element failure rate for a week operation was used in the demonstrative analysis as shown. The probabilistic model demonstrates the capacity for a deductive failure-based analysis in the uncertain ocean environment. The following conclusion is drawn from the present study:

- The study presents a useful tool for ROV operational failure analysis under uncertainty
- For the given operating condition and rate of failure, the ROV operational failure characteristics were reliability predicted. The predicted MTBF of 1183 hours is key in integrity related planning for the ROV
- The result of the model provides core information for a proactive maintenance and condition monitoring framework during operations
- The study offers key operational information based on the importance measure on the most probable link to the ROV failure
- The study provides robust tools that can aid further analysis in risk assessment of ROV operation, especially in accidental impact on the subsea facilities.

The presented approach provides a useful probabilistic tool for ROV operational failure assessment in uncertain offshore environments. However, the model could be further improved by capturing the nonlinearity among critical elements and their unstable characteristics on the failure probability using dynamic intelligent model.

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