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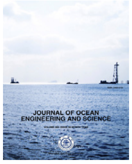

An approach to operational risk modeling and estimation of safety levels for deep water work class remotely operated vehicle—A case study with reference to ROSUB 6000

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Abstract

This paper presents a quantitative approach to operational risk modeling and estimation of safety integrity levels, required for the deep water electric work class remotely operated vehicle with reference to ROSUB6000 developed by the National Institute of Ocean Technology, India. ROSUB6000 is used for carrying out bathymetric surveys, gas hydrate surveys, poly-metallic nodule exploration, salvage operations, and meeting emergency response situations. The system is expected to be in operation for a period of 300 h per year, and has to be extremely safe and reliable. Methods and models for the quantitative assessment of operational safety and estimation of safety integrity levels for ROV are seldom available in the deep water intervention industry. The safety instrumented functions implemented in the ROV should be able to meet the SIL requirements of specific mission. This study indicates that the required safety factors are implemented into the design of the state-of-the-art ROV ROSUB 6000, considering IEC 61508/61511 recommendations on Health, Safety and Environment and it is found that the system is able to meet the required SIL for seven identified functions. This paper gives the design and safety engineers in the ROV industry, an overview of the numerical operational risk assessment methods and safety-centered ROV engineering.

Keywords: Remotely operated vehicle; HSE; Safety integrity level; Safety instrumented function.

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1. Introduction

Work class remotely operated vehicle (ROV) support is found to be highly essential in the oil and gas sector [1], deep water research, and offshore energy sectors [1] where the oil and gas sector is accountable for 75% of ROV usage in drilling, exploration and subsea infrastructural developments [2]. The global annual expenditure on work class ROV operations is set to increase from \$1.6 billion in 2013 to \$2.4 billion in 2017, a compounded annual growth rate of 11.3% [1]. The world fleet of work class ROVs has grown from 641 units in 2011 [3] to 1102 units in 2013 [4]. This is largely due to the move toward deeper waters and more complicated offshore field development programs [5–8]. The essential use of work class ROV in deeper water was clearly demonstrated during the Macondo well head blow-out in the Gulf of Mexico [9] which demanded safe and reliable operation in the challenging environment. This demands the need for relevant safety standards and procedures to be implemented in the fast growing subsea intervention industry, where the vehicle risk tolerance levels and associated safety requirements are dictated by the mission for which the vehicle operations are called. The required safety levels for the intervention system are normally dictated by the Health, Safety and Environmental (HSE) regulations already in place which is usually described by the safety integrity levels (SIL) based on IEC 61508 and 61511 standards [10–12] and the operational SIL of the ROV needs to be in compliant with the required SIL. Thus a quantitative, risk based, operation specific assessment of the vehicle's SIL is required, so as to ensure confidence in the use of ROV for the specific operation. Even though, safety assessment by qualitative methods for the required safety levels in offshore environments [13] and surface vessels [14] exist, such methods are seldom practiced in the ROV industry where

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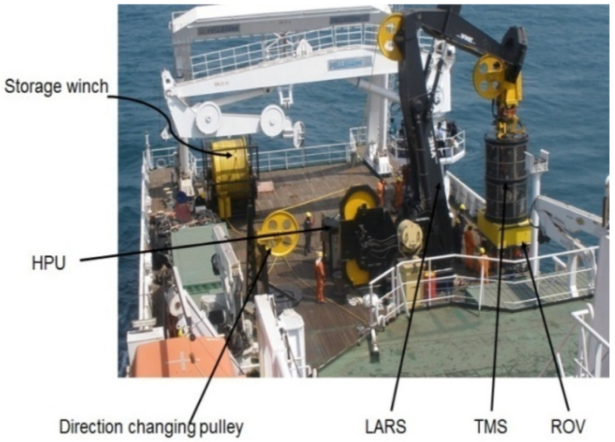

Fig. 1. View of the ROSUB 6000 system prior to launch.

safety assessment has a high level of uncertainty due to the insufficient reported failure data which has been a major concern for risk related decision support. Novel decision making techniques are required to make the design and operation decisions efficiently and in the absence of which, it might be difficult to compare the design costs and operational benefits. Thus, the need for suitable risk assessment and quantitative safety models based on HSE are required. The CAPEX and OPEX of the ROV are decided by the frequency of maintenance required to upkeep the SIL. Thus the maintenance expenditure could be greatly reduced by safety centered design practices. This paper presents an approach to the operational safety modeling and estimation of SIL for deep water electric work class ROV, with reference to the ROSUB 6000 designed by the National Institute of Ocean Technology (NIOT).

2. System description

NIOT has developed an electric work class ROVROSUB 6000 for carrying out deep sea operations such as bathymetric surveys, gas hydrate surveys [15,16], poly-metallic nodule exploration [17] and salvage operations. The ROSUB 6000 system comprises of a remotely operable vehicle (ROV), tether management system (TMS), launching and recovery system (LARS), ship systems, control console, instrumentation, control and electrical system, control and operational system [15,18].The vehicle is equipped with two electrically powered hydraulic actuated manipulators, which can handle a pay load of 150 kg intended for mounting scientific and mission oriented systems.

Fig. 1 shows the overall architecture, where the work-class ROV and the TMS are docked together, and ready for launch from the mother vessel, using the LARS. 6000 m of umbilical cable is housed in a hydraulically operable deck storage winch, and its operation is synchronized with the LARS. The LARS handles the ROV-TMS docked system and undocks it below the splash zone. As the system reaches the desired depth, the ROV is caged out of the TMS. The ROV is propelled by thrusters, and can be operated in any desired direction from the pilot command from the ship. Manipulators are used to carry out subsea tasking operations. After the completion of the task the ROV shall be docked back to the TMS subsea and the system is recovered to the ship.

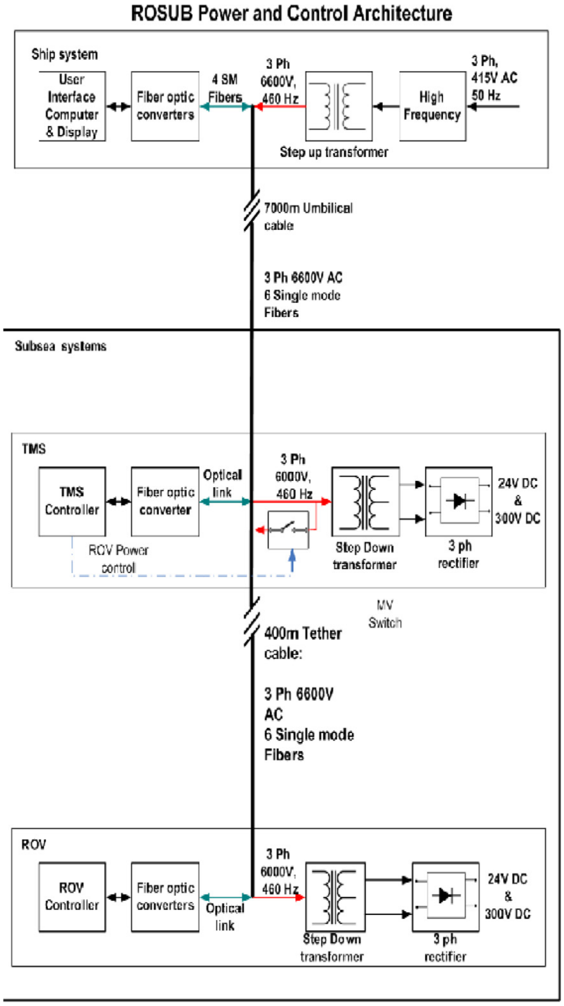

Fig. 2. Electrical and control architecture of the ROSUB 6000 system.

Fig. 2 indicates the power and control system architecture in the TMS, ROV and the ship. Ship power at 400 V and 50 Hz is transformed into 6600 V and 460 Hz using a standard frequency converter and a step up transformer. Electro-optical connectivity between the ship and TMS is achieved by a 6000 m umbilical cable. The connectivity between the TMS and ROV is realized by the 400 m long tether cable, and a ruggedized pressure compensated medium voltage switch [19]. Subsea power converters in the TMS and the ROV convert 6600 V at 460 Hz to the power level required for the subsystems. The system was developed with the aim of carrying out 300 h of deep sea operations per year, with reliability as the key driver, and was identified to have an MTBF of 4.9 years and 6.2 years for ROV-TMS docking and manipulator operations respectively [6–8]. Since its inception in 2007, the system has undergone 37 dives, of which 13 dives were at depths greater than 1000 m [6–8].

The design depth qualification of the system was carried out at the polymetallic nodule site at the Central Indian Ocean

Basin at a depth of 5289 m during April 2010, and the system has been used for scientific exploration in the SONNE field in the South Central Indian ridge during April 2013, where a near real time underwater video was streamed from the Rodriguez triple junction [20].

3. Methodology and standards followed

The following is the list of the major standards followed,

1. FIDES Guide [21] for estimation of failure rate of electronic components and systems considering the mission specifications.
2. MIL HDBK 217F, Military handbook for Reliability Estimation of Electronics Equipment [22] for estimation of failure rate of electric components and electronic components.
3. IEEE 493 IEEE Recommended practice [23] for Design of reliable Industrial and Commercial Power Systems for the failure rate calculation of electric and electronic components.
4. OREDA Handbook [24] for ruggedized mechanical components, considering the operating conditions based on the mission.
5. Functional Safety – A Straightforward guide to applying IEC 61508 and related standards [10,25] for obtaining the hazardous events and SIF.
6. IEC61511 [11,12] for estimating the methodology of the operating SIL level requirements.
7. Naval Surface Warfare Center (NSWC) standards for Prediction of reliability for mechanical equipment [26].

The failure rate determination was done by the following methods,

a. Based on the manufacturers' data and interpretation suitable for the mission profile.
b. For systems where detailed drawings and schematics are available, using component failure data from the respective standards, failure rates are calculated taking mission profile, operating conditions and stresses into consideration.
c. For commercially sourced components, where there is no adequate information, based on the functional specification, the failure rate for the mission profile, is calculated using standards.

The standards were based on feedbacks from operations and existing failure models along with statistical interpretations over the normal operating life period of the involved systems, considering the influence of the operating temperature, amplitude and frequency of the temperature changes, vibration amplitude, humidity and operating stresses during different mission profiles [21] accounting for the manufacturing and integrating quality factor, for computing the failure rates. The standards also support the commercially off the shelf (COTS) approach for calculating the failure rates of the systems for the defined mission profile with the functional requirements, and the mission profile as an input from the user. For subsystems the failure rates are computed from the component level. Table 1 gives the standards followed for the major systems and components. The TOTAL-SATODEV GRIF tool is used for determining the SIL levels. Table 2 details the Failure in Time data of the major systems. The indicated FIT values are adopted suitably for computations.

Table 1
Major standards followed for the reliability study to calculate failure rates.

Component	Standards
CPU,AC-DC Converters, DC-DC Converters, Fuses, Electronics and Optical connectors, Ethernet Converters, Data and video multiplexers, Input and Output modules for Data acquisition cards	FIDES
HF Converters and Transformers, Isolators, Motors,	MIL and IEEE
Power Contactors, halogen lamps	MIL
Umbilical and Tether cables, terminations, subsea sensors	OREDA
O-rings and seals	NSWC

Table 2
Failure-in-time values for major sub-components for the defined mission period.

Component and its failure in time	
Umbilical cable [6–8]	700
Tether cable [6–8]	438
TMS based subsea electro-optic slip ring [6–8]	2220
Data multiplexer in TMS/ROV [6–8]	381
Real time controller [6–8]	1284
Photonic inertial navigation system (PHINS) [6–8]	33,333
Sea battery [6–8]	3140
Water entry detection circuit [6–8]	5
Medium voltage switch [19,22]	500
Transformer [23]	673
Motor [22]	376
Hydraulic pump [6–8]	376
Subsea power and optical connectors [24]	143, 244

Note: *FIT in Billion hours = (number of failures/number of units x operating hours) x 10^9.

4. Operational risk assessment and SIL determination methodology

IEC 61508 is a standard [10,25,27], which is essentially a framework for implementing instrumented safety systems using the principles of Safety Life Cycle and Safety Integrity Level concepts. Protection systems need to perform their intended operations on demand. The probability of failure is the unavailability of a safety system on demand. If a demand occurs after a time, the probability that the system has already failed is the probability of failure on demand (PFD). SIL defines the degree of safety protection required by the process, and consecutively the safety reliability of the safety system necessary to achieve the function. SIL has four levels, 1 to 4. The higher the safer. Table 3 describes the various SIL levels with the corresponding PFD (Table 4).

$$\text{PFD} = \frac{\text{Tolerable frequency of the accident}}{\text{Frequency of the accident with no protection}}$$

Table 3
Safety integrity levels and corresponding PFD.

Safety integrated level (SIL)	Probability of failure on demand (PFD per year)
1	10^{-1}–10^{-2}
2	10^{-2}–10^{-3}
3	10^{-3}–10^{-4}
4	10^{-4}–10^{-5}

Table 4
Factors for SIF demand rate selection.

	Demand rate	Factor (W)
W9	Often > 1/year	9
W8	Frequent 1/1–3 year	8
W7	Likely 1/ 3–10 year	7
W6	Probable 1/10–30 year	6
W5	Occasional 1/30–100 year	5
W4	Remote 1/100–300 year	4
W3	Improbable 1/300–1000 year	3

Table 5
Consequence parameter selection criteria.

Consequence	F+P+W						
Severity level	C	1,2	3,4	5,6	7,8	9,10	11,12
Catastrophic	F	NR	IL1	IL2	IL3	IL4	NA
Extensive	E	NR	NR	IL1	IL2	IL3	IL4
Serious	D	NR	NR	NR	IL1	IL2	IL3
Considerable	C	NR	NR	NR	NR	IL1	IL2
Marginal	B	NR	NR	NR	NR	NR	IL1
Negligible	A	NR	NR	NR	NR	NR	NR

Note: NR, not required; IL, integrity level.

Based on IEC 61508, the SIL requirements are computed taking into consideration the risk consequence, alternate SIF in place, human occupancy and the demand rate for the SIF.

a. *Avoidance parameter P*
The parameter takes values of 0 or 1. Based on the availability or unavailability of the alternate SIF, the parameter is assigned a value of 0 or 1 respectively.
b. *Occupancy parameter F*
Based on the human occupancy the parameter takes the values of 2, 1 and 0 corresponding to continuous, occasional and rare human presence in the mission.
c. *Demand rate parameter W*
This parameter defines the number of times per year that the hazardous event could occur in the absence of SIF.

Having computed the values of *P*, *F* and *W*, the summed up values are plotted against the consequence factor, to obtain the required level of SIL for the SIF. The same is shown in Table. 5.

Table 6 shows the values taken as the input for the risk consequence parameters based on the risk tolerance capacity of NIOT.

FMECA [6] studies done on ROSUB 6000 reveal that the following failures are critical from the HSE point of view,

Table 6
Risk level assignment data.

	Personnel health	Environment	Financial
Consequence*	Extensive	Marginal	Serious

* Catastrophic, Extensive, Serious, Considerable, Marginal, Negligible.

1. Injury to the operating personnel and damage to the system and environment due to system electrical insulation failure and its consequences.
2. Damage to the system due to water leakages inside sealed pressure cases in ROV.
3. Damage to the system due to water leakages inside sealed pressure cases in TMS.
4. ROV hard landing on the sea floor during operations.
5. TMS –ROV tether cable damage.
6. ROV-TMS docking.
7. Manipulator operation.

5. Risk graph matrix for the safety instrumented functions

Risk graph matrix shown in Table 7 is made specifically for the ROSUB 6000 system to_ identify the SIL levels required from the HSE point of view [11,12,28].

In order to meet the unsafe events, appropriate Safety instrumented functions (SIF) are implemented. The following topics details the SIL levels achieved for the implemented SIF.

5.1. Determination of SIL for implemented SIF

SIF 1: Electrical Insulation monitoring
As indicated in Table 7, HSE demands that the safety instrumented function (SIF) [27] implemented should comply with SIL2 levels. The on-line electrical insulation monitoring system installed in the ship side monitors the insulation healthiness of the 6.6 kV circuits, including the umbilical cable, tether cable, and associated in-line electrical components. Whenever an unsafe low insulation condition is detected, the monitoring system switches off the power input to the system. The architecture of the same is shown in Fig. 3. The failure rate of the implemented SIF is computed to be 4250FIT and Fig. 4 shows the achieved SIL which is in line with the calculated HSE requirements, for a proof test interval (PTI) of 5.5 years. The maintenance of the SIF hardware every 5.5 years, shall keep the PFD of the SIF at the SIL2 level.

SIF 2: Water entry detection in ROV power and telemetry pressure cases
The communication link between ROV and rest of the systems is shown in Fig. 5. ROV power and electronics systems are kept inside sealed pressure cases and the connections are established using penetrators and feed through with O-rings for water tight integrity. The life time of the seals depends on the operating stresses such as pressure and temperature, quality of the material and the frequency of utilizations [29,30]. The failure or degradation of the O-rings leads to water leakage into the enclosure, which leads to economic losses. As

Table 7
SIL requirement determination chart for the identified unsafe event.

SIF No	Event	Description of implemented safety instrumented function (SIF)	Consequence		Influence		Demand	Likelisum	Integrity
			Type	C	F	P	W	Sum	IL
1	6 kV electricity hazard due to insulation failure in the high voltage handling systems.	On-line Insulation healthiness monitoring system	H	D	2	1	6	9	IL2
			E	B	1	1	6	8	NR
			F	C	1	1	6	8	NR
2	Water entry into ROV data telemetry and thruster pressure case	Water entry detector system installed	H	A	0	1	5	6	OK
			E	A	1	1	5	7	OK
			F	D	0	1	6	7	IL1
3	Water entry into TMS pressure case	Water entry detector system installed	H	A	0	1	5	6	OK
			E	A	1	1	5	7	OK
			F	D	0	1	6	7	IL1
4	ROV hard landing on the sea bed	Decision making control algorithm implemented using depth sensor	H	A	0	1	5	6	OK
			E	A	1	1	5	7	OK
			F	D	0	1	6	7	IL1
5	TMS - ROV tether cable damage	Cable twist monitoring mechanism to aid docking function	H	A	0	1	5	6	OK
			E	A	1	1	5	7	OK
			F	D	0	1	6	7	IL1
6	ROV-TMS docking failure	System hardware involved in the operation with man-in-loop	H	A	0	1	6	7	OK
			E	A	1	1	6	8	OK
			F	D	0	1	9	10	IL2
7	ROV manipulator failure	System hardware involved in the operation with man-in-loop	H	A	0	1	6	7	OK
			E	A	1	1	6	8	OK
			F	D	0	1	9	10	IL2

H, Health; E, Environment; F, financial loss.

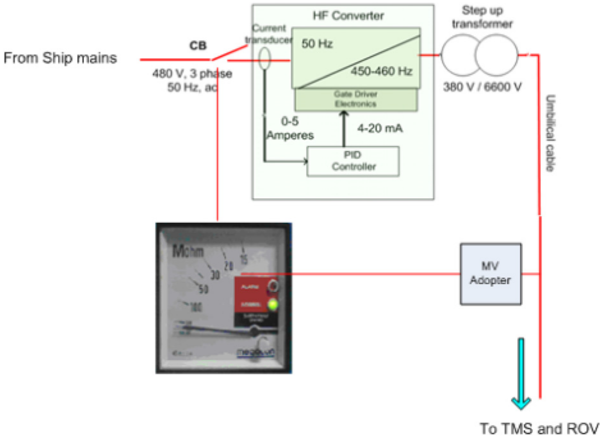

Fig. 3. Online system insulation monitor.

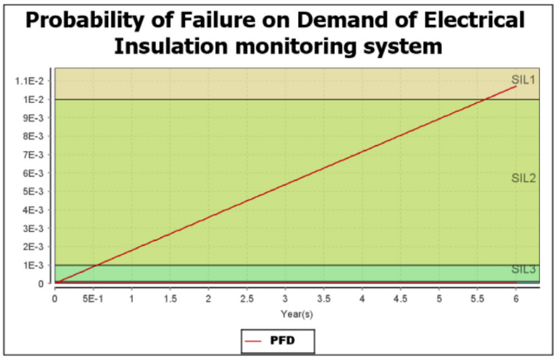

Fig. 4. SIL calculation chart for electrical system insulation protection.

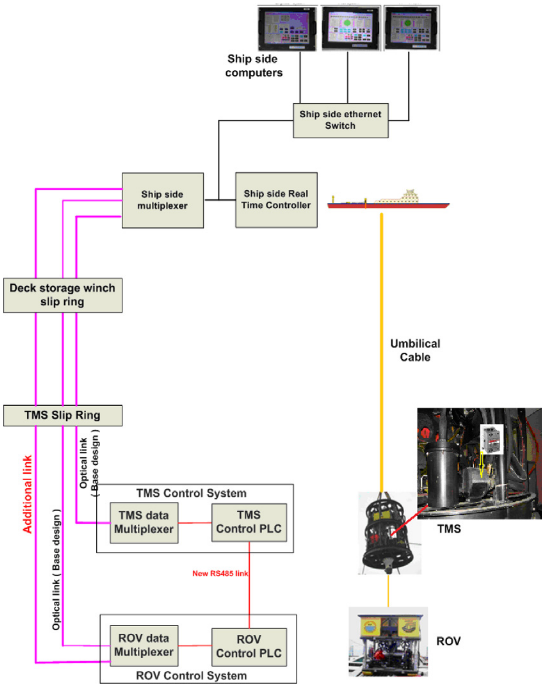

Fig. 5. Schematic of the ROV-TMS-Ship communication interfaces.

indicated in Table 7, HSE demands that the SIF to be implemented should comply with SIL1 levels. SIF is implemented by using a water entry detector inside the enclosures. Whenever water entry is detected by the detectors, the control sys-

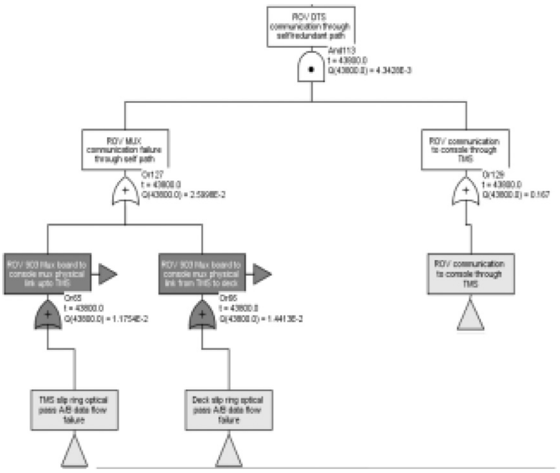

Fig. 6. Trees used for calculating the PLC and communication network FIT.

tem in the ROV, switches off the operating command to the thrusters and pump, and issues a request to the TMS controller to open the MV switch. Fig. 6 shows the failure trees for the control system having a failure rate of 27000 FIT and communication interfaces. The maintenance of the SIF hardware every 6.5 years will keep the PFD of the SIF at the SIL1 level.

SIF 3: Water entry detection in TMS telemetry pressure case

The communication link between TMS and the rest of the systems is shown in Fig. 7. Similar to ROV, TMS electronic systems are also kept inside sealed pressure cases, and the connections are established using penetrators and feed-through. As indicated in Table 7, HSE demands that the SIF to be implemented should comply with SIL1 levels. The SIF is implemented by using a water entry detector inside the enclosures. Whenever water entry is detected, the control system in the TMS issues a request to the ship system to switch off the main deck input power circuit breaker. The failure rate of the SIF is 27000 FIT and the maintenance of the SIF hardware every 6.5 years will keep the PFD of the SIF at the SIL1.

SIF 4: ROV hard contact with the sea bed

The LARS and the umbilical storage winch are operated, such that the ROV-TMS system is taken close to the survey location of interest, and the ROV is undocked from the TMS. The ROV is maneuvered by the pilot from the deployment vessel. In the absence of altitude information or the camera, there are increased possibilities that the ROV may hit the sea bed. This is an unsafe condition. As indicated in Table 7, HSE demands that the SIF implemented should comply with the SIL1. The SIF is implemented using an altimeter, ROV controller and thrusters. Whenever a low clearance between the sea bed and the ROV is detected, the control system in the ROV, switches off the operating command to the top three thrusters. As the ROV is positively buoyant by 20 kg, it tends to move up, thus avoiding or reducing the impact with the sea floor. Once the clearance between the seabed and the ROV increases above the programmed safe limit, the thrusters resume the position prior to the situation. Based on the HSE requirements, maintenance of the SIF hardware every 6.5 years will keep the PFD of the SIF at the SIL1.

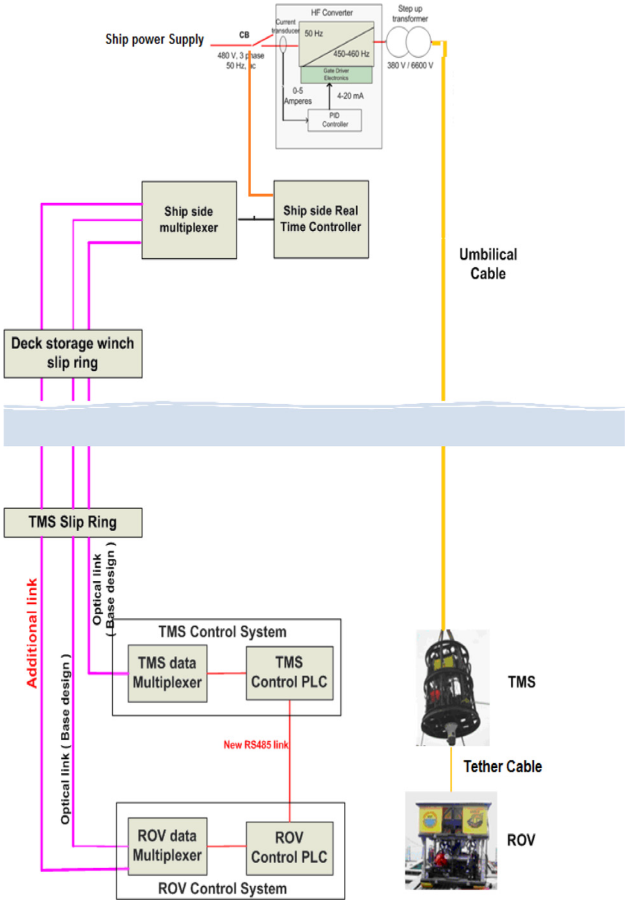

Fig. 7. Schematic indicating subsea system–ship power system interface.

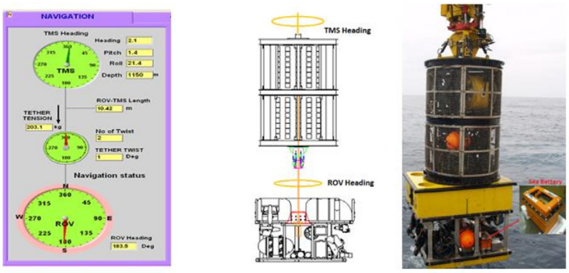

Fig. 8. ROV and TMS having independent heading.

SIF 5: ROV-TMS tether cable failure

In the subsea location, when the ROV is undocked from the TMS, the pilot shall maneuver the ROV to the object of interest. During the process, based on the ROV heading with respect to the TMS, the tether cable will be subjected to twist, and the number of twists depends on the skill of the pilot, the nature of operation and the condition of the sea currents. During the operation, ROV and the TMS shall undergo heading changes which create twists in the tether cable. The number of twists depends on the relative 360° heading counts undergone during the operation and the same is shown in Fig. 8.

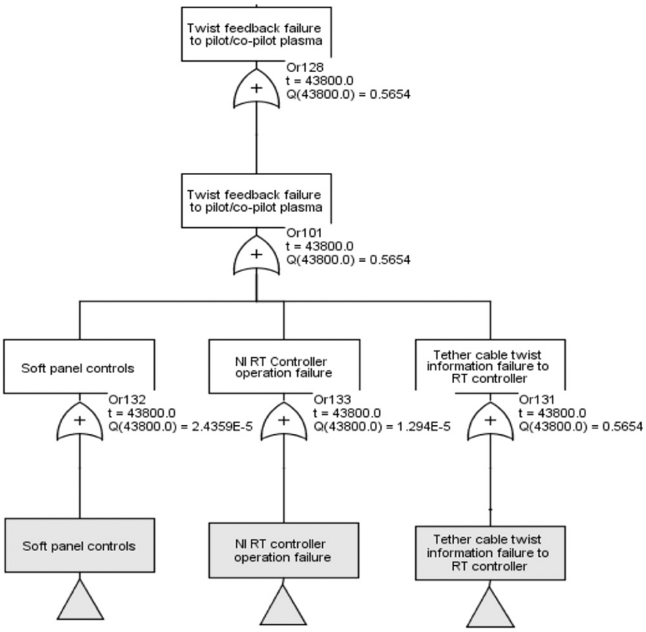

Fig. 9. Failure tree showing twist feedback failure probability.

When the ROV has completed the mission, it shall be docked back to the TMS and the operation needs all the released tether cable to be wound back on the TMS winch without twist. Tether cables are designed to withstand limited number of twists per meter length. When the number of twist per meter exceeds the allowable limit, the cable will be damaged [31]. To avoid cable damage due to twisting, the pilot has to ensure that there is no residual twist on the cable during docking. To aid in hassle free dock, the following sensor parameters are monitored by the control system. The sensors and the control systems are aided by a sea battery as a redundant power source, so that the monitored information is not lost due to a power failure during the docking instance.

i. ROV heading counts which are provided by the PHINS from the ROV.
ii. TMS heading counts which are provided by the heading sensor mounted in the TMS.
iii. Length of the cable reeled out of the drum, which is provided by the tether cable layer counter.
iv. Cable tension, which is provided by the pressure sensor mounted in the winch.

Fig. 8 shows the information being logged in the pilot computer console. As indicated in Table 7, HSE demands that the SIF implemented should comply with the SIL1. Fig. 9 shows the failure trees done to compute the PoF of twist feedback to the ship side from the ROV which has a failure rate of 19000 FIT. It is identified that the maintenance of the SIF hardware every 8.6 years will keep the PFD of the SIF at the SIL 1.

Fig. 10. Illuminated camera view of ROV docking to the TMS.

5.2. Man-in-the-loop safety instrumented functions

SIF 6: ROV-TMS docking operation safety

When the ROV completes the identified mission, it has to be docked with the TMS in the subsea, and the ROV-TMS docked system shall be brought to the subsurface close to the ship so that the system shall be docked with the LARS in the splash free subsurface region and be recovered to the deck. Fig. 10 shows the pilot view of the ROV close to the TMS for just before docking during 2008 operations.

The ROV pilot carries out the docking process with the aid of camera and lights located in the TMS. The following is the process sequence in carrying out a successful subsea docking process.

a. Pilot the ROV close to the TMS location.
b. Level wind the already released tether cable back in the TMS winch, free from twist, by operating the winch in the TMS.
c. Pilot the ROV vertically down the TMS and operate the top thrusters to produce a downward thrust (normally the ROV is upward buoyant by 20 kg) in such a way, that the tether cable is held under minimum tension during winding.
d. With the minimum tension in the cable, operate the TMS winch and wind the tether cable in a way that the cable is wound without any slack.
e. Continue the winding at a slower pace until the ROV enters the TMS cone, and gets into the latches (which will be indicated by the limit switches inside the latches).

Failure in any of the following results in a ROV-TMS docking failure.

a. TMS docking vision support.
b. TMS tether winch operation.
c. ROV operation for docking.
d. Tether cable twist indication from the TMS.
e. Human error.

In such a scenario, the ROV has to be salvaged after bringing it to the water surface. This is done by winding the deck umbilical cable until the TMS surface and docked with the LARS. As the ROV is linked with the tether cable, and as it is positively buoyant, it tends to surface. Fig. 11 shows such a condition. This surfacing is detrimental for the ROV and the released tether cable, as there are increased chances of entanglement with the ship systems such as thrusters. Recovery of the ROV and salvaging the ROV to the deck vessel has to be

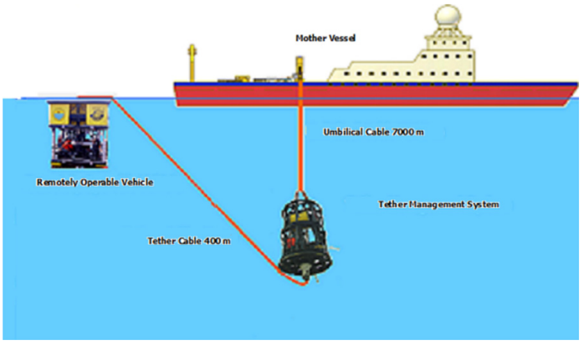

Fig. 11. View indicating system recovery after a docking failure.

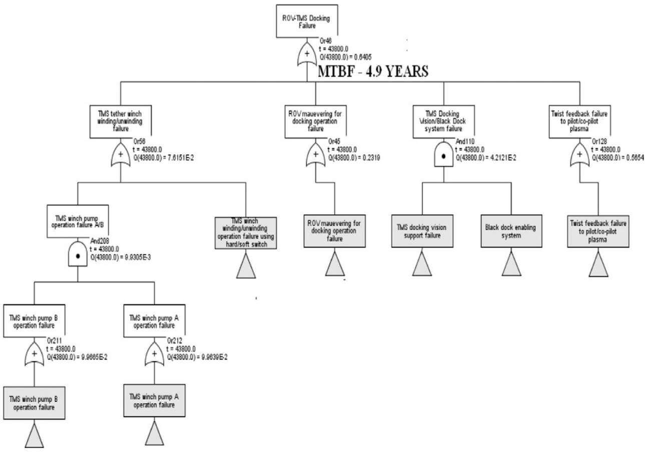

Fig. 12. Tree indicating probability of failure calculation for ROV-TMS docking failure.

done only by divers. This is an unsafe situation in terms of equipment and human safety. As indicated in Table 7, HSE demands that the SIF implemented which is characterized by the man-in-the-loop and should comply with the SIL 2.

From the operational point of view, the following are considered,

a. The system clocking 300 h per year.
b. Ten hours per dive.
c. Two docking operations per dive.

This shall result in around 60 docking operations per year. To have 100 % successful docking operations (i.e., zero PFD), it is required that the SIF should comply with the SIL2.

Fig. 12 shows the FIT for ROV – TMS docking failure computed using a failure tree which has a failure rate of 23350 FIT. The achieved SIL level for the SIF is found to be in line with the HSE computed requirements of SIL2, subject to a PTI of 7.6 months. However, as the SIF is characterized by the man-in-the-loop, the safe and skillful docking operation ensures the risk to be as low as reasonably possible (ALARP).

SIF 7: Manipulator operation safety

The ROV in the ROSUB6000 is equipped with two manipulator arms with 5 and 7 functions for carrying out subsea operation. The manipulators are operated by the personnel from the control console using joysticks. In addition to other vision systems, the manipulator arms are equipped with cameras which will give a real time video feedback to the operating personal. Fig. 13 shows the typical work class ROVs with manipulators involved in different kinds of tasks. The subsea operations depend on the mission objective and may involve tasks such as electric wet mate connector mate/ de-mate, pipe line valve operations, pipe line sacrificial anode fixing, etc. Thus the risk involved in these subsea operations varies widely. Fig. 13 shows the ROV holding one end of the wet mate cable connector for mating with the fixed ROV panel. The other end of the cable could be a part of the permanent subsea installation. When the manipulator operation fails in this condition, the forced retrieval of the ROV by winding back the tether or main umbilical winch, could damage the subsea installation. Thus, the ROV will be anchored to the subsea installation, with other systems connected to the ROV deployment vessel. Such damages could turn disastrous for subsea oil and gas wellheads and manifolds. To mitigate this situation, another intervention vehicle has to be dispatched for crisis management. Similar could be the condition, if the ROV is holding the oil pipe line valve which leads to damages and oil leakages.

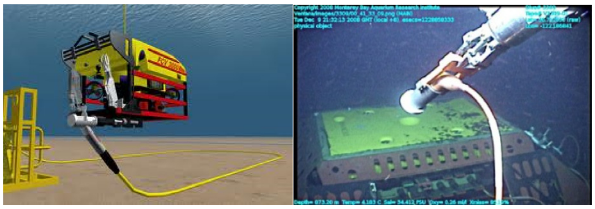

Fig. 13. Typical ROV manipulator in operation (Courtesy Internet and MBARI).

The following could lead to manipulator operation failure,

a. Manipulator functional failure.
b. Hydraulic pump motor electric system failure.
c. Manipulator operation vision support failure.
d. Operator error.

Therefore, the failure of the manipulator system while in operation is a potentially unsafe scenario. As indicated in Table 7, HSE demands that the SIF implemented should comply with the SIL2.

From the operational point of view, considering the diving frequencies mentioned in the ROV-TMS docking operation case, could result in not more than 100 manipulator operations per year. To have 100 % successful manipulator operations (i.e., zero PFD), it is required that the SIF should comply with the SIL2. Fig. 14 shows the PoF of the control and power systems associated with the manipulator operations which has corresponding failure rate of 18287 FIT.

The achieved SIL of the SIF is in line with the calculated HSE requirements subject to a PTI of 10 months. The maintenance of the SIF hardware every 10 months shall keep the SIF at the SIL2. Thus, the hardware and the control logics

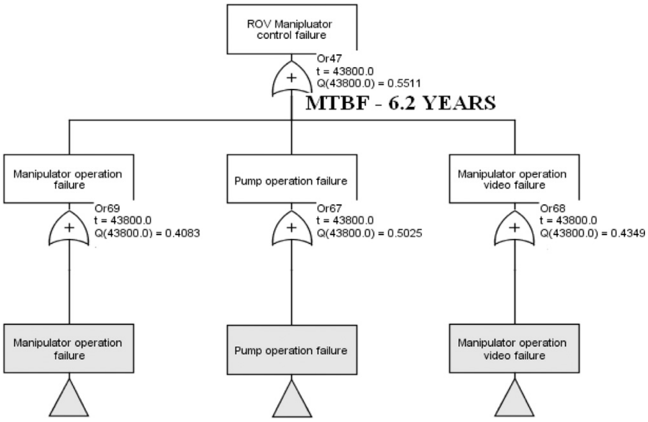

Fig. 14. Tree showing ROV manipulator control failure.

Table 8
Summary of SIL recommended and achieved for each SIF implemented.

Safety instrumented function	Failure rate of SIF (FIT)	HSE recommended and achieved SIL	PTI (years)
SIF 1 to avoid injury to operating personnel and damage to system and environment due to the system's electrical insulation failure and its consequences	4250	SIL2	5.5
SIF 2 to avoid damage to the system due to water leakages inside sealed pressure cases in ROV	25,260	SIL1	6.5
SIF 3 to avoid damage to the system due to water leakages inside sealed pressure cases in TMS	25,260	SIL1	6.5
SIF 4 to avoid ROV hard landing on the sea floor during	25,260	SIL1	6.5
SIF 5 to avoid TMS –ROV tether cable damage	19,000	SIL1	8.6
SIF 6 to avoid ROV-TMS docking failure	23,350	SIL2	0.62
SIF 7 to avoid manipulator operation failure	18,287	SIL2	0.83

involved are found to meet the PFD of SIL2. However, as the SIF is characterized by the man-in-the-loop, the safe and skillful manipulator operation ensures the risk to be as low as reasonably possible (ALARP).

6. Results and conclusion

A quantitative approach to the operational risk modeling and estimation methods of the safety integrity levels required for the deep water electric work class remotely operated vehicle (ROV) with reference to ROSUB 6000 is discussed. The methods and models for the quantitative assessment of operational safety and estimation of safety integrity levels for specific ROV operations are detailed. Table 8 summarizes the SIL levels achieved for the seven implemented safety instrumented functions and Table 9 shows the residential period of the SIF in each SIL zone. This paper which gives an overview of the numerical operational risk assessment methods and safety-centered ROV engineering can serve as guidance for design and safety engineers in the ROV industry.

Table. 9
Summary of SIF and the residential period in each SIL zone.

SIF	Residential period in each SIL zone (years)	
	SIL 2	SIL1
SIF1	5	Extended more than 10 years
SIF2	0.6	5.85
SIF3	0.6	5.85
SIF4	0.6	5.85
SIF5	0.76	7.8
SIF6	0.57	5.5
SIF7	0.77	7.9

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