A STRATEGY FOR RELIABILITY EVALUATION AND FAULT DIAGNOSIS OF AUTONOMOUS UNDERWATER GLIDING ROBOT BASED ON ITS FAULT TREE

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Abstract- Underwater vehicles contribute significantly to exploiting great maritime resources. Autonomous vehicles are one of the various kinds of underwater vehicles which are able to perform operations without operator's interference. Autonomous underwater vehicles can be classified according to their propulsion systems. Autonomous Underwater Gliders (AUG) are among autonomous underwater vehicles which fall under the category of glide type underwater vehicles. They are designed in a way that they benefit low energy consumption and a wide survey range. Their reliable design is one of the challenges facing their manufacturing. Fault tolerance is one of the important attributes in designing reliable systems. Recognizing, evaluating and facing the faults are of great importance in designing fault tolerant systems. This paper studies underwater Glider vehicles' subsystems, considers their faults and causes, and provides a typical fault tree for these vehicles form which glider reliability and the effects of glider subsystems on its failure can be driven.

Keywords- AUV, AUG, Fault Tree, Importance, Reliability, Risk Assessment.

I. INTRODUCTION

Underwater robots enable researchers to explore deep down the oceans and seas. Different types of underwater robots have been created which can be classified, based on their control system, into three groups: remotely operated underwater vehicles (ROVs), semi-autonomous underwater vehicles (SAUVs) and autonomous underwater vehicles (AUVs). Autonomous underwater vehicles use different propulsion systems for cruising under water. The propulsion system for these vehicles is designed in the forms of single thruster, multiple thruster, bio-inspired propulsion system (using wings or moving the body), jet and glider type. Autonomous underwater vehicles that cruise under water without any thruster by using buoyancy rules are called "Autonomous Underwater Gliders (AUG)". Underwater gliders have low energy consumption and are able to undertake distant and long-time missions. This is why they are sometimes called "oceangoing underwater gliders".

In addition to the stated attributes, Due to their higher reliability AUGs are used in various maritime industry applications such as oceanography, oilfields discovering, longtime monitoring of underwater oil and gas pipelines. Designing these vehicles is faced with different challenges such as modeling in nonlinear conditions, path planning and obstacle avoidance, designing reliable controller and risk assessment. Due to long distance cruise of AUGs, these vehicles are always subjected to loss. So, control system of these vehicles must be fault tolerant. Fault tolerance in AUGs involves confronting the faults and evaluating them. Generally speaking, fault tolerant systems possess features such as reliability, safety and performability. This paper constructs the Fault Tree model of AUG through recognition and classification of its faults, and also studies its reliability by means of the model. Risk assessment and fault diagnosis of AUG, based on the constructed model are both carried out.

A. Reliability

Reliability of a system is the probability of its correct functioning for a specified period of time. Reliability in autonomous underwater robots can be define from the two different viewpoints: time and distance. From the time view point reliability is the probability that the AUG carries out its mission at any specific time. From the distance view point reliability is the probability of correct functioning of vehicle at any distance from its mother ship. In addition, reliability can be referred to in case of missing vehicles and mission failures. There are various methods for modeling the reliability of a system among which Markov process, Petri Nets, Reliability Block Diagram (RBD) and Fault Tree Analysis (FTA) can be referred to. This paper uses fault tree method due to its ease of creation and power.

B. Fault Tree

A fault tree illustrates the ways through which a system fails. It states different ways in which combination of faulty components (called the "Basic Events") result in an undesired event in the system (called the "Top Event"). In this model, basic events are connected to each other through logical gates forming upper-level intermediate events. The gates are defined both statically and dynamically. Events describe the way subsystems become faulty, and the gates states the relation between the subsystems. Fault tree is a systematic fault diagnosing and detection method to find weakness points and design bottlenecks of a system in its design process to improve system quality. It is also a commonly used method for risk assessment of systems.

This paper is organized as follows. The next subsection is devoted to a short survey on fault evaluation works in underwater robots. Third section introduces the subsystems of an AUG, and investigates their potential faults. In the fourth section, hypothesis for drawing the fault tree is stated, and the fault tree of AUG is constructed. The discussions ended with a calculation and reliability evaluation.

II. FAULTS IN UVS – A SHORT REVIEW

For the first, reliability and safety of autonomous underwater vehicles was carried out by Ortiz et al. in. In reference, Madsen studied detection of faults in underwater vehicles and presented a logical diagram for depicting faults and their relations. In reference, Winchester and Govar dealt with analyzing maintenance of different kinds of propulsion systems in autonomous underwater vehicles. They evaluated energy systems and their fault probability as the main source for providing electricity for propulsion systems. Reference, studied the faults of Dorado AUV and highlighted its reliability improvement ways. It categorized the failure states of system into five group: "able to perform mission", "unable to perform mission", "able to perform normal mission", "able to perform critical mission" and "able to perform semi critical mission". Strutt et al., in reference, conducted a study on the causes of the loss of AUTOSUB2 under the Fimbulisen. The results of their analysis showed that the main reason for loss of the vehicle was the problem of its internal computer and energy system. Antonelli designed a program for fault evaluation and detection in AUVs and ROVs. A research group from Southampton University studied the faults and the probability of their occurrence in AUV in environments including open water, shallow water, sea ice and ice shelf. In this research 63 faults are recognized and their probability has been estimated. Juhan Ernits and Richard Dearden worked on the reliability evaluation and fault detection problems in underwater robots that must be kept underwater for a long time. Griffiths treated risk management and fault evaluation of AUTOSUB2 subsystems, in oceanography missions. In this study, he used the "Weibull probability distribution" function for the failure of system components in reliability computations. He also evaluated buoyancy system efficiency in three AUGs with high operational depth, and calculated the output for each of them with respect to their consumed energy. Bian and Mou first represented the fault tree of an AUV and analyzed its reliability with fuzzy inputs. In reference the probability of AUG colliding a ship in shallow water has been studied and the results simulated using Monte Carlo method. Brito et al. in examined the performance of 58 AUGs (23 Sea gliders with operational depth of 1000 meters, 16 Slocum G1 vehicles for deep seas, 13 Slocum G1 vehicles for shallow water, 3 Slocum G2 vehicles for deep seas and 3 Slocum G2 vehicles for shallow water) and presented their faults and failure. Hongli Xu et al. presented a fault tree of a type of AUV which can operate in 4500 meters depth, and then evaluated its reliability and MTTF. Zhiqiang Hu et al. analyzed the reliability of the mechanical system of a new conceptual AUV, using FMECA and FTA methods.

In spite of extensive research works conducted so far, there is not a reported research work on the reliability assessment of AUGs from their fault tree model. This paper, for the first time, constructs the fault tree model of AUG from its recognized operational faults, and evaluates its reliability from this model. The results are then compared with the reliability of AUV exist in the literature. The constructed fault tree enables designers to diagnose AUG's faults and their effects on the system performance.

III. FAULTS IN AUGS COMPONENTS

This paper divides the faults of AUGs into nine parts, and investigates the effects of each fault on their operation comprehensively.

C. Power system faults

Power system in AUGs is usually an electronic circuit. In such vehicles, any battery malfunction represents ceasing of all subsystems. Three protection systems monitors its behavior. Monitoring system reports any occurrence of short circuit or early battery discharge. The other two monitoring systems are responsible for monitoring battery voltage and voltage of other parts of the vehicle. Any fault in monitoring and protection systems leads to battery loss and consequently ceases the whole system.

D. Leak detection system faults

An AUG functions in different depths, for instance operating depth of Seaglider is 1000 meters whereas Since the Deepglider functions at operating depth of 6000 meters, it requires the appropriate water tied system. Failing of such system can make the vehicle flooded. On time operation of leak detection system prevents such event whereas its malfunctioning makes the vehicle drown. Power system faults.

E. Diving system faults

Diving systems in underwater robots appear in different types. In gliders, this system usually consists of a bladder and a buoyancy adjusting system. The bladder causes a change in reserve buoyancy which has the role of displacing the mass center. The bladder system functions when a capsule is filled with a fluid (oil or air) with a particular mass less than sea water. When the capsule is full, the existing water in the prepared reservoir is replaced by lighter fluid which brings about an increase in reserve buoyancy. The usual malfunction in bladder system is actually the leakage in the capsule from which the fluid pours out that finally causes the vehicle to drown. Any malfunction in buoyancy pump leads to inability in controlling the mass center.

F. Environment detection system faults

AUGs are equipped with many sensors, each for a specific measure. In addition, all AUGs are equipped with a CTD sensor to measure the amount of conductivity, temperature and depth. Any malfunction of these sensors will abort the vehicle mission**Error! Bookmark not defined.**.

G. Collision avoidance system faults

In order to avoid colliding with obstacles in AUGs, two visual and acoustic systems are used. The visual system usually consists of a camera and a light generating system whereas the acoustic system includes a sonar modem and a sonar transponder. Any malfunction in these systems cause the vehicle to collide with obstacles. In reference, the malfunctions are considered in two forms: the probability of colliding with sea floor, and the probability of colliding with floating objects. Being trapped in fishing nets is also considered in reference as another fault of AUGs.

H. Computer system faults

AUGs have three computers. The first is responsible for storing data; hence, its failure causes the loss of data, makes the mission in vain. The second is designed for path planning, and the third is for managing and monitoring different parts of the robot. Any malfunction or any bug in their software leads to system failure.

I. Propulsion system faults

In AUGs, the wings play the role of propulsion system by means of forming a specific angle along the vehicle's moving direction. In fact, fins change the force which is equal to the resultant force from weight and propulsion system applied vertically into a forward going force and create a coupling, as a result make the vehicle glide. If we consider the glider without wings, it would become an upward and downward moving object. In case of any malfunction in the wings' system or the wings being locked with an angle, the vehicles' propulsion system becomes disarranged. Any failure in rudder system endangers horizontal plan maneuver**Error! Bookmark not defined.**.

J. Communication system fault

A AUGs communicates with its nearest station through two satellite communication systems to send its mission reports to them. Any malfunction of these two systems breaks off the vehicle's contact with the station which makes drifting and getting lost more probable for the vehicle

K. Navigation system faults

In AUGs, the GPS antenna is usually located on one of the horizontal wings. Whenever the vehicle comes to the surface, through its 90 degree rolling movement the antenna locates in the highest place from water surface in order to receive the data in a stable condition. The roller system consists of a slider which carries a battery or a specific weight across the body. In some other types of these vehicles there is a flap behind the main rudder where the antenna is located. If this system or the rolling system confronts any problem, vehicle's location recognition becomes hard and the probability of vehicle’s loss is increased. It is obvious that any malfunction in GPS and its processor cause the vehicle to get lost.

IV. UNDERWATER GLIDER VEHICLE'S FAULT TREE AND EVALUATING ITS RELIABILITY

In this section, a strategy for construction of an AUG's fault tree model is presented, and its reliability is calculated from this model.

L. A Strategy to construct AUG's fault tree

In section 2, AUG's components faults are classified in to 9 groups according to its main subsystems. This subsection explains the construction of fault tree for two AUG's subsystems. The tree is constructed in five steps as follows:

1) Determine the level of faults occurrence (sensor, sub-subsystem, and subsystem). In this paper, the faults of only 3 levels are considered; component, subsystem and main system level.

2) Determine the contribution of each component faults in its upper level faults, and then use appropriate gate (AND and OR gate) to construct subsystem or main system’s fault tree. From probability theory, the output probability of AND and OR gates is calculated from (1) and (2) respectively.

$$P_{AND} = \prod_{i=1}^{n} (P_i) \quad (1)$$

In Equations (1) and (2), i denotes the gate input i^{th}.

$$P_{OR} = 1 - \prod_{i=1}^{n} (1 - P_i) \quad (2)$$

3) Consider each subsystem fault tree as a module of main fault tree. In this paper ten modules, nine subsystem and one unknown fault's sub-trees (triangle-shape event) are used.

4) Find available probability of each component's failure.

5) Construct the main fault tree and evaluate system

reliability by means of an available tool.

M. FT construction of navigation subsystems

According to the first step, the level of navigation subsystem's component is determined. In this subsystem, four basic events exist each one of which enables navigation subsystem and this is the way to use OR gate. Fig 1 shows the FT module of navigation subsystem.

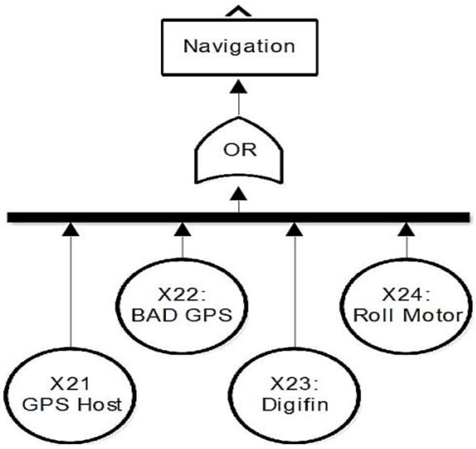

Fig 1. FT module of navigation subsystem in AUG

Using (2) and above FT structure, the reliability of navigation subsystem can be calculated from (3).

$$\begin{aligned} P_{Nav} &= 1-\prod_{i=22}^{25}\left(1-P_i\right) \\ &= 1-\left(1-P_{22}\right)...\left(1-P_{25}\right) \\ &= 1-\left(1-e^{-\lambda_{22}t}\right)...\left(1-e^{-\lambda_{25}t}\right) \end{aligned} \quad (3)$$

The result is time dependent and for time 0 to 2000 hours, reliability of AUG's navigation subsystem is present in Fig6.

N. FT construction of diving subsystems

Buoyancy pump failure and leakage on air bladder are two factors which cause diving subsystem failure and this is why OR gate should be used for their combinations. Fig2 shows the FT module of diving subsystem.

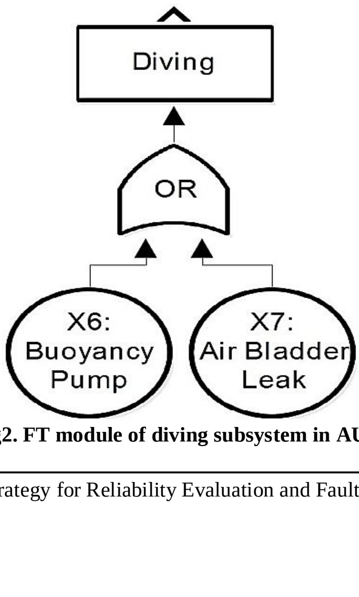

Fig2. FT module of diving subsystem in AUG

To calculate the probability of diving subsystem failure, (4) was written as follows:

$$\begin{aligned} P_{Div} &= 1-\prod_{i=6}^{7}\left(1-P_i\right) \\ &= 1-\left(1-P_6\right)\left(1-P_7\right) \\ &= 1-\left(1-e^{-\lambda_6 t}\right)\left(1-e^{-\lambda_7 t}\right) \end{aligned} \quad (4)$$

Redundancy is one of common methods which is applied to improve the reliability of each system. For example if two buoyancy pumps applied in AUG, then FT module is replaced by Fig3 and (4) rewritten as (5).

$$\begin{aligned} P_{Div} &= 1-\left(1-P_6 \cdot P_6\right)\left(1-P_7\right) \\ &= 1-\left(1-e^{-2\lambda_6 t}\right)\left(1-e^{-\lambda_7 t}\right) \end{aligned} \quad (5)$$

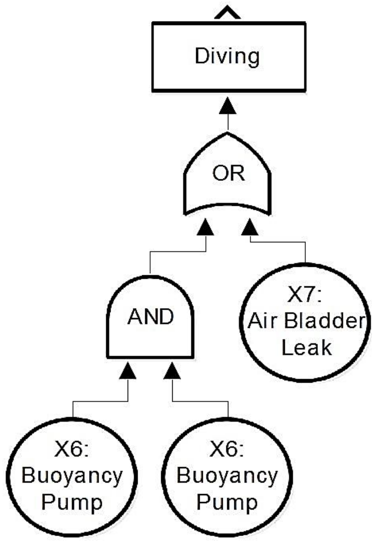

Fig3. FT module of diving subsystem with parallel buoyancy pump

V. NUMERICAL RESULTS

In this section, a fault tree of an AUG is constructed by the mentioned strategy and then implemented in MATLAB Simulink. In this fault tree, the following hypotheses have been considered.

1) The system components failure rate obeys exponential distribution function.
2) The occurrence of more than one fault at the same time is not allowed and the common cause failures (CCFs) are ignored.
3) On-time repairing of vehicle's components is not allowed.
4) Dynamic characteristics such as functional dependency, components' priority and the use of spares are not applied in the model.

By using of these hypothesis and the failure rate of components, extended from the fault tree model of AUGs is constructed and shown in Fig 4. This tree is now a valuable vehicle for diagnosing the system faults. The causes and effects of any intermediate event can be easily seen from the tree. For example the failure of "Power subsystem" is due to the failure of the either X5 or X4 or X3 or X1 and meanwhile it causes the system failure. From this model, the reliability of AUG is calculated for 2000 hours mission time. The obtained results are then compared with the AUV reliability values obtained from. As seen, AUG possesses 10 to 12 percent higher reliability than AUV. The reliability comparison results for power systems, navigation systems, and computer systems are also presented in Figs 6, 7 and 8 respectively. Power systems of both AUV and AUG have close reliability, whereas there are a big difference in the reliability of other two systems. It can be concluded that the difference in the reliability of AUV and AUG roots in the considerable differences in the reliability of their navigation and computer subsystems.

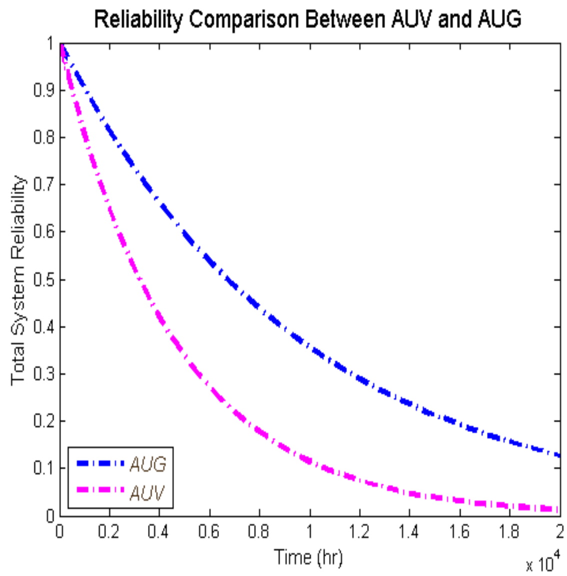

Fig4. Reliability comparison between AUV and AUG

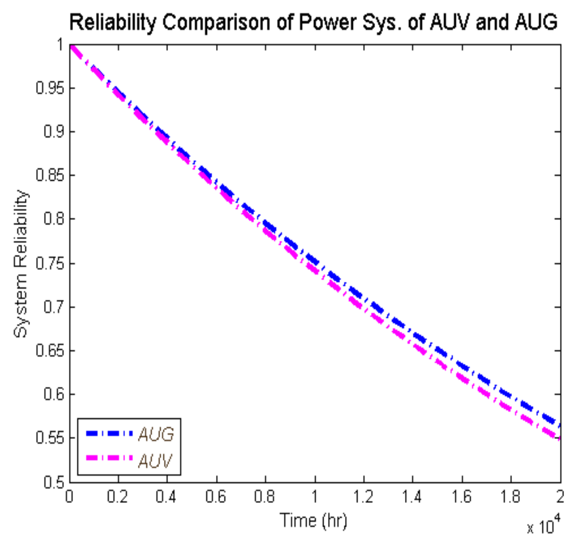

Fig 5. Reliability comparison of power systems in AUV and AUG

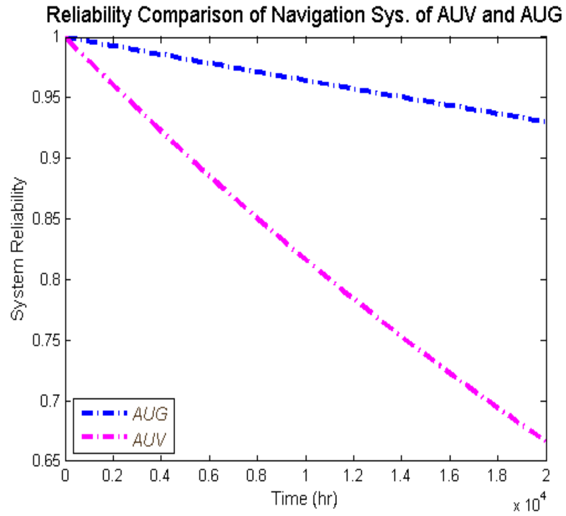

Fig6. Reliability comparison of navigation systems in AUV and AUG

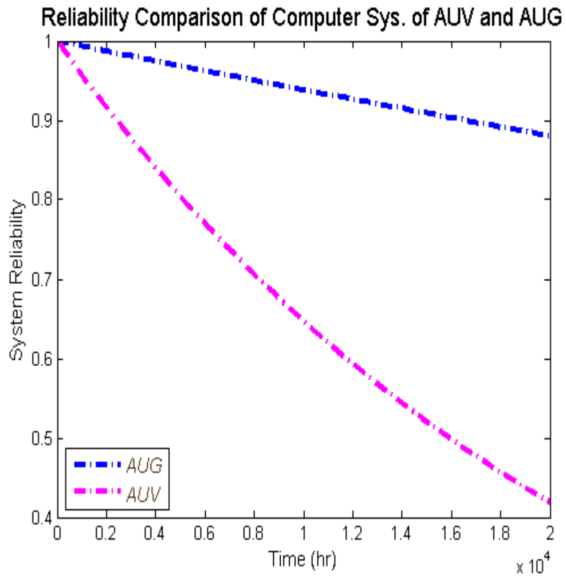

Fig7. Reliability comparison of computer systems in AUV and AUG

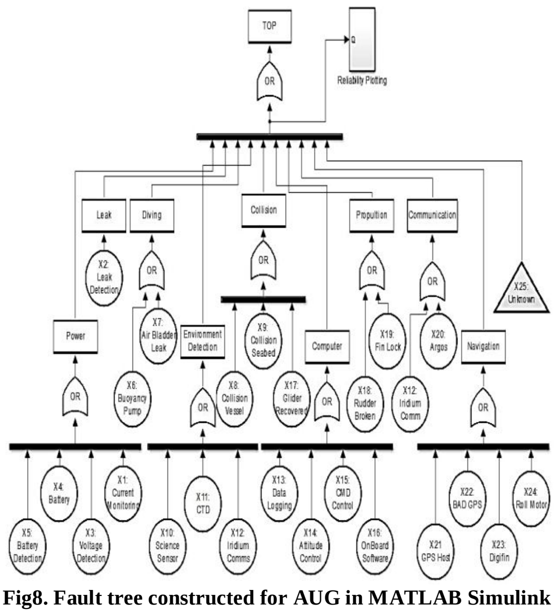

Fig8. Fault tree constructed for AUG in MATLAB Simulink

In the worst case when the system undergoes no repair, AUG can function at least for 2000 hours with reliability of about 0.8 and for 4000 hours with reliability of about 0.7. These rates are not acceptable in reality and the designers should use strategies such as online repairing, hardware and software redundancies and high quality components to improve system reliability. Using (6), one can evaluate the minimal cut-sets' importance from which the following are achieved further more Table I is deduced, using (6):

1) Finding the effect of any subsystem failure on the entire failure of the system.
2) Finding critical subsystems contributing the most of the system's unreliability.
3) Finding the impact of each subsystem's failure rate on the top event occurrence probability.
4) Finding cost effective ways to improve system reliability.

$$MCsI_i = \frac{P(MCs_i)}{P(TOP)} \quad (6)$$

TABLE I. PROBABILITY OF MINIMAL CUT-SETS AND MINIMAL CUT-SETS IMPORTANCE

AUG Sub-Systems	P(MCs)	MCsI
Power Sys.	0.5637863	4.45292
Leak Detection Sys.	0.7620066	6.01851
Diving Sys.	0.8808393	6.95708
Environment Detect Sys.	0.8616035	6.80515
Obstacle Avoidance Sys.	0.8650568	6.83243
Computer Sys.	0.8807865	6.95666
Propulsion Sys.	0.9643316	7.61652
Communication Sys.	0.9133464	7.21383
Navigation Sys.	0.6221463	4.91386

The study of Table I proves that the "power system" is the bottleneck for glider failure. Navigation system and leak detection system have the highest failure probability. The priority for redundancy applying or repairing strategy for subsystems can be assigned to the subsystems in Table II.

TABLE II. FAILURE RATE OF AUG COMPONENTS

Basic Event	Sub-Systems Failure	FR $\left(\lambda - \times 10^{-6}\right)$
X1	Current Monitor	6.500
X2	Leak Detection	13.590
X3	Voltage Detection	6.500
X4	Power/battery	8.154
X5	Battery Detection	7.500
X6	Buoyancy pump	5.436
X7	Air bladder leak	0.908
X8	Collision- vessel	3.624
X9	Collision - seabed	1.812
X10	Science sensor	3.624
X11	CTD	0.200
X12	Iridium communication	3.624
X13	Data logging	1.812
X14	Attitude control	2.719
X15	Command/control	0.908
X16	Onboard software	0.908
X17	Glider recovered by boat	1.812
X18	Rudder broken	0.908
X19	Fin locked at angles	0.908
X20	Argos	0.908
X21	GPS Host Computer	8.500
X22	Bad GPS	13.413
X23	Digifin not working	0.908
X24	Roll motor	0.908
X25	Unknown	3.624

CONCLUSION

Due to the low energy consumption and wide survey range of AUGs, these robots are at the center of attention for marine industries and oceanography researches. Designing reliable AUG is one of the challenges in academic area. Recognizing, evaluating and facing the faults are of great importance in designing fault tolerant systems. This paper studies underwater Glider vehicles' subsystems, considering the faults and their causes, and provides a typical fault tree for these vehicles from which glider reliability and the effects of glider subsystems on its failure can be driven.

ACRONYMS AND ABBREVIATIONS

AUV	Autonomous Underwater Vehicle
AUG	Autonomous Underwater Glider
BE	Basic Event
CTD	Conductivity, Temperature, Depth
FT	Fault Tree
FTA	Fault Tree Analysis
FR	Failure Rate
MCs	Minimal Cut-set

MCsI Minimal Cut-set Importance
ROV Remotely Operated underwater Vehicle
SAUV Semi-Autonomous Underwater Vehicle
UV Underwater Vehicle

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