A REPORT ON RISK ASSESSMENT OF UNDERWATER GLIDERS USING UNCERTAINTY ANALYSIS AND FAULT TOLERANT CONTROL

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ABSTRACT

Underwater gliders are important autonomous underwater vehicles for ocean observations. They are characterized by long endurance, low speed and high efficiency. Improvement of these vehicles can be achieved through decreasing uncertainties and increasing reliability in navigation. Uncertainty and reliability analysis is an efficient way of determining key points that have to be improved. Also, FTC is a widely used control method in autonomous systems, satisfying system continuity in errors. It is essential to apply it to underwater glider navigation system. Uncertainty analysis and FTC method can be used together to enhance system behavior and further determine important design factors.

Key Words: Underwater glider, uncertainty, reliability, FMEA, FTC.

1. Introduction

The significant part of the Earth's surface is covered by the ocean. Exploration of the ocean becomes crucial activity to understand the operation of the Earth (Tropea et al., 2007). However, some factors that prevent the explorations take considerable time. Quantity of the ocean, inhospitable environment for human being, price that need to be paid, uncertainty and fluxional situations definitely can be example to these factors. Research and examination of the ocean is crucial to protect and improve these effects and resources.

Observation, exploration and development are important parameters for improvement of the ocean observation systems. Stationary and passive systems have many disadvantages against mobile systems like AUVs, ROVs and AUGs with their high maneuverability and controllability (Zue, 2015). In addition to that, coordination and communication with multiple underwater vehicles can perform difficult and time consuming tasks easily. While designing and building these vehicles mathematical models of the system, the physical parameters of the vehicle, the loads and the working environments are taking into account. However, parameters like uncertain current and uncertain density of the seawater creates uncertainty problems in real engineering (Lei, 2016). So making the necessary uncertainty analyses is really important. Also, it is a lot more important to design a fault proof system for gliders as their work durations reach months. To do that, a fault detection and analysis mechanism with a fault control system that can repair and improve itself is necessary. In this paper there is an analysis of uncertainties of the glider and importance of the systems within, and also overviews of fault identification method FMEA and fault control method FTC with their applications on a part of glider navigation system.

2. Underwater Gliders

Underwater gliders are the vehicles that can operate unmanned and autonomously throughout the water column. Navigation and glide control are accomplished with usage of sensors together and in combination. Wetted sensors are used for gathering the physical, chemical and biological oceanographic data. Sensors on gliders can measure physical variables as pressure, noise (background, ambient, ships, marine mammal calls, etc.), temperature, salinity, current, biological variables relevant to the quantity of phytoplankton and zooplankton, and ecologically important chemical variables such as dissolved oxygen and nitrate.
Buoyancy driven underwater gliders use buoyancy engine to change their volume for propulsion and movement rather than conventional propeller. This mechanism has low energy consumption values and gives advantage to gliders operate in long term projects. They have inflatable external bladders to increase the volume of the glider. When the external bladder filled with liquid, buoyancy force is increased and initiate the upward motion (Barker, 2012).

Wings are the main components for the underwater gliders to gain horizontal motion and propulsion in the ocean while profiling. Wings use vertical motion to generate hydrodynamic lift force for horizontal motion and have an important effect on glide slope and angle (Lippsett & Carlowicz, 2008). Underwater gliders move with sawtooth pattern in vertical plane however in horizontal plane follow random route because of the currents and their effects.

Sensors are integral parts of the underwater gliders to collect data. Gliders can be used in different missions when sensors are replaced with suitable one. According to Kongsberg Underwater Technology, Inc. CTD sensors, fluorometers, dissolved oxygen sensors, PAR sensors, current profilers (ADCPs), optical backscatter and other sensors can be mounted to underwater gliders (2013). With the help of gliders, salinity and temperature profiles versus depth can be obtained, pollutants in the ocean can be tested and monitored in an automated way. Depending on the vehicle's configuration scientists can measure the health of the ocean with the help of phytoplankton. While climate is based on ocean currents, collected data and instant data transmission by underwater gliders help scientists to refine climate models and improve forecasting (Dent, 2014). Underwater glider fleets also help to collect data for improvement of storm intensity forecast during hurricane seasons (Oceanservice.noaa.gov, 2013).

Another usage area of the underwater gliders is military applications. Silence and stealthiness are important properties for Navies. Usage of buoyancy changing mechanism as propulsion system makes gliders pretty quiet and hard to detect. Small dimensions and body, easy deployment even from a small boat also significantly satisfy the Navy’s desires and requirements. Firstly, gliders are being used in Navy to collect crucial data and guide the fleet. For example, U.S. Navy Lt. Cmdr. Patrick Cross mentions that “The gliders are a great way to have a persistent sensor out there to continuously feed us data on what the ocean is doing. Then we can feed that to our shore-based computer models and get a better picture of the ocean” (Rush, 2005). Secondly, gliders can be used to spot submarines and underwater mines with their capability of environmental characterization of denied areas, passive detection of acoustic sources, sustained monitoring and surveillance of marine regions, and multistatic acoustic detection (Cmre.nato.int, 2014).

3. Uncertainty

Uncertainty analysis investigates the effect of lack of knowledge or potential errors of the model. Uncertainty is incomplete knowledge and information about a system as well as inaccuracy of the behavior of systems. Uncertainty can be categorized into three groups as physical uncertainty, statistical uncertainty, and modelling uncertainty (Thof & Murotsu, 1986). Physical uncertainty caused by physical quantities, such as loads, material properties and environmental changes. This uncertainty also be called aleatory and random uncertainty. This type of uncertainty cannot be reduced or eliminated by means of collection of additional information because of that there is always be unpredictability in the variables. However, uncertainty can be quantified by examination of the data. The statistical uncertainty arises due to a lack of information. Distribution parameters can be considered as random variable according to given data set. This uncertainty also be called epistemic and systematical uncertainty. Caused by limited information or lack of knowledge on a quantity. The model uncertainty caused by assumptions and unidentified boundary conditions and their interaction with the model. To design and develop a model, a lot of assumptions and hypotheses have to be defined. Even if these assumptions are chosen correctly, model need to match with the real world conditions. (Liu, 1996).

An uncertainty analysis uses the occurrence levels to determine the possible outputs and possibilities of the outputs. The probabilities of observing particular range of values of a random variable are described or defined by a probability distribution.

Uncertainty analyses involve identifying characteristics of various probability distributions of model input and output variables, and subsequently functions of those random output variables that are performance indicators or measures.

Uncertainty analyses can be used for:

- Determination of probability and outputs range and tresh holds.
- Determination of standard deviation of the system and the effects of inputs to the outputs.
- Determination of the total relaibility of the system and estimating the possible outcomes.

3.1 Sensitivity

Sensitivity is another important parameter for the system reliability with the uncertainty. Sensitivity analysis is a method to determine which variables, parameters or other inputs have the most influence on the model output. This involves a study of the effect each of the different parameters has on results of reliability analysis of the overall system. If the overall effects of changing a variable are found to be small, then the variable can be treated deterministically. However, where changes in a variable are found to affect the overall reliability significantly, then it is important to model the variable by using the best available distribution.

3.2 Uncertainty Analysis on Underwater Gliders

3.2.1 Faults in Underwater Gliders

Potential faults in underwater gliders can be grouped under these titles:

Power System Faults: Battery problems is the most important parameter in the gliders because any malfunctioning cause stopping of all systems. Because of that all battery systems are being monitored autonomously all the time for short circuit, voltage changes and voltages on components.

Leak Detection System Faults: Underwater gliders' working depths can reach up to 5000 meters. That means these vehicles needs proper sealing and water tide systems. Leak detection system faults can be end with loss of the vehicle. While operation continue this system protect the vehicle from drowning with surfacing if there is a leak.

Diving System Faults: There are two type of diving mechanism that control the glider. Most important one is the bladder system that can change the reserve buoyancy of the vehicle with changing the fluid inside the capsule that located aft side of the vehicle. Water inside the capsule is replaced with the lighter fluid like oil which is kept inside reservoir cause increase in buoyancy. Second type is the ballast system that can take and discharge the water with pumps. Leakage in the capsule block the diving system and make impossible to change buoyancy which result in drowning of the vehicle. Malfunctioning in buoyancy pumps prevent the changing center of gravity that affect the control of the glider.

Environmental Detection System Faults: Underwater gliders can be equipped with various type of sensors that can collect physical, chemical and biological data. However, every underwater glider equips CTD (Conductivity Temperature and Depth) that can collect changing salinity and temperature with depth. Malfunctioning in these sensor will abort the mission because of the inability of the collection of required data.

Collision Avoidance System Faults: Collision of the underwater gliders can be classified in two groups that are collusion with sea floor and collusion with the floating objects. Trapping in fish nets also can be considered as the probability of the collusion of underwater glider systems. Underwater gliders use sonar modem, sonar transponders and altimeter to prevent the collusion. Any malfunction of these systems can be end with the collusion.

Computer System Faults: Underwater gliders mainly have 3 different computer systems. First one is for storing the collected data. Faults in this computer makes the mission useless. Second one is for navigation and planning. Last on is for monitoring the systems and coordination. Malfunctioning in these computers jeopardize the mission and can lead to system failure.

Propulsion and Stability System Faults: There no propeller on the underwater gliders however propulsion is fulfilled with the help of wings and fixed fins. Failure or rupture on these parts affect the gliders moving mechanism. Thus, glider cannot move in horizontal plane and correction of the diving angle will be impossible. Pitch and roll motion correctors failure lead to unstable diving and wrong navigation. These faults lead the failure of the mission.

Communication System Faults: Underwater gliders communicate with the control center throughout satellite. Connection occur at surface and glider transmit the collected data and take the upcoming mission requirements. If communication cut off glider can be lost and start to drift uncontrollably.

Navigation System Faults: Location data collected with the GPS antenna which can be located on one of the wings or aft section of the underwater glider. Antenna locates on the surface in order to get data in a stable condition. If the antenna locates on one of the wing gliders need to roll at the surface with moving its battery side to side. Other type need to put its aft section out of the water with the help of buoyancy mechanism. Any malfunction on these systems resulted in loss of the glider.

3.2.2 Uncertainty and Reliability of Underwater Gliders

Underwater gliders are autonomous and unmanned systems therefore reliability is the most important parameter to prevent the loss. Minimal cut sets and cut sets will be used to determine the effect of subsystems to the entire system failure, to find the focus points on the subsystems and which system create the most unreliability on the entire system. Cut sets are the unique combinations of component failures that can cause system failure. Minimal cut sets can be used to understand the structural vulnerability of a system. The longer a minimal cut set is, the less vulnerable the system is to that combination of events. Also, numerous cut sets indicate higher vulnerability. Cut sets can also be used to discover single point failures (one independent element of a system which causes an immediate hazard to occur and/or causes the whole system to fail). To find the minimal cut sets, formula (1) that below is used and the chart is created. P(MCs) and MCsI values are found with the stress and reliability tests that applied to glider. These tests showed effect of the subsystem failure to the entire failure of the system and critical subsystems for the system unreliability. Tests also revealed that the failure rate of the subsystems and the occurrence probabilities.

$$MCsI = P(MCs)/P(Loss) \quad (1)$$

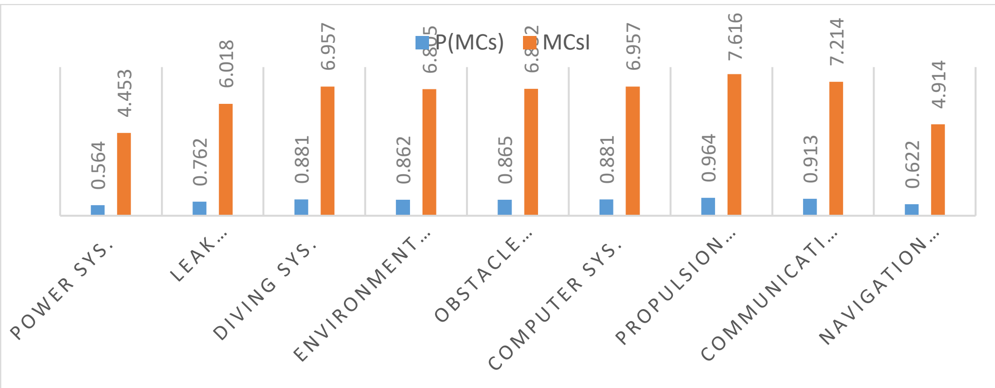

Figure 1. Minimal cut-sets (MCs) and minimal cut-sets importance (MCsI) of the systems

Created chart shows that the power system is the heights probability of failure. This affects the reliability of the vehicle and need to be improved. Power system is the energy source of the glider and first parameter need to work perfectly. Any malfunctioning in this system lead to loss of the underwater glider. Navigation system and leak detection system have the highest failure probability after the power system. Improvement priority need to be organized according to the failure probabilities and rates of the subsystems. (Aslansefat, 2014).

Table 1: Failure rate of the subsystems

Sub-System Failure	FR(λx10^{-6})	Sub-System Failure	FR(λx10^{-6})	Sub-System Failure	FR(λx10^{-6})
Current Monitor	6,5	Science Sensor	3,62	Rudder Broken	0,91
Leak Detection	13,59	CTD	0,2	Wing Broken	0,91
Voltage Detection	6,5	Iridium	3,62	Argos	0,91
Power/Battery	8,15	Data Logging	1,81	GPS Host	8,5
Battery Detection	7,5	Attitude Control	2,72	Bad GPS	13,41
Buoyancy Pump	5,44	Command/Control	0,91	Pitch Motor	0,91
Air Bladder Leak	0,91	Onboard Software	0,91	Roll Motor	0,91
Collision Vessel	3,62	Glider Recovered	1,81	Unknown	3,62
Collision Seabed	1,81				

4. Fault Tolerant Control

As underwater gliders are autonomous vehicles they benefit from the FTC method a lot in every aspect of their operation. In the case of a glider, most important operation it does is navigation. Its data quality, maximum work time and damages to vehicle is all related to navigation efficiency and success. So navigation related errors are one of the most important possible error types in a glider. In this part possible navigation errors are defined using FMEA method and FTC method is used to create a fail-safe system.

4.1 FMEA Method

To determine possible problems and understand their effects on the system FMEA method is a good choice. Results of FMEA method is also adaptable to FTC system very well. FMEA stands for “Fault Mode and Effects Analysis”. Carlson states that FMEA is an engineering study that is done by a team of experts on subject to find and fix the weaknesses early on (2014). In that matter, FMEAs depend mostly on expert knowledge and error data if available. By applying FMEA, we can prevent dangerous errors before operation, increase reliability of the system and evaluate the system from a new point.

FMEA has six steps approach. Those are; determination of failure modes, evaluating severity, probability and detection numbers, calculating risk priority number and determining the necessary actions. Severity number tells that how serious the failure is, probability number show how likely is it for the failure to occur and detection number states is the detection of the failure early on is easy or not. When those three numbers are multiplied the RPN number occur. If the RPN number is high, it means that the failure is a dangerous one for our system and has the priority on getting fixed. Generally, all that information is collected on a table with severity, probability, detection and RPN numbers; name, position, cause and effect of the failure and also the suggestion on how to deal with the failure giving the user a good overview.

There are a lot of direct and indirect benefits of the method. First of all, FMEA is an easy process to make. It also supplies other failure detection and isolation techniques with meaningful data. FMEA increases reliability, quality and safety of the finished product. Those improvements increase customer satisfaction. On the other hand, method requires experts of different disciplines to work together and their performance will affect the performance of the method directly.

4.2 Fault Tolerant Control Method

Fault tolerant control is the main systematic for most of our modern day autonomous applications. It is basically a method, used to make a system continue working even if there are errors in the system. When a fault occurs in a system, ideally it has to be detected fast and then replied with a fix if possible. Main frame of FTC system consists of a self-repairing, reconfigurable and self-designing control structure. It consists of two main parts; fault diagnosis and control redesign. Faults in a system are diagnosed and identified in the fault diagnosis step and then in control redesign step controllers are adapted to the system with fault so that it can continue working. If severity of the error is high, power degradation is also an acceptable solution. Fault tolerant control can be applied to all systems. However, FTC is a complex mixture of three research fields; FDI (Fault Detection and Isolation), robust control, and reconfigurable control which make it a complicated and expensive. So it is applied into systems within the condition of critical safety.

4.2.1 Structure

There are several different structure types of FTC and they are grouped under 3 categories. However, before that terminology should be understood. Here is the basic terminology used in FTC applications:

- Fault: A deviation of a parameter of the system from acceptable condition
- Failure: A permanent interruption of system's ability to perform its goal
- Error: A deviation between measured and computed value
- Controlled system: A plant under consideration with sensors and actuators
- Fail-operational: Operational system without a performance change despite failure
- Fail-safe: A system that fails to a state which is considered safe

Fault types are also separated to three categories as seen below:

- Plant faults: Changes dynamics of I/O properties. Physical parameter of system changes such as coefficients.
- Sensor faults: Plant properties are stable but sensors have errors. These faults represent incorrect reading from the sensors. They can happen due to wire defects.
- Actuator faults: Plant specifications are not changed but controller effect on the plant is disturbed. They represent partial or complete loss of control action

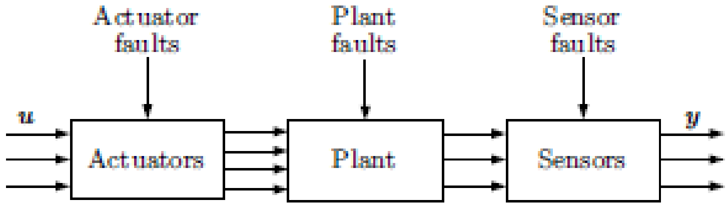

Figure 2. Way of input to output with faults (Blanke et al., 2006)

Timing of the faults are also important for FTC structure. Abrupt faults occur instantly and can happen as a result of hardware damage. Incipient faults are the ones that occur or change slowly with time. Intermittent faults come and go randomly, many time.

Structures of the FTC can be categorized in three main title. Those are embedded systems approach, distributed diagnostics and remote diagnosis. In embedded systems approach fault analysis and controller reconfiguration is done on the main control of the system. Main computer can reach all error information and all algorithms that can be used in faults. Distributed diagnosis is a structure that distributes information and possible answers to a problem between multiple systems, linking them to each other. It is used to find fixes to faults that require a lot of computational work. Remote diagnosis is the last structure type. It uses an on board controller and an off board controller group. Onboard one has limited power but off board group has a huge computing power. On board system detects the possible faults while off board group is responsible for identifying and isolating the fault.

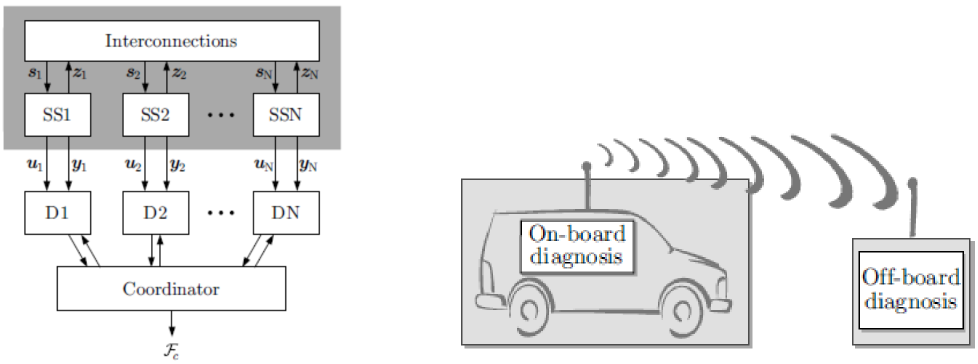

Figure 3. Coordinated diagnosis and remote diagnosis structure (Blanke et al., 2006).

4.2.2 FTC Types

There are mainly two types of FTC. One of them is passive and the other one is the active fault tolerant control. Passive FTC is also called robust control and handles failures without the need of a FDI system. It has high reliability for a certain number of faults and uncertainties. In robust control the worst case scenario algorithms are used. Even in case of a little fault this setup may cause power degradation in system. On the other hand, robust control gives fast and exact responses to faults in its range. Active fault tolerant systems depend on an assistant FDI system. AFTC system has a complex structure and it responds to failures actively. AFTC can answer a wider variety of faults and can improve itself over them. AFTC has many sub-method and also has a wider variety of application. It also has research possibilities and many areas to improve. But it is complicated and because of its high mathematical requirements, it is expensive and hard to apply. Fault Detection and Isolation system or FDI is one of the most important parts of AFTC. Its function is to detect the failure and the find its location. Reliability of this system plays a great role in reliability of the AFTC in general.

4.3 Application of FMEA Method

FMEA will be a guide to supply necessary information for FTC method later. To apply FMEA, we need to first determine possible failure modes, second, assign severity, probability and detection values and third, calculate the risk priority numbers (RPN) for each failure mode. For this work, experience, technical sheet information of individual parts of the system and some experimental data are used rather than statistical failure data as there was not enough data. For severity, probability and detection values general tables and ranking are used. In the, Table 2, 3 and 4 below, the used parameters can be seen for these values.

Table 2: Severity Table

Effect	Severity	Ranking
Hazardous without warning	Failure mode affects safe system operation without warning	10
Hazardous with warning	Failure mode affects safe system operation with warning	9
Very high	System inoperable with destructive failure	8
High	System inoperable with equipment damage	7
Moderate	System inoperable with minor damage	6
Low	System inoperable without damage	5
Very low	System operable with significant degradation of performance	4
Minor	System operable with some degradation of performance	3
Very minor	System operable with minimal interference	2
None	No effect	1

Table 3: Probability table

Probability of Failure	Probability	Ranking
Very High	>1/2	10
	1/3	9
High	1/8	8
	1/20	7
Moderate	1/80	6
	1/400	5
	1/2000	4
Low	1/15000	3
	1/150000	2
Remote	<1/1500000	1

Table 4: Detection Table

Detection	Likelihood of Detection by Design	Ranking
Absolute uncertainty	Cannot detect	10
Very remote	Very remote chance of detection	9
Remote	Remote chance of detection	8
Very low	Very low chance of detection	7
Low	Low chance of detection	6
Moderate	Moderate chance of detection	5
Moderate high	Moderately high chance of detection	4
High	High chance of detection	3
Very high	Very high chance of detection	2
Almost certain	Design control will detect the failure	1

The possible failure modes in the navigation system are determined in sub-system basis. In the ballast mechanism there are ballast pump, tank and coupler parts. Main control unit is made of mother board. Pitch Motion system has pitch motor, shaft and coupler. Roll motion system is made of servo and a coupler. Energy unit has batteries and cables. Antenna is a part of communication system. Pressure sensor, altimeter, gyro and collision sensor are parts of sensory unit. Lastly, wings are included under hull sections. When all of those sub-systems are investigated the most possible failure types can be understood and the effect of the failure can be derived from there using experience or computer simulation methods. If we group all the information for FMEA in a table, Table 5 appears.

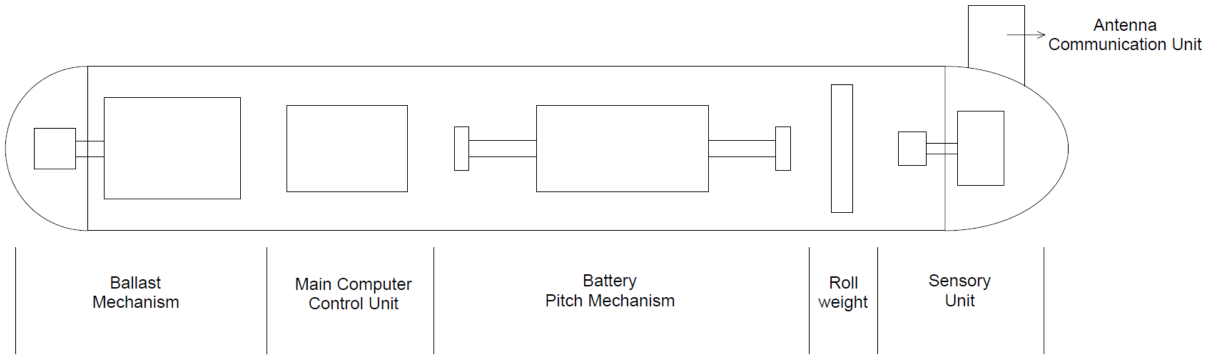

Figure 4. A generic underwater glider with sections used in navigation

Table 5: FMEA table for possible glider navigation system errors

Parent Mechanism	Item / Function	Potential Failure Modes	Potential Effect of Failure	Sev	Potential Causes of Failure	Prob	Detection Mode	Det	RPN
Ballast Mechanism	Ballast Pump	Break down	Cannot pull/push water	6	Low power-Cable separation-High pressure-Random	5	Vehicle cannot change direction	9	270
	Ballast Tank	Crack	Water fills in hull- Overall weight increases	9	Material fracture	1	Vehicle cannot go up	3	27
	Coupler	Separation	Pump cannot pull/push water	5	Material deformation/fracture	2	Vehicle cannot change direction	7	70
Main Control Unit	Mother Board	Break down	Information transfer to motors and communication units stops	10	Random	2	Control unit cannot get signal or cannot connect satellite vehicle cannot move as needed	8	160
Pitch Motion system	Pitch Motor	Break down	Unable to change longitudinal center of mass	5	Low power-Random	5	Cannot achieve nose up/down position gyro pitch reading is stable over time	9	225
	Mill	Stuck	Unable to change longitudinal center of mass	5	Material fracture-bending	5	Cannot achieve nose up/down position gyro pitch reading is stable over time	5	125
	Coupler	Separation	Unable to change longitudinal center of mass	5	Material deformation/ fracture	2	Cannot achieve nose up/down position gyro pitch reading is stable over time	7	70
Roll Motion System	Roll Servo	Break down	Unable to change transverse center of gravity	4	Random	5	Cannot achieve turning with necessary angle cannot achieve needed location	9	180
	Coupler	Separation	Unable to change transverse center of gravity	4	Material deformation/ fracture	2	Cannot achieve turning with necessary angle cannot achieve needed location	7	56
Energy Unit	Battery Unit	Break down	Power loss at mother board and engines	7	Random	5	Emergency control/battery unit cannot get signal from main control/battery unit	9	315
	Battery Unit	Short circuit	Unable to achieve necessary voltages- main computer and/ or electrical engines stop-fire	9	Open cable/ Human error-water in hull	3	Circuit controller sensors	4	108
	Cable	Connection Fail	One or more motors stop-Mother board stop- short circuits	7	Material fraction-random	6	Circuit controller sensors-information of motors not working- no signal from main control	7	294

Parent Mechanism	Item / Function	Potential Failure Modes	Potential Effect of Failure	Sev	Potential Causes of Failure	Prob	Detection Mode	Det	RPN
Comm. System	Antenna	Crack/ Break/ Underwater	Unable to connect to satellite or low rates of connection	4	Collusion	4	Cannot transfer or retrieve data from satellite or very slow rates- transfer taking a lot more than usual	8	128
	Satellite	No connection /offline satellite	No satellite connection	4	Human error-random	3	Cannot transfer or retrieve data from satellite for long time	5	60
Sensory Unit	Pressure sensor	Breakdown-Connection - false readings	Unable to detect water depth/ adjust pitch of vehicle	5	Random-systematic	3	A different reading than expected set-cannot get any depth value	8	120
	Altimeter	Breakdown-Connection - false readings	Unable to detect sea floor distance/adjust pitch of vehicle	4	Random-systematic	4	A different reading than expected set-cannot get any value	9	144
	Gyro	Breakdown-Connection - false readings	Unable to determine pitch and roll angles of vehicle	5	Random-systematic	3	A different reading than expected set-cannot get any value	7	105
	Collision sensor	Breakdown-Connection - false readings	Hit an object or stop movement	6	Random-systematic	2	A different reading than expected set-sensor is offline	8	96
Hull	Side Wings	Crack/Break	Loss of forward velocity	7	Collusion-Material fracture	4	Unable to achieve necessary distance between 2 satellite connections	8	224

4.4 Application of FTC Method

Most of the errors in a glider are the type that can bring system in the edge of loss of vehicle. However, there are also some measurements that can be taken to increase mission time if errors can be identified beforehand. First we need to determine how each sub-system work and what to do in a total failure situation. It can be done by making basic flow charts for all subsystems. In the Figure 5 the main control logic can be seen. For underwater vehicles, thruster related faults are a significant source as they have direct effect in performance of UV and in recent years some FTC studies emerged for UV splitting the system into thruster and sensor subsystems (Liu & Zhu, n.d.). For underwater gliders there are no external thruster, but internal motors are used a lot and they also the most important performance aspect in glider navigation. An example of pitch motion flow chart is in the Figure 6 below.

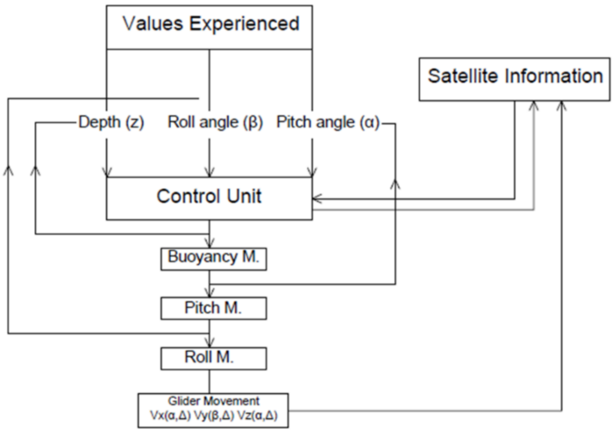

Figure 5. Main logic of navigation system control

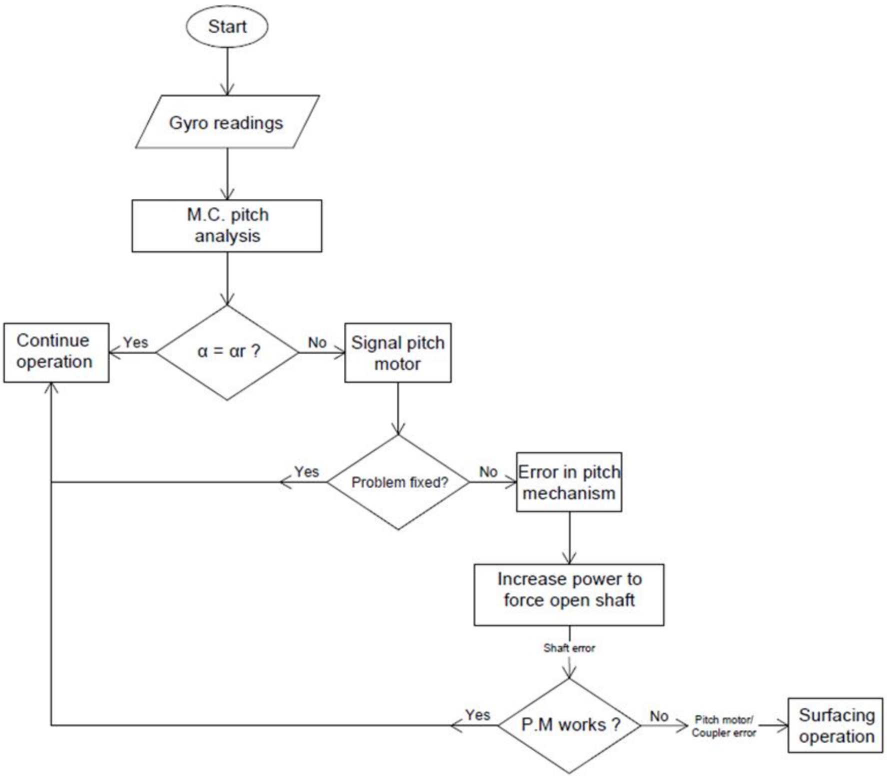

Figure 6. Pitch control unit flow chart as an example (α_r is reference pitch angle)

The flow charts are made to see how the mechanisms should work. Now it is needed to do an importance ranking in all of those errors and insert some redundant hardware or software for the ones with most benefit/cost ratio. Benefit/cost ratio is our limiting point here as there may be numerous improvements for each sub-system making design stage a lot longer.
It is clear that in a glider an emergency mother board and battery pack is required as redundant hardware. What is harder to determine is that what improvement can be made to high RPN motor and sensory breakdowns. To give an example to let's take pitch control system as in the flow chart above. If the shaft on weight transfer unit gets jammed the pitch motion will stop. The first mission of a fault-tolerant control is finding and identifying the faults that are present (Blanke et al., 2006). So it should be found that if fault is there. By taking data from the gyro we can determine whether center of gravity shifted enough or not. Of course there can be little disruption on the measured pitch angle but by taking data every sampling time for brief time steps, it is possible to pick the error that is important to us. To detect the error, we can use a simple formulation as follows:

$$e(k) = \frac{1}{5}\sum_{k=k_0}^{k_0+5}\left(\alpha(k) - \alpha_r(k)\right)^2 \qquad (2)$$

Where $\alpha(k)$ is signal and also pitch angle of the vehicle and $\alpha_r(k)$ is reference pitch angle; if e(k) > λ (fault limit) then there is an fault. The extend of the fault can be found by using fault identification networks like SOM, CMAC or ICMAC and the output from there gives us parameters of degree of fault. For our case it can be a “c” parameter where:

c=1.0 for normal state
c=0.66 for jammed state where weight movement in unit time on shaft is between full value and half value.
c=0.33 for jammed state where weight movement in unit time on shaft is between half value and zero.
c=0 for complete stop

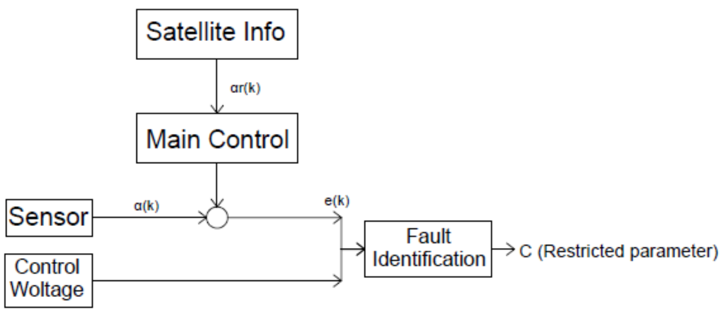

Figure 7. Mechanism to verify fault and restricted parameter.

After we got our “c” value main control system will adjust the voltage that goes to pitch motor. By that, motor will produce more power and break-pass the jammed part opening the shaft or else system will act as in the flow chart. The error calculation and the restricted parameter value can be made exact for the sub-system by increasing simulation and experiment amounts. With every error situation system will go for a finer error fix state, cutting unnecessary performance degrading actions.

FTC method in general is a hard method to apply but even the easiest part that is done in this paper can improve operation quality a lot. If this can be applied to all sub-systems, effects of errors on the system would very low.

5. Conclusion

Underwater glider is still a developing vehicle. Long endurance, large cover area, variety of sensors and autonomous control parameters increase attention for marine researches. However, reliability is a big concern for these vehicles. Gliders are formed with various subsystems and controlling these systems is important to prevent the lost. Uncertainty analysis can be efficient way to narrow down the possibilities of failure. Determination of possible malfunctioning points, failure rates and causes can be the key of increasing reliability of the whole system. Uncertainty analysis is a useful method for defining and analyzing the failure probabilities.

On the other side, FTC is a good method to use in designing a fault proof autonomous underwater vehicle and it is gaining popularity. The core of the method and its branches are highly mathematical modelling orientated which makes its application hard in complex systems. As a result of gliders special movement mechanism, finding error information and developed control system charts from other UV types, in literature is a lot harder. This creates requirement of expert knowledge and model simulations. In the future, when the collective information on those systems increases, all of the possible errors that are talked about in the paper can be analyzed to core and developed according to FTC.

Synthesis of FTC with uncertainty analysis is also very important. Nearly all of the errors analyzed with FTC have uncertainty problems in it. So, whether we are doing a standalone uncertainty analysis or a FTC analysis, mixing the methods and understanding the uncertain parameters will have a big importance.

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