Fault Tolerance Considerations for Long Endurance AUVs

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SUMMARY & CONCLUSIONS

Autonomous Underwater Vehicles (AUV) work in a harsh and uncertain environment which imposes challenges on their energy, navigation, and communications. Given the environment, there is little bandwidth to communicate solutions to an on-board fault or failure. The AUV application discussed is for Naval Mine Countermeasures (NMCM) survey and minehunting missions. For such missions, operational availability, reliability demands, and system safety are of high importance. To address this, an on-board Fault Detection, Isolation and Recovery (FDIR) system is provided by the manufacturer for basic faults like slow leaks, over-depth, and time-outs due to unreceived operator commands. With that, most AUVs can implement a scripted mission but are generally unable to recover from more complex failures like low energy, or reduced functionality in hydroplanes. These two cases are presented here as implemented examples. The examples show that an autonomous on-board recovery system could be devised and implemented for timely recovery from these types of failures. With such measures, the AUV can be adaptive and as fault tolerant as possible to unexpected changes in itself, the environment and the mission. The recovery employed machine learning to gain insight into the best solution for a specific failure and the reason for failure from observations on faults/failures. Further, dynamic Bayesian networks (DBN) are proposed as a novel FDIR approach towards AUV reliability for long endurance NMCM missions. DBN are suited to address partial observability, uncertainties inherent in the AUV subsystems' evolution, and the subsystems' interaction with the harsh and uncertain environment. This makes advanced reactive and preventive fault/failure recovery possible.

1 INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are underwater robots with active hydroplanes, propellers, inertial navigation systems (INS), and embedded processors among other subsystems. They are usually torpedo-shaped and transit at 2 – 5 knots. Their hulls are pressure vessels designed for a specific maximum operating depth. For example, they are used in scientific, commercial, and military applications for underwater/under-ice surveys, inspections, monitoring, searching for oil and minerals and detection of mines, submerged aircraft and shipwrecks. Figure 1 shows several types of autonomous vehicles, including AUVs, for underwater mine detection. AUVs work within constraints imposed by energy, navigation, communications (coms), and the environment.

AUVs carry all their energy on-board in the form of high energy density batteries (e.g. lithium-ion) so energy is stringently budgeted and monitored. AUV navigation is challenging as there are no universal positioning systems like the Global Positioning System (GPS), underwater.

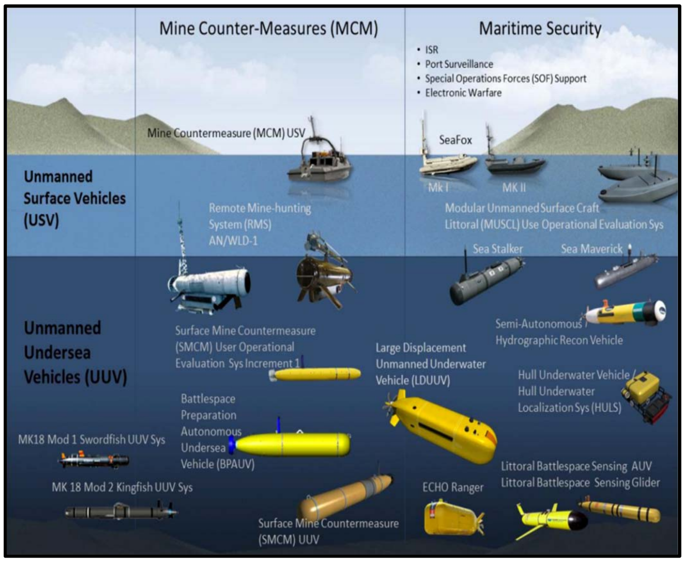

Figure 1 – Various NMCM Unmanned Systems: Source US DoD Unmanned Systems Roadmap FY 2013-3038

Navigation is achieved through dead-reckoning with occasional surfacing for a GPS position re-calibration. Acoustic beacons and baseline navigation, which require other assets be deployed and recovered, are other possibilities.

Underwater sensing tends to be acoustic-based as it yields the best performance – an example is underwater micromodems for ranging and coms. However, the low speed of sound in water means latencies in coms which make timely messaging, challenging. Multi-path and attenuation is common with acoustic coms which means at longer ranges and higher transmission rates, the coms may be unreliable. Additionally, micromodems have limited bandwidth and range due to their low frequency (~25kHz) and environment, respectively.

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AUVs operate in an environment which is dynamic, non-stationary, unstructured, and only partially observable (hence, uncertain). The AUV operational status depends on its internal subsystem and component reliability as well as external environmental factors such as temporally and spatially varying temperature, density, pressure, vibrations, waves, and wind, affecting AUV reliability, safety and AUV-environment interactions (e.g. collision, trim, leaks). AUVs are susceptible to faults and failures as they are complex electronics and sensitive sensors operating in this rough environment. The faults can cause mission degradation and subsystem failures. To make AUVs reliable, faults and failures need to be addressed. One way is through a fault detection, identification, and recovery (FDIR) system – the subject of this paper.

AUV faults/failures can be classified in many ways. The way chosen here is: subsystem hardware (failed component), capability (functionality compromised), and impact (effect of failure on NMCM mission). Impact can be further classed as: minimal (no action taken); mild (effective corrective action); loss of functionality (reconfigured to adapt but not a full recovery); and safety critical (e.g. collision, battery short). Examples of faults/failures that cause reliability issues include:

- low energy – due to being pushed off course by currents;
- failed to dive (waves) or rise (large fresh water layer);
- compromised or missing hydroplanes;
- loss of one side of a side-scan sonar;
- Doppler velocity log (DVL) unable to achieve bottom-lock to measure speed over ground for dead-reckoning;
- link between OEM and payload processor has crashed;
- unexpected mission abort, and
- silence from modem – either water conditions or hardware.

These failures present risks and challenges to mission success, reliability, readiness, and safety. These failures may be caused by hardware, software, the environment or their interactions.

For the case of interest, long endurance, unattended operations, faults *will* occur as the AUV and environment will evolve given a long interval. This motivates AUVs to be as adaptive and fault tolerant as possible to unexpected changes in themselves, the environment, and the mission. The next section briefly describes the AUV equipment and sensors to provide insight into the subsystems and the NMCM mission.

2 AUV INTERNAL SUBSYSTEMS AND COMPONENTS

2.1 On-board Sensors and Equipment

Typical AUV payload sensors include: side-scan and/or bathymetric sonars; conductivity, density, and temperature sensor; acoustic Doppler current profiler, and sub-bottom profiler. The AUV may navigate and position with an INS, DVL, and compass for dead-reckoning. The original equipment manufacturer`s (OEM) embedded processor provides closed-loop control for basic tasks like maintaining attitude, altitude, transits between waypoints, sensor settings, and dead-reckoned navigation.

Mission-planning tools can be on the OEM processor or on the user configured payload processor which the OEM processor is interfaced to. If there is a payload processor, it may receive a periodic stream of AUV status information from the OEM processor which can be considered in payload mission-planning. The payload processor is where the on-board, deliberative autonomy, is located. These processors act like 2 integrated brains. Either one could surface the AUV if needed.

2.2 Application of AUVs to NMCM Missions

The AUV application here is naval mine counter-measures (NMCM) route and minehunting survey missions. With route surveys, side-scan sonars image an area when the sea bed is clear of mines. This provides a reference against which subsequent minehunting surveys can compare against. A basic scripted mission is defined by the waypoints, survey altitude, vehicle attitudes, side-scan sonar gains, and fault responses. The on-board automated target recognition (ATR) analyzes sonar images in near real-time to extract and localize targets for the minehunting survey to re-acquire (confirm) or to compare against the route survey.

Presently, AUVs on NMCM missions are not given much more time than their surface ship predecessors (which gather side-scan sonar data at 5+ knots) to clear a route or secure an area as safe from mines. The localization of the mine, to within a small error, is critical to ensure the minehunting phase is not unduly prolonged in re-acquiring a mine. In situ and on-board ATR and other autonomy tools have made this somewhat possible.

Within the last six years, on-board autonomy development has been a focus. As AUVs may enter operational service for the Royal Canadian Navy, a discussion on their reliability is timely. This paper also considers how a FDIR system might be integrated into the on-board autonomy to increase reliability. With an understanding of the system and its mission, a general AUV on-board autonomy architecture is described next.

3 NMCM ON-BOARD AUTONOMY

On-board autonomy requires an architecture for reasoning. Such architectures have a *planning & decision* component which plans missions to fulfill goals with the *sensing & perception* environment model. This model augments a priori knowledge with timely in situ information from underway sensor measurements, other robots, and network nodes. *sensing & perception* interacts with *planning & decision*. For example an AUV detects a target with ATR (*sensing & perception*), geo-locates the target (*planning & decision*), then plans a mission (*planning & decision*) to re-acquire the target (*sensing & perception*) for further action (*planning & decision*). Such mission autonomy has the following attributes [1]:

- reach / endurance: Greater mission endurance allows the AUV to deploy covertly from further away and operate at greater stand-off distances from the ship and thus extends the ship's reach. This is limited by the AUV battery energy density.

- persistence: Long on-station time facilitates situational awareness and the ability to work for extended intervals on time-critical missions. Being at considerable range for extended periods from an operator places reliance on the autonomy. Persistence is limited by the on-board battery energy density, sensors, and computation power.
- collect data independent of operator: With extended reach and persistence, the AUV is beyond the range of high bandwidth communications. The ability to make decisions, re-plan missions, sense and perceive, process data into information and mitigate system faults supports autonomous data collection.
- ability to transmit high-res information: Despite on-board ATR extracting target images and determining confidences, the decision on whether a target is a mine requires an operator's scrutiny. Successful image transmission to the operator is limited by the underwater coms channel.
- covert and non-covert communications: Assuming receivers are in range, covert coms may require terse, low power transmissions to not reveal the transmitter or receiver locations. With non-covert coms processed data and operational status may be regularly transmitted to the operator.
- navigate with denied and/or degraded GPS: This is naturally the case underwater but can also occur when the AUV is surfaced due to jamming, poor weather, or at high latitudes.

planning & decision facilitates a mission to consider in situ sensor measurements, mission updates, etc. to adapt a mission beyond the scripted mission originally planned. *planning & decision* can also use information from *monitoring & diagnosis* for adaptive mission-planning taking AUV status into account.

monitoring & diagnosis performs fault and failure detection and prognosis. It could model sensors and subsystems to provide estimates and performance measures to *planning & decision*. Given a fault or failure, it provides recommendations to *planning and decision* to reconfigure sensors and/or subsystems to enhance mission success, survivability and reliability. This paper presents the concept for an on-board autonomous FDIR system for monitoring *& diagnosis*. The argument is made for autonomous FDIR as AUVs do not have the range or bandwidth for an operator-driven recovery.

4 ADVANTAGE OF AUTONOMOUS FDIR

The best measure of mission success is the AUV arriving at its recovery point without unrecoverable faults or failures and with all data intact. Fault (or failure) detection recognizes something has gone wrong. It monitors sensors and differences between feedback (observed) and setpoint (desired) values. If a system has closed-loop control both the inputs and outputs of the control system must be monitored along with the sensor measurements. The correct selection of sensor locations and monitored values is critical to timely fault detection. Fault detection that only monitors the control system will not detect the problem – differencing feedback and setpoint values are necessary. For example, a fault in a thruster could be monitored with a Hall-effect sensor. The setpoint is determined by mission objectives and the output is the thruster rotation rate from this sensor. Large differences may be indicative of a fault.

Fault isolation is a special case of fault diagnosis and identification. Isolation/diagnosis/identification infers the most plausible causes for an unexpected behavior given a set of observations. Its objective is to determine the subsystem that failed and the cause of its malfunction. This could be addressed through Artificial Intelligence-based approaches given insight into causal relationships between faults and AUV behaviours. Examples include fault trees, Bayesian inference, and Bayesian Networks.

Fault recovery attempts to correct the fault or work around the fault to save the mission. Given the fault location from fault isolation and the design or possible reconfigurations of the AUV, it attempts to find a configuration that provides equivalent functionality. Classical recovery actions are pre-planned and tested for anticipated faults (e.g. primary battery fails so switch to secondary one). For difficult faults adaptive FDIR may mean a mission abort is not the only solution. Autonomous FDIR considers adaptive recoveries, or controlled degradation, to continue a mission where possible.

When defining requirements, the fully autonomous FDIR may not be obtained initially. A phased approach is advocated. Fault tolerance should be a consideration in requirements definition. Asking for at least the traditional FDIR based on look-up tables and a priori responses to a fault/failure is a reasonable approach – though it is not considered autonomous. However, OEMs can be asked to instrument for-but-not-with the ability to monitor and implement autonomous FDIR. In the near future a fitted-for-but-not-with approach for AUV FDIR will be a reality.

There is less reported work with *monitoring & diagnosis* for increased AUV reliability and maintenance – even less so for autonomous FDIR on long endurance underwater missions. Some relevant literature is reviewed next.

5 BRIEF LITERATURE SURVEY

Methodologies in AUV reliability analysis include reliability growth analysis [5], reliability block diagrams, and model-based methods [8]. Specific areas are in frameworks and analysis [6-8], critical subsystems like thrusters [5], control hydroplanes [5][12]], and navigation [2], or mission endurance [3][9][11][13].

Earlier AUV reliability implementations [6] embedded a critical safety layer in the control architecture that was reactive, and a preventive safety layer, which did not interfere with the critical layer. The emphasis was on early detection and redundancy as measures to enhance safety. The work of [7] built a diagnostic layer onto an existing control layer using function oriented modelling. Their motivation was deep water or under-ice where the AUV is out of communications range.

More recently, fault trees have been applied [4] to recognize and evaluate faults. [4] modeled AUV subsystems like power, propulsion, leaks, diving, environment, collision avoidance, computer-based, communications and navigation to obtain subsystem and overall vehicle reliability measures and compared their analysis (good effectiveness) against an AUV without such measures. [3] addressed fault tolerance by having multiple AUVs in the water in either low energy usage (monitoring and relaying on surface) or high energy usage states performing missions. They found they could switch spent underway AUVs with the lower energy AUVs to increase endurance and fault tolerance through redundancy. Thus the work to date does not really consider autonomous FDIR approaches for AUVs. The next section introduces this and presents complex examples of reliability issues and their recoveries through autonomous FDIR to highlight its efficacy.

6 USE OF EXISITNG AUV AUTONOMOUS FDIR

6.1 Increased AUV Reliability with Autonomous FDIR

Many FDIR systems are based on noted design-time faults augmented with run-time observations of the AUV operational status. As mentioned earlier, recovery actions are based on hard-wired reactive solutions from a look-up table and are procedural in nature. In some cases the objective is to put the system in a safe configuration until a human operator can intervene. As the AUV and its environment are only partially observable to the FDIR system, there is uncertainty in observations of both. This has been the reason to defer to an operator with the experience to craft an appropriate recovery action.

Classical FDIR is also limited in that it does not provide a prognosis for a fault/failure. It is adequate for basic, statically captured AUV configurations but falls short for dynamic aspects of the AUV such as recovery actions, reconfiguration, and prognosis. They do not address evolution of AUV characteristics (e.g. change in trim from gradually deployed payload) and the history of the AUV interaction with its environment (change in trim due to change in water density). Classical methods do not capture, or use: probabilistic causal dependencies between failures/faults and AUV capabilities, the AUV-environment interaction evolution, and AUV dependability characteristics. Capturing this means on-board recovery actions could be devised and implemented in an autonomous FDIR system.

The AUV comes from the manufacturer with basic fault diagnostics and recovery measures for events like slow leaks, over-depth, time-outs from lack of an operator command as well as warnings like over-pitch and low energy. Most AUVs can implement a scripted mission and maybe relay what might be wrong but they are generally unable to recover from more global failures like low energy, reduced functionality in hydroplanes, malfunctioning payload sensor, etc. That level of FDIR requires more deliberative measures than is standard on AUVs. An autonomous FDIR system can make decisions, implement a re-planned mission, communicate with reduced bandwidth, alter speed, or re-task control authority as needed. Two examples are presented next to highlight the value.

6.2 Value of Autonomous FDIR Recovery Actions

As shown in the literature review, a hydroplane failure can be critical. If it was a hydroplane for depth-keeping, failure to adapt in a timely manner could result in a vehicle loss. The recovery for a ‘stuck’ hydroplane could be a re-tasking of control authority amongst the remaining functioning hydroplanes [12]. This would be a degraded recovery but one that preserves the AUV. To account for this, the autonomy employed evolutionary algorithms to gain insight into the optimal solution for a specific failure configuration recovery. An on-board AUV dynamics and control model describes the causal relationship between the fault (compromised hydroplane) and subsequent AUV performance. For this type of fault, it would be difficult to prescribe an a priori recovery action as it is specific to which hydroplane and its angle. This recovery is adaptive and reactive. The prognosis for the fault was that depth-keeping is compromised and if more depth-keeping control authority is needed (e.g. rising unexpectedly against a fresh water layer) there will be an issue. FDIR recoveries can also be preventive as the next example illustrates.

6.3 Preventive and deliberative recovery through FDIR

An informed estimate is made for the required energy for a mission. However, if unanticipated currents cumulate over a long mission, this unexpectedly increases energy consumption and an energy shortfall can occur. One validated deliberative solution [13] proposed an on-going energy evaluation in the FDIR that assesses the ability to complete the mission through an agent that considers the instantaneous operational status, non-linear vehicle dynamics, recent learned performance history, and archived history to project an energy shortfall. When the shortfall occurs, an on-board FDIR re-plans the survey mission using on-line learning with a genetic algorithm constrained by the present operating state and is optimized for the remaining energy budget, mission duration, and survey area dimensions. The re-planned mission would be at a lower speed and higher sonar swath spacing but still provides the sensor coverage albeit with less overlap. The goal being for the AUV to arrive at the recovery location on schedule, and with the area surveyed. This can be used as a reactive recovery when the energy falls beneath a threshold.

It can also be used for a preventive recovery to re-plan and implement an adapted mission before the energy level is critical based on trending very recent AUV energy consumption and performance. The FDIR could also choose to communicate less frequently, or more tersely. An AUV, without such deliberative on-line energy management in its FDIR, would abort the mission at a pre-set energy threshold and surface at an unplanned location with the survey incomplete.

These examples highlight the value of deliberative on-line recovery in an autonomous FDIR for two common AUV reliability issues. Proposed as part of such an autonomous FDIR system are tools based on dynamic Bayesian networks (DBN) which would augment these agents by including probabilistic tools to account for uncertainty in the AUV systems and environment, as described next.

7 FAULT-TOLERANCE AND MISSION REQUIREMENTS

Autonomous FDIR can reason through fault/failure observations based on knowledge of the AUV, its capabilities, its current operational status, the environment, and AUV-environment interactions in the presence of uncertainty, dynamic evolution, and partial observability. Importantly, an autonomous FDIR takes into account the AUV's instantaneous operating state in devising a recovery plan. Beyond autonomous FDIR, dynamic Bayesian networks (DBN) are proposed as a novel FDIR approach towards AUV reliability for long endurance and NMCM missions. DBN are suited to address partial observability, uncertainties inherent in the AUV subsystems' evolution, and these subsystems' interaction with the unstructured, non-stationary environment. The predictive and inference abilities in DBN are used to provide a prognosis for a fault and to mitigate imminent failure. The DBN approach would be one capability in the overall AUV autonomous FDIR system that includes reliability growth analysis, fault trees and reliability block diagrams. In this way, reactive and preventive recovery on AUVs can be implemented.

The reliability of the AUV to perform its mission extends beyond the vehicle and its autonomy and includes considerations for the support systems and the criteria it must operate to.

8 CONCEPT OF SUPPORT

8.1 Equipment System and Materiel Readiness

An AUV used in NMCM missions is a key component of the capability required by the warfighter. However, the AUV on its own cannot provide that capability; it is dependent on a system to support and sustain the mission equipment. When the mission equipment is integrated with the support system to define a holistic system, it is referred to as the Equipment System [10] (Figure 2).

Figure 2: Relationship between mission equipment and support system to material readiness.

For system readiness, reliability is the duration, or probability of, failure-free performance while conducting a mission or task. Reliability is normally determined by establishing the system's overall Mean Time Between Operational Mission Failures (MTBOMF). Using the mission equipment approach, AUVs should have a MTBOMF, for the entire vehicle, of 80 hours throughout their life-cycle. This value is typical and is often used by the warfighter to express an operational requirement for NMCM projects executed by the Directorate of Naval Combat Systems (DNCS) of the Canadian Department of National Defence (DND).

Taking into account the required operational detection, accuracy and coverage rates, the payload usage factors can be estimated. Usage factors are important for determining the support system, support locations, reliability and costs. When usage factors are added to reliability block diagrams, or availability calculations, the acquisition costs are reduced and the design can be more easily supported. Modelling work at DNCS has shown that availability and reliability are major cost drivers [10]. The following are examples of usage factors:

- annual operating hours per payload;
- annual ready time per payload;
- annual number of missions per payload;
- maximum length of mission per payload;
- maximum daily use per payload hours;
- maximum hours per mission (per individual AUV); and
- maximum number of AUVs per payload operated simultaneously

8.2 Open Architecture Design

In order to continue to realize desired FDIR systems during the AUV life-cycle an open architecture (OA) will be necessary. This is a design that uses recognized industry standards and thus facilitates replacements, additions and upgrades to components. Key interfaces, such as those between the processors in an AUV, should use widely-supported, consensus-based standards that are published and maintained by a recognized industry standards organization.

8.3 Technology Refresh and Insertion

As the use of Commercial-Off-the-Shelf components is often a project objective including obsolescence management, there is an added requirement for DNCS to institute regular software and hardware updates, referred to as technology refresh, and is dictated by the relatively short supportability lifespan of commercial components. To allow for future technology insertions, an OA design should be adopted to ensure that system components can be cost-effectively expanded, supported, and upgraded over the in-service life.

The design of AUV autonomy and FDIR software should be such as to allow for introduction of new algorithms and techniques into appropriate points in the processing chain for the purposes of evaluation and eventual technology insertion.

In conversation with various Royal Canadian Navy operators and maintainers, as well as those in certain allied navies, this concept of support is becoming widely recognized and has been found to be applicable to AUVs. When AUVS use an equipment system paradigm, an open architecture design, technology refresh and technology insertion it will be easy for operators and maintainers to add on-board FDIR and fault-tolerance features in a cost-effective manner.

9 CURRENT AND FUTURE WORK

The inclusion of dynamic Bayesian Networks in the autonomous FDIR has been underway and will be ready for in-water testing during the upcoming field trials season.

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