COLLABORATIVE AUTOSUB SCIENCE IN EXTREME ENVIRONMENTS

MASTERCLASS

IN

AUV TECHNOLOGY FOR POLAR SCIENCE

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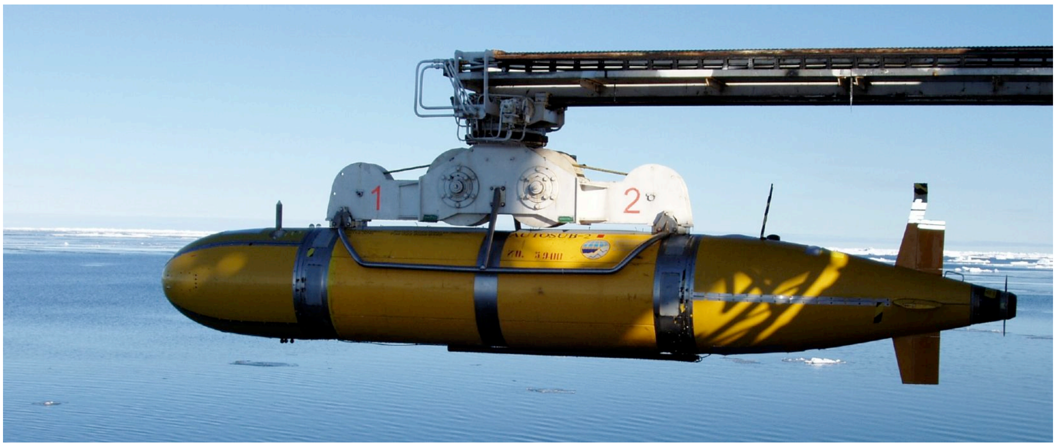

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TOWARDS A RISK MANAGEMENT PROCESS FOR AUTONOMOUS UNDERWATER VEHICLES

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ABSTRACT

There is increasing interest from the marine science community in using autonomous underwater vehicles (AUVs) under ice shelves and under sea ice. These environments pose challenges to the vehicle and support team, and they mean that recovery may be almost impossible, or very expensive, should the vehicle develop a fault particularly when beneath ice. This paper reviews recent published work on AUV reliability and develops a risk management process (RMP-AUV) tuned to the needs of the responsible owner working with a technical support team. The RMP-AUV provides a framework for the responsible owner to determine an acceptable risk using mainly objective information, augmented with subjective judgement on the priority of the proposed vehicle campaigns. A process is defined whereby the technical team determines the probability of loss based on the most applicable historic data for the vehicle. If this is less than the risk acceptable to the owner, RMP-AUV then requires this assessment to be verified, for example through a proving campaign. How a campaign can be designed to meet this objective is discussed and other risk mitigation strategies are outlined. Worked examples are included to illustrate the how the proposed RMP-AUV would work, using actual reliability data from the Autosub AUV. We are some way from having sufficiently reliable (or sufficiently inexpensive) AUVs that the task of risk assessment in polar environments becomes trivial. Until that time careful performance and risk assessments will be needed. Furthermore, those assessments should be used to drive forward improvements in AUV reliability so that the full potential of autonomous systems to deliver data from the polar regions can be realised.

1. INTRODUCTION

On 16 February 2005, at Fimbulisen on the edge of the Antarctic ice cap, an autonomous underwater vehicle set out on a science mission under the ice shelf. The vehicle did not return. *Autosub2* was lost, under 200 m of ice, some 17 km from the face of the ice shelf. The exact reason remains unknown. The previous mission had been successful, bringing back startling and unexpected information on the roughness of the under side of the ice shelf (Nicholls *et al*., 2006). It is quite possible that the cause or causes for the loss had nothing to do with the polar environment itself (Strutt, 2006), and yet the environment was a major factor, as it precluded recovery of *Autosub*. With increasing scientific interest in using autonomous underwater vehicles (AUVs) to make observations beneath ice shelves and beneath sea ice, funding agencies are asking whether they can afford the risk of operating expensive vehicles in an environment from which recovery is nearly impossible, or at least very expensive should there be a failure.

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What is clear from anecdotes (Stokey *et al.*, 1999) and from the increasing cost of insurance (Griffiths *et al.*, 2006) is that the reliability of AUVs needs to be improved. Unfortunately, there is a severe lack of data and analysis in the open literature on AUV reliability. What there is gives rise to concern. Published results for *Autosub2* (National Oceanography Centre, Southampton) and *Dorado* (Monterey Bay Aquarium Research Institute) suggest that for both vehicles the historic probability of completing a 24-hour mission without a fault was below 61% (Griffiths *et al.*, 2003a; Podder *et al.*, 2004). Figure 1a shows the reduction in probability of *Dorado* missions ending successfully as the mission time increases, and shows growing uncertainty in the estimated probability of success as mission time increases. For Autosub, Figure 1b shows the probability of survival for under ice shelf missions of increasing range based on a Weibull model fitted to the reliability data gathered over 240 missions. It was this analysis that was accepted by the UK Natural Environment Research Council (NERC) indicating that the Autosub Under Ice programme was indeed high risk, but with high gain potential. The analysis was shared with the vehicle's insurers and led to an annual premium quotation of 95% of the vehicle's value (with a return of part of the premium for each year the vehicle survived). As this level of premium was unacceptable, NERC took the decision to fund the construction of a second Autosub (now *Autosub3*) as insurance for the research programme.

However, there are signs that AUV reliability is improving. Since the Podder *et al.* (2004) paper, MBARI has used a new vehicle *AUVCTD* bimonthly on a 100 km transect in Monterey Bay the reliability has increased over time, due to the engineering team's ability to find and then correct faults, followed by use at sea on such a regular basis (Thomas, 2006). AUVs such as Autosub that have been used on an expeditionary basis have not had the benefit of such regular use, static configuration and from one location to help drive down fault occurrence. A polar equivalent to the *AUVCTD* programme is not infeasible; for example, a programme sea ice studies using an AUV from a shore base – perhaps from an underwater garage. However, it is likely that the sponsors of such a programme would need to accept higher risk during the initial period while the reliability improvement was being achieved.

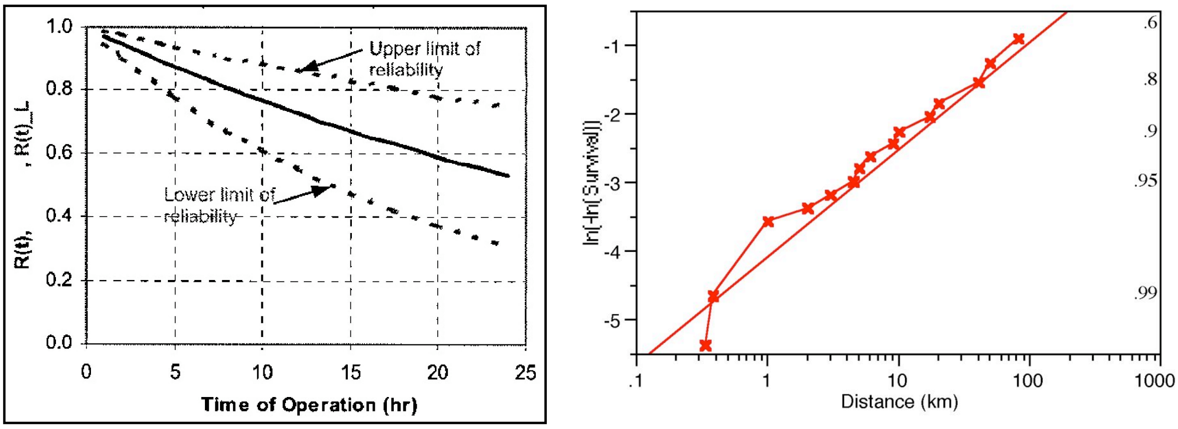

Figure 1. (Left) probability of missions ending successfully (that is, without a fault causing a premature termination) for the Dorado AUV, from Podder et al. (2003) and (right) probability of survival for the Autosub AUV under an ice shelf based on data from 240 missions estimated using a Weibull distribution with $\alpha = 403.9$ and $\beta = 0.678$, the right hand scale shows probability of survival, from Griffiths et al. (2003a).

Regular use with a set, or slowly evolving, vehicle configuration has also been a major factor in improving the reliability of AUVs used by industry. Experience with the *C-Surveyor* AUV showed that as delivered from the manufacturer the availability was low, but that extensive use over 12 months and more improved the availability in any one month to over 90% (Figure 2; Chance, 2003). In this figure, 'availability' is not explicitly defined, but using the accepted definition of:

((Mean Time Between Failures) / (Mean Time Between Failures + Mean Down Time)) x 100%

shows that availability and reliability, although related, can be decoupled to a certain degree. That is, a high availability can result from a system with regular failures if the mean down time from those failures is much smaller than the failure interval. Conversely, availability can be low if a simple failure results in an extended down time due to lack of spares or consequential damage, e.g. a minor in-water failure leading to premature recovery during which the vehicle sustains sever damage completely unrelated to the initial failure.

As modifications were made to the *C-Surveyor* vehicle, the availability dropped, as shown by the downward excursions in Figure 2. This effect of modifications and upgrades leading to a temporary reduction in reliability has also been shown for *Autosub2* (Griffiths et al, 2003b).

It is against this background that we consider it timely to move towards a proactive and systematic risk management process for autonomous underwater vehicles (RMP-AUV). The basic elements of a risk management paradigm that could be adapted for use with AUVs has been set out by Strutt (2006) in the report of the Autosub Loss Inquiry Board. In this paper, we develop the basic risk management paradigm into a process tuned to the AUV application, recognising the elements and the uncertainties involved when dealing with autonomous systems.

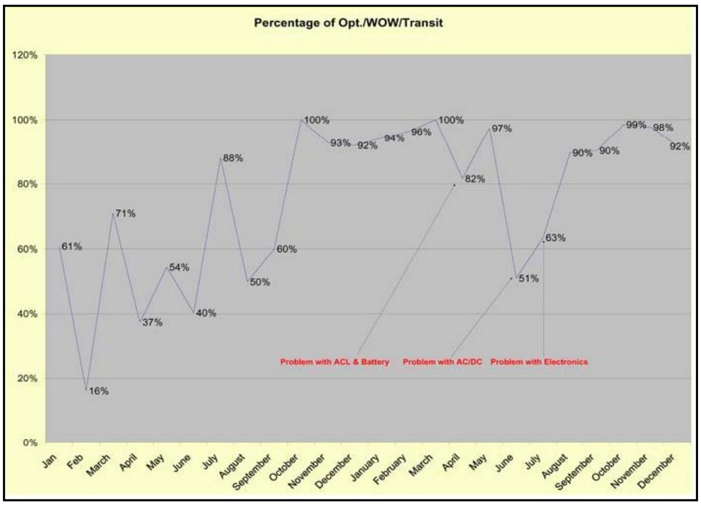

Figure 2. Availability for C&C Technologies AUV over 2 years and 24,000 km in offshore industry. Delivered, availability was ~20%, but grew to 90-100% over yearlong operations (Chance, 2003).

The key steps in developing the RMP-AUV are:

(i) The design of a risk acceptance process, including the issues over identifying who might be the responsible owner of the risk and who might comprise the technical team.

(ii) Defining a method by which the responsible owner might determine the acceptable risk for any particular mission or campaign[1].

(iii) How the technical team could perform fault assessment and subsequently calculate the probability of the vehicle surviving the missions or campaign, including assessing the trials time needed to obtain confidence in the fault statistics.

(iv) A risk evaluation stage within the risk acceptance process that tensions the risk acceptance of the responsible owner against the expected probability of survival calculated by the technical team.

(v) Risk mitigation strategies, to include procedural measures, technical, demonstrated quality assurance, and use of tools such as fault tree analysis (FTA) and fault modes effects and criticality analysis (FMECA).

2. THE BASIS OF A RISK MANAGEMENT PROCESS FOR AN AUV

2.1 A risk acceptance process

The basic risk acceptance process of an RMP-AUV is shown diagrammatically in Figure 3. This has been built from the basic paradigm for risk management outlined in Strutt (2006). The process begins with step 1, where the responsible owner states an acceptable degree of risk. This degree of risk might be expressed as an acceptable probability of loss, or an acceptable insurance premium, or an acceptable financial risk over any particular campaign. In practice, different presentations of risk acceptance are unlikely to be independent; indeed they are likely to be strongly linked. For example, the insurance premium is likely to be strongly influenced by the probability of loss if, as should be the case, all factors are declared to the insurance brokers and underwriters (Edwards, 2000; Griffiths *et al*., 2006). The annual premium is unlikely to be lower than $L^* C$ where L is the probability of loss in any one year and C the capital cost of the AUV. In the process developed here, we assume that the responsible owner will declare their risk acceptance as a probability of loss (L) over a campaign. In section 2.3 we explain how the owner might arrive at an acceptable probability of loss.

In step 2 the campaign and mission requirements are set out by the commissioner of the work (e.g. the principal investigator of a science project). The requirements must include sufficient detail for the technical team to be able to assess the risk. The factors that might affect risk include, among others:

- The environment in which the missions and campaign will take place, e.g. in open water; in water depth exceeding the pressure rating of the vehicle; under sea ice; under shelf ice; close to the seabed, in gentle or in rough terrain, and at what height, the likely sea and weather conditions at launch and recovery.
- The number, type and duration or track lengths of the individual missions that are needed to deliver the campaign objectives.
- The mode of operation, e.g. under escort and in continual communication or unattended.
- Whether the campaign uses robust, well-proven instrumentation or whether novel or untried instruments or systems are included, including instruments that take in water.
- The complexity of the mission programming requirements.

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[1] We define a campaign as a series of individual missions sharing a common theme or location or deployment vessel.

- Whether, and to what degree, the ship, the officers and crew have experience with AUVs.

Risk factors for AUV operations are discussed in more detail in Griffiths, Millard and Rogers (2003).

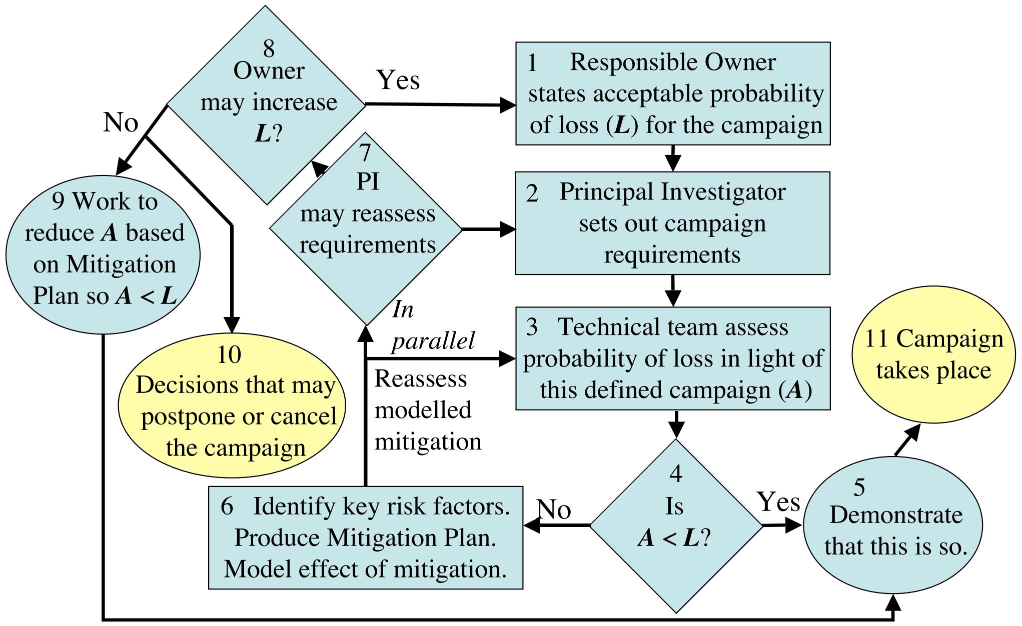

Figure 3. A flow chart of the Risk Acceptance Process within the RMP-AUV.

In step 3 the technical team takes the information on campaign requirements and arrives at an estimate of the probability of loss (A) using the procedure described in Section 2.4. Step 4 involves comparing the acceptable probability of loss L of the owner with the estimated probability of loss A calculated by the team. If A is less than L then the indications are that the risk of loss during a campaign as defined by the requirements is acceptable. In this case the next step (step 5) would be for the technical team to demonstrate that their assessment of the risk was realistic. This could be, for example, by mounting a reliability trials cruise and demonstrating that during the trials the vehicle reliability statistics were no worse than those used to assess the likelihood of loss in step 3. If the statistics during the trials cruise were worse, then step 3 should be repeated with the updated through-life statistics and the comparison step 4 repeated. If not, then the campaign would take place (step 11).

If the comparison at step 4 shows that A is greater than L the indications are that the probability of loss would be unacceptable to the owner. Should this be the case, we propose that step 6 should require the technical team to identify the key risk factors, produce a written Mitigation Plan, with a budget and timetable. The effects of the proposed mitigation measures on the probability of loss would be modelled, in a way that would take into account the reliability history of the vehicle. In light of the outcome of the initial analysis of step 4, and the likely effect of mitigation from the modelling exercise, in step 7 the client (principal investigator) may review the campaign requirements to reduce the risk. This could be, for example, by reducing the track lengths or the number of missions with the highest risk. Steps 3 and 4 would then be repeated with the new requirements. There may well be tension between the client, perhaps unwilling to reduce the campaign requirements for valid scientific reasons, and the owner, who may require review. Furthermore, it is possible (certainly in the case of a funding agency such as NERC) that the client may be funded through a grant from the same organisation that is, in effect, the owner of the AUV. Additional and/or more complex tensions may exist in cases where the client and the responsible owner fall under different organizations or funding sources.

If the measures considered so far (risk mitigation and revised campaign requirements) do not lead to an acceptable mission risk, in step 8 the owner would be asked whether they would be willing to increase the probability of loss that they would accept. If this is not possible, and it may well depend on the increase in risk being demanded, the outcome would either be (i) a decision to postpone or cancel the campaign (step 10) or (ii) if there was an expectation that the measures in the Mitigation Plan would reduce $\boldsymbol{A}$ so that $\boldsymbol{A} < \boldsymbol{L}$, work would take place according to the Mitigation Plan (step 9). This would inevitably involve expenditure and would require further sea trials to demonstrate an increase in reliability (step 5), and if successful, would be followed by the science campaign (step 11).

It is possible to assess the cost-benefit of the expenditure (E) to improve reliability against the cost of increasing the owner's acceptable probability of loss (upward from L). If $E < (A - L) * C$ then there is an immediate net benefit to improving the vehicle's reliability, if not, the indication is that the cost of improving the reliability of the vehicle would need to amortised over more than one campaign.

2.2 Who might be the responsible owner?

For a commercial operator of an AUV the answer to the question of who is the responsible owner as regards risk management may be straightforward, for example, it may be the Chief Financial Officer. In a research environment the answer may be rather more complex. It may depend on whether the AUV has been purchased as an asset on a grant to an individual or consortium and operated by the individual or consortium for their own purposes or whether the AUV is an asset in an equipment pool, funded for the benefit of a broader community. In the former, the consequences of risk and loss are contained within a group or consortium; in the latter, the consequences may be more far-reaching.

In the case of an individual or consortium operating an AUV purchased with a grant, and the legal ownership of the vehicle resting with an institution (rather than the grant-awarding body), the responsible owner is likely to be the principal investigator, perhaps with oversight from their head of department. Where the vehicle is part of a facility, whether the vehicle is owned by the facility operator or by the body that funded the vehicle, it would be appropriate for the Director in charge of the facility to be the responsible owner. However, where the risk of loss is small in the envisaged campaign, the Director may delegate the responsibility, e.g. to the Head of the Facility or the operating group. 'Small' may be defined as the level of risk that would be insurable (in current markets, below 15–20%), even if insurance was not purchased. The indications are that underwriters are now unlikely to accept AUV risks that would require annual premiums above 15 to 20% of the vehicle's replacement cost (Griffiths *et al.*, 2006).

2.3 A process for the owner when deciding on an acceptable risk

We propose a process for the owner to use when deciding on an acceptable risk that is informed by the major costs of owning and operating an AUV. The process is shown diagrammatically in Figure 4.

Step 1 identifies the capital cost of the vehicle C. This may be its build or purchase cost or the cost to replace. In step 2, the typical daily cost of operation (D) is estimated based on the type of campaign proposed, the AUV technical support requirements, the cost of capital for the vehicle and part of the charter rate for the class of vessel and the cost of the on-board science team. This recognises that the vessel and science team may spend time on non-AUV activity. These two steps are purely objective. Others involve subjective judgement on the part of the responsible owner.

Step 3 requires the responsible owner to state what fraction (x %) of the daily rate D they are willing to accept as a loss replacement charge for each day of AUV operation throughout its service life. This may be a real or a notional charge, and is likely to be informed by the policies and practices of the organisations involved. There is unlikely to be a single figure that will suit all scenarios. In the case of an individual or consortium operating an AUV considerations might include, among other factors, the quality and novelty of the science proposed, its timeliness, the international context, the vehicle's prior and future programme and the importance of the proposed research to the individual or consortium. However, for an AUV operated as a facility, it would not be appropriate for facility staff to make judgements on these factors. In which case a fixed loss replacement charge would be fair.

Irrespective of how x is determined, the required service life in days can then be calculated in step 4 as:

$$S = 100.C / x.D$$

Implicit in this calculation is that the same loss replacement charge is attributable to all of the users, irrespective of the risk profile of their particular campaign.

Step 5 recognises that the vehicle will undertake campaigns with varying risks throughout its service life. The service life is split into n user determined subsets. Each subset i, of S_i days, has a relative risk assessment of R_i, where R for the lowest risk open water missions is subjectively taken as 1. Assessing relative risk depends greatly on eliciting opinion on risk from experts – a subject in itself (e.g. O'Hagan *et al.*, 2006).

In step 6 the owner declares the minimum acceptable probability (K) that the vehicle will survive to the end of its service life[2], from which the hazard rate (λ) can be calculated (step 7):

$$\lambda = -\ln(K) / \sum_{i=1}^{n} R_i.S_i$$

assuming a constant baseline hazard rate for the lowest risk open water missions throughout the vehicle's life.

The acceptable probability of loss for a proposed campaign of y days with m subsets of activities S_j, each with a risk factor R_j is calculated in step 8, where:

$$y = \sum_{j=1}^{m} S_j \quad \text{then:}$$

$$P(loss) = 1 - \exp\left(-\lambda.\sum_{j=1}^{m} R_j.S_j\right)$$

A worked example for the Autosub AUV is shown in Box 1. Typical information that is required to set up the problem is shown. Three different risk scenarios are included – open water, under sea-ice and under shelf-ice – that will be encountered during the vehicle's service life. These are used to calculate the through-life hazard rate. For the particular campaign whose risk acceptance needs to be

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[2] Clearly K (probability of completing service life) must be less than $(1 - L)$ the probability of surviving the campaign being considered.

calculated, these scenarios (or others) may be used. The relative risks need to be kept under review as new information is gleaned from the operation of Autosub and other AUVs under different conditions. For this exercise, we suggest that the Risk Factor for operation under sea-ice is taken as 3, and 10 for under shelf-ice, reflecting the far lower probability of recovery from malfunction under an ice shelf.

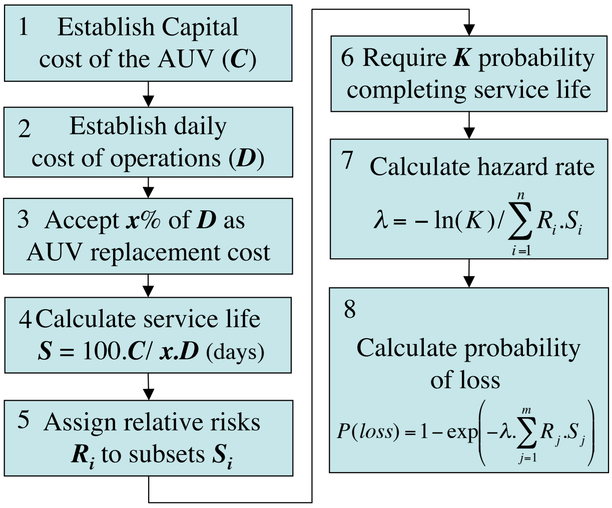

Figure 4. A flow chart for the owner when determining an acceptable risk for a particular campaign.

At this stage of development of the RMP these risk factors have a high degree of uncertainty and subjectivity. In polar regions (the focus of this chapter) the risk factors are most clearly differentiated in recovery potential, yet in other missions and settings the critical Risk Factors may exist in other operational domains - for example in shallow shelf and harbour settings it is not so much a matter of recovery difficulties but risks associated with collisions or theft, or in military campaigns it may be loss from attack. Actually biological attacks - namely killer whales and leopard seals may be a real Risk Factor in polar settings- it was the case for Fetch1 off the Antarctic Peninsula.

The example in Box 1 is for an under-ice campaign that begins with open water trials for 10% of the 17 days of operation, followed by a mix of under sea-ice (30%) and under shelf ice (60%) missions. In this example, accepting a 20% probability of loss would be the outcome of the decisions made by the owner in completing the input cells.

The spreadsheet calculator[3] can be used to assess the impact of changing risk acceptance criteria on the acceptable probability of loss. For example, should the owner change the 'required probability of reaching end of life' from 10% (in this example) to 50% then the acceptable probability of loss during this campaign would reduce to 6%. If the 'risk premium' in step 3 was to be increased to 50% (from 33%) of daily operations (and the probability of reaching end of life remaining at 10%) then the owner could accept a 28% probability of loss for this example campaign.

This process could be applied to analyses where loss does not necessarily mean complete loss of the vehicle but rather failure to complete mission requirements. Risk Assessment and Risk Management can be applied to the planning of science missions for which the more likely loss outcome is failure to obtain the mission objectives - giving a more universal applicability to this work.

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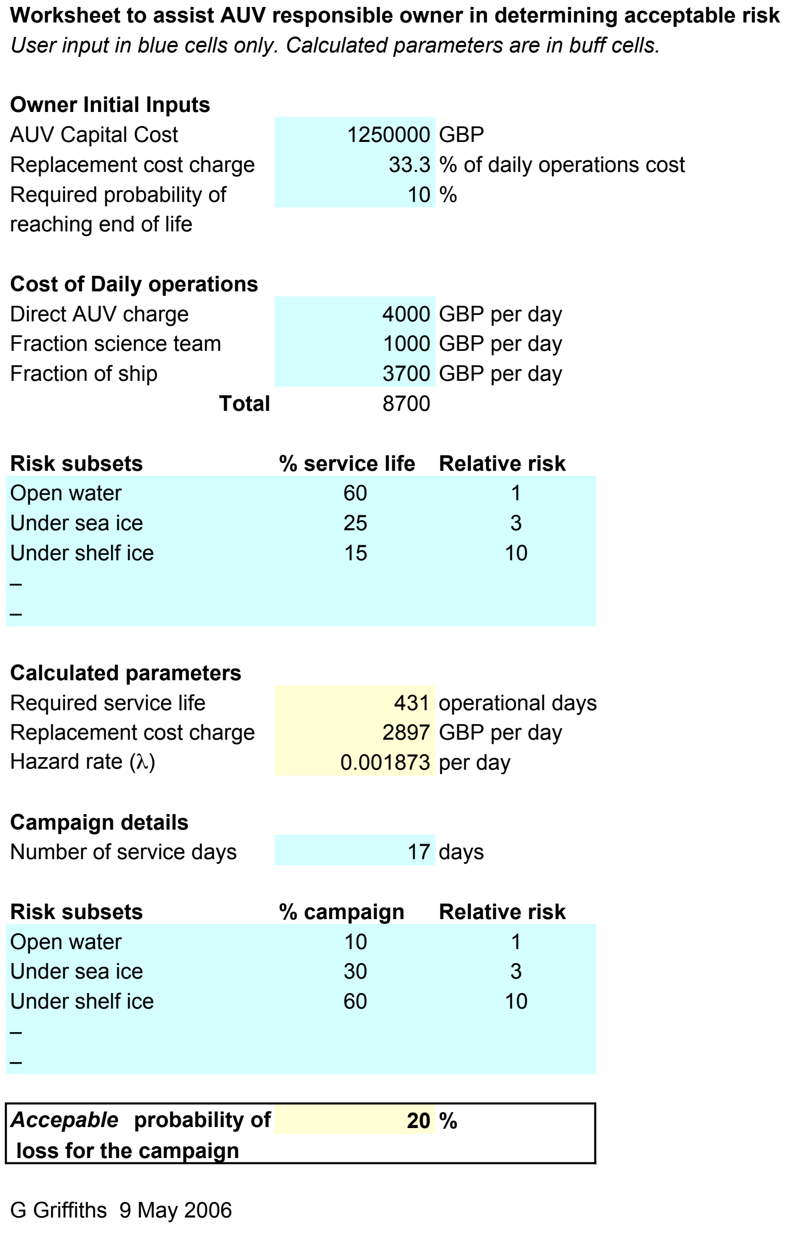
[3] The spreadsheet is available at http://www.noc.soton.ac.uk/OED/gxg/AUVrisk.xls

Box 1 Worked risk acceptance example using Autosub data.



Worksheet to assist AUV responsible owner in determining acceptable risk

User input in blue cells only. Calculated parameters are in buff cells.

Owner Initial Inputs		
AUV Capital Cost	1250000	GBP
Replacement cost charge	33.3	% of daily operations cost
Required probability of reaching end of life	10	%

Cost of Daily operations		
Direct AUV charge	4000	GBP per day
Fraction science team	1000	GBP per day
Fraction of ship	3700	GBP per day
Total	8700	

Risk subsets	**% service life**	**Relative risk**
Open water	60	1
Under sea ice	25	3
Under shelf ice	15	10
–		
–		

Calculated parameters		
Required service life	431	operational days
Replacement cost charge	2897	GBP per day
Hazard rate (λ)	0.001873	per day

Campaign details		
Number of service days	17	days

Risk subsets	**% campaign**	**Relative risk**
Open water	10	1
Under sea ice	30	3
Under shelf ice	60	10
–		
–		

***Accepable* probability of loss for the campaign** **20** %

G Griffiths 9 May 2006

2.4 A process for the technical team to assess probability of loss

In step 3 of the Risk Acceptance Process the technical team is required to take the information on campaign requirements and arrive at an estimate of the probability of loss (A). Underpinning the capability of the technical team to make this estimate is their prior experience and track record with the AUV. This can be done using the method described in Griffiths *et al*. (2003a). To summarise, the first requirement is to have a fault reporting and impact assessment process, such as outlined in the flow chart in Figure 5. Engineering actions to correct faults will help make the vehicle more robust. However, the fault history, particularly those high impact faults when underway, can be used to help predict the likelihood of vehicle loss. High impact faults are defined as those that could directly lead to vehicle loss. Examples include: severe collision with topography; leak(s) within large pressure vessels; the vehicle exceeding its design depth; complete loss of power or network transmission; leaks, short or open circuits in critical power or data connectors[4]. Should such problems happen under ice, for example, the vehicle could be irretrievably lost. In other words the locale of operations makes what would be less than high impact faults in open water critical faults within the operating locale. This is an area where the eliciting expert judgement is important in setting the risk factors.

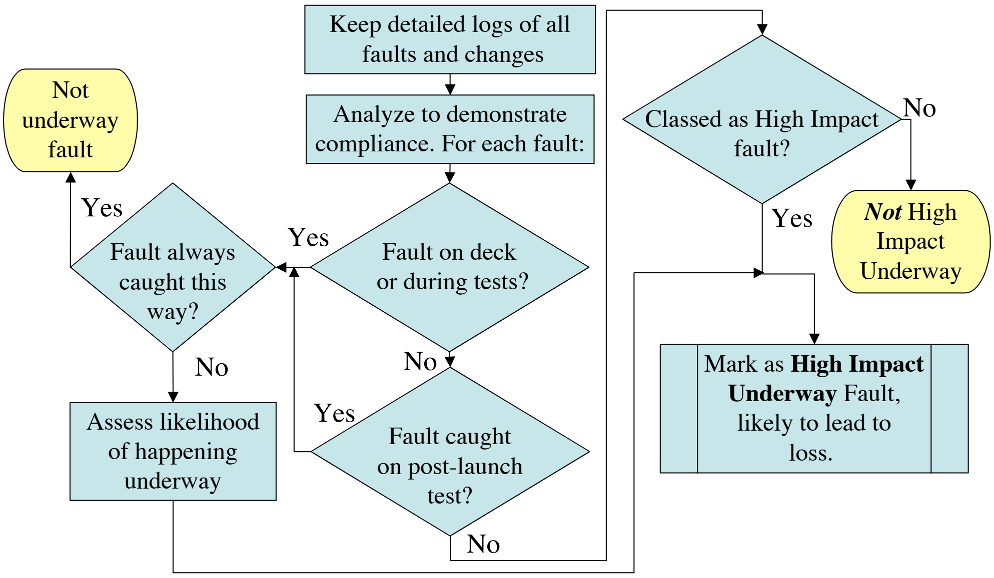


Figure 5. A flow chart for the fault assessment process to be undertaken by the technical team.

The mission phases considered in the RMP have been restricted to those described by different operating locales – open water, sea ice and shelf ice, but this is an over-simplification. In reality, there are a multitude of mission phases independent of locale, e.g. launch, recovery, where increased risk could and should be modelled. Transition between phases, e.g. from surface to dive may also hold separate risk factors. While we recognise these circumstances, with our present state of understanding and our limited data, there would be too much conjecture or subjectivity in assessing each risk.

It is prudent to perform pre-deployment checks on an AUV. Ideally, tests on deck would be followed by in-water tests immediately prior to committing to a mission. Faults caught during such tests would not normally be classed as underway faults. However, if they were high impact faults, there is a need to assess the probability that the fault would or could have occurred when underway. That is, the probability that the fault would not have been caught pre-committal to mission is estimated. [Note: this has yet to be built in to the process.]

Box 2 shows the steps in calculating the probability of loss with example data from historic Autosub records. The output of the fault assessment is a table of mission number, the mission track distance (km) and a flag as to whether or not the mission suffered a high impact fault underway. The table forms the input data set for an analysis that fits a Weibull distribution, using, for example, a maximum likelihood method as in SAS Institute's JMP data analysis package[5]. The Weibull model parameters are then used to predict the probability of survival for the mission ranges envisaged in the

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[4] For further examples, a list of possible technical and root-causes of the *Autosub2* loss is given in Strutt (2006).

[5] See http://www.jmp.com

planned campaign. Each of the missions should be give a relative risk, as discussed earlier, and this modifies the α Weibull parameter to reflect the risk for each mission. The overall probability of surviving the campaign of several missions is the product of the probability of surviving each mission. In this particular example, the probability of losing the vehicle, at 67%, is far higher than the owner's acceptable risk. The vehicle reliability must (a) be improved greatly and (b) it must be demonstrated that reliability growth has been achieved before the owner would contemplate the polar campaign envisaged in this example or the owner must be convinced to amend the acceptable risk level. This example has illustrated steps 1 through 7 (except 5) in the Risk Acceptance Process of Figure 3.

Step 5 requires demonstrating that the vehicle can achieve the required reliability, and step 9 requires the reliability to be improved. These can be treated together, and section 3 shows how the information gained through trials and through targeted reliability improvement can be used to inform both steps.

3. ROBUSTNESS AND RISK MITIGATION

3.1 Demonstrating that the required reliability can be achieved – ashore

The Strutt (2006) report recommended additional risk identification and mitigation measures that could be applied to AUV development ashore. These included *a priori* use of tools such as FTA, FMECA and Root Cause Analysis (RCA). Of these, FTA has begun to be used within Autosub (notably at the design stage of the pressure-compensated battery modules for *Autosub6000*). However, broader use of these techniques will require additional resources. These resources have been requested in the NERC Marine Centres' Oceans 2025 programme proposal of March 2006.

3.2 Demonstrating that the required reliability can be achieved – at sea trials

The risk acceptance process requires that the technical team demonstrate that the reliability needed to ensure that the responsible owner's level of risk is not exceeded. Historical fault data will have informed the process as described in Box 2, however, results from trials at sea should be used to validate that the vehicle reliability is indeed no worse than expected. The sea trials should be designed to validate the vehicle in conditions as close to the planned campaign as can be achieved. Key conditions should include, among others, depth, duration, collision avoidance parallels, terrain following patterns and sensor payload.

Unfortunately, trials are apt to be short, and the statistical uncertainty for the Weibull distribution parameters α and β will, as a consequence of few missions, be large. Nevertheless, we do consider the sea trials approach a valid demonstration of system performance under near-actual conditions.

Survival analysis packages such as JMP can be used to help set out requirements and analyse trials results. For example, in Box 3 a hypothetical trials campaign took place with six missions, of lengths 5, 36, 72, 144, 200 and 250 km (707 km in total, or ~110 hours of vehicle run-time). On these trials we posit that one high impact underway fault occurred, and we examine the impact of which mission the fault happened on the Weibull α and β parameters[6], which in turn determine the estimate of surviving the proposed campaign set out in Box 1. If the fault happens on the short 36 km mission, the predicted probability of survival for the Box 1 campaign is 65.8%, which exceeds the responsible

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[6] Note that the JMP analysis cannot handle a fault on either the shortest (5 km) or longest (250 km) missions.

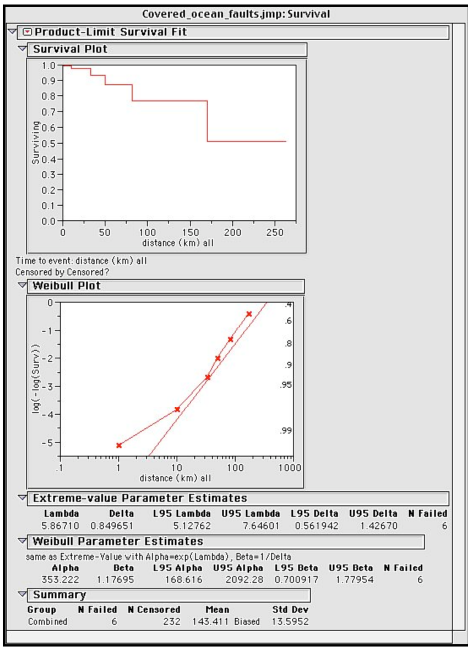
owner’s allowed risk. If, however, the fault occurred on the 200 km mission, the probability of surviving the proposed campaign increases to 98.4%, comfortably within the owner’s allowed risk.

Box 2 Worked example risk calculation using Autosub vehicle data historical for a short under ice campaign of three ice shelf and two sea ice missions.

1. Tabulate the mission data, range and whether high impact fault occurred underway that could lead to loss in under ice missions.

Mission	km	HI fault?
1	10	N
2	30	N
…	…	N or Y
n-1	40	Y
n	80	N

2. Use an analysis programme (for example SAS Institute's JMP $^{(R)}$ package) to fit a Weibull distributionto the data, where x is the distance variable, α the characteristic life and β the shape parameter. As a precursor, a Kaplan Meier staircase estimator of survival may be derived. Below, from a JMP analysis of 118 Autosub missions, the upper plot is the Kaplan Meier estimate, and the lower, a Weibull parametric fit.



```
Time to event: distance (km) all
Censored by Censored?

Extreme-value Parameter Estimates
   Lambda      Delta  L95 Lambda  U95 Lambda  L95 Delta  U95 Delta  N Failed
  5.86710   0.849651     5.12762     7.64601   0.561942    1.42670         6

Weibull Parameter Estimates
same as Extreme-Value with Alpha=exp(Lambda), Beta=1/Delta
    Alpha       Beta  L95 Alpha  U95 Alpha  L95 Beta  U95 Beta  N Failed
  353.222    1.17695    168.616    2092.28  0.700917   1.77954         6

Summary
Group     N Failed  N Censored     Mean          Std Dev
Combined         6         232  143.411  Biased  13.5952
```

3. From the Weibull fit, the parameters α and β and their upper and lower 95% confidence limits can be determined, as in this table from Autosub, where out of 118 missions, 9 failed with high impact underway faults and 109 did not. Note that even with this sample set of over 100 missions, the confidence limits on α and β are large.

α	β	L95 α	U95 α	L95 β	U95 β	N Fail	Censored
483	0.78	173	5105	0.46	1.16	9	109

4. Using this analysis, calculate the Weibull reliability function for the planned missions each of range *x,* where R_{shelf} is the shelf ice relative risk and R_i the relative risk for the particular mission:

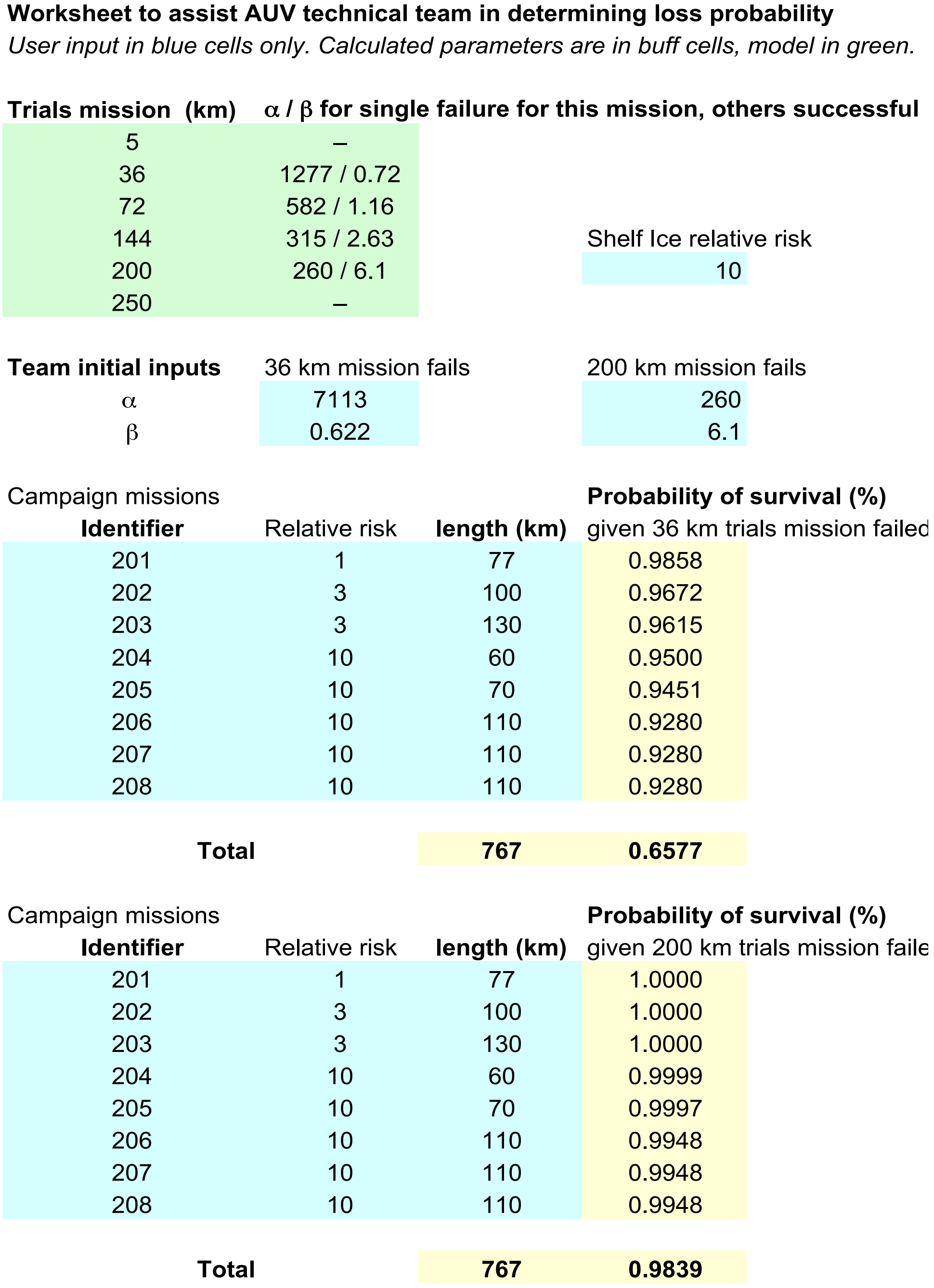
$$R(x) = \exp\left(-\left(\frac{R_i.x}{R_{shelf}\alpha}\right)^{\beta}\right)$$

In the table below five under ice missions are listed, which might take place over 15 days, and against each mission range is the calculated probability of the mission ending successfully. For this five-mission campaign, with two missions under sea ice and three missions under shelf ice, the overall probability of returning with the vehicle is 0.333. That is, there is ~67% probability of loss.

Mission	R_i	km	$R(x)$
201	1	77	0.961
202	3	100	0.892
203	3	130	0.869
204	10	60	0.822
205	10	70	0.801
206	10	110	0.730
207	10	110	0.730
208	10	110	0.730
		767	**0.190**

5. A 67% probability of loss is greater than the owner's acceptable probability of loss of 20%. As this example campaign haslittle or no scope for reducing the missin ranges, the vehicle reliability must (a) be greatly improved and (b) it must be demonstrated that reliability growth has been achieved before the owner would contemplate the polar campaign envisaged in this table.

Box 3 Example of how trials outcomes may influence the expected probability of survival



Worksheet to assist AUV technical team in determining loss probability

User input in blue cells only. Calculated parameters are in buff cells, model in green.

Trials mission (km)	**α / β for single failure for this mission, others successful**
5	–
36	1277 / 0.72
72	582 / 1.16
144	315 / 2.63
200	260 / 6.1
250	–

Shelf Ice relative risk
10

Team initial inputs	36 km mission fails	200 km mission fails
α	7113	260
β	0.622	6.1

Campaign missions **Identifier**	Relative risk	**length (km)**	**Probability of survival (%)** given 36 km trials mission failed
201	1	77	0.9858
202	3	100	0.9672
203	3	130	0.9615
204	10	60	0.9500
205	10	70	0.9451
206	10	110	0.9280
207	10	110	0.9280
208	10	110	0.9280
Total		**767**	**0.6577**

Campaign missions **Identifier**	Relative risk	**length (km)**	**Probability of survival (%)** given 200 km trials mission faile
201	1	77	1.0000
202	3	100	1.0000
203	3	130	1.0000
204	10	60	0.9999
205	10	70	0.9997
206	10	110	0.9948
207	10	110	0.9948
208	10	110	0.9948
Total		**767**	**0.9839**

The implication is that the modelled probability of survival is severely affected by a high impact underway fault on short trials missions [‘short’ can be defined either in spatial or temporal terms- there being a general equivalence between the two related to average speed]. This result reinforces the importance of tracking down, finding the cause, finding a solution, and proving the solution works when such a fault arises. Proving the solution works may well require a further sea trial. It is therefore most important that the vehicle is thoroughly prepared before a sea trial and is in as near-operational condition as possible. Faults that could have been identified in the workshop or in a test tank should have been found and corrected. In assessing reliability, sea trials should be used to run the vehicle on long missions that simulate as closely as possible likely mission conditions.

4. CONCLUSIONS

In this paper we have proposed and described, with worked examples, a risk management process for autonomous underwater vehicles. RMP-AUV requires close cooperation and a high degree of trust between the responsible owner and the vehicle's technical team. We propose that it is the duty of the responsible owner to set out the risk that they will accept for proposed campaigns. It is the duty of the technical team to estimate the risk of undertaking the campaign using historical information and, if the estimate shows that the risk of the proposed campaign is acceptable to the owner, it is up to the technical team to demonstrate that it is indeed so, for example through sea trials. It is for the responsible owner to ensure that adequate resources are available to the technical team to verify the risk assessment, for example by funding trials.

From the worked examples in this paper, it is clear that the historical reliability of research AUVs has been low. This needs to be addressed as a matter or urgency if the technology is to continue to receive support by research agencies. The experience in industry (C&C Technologies with *Hugin*) and in research (MBARI with *Dorado*) is that persistence, consistence, and extensive use at sea is needed to grow reliability. A two-week trial cruise is no substitute for the months at sea dedicated to improving reliability (Figure 2 – C&C Technologies) or for the bimonthly missions run by *AUVCTD* (Thomas, 2006).

How might this be tackled for Autosub and UK AUVs? The C&C Technologies route to reliability growth requires extensive periods at sea with a vessel in attendance in deep water. It would be enormously costly. The MBARI route uses a small vessel for near shore deployment, and the vehicle quickly reaches the deep waters of the Monterey Canyon, California. The UK is not well placed geographically to take the MBARI route – our continental shelf is too extensive. However, we do not think that this is a UK-only problem. Neither is it a problem limited to propeller-driven AUVs. Recent NOCS experience with commercial deep-water gliders shows that this emerging technology is also prone to faults underway. It may be appropriate to explore, perhaps on an European basis, the establishment of a test facility for autonomous underwater vehicles. The facility would need to have ready access to deep water (over 1000 m) as at MBARI, with facilities for launch and recovery, space for support facilities such as a workshop and sufficient infrastructure to support unplanned recovery when things do go wrong.

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