"Bringing together Research and Industry for the Development of Glider Environmental Services"

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DELIVERABLE D3.1
"Standards and Guidance for Sub-Sea Gliders"

ABSTRACT

The overall goal of BRIDGES is to develop two autonomous sub-sea gliders to operate in the deep-sea environment (up to 5,000 metres). The use of the acquired knowledge from previous sub-sea glider projects such as the SEA EXPLORER product, the SPAN vehicle, and the AUTOSUB LR from National Oceanography Centre will be an asset and helpful for this purpose.

Effective and easily-applied standards are essential for cost-effective manufacturing of vehicles and payloads and to enable commonality across the system. These standards must ensure flexibility, modularity and the ability to economically implement future upgrades.

This document provides an assessment of the current state of standards available for manufacturing the underwater vehicles, best practice recommendations and the current state of the design and standards planned to be used. In addition, an assessment of the regulatory approaches used in other fields was undertaken to aid in the development of standards for sub-sea gliders.

During the remainder of the BRIDGES project the results of this document will be further refined, taking into account experiences gathered through prototyping activities and other relevant projects.

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1 Introduction

1.1 Bringing Together Research and Industry for the Development of Glider Environmental Services (BRIDGES)

1.1.1 The BRIDGES project is funded under the European Commission Horizon 2020 programme and aims to develop tools to further understanding, monitoring and sustainable exploitation of the marine environment. The four year project has the objective to improve sub-sea glider technology, system integration, operational management and standardisation.

Figure 1.1 - Logo of the EC Horizon 2020 BRIDGES Project

1.1.2 The BRIDGES consortium is composed of 19 public and private partners from 7 European Union (EU) countries and 2 associated countries, covering renowned scientific institutes, industrial groups and innovative Small to Medium Sized Enterprises (SMEs).

1.1.3 BRIDGES aims to provide new opportunities for offshore industries, such as oil and gas, sea mining, marine research and environmental monitoring. This new tool consisting of sub-sea gliders, that are robust, cost effective, relocatable, versatile and easily deployable, will support autonomous long term in situ exploration of the deep ocean over a wide range of spatial and temporal scales. Two Explorer sub-sea gliders will be developed that are built on the successful unique European sub-sea glider, the SEA-EXPLORER. During BRIDGES the two new gliders will be modularized and adapted to more diverse operations.

1.1.4 The two sub-sea glider designs will be optimised for missions at 2,500 metres ("Deep") and 5,000 metres ("Ultra-Deep") sea depth. Given that the average depth of the ocean is considered to be approximately 3,700 metres, the two sub-sea glider designs being proposed as part of BRIDGES will be capable of servicing a large proportion of the ocean.

1.1.5 Multiple nearshore and deep sea trials and demonstrations are planned, with a forecast market introduction of the Explorer sub-sea gliders of 2020.

1.1.6 This report aims to identify current standards and regulations that are applicable to sub-sea gliders and provide pertinent information that will be required in the creation of a set of standards and guidance applicable to sub-sea glider manufacturers, maintainers and operators. This set requires research and development as current standards applicable to comparable fields, such as the Unmanned Aerial Vehicle (UAV) market, lack direct applicability to a system designed to operate at low speed and low power.

1.2 The Role of Standards in BRIDGES

1.2.1 Almost every industry currently active worldwide will have some form of regulation or standards that affects them. In general these standards and/or regulations establish the requirements that a device must obey as well as laying out typical methods and approaches that are considered good industry practice. Whether the source of requirements stems from international agreement, government agencies or even from industry regulating itself, these standards often evolve over time becoming more refined as a greater number of industry experts get involved in their creation, review and update.

1.2.2 Standards can be categorised into a number of generic types and serve a variety of purposes, although in general the principal types of standards commonly applied to technical projects (such as BRIDGES) include:

a. Standard definition – used to formally establish terminology;

b. Standard units – commonly applied metrics for physical measurements;

c. Standard specification – an unambiguous statement of requirements for a physical item, material, system or service;

d. Standard test method – defines an approach to perform an unbiased and repeatable measurement of physical properties or performance;

e. Standard practice – a common set of instructions for performance of an operation.

1.2.3 The application of standards typically provides a range of benefits that encompass:

a. Statements of what is known to be common industry practice;

b. Definition of an acceptable means to comply with relevant regulations;

c. Ensuring commonality of approach to facilitate integration of elements within a system;

d. Interoperability of systems with each other and the interaction of systems that may come in to conflict;

e. Product commercialisation, including:

   (i) Market access;

   (ii) Economies of scale;

   (iii) Encouraging innovation;

   (iv) Increased awareness of technical developments and initiatives;

   (v) Increased customer choice via the provision of a foundation for new features;

f. Ongoing system upgrade, enhancement and technology insertion;

g. Consistency in the conduct and performance of design, manufacture, operation, maintenance and disposal.

h. Safety and reliability.

1.2.4 Whilst not all areas are directly applicable to sub-sea gliders, the development of a set of specifications and procedures will greatly benefit ongoing sub-sea glider development and operation.

1.2.5 **Recommendation 1 – Whilst the driver for this report is a set of standards that encourage cost-effectiveness and commercialisation, the eventual set of standards that is created should cover the full range of all applicable standardisation areas.**

1.3 Approach

1.3.1 To facilitate the investigations undertaken as part of this project, a multi-stage approach to the research was undertaken.

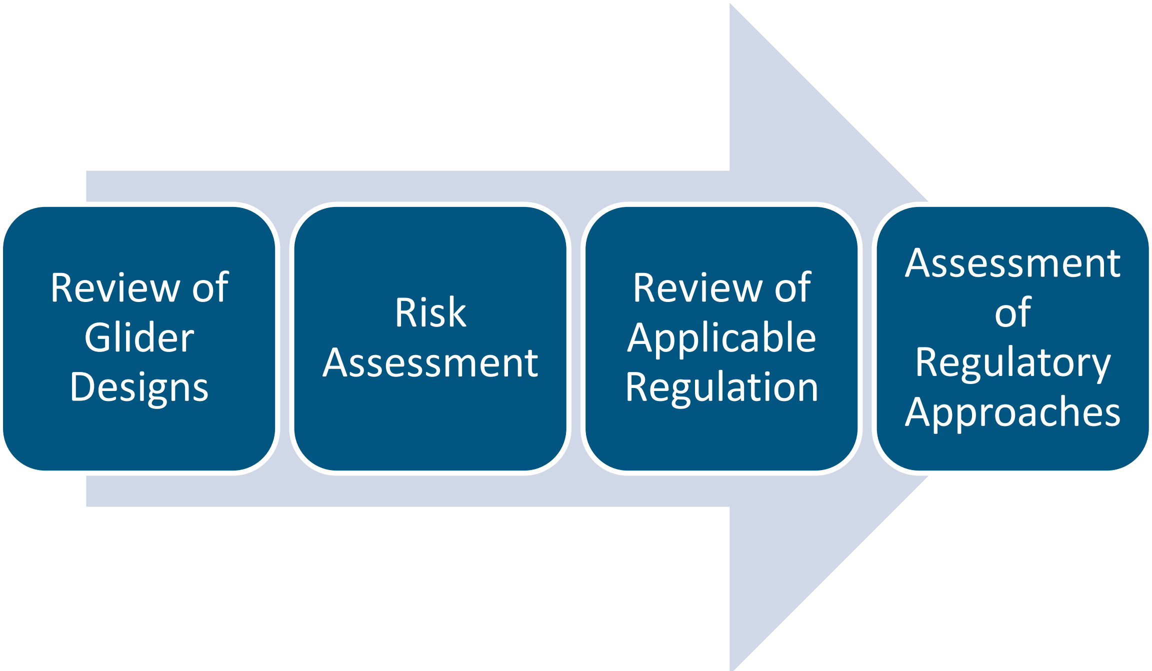

Figure 1.2 - Glider Research Approach

1.3.2 The research stages were as follows:

a. Review of Glider Designs;

(i) A generalised review of currently in service sub-sea glider designs alongside the proposed preliminary designs that have been developed as part of the BRIDGES project. This will include other applicable technologies that may prove analogous to sub-sea gliders.

b. Risk Assessment;

(i) To ensure that all areas that pose hazards are covered by the standards (be those hazards safety, environmental or mission), two different risk assessment techniques were employed to find as many applicable hazards as possible.

c. Review of Applicable Regulations;

(i) Whilst it is known that there is a limited amount of directly-applicable regulations that apply to sub-sea gliders, there are still some regulations that will need to be adhered to and thus these have been researched.

d. Assessment of Regulatory Approaches;

(i) There are a number of different approaches that are taken to standards, guidance and regulations some of which may prove appropriate for sub-sea gliders.

1.3.3 By taking this approach it has proven possible to develop a series of guidance areas that it is recommended be included in the eventual standards that are created.

1.3.4 Whilst safety is not the primary motivation for standardisation on BRIDGES, efforts to ensure best safety practices are followed should be considered concurrently with the drive for cost effectiveness and commercialisation.

2 Review of Sub-sea Gliders and their Designs

2.1 Brief History of Sea Exploration and Underwater Research

2.1.1 Underwater exploration has been conducted historically for both scientific and commercial purposes, but the development of unmanned submersibles is a relatively new technology to support these endeavours.

2.1.2 Over the years, underwater Remotely Operated Vehicles (ROVs) have seen increased usage in multiple fields, especially the oil and gas markets, and further research has led to the development of Autonomous Underwater Vehicles (AUVs). One of the first true unmanned submersibles was created in the 1950s and research and improvements have continued to be introduced in the years that have followed.

2.1.3 Gliders (a subset of AUVs) provide us with a relatively safe option in order to observe and gain information of undersea conditions over longer periods of time. While development of sub-sea glider technologies has been ongoing for more than two decades, it still is an immature domain that is evolving as new technologies are established. The BRIDGES project is part of the drive to improve sub-sea glider technology, ideally creating an inexpensive device that will be able to record information in an accurate and dependable way, whilst posing minimal risks to other users of the water space and the ocean environment.

2.2 Introduction to Sub-sea Gliders

2.2.1 Initial development of sub-sea gliders that we know today began in the late 1980s and early 1990s with realistic depth and distance targets for the time, although the concept of a sub-sea glider was originally prototyped as a manned version as early as the 1960s. These targets have long since been met and exceeded, however there is still a lot more that could be achieved as development of sub-sea glider technology continues.

2.2.2 A sub-sea glider is a type of AUV which is propelled by changes in buoyancy and achieves lateral motion by the lift generate through the flow of water over its 'wings'. The resulting 'saw tooth' profile through the water allows measurements to be made at a range of depths. This energy efficient technique allows sub-sea gliders to travel thousands of miles and operate for months at a time.

2.2.3 The aim of sub-sea glider use is to be able to explore the depths of the oceans for extensive periods of time, observing the changes in environments while at the same time not causing any human risk (risk typically associated with manned underwater vehicles) as well as little harm to marine life or habitats as possible. Sub-sea gliders are currently used for oceanographic research and monitoring but have the potential to operate in other sectors such as the oil & gas and offshore mining industries.

2.2.4 Power requirements are typically met through use of batteries; both rechargeable and single use battery packs have been successfully designed for use on sub-sea gliders. The battery packs will typically run both the sensor systems included on the sub-sea glider and the buoyancy / movement systems, requiring careful design and management to ensure that all power requirements are met simultaneously.

2.2.5 The buoyancy of a sub-sea glider is typically altered by one of four methods, pumping ballast water into and out of a tank in the sub-sea glider, using a compressed air buoyancy engine, pumping oil into and out of an external bladder, or relying on the thermal gradient between water at the surface and at depth. Challenges for ultra-deep operations include pumping displacement volume out against external pressures reaching 500 atmospheres at depths of 5,000 metres and the compressibility of the hull, which will increasethe sub-sea glider's buoyancy at depth passively (without any pumping). To continue the dive, a glider with non-compressible hulls will then have to "bleed" displacement volume on the descent, which must later be pumped, at great energy cost, especially for great depths. High compressibility hulls that nearly match the compressibility of seawater have been produced to minimize this (e.g. Seaglider) but these are limited to 1000 m depth.

2.2.6 A hybrid propulsion system, incorporating a motor and propeller in addition to the sub-sea glider's wings, can increase the speed and manoeuvrability of a sub-sea glider but the additional power and weight requirements can reduce the overall range and endurance.

2.2.7 The pitch, and hence the glide angle, of the sub-sea glider can be controlled by adjusting the position of the vessel's centre of gravity, usually by moving a mass fore and aft within the hull. The sub-sea glider's heading can be altered using a conventional rudder on a fin or by displacing the center of mass laterally (athwart ship).

2.2.8 Mission duration is usually dictated by the application or mission requirements in light of the glider's maximum endurance. Currently sub-sea glider missions can vary from as little as 12 hours and upwards to months at a time for longer missions.

2.2.9 Sub-sea glider operations rely on transmission of data through satellite communication methods. To recover the full set of ocean and engineering data, it is required to retrieve the system. The biggest restriction in navigation and communication is caused by radio signals being unable to penetrate the water, limiting navigational systems to dead reckoning and surface based methods. Due to this, most sub-sea gliders regularly surface in order to gain a Global Positioning System (GPS) location and use dead reckoning when submerged to move from location to location.

2.2.10 Communication between operators and the sub-sea gliders is typically by satellite modem, as the short antenna height when surfaced limits the range of terrestrial radio communications. Operator 'tracking' of sub-sea gliders is based on simulation models, as the sub-sea gliders cannot communicate when submerged and they may stay submerged for extended periods of time. An on-board GPS sensor allows sub-sea gliders to get a positional fix when surfaced, and in some systems an inertial guidance system is used to maintain positional awareness underwater (though this is rare and expensive). The difference between the predicted or simulated position and the GPS fix is typically used to estimate average currents over the dive.

2.2.11 Besides standard hydrographic measurements,the sensor package on a sub-sea glider may include acoustic (active and passive) instruments, particle measurement devices and dissolved oxygen sensors, as well as on-board chemistry analysis labs. For long duration missions, the sensor power budget may only be a few watts, shared between the instruments. Data from the sensors may be transmitted whilst the sub-sea glider is surfaced and/or stored on-board for download and analysis when the sub-sea glider is recovered at the end of its mission.

Figure 2.1 - Early Concept for the BRIDGES Deep Explorer Sub-Sea Glider

2.3 Alternative AUV designs

2.3.1 The current AUV market represents a varied field spanning many potential mission objectives, including areas such as:

a. Cable Deployment;

b. Environmental Monitoring;

c. Harbour and Port Security;

d. Hull Inspection;

e. Hydro-acoustic Research;

f. Inspection Maintenance and Repair;

g. Intelligence, Surveillance, and Reconnaissance;

h. Military, including:

(i) Submarine Warfare;

(ii) Explosive Ordnance Disposal;

(iii) Mine Countermeasures;

(iv) Training Target drones.

i. Mapping (Coastal, Seabed, Freshwater etc.);

j. Polar Exploration;

k. Scientific Research;

l. Search and Recovery;

m. Sensor Development;

n. Marine Surveys, including:

(i) Cable/Pipeline Routing;

(ii) Geophysical;

(iii) Oceanographic;

(iv) Oil and Gas;

(v) Photometric;

(vi) Pre and Post dredging;

2.3.2 The saw-tooth movement pattern of a sub-sea glider does provide benefits over other propulsion methods with regards to energy efficiency, however the slow movement speed and the device's lack of ability to directly control its own motion over and above dead reckoning does render it unsuitable for certain mission profiles.

2.3.3 To meet the demands of such varied missions and goals a number of differing designs for AUVs have been developed, each design offers advantages and disadvantages over the others thus enabling differing devices to be used to match the circumstances at hand. Some key categories include:

a. Biomimetic - AUVs in this category are designed to look or act similar to biological entities. By emulating the shapes and movement patterns that developed from years of evolution it is possible to construct a device that interacts with the aquatic environment efficiently (Figure 2.2).

b. Drone Submarines - Designed to mimic the actions and signatures of manned submarine counterparts, these devices are often used to aid training of military forces in tracking and targeting of enemy sub-sea devices.

c. Rigid Frame - Often constructed from interlocking struts to form a solid structure for the mounting of equipment, often buoyancy is added to the top of the structure to aid in stability and workability.

d. Torpedo - Torpedo shaped AUV have the advantage of low cross sectional areas with good hydrodynamic properties, devices in this category come both with and without ‘wings’. Sub-sea gliders tend to fit within this category, though often torpedo designs may be used for other purposes and shun the buoyancy engine system of movement for a more direct propulsion method.

Figure 2.2 - BMT SHOAL Robotic AUV Prototype

2.4 Current Sub-Sea Glider Designs

2.4.1 Design specifications for sub-sea gliders vary greatly depending on their planned use; the myriad of operating environments and research objectives means that often sub-sea gliders are constructed to very different specifications. There are however typically three main methods sub-sea gliders may employ to achieve motion:

a. Using thermal gradients;

b. Buoyancy engine (using electrical power to mechanically adjust buoyancy);

c. Hybrid designs:

(i) These designs will typically include both a buoyancy engine and a more traditional propeller based system.

2.4.2 Typically, weights, dimensions and load outs will be designed to meet the expected conditions, although on average figures can be expected to be within the following ranges:

a. Weight: Between 50 and 200 Kilograms.

b. Length: Between 1 and 3 metres.

c. Diameter: Between 0.25 to 0.5 metres.

d. Velocity: Up to 1.5 metres per second.

e. Depth Capabilities: typically between 200 and 1000 m.

Figure 2.3 - Deployment of SEA-EXPLORER

2.4.3 The majority of current sub-sea gliders utilise lithium ion, lithium polymer or nickel metal hydride batteries due to the high capacity limits of such batteries and their well-understood discharge cycles. This is despite being comparatively more expensive than more traditional lead-acid and alkaline batteries which suffer from excessive weight and less stable voltage supply levels through the discharge cycle. Energy requirements and usage patterns are mission dependent, however in general the design will be based on the concept of an ‘energy budget’ and the energy consumption will be a trade-off between capability, duration, speed, etc.

2.4.4 Some sub-sea glider designs will also make use of external environmental conditions, where possible, to further reduce energy use and thus extend battery duration. For example, some sub-sea gliders are designed to utilise underwater thermal gradients. By using the temperature-dependent state change of a particular material to cause displacement, the sub-sea glider requires less to surface than might otherwise be required.

2.5 BRIDGES Specification

2.5.1 The Deep and Ultra-Deep sub-sea gliders will be an evolution of the currently in service SEA-EXPLORER, but will feature a number of important upgrades and design developments. Not least is the increased operational depth required by these new vehicles. The design requirements also specify the need for a modular design, allowing the flexibility to equip the system for a multitude of mission types.

2.5.2 In addition this new design will be a hybrid design (incorporating a propeller) thus enabling greater market penetration by allowing for a greater number of mission objectives (such as sea bed mapping missions).

2.5.3 The Deep sub-sea glider has a target operating depth of up to 2,500 metres and will need to be in active service for at least 25 years. In comparison, the Ultra-Deep sub-sea glider will be able to submerge to a depth of 5,000 metres.

	Deep Explorer	Ultra-Deep Explorer
Maximum Operational Depth	2,500 metres	5,000 metres
Test Depth	3,125 metres	6,000 metres
Design Depth	3,750 metres	6,500 metres

Table 2.1 - BRIDGES Depth Specifications

2.5.4 The Deep and Ultra-Deep sub-sea gliders will have a removable nose cone to make replacement and repairs simple. The main body and nose cone will also both be independently buoyant. To increase maintainability, the nose cone on both the Deep and Ultra-Deep sub-sea gliders will be interchangeable to simplify manufacturing.

2.5.5 The sub-sea gliders will be made lightweight by constructing the wet hull of Low-Density Polyethylene (LDPE) (if possible) whilst utilising detachable panels to help with maintenance. The wet hull is designed to act as a cover for the pressure vessels and aids in reducing hydrodynamic drag on the sub-sea glider.

2.5.6 The main visible difference between the two designs of the Deep and the Ultra-Deep is the wings (detachable). The goal is to provide the same basic structure (though utilising differing materials for construction for the two hulls) of the vessels but the wings are different.

2.5.7 Buoyancy is one of the main areas of interest in designing the sub-sea glider and is provided by the pressure vessels. Extra buoyancy will be given by syntactic foam and the use of low density Pressure Balanced Oil Filled (PBOF) bladders.

2.5.8 When submerged, the pressure hulls will be compressible (1.5% at 500 bar) and the compressibility compensation is part of the subsystem. The resultant fatigue caused by repeated compression is also to be designed for, assuming a worst case of 2 cycles from 0 to 500 bars per day.

2.6 Preliminary Design for BRIDGES

2.6.1 As part of the BRIDGES project, ALSEAMAR undertook development of the preliminary designs. The resultant documentation Deep Explorer Preliminary Design v1.1 (Reference 1) and Ultra Deep Explorer Preliminary Design v1.1 (Reference 2) were released in November 2015 and were used to influence the development of this report.

2.6.2 Key to this were the design rules under which they were operating, in summary these included:

a. Ease of Use:

(i) Ergonomics;

(ii) Limited need for prerequisites;

(iii) Feedback from SEA-EXPLORER.

b. Security:

(i) Compliance with regulations;

(ii) Identification of critical safety failures;

(iii) Human and or technical risk reduction barriers.

c. Testability:

(i) Ability to perform checks using simple tools;

(ii) Ability to perform checks on the security features;

(iii) Ability to monitor the performance.

d. Maintainability:

(i) Ability to aid users in troubleshooting;

(ii) Regulatory constraints;

(iii) Preference for commercial off the shelf equipment;

(iv) Avoidance where possible of obsolescence issues and ensuring long term availability of spare parts;

(v) Reliability studies.

2.6.3 The preliminary design covered both the general system design and individual subsystems including:

a. Payload;

b. Structure;

c. Pressure hulls;

d. Cabling and power distribution;

e. Energy subsystem;

f. Actuators;

g. Command and control;

h. Safety;

i. Launch and recovery.

2.6.4 Please see Figure 2.4 for an expanded subsystem diagram.

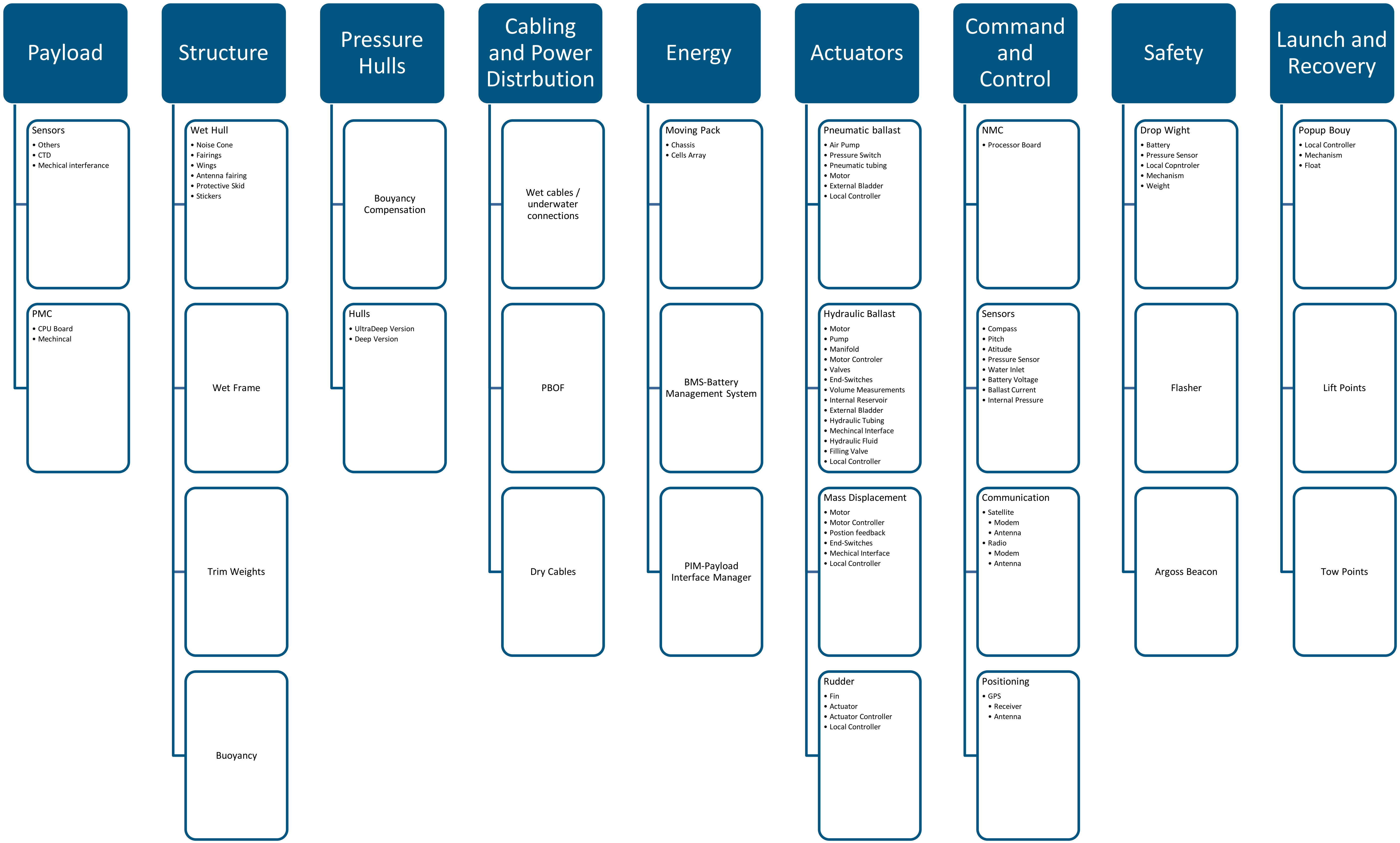

Figure 2.4 - BRIDGES Sub-Sea Glider System Diagram

3 Understanding Risks - A Hazard Based Approach

3.1.1 For the purposes of this assessment, hazards are defined as having impacts on three distinct areas:

a. Safety (personal);

b. Environmental;

c. Mission.

3.1.2 Broadly speaking, the sub-sea gliders produced as part of the BRIDGES project will present risks during four lifecycle stages:

a. Construction;

b. Configuration, maintenance and launch;

c. Operation;

d. End of life.

3.1.3 Each of these stages pose different challenges that will need to be met through appropriate guidelines, regulations and controls. Construction methods and hazards posed to industry during construction falls outside the scope of the BRIDGES project as hazards incurred in this phase will not be unique to sub-sea gliders and will instead be more generalised to the manufacturing industry. Through appropriate use of common hazard identification techniques it has been possible to create a short list of hazards that exist within the remaining three lifecycle stages (Table 3.1, Table 3.2 and Table 3.3).

3.1.4 The configuration, maintenance and launch periods are those periods where personnel may be directly interfacing with the sub-sea glider, be that on-board ship or in workshops, during which certain elements of the system pose hazards to the personnel.

3.1.5

a.

b.

c.

Hazard Title	Hazard Description	Risks		
		Safety	Env	Mission
Drop Hazard	Sub-sea glider drops during launch and recovery operations potentially injuring crew	✓		
Manual Handling	Sub-sea glider weight is above guidance for safe manual handling.	✓		
Moving Parts	Various moving parts (specifically propellers) may pose hazards to personnel configuring and maintaining the unit.	✓		
Hot and Cold	Depending on usage, parts of the sub-sea glider may become excessively hot or cold and pose contact hazards.	✓		

Hazard Title	Hazard Description	Risks		
		Safety	Env	Mission
Contamination	Depending on usage, the unit may become contaminated with dangerous chemicals that may pose a hazard to personnel working with the device.	✓	✓	
High Pressure Discharge	Accidental pump activation on surface would result in a high pressure discharge in the proximity of personnel. Flooded pressure housing at depth may retain high pressure during ascent, which it is not designed for also could result in explosive rupture and discharge.	✓		
Transportation	Air/Marine travel regulations interfere with transport.			✓
Sea State	Attempts at launching and recovering in high sea states.	✓		
Electrical	Sub-sea gliders contain high capacity batteries that could discharge at an inappropriate time.	✓		
Fire	The batteries in use could combust, leading to a fire that is hard to control and put out.	✓		✓

Table 3.1 - Configuration & Maintenance Hazards

3.1.6 During the operational phase, the sub-sea glider will be acting autonomously and may be out of contact for extended periods of time. The sub-sea glider itself will be required to make decisions to help mitigate dangers it encounters.

Hazard Title	Hazard Description	Risks		
		Safety	Env	Mission
Fire	The batteries in use combust, causing a fire and damaging the sub-sea glider.	✓	✓	✓
Entanglement	Sub-sea glider gets entangled during operations, limiting its ability to continue its mission and potentially (in the case of entanglements with fishing nets and similar) causing risks to members of the public operating these source of entanglement.	✓		✓
Collision	Collision with Manned Vessels, Members of the Public, Fixed Infrastructure or the Sea Bed. Potentially causing damage/injury to either the sub-sea glider or the object with which it collides.	✓	✓	✓
Navigational Obstruction	The sub-sea glider presents a navigational obstruction to passing vessels. Due to a lack of manoeuvrability of the sub-sea glider it is possible that this would result in the vessel in question having to alter course and potentially conduct unsafe navigational actions.	✓		
Discharge	During normal operations and fault conditions the sub-sea glider may discharge elements that are hazardous to the environment.	✓	✓	

Hazard Title	Hazard Description	Risks		
		Safety	Env	Mission
Inadvertent Handling by Public	Due to repeated surfacing and the risk of being washed ashore, members of the general public may come into direct, unsupervised contact with hazardous elements of the sub-sea glider.	✓		✓
Harmful Interaction with Environment	Depending on location, the sub-sea glider could damage local flora and fauna.		✓	
Contamination of Sub-Sea Glider	Some ecological factors such as oil spills could coat the sub-sea glider and limit its ability to perform its mission. It could also transfer that contamination to other locations.		✓	✓
Surface in Wrong Location	Given stronger than expected current flows, the sub-sea glider may surface outside of the expected areas and be out of range for contact.		✓	✓
Security / Hacking	Due to the isolated nature of the sub-sea glider it is possible that outside malicious interaction could be conducted.	✓		✓

Table 3.2 - Operational Hazards

3.1.7 End of life hazards occur during decommissioning, disposal or total loss of sub-sea glider subsystems or the sub-sea glider itself.

Hazard Title	Hazard Description	Risks		
		Safety	Env	Mission
Loss of Sub-Sea Glider	Any number of system failures in the sub-sea glider could result in mission failures, and potentially (depending on failure type) environmental damage.	✓	✓	✓
Disposal	Some elements of sub-sea glider construction may prove environmentally damaging following disposal of the sub-sea glider system.		✓	

Table 3.3 - End of Life Hazards

3.2 Aspects to be Standardised

3.2.1 The risks presented during four lifecycle stages are associated with standardisation in order to be managed properly.

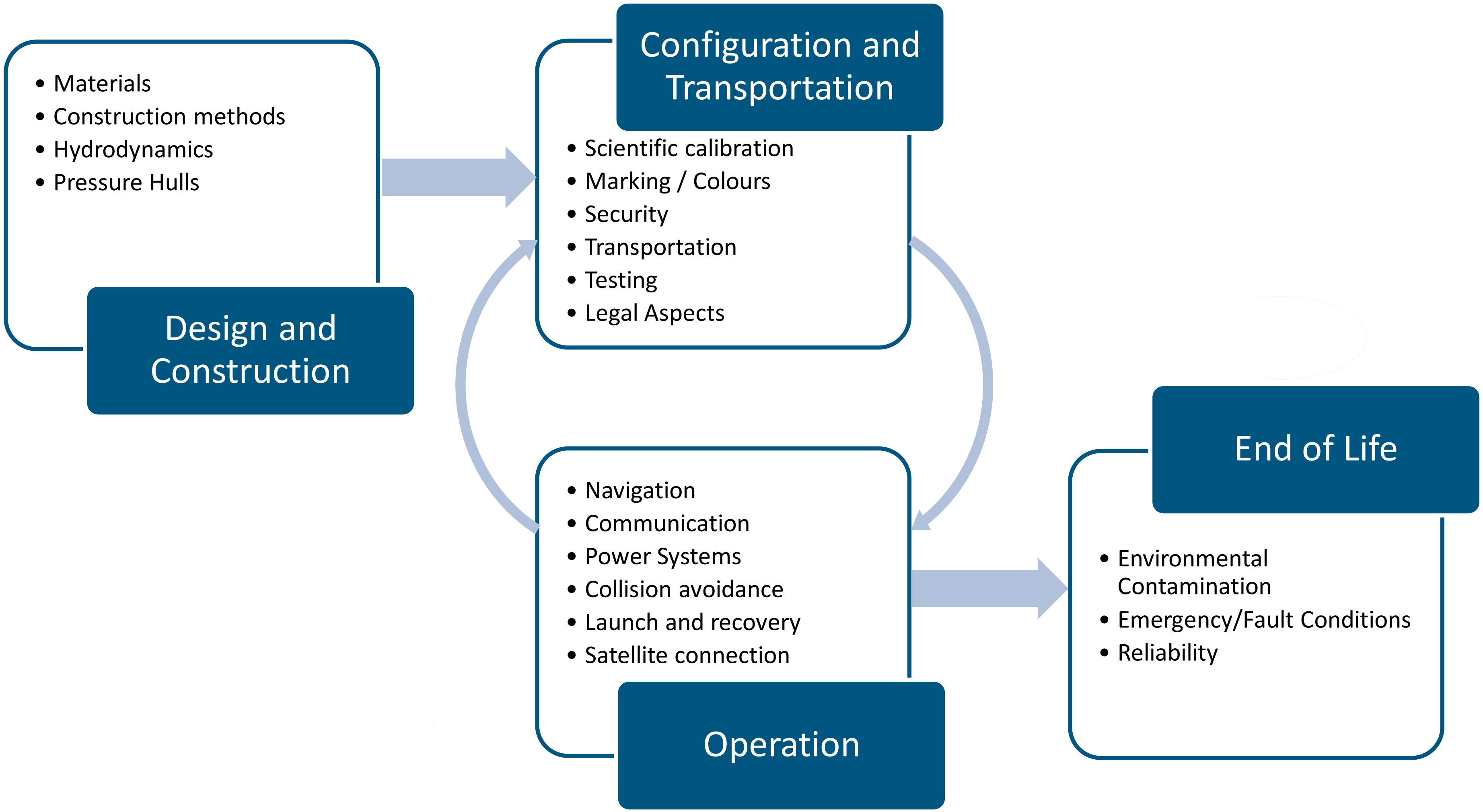

Figure 3.1 - Aspects to be Standardised

4 Understanding the Risks - A Security Based Approach

4.1 Introduction

4.1.1 The notion that security-related risks can have an impact on safety is widely acknowledged and is incorporated into both civilian standards (e.g. IEC 61508) (Reference 3) and United Kingdom (UK) military standards (e.g. Defence standard 00-55 Issue 3) (Reference 4). However, there is a continued perception that the goals of both safety and security are mutually incompatible. An example of this is a safety requirement that operators have easy access to control equipment versus a security requirement that such equipment has restricted access and is locked away to prevent unauthorised use.

4.1.2 One of the reasons for this divergence is that safety and security are treated as different properties to be assessed. Safety practitioners attempt to mitigate the effect of unintentional activity by benign actors, while mitigations in the security domain are developed through considering intentional activity by malicious actors.

4.1.3 Not all security risks translate to the safety domain, but there is a cross-over that may not be analysed. Critically, such a division also ignores other categories of hazard that need to be controlled, such as well-intentioned but unsafe actions by benign actors.

4.1.4 This section begins by describing the complete taxonomy of hazards that need to be considered, which was used as a prompt for safety practitioners. A brief description of Systems-Theoretic Process Analysis (STPA), which was used to identify the specific hazards for the sub-sea glider, is also provided. This is compared to a separate study that used the same approach and same system model for the hazard analysis, but where the safety practitioners were not prompted to consider security using the developed taxonomy.

4.2 Taxonomy of Hazards

4.2.1 In complex systems, particularly those containing programmable hardware or software, there are multiple means by which unsafe behaviour could be introduced. Conventional hazard identification would identify systematic flaws introduced in the specification, design and implementation of the equipment as a source of hazards.

4.2.2 Mitigations for such hazards would be a combination of development practices conforming to recognised good practice commensurate with the level of risk, and Standard Operating Procedures (SOPs) to ensure that equipment is used within the safe operating envelope defined in the safety case.

4.2.3 Such hazards and mitigations fall into the category of unintentional action by benign actors. For example, equipment manufacturers do not intend to introduce unsafe functionality. However, this assumes that the safety of the system as determined during design and commissioning remains constant during operation. When malicious actors deliberately attempt to compromise systems, for example by introducing software backdoors or zero day bugs during design or maintenance, these actions will almost certainly undermine the assumptions made in determining the safe operating envelope for the equipment. This in turn undermines the basis for SOPs and operator expectations, resulting in the realisation of hazards.

4.2.4 Additionally, the benign actor/unintentional action model of hazard analysis is undermined by experience. Faced with SOPs that introduce onerous steps to ensure safety, operators ultimately seek the path of least resistance and may violate SOPs to achieve an operational objective and so introduce hazards that a safety practitioner would not identify by assuming perfect behaviour on the part of operators.

4.2.5 A complete taxonomy of hazards would therefore include both benign and malicious actors, and their unintended and intended actions that can result in hazards. Table 3.1 presents a matrix that shows the product of these factors.

	Unintentional Action	Intentional Action
Benign Actor	Controller or operator undertaking an activity in accordance with expectations and assumptions established during design, during which a fault occurs.	Controller deliberately attempts to achieve objective through undocumented/non-standard means. Incorporates all "well-intentioned" operator scenarios.
	Examples: Random hardware failures. Systematic hardware/software failures. Human factors problems in the interface. Poorly defined/inadequate SOPs Software corruption	Examples: Operator circumvents safety-related procedures/systems to simplify task. Unauthorised modifications to "improve" platform. Poor development / maintenance practices. Poorly defined/inadequate SOPs.
Malicious Actor	Controller, operator or third party attempting to achieve an unauthorised objective unrelated to the affected system. No direct attempt to disrupt systems and operations, but this occurs as a side-effect of an unrelated malicious action.	Controller or operator undertaking an activity to deliberately disrupt systems and operations. May involve deliberately undermining assumptions and expectations established during design.
	Examples: Corporate network disruption, with unintended impact on safety monitoring. Infected computer floods network with traffic, preventing control/monitoring of functions.	Examples: Built-in backdoors or zero-day events introduced at commissioning or maintenance. Deliberate sabotage by personnel.

Table 4.1 - Hazard Actors Matrix

4.2.6 All four quadrants of this matrix provide ways of hazards being introduced, yet conventional safety analysis primarily considers only one of these. By considering all four quadrants, mitigations to all forms of hazard can be introduced into the design and so produce safer equipment and platforms. For example:

a. A malicious/unintended action where an infected computer overloads a platform management system network and so results in loss of propulsion control. Introducing measures to detect/act against equipment overloading the network, or providing alternative communications routes for critical systems.

b. A benign/intended action where poor maintenance procedures allow unsuitable code to be installed on a platform. This can be mitigated by requiring suppliers to have maintenance procedures that are commensurate with the risk, and conducting regular audits to ensure that they are being followed.

4.2.7 A significant benefit of this model of hazard source is that it incorporates security-specific safety concerns (as the malicious/intended quadrant) directly in the consideration. This would lead to significantly fewer conflicts when attempting to merge safety and security assurance cases.

4.2.8 Having identified this matrix, it was necessary to see whether a safety practitioner, prompted by the matrix in Table 3.1, would identify additional hazards that could be used to generate appropriate mitigations. To do this, we applied a hazard analysis technique called STPA to a concept sub-sea glider being designed under the BRIDGES project. This technique is described in the following sub-section.

4.3 System-Theoretic Process Analysis

4.3.1 The STPA approach considers safety implications in complex interacting systems by representing the system as a series of control loops. In this way, control actions are identified that could contribute to the occurrence of a hazardous state. These control actions can be both intended or driven by faults or failures, thereby ensuring that the full spectrum of potential contributory factors to any given accident/incident are identified and assessed. It is described fully in Nancy Leveson's book Engineering a Safer World - Systems Thinking Applied To Safety (Reference 5).

4.3.2 This is a top-down analysis approach that is appropriate for complex systems such as the BRIDGES sub-sea glider, and has the advantage that all potentially hazardous system behaviours are considered. As such, it acknowledges that system properties such as safety and security are emergent properties of a system and cannot be decomposed into contributions from individual subsystems and equipment.

4.3.3 The technique requires the development of a functional control diagram showing how the various components of a system interact; and it requires that safety requirements, systems hazards and safety constraints are identified.

4.3.4 The analysis then proceeds in two steps:

a. Identify the potential for inadequate control of the system that can result in a hazardous state. Four possibilities are considered:

(i) Control action is not provided;

(ii) Unsafe control action is provided;

(iii) Control action is provided too early or too late;

(iv) Control action is stopped too soon or applied for too long.

b. Determine how the potentially hazardous control actions identified in the first step can occur. This includes:

(i) Examining how unsafe control actions could be induced by examining each part of the functional control loop;

(ii) Considering how designed controls and mitigations could degrade over time, and introduce protection such as maintenance procedures, safety audits, etc.

4.3.5 This structured approach to hazard analysis was applied by two independent teams to the proposed design of the BRIDGES sub-sea glider: one with and the other without the matrix from Figure 1 as a prompt. The goal was to compare the outputs from the two teams of safety practitioners and evaluate whether it provided any additional benefit.

4.4 Applying STPA Using Security to BRIDGES

4.4.1 In order to apply STPA, a functional control model for the sub-sea glider was required. This is shown in Figure 3.1.

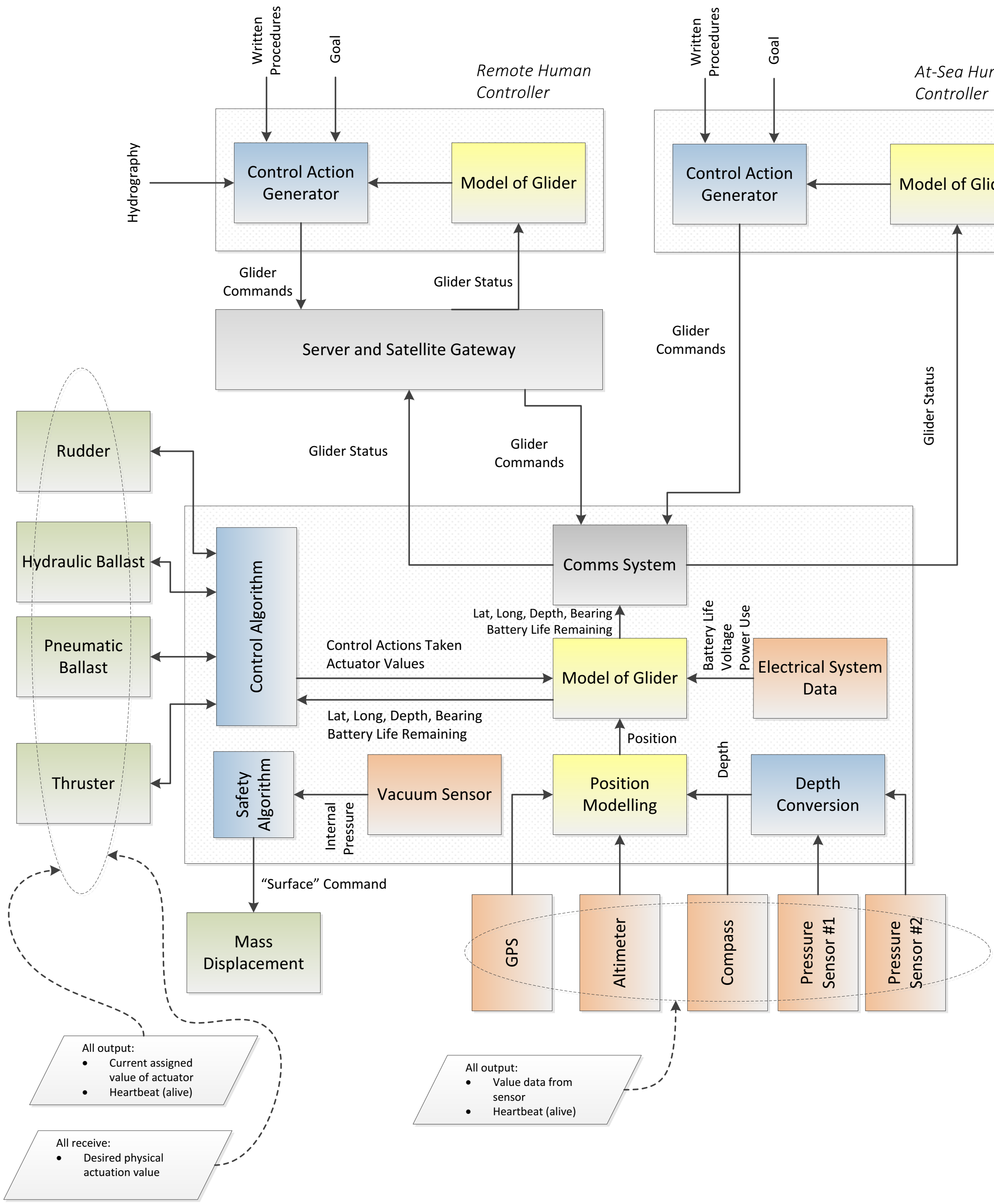

Figure 4.1 - Example of the Control Model Used in the Application of STPA to the Sub-Sea Glider's Sea-Bed Avoidance Function

4.4.2 The sub-sea glider can receive orders from two sources: remotely via satellite, and locally via antenna. The local control is intended for use when initially launching the sub-sea glider, but remains active during operation. In either case, commands can only be received by the sub-sea glider when it is at the surface.

4.4.3 When it is submerged, the sub-sea glider attempts to follow its received commands and these cannot be countermanded until it re-surfaces. Depth is determined by using a measurement of pressure, with two pressure sensors provided for redundancy. These and other sensors feed an internal sub-sea glider model that uses this information and a dead reckoning algorithm to estimate its present location. Actuators (shown in green) are then used to target the commanded depth and course bearing.

4.4.4 An internal measurement of pressure (the vacuum sensor) is used as a fail-safe to detect leaks and cause the sub-sea glider to surface in an emergency.

4.4.5 The autonomous operation of this sub-sea glider presents numerous safety challenges, including offshore structures and presence in shipping lanes. For the purpose of simplifying the analysis, we only considered a single safety requirement: that the sub-sea glider should not strike the sea bed. Striking the sea bed would potentially result in environmental damage, a loss of operational capability and safety hazards if it occurred near underwater works.

4.4.6 So, for the initial inputs for the STPA analysis, we have the following parameters:

a. Hazard: Sub-sea glider strikes sea bed;

b. Safety Constraint: Issued dive commands will be configured for depths less than the known sea-bed depth at the estimated location of the sub-sea glider;

c. Functional Requirements: Sub-sea glider needs to be able to detect/transmit location; bathymetry must be known or estimated.

4.4.7 To conduct the analysis, two teams of safety practitioners were used. For both teams, there was no difference in Step 1 of the STPA process, so this was conducted separately.

4.4.8 A piece of in-house software was used by BMT to partially automate Step 1 of the STPA assessment. This tool has a limited number of built-in constraints and utilises some simple data entry to populate a table of all conceivable control errors based on the four possibilities identified in the technique. Since the automation is based on simple string concatenation, two additional, manual steps are needed:

4.4.9 Eliminate any control errors that are not hazardous. For example, the algorithm identified that the “Providing” Electrical Data into the Model of the sub-sea glider causes “Confirmation of Power Use”.

a. Eliminate any control errors that do not contribute to our chosen hazard of “strikes sea bed”. For example, it is obvious that the GPS “not providing” a location to the sub-sea glider may contribute to certain hazards. However, the GPS can only provide data when it is at the surface, and so does not contribute to the hazard of striking the sea bed. In some gliders, that use GPS fixes to lookup the bathymetry value from an on-board table, this may not be true.

b. This elimination was done as a team exercise and the remaining control errors contributing to the hazard are shown in Table 3.2. As a result of the automation step, the whole of STPA Step 1 was completed in about 2 hours and there is a high confidence that no potential errors were ignored.

4.4.10 In Step 2, one team was asked to conduct the analysis of the functional control model normally; the other team was briefed on the matrix shown in Table 3.1 and instructed to use it as a prompt for their deliberations. The outputs were then compared by the authors to examine the effect of the prompting.

4.4.11 The results of this exercise are integrated in Table 3.3, where the Unprompted Standard Approach column shows the results garnered by the team who did not have the guide in Table 3.1. The other team naturally categorised their considerations along the lines of each of the four quadrants and this is shown in the four columns on the right of Table 3.3.

4.4.12 In broad terms, we observed that the potential causes identified by the unprompted team were a subset of those using the security-prompted approach. In addition, numerous other potential causes of hazards were identified. Some of these were security-related, such as:

a. Sub-sea glider GPS reconfigured - this related to spoofing GPS signals or otherwise forcing a mismatch between the remote controller's idea of where the sub-sea glider was and where it was in reality.

b. Induced communications errors - false data apparently being sent to and from the sub-sea glider, causing a mismatch in the various controllers in the system.

4.4.13 This suggests additional safety requirements for the sub-sea glider communications system, such as authentication, that would traditionally have been incorporated in a security assurance case.

4.4.14 However, numerous additional non-safety causes were also identified. For example, circumventing written procedures appears in numerous places. A fundamental consideration in safe system design should be that a system does not allow an operator to do something dangerous, so the design should be examined to see how the reliance on written procedures can be reduced, or human factors specialists should be called upon to reduce the likelihood of error. This is not a conclusion one would have automatically drawn from the unprompted assessment.

4.4.15 **Recommendation 2 - Standards and guidance should be developed in such a way as to limit the reliance of users on written procedures.**

Control Action	Originator	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing or Order Causes Hazard
Current Reading Value	Sensors - GPS	N/A	Provide incorrect location	Provides data too late and sub-sea glider drifts out of position
Sub-Sea Glider Commands	Misc. - Server and Satellite Gateway	N/A	Proved incorrect orders	Provides commands too late and sub-sea glider drifts out of position
Sub-Sea Glider Commands	At Sea Controller - Control Action Generator	N/A	Proved incorrect orders	Provides commands too late and sub-sea glider drifts out of position
Sub-Sea Glider Commands	Remote controller - Control Action Generator	N/A	Proved incorrect orders	Provides commands too late and sub-sea glider drifts out of position
Sub-Sea Glider Commands	Sub-Sea Glider - Comms System	N/A	Proved incorrect orders	Provides commands too late and sub-sea glider drifts out of position
Sub-Sea Glider Status Data	Sub-Sea Glider - Comms System	N/A	Provide incorrect location	Provides data too late and sub-sea glider drifts out of position
Sub-Sea Glider Status Data	Sub-Sea Glider - Comms System	N/A	Provide incorrect location	Provides data too late and sub-sea glider drifts out of position
Sub-Sea Glider Status Data	Misc. - Server and Satellite Gateway	N/A	Provide incorrect location	Provides data too late and sub-sea glider drifts out of position
Goal	External - Data and information feeds	N/A	Provide incorrect Goal	N/A
Goal	External - Data and information feeds	N/A	Provide incorrect Goal	N/A
Heartbeat	Sensors - GPS	N/A	N/A	N/A
Hydrography Data	External - Data and information feeds	N/A	Provide incorrect hydrography	N/A
Hydrography Data	External - Data and information feeds	N/A	Provide incorrect hydrography	N/A
Lat Value	Sub-Sea Glider - Model of Sub-Sea Glider	N/A	Provide incorrect location	Provides data too late and sub-sea glider drifts out of position
Long Value	Sub-Sea Glider - Model of Sub-Sea Glider	N/A	Provide incorrect location	Provides data too late and sub-sea glider drifts out of position
Modelled Sub-Sea Glider Status Data	At Sea Controller - Model of Sub-Sea Glider	N/A	Provide incorrect model	Provides data too late and sub-sea glider drifts out of position
Modelled Sub-Sea Glider Status Data	Remote Controller - Model of Sub-Sea Glider	N/A	Provide incorrect model	Provides data too late and sub-sea glider drifts out of position
Position	Sub-Sea Glider - Position Modelling	N/A	Provide incorrect location	Provides data too late and sub-sea glider drifts out of position
Written Procedures	External - Data and information feeds	Provide incorrect commands	Provide incorrect commands	N/A

Table 4.2 - STPA Part 1

Hazardous Behaviour	Unprompted Standard Approach	Security-Prompted Approach			
		Benign/Unintended	Benign/Intended	Malicious/Unintended	Malicious/Intended
1. GPS provides incorrect location or data is provided too late	Primary Sensors Causes: GPS module failure Data format mismatch Correct location data sent but not received	Primary Sensors Causes: GPS module failure Correct location data sent but not received	Primary Sensors Causes: Incorrect GPS module fitted	Primary Sensors Causes: GPS module failure Data format corrupted causing mismatch	Primary Sensors Causes: GPS module reconfigured False location data sent
2. Server and Satellite Gateway provides incorrect orders or provides commands too late	Server and Satellite Gateway Causes: Server and Satellite Gateway failure Incorrect orders received from Control Action Generator Corruption of orders in transmission Data latency in transmission Comms System Causes: Missing or spurious sub-sea glider status data Remote Controller Control Action Generator Causes: Control Action Generator provides incorrect commands	Server and Satellite Gateway Causes: Server and Satellite Gateway failure Data latency in transmission Comms System Causes: Missing sub-sea glider status data	Server and Satellite Gateway Causes: Incorrect Server and Satellite Gateway fitted	Server and Satellite Gateway Causes: Server and Satellite Gateway failure Corruption of orders in transmission	Server and Satellite Gateway Causes: Server and Satellite Gateway reconfigured False orders received from Control Action Generator Comms System Causes: False sub-sea glider status data Remote Controller Control Action Generator Causes: Control Action Generator provides incorrect commands
3. At Sea Controller Control Action Generator provides incorrect orders or provides commands too late	Model of Sub-Sea Glider Causes: Model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Comms System Causes: Comms System failure Missing or spurious sub-sea glider status data At Sea Controller Control Action Generator Causes: Control Action Generator Failure Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Written procedures / goal incorrectly specified or interpreted External Data Feeds Causes: Written procedures / goal incorrectly specified or interpreted	Model of Sub-Sea Glider Causes: Model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement implemented incorrectly in software Comms System Causes: Comms System failure Missing sub-sea glider status data At Sea Controller Control Action Generator Causes: Control Action Generator Failure Requirement not passed to designers / developers or incorrectly specified	Model of Sub-Sea Glider Causes: Previous version of Model used under impression it was more suitable External Data Feeds Causes: Written procedures / goal bypassed in attempt to improve efficiency	Model of Sub-Sea Glider Causes: Model corrupted Comms System Causes: Comms System failure At Sea Controller Control Action Generator Causes: Control Action Generator Failure External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee dissatisfaction	Comms System Causes: False sub-sea glider status data At Sea Controller Control Action Generator Causes: False Requirement implemented in software External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee sabotage

Hazardous Behaviour	Unprompted Standard Approach	Security-Prompted Approach			
		Benign/Unintended	Benign/Intended	Malicious/Unintended	Malicious/Intended
4. Remote Controller Control Action Generator provides incorrect orders or provides commands too late	Model of Sub-Sea Glider Causes: Model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Server and Satellite Gateway Causes: Server and Satellite Gateway failure Missing or spurious sub-sea glider status data Remote Controller Control Action Generator Causes: Control Action Generator Failure Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software External Data Feeds Causes: Failure of data feed(s) Written procedures / goal incorrectly specified or interpreted Missing or spurious hydrography data	Model of Sub-Sea Glider Causes: Model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement implemented incorrectly in software Server and Satellite Gateway Causes: Server and Satellite Gateway failure Missing sub-sea glider status data Remote Controller Control Action Generator Causes: Control Action Generator Failure Requirement not passed to designers / developers or incorrectly specified Requirement implemented incorrectly in software External Data Feeds Causes: Failure of data feed(s) Missing or spurious hydrography data	Model of Sub-Sea Glider Causes: Previous version of Model used under impression it was more suitable External Data Feeds Causes: Written procedures / goal bypasses in attempt to improve efficiency	Model of Sub-Sea Glider Causes: Model corrupted Server and Satellite Gateway Causes: Server and Satellite Gateway failure External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee dissatisfaction	Comms System Causes: False sub-sea glider status data At Sea Controller Control Action Generator Causes: False Requirement implemented in software External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee sabotage
5. Comms System provides incorrect orders or provides commands too late to Model of Sub-Sea Glider	Model of Sub-Sea Glider Causes: Missing or spurious sub-sea glider status data On-board Processor Causes: Processor task-saturated and delays processing of sub-sea glider commands Server and Satellite Gateway Causes: Missing or spurious sub-sea glider commands Comms System Causes: Comms System failure Missing or spurious sub-sea glider status data received Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software At Sea Controller Control Action Generator Causes: Missing or spurious sub-sea glider commands	Model of Sub-Sea Glider Causes: Missing sub-sea glider status data Server and Satellite Gateway Causes: Missing sub-sea glider commands Comms System Causes: Comms System failure Missing glider status data Requirement not passed to designers / developers or incorrectly specified At Sea Controller Control Action Generator Causes: Missing sub-sea glider commands	None identified.	Comms System Causes: Comms System failure Corrupted sub-sea glider status data received On-board Processor Causes: Processor task-saturated by attack and delays processing of sub-sea glider commands	Model of Sub-Sea Glider Causes: False sub-sea glider status data Server and Satellite Gateway Causes: False sub-sea glider commands Comms System Causes: False sub-sea glider status data received At Sea Controller Control Action Generator Causes: False sub-sea glider commands

Hazardous Behaviour	Unprompted Standard Approach	Security-Prompted Approach			
		Benign/Unintended	Benign/Intended	Malicious/Unintended	Malicious/Intended
6, 7. Comms System provides incorrect sub-sea glider status data	Model of Sub-Sea Glider Causes: Missing or spurious position sub-sea glider status data On-board Processor Causes: Processor task-saturated and delays processing of sub-sea glider status data Server and Satellite Gateway Causes: Missing or spurious sub-sea glider commands Comms System Causes: Comms System failure Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software At Sea Controller Control Action Generator Causes: Missing or spurious sub-sea glider commands	Model of Sub-Sea Glider Causes: Missing position sub-sea glider status data Server and Satellite Gateway Causes: Missing sub-sea glider commands Comms System Causes: Comms System failure Requirement not passed to designers / developers or incorrectly specified At Sea Controller Control Action Generator Causes: Missing or spurious sub-sea glider commands	None identified.	Model of Sub-Sea Glider Causes: Corrupted sub-sea glider status data Server and Satellite Gateway Causes: Corrupted sub-sea glider commands Comms System Causes: Comms System failure At Sea Controller Control Action Generator Causes: Corrupted glider commands On-board Processor Causes: Processor task-saturated by attack and delays processing of sub-sea glider commands	Model of Sub-Sea Glider Causes: False position sub-sea glider status data Server and Satellite Gateway Causes: False sub-sea glider commands At Sea Controller Control Action Generator Causes: False sub-sea glider commands
8. Server and Satellite Gateway provides incorrect location or provides data too late	On-board Processor Causes: Processor task-saturated and delays processing of location data Server and Satellite Gateway Causes: Server and Satellite Gateway failure Transmission latency Comms System Causes: Missing or spurious position sub-sea glider status data Remote Controller Control Action Generator Causes: Missing or spurious sub-sea glider commands	Server and Satellite Gateway Causes: Server and Satellite Gateway failure Transmission latency Comms System Causes: Missing position sub-sea glider status data Remote Controller Control Action Generator Causes: Missing or spurious sub-sea glider commands	None identified.	Server and Satellite Gateway Causes: Server and Satellite Gateway failure Comms System Causes: Corrupted sub-sea glider status data Remote Controller Control Action Generator Causes: Corrupted sub-sea glider commands On-board Processor Causes: Processor task-saturated by attack and delays processing of sub-sea glider commands	Comms System Causes: False position sub-sea glider status data Remote Controller Control Action Generator Causes: False sub-sea glider commands
9, 10. Incorrect goal provided to Remote Controller Control Action Generator	External Data Feeds Causes: Failure of data feed Goal incorrectly specified or interpreted	External Data Feeds Causes: Failure of data feed Goal incorrectly specified or interpreted	None identified.	External Data Feeds Causes: Failure of data feed Goal corrupted	External Data Feeds Causes: False data feed supplied
11. Incorrect GPS heartbeat	Primary Sensors Causes: GPS Module failure Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software	Primary Sensors Causes: GPS Module failure Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software	None identified.	Primary Sensors Causes: GPS Module failure	None identified.

Hazardous Behaviour	Unprompted Standard Approach	Security-Prompted Approach			
		Benign/Unintended	Benign/Intended	Malicious/Unintended	Malicious/Intended
14, 15. On-board model of sub-sea glider provides incorrect location data	Sub-Sea Glider Position Modelling Causes: Model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Missing or spurious position data Model of Sub-Sea Glider Causes: On-board model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software On-board Processor Causes: Processor task-saturated and delays processing of position data Electrical System Causes: Missing or spurious electrical system data Control Algorithm Causes: Algorithm incorrect	Sub-Sea Glider Position Modelling Causes: Model incorrect Requirement not passed to designers / developers or incorrectly specified Missing position data Requirement not implemented correctly in software Model of Sub-Sea Glider Causes: On-board model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Electrical System Causes: Missing or spurious electrical system data Control Algorithm Causes: Algorithm incorrect	None identified.	Sub-Sea Glider Position Modelling Causes: Model corrupted Corrupted position data Model of Sub-Sea Glider Causes: On-board model corrupted Electrical System Causes: Corrupted electrical system data Control Algorithm Causes: Algorithm corrupted On-board Processor Causes: Processor task-saturated by attack and delays processing of sub-sea glider commands	Sub-Sea Glider Position Modelling Causes: Model changed to be incorrect False position data Model of Sub-Sea Glider Causes: On-board model changed to be incorrect Electrical System Causes: False electrical system data Control Algorithm Causes: Algorithm purposefully changed to be incorrect
12, 13. Incorrect hydrography data provided	External Data Feeds Causes: Hydrography database incorrect or corrupted	External Data Feeds Causes: Hydrography database incorrect		External Data Feeds Causes: Hydrography database corrupted	External Data Feeds Causes: Hydrography database falsified
16. At Sea Controller Model of Sub-Sea Glider provides incorrect model or provides information too late	Model of Sub-Sea Glider Causes: At Sea Controller Model of Sub-Sea Glider incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Comms System Causes: Missing or spurious sub-sea glider status information Data latency in transmission	Model of Sub-Sea Glider Causes: At Sea Controller Model of Sub-Sea Glider incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Comms System Causes: Missing or spurious sub-sea glider status information Data latency in transmission	Model of Sub-Sea Glider Causes: Previous version of Model used under impression it was more suitable External Data Feeds Causes: Written procedures / goal bypasses in attempt to improve efficiency	Model of Sub-Sea Glider Causes: At Sea Controller Model of Sub-Sea Glider corrupted Comms System Causes: Corrupted sub-sea glider status information External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee dissatisfaction	Comms System Causes: False sub-sea glider status information External Data Feeds Causes: Model of sub-sea glider updated incorrectly due to employee sabotage
17. Remote Controller Model of Sub-Sea Glider provides incorrect model or provides information too late	Model of Sub-Sea Glider Causes: Remote Controller Model of Sub-Sea Glider incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Server and Satellite Gateway Causes: Missing or spurious sub-sea glider status information Data latency in transmission	Model of Sub-Sea Glider Causes: Remote Controller Model of Sub-Sea Glider incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Server and Satellite Gateway Causes: Missing or spurious sub-sea glider status information Data latency in transmission	Model of Sub-Sea Glider Causes: Previous version of Model used under impression it was more suitable External Data Feeds Causes: Written procedures / goal bypasses in attempt to improve efficiency	Model of Sub-Sea Glider Causes: Remote Controller Model of Sub-Sea Glider corrupted Server and Satellite Gateway Causes: Corrupted sub-sea glider status information External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee dissatisfaction	Server and Satellite Gateway Causes: False status information External Data Feeds Causes: Model of sub-sea glider updated incorrectly due to employee sabotage

Hazardous Behaviour	Unprompted Standard Approach	Security-Prompted Approach			
		Benign/Unintended	Benign/Intended	Malicious/Unintended	Malicious/Intended
18. Sub-sea glider position modelling provides incorrect location or data is provided too late and sub-sea glider drifts out of position	Primary Sensors Causes: Missing or spurious sensor heartbeat(s) GPS Module failure Altimetre failure Compass failure Pressure sensor(s) failure Missing or spurious depth information Depth conversion algorithm incorrect Sub-Sea Glider Position Modelling Causes: Position model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Correct position sent but not received On-board Processor Causes: Processor task-saturated and delays processing of position data	Primary Sensors Causes: Missing or spurious sensor heartbeat(s) GPS Module failure Altimetre failure Compass failure Pressure sensor(s) failure Missing or spurious depth information Depth conversion algorithm incorrect Sub-Sea Glider Position Modelling Causes: Position model incorrect Requirement not passed to designers / developers or incorrectly specified Requirement not implemented correctly in software Correct position sent but not received On-board Processor Causes: Processor task-saturated and delays processing of position data	None identified.	Primary Sensors Causes: GPS Module failure Altimetre failure Compass failure Pressure sensor(s) failure Corrupted depth information Depth conversion algorithm corrupted Sub-Sea Glider Position Modelling Causes: Position model corrupted On-board Processor Causes: Processor task-saturated by attack and delays processing of sub-sea glider commands	Primary Sensors Causes: GPS Module tampering Altimetre tampering Compass tampering Pressure sensor(s) tampering False depth information Depth conversion algorithm tampered with Sub-Sea Glider Position Modelling Causes: Position model falsified
19, 20. Written procedures define operating parametres that will not function	External Data Feeds Causes: Written Procedures incorrectly specified or interpreted	External Data Feeds Causes: Written Procedures incorrectly specified or interpreted	None identified.	External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee dissatisfaction	External Data Feeds Causes: Written procedures / goal incorrectly entered due to employee sabotage

Table 4.3 - STPA Part 2

5 Standards and Regulatory Approaches from Other Domains

5.1.1 A review was undertaken into a number of related domains in order to understand and characterise the approach taken to regulation and standards. The review findings are summarised in the following sub-sections. The domains chosen were considered relevant to the BRIDGES project because they met one or more of the following criteria:

a. Aspects of the regulation and standards are directly applicable to BRIDGES;

b. The domain displays key technological features that were analogous to sub-sea glider technologies;

c. The domain addresses analogous risk issues to those identified as applicable to sub-sea glider operations.

5.1.2 At the end of this section, a table summarises the characteristics of the regulations and standards within the various domains.

5.2 Maritime

5.2.1 The maritime industry is regulated through a hierarchal arrangement with the International Maritime Organization (IMO) providing the global standard setting authority for the safety, security and environmental performance of international shipping. IMO conventions cover all aspects of international shipping from ship design, construction, equipment, manning, operation and disposal to ensure safety, environmental protection, energy efficiency and security of international shipping. The IMO applies the Formal Safety Assessment (FSA) (IMO, 2002) (Reference 6) methodology to the development of its conventions. FSA is a structured and systematic methodology that utilises risk analysis and cost benefit assessment to derive regulation that achieves a balance of risk reduction and cost.

5.2.2 The IMO's principle conventions include:

a. The International Convention for the Safety of Life at Sea (SOLAS) (Reference 7) is an international maritime safety treaty. Its primary objective is to specify minimum standards for oceangoing vessels, and it ensures that ships' flag states remain responsible for minimum safety standards in construction, equipment and operation.

b. The International Convention for the Prevention of Pollution from Ships (MARPOL) (Reference 8) was developed by the IMO and is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes.

c. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) (Reference 9) establishes basic requirements for training, certification and watchkeeping for seafarers on an international level.

d. The International Ship and Port Facility Security (ISPS) Code (Reference 10) prescribes responsibilities to governments, shipping companies, shipboard personnel, and port/facility personnel to identify security threats and take preventative measures against security incidents.

5.2.3 Commercial vessels are registered or licensed by the 'flag state' who have the authority and responsibility to enforce regulations over vessels registered under its flag.

Figure 5.1 - Commercial Vessel Operating Under Flag State Authority

5.2.4 Marine equipment can only be installed on board ships flying the flag of an EU country, Norway, Iceland and other flag states if it is marked with the Marine Equipment Directive (MED) 96/98/EC (European Union, 1996) mark of conformity, also known as the “wheelmark”.

5.2.5 Classification societies are nongovernmental organisations that establish and maintain prescriptive technical standards for the construction and operation of ships and offshore structures.

5.2.6 The maritime regulations and standards detailed in this section are generally only applicable to manned surface vessels and therefore will not apply directly to sub-sea gliders or any other form of marine autonomous vessel. The UK based Maritime Autonomous Systems (MAS) Regulatory Working Group (RWG) (Society of Maritime Industries, 2015) is an organisation that is leading the development of a best practice regulatory framework for MAS that will be submitted to the UK Maritime and Coastguard Agency (MCA). This may ultimately lead to the MCA making recommendations for changes to the IMO conventions to accommodate MAS.

5.2.7 **Recommendation 3 - The Maritime Autonomous Systems Regulatory Working Group is leading development of a regulatory framework for marine autonomous devices; efforts should be made to keep informed of any documentation that the group may release and its impact(s) upon BRIDGES or any resultant standards that the BRIDGES project may create.**

5.2.8 The International Regulations for Preventing Collisions at Sea (Colregs) (Reference 11) specifically deal with the applicability to vessels of special construction in Part A - General:

a. “Whenever the Government concerned shall have determined that a vessel of any special construction or purpose cannot comply with the provisions of any of these Rules with respect to the number, position, range or arc of visibility of lights or shapes, as well as to the disposition and characteristics of sound-signalling appliances, such vessel shall comply with such other provisions in regard to the number, position, range or arc of visibility of lights or shapes, as well as to the disposition and characteristics of sound-signalling appliances, as her Government shall have determined to be the closest possible compliance with these Rules in respect of that vessel.”

5.3 Offshore Oil and Gas

5.3.1 Offshore regulation of the Oil and Gas Industry is spread over three authorities in the UK, comprising:

a. Health and Safety Executive (HSE), with responsibilities for human safety;

b. Department for Environment and Climate Change (DECC) with responsibility for environmental compliance and leak containment;

c. The MCA with responsibility for spill clean-up at sea.

5.3.2 The HSE regulates offshore safety using a goal-driven safety case regime focused around regulatory expectations. Operators have the opportunity to be innovative and to achieve the required high levels of safety by adopting practices that meet the particular circumstances outlined in the regulatory standards. This approach fosters innovation and continuous improvement in operational and technological integrity. This approach is supported through mechanisms in place for independent, third party verification in the crucial areas of well design and integrity of safety critical equipment.

5.3.3 In contrast, the offshore environmental regulation regime is based on the implementation of EU regulation. This aspect of the regulation is largely focused on preventing or minimising any leakage of hydrocarbons during normal operations. Consequently it is relatively prescriptive compared to the safety regime, with less scope or encouragement for innovation in approach.

5.3.4 The oil and gas industry is arguably one of the first domains to exploit the potential of unmanned systems. ROVs represent a type of unmanned system that has been in regular service since the mid-1960s, undertaking a variety of operations predominantly in exploration, installation and maintenance. NORSOK, the Norwegian petroleum industry body, has developed standards for ROV operations. NORSOK U102 ROV Services (Reference 12) has been produced containing information and typical requirements, deliveries and documentation expected from operators of ROVs. It also contains requirements for ROVs and for other services which have similarities to the ROVs and the way they are operated, including AUVs, remotely operated tools (ROTs), remotely operated towed vehicles (ROTVs) and dredging machines.

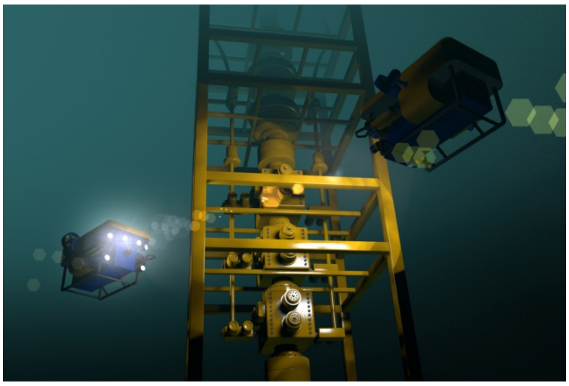

Figure 5.2 - Remotely Operated Underwater Vehicles

5.4 Defence Unmanned Maritime Systems

5.4.1 Unmanned Maritime Systems (UMS) is one of the agreed 22 priority areas with the potential to become successful as joint European research work in the European Defence Research & Technology (EDRT) strategy. As a result, several research projects with participation from many EU nations in the area of UMS came together in the European Defence Agency UMS programme.

5.4.2 UMS has the objective to enhance European capabilities in a number of naval applications by means of several research projects related to unmanned systems. Unmanned vehicles in particular are expected to be an integrated part of modern fleets. Given the expeditionary nature of modern European naval operations it is necessary to address interoperability issues.

5.4.3 It was recognised that national or international rules, regulations and legislation governing safe operation of unmanned maritime vehicles at sea are virtually non-existent. Common understanding of minimum safety procedures and a joint view on rules and regulations among European Navies would enhance interoperability in future joint maritime operations and training. To establish a foundation for achieving interoperability, a forum was created to address all regulations, legislation and safety issues related to design and operations of UMS - the European Defence Agency (EDA) Safety and Regulations for European Unmanned Maritime Systems (SARUMS) forum.

5.4.4 The objective of SARUMS is to provide European navies with a best practice safety framework for UMS that recognises their operational usage, legal status and the needs of navies. The philosophy behind this guidance will be based on the management of risk as well as applicable rules and regulations. The group is currently developing a document for this purpose titled “Best practice guide for UMS handling, operations, design and regulations”. A significant improvement in interoperability and standardisation in design and operation of UMS is expected if nations decide to adopt this guidance document.

5.5 Unmanned Civil Aviation

5.5.1 The civil aviation industry has adopted unmanned technologies and has seen a proliferation of Unmanned Aerial Systems (UAS), particularly at the smaller end of the spectrum where they are used in a variety of survey, photography and monitoring applications as well as for recreational use. The vast majority of these systems are remotely piloted with limited autonomous operation capability.

5.5.2 In the UK, regulation of civilian airspace is the responsibility of the Civil Aviation Authority (CAA) through the application of the Air Navigation Order (ANO), CAP 393 (Reference 13). Safety of smaller UAS is principally controlled through the ANO Articles 94 and 95 which apply to what the CAA define as ‘Small Unmanned Aircraft’. UAS are therefore considered aircraft but the CAA effectively allows derogation from the vast majority of requirements that would apply to larger manned craft, so long as the UAS meets a set of defined criteria and articles 94 and 95 of the ANO are adhered to in relation to the responsibilities of the ‘Remote Pilot’. The ‘Remote Pilot’ is required, amongst other obligations, to:

a. Ensure the system is airworthy and safe to fly;

b. Maintain visual contact with the craft through Visual Line of Sight (VLOS) operations so as to avoid collision;

c. Not permit overflight of persons, structure or vehicles;

d. Liaise with Air Traffic Control (ATC) when operating in controlled airspace.

Figure 5.3 - Unmanned Autonomous Quadcopter

5.5.3 For larger UAS, or operations outside of those prescribed for Small Unmanned Aircraft in the ANO, the CAA requires airworthiness to be assessed and the safety of operations to be justified through a formal Safety Case submission. Relatively few UAS have been approved for operation through this route, principally due to the lack of robust sense and avoid technologies and a requirement to maintain separation from other airspace users. Autonomous Systems Technology Related Airborne Evaluation & Assessment consortium (ASTRAEA) is a UK industry led consortium focusing on the technologies, systems, facilities, procedures and regulations that will allow autonomous vehicles to operate safely and routinely in civil airspace over the United Kingdom (ASTRAEA, 2015). ASTRAEA is one of the few civilian programmes to have successfully trialled operation of an autonomous aircraft outside of restricted airspace.

5.5.4 The CAA has published guidance for unmanned aircraft system operations in UK airspace as CAP 722 (Reference 14). This guidance covers aspects such as Approvals, Regulatory Policy, Airworthiness and Operations. Reference is made in the ANO to acting 'reasonably' which a court would likely interpret as meaning standard practice, custom or guidelines have been followed. In this way, these published guidelines effectively become part of the regulatory requirement.

5.5.5 Meteorological balloons are another aspect of aviation that provides parallels with autonomous sub-sea glider applications. These balloons are unguided and will typically operate at very high altitudes, above the majority of other airspace users. They are required to traverse through operational airspace during ascent and parachute controlled decent phases where the risk of collision with other air users exists. This risk is controlled through the requirement of the operator to:

a. Obtain permission from the CAA to operate;

b. Apply for a Notice to Airmen (NOTAM) to ensure other airspace users are aware of the operation;

c. Liaise with ATC.

5.5.6 **Recommendation 4 - Sub-sea glider operators should make every attempt to inform local marine traffic of their intention to operate sub-sea gliders in the area.**

5.6 Space

5.6.1 Due to the high level of platform autonomy, restrictive electrical power budgets, limited contact with ground based controllers and the extreme physical environment in which they operate, spacecraft share many similarities with sub-sea gliders. As the launch costs for spacecraft are so great (in the order of $10,000 per kilogram of payload inserted into Low Earth Orbit), very high platform and subsystem reliability are critical to the success of a mission.

5.6.2 In order to ensure that a completed spacecraft will be reliable enough to complete its mission, testing is conducted on individual components and subsystems in addition to the integrated spacecraft. Due to the high manufacturing costs for spacecraft, testing is often conducted on the real flight articles, rather than dedicated test prototypes. So, for instance, the actual completed spacecraft will be subjected to the extremes of vacuum, high and low temperatures, vibration, noise and shock that it will encounter during launch and operation.

5.6.3 **Recommendation 5 - Maintenance schedules should be developed to encourage testing on individual mission critical subsystems and components to help mitigate the risk associated with the loss of the sub-sea glider itself.**

5.6.4 Space agencies such as the USA National Aeronautics and Space Administration (NASA), the European Cooperation for Space Standardization (ECSS), the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) have developed a number of technical standards to de-risk the design and manufacture of satellites and space probes. Amongst many others, these include:

a. The use of design tools, such as NASASTD(I)0007 NASA Computer aided Design Interoperability (Reference 15);

b. Manufacturing techniques, such as NASASTD5006 General Welding Requirements for Aerospace Materials (Reference 16); and

c. Testing and inspection procedures, such as NASASTD7002 Payload Test Requirements (Reference 17).

5.6.5 These standards may be generic (nonprescriptive), entirely prescriptive requiring the use of specified techniques and templates, or a combination of the two.

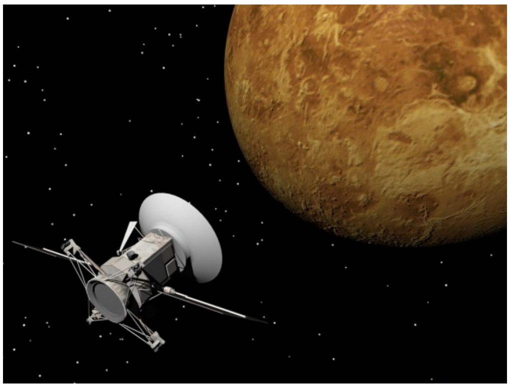

Figure 5.4 - Interplanetary Space Probe

5.7 Other Generic Standards

5.7.1 Other standards that were reviewed for potential relevance to the BRIDGES project included:

5.7.2 IEC 61508 (Reference 18) which is concerned with the functional safety achieved by safety related systems that are primarily implemented in electrical and/or electronic and/or programmable electronic (E/E/PE) technologies. It covers:

a. A risk based approach to determine safety integrity requirements of E/E/PE safety related systems;

b. A safety lifecycle model as the technical framework for the activities necessary for ensuring functional safety is achieved;

c. System aspects to include: hardware and software subsystems; and failure mechanisms (random hardware and systematic);

d. Preventing failures and controlling consequences;

e. The techniques and measures that are necessary to achieve the required safety integrity.

5.7.3 ISO 9001 (Reference 19), a certified quality management system for organisations that want to consistently provide products and services that meet the needs of their customers and other relevant stakeholders. ISO 9001 is based on seven quality management principles and divided into several sections. The most relevant sections to BRIDGES are likely to include Product Realization and Measurement, Analysis and Improvement.

5.7.4 **Recommendation 6 - The standards and approaches used by other international and national regulatory bodies should be regularly reviewed for changes that may be applicable to sub-sea glider operations. Likewise any changes and updates to sub-sea glider technology and standards should be shared with other organisations to ensure effective co-operation between interconnected fields.**

5.8 Characterisation of Approaches to Standards and Regulations

	Maritime	Oil and Gas	Defence	Civil Aviation	Space
Precedence	International conventions enacted through national regulatory bodies and non-governmental classification	European Law enacted through national regulatory bodies with split of responsibility for safety, environmental compliance and spill clean-up. Industry driven standards developed in unregulated areas (e.g. ROVs)	User/industry driven standards	International conventions enacted through the national regulatory body	User/industry driven standards
Prescription	Risk based approach to the development of typically prescriptive requirements	Goal-driven safety regime and prescriptive environmental requirements	Non-prescriptive guidance	Highly prescriptive regulation for standard recognized operations, risk based approach to address safety of non-standard aircraft and operations	Highly prescriptive standards reflecting the potentially high consequence of mission failure
Regulation or Standards	Regulation supported by nominated standards	Regulation supported by nominated standards	Standards providing description of best practice approach	Regulation supported by nominated standards	Prescriptive standards
Depth of Detail	Detailed coverage of design, build and operational aspects	Detailed coverage of design, build and operational aspects	Detailed coverage of operational aspects, limited coverage of design and build where industry best practice is yet to be established	High depth of detail on commercial craft, lower levels required for small scale personal craft.	Detailed coverage of design, build and operational aspects

Table 5.1 - Characterisation of Standards and Regulatory Approaches

6 Defining Standards Requirements

6.1 Standardisation Approach

6.1.1 The use of autonomous sub-sea gliders is still a relatively new area and development activities are still being conducted to find the most appropriate combination of design elements to make these devices as effective as possible. This is currently leading to creative ideas being tried and tested in the field and whilst regulations and standards will always play a role in the development and use of these devices, it is important that these rules do not become too restrictive and thus stifle innovation in the still evolving domain.

6.1.2 It is known that a number of regulations (especially those relating to environmental protection) will have prescriptive elements that still apply to sub-sea gliders, but in most areas the existing regulations will not be applicable to such a vessel. Where this is the case, innovation and new ideas can be developed by using a more goal based approach to reduce risks to an acceptable level through standards that are applied.

6.1.3 Goal based approaches to standards and regulations rely on setting high level targets that have to be met rather than setting specific values for individual attributes or components. By setting these high level targets it is possible for a set of standards to address the underlying concerns, issues and risks without prescribing a strict solution or method. This allows the designers to consider alternative methods for approaching their design and achieving the 'goal' that has been set without limiting their options for innovation. The IMO has produced a set of Generic Guidelines for Developing IMO Goal-Based Standards (Reference 20) that would serve well as a basis for sub-sea glider standards.

6.1.4 Recommendation 7 – Many regulatory regimes operate a "goal-setting" approach to foster innovation and improvements in design; a similar approach would be suitable for sub-sea glider standards.

6.1.5 Regulations and guidance are currently limited; this is in part due to the lack of regulatory recognition of the risks in this arena. This is leading to an industry driven approach to regulation, similar to the industry driven guidance issued by operators of ROVs in the oil and gas fields. In the long term it might be expected that the data and experience gained from sub-sea glider use will enable the regulations and standards to deal with detailed features of sub-sea glider design. However, in the current climate with the existing lack of historical data on sub-sea glider use, standards will, by necessity, be relatively high level.

	Precedence	Prescription	Regulations or standards	Depth of detail
Sub-sea gliders	Industry driven standards developed in an unregulated area	Goal Based	Standards (there is currently no governing body to implement regulations)	High level summary, expanding as usage levels and historic records increase

Table 6.1 - Recommended Standards Approach

7 Standards Development

7.1.1 The over-arching goal will be a set of standards that help facilitate a systematic approach to the creation of sub-sea glider devices; an approach that will result in reliable and flexible designs that allow for enhancement and technology insertion as the market expands and matures, all whilst ensuring that safety and environmental concerns are addressed and monitored with due care and diligence.

7.1.2 To aid in this goal it is recommended that the eventually developed standards contain, at a minimum, the following sections:

a. Scope;

b. Terminology, Glossary and Abbreviations;

c. Classifications of Sub-Sea Gliders;

d. Technical Requirements;

e. Construction Requirements;

f. Maintenance and Testing Requirements;

g. Operational Requirements;

h. Disposal Requirements;

i. Administrative Requirements;

j. Health and Safety Requirements;

k. Environmental Requirements;

l. Other Legislative Requirements.

7.1.3 Further details on suggested contents of these areas are supplied in the following sections.

7.2 Scope

7.2.1 It is vital that the development of any and all standards are clear as to the exact boundaries of the standards applicability.

7.2.2 Key to this question is the types and designs of sub-sea gliders that require consideration. Whilst the BRIDGES project is primarily focused on two specific designs of sub-sea gliders, it may be pertinent to consider other types of sub-sea gliders and possibly other AUVs.

7.3 Terminology, Glossary and Abbreviations

7.3.1 Terminology should be kept as consistent as possible throughout the standards and any associated documentation. Inconsistent or ill-defined terminology could potentially lead to confusion by the reader of the standard, whereby the reader believes a definition that is contrary to what is used within the standards.

7.3.2 Having a complete listing of all key technical and legal terminology at the beginning of the document will help mitigate the probabilities of such issues arising and will enable sub-sea glider manufacturers and operators to consider using the same terminology across their work packages.

7.4 Classifications of Sub-sea Gliders

7.4.1 Depending on the scope established, the classifications of different sub-surface vehicle types should be considered. This will enable subsequent sections to differentiate between differing requirements

7.4.2 For example, a long distance, long endurance sub-sea glider will carry significant amounts of battery capacity, which may facilitate additional standards and controls over and above that of a shorter endurance device.

7.4.3 Suggested options that could be used for the classification of sub-sea gliders:

a. Maximum depth;

b. Maximum endurance;

c. Weight class;

d. Hull/body type;

e. Propulsion type(s).

7.5 Technical Requirements

7.5.1 The technical requirements section will allow for the laying out of those standards that are pan-life-cycle stage. Areas included here will likely be those required by all possible users of the standards documentation ranging throughout the lifespan from manufacture through to disposal. This includes:

a. Standard Measurements and units to be used;

b. Standard connection types;

c. Battery specifications.

7.6 Maintenance and Testing Requirements

7.6.1 In general terms, a system for the correct maintenance and upkeep of any sub-sea glider system should be mandated. Safe and effective maintenance is necessary to ensure safe and secure operations of sub-sea gliders. Minimum requirements included in the standards for a maintenance system are likely to include:

a. Mandating a preventative maintenance policy, including:

(i) Critical components maintenance;

(ii) Historical data analysis and Learning From Experience (LFE);

(iii) Continuous improvement plans.

b. Inventory and equipment lists;

c. Suggested maintenance schedules / maximum operating periods.

7.6.2 Personnel involved in the maintenance must be correctly trained and there should an appropriate number of people working on the sub-sea glider in order for the repair to be carried out correctly. Where possible, standards should encourage safe working practices with regards to maintenance and testing.

7.6.3 Maintenance may need to be carried out at any point, even during a mission if a failure occurs. For this reason guidance should encourage users to always conduct repairs in suitable locations that are safe and appropriate. For example, it may not be suitable for a sub-sea glider to be repaired on board a vessel during high seas and operators manuals should allow for missions to be aborted should conditions not be suitable for remote repairs to be conducted safely.

7.7 Operational Requirements

7.7.1 In general this section should lay out the level and rigour with which operational procedures will be constructed, including suggested procedures for:

a. Risk assessments;

b. Familiarisation training;

c. Experience transfer;

d. Operational logs;

e. Operational management;

f. Mobilisation / retrieval;

g. Functional testing (prior to launch).

7.8 Administrative Requirements

7.8.1 It is suggested that the eventual standards should contain administrative requirements on companies manufacturing, maintaining and operating sub-sea glider systems.

7.8.2 At a minimum, such companies should have a quality management system in place, accredited to ISO 9001 (or relevant equivalent) and should ensure that this system is used to:

a. Ensure accurate and repeatable outputs;

b. Document change management;

c. Conduct compliance checks:

   (i) Where non-compliance issues are raised, the companies' systems will be expected to include procedures to review and correct these issues.

7.8.3 The standards may also wish to mandate standard document sets that should accompany sub-sea glider systems, these would likely change depending on the user affected. Example data sets would include:

a. Construction:

   (i) Materials list;

   (ii) Design specifications;

   (iii) Technical description.

b. Maintenance:

   (i) Maintenance plans (proactive and reactive);

   (ii) Maintenance records;

   (iii) Spare parts listings.

c. Operation:

   (i) Mobilisation plans;

   (ii) Operational area report;

   (iii) Minimum / maximum load out;

   (iv) Configuration.

7.9 Health and Safety Requirements

7.9.1 The standards should lead to the creation of a system to ensure safety, this will likely take the form of a Safety Management System. This system will exist to aid in the identification of hazards and mitigations through a systematic framework. It should be constructed to cover:

a. Safety requirements and criteria;

b. Hazards and accidental events;

c. Risk-reduction measures;

d. Performance.

7.9.2 Occupational Illness:

a. The occupational Illness section of the standards should be designed to highlight and help mitigate the specific and perhaps even unique hazards that exist for crew members involved in sub-sea glider operations. This should include all potential hazards that occur in any phase of operation and may include the following (non-exhaustive) list:

(i) Chemicals;

(ii) Vibration;

(iii) Radiation;

(iv) Ergonomic; and

(v) Organisational factors.

b. The standards will need to ensure that sub-sea glider operators are implementing all suitable preventative measures to help limit the effects of Occupational illnesses. This will likely include implementation of both administrative and technical solutions, and applicable changes to personal protective equipment. In addition, a suitable reporting and feedback system is recommended to help identify issues that are occurring and allow for remedial action to be undertaken where appropriate.

7.9.3 Chemical Health Hazard:

a. Whilst it is not envisaged at this stage that many chemical components will be required by the sub-sea glider system itself, cleaning and maintenance operations may require the use of chemicals that present hazards to health. As such a small section stating that all chemicals used will be chosen based not only on functionality but also on their ability to meet health and safety assessment is required. This will help ensure that all chemicals used are suitable for purpose without generating unnecessary health hazards. It is noted that in the future, gliders should consider the possibility of fairly large volumes of chemical reagents on board for the inclusion of lab-on-chip wet chemical sensors, as in the case of the BRIDGES gliders.

7.10 Environmental Requirements

7.10.1 Environmental impacts are likely to be limited with regards to sub-sea gliders, however the standards that are developed should encourage those who work with sub-sea gliders in any form to consider methods for reduction of any environmental impacts that do exist (such as disposal, chemicals used during construction, collision and subsequent loss of the sub-sea glider in sensitive environmental areas etc.). One example is the possible requirement that gliders use biodegradable lubricants, which would have significant impact on hardware maintenance and lifetime.

7.11 Collision

7.11.1 A collision between a sub-sea glider and another sea user is considered to be of relatively small probability due to the size and relative depths that sub-sea gliders will operate in. However, sub-sea glider operators should be encouraged to include a section in their policy that relates to this topic should this unlikely event occur. Depending on the area of operation and the nature of the craft that the sub-sea glider makes contact with, potential legal issues may result and it would be advised that sub-sea glider operators consider the implications of such an incident.

8 Specific Aspects to be Standardised

8.1.1 Whilst standardisation may become useful in all areas of BRIDGES, it is important to focus on those areas that may lead to safety, environmental or mission related risks. These are the areas that are likely to lead to difficulties should the risks solidify into actual incidents.

8.1.2 The following sections describe specific aspects to be considered for standardisation within the BRIDGES project, over and above those more general areas mentioned in section 7.

8.2 Materials

8.2.1 The sub-sea gliders will be operating in varied environments and will interact with a number of different operating conditions. It is important that the materials used in construction are known to be able to handle such environmental hazards as corrosion, extreme heat (hydrothermal vents) and extreme cold (artic waters) whilst remaining strong enough to handle shocks and impacts that may occur during missions and transport operations.

8.2.2 Both mechanical and electrical stress and degradation become more pronounced at extreme temperatures and adequate protection systems and/or coatings should be considered to ensure that the components used within the sub-sea glider maintain their integrity.

8.2.3 Hydrothermal vents tend to occur along the joints between tectonic plates, specifically where these plates are diverging. Water is drawn into the system and heated by magma flows close to the surface (among other factors). Such vents are known to have temperatures ranging upwards from temperatures of 60° Celsius and have been recorded at temperatures exceeding 400° Celsius. depending on ambient conditions the water in question can sometimes form supercritical fluids, which results in a fluid that displays properties of both liquid and gas forms making construction of systems capable of withstanding these fluids difficult.

8.2.4 Typical ocean temperatures in regions of hydrothermal vents tends to be around the 2° Celsius mark, thus requiring a sub-sea glider to cope with the potentially extreme heat that a vent may issue and significant temperature differential in a short time period. Issues surrounding thermal shock should be considered, and measures may be required to increase the strength of the materials used in sub-sea glider construction, or reducing the thermal expansion coefficients of these materials.

8.2.5 The nature of artic waters necessitates consideration being given to the possibility of ice build-up, specifically this may affect the pumping systems used for dive and surface systems. Ice building up in this system may limit a sub-sea glider's ability to pump water in and/or out of the ballast tank, and thus result in a sub-sea glider that is incapable of anything except propeller based movement, significantly reducing range and longevity of the unit.

8.2.6 The American Bureau of Shipping & Affiliated Companies (ABS) Guide for building and classing vessels intended for navigation in polar water (Reference 21) contains numerous sections that may prove suitable for inclusion in recommendations and guidance for sub-sea glider construction. Specifically the following sections of the ABS guide may prove helpful:

a. Material, Welds and Coatings;

b. Hull construction and equipment;

c. Vessel systems and machinery.

8.2.7 The Guidelines for Ships Operating in Polar Waters (Reference 22) aims to help mitigate the risks that occurs when operating in harsh climatic and environmental waters. Where operations are planned for polar waters, reference should be made to the aforementioned guidance document.

8.3 Construction Methods

8.3.1 The modular design of the sub-sea glider system will allow for great versatility in the operation of the BRIDGES sub-sea gliders, but this comes at a cost of needing to ensure that all manufacturers are working to the same standards and using similar construction methods. A failure to achieve this may result in parts with radically different lifespans or, in extreme cases, modules that simply cannot interact in the way they are meant to.

8.4 Scientific Performance

8.4.1 The BRIDGES sub-sea gliders will be designed to allow for accurate and useful data retrieval from areas that have been previously inaccessible or simply too costly to access. To allow the retrieved data to be as useful and as scientifically valid as possible, it is essential that there are methods in place to coordinate the retrieval of this data. Due to the conditions that the sub-sea gliders operate in, the system will need regular calibration and assessment to ensure that they remain functioning as accurately as required.

8.4.2 Organisations such as the National Institute of Standards and Technology (NIST) work to promote innovation and competitiveness via the improvement of measurements, standards and technology. Working alongside such agencies and enacting procedures based upon their guidance would help ensure that all scientific equipment is correctly configured prior to launch.

8.4.3 **Recommendation 8 - Scientific instruments should be calibrated and tested according to a recognised standard and auditable process**.

8.5 Navigation

8.5.1 The maritime community operates under a number of regulations and standards that control how vessels at sea operate and navigate. This system ensures that the worldwide community of marine operators can interact safely at sea and accurately navigate to their destinations. The sub-sea gliders will, at times, be interacting with this community and, as an oceangoing vessel, may well be required to meet some of the guidelines and standards that other marine vessels act under.

8.5.2 In addition, due to sub-sea gliders being autonomous craft capable of acting independently for long periods of time over great distances, it is vital that the navigational system used by sub-sea gliders is fit for purpose. Checks should also be in place to ensure that all navigation software is regularly updated and monitored.

8.6 Communication

8.6.1 The communication systems between both the sub-sea glider and base station and between the sub-sea glider's various systems will inevitably form a complex system with many elements and possible complications. Bandwidth for transmission of mission results and data will be limited at times, so care will be needed to ensure that vital data is prioritised for transmission, with lower priority data being stored for retrieval at the end of the mission.

a. Note that this subject is likely to be covered as subset of a report being prepared as part of part of the overarching BRIDGES project : Deliverable 3.2 Standardization of data/metadata for sub-sea gliders supporting marine science and blue economy.

8.7 Contamination / Environmental Pollution

8.7.1 Due to the wide range of areas that the sub-sea glider may operate in, it is possible that contamination may occur to the sub-sea glider itself; with the long range abilities of sub-sea gliders it is feasible that contamination could also be transferred into other areas of operation. Regulations already exist for managing the transfer of ballast water, the effects of antifouling systems and environmental guidelines for arctic water travel; all of these regulations may bear some important lessons for sub-sea glider use.

8.7.2 Whilst preliminary designs (References 1 & 2) demonstrate that there are no current plans to apply anti-fouling coatings, this will be mainly due to the limited operation times that the sub-sea glider will be active for. The time is insufficient to allow a significant build-up of fouling agents, however the eventual standard created following the BRIDGES project should consider whether later iterations of sub-sea glider technology may provide sufficient mission time for fouling to become an issue. The International Convention on the Control of Harmful Anti-Fouling Systems on Ships (Reference 23) may become applicable to sub-sea gliders should endurance increase significantly enough to warrant such anti-fouling systems.

8.7.3 **Recommendation 9 – Include within standards and guidance appropriate methods for assessing the need to use anti-fouling systems on long duration sub-sea glider technology**.

8.7.4 Certain marine areas are protected due to their significance in either ecological, socio-economic or scientific characteristics. Areas such as these are deemed Particularly Sensitive Sea Areas (Reference 24) by the IMO. Whilst typically more concerned with larger scale shipping, areas assessed to be particularly sensitive may still have some risk mitigation policies in place that could have an effect on sub-sea glider operations.

8.7.5 When operating in these areas it would be wise to consider the possible impacts that may be caused, not only by the sub-sea gliders' general operation, but also impacts caused by fault conditions. A complete loss of a sub-sea glider could have untoward affects in such areas if it proves impossible to recover the sub-sea glider following loss. One example previously mentioned includes the type of lubricants used in the glider construction and maintenance.

8.8 Power Systems

8.8.1 The largest factor upon a sub-sea glider's feasible range is the suitability of the power systems. The sub-sea glider's power supply will need to be able to maintain both the buoyancy and manoeuvring systems, and the various sensor payloads that are installed. Power systems will need to be rated to handle the stress and stains that occur at significant depths, depths which may also affect battery performance and longevity.

8.8.2 Potentially a combination of miniaturisation, power budgeting techniques and power usage data could result in a system that can manage its own power requirements to ensure mission success.

8.8.3 The battery and Battery Management System designers will need to be aware of the following:

a. Battery Options:

(i) Functionality;

(ii) Technology;

(iii) Topography;

b. Battery management functions:

(i) Measurements - Voltage measurements may be insufficient depending on battery type;

(ii) Battery Management - charge and discharge cycles will need management to ensure battery life is at the levels expected;

(iii) Evaluations - prior to launch, batteries will require evaluation to ensure they are likely to have the power required for the upcoming mission;

(iv) External communications - battery status should be reported during communication periods, enabling the sub-sea gliders hosts to change mission parameters should it become clear that more or less power has been consume than expected;

(v) Logging;

(vi) Telemetry;

c. Deployment methods:

(i) Installation in the sub-sea glider;

(ii) Mission Configuration;

(iii) Testing and Troubleshooting.

8.8.4 The battery management system should be designed to monitor the remaining charge in the battery and adjust its functions to ensure mission success. As the battery discharges it may become necessary to activate sequenced shut down operations to maintain the core abilities of the sub-sea glider and ensure the sub-sea glider can maintain its data integrity and be retrieved.

8.8.5 This in itself will prove a challenging prospect, most lithium based batteries have a very shallow voltage discharge curve, with a quicker voltage fall profile when the battery is approaching zero charge. As such, voltage measurements may not be sufficient to track the batteries' charge statuses. Ensuring that a sufficient amount of power is available to enable the sub-sea glider to surface and broadcast it position is vital at all times.

8.9 Collision Avoidance

8.9.1 The International Regulations for Preventing Collisions at Sea (The COLREGs) requirements do not directly apply to sub-sea gliders, but must be considered in terms of how other users would recognise and interact with a sub-sea glider operating at, or near, the sea surface.

8.9.2 Current generations of sub-sea gliders do not include sense and avoid systems for ships per se, and, from a maritime perspective, act as 'dumb' objects (when surfaced). As such, it will be other maritime operators that will need to take action to avoid collisions where possible. As such, steps should be considered in each sub-sea glider design to improve visibility and consideration should be given to passive detection techniques such as Automatic Identification System (AIS) and radar signature improvement systems.

8.9.3 Similar to weather balloons, where possible consideration should be given to warning other marine operators of ongoing sub-sea glider operations. It should however be noted that given the inherently unpredictable surfacing locations of sub-sea gliders this may not always be feasible.

8.10 Emergency / Fault

8.10.1 Collisions, fire, equipment failure and other factors could result in emergency situations for the sub-sea glider, potentially removing the sub-sea glider's ability to continue its mission. In situations such as these it will be important that the responses that occur are known in advance. Minimum equipment lists, redundancy and emergency location devices may play roles in the sub-sea glider configurations, and intelligent response systems to known possible faults may define how the sub-sea glider reacts in situations that are unrecoverable.

8.11 Manoeuvrability

8.11.1 The very design of sub-sea gliders limits their manoeuvrability; the combination of low power usage, buoyancy based travel mechanics and low movement speed limits sub-sea gliders to slow turns and slow dive / ascents. Whilst on the surface, a sub-sea glider's movement options are limited to its ability to dive and it therefore becomes a passive object when surfaced, potentially causing navigational issues for other sea going vessels.

8.12 Hydrodynamics

8.12.1 The sub-sea gliders will be designed with the aim of presenting a suitably hydrodynamic body, enabling the sub-sea glider to make the most efficient use of battery power. The modular nature of the science bays may present threats to that hydrodynamic profile, and certain sensors that penetrate the hull may reduce the effectiveness of the rudder and propeller. Standards could help guide the manufacturers of the science bays into what protrusions would affect performance.

8.12.2 Specific attention should be paid to setting limits on the size of protrusions and locations of these protrusions. A large or inappropriately located protrusion could limit water flow to the rudder limiting manoeuvring ability.

8.13 Markings / Colours

8.13.1 Current oceangoing vessels operate under a strict set of guidelines concerning visibility; typically this is achieved through the use of lighting systems on board. Sub-sea gliders sometimes have the capacity to host lighting systems (flashers) but this is not standardized.. Reflective tape is often used to achieve visibility through other means. The overall colour scheme of the sub-sea glider, and additional written markings could be used to alert the general marine population of both the presence of the device, and any potential dangers that the device presents.

8.13.2 Marking the sub-sea glider in bright and noticeable colours also however, creates potential issues involving unwanted attention from unauthorised users (see security). Making the sub-sea glider easier to spot could increase the chances that someone may interact with the sub-sea glider in a harmful way (whether with malicious intent or just from curiosity).

8.13.3 Factors that will require thought and attention include:

a. Colours to be used;

b. Standardised markings:

   (i) Manufacturers and operators logos;

   (ii) Safety warnings;

   (iii) Return information (if lost).

8.14 Pressure Hull / Penetrations

8.14.1 Pressure hulls are a regular feature of many sub-sea vehicles, and there are many construction and testing requirements that help ensure the safety of these hulls. In the case of the sub-sea gliders, the risks associated with the pressure hull failing are unlikely to affect the safety of persons (yet a possible hazard still exists that unintended internal pressurisation by degradation/flooding at depth or combustion of batteries occurs). and thus most current regulations are not directly applicable. However, the integrity of these hulls still affects the ability of the system to complete its mission as a failure of the hull would likely be catastrophic for the sub-sea glider.

8.14.2 Specific regulations that affect pressure vessel construction include:

a. Pressure Equipment Regulations 1999 (SI 1999/2001) (PER) (Reference 25);

b. Simple Pressure Vessels (Safety) Regulations 1991 (SPV) (Reference 26);

c. Pressure Systems Safety Regulations 2000 (PSSR) (Reference 27).

8.14.3 It should be noted that under the above regulations sub-sea glider technology may, in some areas, be exempt. This is due to the pressure vessel being specifically for use as part of the propulsion system of the sub-sea glider, which would be sufficient to exempt a more typical vessel/ship design.

8.15 Security

8.15.1 The systems included in autonomous craft typically concentrate on the goal of mission success and focus on the physical limitations of the equipment and the environment it will be operating in. Malicious or unauthorised usage of these devices are a very real possibility that should also be considered (please see section 3 for further information).

8.16 Reliability

8.16.1 The sub-sea glider systems will need to operate autonomously for extended periods of time, in environments that have, at times, been unexplored. Any equipment failure could be catastrophic and yet it will be difficult to fully assess component lifespans when the components may never have been used before, or at least have not been used in conditions as extreme as expected.

8.16.2 **Recommendation 10 - It is suggested that suitable in-depth reliability studies are encouraged for all sub-sea glider operators and manufacturers to help improve dependability of the sub-sea glider systems being produced.**

8.17 Launch and Recovery

8.17.1 Due to the expected weight of the sub-sea glider systems, suitable systems will be required for launch and recovery operations. Depending on what these systems entail, regulations such as the Lifting Operations and Lifting Equipment Regulations 1998 (LOLER) (Reference 28) or The Merchant Shipping and Fishing Vessels (Lifting Operations and Lifting Equipment) Regulations (Reference 29) may be applicable.

8.17.2 The use of Launch And Recovery Systems (LARS) will limit the options that are available for launching craft. Many LARS have significant weight and size and thus the vessel used for launching operations will likewise require sufficient deck space and carrying capacity to house such a system.

8.18 Units, Terminology and Language

8.18.1 Due to the BRIDGES project being funded by the EU it seems likely that the units used throughout construction will be SI units. However, due to numerous failures of large scale projects due to inconsistent units it is still vital that the units used are stated and standardised throughout the sub-sea glider lifecycle.

8.18.2 The use of a common set of terminologies and common language(s) will also aid in the reduction of errors during production and use.

8.18.3 Within this area rests other unit conventions such as orientation and coordinate conventions. The sub-sea glider will operate within an environment that allows for movement in all three dimensions, and thus any co-ordinate system involved will be required to take account of these dimensions in a way suitable for communication, such as:

a. Co-ordinates relative to the sub-sea glider;

b. Co-ordinates relative to the environment (lat/long);

c. Orientation coordinate (for controlling pitch, yaw and roll).

8.19 Software Packages

8.19.1 The BRIDGES project will bring together an array of different companies, all of which will need to, at some point, exchange plans, ideas and reports which may have been produced in a number of different software packages.

8.19.2 Key software types that are likely to require some form of standardisation between respective companies include:

a. Computer Aided Design (CAD) programs;

b. Office suites (such as Microsoft Office);

c. Fluid modelling programs;

d. Sensor integration programs.

8.19.3 CAD standards exist, though largely these are designed for the manufacturing industry. Systems such as ISO13567 (Reference 30) and BS1192 (Reference 31) combine various conventions to ensure that CAD diagrams maintain interoperability in the following fields:

a. Naming conventions;

b. Numbering conventions;

c. Scales;

d. File naming.

8.19.4 It is worthy of note that the Deep Explorer Preliminary Design (Reference 1) and the Ultra-Deep Explorer Preliminary Design (Reference 2) made note of which software packages were used throughout the design stage. It is advisable to seek feedback from ALSEAMAR as the effectiveness of these software packages and any associated naming/numbering conventions that may have been in use in these packages.

8.20 Transportation

8.20.1 The complete sub-sea glider systems will involve varied and potentially dangerous elements. Some transportation providers may be reluctant to transport the sub-sea gliders even with the suitable controls. Specifically there are currently strict requirements for air transportation, where the transport of high powered batteries is heavily controlled and may be too restrictive for the regular transport of sub-sea gliders by this route.

8.20.2 Efforts will be required to ensure that transportation issues do not create unreasonable delays when moving the sub-sea glider systems. Areas that will need to be considered prior to each transport include:

(i) Size and shape restrictions;

(ii) Transit times;

(iii) International import procedures;

(iv) Dangerous/hazardous transport restrictions (battery systems).

8.21 Testing

8.21.1 Testing procedures are vital in every scientific field and ensuring that a device will operate correctly and return accurate and usable data is essential. Testing guidance and procedures should be an integral part of the systems that support sub-sea glider operation and, when dealing with scientific equipment, unsuitable calibration standards should also be applied.

8.22 Satellite Communications

8.22.1 The current preliminary design outlines a plan to include an Iridium satellite-modem, with potential plans to change to Thuraya system. Both modems will connect to pre-existing commercial networks so regulatory requirements for communication will already have been met with regards to the infrastructure in use. However, should designs change to a more custom solution then care would be required to ensure that all regulations are met and the system remains fit for purpose.

8.23 Legal Aspects

8.23.1 The sub-sea gliders will be required to meet numerous legal requirements, including certifications and approvals before being able to be effectively used in certain territorial waters. For example, whilst it is envisaged that the sub-sea gliders will primarily operate in international waters, the nature of sea currents and certain close to shore survey missions will require that each country of operation's own regulations are followed, either for a purposeful launch in the area or simply that the sub-sea glider drifts accidently into the waters in question. Please see reference 32.

8.24 Interface

8.24.1 The various interfaces between the sub-sea glider systems and the support vessels/installations are of critical importance with regards to mission success/failure. Features of the sub-sea glider will need to be standardised to ensure that interface issues do not cause missions to be aborted or to fail.

8.24.2 Typical Interfaces include

a. Weight limits on-board vessels and their lifting equipment;

b. Physical connection points for data transmission;

c. Telecommunication connections.

9 Summary

9.1.1 BRIDGES is a long term project spanning a number of years and there is still much research, development and design work to be conducted. The approaches and topics discussed in this paper will form the basis of the ongoing study into standards and guidance, and whilst this will not result in a complete set of standards, it will lead the way to the eventual creation of such a set of guidance.

9.1.2 There are a number of IMO conventions and other marine regulations that may bear relevance/importance to this project, however the bulk of the standards and guidance that exist do not cater for sub-sea gliders. Despite this, there are still lessons to be learnt from the ways in which the existing regulations have been developed and these lessons need not only come from marine industries.

9.1.3 The drive for innovation and creative design work has led to the conclusion that the regulations and standards that are applied to sub-sea gliders should be as nonprescriptive as possible, with goal based approaches supporting manufacturing methods. Due to there currently not being an international oversight committee or organisation, industry will be required to push forward standards and guidance, which in turn will allow those standards to evolve naturally over time, without limiting innovation or the growth of the market.

9.1.4 Regardless how the eventual standards and guidance are developed, there will always be room for improvements to be made. Complacency should not be allowed and a system for regular improvements and analysis of the standards should be put into place to ensure that that future developments are considered.

9.1.5 **Recommendation 11 – Suitably qualified and experienced persons should regularly meet to review and agree improvements to standards to aid in keeping up with industry best practice and technology improvements**.

10 Recommendation Summary

10.1.1 **Recommendation 1 – Whilst the driver for this report is a set of standards that encourage cost-effectiveness and commercialisation, the eventual set of standards that is created should cover the full range of all applicable standardisation areas.**

10.1.2 **Recommendation 2 - Standards and guidance should be developed in such a way as to limit the reliance of users on written procedures.**

10.1.3 **Recommendation 3 - The Maritime Autonomous Systems Regulatory Working Group is leading development of a regulatory framework for marine autonomous devices; efforts should be made to keep informed of any documentation that the group may release and its impact(s) upon BRIDGES or any resultant standards that the BRIDGES project may create.**

10.1.4 **Recommendation 4 - Sub-sea glider operators should make every attempt to inform local marine traffic of their intention to operate sub-sea gliders in the area.**

10.1.5 **Recommendation 5 - Maintenance schedules should be developed to encourage testing on individual mission critical subsystems and components to help mitigate the risk associated with the loss of the sub-sea glider itself.**

10.1.6 **Recommendation 6 - The standards and approaches used by other international and national regulatory bodies should be regularly reviewed for changes that may be applicable to sub-sea glider operations. Likewise any changes and updates to sub-sea glider technology and standards should be shared with other organisations to ensure effective co-operation between interconnected fields.**

10.1.7 **Recommendation 7 – Many regulatory regimes operate a "goal-setting" approach to foster innovation and improvements in design; a similar approach would be suitable for sub-sea glider standards.**

10.1.8 **Recommendation 8 - Scientific instruments should be calibrated and tested according to a recognised standard and auditable process**.

10.1.9 **Recommendation 9 – Include within standards and guidance appropriate methods for assessing the need to use anti-fouling systems on long duration sub-sea glider technology**..

10.1.10 **Recommendation 10 - It is suggested that suitable in-depth reliability studies are encouraged for all sub-sea glider operators and manufacturers to help improve dependability of the sub-sea glider systems being produced.**

10.1.11 **Recommendation 11 – Suitably qualified and experienced persons should regularly meet to review and agree improvements to standards to aid in keeping up with industry best practice and technology improvements.**

11 Acronyms

Acronym	Definition
ABS	American Bureau of Shipping & Affiliated Companies
ANO	Air Navigation Order
ASTRAEA	Autonomous Systems Technology Related Airborne Evaluation & Assessment
ATC	Air Traffic Control
AUSS	Advanced Underwater Search System
AUV	Autonomous Underwater Vehicle
BRIDGES	Bringing Together Research and Industry for the Development of Glider Environmental Services
CAA	Civil Aviation Authority
CAD	Computer Aided Design
CCTV	Closed-Circuit Television
DC	Direct Current
DECC	Department for Environment and Climate Change
ECSS	European Cooperation for Space Standardization
EDA	European Defence Agency
EDRT	European Defence Research & Technology
ESA	European Space Agency
EU	European Union
FSA	Formal Safety Assessment
GPS	Global Positioning System
HSE	Health and Safety Executive
IMO	International Maritime Organization
ISPS	International Ship and Port Facility Security
JAXA	Japan Aerospace Exploration Agency
LARS	Launch And Recovery Systems
LDPE	Low-Density Polyethylene
LFE	Learning From Experience
LOLER	Lifting Operations and Lifting Equipment Regulations
MARPOL	International Convention for the Prevention of Pollution from Ships
MAS	Maritime Autonomous Systems
MCA	Maritime and Coastguard Agency
MED	Marine Equipment Directive
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NOC	National Oceanography Centre
NOTAM	Notice to Airmen
PBOF	Pressure Balanced Oil Filled
PER	Pressure Equipment Regulations
PSSR	Pressure Systems Safety Regulations 2000
RWG	Regulatory Working Group
SARUMS	Safety and Regulations for European Unmanned Maritime Systems
SOLAS	Safety of Life at Sea
SPV	Simple Pressure Vessels

Acronym	Definition
STCW	Standards of Training, Certification and Watchkeeping for Seafarers
STPA	Systems-Theoretic Process Analysis
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
UMS	Unmanned Maritime Systems
USA	United States of America
VLOS	Visual Line of Sight

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