Large Naval UUVs – Navigating Between Simple and Very Complex

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Synopsis

There are a wide range of Unmanned Underwater Vehicles (UUVs) in operation today and they already include a vehicle with 45te displacement. Technology developments in underwater communications, autonomy, and battery and power systems, driven in part by the automotive industry, mean that many previously perceived barriers/blockers can be overcome, and underwater capability opportunities realized.

These opportunities include distancing operators from threats, reducing cost, but also reducing manpower requirements for mundane operations. Many nations require these roles in territorial waters, the extended neighbourhood and expeditionary operations. This and payload requirements conspire to drive future vehicles into a less well understood design bracket between current small UUVs and manned diesel-electric submarines.

This paper describes some of the resultant Large UUV design challenges and opportunities such as shorter development cycles, the risk of an unstable design space between relatively simple expendable UUVs and very complex manned submarines, the need for reliability and applicable rules and standards. It describes a design methodology that applies light-touch system engineering principles to vehicle concept development to address these challenges. This is supported by development and description of an illustrative Large UUV design which provides a good balance of cost, complexity, and capability.

Keywords: Large UUV, Design Methods, Design, Marine Systems

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1. Introduction: Why Large UUVs and What are the Challenges?

1.1 Background

This paper describes a recent internal project at Steller Systems to address some of the design challenges that emergent Large Unmanned Underwater Vehicles (UUVs[1]) pose. Naval and commercial UUVs typically have a displacement less than 10te, for example the Kongsberg Hugin family of vehicles. The exception to this is Boeing's recent 45te displacement Echo Voyager which is considered a Large UUV.

The operational 'pulls' for larger vehicles are increasing the stand-off for operators, more range and endurance, reduced manpower needed in mundane roles, and larger and more complex payloads, all whilst being more cost effective than the equivalent manned asset. The main barriers to date have been the energy density of air independent energy storage and the difficulty of maintaining communication and control/avoiding latency. There have been improvements in underwater communications, as demonstrated by a live Sky News broadcast from a submersible [1], however not to the extent that direct control or minimal latency can be guaranteed. Autonomy is being developed in the automotive industry where there is general acceptance that driverless cars will, in the not too distant future, be commonplace. The requirement for cleaner energy storage for both cars and industrial vehicles is driving significant investment into fuel cell, battery, and motor development. This paper does not discuss these technologies in detail, rather they are assumed to be available and sufficiently developed for UUV

[1] UUVs is used in this paper as a collective term for all unmanned underwater vehicles including Autonomous Underwater Vehicles (AUVs) in the commercial sector

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application in the near future, although it is accepted that the challenges of UUV operation are, in some cases, very different to those in the automotive industry.

The lifting of these barriers presents new challenges and opportunities for overall UUV design. These principally relate to the short development and lifecycle, and the risk of an unstable design space between current UUVs and manned Diesel-Electric Submarines (SSKs) where growth is almost irresistible. All designs tend to grow, growing threats, sensitive and complex roles and longer endurances warrant complex payloads and better reliability. The resulting larger more expensive vehicle deserves better sensors, even better reliability and further complexity until the original UUV benefits could be negated. Where a Large UUV is too expensive to be expendable, further growth and complexity could be required until there is confidence that the vehicle will successfully return from its mission. This is analogous to early experience with the UK Type 23 frigate design where the original concept was too expensive to be expendable and had to shrink or grow to allow for some defensive armament [2].

1.2 Development & Lifecycle

Figure 1 shows a comparison of a notional SSK lifecycle with a potential Large UUV one. Major warships like submarines can take decades to design and build, and their operational life may be over 25 years. Evolutionary types e.g. teardrop or surface optimized configurations relevance is measured in half centuries. Conceivably Large UUV classes will have a prototype vehicle, vehicle operational life could be as short as 10 years due to obsolescence with subsequent classes taking advantage of emergent technology developments.

For the designer this suggests a look ahead across potential future classes with a view to starting the vehicle evolutionary path in the appropriate direction, necessarily resulting in some increased effort in the early stages. The look ahead needs to account for future threats and technologies that may become available, making provisions, be they space, weight and power or complementary technology, so that all the development effort need not be completely repeated for each class.

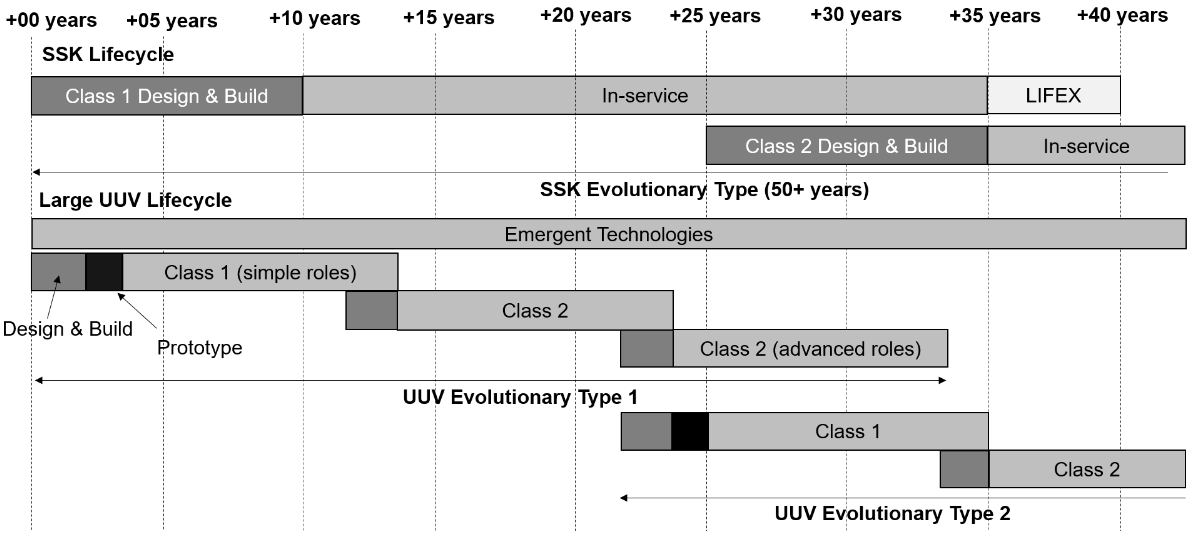

Figure 1 – Notional SSK and Large UUV Lifecycles

1.3 Design Methods

The emphasis of this paper and the required importance to address the challenges identified should be on the vehicle or vehicles concept phase where the majority of costs are committed [3]. In the system engineering V-diagram this is the often not shown iteration of User Requirements, System Requirements and vehicle concept options. Figure 2 shows the process diagram that was developed to explore those challenges identified. The project defined a series of representative customer roles and constraints (e.g. available Technology Readiness Levels (TRLs)) and developed an illustrative design which was iterated with the requirements.

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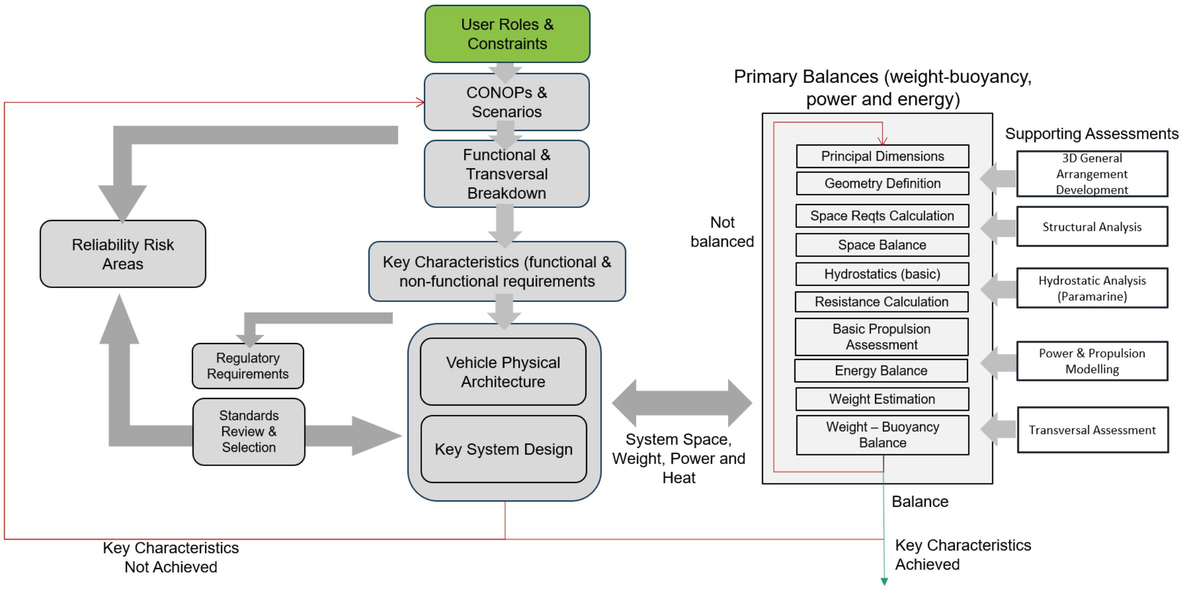

Figure 2 – Concept Design Method

2. Requirements & Key Characteristics

2.1 Vehicle Roles

The most common role for commercial UUVs is conducting hydrographical survey, with Mine Countermeasures (MCM) a common role for naval UUVs. The US UUV Masterplan [4], RAND survey of UUV Missions [5] and Binns et al [6] list a series of potential roles for UUVs that require increased complexity, range and endurance and are comparable to roles conducted by SSKs. These can be distilled to the following broad additional headings:

a. Deploy payloads/cargo, e.g. sensors, sensor arrays;
b. Near-land harbour monitoring;
c. Monitoring Undersea Infrastructure;
d. Inspection/identification;
e. Anti-Submarine Warfare (ASW), including training.

Roles a-d have been treated as the requirement for the first of class with allowance to be made for progression to more complex roles like ASW while taking the lessons learnt from the first class and avoiding complete redevelopment of the vehicle.

2.2 Functional & Transversal Breakdown

New classes of submarines design are evolutionary due to their complexity with only small levels of innovation introduced from one class to the next, Burcher [7] suggests a value of 10% so that cost and programme estimations can be met. Arguably this results in ever increasing complexity as systems are added to the evolutionary type. Whilst Large UUVs are significantly smaller and cheaper than submarines there is also the opportunity for more innovation per class, particularly if a prototype is expected. A functional and transversal breakdown was used to derive performance characteristics from the roles and structure requirements. It was also used to encourage a 'blank sheet of paper' philosophy, focus system design on required functions and to avoid unnecessary functionality and complexity. This is similar in some respects to the Float, Move, Fight headings used in warship survivability analysis and safety cases, although this breakdown was structured from the following top level functions; Mission Functions, Float (Surface and Submerged), Move, and Provide Power (see Figure 3 for levels I-II).

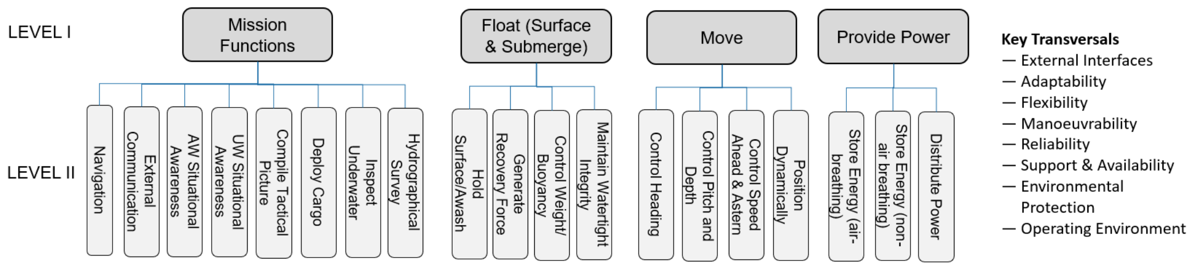

Figure 3- Simplified Functional & Transversal Breakdown

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2.3 Initial Key Characteristics Trade Space

The vehicle key characteristics trade space derived from the required roles is summarized in Appendix A. The vehicle must be safe in terms of navigation as a minimum. Optronic and Electronic Warfare (EW) sensors are required to conduct above water surveillance. A range of communication methods are available, from short range underwater acoustic and optical to longer range satellite/UHF that require an antenna to be raised above the surface, potentially compromising the vehicle's position. Potential payloads/cargoes could vary and there is scant information on underwater sensor networks in the public domain. A neutrally buoyant cargo space of 2-5m^3 was specified for the project which correlates with Allison [8].

The maximum operational depth of existing UUVs conducting hydrographical survey range from a few hundreds of meters to over 6,000m for very specialized vehicles. The roles that require activity on the seabed were assumed to be on the continental shelf, resulting in a maximum operating depth specification of 200-400m.

Current UUVs with relatively short ranges generally vary solid ballast to achieve neutral buoyancy. Longer ranges mean that a large range of seawater densities will be encountered; from open ocean to near freshwater conditions in the littoral. Operating at or near neutral buoyancy is desirable in terms of slow speed control and minimizing energy consumption.

Small UUV endurances are typically a few days at 4-5 knots [9]. Large UUVs are differentiated by having endurances that are measured in weeks and months. A target was set for an endurance of 2-3 months at 5 knots, or a single 7,000-11,000nm transit which constitutes a significant amount of time without direct human intervention. A maximum speed of 10 knots was set to allow faster transit and effective sprint if required. Submerged radius of operation of 200nm was specified to allow covert transit to and from an operational area.

The long endurances without support and covert operations in sensitive areas mean that the vehicle must be reliable[2]. Reliability of the vehicle could be ensured by long test and trials programmes before entering service which may be possible in the academic sector, and/or introducing significant redundancy and cross connections on all systems, which both drive in cost and complexity and start to negate the UUVs benefits. The approach taken was to permit some degradation in performance, except navigation, but avoid complete failure of the vehicle function that would require recovery or surfacing in a sensitive area. These areas included maximum speed, environmental conditions, combat systems and accuracy of depth control.

The range set allows long distance, low speed transits. Transportability by road, air, rail and sea for rapid reposition to other base ports in the home country or overseas, or purely for maintenance, is considered beneficial. Containerisation is an obvious solution and potentially a prudent cap on vehicle size as requirements conspire to drive the vehicle larger.

The need for adaptability in terms of identifying the operational evolutionary path has been identified. There is also a need to link future supplementary roles with potentially available future technologies. Sensor fits and battery technologies will continue to evolve and the efficiency of technologies like fuel cells may be useful too.

2.4 Certification & Standards

In a submarine lifecycle significant risk management is undertaken with the primary focus being on risk to life, the environment, and the asset itself. When considering risk to life, the crew are most at risk. While external third parties are largely unaffected by the primary hazards considered, they are not exclusively so, a submarine can present a hazard to shipping in terms of collision. In the case of a UUV, or any unmanned system, there is no risk to the operator, so the primary risk to life is that to external third parties. An example of the difference this makes is that for a regular submarine an event which causes maximum depth exceedance are generally considered a higher risk than one which results in uncontrolled surfacing, despite the resultant hazard to other shipping. For a Large UUV this hazard to other shipping is still present, but the risk to life from exceeding maximum depth is not. Risk to the UUV itself does not present a hazard to life in the traditional sense, and as such is referred to as a reliability risk in this paper.

An initial look at events that would present a hazard identified that a failure of a limited number of the functional areas would directly present a hazard to shipping, including most of the MOVE functions as well as navigation and weight and buoyancy control. To develop any design, a formal HAZID is required to quantify the risk.

Since UUVs and their commercial counterparts are not yet regulated, many organisations and users are using self-regulation through codes of practice. Several codes of practice have been developed for underwater vehicles [10] with a focus on safe navigation and avoiding collisions. The Maritime Autonomous Surface Ships (MASS) UK Voluntary Code of Practice [11] suggests that design justification would be achieved by demonstrating that the performance requirements are the same as would be required for an equivalent manned vessel. Where there are departures the justification shall demonstrate the requirement is redundant (e.g. lifesaving equipment) or a different solution is required (e.g. automated firefighting instead of manual systems). It is considered that complying with this will result in unnecessary cost and complexity in UUVs because the likely

[2] Reliability is defined as the probability that failure will not occur in the period of interest

consequence of a catastrophic failure would be the UUV sinking to the seabed, which, although posing an environmental hazard if not recovered, does not in itself present a threat to life.

An example of the potential implied cost of this statement are the pressure hull safety factors that can account for the consequence of loss of the vessel. Arguably this factor should be reduced for an unmanned vehicle which has lower monetary value than a manned counterpart and lower military value if purely conducting peacetime hydrographical survey. However Large UUVs could cost significantly more than the UK Value of a Prevented Fatality. The vehicle could also be operating in sensitive areas performing roles where the consequences of loss could have significant political implications. This is not to say that all manned underwater standards will be applicable, rather a pragmatic approach is required ultimately based on user requirements. It is worth noting that consideration is required not only for performance related aspects of standards but also levels of independent assurance.

After a comparison between DNV GL Rules for the Classification of Underwater Technology (UWT) [12] and the DNV GL Naval Submarine Rules, the project used UWT rules, augmenting them where required for the roles identified. The main differences highlighted were those relating to the safety of life onboard a regular submarine, with generally relaxed safety margins in certain areas for unmanned vehicles.

2.5 Reliability Risk Areas

It is difficult in warship concept design to meaningfully address reliability. However, with Large UUVs relatively simple it is easier and was considered through a series of 'reliability risk areas' mapped against operational modes and scenarios in the CONOP, and challenging the overall systems design against this mapping. Griffiths et al [13] adopted a Pareto approach for the University of Southampton Autosub because the programme budget was insufficient to delve into the detail of the 'insignificant many' at the expense of dealing thoroughly with the 'significant few'. They also presented a Pareto diagram of the failure modes and their arisings during missions. Failure modes will vary with the specifics of each vehicle, but the failure modes presented were used to inform the list of risk areas. An illustration of the mapping is shown in Figure 4. Fire is the main addition based on the authors' submarine experience and Manoeuvring and Control covers grounding and collision as a result of the loss of the capacity to manoeuvre the submarine. Stressing scenarios during operating modes were also considered. Perhaps unsurprisingly the most stressing mode is snorting/snorkelling whilst replenishing batteries. This presents concurrent navigational and situational awareness challenges in terms of avoiding collision, risk of fire, watertight integrity issues due to several temporary openings in the pressure hull, and accurate depth control and propulsion challenges when exposed to surface and near-surface effects.

		Normal Operating Modes						
		Mission Planning	Harbour Transit	Harbour Approaches Transit	Open Ocean Transit	Covert Transit	Seabed Activity	Return Modes
Reliability Risk Areas	Navigation							
	External Communication							
	Watertight Integrity							
	Manoeuvring & Control							
	Propulsion & Manoeuvring							
	Fire							
	Structural strength							
	Software							
	Human Error							

Figure 4 – Illustration of Mapping of Reliability Risk Areas against Normal Operating Modes

3. Design Illustration

3.1 Architecture

The design illustration shown in Figure 5 was developed with distinct functional zones to make it adaptable, assist future changes and upgrades, and allow it to be separated for maintenance or transportation in two ISO 40' containers. This avoided where practicable distributing systems over the length of the vehicle which complicate build and requires more disconnect and connection for transportation. For example the Variable Ballast System (VBS) consists of two stand alone modules fore and aft, and a central R compensation tank for weight control at shallow depth.

The relatively low maximum diving depth meant that a main cylindrical pressure hull could be adopted as opposed to spherical pressure vessels required in deeper diving vehicles. The pressure hull is internally framed, making it more difficult to fabricate but allowing external space for ballast tanks and additional sensors that may be required in the future.

The central section accommodates the air breathing energy source, this is an 80kW diesel generator that may be replaced with an air breathing fuel cell when the technology enables this. The forward section is dedicated to Command and Control (C2)

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and the 5m^3 neutrally buoyant cargo space which can be accessed from above and below for dropping cargo. The top of the vehicle is dedicated to above water systems that include a rotating combined Optronic and EW mast, and the Snort/Snorkel induction mast. Being still a relatively small vessel, depth control will be difficult in any kind of seastate, and whilst snorting the vehicle will predominantly be awash and at risk of detection. This difficulty places greater emphasis on systems like towed buoys that allow the vehicle to remain at depth when operating covertly.

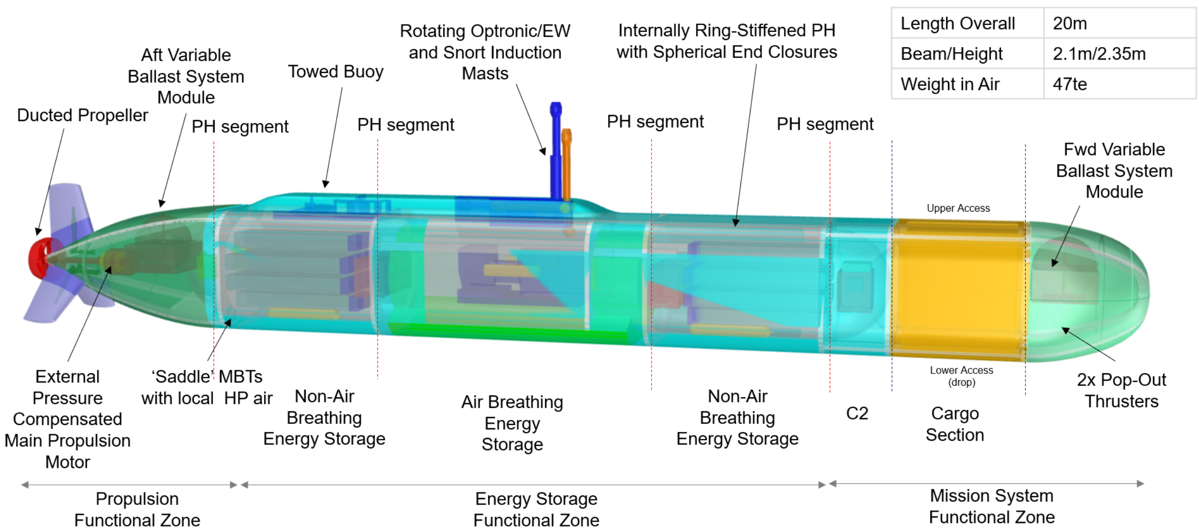

Figure 5 - Design Illustration Architecture

3.2 Mission Systems

The covert navigation function hinges on the vehicle having an adequate estimate of its position whilst submerged and without GPS. There are a series of methods available to estimate underwater position such as Optical with beacons, Geophysical gravity, magnetic and sonar methods and Acoustic Ranges with Long and Short Baselines (LBL and SBL). These require prior survey of the operational area, a nearby surface support ship or prior deposit of navigational aids like LBL transponders, none of which can be guaranteed. As a result, there will be heavy reliance on inertial/dead-reckoning navigation. A notional mission system is presented in Figure 6, numbers and redundancy of sensors depend on analysis of specific equipment Mean Time Between Failures. However, given the criticality it is anticipated that triple redundancy and associated voting systems will be required for components of the navigation system so that erroneous sensors can be confirmed. Similarly, the main processors that control navigation and overall autonomy will require these kinds of arrangements. This is common in aerospace where there are many variations of the concept, for instance the Predator B UAV has a triple redundant avionics system architecture [14]. Boeing's Echo Voyager UUV has four primary computer systems and six emergency controllers [15]. This requires additional external real estate for additional sensors and budgets for more internal dry processing.

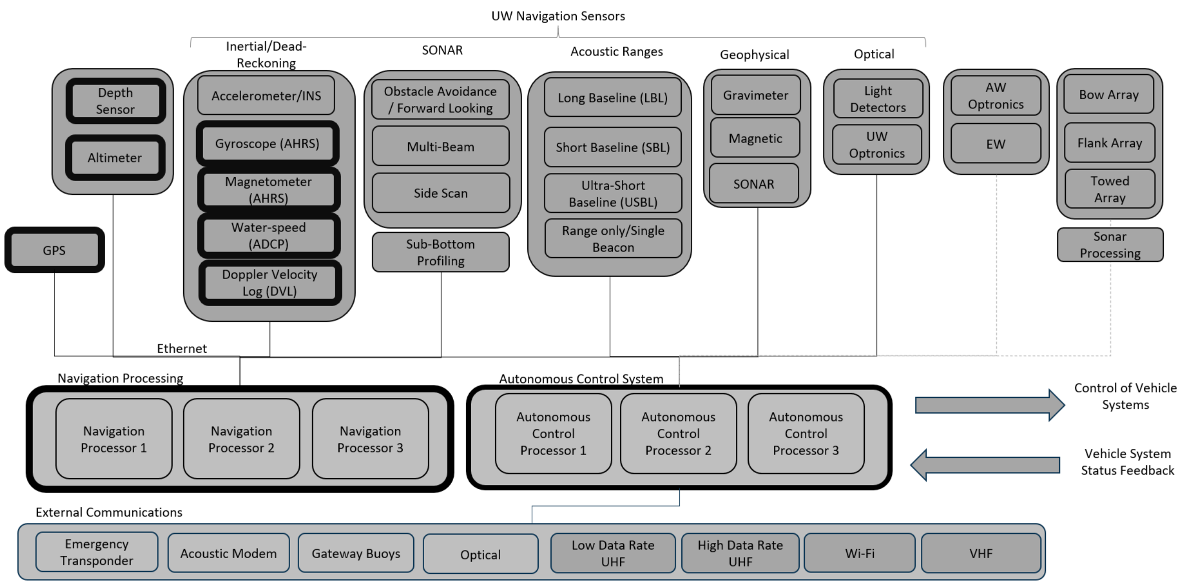

Figure 6 – A Notional Simplified Mission System (focused on Navigation)

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3.4 Float & Submerge

Reserve of buoyancy (ROB) contributes to a number of functions. The most obvious are that it enables the vessel to surface and remain surfaced, and grants freeboard which is essential on a regular submarine due to the need for casing access and open hatches. It also contributes to stability, seakeeping, the ability to accommodate changes in weight, flood recovery, propulsor and appendage immersion. ROB existence and extent is normally mandated by standards, with 10% a common value. Provision of this amount of reusable ROB mandates large external MBTs which require a significant amount of external structure and additional systems. As a result the overall volume of the submarine is much increased. For a UUV, even a large one, a significant amount of equipment is being squeezed into a relatively small envelope, so large MBTs are undesirable if avoidable.

For a UUV many reasons for requiring significant ROB do not exist, for example there are no operators requiring access to the casing, and hatches would not need to be opened at sea. While some level of ROB is still required, by operating the UUV in a different way to a submarine (for example operating with decks awash when at the surface), and by incorporating alternative design features (for example solid ballast, drop weights, rapidly inflating buoyancy bags) a much reduced direct reusable ROB provision would be acceptable, in the order of 1%. As a result the philosophy taken was to retain reusable ROB provision in the illustrative design that may be useful during trials and development where frequent surfacing and human intervention may be required, with the expectation that this would be replaced by payload in future iterations.

To size the VBS a trim polygon was constructed to ensure that the design would maintain full control of depth and attitude in all feasible situations. As the vehicle is unmanned, the list of consumable items was relatively short when compared to a manned submarine, with no fresh, grey, or black water tanks to account for. However, this did mean there was more emphasis on estimating compression, seawater density range, and payload capacity. Rubber tiles were looked upon as unnecessary as, compared to conventional submarines. This meant that only pressure hull compressibility was considered. The expected seawater density range was assumed to be 1.015te/m^3 – 1.027te/m^3 to cover the majority waters accounting for the diving depth. The analysis confirmed the need for an R comp tank along with the forward and aft trim tanks. Having a central comp tank and, as discussed above, a 1% ROB meant that the VBS system is also sized to include the volume that would normally be main ballast tank in a regular submarine.

3.5 Move

The Level II Move functions includes Control Heading, Control Depth and Pitch and Control Speed Ahead and Astern functions, which would also be expected for a regular submarine. Where the illustrative design differs from most regular submarines is the Position Dynamically Level II function, which requires a design solution that offers more than the traditional propulsion and control surfaces only. The Level II functions were divided into high, low and zero speed categories, with manoeuvrability requirements, in terms of the 6 degrees of freedom, allocated to each. The resulting manoeuvring functionality is shown in Appendix B.

To generate and refine the design solutions from the information in Appendix B further assumptions need to be made, particularly concerning redundancy. Redundancy is required to primarily offer a 'get home' or reduced speed functionality, offering some propulsion, course changing and keeping, and depth changing and keeping capability. Where this enables continuation of the mission it is considered desirable but not essential.

The illustrative design features a single 5-bladed propeller with a decelerating duct supported by fixed skegs. The propeller is a single point of failure, however a get home/ reduced speed capability is provided by thrusters supporting the dynamic positioning function. The duct and fixed skegs provide some protection from propeller fouling which will be a greater risk in shallow water. The decelerating duct also lowers the probability of cavitation whilst near the surface snorting or where the propeller is suddenly heavily loaded whilst shallow. The main propulsion motor consists of an external oil-filled, pressure compensated permanent magnet brushless motor derived from the automotive industry with twin armatures. The twin armatures provide redundancy in what is a single point failure and may be a development item. The external pressure compensated motor negates reliability issues from a main shaft seal and simplifies the aft construction design and production.

To achieve the zero-speed position control it is clear that multiple thrusters are required. A number of thruster capabilities (i.e. azimuthing and fixed) and arrangements were considered to provide thrust in the x, y and z directions. While some options achieved the required capability with fewer thrusters, these incorporated thrusters at the midships of the UUV, which could be ruled out early due to the set constraint of maintaining a single pressure vessel which would be disrupted by locating thrusters at midships. The remaining options incorporated multiple thrusters located both forward and aft, with the final architecture adopting two retractable thrusters both forward and aft that azimuth to provide thrust in the vertical and ahead/astern directions, and forward and aft fixed thrusters providing lateral thrust. The VBS is also expected to contribute by producing pitch moments and heave forces.

It is assumed that at high speed the thrusters are not utilized to generate any yaw or pitch moment, however they are available for use at low speed. It is therefore necessary to provide hydrodynamic control surfaces to generate the required moments at higher speeds. Various control surface configurations were considered before an inverted Y-stern was selected, with no bowplanes. The advantages of the inverted Y configuration are that a horizontal force can be applied without a vertical one, the horizontal and vertical forces can be balanced which can be difficult with X-planes, and there is less associated equipment at the stern of the vessel than for an X-plane configuration. Conversely, the disadvantage is that there is less redundancy than for an X-plane configuration, however it does still offer a layer of redundancy in both the vertical and horizontal planes, and on a UUV with the thruster configuration outlined above the additional redundancy in the control surfaces is not seen as essential.

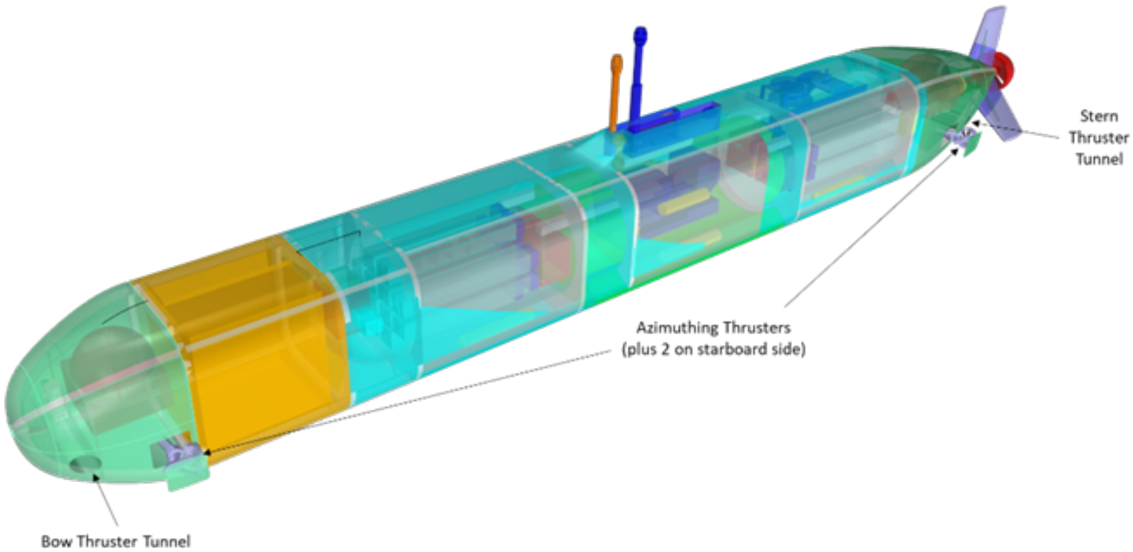

Figure 7 - Thruster Configuration

3.6 Energy Storage and Power

Power is provided by the single 80kW diesel generator to achieve the 2-3 month endurance at 5 knots. Multiple diesel generators were considered for redundancy however this results in a significant increase in complexity primarily in the ancillary systems. The reliability implications of the single diesel generator were mitigated by having a main storage battery sized to allow the vehicle to leave sensitive areas covertly and reach a safe distance before recovery. The main storage batteries are 'fault tolerant' lithium technology units rated at approximately 1,000kWhr. Whilst these cells feature a lower energy density compared to more advanced Lithium-Ion cells, the selected units are in service in both UUV and AUV applications and represent a lower risk solution compared to other battery technologies.

The ability to snort will be heavily constrained by seastate, the submerged endurance allows the vehicle to wait days until there are suitable conditions. This may include entering a prolonged hibernation mode at depth to wait out unfavourable weather for long periods. Diesel fuel is stored in bladders which are common in the commercial, pleasure boat and defence industries. The bladders prevent pollution from compensating seawater mixing with fuel, seawater contaminating diesel fuel which is a major source of engine reliability issues and negates the complexity of an additional separator to manage this problem.

As identified, snorting requires a series of temporary openings in the pressure hull for the air intake, exhaust, and seawater cooling. Making these systems resilient to maximum diving depth pressures is impractical particularly with Commercial Off The Shelf (COTS) equipment. This necessitates the use of hull valves. Failure of one of these valves to close will result in the loss of the vehicle, implying the requirement for back up valves and the complexity that this entails.

Several options were considered for the electrical distribution architecture. Credible scenarios were events such as minor fires, flooding, or electrical faults in any one compartment of the vehicle or single component failure. A Zonal DC system provided the best overall survivability and mitigated the risk of widespread damage in a section of the vehicle, but also featured the highest cost, volume and complexity. On the other hand the Radial DC system selected (Figure 8) provides redundancy in terms of component failure offering a reduced submerged endurance and speed in the event of a complete compartment loss but offered a simpler, lower volume arrangement and at a lower cost.

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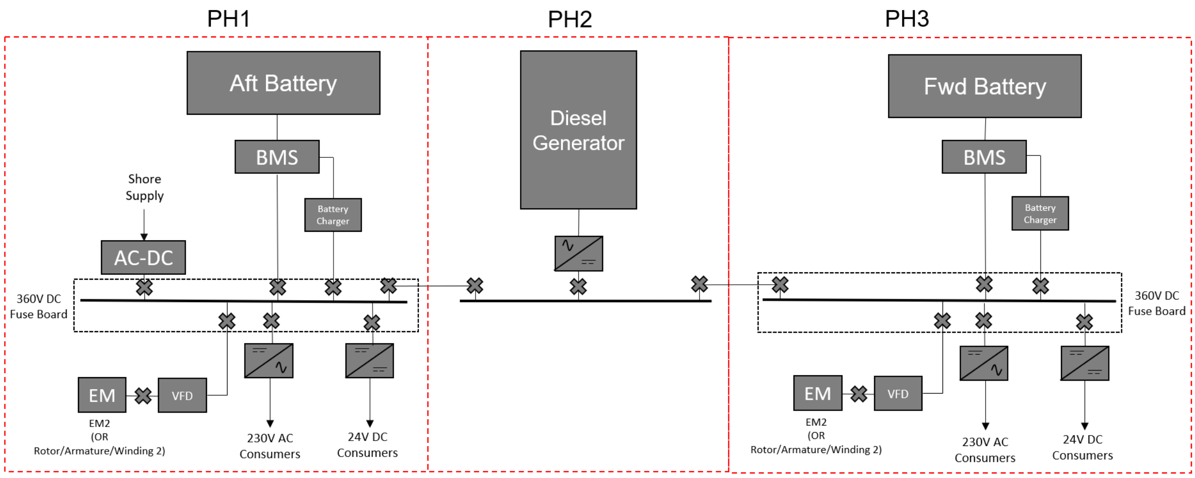

Figure 8 – Indicative concept of a UUV Radial Electrical Distribution System

5. Conclusions

The operation of Large UUVs in complex naval roles is becoming a realistic proposition where some of the autonomy and technology barriers are being addressed by commercial pressures in parallel industries. Complex roles and payloads drive a spiral of increasing complexity with range and endurance, reliability, vehicle size and cost which can negate UUV benefits. Whilst relatively simple, there is an opportunity for very short 'flash to bang' in terms of development cycles and faster drumbeat of evolutionary types to meet emergent threats. In response to these challenges and opportunities this paper has described a design methodology that applies light-touch system engineering principles to vehicle concept development, focusing on required vehicle functions, taking a pareto approach to reliability risk areas, permitting graceful degradation of functions and making these trades in the context of the CONOP. It is anticipated that new standards and rules for Large UUVs will evolve based on operational experience. Until then, a systematic approach is required to derive detailed design parameters from the CONOP. The paper has presented an illustrative design to demonstrate the method, using a functional breakdown to derive key characteristics. In this design transportability proved to be a prudent limit on vehicle dimensions and weight. The design focused on the use of proven COTS equipment, but it was highlighted that covert near surface control will be challenging and this will place greater focus on the importance of compact towed buoy systems.

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Appendices

Appendix A: Initial Key Characteristics Summary

Mission Functions	Navigation	Safe navigation at all times
	External Communications	Iridium (Sat-Com)
		WiFi Antenna
		Acoustic Modem
		Gateway Buoys
		Transponder Locator Beacon
	Above Water Situational Awareness	Optronics
		ESM
	Below Water Situational Awareness	Bow Array (Active and Passive)
		Flank Array
		Towed Array
	Flexible Cargo	Neutrally buoyant Cargo 2-5 m^3
Submerge	Maximum Operating Depth	200-400m
	Seawater Density Range	1,015-1,027 kg/m3
Move	Submerged Endurance	200nm ROO at 5 knots
	Maximum Speed	8-10 knots
	Total Hybrid Mode Endurance	2-3 months at 5 knots
Transversal Areas	Transportability	Compatible with 1-2 container transportation
	Adaptability	Evolutionary design paths for: ASW Roles and Fuel Cell Power Generation
	Reliability	Essential functions: Navigation, Move (reduced functionality in maximum speed and depth control), Submerge (reduced functionality in variable ballast)

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Appendix B: Manoeuvring Functionality

Speed Category	Level II Function	Motion Requirement	Solution Option(s)
High Speed	Control Heading	Yaw	Move Control Surface(s) to generate hydrodynamic yaw moment
	Control Depth	Pitch	Move Control Surface(s) to generate hydrodynamic pitch moment
	Control Speed Ahead and Astern	Surge	Generate Ahead and Astern thrust with propulsion train
Low Speed	Control Heading	Yaw	Move Control Surface(s) to generate hydrodynamic yaw moment
			Generate unequal horizontal force
	Control Depth	Pitch	Move Control Surface(s) to generate hydrodynamic pitch moment
			Generate unequal horizontal force
	Control Position (Horizontal)	Sway	Generate equal horizontal force
	Control Depth	Heave	Move Control Surfaces (Fwd & Aft) to generate hydrodynamic heave force
			Generate equal vertical force (thrust)
			Generate equal vertical force (hydrostatic)
	Control Speed Ahead and Astern	Surge	Generate ahead and astern thrust with propulsion train
Zero Speed	Control Heading	Yaw	Generate unequal horizontal force
	Control Angle	Pitch	Generate unequal vertical force (thrust)
			Generate unequal vertical force (hydrostatic)
	Control Position (Horizontal)	Sway	Generate equal horizontal force
	Control Position (Vertical)	Heave	Generate equal vertical force (hydrostatic)
			Generate equal vertical force (thrust)

Disclaimer

The opinions expressed in this paper are those of the authors and not those of Steller Systems, other companies, or any Defence Agency.

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