

Autosub 2000 Under Ice: Design of a New Work Class AUV for Under Ice Exploration

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Abstract—The ice covered portions of the world’s seas and oceans are some of the most inaccessible areas on the planet, yet hold crucial clues to the behaviour of the world’s climate. Largely inaccessible by manned vessels, robotic platforms provide our best opportunities to explore and learn about these regions. Autosub2000 Under Ice (Autosub2KUI) will become the newest iteration of the Autosub family of Autonomous Underwater Vehicles which have played a significant role in under ice exploration over the last two decades. Autosub AUVs have conducted over 30 missions under sea ice and tidewater glaciers in both the Arctic and Antarctic. This paper outlines the design of Autosub2KUI with a focus on the adaptations required for operation under ice.

Index Terms—Autonomous Underwater Vehicle, scientific exploration, marine robotics, under ice

I. INTRODUCTION

Autonomous Underwater Vehicles are capable of collecting unique data sets in under ice environments including: beneath frozen lakes [1], under sea ice [2]–[4] and in cavities beneath tidewater glaciers [5], [6]. The data collected by AUVs has provided unique insights into these domains and led to calls for the continued use and development [7]–[10].

International Submarine Engineering (ISE) pioneered the use of large AUVs in ice covered areas. Their Theseus vehicle undertook a series of under ice missions in the Canadian Arctic in the mid-90s laying fibre optic cables [11]. ISE also undertook significant Arctic operations with an Explorer AUV as part of Canada’s UNCLOS under ice survey [12].

The Autosub programme [13] was another early pioneer of operations in polar waters, having conducted deployments in both the Arctic and Antarctic. Autosub2 conducted a series of successful under ice campaigns [14]–[19] which ultimately ended in the vehicle’s loss under the Fimbul Ice Shelf in February 2005 [20]. Following this loss, an upgraded variant, Autosub3, successfully explored under the Pine Island Glacier in 2009 [21] (see Figure 1a), providing unprecedented multi-beam imagery of the underside of the ice [5], [22]. Following a decade of service Autosub3 was retired in 2017. Further under ice missions were conducted with an Autosub Long Range 6000 (ALR6000) vehicle under the Filchner-Ronne Ice Shelf in 2018 [23], see Figure 1b.

More recently in 2019, the *nupiri muka*, an ISE Explorer operated by the Australian Maritime College completed missions beneath the Sørstøl Glacier in Antarctica [6], [24], while in



(a) Autosub3 activities under the Pine Island glacier.



(b) Autosub Long Range 6000 operations under the Filchner-Ronne Ice Shelf.

Fig. 1: Previous Autosub AUV Under Ice Operations

the same season *Ran* a Kongsberg Hugin completed missions under Thwaites Glacier [25].

This paper describes Autosub 2000 Under Ice (Autosub2KUI), a new AUV being developed to replace the high power survey capability of Autosub3 which will be equipped with a range of acoustic and optical sensors. She will complement the ongoing low power, long range under ice activities of Autosub Long Range. The remainder of this paper is structured as follows: Section II describes some of the challenges associated with operation under ice, Section III provides an overview of the design of Autosub2KUI, Section IV provides

an indicative performance specification and compares this with previous Autosub AUVs, finally Section V presents conclusions and future work.

II. CHALLENGES ASSOCIATED WITH UNDER ICE OPERATION

AUVs operating under ice present additional challenges compared to open ocean operation [26]. A number of the key challenges are discussed below. It is important to note that addressing these issues is only partially a vehicle design problem, the experience of the team, operating procedures and mission planning, among other factors, are also critical [27].

A. Unsupervised Operation

For under ice operation the AUV may be operating for several days with no mechanism for human intervention. Therefore the AUV must be developed with sufficient on board autonomy to enable multi-day operation in complex and often dynamic environmental conditions.

For example, when operating near ice it is not always possible to be certain that the intended recovery position is ice clear, this is particularly challenging when operating in dynamic ice areas or over extended durations.

For large work class AUVs, often operating outside of standard acoustic communications, this presents a challenge. To address this, Autosub3 was equipped with three spherical hydrophones together with a three-channel correlation receiver which was able to calculate range and bearing to a 4.504kHz beacon transmitting from the ship at ranges of up to 15km [17]. This system was demonstrated during mission 365 where the intended recovery position had been covered with sea ice. ISE Explorers have been fitted with seven element hydrophones, the LRAB array, which are able to detect a 1.3kHz source at a range of 30km [28].

B. Increased Mission Risk

Operation of AUVs under ice inevitably attracts a higher probability of vehicle loss than open ocean operation [26]. Whilst many of the failure modes are common irrespective of operating area, the consequences of faults arising under ice are typically more severe. In open water the typical large AUV contingency action, in the event of a identified issue, is dropping an abort weight and immediately surfacing [12]. While under thick ice this action would likely result in the AUV being stuck on the under side of the ice, in many scenarios this would in turn lead to vehicle loss as recovery from such a scenario is likely to be infeasible unless the vehicle is close to the ice edge.

Such events unfortunately do happen, Autosub2 was lost 18km under the Fimbul Ice Shelf in 2005 (Mission 383) after several previously successful deployments. A panel of experts concluded the loss was caused by a technical systems failure on board the AUV [20].

The Autosub programme is not alone in losing AUVs during under ice operations: Ocean Infinity lost AUV7, a Hugin AUV, during the search for Shackleton's *Endurance* in the Weddell

Sea [29], UBC *Gavia* was temporarily lost in Lake Kilpisjärvi in 2013 [30] and a WHOI Sea-Bed Class AUV had to be rescued by another robot while measuring under sea ice in Antarctica [31].

Autosub Long Range (ALR) deployed under the Filchner ice shelf (Mission 47) developed a fault with its rudder system 35 hours into a deployment, this resulted in the AUV conducting circles for 3.5 hours, before the rudder became unstuck and the AUV resumed its mission and was recovered successfully [23]. This fault was only identified following post processing of the mission data, if the fault had not rectified itself it is likely it would have led to the permanent loss of the ALR.

To manage these increased risks AUV control systems must include different contingency behaviours depending on mission phase and if ice is overhead, for example, the use of the abort weight should only be activated in open ocean [21].

C. Under Ice Navigation

Navigation is a key challenge for AUVs operating significant distances under ice, since many of the standard approaches utilised in open water are no longer practical [32]. In particular, regular surfacing for a GPS signal or acoustic aiding from a ship mounted USBL is not possible. The situation is complicated when operating in ice covered deep water where the AUV is unable to maintain DVL bottom lock with the seabed while the ice above is also moving [33], or when operating at very high latitudes where the horizontal component of the earth's magnetic field drops to less than 12% of the low-latitude value thus making the use of magnetic compasses unreliable [34]. As with open ocean operation, a range of navigation techniques have emerged to address the under ice navigation challenge.

D. Under Ice Collision Avoidance

Close-shaves in previous deployments have highlighted challenges for AUV control systems when operating under ice. The presence of the ice results in complex terrain both above and below the AUV. The need for collision avoidance was demonstrated by Autosub2 when operating under fast sea ice off North East Greenland for several ice thickness profiling missions [15]. Whilst returning from one 24 hour mission, the collision avoidance behaviour was triggered due to a limited headroom event caused by coincident ice ridges and shallow water depth. The AUV successfully negotiated the obstruction and returned to the nominal recovery location at 50 m depth. However, sea ice had blown over the recovery position and hence it was necessary to use the AUV homing system to shepherd the AUV to an ice clear area, where it could safely surface and be recovered on-board the RRS *James Clark Ross* [35].

On Autosub3's fourth under ice mission at Pine Island Glacier (Mission 431) [21] the AUV had been programmed to head towards the grounding line. As expected the AUV reached a minimum head room (distance between ice keel and seabed) condition and attempted to return to open ocean,

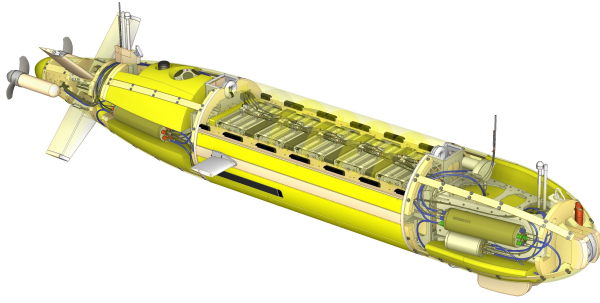


Fig. 2: Concept Design

in the process of which it ascended up into a deep fissure. In this instance, the obstacle avoidance strategy of retreat and try again that had worked well in the previous deployment in Greenland was not effective and a timeout event, which caused the AUV to dive, freed the AUV enabling it to travel the 70km to the recovery position.

III. AUTOSUB2KUI DESIGN

Rather than retrofitting an under ice capability, Autosub2KUI has been developed specifically for under ice and thus the design has been developed to address the challenges raised above. For Autosub2KUI, identified science applications require a 250km usable science mission range (excluding: initial in-water checks and de-risking, dive phases, recovery and any required contingency) with a 2000m depth rating and a core sensor fit comprising of Multi-Beam Echo Sounder (MBES), SideScan Sonar (SSS), Sub Bottom Profiler (SBP) and Conductivity Temperature & Depth (CTD) sensor.

Autosub2KUI is designed to be 5.8m long and weigh 25kN in air (shippable in a standard 20' container assembled). Externally she resembles Autosub6000 [36] though the mechanical, electrical and software systems have all been completely redesigned. However, like Autosub6000 she is designed to consist of three sections (see Figure 2):

- **Free Flooded Nose:** providing primary payload space. This area houses the forward control/payload tube, Seabird 9+ CTD, Norbit WBMS-bathy MBES, Norbit Obstacle Avoidance Sonar (OAS) and a large modular space for additional mission specific sensors. A homing system will be added at a later date.
- **Central Section:** with 2000m rated syntactic foam encasing pressure tolerant lithium polymer battery packs. At either end are the primary launch and recovery lift points. It also houses the transducers for the Edgetech 2205 SSS and SBP.
- **Free Flooded Tail:** housing the power tube, aft control/payload tube, navigation system, actuators and thrusters. The navigation system is based around a Sonardyne Sprint Nav 700 combined: 600kHz DVL, pressure sensor and INS system, with a second 600kHz DVL pointing upwards and a Sonardyne Avtrak providing acoustic communications and position aiding when available.

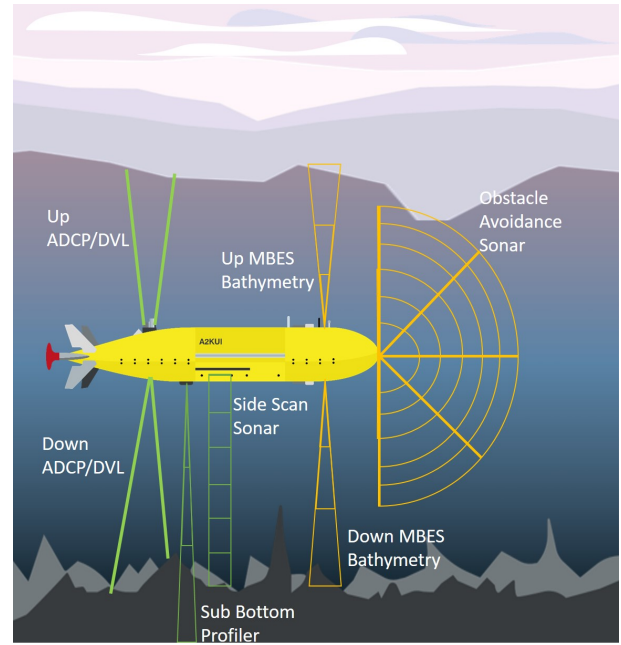


Fig. 3: Sensor Configuration

All systems apart from the syntactic foam are being developed for 6000m operation, enabling a deeper rated derivative to be built at a later date.

During normal operation, altitude from the seabed will be provided by the downwards facing DVL, distance to the ice above (upAltitude) will be provided by the upwards facing DVL and forward looking obstacle avoidance will be provided by a multi beam obstacle avoidance sonar (OAS) oriented in the vertical plane with a 180° field of view enabling it to see the ice above and seabed below, see Figure 3.

Like previous under ice Autosub vehicle configurations, Autosub2KUI is designed with both up and down facing ADCP/DVLs. This allows the AUV to navigate with respect to the seabed, underside of the ice or relative to the water column depending on the measurements available to the AUV. Depending on the local water depth and ice draft, it has previously been common for Autosub vehicles to undertake a truncated triangular profile inside the cavity with DVL bottom lock only during the deeper phases and top lock only during the shallower phases [23]. Therefore the ability to seamlessly transition between localisation modes is critical to maintain a good position estimate.

The DVLs will be coupled to a Sonardyne INS and pressure sensor. This combination provides the primary localisation solution for the AUV. In the event of failure of the primary navigation system the AUV will also be able to dead reckon using the pressure from the Seabird 9+ CTD, propeller rpm measurements and a MEMS IMU mounted in the forward payload tube.

A. System Design

AUVs developed for open ocean operation commonly have numerous single points of failure (e.g. single propulsor). While deemed acceptable for open ocean operations, this could lead to catastrophic loss while under ice. Following the loss of Autosub2, NOC engineers have been evolving the system design to reduce single points of failure and mitigate previously observed failures. Figures 4 and 5 illustrate the core architectures for Autosub6000 as an example open ocean AUV and Autosub2KUI which is being developed with a focus for under ice operation. The key differences:

- Autosub6000 has a distributed guidance, navigation and control GNC system built around LonWorks microprocessor nodes with no redundancy - Autosub2KUI's design includes two dedicated Guidance Navigation and Control (GNC) computers, a master in the rear payload tube and a secondary system in the forward payload tube. Each is directly connected to sufficient navigation sensors to generate a navigation solution.
- Autosub6000 has a single thruster - Autosub2KUI has been designed with twin thrusters each capable of providing sufficient thrust to ensure the AUV operates above its minimum speed.
- Autosub6000 has two pairs of control surfaces in a cruciform arrangement, failure of either of the two actuators will result in the AUV being unable to navigate - Autosub2KUI has been designed with four individual actuated control surfaces in an 'x' configuration and will thus be able to maintain control authority in vertical and horizontal planes in the event of a single actuator failure.

Mass, cost, volume and complexity considerations all point to it being typically infeasible to operate a fully dual redundant AUV for under ice operation. However, it is feasible to design an AUV that is robust to most common failures with an ability to still safely navigate out from under the ice in 'limp home mode'. For example, loss of Autosub2KUI's primary navigation system (Sonardyne SprintNav) will reduce navigational accuracy from $<0.04\%$ of distance travelled in a straight line to circa 20% when relying on the MEMS IMU, prop rpm and pressure from the CTD to provide a navigation solution.

B. Mechanical Design

The Autosub's national capability function to support the UK science community has resulted in the AUVs being adapted and extended to support an evolving set of science requirements. Recognised by the design team is a need to facilitate the installation of future and novel payloads. To facilitate this approach the nose and tail have been designed to provide large re-configurable free flooded spaces.

Unlike Autosub6000, which has a chassis based on aluminium extrusion that is subject to long term corrosion, Autosub2KUI's structure is designed around a machined titanium structure with additional polyethylene support, see Figure 6. The centre section has two lift frames which double as

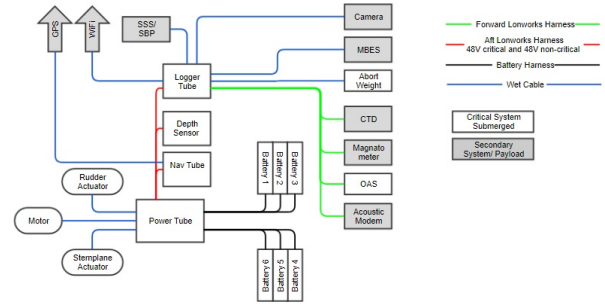


Fig. 4: Autosub6000 - Simplified core system architecture

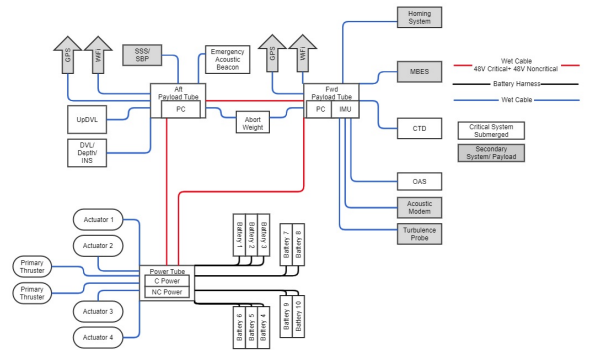


Fig. 5: Autosub2KUI - Simplified core system architecture

recovery line hoopers. These are linked by two titanium ladder sections. The structure has been developed to survive real world launch and recovery loads observed with Autosub6000. As such the structure has been designed so that lift is possible from a single lift point in a sea-state 6, well above the nominal recovery of sea-state 4.

To provide redundancy, the control surfaces will each be individually actuated and are arranged in an 'x' configuration, see Figure 7. The twin thrusters are variants of the magneti-

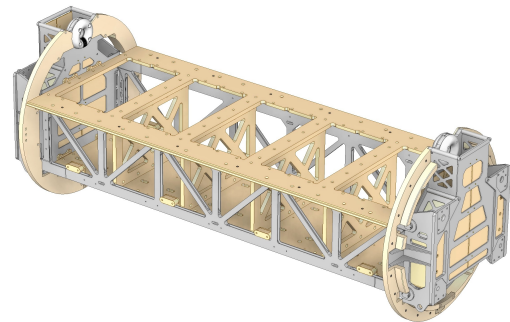


Fig. 6: Autosub2KUI chassis design

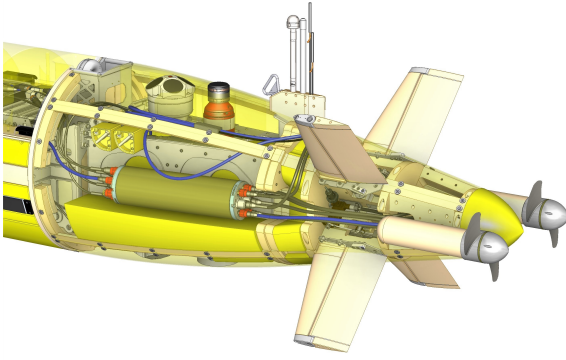


Fig. 7: View of Autosub2KUI's control planes and thrusters

cally coupled self contained thruster units developed by NOC for both ALR [37] and the Bridges underwater gliders [38]. A bespoke magnetic coupling has been designed to couple the torque from the thrusters to the bespoke two bladed propellers. The thrusters have been sized to provide the AUV with a maximum cruise speed of 1.6 m/s while also ensuring that the AUV can operate well above its minimum speed to maintain depth authority [39] with a single thruster in the event of a failure.

C. Electronic Design

1) *Pressure Tolerant Batteries:* For shallow rated AUVs, batteries and associated electronics are typically housed in pressure vessels which protect them from both (sea)water and hydrostatic pressure. However, as depth rating increases, the weight of pressure vessels increases; this restricts the mass budget available for a vehicle of a constrained size or results in more massive AUVs for the same capability. An alternative approach is the use of pressure tolerant battery technologies housed in a compliant non conducting medium [40]. Such an approach is widely used for very deep diving AUVs [36], [41], [42]; while Autosub2KUI is being initially designed for 2000m depth rating, all the systems except the syntactic foam are being designed for full ocean depth (6000m).

The Autosub2KUI batteries are based around Kokam 12Ah poach cells. 2P14S cells are arranged into a module with a bespoke BMS, four modules are arranged in parallel in each battery to provide 4.97kWh per battery at a nominal 51.8V and 49.7 kWhrs for the submarine. This compares to the 22.86 kWhrs installed in Autosub6000. Each module and battery will be manufactured by Steatite Ltd and go through UN38.3 testing, enabling the batteries to be shipped assembled.

To provide the compliant housing which transmits the hydrostatic pressure to the batteries while also providing protection from seawater, the batteries will be housed in bespoke polyethylene battery boxes.

2) *Core Tube Electronics:* To mitigate the risk of very large pressure vessels which would sink the AUV if flooded, the electronics are distributed into three core pressure vessels

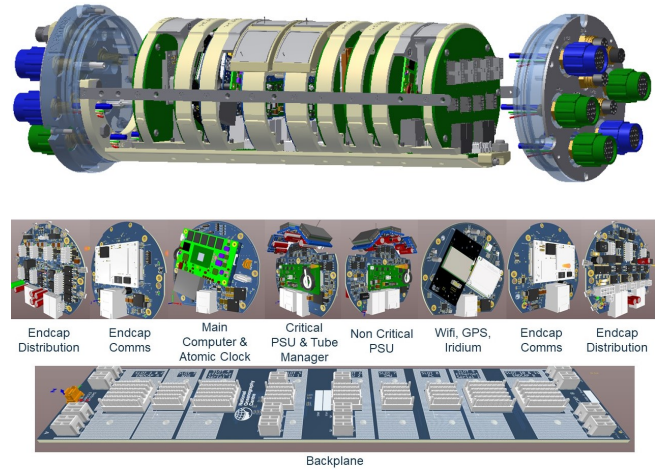


Fig. 8: Payload tube design

(Power, Aft Payload, Fwd Payload), with secondary pressure vessels for navigation and science sensors. All pressure vessels are limited to an internal floodable volume of $< 8L$ to ensure the abort weight is able to counter lost buoyancy due to a single pressure vessel failure.

The electronic design draws through lessons learnt from Autosub2 which were implemented on Autosub3, such as separation of critical and non critical power supplies [21]. Each tube will receive a short circuit protected raw battery feed of up to 1.5kW, within the tubes six 320W DC-DC converters providing critical and non-critical 12, 24 and 48V supplies. Within the core pressure vessels, the electronics have been designed around a common back-plane fitted with a series of individually replaceable daughter-cards (e.g. external comms board, PC board etc), see Figure 8.

Each tube will also be fitted with a tube manager micro-processor (SAM 4E) to manage low level functions including device power switching, device power monitoring, device triggering, and tube health (pressure, temperature, humidity, leak and ground fault).

Primary processing for Guidance, Navigation and Control (GNC) will be undertaken by two embedded PCs (Kontron COMe-mAL10(E2)) - one per payload tube. These PCs will communicate with the distributed devices via RS232, Ethernet(100Mb & 1Gb) and RS485. Flexibility is provided to add additional daughter cards including additional backseat computers.

Externally the single power tube is designed to connect to all the thrusters, actuators and batteries. Internally the tube is fully dual redundant with the batteries and thrusters split equally between the internal electronics. The Actuators are themselves dual redundant with each having two communications and power inputs allowing them to be connected to both sides of the power tube. To mitigate the risk of tubes flooding all the AUVs pressure vessels have been designed with dual o-rings and will be partially evacuated to create a partial vacuum, this seats the o-rings before they enter the water and prevents low pressure leaks.

For primary internal communications a looped Ethernet network enabled with Spanning Tree Protocol (STP) has been designed. STP manages the on board Ethernet network, re-directing the communications down the alternative path in the event of a wet cable failure.

3) *Standalone Devices*: In the event of a complete AUV power loss, the only remaining courses of action are to release the abort weight and make the vehicle as easy to find as possible. The abort is designed as a simple standalone system consisting of a reset-able count down timer, battery and weight release. If communications are lost with the main control system the abort timer continues to count down. Once the count down timer reaches zero the weight release mechanism is activated using the energy in its on-board battery.

The AUV is designed to carry stand alone location beacons with an operational life of >1year (transmission rate dependant). For subsea location finding as well the primary Sonardyne Avtrak an additional Marker 6 beacon will be fitted, along with a low frequency emergency beacon comparable to one fitted to Autosub2 [17]. For location finding on the surface, three conductivity activated Novatech light flashers and two Novatech iridium beacons will be fitted; they are spaced at opposite ends of the vehicle, since if a pressure vessel has flooded it is probable one end of the submarine will still be submerged preventing visual and satellite communication. Future work will involve adding a standalone AIS beacon.

D. On-board Control System

The NOC's Oceanids On-board Control System (OCS) project [43] is developing a unified software architecture for on-board control of the NOC developed Autosub vehicles. Already operational on both variants of Autosub Long Range, ALR6000 and ALR1500, the software is being extended for use with Autosub2KUI. The OCS represents a transition from a plethora of different legacy vehicle software architectures (e.g. Autosub6000 LonWorks [36], ALR6000 WinCE) to a modern distributed architecture based on the Robot Operating System (ROS) [44]. The primary GNC computers both run Debian 9 and ROS Melodic.

The software architecture is evolving from that used on ALR1500 with additional modifications to manage the alternative control planes and thrusters configuration as well as under ice considerations.

1) *Supervisory Level*: The mission executive starts, co-ordinates, oversees and controls the execution of missions throughout a deployment. It listens to the safety notifications from the NOCS Health Service and instigates a contingency behaviour if any abnormality is observed. The mission executive is implemented through Behaviour Trees [45] and is able to receive new mission scripts in the form of mission tracks (waypoints) and translate these into primitive vehicle control demands (heading, speed, depth).

The structure of the Behaviour Tree and therefore the behaviour of the vehicle is entirely configurable from an eXtensible Markup Language (XML) file so it can be easily

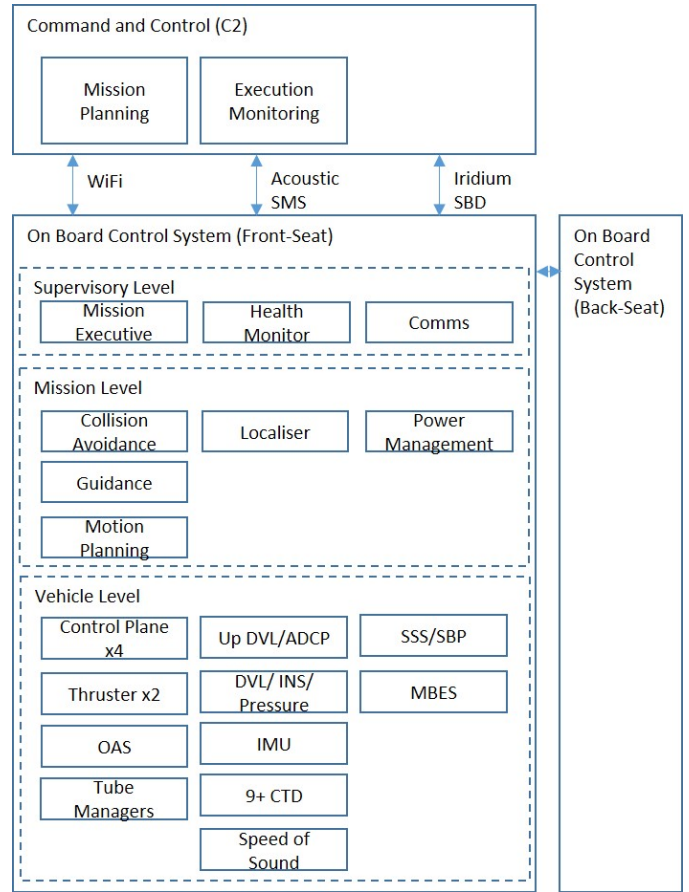


Fig. 9: Simplified control systems basic block diagram

configured for each specific vehicle and deployment without the need to rebuild any code.

For operation under ice, additional contingency behaviours are required beyond the standard stop, surface and abort used previously for ALR1500 in open ocean [46], for example the ability of the AUV to retreat to a safe recovery location or to follow a trail of 'breadcrumbs' for rendezvous with a support vessel. The health monitoring system ensures the AUV is operating within normal bounds and is able to trigger contingency behaviours.

2) *Mission Level*: Collision avoidance, guidance, motion planning and localisation are all managed by the mission level. Collision avoidance is considered in both a reactive and deliberative sense [47], modifying the mission executive's demands to maintain the vehicle safety during the planned mission or providing alternative paths to the goal should the original one be deemed unsafe. Tracks and depth demands are output to the guidance layer, which converts them into velocity and attitude demands managed by the motion controller.

3) *Vehicle Level*: The interface to actuators and sensors is managed in the vehicle level. This includes both low-level routines used to establish communication with hardware devices and transmit data exploiting different communication protocols (such as serial or Ethernet) and the methods required

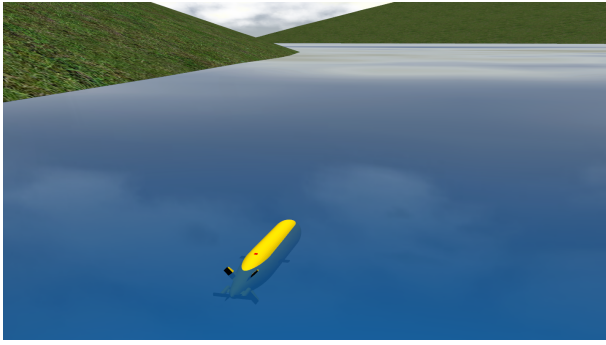


Fig. 10: UUV Simulation visualisation of an Autosub2KUI mission

to parse the data streams received from such devices into useful information which is then passed to the other components of the system.

IV. AUTOSUB PERFORMANCE COMPARISON

Work is ongoing to benchmark the performance of Autosub2KUI in simulation using the Unmanned Underwater Vehicle (UUV) simulation with Gazebo [48], see Figure 10. Autosub2KUI has been developed for high power multi-day under ice exploration, how this capability maps to the rest of the Autosub family of AUVs is illustrated in Table I.

V. CONCLUSIONS

The Autosub2KUI vehicle is being developed as a significant evolution of the previous work class Autosub vehicles; sharing a number of broad design concepts but significantly redesigned and upgraded for under ice operation. By designing for under ice operation from the outset additional redundancy has been incorporated into the design to enable the AUV to safely navigate in the event of common failure modes. The software architecture has been adapted to manage the additional redundancy and to provide suitable contingency behaviours to enable under ice operation.

Assembly of the vehicle is underway at the NOC and initial in water trial activities are planned for 2021. Once fully operational Autosub2KUI will join a small number of large AUVs available to the science community for high power under ice exploration. Furthermore the core modular technologies developed are being utilised for additional forthcoming Autosub vehicles.

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TABLE I: AUTOSUB MODEL PERFORMANCE COMPARISON

Parameter	Autosub3 [21]	ALR1500 [49]	ALR6000 [37], [50]	Autosub6000 [36]	Autosub2KUI
Dry Weight (kN)	24	0.7	0.7	18	20
Displaced Volume (m^3)	3.6	1.3	1.3	2.8	2.8
Length (m)	7	3.7	3.7	5.8	5.8
Depth rating (m)	1600	1500	6000	6000	2000/6000
Typical Endurance	80 hrs	6 months ¹	2 months ¹	24 hrs	52 hrs
Typical Range (km)	400	4000 ¹	1800 ¹	180	300
Navigation Sensors	Phins INS RDI 150kHz (down) RDI 300kHz (up) DigiQuarz pres.	PNI TCM XB RDI 300kHz ADCP CTD (SBE 52-MP)	PNI TCM XB Nortek 500kHz ADCP CTD (SBE 52-MP)	Phins INS RDI 300 kHz ADCP DigiQuarz pres.	SprintNAV 700 Syrinx DVL (up) CTD (SBE 9+)
Nav. Accuracy ²	0.1%	1%	1%	0.1%	< 0.04%
Typical Payload	CTD/ADCP/SSS SBP/MBES	CTD/ADCP	CTD/ADCP	CTD/ADCP/SSS/SBP MBES/Cameras	CTD/ADCP/SSS SBP/MBES
Applications	High power under ice exploration	Mid water basin crossings	Long endurance deep water science	Deep water benthic survey	High power under ice exploration

¹maximum range with minimum sensor fit²straight line navigational accuracy in DVL bottom lock range

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