Agile Design of Low-Cost Autonomous Underwater Vehicles

Alexander B. Phillips, Naomi Gold, Nick Linton
Catherine A. Harris, Ella Richards,
Robert Templeton, and Sebastian Thuné
Marine Autonomous and Robotic Systems
National Oceanography Centre
Southampton, UK
Email: abp@noc.ac.uk

Jeremy Sitbon, Marcus Muller,
Iain Vincent and Terry Sloane
Planet Ocean Ltd
Camberley, UK

***Abstract*—The capital cost of autonomous underwater vehicles (AUVs) is still prohibitive for wide spread mass adoption. To address this, the ecoSUB programme is developing small low-cost reusable AUVs designed to minimize platform cost while acquiring measurements of essential physical and biogeochemistry ocean variables for scientific or industrial applications. This paper describes: the agile design methodology adopted for the ecoSUBμ5 development, presents results from initial trials and reflects on the advantages and disadvantages of utilising iterative development when compared to a more conventional waterfall design process.**

I. Introduction

Autonomous underwater vehicles (AUVs) are now routinely used for a wide range of applications: from pipeline tracking within the oil and gas industry; to operating under-ice, collecting scientific data to inform climate change models. The current generation of AUVs are typically operated individually [1] or in very small numbers due to their high capital cost and significant operational costs.

The ecoSUB programme is exploring new operational paradigms involving large fleets of very low-cost minro AUVs (the target cost per vehicle is up to two orders of magnitude below that of conventional AUVs). The ecoSUB family of vehicles is currently undergoing development and consists of multiple AUV models with varying size, capabilities and payloads. In this paper, we focus on the ecoSUBμ5, the original vehicle within the ecoSUB project. The goal is to investigate the effective and economic use of this technology to make ocean measurements on very large 3D scales in meaningful time-frames to enable a rapid response to large evolving ocean phenomena, such as oil spills or harmful algal blooms. While other micro AUVs are approaching market readiness: e.g. Vertex [2] Riptide [3], the ecoSUBμ5 is focussed on over the horizon operation. This concept of operation evolved from a previous feasibility study conducted at the National Oceanography Centre (NOC) to develop low-cost air-launched AUVs [4]. However, within the current ecoSUB project, this concept has been extended to consider launch from small boats, Unmanned Surface Vessels (USVs), planes, helicopters and Unmanned Aerial Vehicles (UAVs).

The target price of an ecoSUBμ5 is over an order of magnitude less than a commercial underwater glider and two orders of magnitude less than a large work-class AUV. Such vehicles have the potential to radically reduce the cost per data point, enable high risk deployments which would be inappropriate with larger vehicles or enable deployments of large fleets to survey and triage large spatial areas. However, there is an element of expectation management, as a low-cost navigation suite will not have the navigational accuracy of a work-class AUV equipped with a high-precision inertial navigation system; and a small propelled vehicle will not have the endurance of an underwater glider. Yet, working with commercial and science end-users, it is apparent that there is an appetite for low-cost platforms for: triaging large areas of ocean, thus enabling a subsequent targeted deployment of higher-cost assets; or for high risk deployments.

When working at this scale, the comparatively low-cost of mechanical and electrical components, coupled with 3D printing technologies, enabled the design team to adopt an implementation of the agile design methodology. This is in contrast to the conventional waterfall development process which has previously been adopted by the Marine and Autonomous Robotic Systems (MARS) groups at the NOC for the development of the Autosub family of AUVs [5], [6] as well as other vehicles developed by the team [7].

This paper describes the development process adopted for the ecoSUBμ5. Section II describes the product and initial requirements. Section III describes the development process, discusses the agile sprints, the evolution of the platform and initial results from field trials. Section IV presents initial conclusions from the ecoSUB programme and reflects on the agile methodology adopted for their development.

II. Product

Design of the ecoSUBμ5 vehicle was informed by close consultation with eventual users, from both science and industry, who identified key design features which the eventual AUV should have. Since, the central concept of the ecoSUB programme has been the ability to rapidly launch the AUVs from a variety of host platforms including USVs, an

assessment of potential launch vehicle payload capacity and associated launcher constraints produced the following AUV design constraints:

- Length overall including antenna must not exceed 917mm and a diameter of 120mm (dimensions of a Sonarbuoy A), to permit launch from existing aircraft mechanisms.
- Mass of less than 5kg (payload capacity of suitable UAV launch platform [8].

Potential science users envisaged a flexible vehicle capable of undertaking a range of missions including conventional applications such as biogeomchemistry measurements on the shelf in either the horizontal or vertical plane (reusable XBT profiles), through to more ambitious applications such as aerial launch for rapid response monitoring of oil spills or accessing polynyas in the ice. Consequently the following product features or requirements:

- Depth rating of 500m to enable operation throughout the water column in shelf seas.
- Endurance in excess of 24 hours.
- Flexible payload capability.
- Speed in excess of 0.5m/s.
- Over the horizon operation.
- Flexible payload with support for a Conductivity and Temperature (CT) sensor as a minumum.

III. Agile Development Cycle

Development has been conducted using a series of sprint cycles or iterations, illustrated as black arrows in Figure 1. Each sprint was intended to last three months, but in practice lasted 4 months due to lead times of externally manufactured components. Each sprint started with a set of features taken from the product backlog for that iteration, a plan was then formulated, the vehicle designed using CAD, before being built, tested and the functionality reviewed.

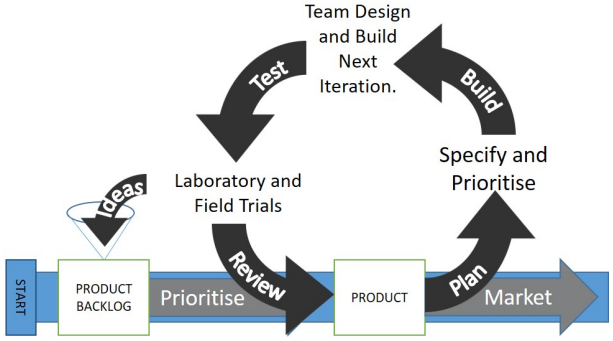


Fig. 1: Schematic showing the agile development cycle adopted.

In general, design work was conducted in month one, manufacturing in months two and three with vehicle assembly and testing in month four. However, this was adapted to suit the development needs of individual components of the system, with software testing taking place alongside software development. Each sprint-cycle resulted in incremental and measurable increases in performance.

The core development team comprised of a mechanical engineer, a software engineer and an electronic engineer with support and mentorship from engineers within the NOC's MARS group. The core development group was housed internally within the NOC building, allowing close daily collaboration with the MARS mentors. Informal scrum-style meetings were held weekly to ensure the entire team was kept informed of progress and appreciated the implications of design decisions on all aspects of the vehicle. This is especially important within the field of AUV development as all aspects of a design are heavily interdependent and interactions can have significant consequences for the overall performance and endurance of the vehicle. At the end of each sprint the design, functionality and test results were presented to the project stakeholders and reviewed, allowing the designs to be evaluated and requirements to be updated in response to changing science and industry drivers.

The design of the ecoSUBμ5, see Figure 2, consists of a cylindrical pressure vessel with free-flooding hydrodynamic fairings for the nose and tail as well as a trailing antenna to maintain a cylinder profile and satisfy the design constraints for ease of launch, discussed in section II. To both raise the antenna, and enable pitch/depth control the vehicle is equipped with a moving-mass mechanism which shifts the longitudinal centre of mass and therefore alters the pitch angle adopted by the vehicle. This enables the AUV to pitch almost vertically nose-down, raising the antenna out of the water.

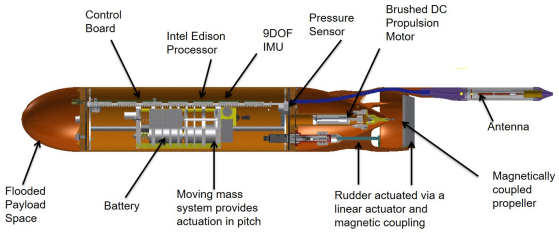


Fig. 2: Schematic of the ecoSUBμ5 platform (Iteration 2)

Figure 3 illustrates the mechanical and electrical components of an ecoSUBμ5. The colour coding indicates which sprint each item was first considered. Green indicates sprint 1, orange indicates sprint 2, blue indicates sprint 3 and yellow is forthcoming in sprint 4. Items developed in the earlier sprints have been refined based on empirical observations.

The command and control system developed for the vehicle is running on an Intel Edison processor using the ubilinux 2.0 operating system. Software is created using the Robot Operating System (ROS) middleware framework [9] using the Indigo release. The software architecture is illustrated in Figure 4. Onboard the vehicle is a three-layered architecture consisting of: a hardware interface layer; a hardware abstraction layer, responsible for low level control and localization; and a mission executive, consisting of a reconfigurable SMACH state machine [10] which allows complex missions to be constructed from simple building block behaviours.

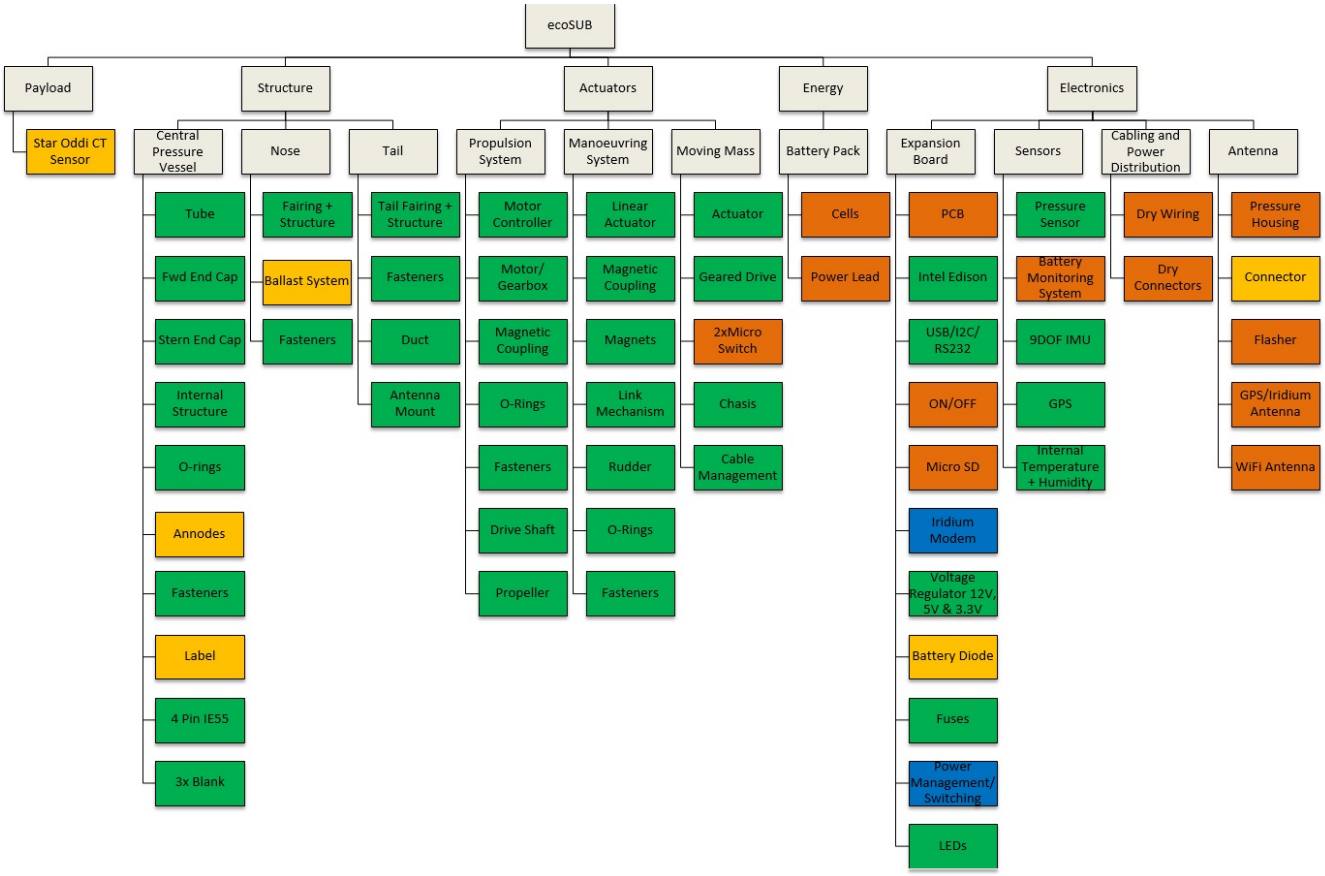


Fig. 3: ecoSUB system tree. Colour coding represents the first sprint in which the design of the component was first developed. Green indicates sprint 1, orange indicates sprint 2, blue indicates sprint 3 and yellow is forthcoming in sprint 4.

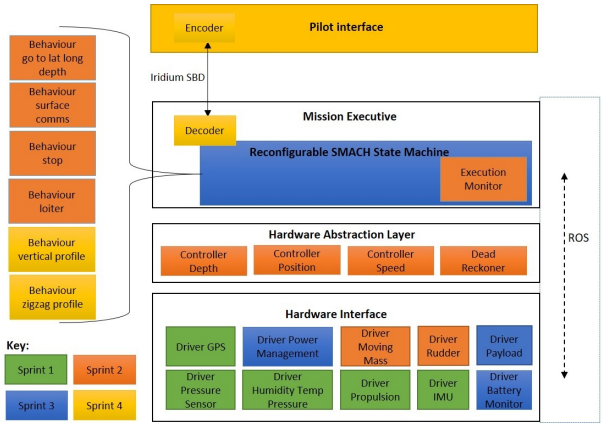


Fig. 4: Block diagram showing the constituent components of the ecoSUB software architecture.

Due to long manufacturing lead times, the design and manufacture of the central watertight pressure vessel, containing the electronics and batteries became the critical-path activity for each of the sprints. The significant operating depth requirement of the vehicle precluded the use of rapid prototyped components for the pressure-resisting components.

A. *Sprint 1*

The initial air-launched AUV study [4] provided a conceptual starting point for the vehicle and the resulting cylinder constraint for launch quickly drives many of the design decisions. The initial air-launched study had highlighted a number of potential issues with the micro AUV concept:

- Achieving suitable control authority using control surfaces within the maximum permitted vehicle diameter given the cylinder rule constraint.
- Ensuring sufficient on-board batteries to provide a meaningful range and endurance given the identified scientific and industrial use-cases.
- Ensuring the antenna is able to be raised sufficiently out of the water to receive GPS and receive/transmit wireless communication.

The first iteration, see Figure 5, was a non-functioning space model exploring the actuation options. This space-model also proved the mircoAUV concept and validated the feasibility of adhering to the cylinder rule. During this iteration, initial weight and buoyancy estimates were refined, enabling a more accurate estimation of the range of the eventual vehicle. The space-model made use of in-house rapid prototyping facilities, including a laser cutting machine and a fused deposition model

(FDM) 3D printer.

For the final vehicle, the pressure vessel is a key functional component, contributing approximately 33% of the vehicles in air mass. Consequently an iteration 1 aluminium pressure vessel was also manufactured. Destructive tests on the prototype pressure vessel conducted at the National Oceanography Centre's pressure pot facility failed at $10MPa$ $(1000m)$ through three node buckling, see Figure 6.

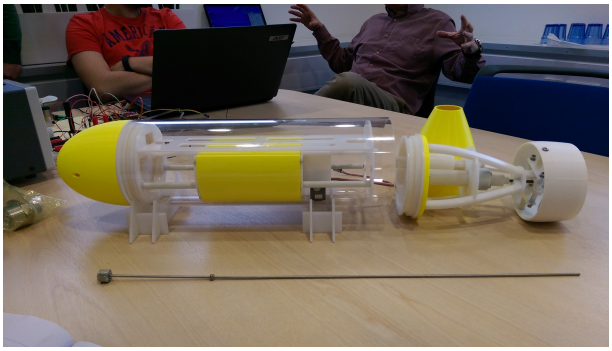


Fig. 5: Iteration 1 vehicle using a representative perspex pressure vessel.



Fig. 6: Destructive testing of the initial pressure vessel design. Failure occurred at 1000m, two times the maximum operational service depth.

B. Sprint 2

The second sprint built on understanding gained from the first sprint with the goal of developing a complete waterproof prototype. For this iteration the following features were prioritised:

- Development of the ecoSUB control electronics.
- Development of the onboard control system software to enable basic operation.
- Implementation of Wi-Fi mission uploads and data downloads.
- Actuation in pitch, yaw and surge.
- Battery pack design.
- Navigation sensors integrated (GPS, pressure sensor, MEMS IMU).

The resulting vehicle is illustrated in Figure 7. The functioning platform further proved the concepts and was able to conduct basic functionality, including forwards motion, diving, Wi-Fi communications and heading change. However from a mechanical perspective there were reliability issues. The propulsion system initially lacked robustness due to the length of the propeller shaft, an issue that was rapidly addressed by the development of a iteration 2.5 propulsion system. The moving-mass mechanism proved to lack robustness due to the reliance on laser cut Delrin and FDM-printed parts. However, due to time constraints it was decided to leave resolving this issue until the next sprint.

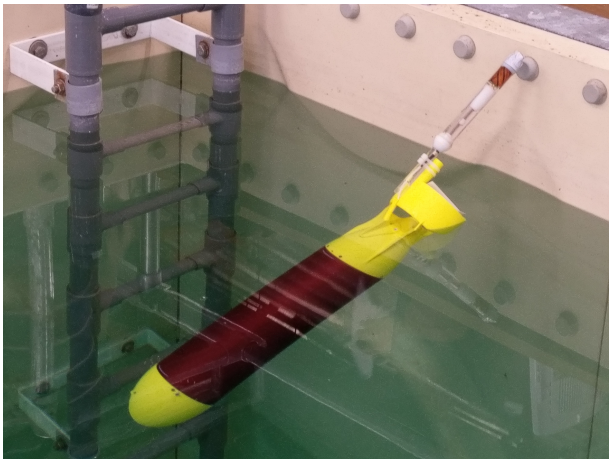


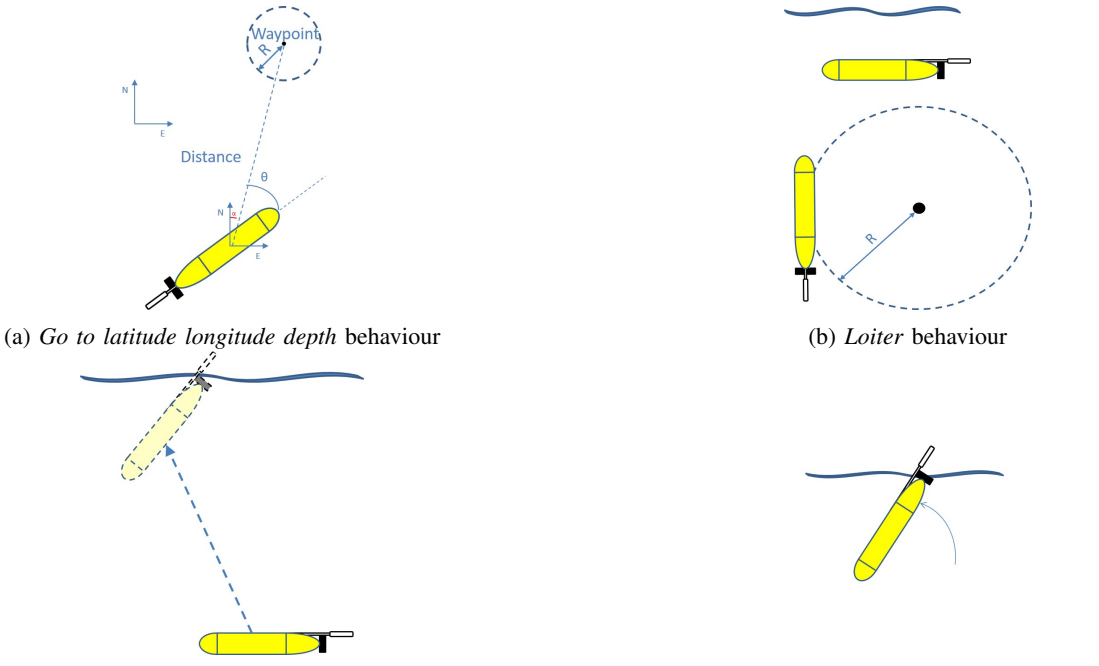
Fig. 7: Iteration 2 vehicle.

The software development for sprint 2, highlighted in orange in Figure 4 continued in spite of challenges with the mechanical system. The use of a basic simulation environment enabled the development and testing of the vehicle behaviours and controllers whilst the physical hardware was unavailable

1) Iteration 2 Vehicle Behaviours: Within the ROS middleware, the SMACH Python library [10] provides a flexible framework for the creation of nested state machines. The vehicle software utilises this approach to build complex missions from smaller building-block behaviours. Using the simulation, the following behaviours where developed:

- *Go to latitude longitude depth* - uses a line of sight approach to navigate to a given waypoint, see Figure 8a
- *Loiter* -the vehicle will float to the surface if the propulsion power is switched off. Consequently, to loiter at a depth it must circle a waypoint, see Figure 8b.
- *Stop* - stop all actuators and rise to the surface as an effect of the vehicles net positive buoyancy. Then enter a communication session, see Figure 8c.
- *Communication Session* - tail up GPS, Wi-Fi and Iridium turned on, see Figure 8d

2) Iteration 2 Vehicle Controllers: There are three independent controllers that control the vehicles three actuators. Each controller is implemented as a stand alone ROS node.



(a) *Go to latitude longitude depth* behaviour

(b) *Loiter* behaviour

(c) *Stop* behaviour

(d) *Communication Session* behaviour.

Fig. 8: Standard behaviours available on ecoSUB Iteration 2.

Each controller can operate in several modes allowing greater command flexibility.

- horizontal position - heading - rudder angle
- speed - rpm - propeller setpoint
- depth - pitch - moving mass position

The system block diagram for the depth controller is illustrated in Figure 9. A cascaded configuration is used. In the first stage, a PI controller is used to derive a pitch demand from the depth error. The pitch demand is limited to minimum and maximum limits and is then used as the input to a PD pitch controller which in turn outputs a moving mass position demand. The mode of the depth controller can be modified to insert a depth, pitch or moving mass demand depending on the mission phase and required behaviour. For horizontal flight, the depth demand is utilised; for vertical or saw tooth profiling the pitch demand is utilised; and for communication sessions, the moving mass position demand is utilised to achieve the maximum nose-down pitch angle to ensure the antenna is lifted clear of the water surface.

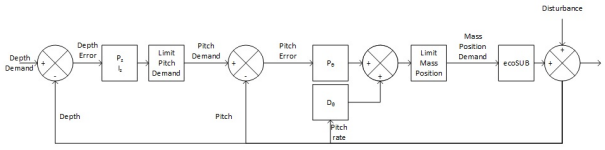


Fig. 9: System block diagram for the depth controller.

C. Sprint 3

The third sprint prioritised the development of a rugged system to maximum in-water testing time. Consequently the following features were prioritised:

- Ruggedisation of the moving-mass mechanism
- Refinement of all plastic parts, redesigning for manufacture using nylon Selective Laser Sintered (SLS) instead of fused deposition modelling.
- Reducing structural weight to enhance battery carrying capacity wile maintaining weight buoyancy balance.
- Implementation of satellite communication via Iridium Short Burst Data messaging, to facilitate over the horizon operation.
- Refinement of the manoeuvring system.

The resulting iteration 3 vehicle is shown in Figure 10. The moving mass system from iteration 2 was completely redesigned using a linear actuator rather than a small radio control servo. This change was incorporated as part of a whole-scale redesign of the internal structure to take advantage of SLS manufacturing. Which enabled significant reductions in the weight of the mechanical structure, see Figure 11, thus increasing the available mass for batteries



Fig. 10: Iteration 3 vehicle testing at Vobster Quay, Somerset.

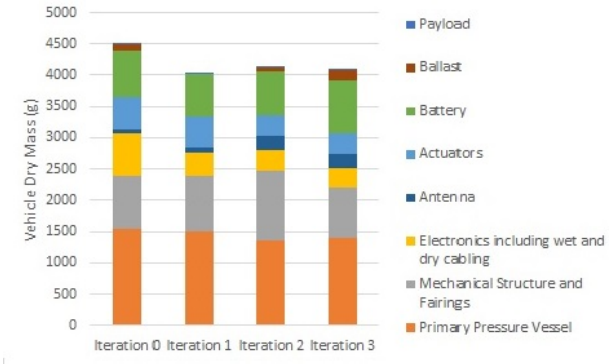


Fig. 11: Mass distribution for each iteration.

D. Field Trials

The ecoSUBμ5 iteration 3 vehicle has been deployed for preliminary engineering trials at Vobster Quay in Somerset. This flooded inland quarry is approximately rectangular with a length of 430m, a width of 140m and a maximum depth of around 40m, providing a safe known environment for initial testing.

1) Horizontal Navigation Performance: While on the surface with the antenna raised the vehicle localises using GPS. Once the antenna is in the water the vehicle navigates using dead reckoning (integrate speed and heading measurements to estimate position). The ability of the AUV to navigate between waypoints is illustrated in Figure 12. The vehicle starts at the south of the Figure; and then transits to waypoint 1 (SE Waypoint), the vehicle surfaces for a GPS fix; then transits North to waypoint 2 (NE waypoint); East to waypoint 3 (NW waypoint); South to waypoint 4 (SW waypoint); and finally back to waypoint 1, completing a 40m x 40m square. The vehicle considers itself to have successfully reached a waypoint, if its estimated range to the waypoint is under 5m. At each waypoint the vehicle surfaces and acquires a GPS fix; this is the cause of the discontinuities in the plots which reflect dead reckoning error.

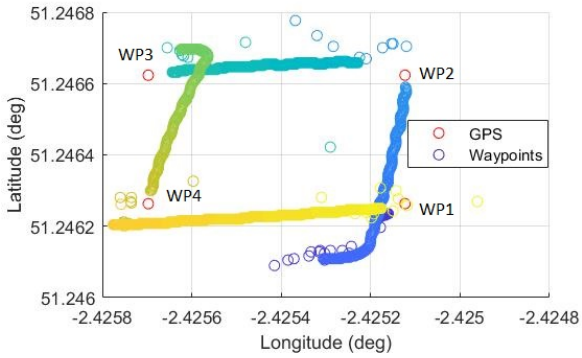
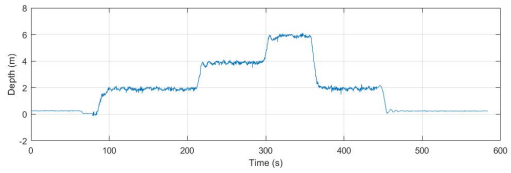
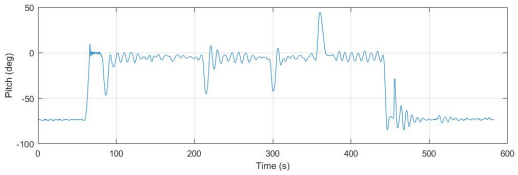


Fig. 12: Waypoint navigation for the ecoSUBμ5.

2) Vertical Performance: Figure 13 illustrates indicative performance of the depth and controller during a single dive given a series of depth demands corresponding to 2m, 4m, 6m and 2m. Steady-state depth error is of the order of 0.05m. Figure 13b illustrates the pitch adopted by the vehicle during the dive. A negative pitch angle corresponds to a nose-down pitch while a positive pitch angle corresponds to a nose-up pitch. To achieve level flight at $0.75m/s$ the vehicle adopts a nose down pitch angle of approximately -5^o to enable the vehicle to overcome the positive buoyancy associated with submerging the antenna. The large negative pitch angles at the start and end of the mission correspond to the communication behaviour.



(a) Depth control given a series of sequential increments in depth demand.



(b) Pitch angle corresponding to the series of depth demands in (a), positive pitch corresponds to nose-up orientation.

Fig. 13: Performance of the cascaded depth/pitch controller.

E. Sprint 4 - Underway

The current sprint is concentrating on design of a viable production vehicle. Consequently this final sprint is focussing on the following tasks:

- Integration of prospective payloads, e.g. conductivity and temperature sensor (CT).
- Commericalisation - price reduction through economies of scale and design ofr manufacture

- Software re-factoring for reliability and ease of use.
- Upgrade of the IMU sensor and calibration of the dead reckoning system.
- Utilisation of alternative battery technologies to enhance range and endurance.
- Development of more complex behaviours such as glider style profiling and operation as a virtual-mooring.
- Demonstration of over the horizon operation using satellite communications for mission upload and data download.

This iteration will go through rigorous in-water trials including over the horizon operation in deep water.

IV. Conclusion

Development of low-cost platforms allows engineers the freedom to experiment with alternative development approaches, which would not be feasible process for larger marine autonomous systems with their high capital cost and complex machined parts. The low-cost AUV described in this paper, the ecoSUBμ5, is $680mm$ long (excluding the antenna) and has a dry mass of approximately 4kg. It has been designed for a maximum operating depth of $500m$ with a multi-day endurance. Satellite communications will enable over the horizon operation for while ongoing work will: enable launch and recovery from larger unmanned assets such as USVs or UAVs; and the integration of additional payloads; extending their concept of operations.

The agile approach described in this paper has provided a successful framework for the development of new very low-cost AUV platforms. The iterative nature of the design methodology has allowed the development team to learn and enhance the design through initial testing and stakeholder feedback.

This project has moved from a blank piece of paper, to production of a commercial system with a primary development team of 3.5 engineers in 18 months using 4 sprint cycles. However, the agile development methodology has presented challenges, primarily around aligning the sprints for the disparate and highly interconnected disciplines (mechanical, software and electronics) which by nature have different modes of working and production time-scales. The long lead-time associated with some of the machined metal parts which dominated the schedule and elongated the length of each sprint beyond the initially planned three months.

Acknowledgments

This work was funded by Innovate UK under their Marine Autonomous Systems Collaborative Research and Development Call. Project 'Launch & Recovery of Multiple AUVs from an USV', project Number 102302.

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