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222: 53
DOI: 10.1243/14750902JEME81

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What is This?
Autonomous underwater vehicle collision avoidance for under-ice exploration

M Pebody
Underwater Systems Laboratory, National Marine Facilities, National Oceanography Centre Southampton, European Way, Southampton, SO14 3ZH, UK. email: m.pebody@noc.soton.ac.uk

The manuscript was received on 6 February 2007 and was accepted after revision for publication on 18 July 2007.

DOI: 10.1243/14750902JEME81

Abstract: On 22 August 2004 the Autosub-2 autonomous underwater vehicle (AUV) was on its return leg of a 144 km, 24 h under-ice mission in the Arctic sea over the Northwind Shoal off the northeast Greenland coast when it found its path blocked by a deep ice keel that had drifted across its planned mission route. After three attempts, the Autosub found a way around the keel and continued on its way to rendezvous with its mother ship. This paper reports the development, testing, and operation of collision and obstacle avoidance techniques used in the Arctic and Antarctic under-ice expeditions of the Autosub-2 AUV.

Keywords: autonomous underwater vehicle, underwater robotics, collision avoidance, obstacle avoidance, underwater navigation

1 INTRODUCTION

The autonomous underwater vehicle (AUV) Autosub has been designed, built, and operated by the National Oceanography Centre, Southampton. In 2001, after 3 years and 300 missions covering 2000 km for the oceanographic science community, a new programme of development was initiated to support a series of long-duration under-ice deployments in both the Arctic and the Antarctic. One of the main features of the Autosub upgrade was the adaptation of the vehicle’s systems to provide collision and obstacle avoidance. This included, among other measures, the addition of control behaviours to the command control and mission management system. This paper details a systems-oriented approach to collision and obstacle avoidance.

A brief description of the control system and operations of the pre-2000 Autosub-1 vehicle follows in section 2. Section 3 then provides an overview of the Autosub under-ice science programme and the under-ice operating environment. This is followed by a breakdown of the integration of a collision and obstacle avoidance control strategy into the existing Autosub-1 vehicle in section 4. Section 5 describes the sea trials and operational use of the new control behaviours in the upgraded Autosub-2 AUV. Section 6 concludes with a discussion of the outstanding issues and topics of further development.

2 AUTOSUB-1

Autosub is a relatively large flight-class AUV designed to provide a long-range long-duration oceanographic survey capability. The vehicle is 7 m long and 1 m in diameter and displaces of the order of 3.5 t. Power is supplied from a pack of primary alkaline cells with a capacity of 60 kW h. Propulsion is from a 650 W brushless d.c. motor. A typical range is of the order of 650 km depending on the payload power requirements, the payload drag, and the maintenance of 380 W propulsion power (a typical cruising speed at this power is of the order of 1.5 m/s). At low speeds, ranges in excess of 700 km have been demonstrated. The vehicle attitude is effected by two pairs of control surfaces: stern plane and rudder, which function over a water speed range of 1–2.2 m/s. This form is shown in Fig. 1. The Autosub command control and mission management system is implemented on a distributed Lonworks network [1] of 12 processor nodes with additional processors being added as needed for varying sensor payloads. More details of the basic Autosub control can be found in references [2] and [3].
2.1 Navigation

Autosub-1 navigation was by global positioning system (GPS) initialized dead reckoning. Velocity information was provided by an RDI 300 kHz ‘workhorse navigator’ acoustic doppler current profiler (ADCP) with seabed tracking [4, 5] up to an altitude of 250 m. Vehicle attitude information was supplied by a Kongsburg Seatex MRU6 attitude sensor [6] that incorporated a fluxgate compass.

When on the surface, the vehicle navigated with GPS position information and, when submerged, navigation was by dead reckoning. During the course of a mission the vehicle usually surfaced to reset the navigational errors acquired during the dead reckoning with a GPS position fix. While dead reckoning, and with ADCP ground speed information, the navigation of the Autosub-1 vehicle accumulated an error of typically 2 per cent of distance travelled. Consequently more accurate navigation required more frequent surfacing for GPS position fixes.

2.2 Rudder control

When the AUV is under way, the effect of the rudder is to change the heading of the vehicle. An altering rudder angle will provide a turning momentum around the vehicle’s centre of gravity. The vehicle control utilizes a multi-stage cascade design (Fig. 2) using proportional plus derivative (PD) control loops to effect the heading of the vehicle. The turning radius of the vehicle is of the order of 20 m.

The rudder control of the Autosub-1 vehicle takes commands from the vehicles mission control and operates in one of three modes: actuator angle; vehicle heading; vehicle position and vehicle track. The navigation sensory input is taken from sensors via the vehicle’s Lonworks control data network [3] and includes position, heading, and turn rate data from the GPS receiver, ADCP, and MRU6. At the lowest level of the control cascade, safety limits are applied to the actuator angle limits control output.

2.3 Stern-plane control

When the AUV is under way, the effect of the stern plane is to change the pitch of the vehicle. An altering stern-plane angle will provide a turning momentum around the vehicle’s centre of gravity. The vehicle control utilizes a two-stage cascade design using PD control loops to affect the pitch of the vehicle (see Fig. 2).

The stern-plane control of the vehicle takes commands from the vehicle’s mission control and operates in one of three modes: actuator angle; vehicle depth; vehicle altitude. At each level of the control cascade, safety limits are applied to the control outputs, namely the angle limits, pitch limits, depth limits, and altitude limits. Pitch rate data from the MRU6 are used for all modes of control. In depth control, mode sensory inputs are taken from a Digiquartz 4000m pressure sensor [7]. The altitude control uses a combination of inputs from the ADCP with a maximum range of 250 m and a forward-looking Simrad Mesotech 200 kHz echo sounder which has a maximum range of 75 m (see Fig. 1).
2.4 Mission control

Autosub missions are specified in a text script format using event triggers, waypoint defined tracks, and either depth or altitude demands [8]. The text is translated into a binary format and uploaded to the vehicle for execution by the vehicle’s mission control subsystem. As an example, a mission element might trigger on a ‘got position’ event and specify a new track consisting of two waypoints in latitude and longitude. This system may be regarded as the lower two levels of the standard three-layer control architecture presented in reference [9].

2.5 Collision avoidance

Autosub was originally designed to fulfill an open-water oceanographic survey role. In this mode of operation the main obstacle that poses a threat is the seabed terrain itself. Other hazards such as surface vessels and coastal features were managed by careful mission planning and operational procedures. In an effort to reduce control complexity the strategy to deal with detected bottom features was simply to provide a mission specific ‘minimum altitude’ limit that overrode all depth- and altitude-based control actions. When in altitude-limited mode, the maximum upwards pitch of the vehicle was increased and PD control coefficients switched to a more reactive setting.

The detection of altitude consisted of a combination of the two forward beams of the vehicle’s ADCP and the forward-looking range sensor angled down at 30° to horizontal. The forward range was scaled by a mission configurable parameter $K$ to allow for tuning of the vehicle’s response to the forward range sensor. The two data sources were combined according to

$$\text{MinimumAltitude} = \text{Least}_\text{of} (\text{ADCP \ Range}, (\text{echo\_sounder\_range} \times K))$$

The different terrains encountered during the variety of mission types undertaken by the Autosub-1 vehicle were accommodated to some degree by tuning the stern-plane control PD terms to make the vehicle more or less responsive to perturbations. The trade-off was a compromise in straight and level flight stability. Limited under-ice missions in the Antarctic were undertaken and involved careful planning and specification of safe working mission depths. However, other work in the Mediterranean in 2000 caused the vehicle to become stuck under an overhanging cliff [10], demonstrating the shortfalls of this avoidance implementation.

3 UNDER-ICE OPERATIONS

3.1 The environment

The concept of the Autosub under-ice mission series was to explore the marine environment beneath sea ice and the floating continental ice in the Arctic and Antarctic using an AUV. The areas for research were ice shelves and proximate continental shelf areas, first, in the eastern Pacific sector of Antarctica, in the vicinity of Pine Island Glacier (PIG), second, near the
79N glacier at the east margin of the Greenland Ice Sheet, and, thirdly, The Wilkins and George VI ice shelves in the Weddell Sea sector of Antarctica, under and north of the Filchner–Ronne Ice Shelf (FRIS). The regions proposed included both open ocean ‘sea ice’ and glacial ‘shelf ice’ and are shown in Fig. 4.

The multi-disciplinary Autosub under-ice science programme was funded and managed by the UK Natural Environment Research Council. A number of scientific goals were selected that had various mission requirements:

(a) physical oceanography involving surveys of water volumes under sea and shelf ice;
(b) glaciology and sea ice involving the collection of ice underside data;
(c) geology and geophysics involving the collection of sea-floor bathymetry and sediment data;
(d) biology with sea-floor photography.

These missions were to be of a relatively large scale of up to 400 km over a duration of approximately 4 days.

The mission requirements were translated into under-ice operations requirements for an AUV which can mainly be categorized in terms of risk. These are itemized as follows.

1. Extensive time periods (days) without surfacing for a GPS fix are necessary.
2. In the event of problems the vehicle cannot cut power and drop ballast to surface.
3. The seabed terrain is unknown and also effectively mirrored in the form of overhead ice terrain.
4. Sea ice is mobile. Clear areas may be populated with a moving ice flow in a number of hours, closing off a preplanned surfacing and recovery location.
5. Icebergs may be grounded and shelf ice is also effectively connected to the sea floor, presenting a dead-end and choke point scenario.
6. Unknown currents can impact on navigation if the ADCP is unable to track the sea floor (this is likely in several of the proposed work areas).

At the onset of the Autosub under-ice programme it was clear that the AUV would require considerable enhancements. Analysis of mission requirements and likely environmental features, in conjunction with experience gained from previous under-sea-ice missions [12], provided a number of scenarios that would have to be dealt with as a minimum specification. At the same time it was realized that any significant alterations to the existing AUV would have an impact on reliability and would require thorough testing in simulation and with full sea trials.

3.2 Under-ice collision avoidance requirements

The mission requirements for the under-ice programme ranged from near-bottom terrain, which followed from carrying out a photographic survey, to oscillating profiles between the sea floor and the ice underside. The likely obstacles and hazards are as follows and are illustrated in Fig. 4 and as part of Fig. 8 later:

(a) moving icebergs and ice keels;
(b) drifting sea-ice fields;
(c) grounded icebergs (where the iceberg has become stuck against the sea floor);
(d) extensive shelf ice with unknown features;
(e) unknown bottom terrain;
(f) coastal ice cliffs, overhangs, choke points, and dead ends.

Given the duration and distance of the missions to be undertaken it was important to ensure that the number of false alarms was minimized. Time spent attempting to avoid and circumnavigate a fictitious obstacle would be wasted mission time, with data not being collected, unnecessary battery power consumption, and a delayed rendezvous with the support ship. All these have a financial impact, although this weighs against the significant financial impact of colliding with an obstacle and the possible loss of the AUV.

4 THE PROPOSED SOLUTION

The primary engineering task was to upgrade the Autosub-1 vehicle so that under-ice operation was as safe and reliable as possible. The solutions arrived at were the result of a complete vehicle systems review and so cover areas from avoidance control algorithms to navigational accuracy and the addition of a long-range emergency beacon. From this starting point the vehicle’s existing characteristics were a dominant factor in the definition of a solution. Possibly the most important factors influencing any solution for this vehicle type are, first, the necessity to maintain a forward speed through the water to maintain control, second, the vehicle’s 20 m turning radius, and, third, the need to operate with an up-and-down pitch limit of 16° to maintain sea-floor bottom lock of the ADCP velocity logs (although in extreme situations this restriction could be overridden). The following sections detail the enhancements to the Autosub while Fig. 5 shows the sensing and actuation of the
Autosub-2 vehicle. It will be observed that an imaging sonar was not used. This was largely due to the lack of a suitable off-the-shelf sensor and the complexity, and associated reliability risk, of integration into the vehicle control system. It was also decided that (despite successful work reported in references [13] and [14]) the requirements, environment, and mission scale of the Autosub under-ice programme did not call for such a solution.

Within this work, collision avoidance refers to the detection and reflexive control response to prevent damage to the AUV from striking an object. Obstacle avoidance refers to the subsequent sequential control strategy of attempting to circumnavigate or escape from the detected feature. The avoidance work presented in reference [13] also uses this differentiation. Additionally, other aspects of the AUV system play an important role in avoiding dangerous situations. Consequently a systems approach to the problem of collision and obstacle avoidance was taken that also included the implementation of a homing system, an emergency beacon, and improvements to navigation.

4.1 Autosub-2 sensing summary

Figure 5 shows the sensory systems of the Autosub-2 vehicle and these are summarized as follows.

1. The downward ADCP was changed to a 150 kHz model for increased range to 450 m and hence bottom-tracking navigation in deeper waters.
2. An upward-looking 300 kHz ADCP was used as an overhead range sensor and also to allow navigation tracking on overhead ice should the downward ADCP be out of range.
3. An Ixsea PHINS inertial navigation system (INS) was integrated and mechanically coupled with the downward-looking ADCP to reduce navigational errors to 0.2–0.1 per cent of the distance travelled (with the aid of the bottom-tracking ADCP).
4. The forward Simrad Mesotech range sensor was adjusted to look straight ahead. The frequency change to 120 kHz increased the sensors range to approximately 150 m.
5. A depth sensor provides context to returns detected from upward-looking sensors. This device was the same as that used in Autosub-1.

4.2 Navigation

The ability to navigate accurately is a fundamental component of any collision and obstacle avoidance solution. If the vehicle is unable to navigate accurately along its track, then the operator is unable to rely on their knowledge of the working area to plan the mission around known obstacles. This is particularly relevant for long-range under-ice operations where an AUV is unable to surface for GPS updates or to be in range of any acoustic navigational aids. The fluxgate compass and 300 kHz ADCP combination used for the Autosub-1 with a navigational error of 2 per cent of the distance travelled was not deemed adequate. In particular, several areas of operation were to have water depths far in excess of 250 m, meaning that the vehicle would be unable to counter adverse currents.

One of the most significant systems changes to the Autosub-1 vehicle was the upgrade to the navigation system. The Seatex MRU6 attitude sensor and single 300 kHz ADCP were replaced with the INS [15] which was physically mounted on top of a 150 kHz ADCP and fitted beneath an upward-looking 300 kHz ADCP.

The range of the 150 kHz ADCP was of the order of 450 m, increasing the operating altitude of the Autosub by 200 m. Additionally it was proposed to use the upward-looking ADPC to track and navigate relative to the ice overhead. Thus the upgraded vehicle would be able to track and cope with current within a 700 m water column from ice bottom to sea floor. The integration of the INS also reduced the navigational error to between 0.1 and 0.2 per cent of the distance travelled when aided by the bottom-tracking ADCP.

4.3 Sensing a situation that requires avoidance

The behaviour control involved in avoiding collisions and obstacles requires sensory input. After analysis of the under-ice environment and given the continuous flight and track following navigational characteristics of the Autosub, it was apparent that the minimum required information for robust collision and obstacle avoidance included an indication of an approaching object in the vehicle’s flight path and an indication of the headroom available to the vehicle that consisted of range to the ice overhead and the sea floor below. The single trigger for an avoidance action was termed ‘collision imminent’ and was generated from a combination of sensory and mission contextual information. This minimalist approach was taken for reasons of integration and test simplicity as discussed above.

4.3.1 Object ahead; collision imminent

This signal was generated from the single 10° beam of the Kongsberg Simrad Mesotech 1007 series
120 kHz echo sounder. At a range of 150 m the beam diameter would be approximately 26 m and thus more than adequate for ensuring a clear path ahead for an AUV with 1 m diameter.

Acoustic sensors are particularly susceptible to noise and false signals. Noise can be in the form of either thermal noise within the sensor or environmental noise such as waves, ships, and, in polar regions, creaking ice. False signals, or unwanted returns, may come from particulates in the water, e.g. bubbles, fish swim bladders, and multi-path reflections. A simple algorithmic filter was used to reduce the likelihood of false alarms. Ten continuous returns had to be received at a consistently reducing range with a 1.5 s update rate in order to trigger an ‘object ahead’ indication. The margin for detection within the 150 m sensor range at a vehicle speed of 2 m/s was

\[ \text{range} = 150 - (10 \times 1.5 \times 2 \text{ m/s} + 20 \text{ m turn radius}) = 100 \text{ m}. \]

Additionally, a particular problem that was associated with the Autosub echo sounder occurred when the vehicle was in close proximity to and approaching pitch up towards the surface. In this situation it was found that an ‘object ahead’ indication could be triggered in two ways: first, by acoustic returns from the approaching surface and, second, by returns from an acoustic side-beam sensor artefact and the sea surface directly overhead. The first of these problems was filtered by comparing the acoustic range with a calculated approximation of the range to the sea surface given: range = depth/sin(pitch). Equivalent ranges within a 2 m envelope were discounted. The second problem required a simple comparison between the vehicle depth and the indicated obstacle range, with ranges equal to the vehicle’s depth being discounted, again with a 2 m tolerance.

4.3.2 Headroom limited

This trigger was generated by comparing the current altitude above the sea floor and the range to ice overhead against preset range thresholds. If both thresholds were crossed, then the signal was set (see Fig. 8 later) according to

\[
\text{IF range up < overhead limit AND range down < altitude limit THEN HeadroomLimited } = \text{TRUE}
\]

4.3.3 Ice overhead

This trigger was used by the depth control system to dictate the surfacing control behaviour of the vehicle. If this state was true, then the vehicle was prevented from surfacing and the emergency abort system prevented from dropping ballast. The signal was generated from a combination of the upward range and the current depth of the vehicle and relied on the fact that ADCP acoustic returns from the surface could be compared with the vehicle’s depth using a preset threshold of the minimum allowed ice thickness according to

\[
\text{IF current depth } - \text{ range up} > \text{ minimum ice thickness THEN IceOverhead } = \text{TRUE}
\]

4.4 Rudder (position) control

Autosub-1 did not have a collision avoidance behaviour that functioned in the horizontal plane. This was clearly a requirement for the under-ice programme and one that would require careful integration into the existing control hierarchy. Analysis of the Autosub under-ice operation scenarios showed that the responses to either of the signals ‘object ahead’ or ‘limited headroom’ were the same: turn away from the obstacle, retreat to a safe distance, and then try to find a way around.

The strategy of avoiding a collision and then subsequently attempting to circumnavigate it was kept as simple as possible and is illustrated in the plot of a simulated mission in Fig. 6. To implement the collision and obstacle avoidance control behaviour a three-state process was added to the top of the position control hierarchy. By using the lower levels of the existing position control software it was possible to realize the avoidance behaviour in terms of navigation tracks between two waypoints. The three states are depicted in the state space diagram in Fig. 7. During normal operation the avoidance process was in a ‘waiting’ state, taking no action. Once triggered, the state of the avoidance process would switch to ‘retreating’. The actions initiated involved an immediate 180° turn and then a track back along the way that it had come for a prescribed distance. The direction of the turn could be biased as part of the premission programming configuration but otherwise was not actively controlled since the information to optimize the turn to the port or starboard was not available. The retreat was implemented by issuing a series of waypoints to the track following the control process. The waypoints for the retreat navigation were backtracked from a circular memory array that is continuously updated at regular intervals with the vehicle’s current position.
When the retreat distance was covered a ‘collision avoided’ event signal is output to the vehicle mission control system and the avoidance control state switches to its third state: ‘trying a new track’. A new navigation track parallel to the original line that the vehicle was following is generated. The new track is offset from the original by a random distance (within a predefined maximum limit). If another (or the same) obstacle is encountered while the new track is being attempted, then control would switch back to the retreating state and the vehicle would backtrack again along its saved line of waypoints for the prescribed distance. Once the vehicle had completed twice the retreat distance (labelled Clearance Distance Covered in Fig. 7) along the new track, then an attempt to reacquire the original track was made and an ‘obstacle avoided’ signal sent to the mission control. Should the reacquisition fail, then the Autosub would again enter the ‘retreat’ state.

4.4.1 Avoidance interrupts

When the avoidance control leaves the ‘retreat’ state, it issues a ‘collision avoided’ signal to the Autosub mission control. At this point, and if the planned mission has specified the trigger, the mission control may interrupt the obstacle avoidance behaviour by issuing a new position control instruction from the mission script.

The control behaviour will repeatedly switch between retreating and trying a new track if an obstacle is encountered. However, this sequence is unlikely to reach a limit cycle because the depth control limits (detailed in section 4.5) will be changing.

When the first retreat from collision is initiated, a timer is started and a count of the number of times that the retreat state is entered. If either the timer or the count reaches a preconfigured value, then an ‘avoidance failed’ signal is output to the mission control. The mission control may be programmed to respond to this (see section 4.6).

4.5 Stern-plane (depth or altitude) control

The avoidance strategy implemented for the vertical control dimension (depth or altitude) was a relatively straightforward enhancement of the Autosub-1 use of ‘safe’ control limits. This continuous control solution was chosen for its simplicity over a multi-state solution. The safe control limits of Autosub-2 are depicted in Fig. 8. It can be seen in the lower half that the sea-floor-related limits are the same as Autosub-1 (Fig. 3). The under-ice limits are a reflection of the sea-floor limits with a minimum depth specifying the edge of a dangerous surface zone where floating ice and ice keels may exist. The minimum ice clearance is the equivalent to minimum altitude.

An additional feature of the Autosub-2 depth or altitude control was the introduction of a set of ‘safe’ control limits. The purpose of these was that, for each of the normal control limits (maximum depth, minimum depth, minimum altitude, and minimum ice clearance), there would be a second conservatively set safe value. For example, for a minimum ice clearance of 50 m, a safe minimum might be set at 150 m. The switching between these sets of limits was controlled by the same triggers as the position control avoidance processes details in section 4.4 (‘obstacle ahead’ or ‘limited headroom’) to trigger the safe limits. The ‘obstacle avoided’ output of the position control avoidance process was used to revert to the normal depth and altitude limits.
4.5.1 Surfacing mode

With the addition of the minimum depth limit the original method used by Autosub-1 of commanding the vehicle to surface would not work. A depth demand of zero would never be acquired since the control would be limited to the minimum depth. This was taken care of with the useful addition of a dedicated surfacing control mode in which the depth demand was fixed at zero and the minimum depth limit ignored.

4.5.2 Generation of the 'headroom limited' signal

The depth control process was given the task of maintaining the state of the 'headroom limited' trigger signal that was used by the position control avoidance states. This output was set when the sum of the minimum ice clearance limit and minimum

Fig. 4  From left to right, the location of the first Antarctic campaign to the PIG, the two Arctic regions off the east coast of Greenland and again in the Antarctic the FRIS. On the far right is a cross-section view of the Ronne Ice Sheet [1]

Fig. 5  Autosub-2 sensing and actuation

Fig. 6  A simulated avoidance showing the navigation of the collision and obstacle avoidance behaviour
altitude limit was greater than the sum of the actual range to ice overhead and the vehicle altitude, i.e. when the limits overlapped as shown in Fig. 8. The normal limits were used at all times to generate this signal to prevent the possibility that the vehicle is artificially cut off from its exit by overlapping safe limits (also in Fig. 8).

4.6 Homing

The Autosub-2 was equipped with a homing system that was developed in house. This consisted of a 4.5 kHz narrow band swept pulse over 20 Hz transmitted from the mother ship. This had a design range of up to 50 km. The receipt of this signal by the Autosub was used to generate an absolute heading to the ship. The Autosub mission control system used this heading to update the rudder control system with a heading demand. Once within range of the ship, shorter-range telemetry would then be used to monitor the vehicle’s systems and transmit surfacing commands. If an obstacle is encountered during homing, the collision avoidance will enter the 'retreating' state. Once the retreat was complete, the AUV would return to its homing mode rather than subsequently attempting a new track. This is because the Autosub homing mode operates in terms of heading rather than track-based navigation. When the AUV is in its homing mode, the mission is
effectively ended and the onus is on the operator to navigate the vehicle safely. This may be accomplished by moving the mother ship so that the homing Autosub follows.

4.7 Mission control

Alterations to the mission control subsystem were made to support the other collision and obstacle avoidance-related changes within the Autosub.

4.7.1 Mission termination scripts

The Autosub-1 executed a single sequence of mission instructions. If a problem was encountered, then the mission was terminated, and the vehicle dropped ballast and surfaced. Obviously this action is not suitable for the under-ice environment where the vehicle would most probably become irrecoverable. Scenarios were identified for which the specification of alternative emergency mission endings would be useful. A number of mission events were used to trigger a mission exception. For example the detection of an obstacle could trigger an immediate switch to an alternative mission ending to take the AUV to a safe location for rendezvous with the support ship.

4.7.2 Homing mode

A homing state was added to the mission control. If at any point in the execution of the mission a homing system heading was received, the mission control would switch to a homing mode. A pre-configured depth demand would be sent to the depth control and the homing heading sent to the rudder controller. If the heading updates ceased, then a mission termination script was triggered to take alternative action, such as navigate to a predetermined safe waypoint. Should the homing signal heading data resume, the homing behaviour would be reinitiated.

5 TESTING, TRIALS, AND OPERATIONS

After extensive stand-alone and full system simulation, sea trials were conducted of the full Autosub-2 vehicle. This section details those trials and then presents an example of the collision avoidance behaviour being used during a science mission in the Arctic off the north coast of Greenland.

5.1 Sea trials

There are many problems associated with testing a collision and obstacle avoidance system in the real world. Not least is the fact that, during a test, unforeseen problems may occur which might endanger the AUV. For the avoidance control behaviour there were two scenarios that required testing: first, avoidance triggered by limited headroom and, second, avoidance triggered by an object ahead.

![Fig. 9 A data flow block diagram of the Autosub-2 control system. Bold-framed white blocks and bold connectors indicate that the modifications were made for the upgrade from Autosub-1](image-url)
To test the functionality of the limited headroom scenario a suitable mound on the sea floor was found, which would provide sufficient depth change to close a gap between the vehicle’s altitude and overhead clearance. These sensory inputs are taken from the ADCP sensors and it was possible to ‘trick’ the upward ADCP into returning ranges to the underside of the sea surface as though it was ice overhead. When this was combined with a judicious setting of the normal and safe depth control limits, it was possible to trigger a ‘limited headroom’ indication as the Autosub approached and rose up over the sea mound. The required avoidance behaviour was observed with the depth control subsystem switching to the safe control limits and the position control subsystem entering the ‘retreating’ state.

The scenario in which the Autosub approached an obstacle dead ahead was more difficult to set up. The main problem was to provide an iceberg-like obstacle for the AUV that would not damage it should the avoidance control behaviour fail to function as intended. To this end a curtain of bubbles was created that could be towed behind the trials support ship. This consisted of compressed air being pumped down a series of perforated pipes which were ballasted and buoyed to float at approximately 20 m depth in a stream behind the ship. A surface view of this is shown in Fig. 10.

The test consisted of programming a simple mission to run the Autosub repeatedly backwards and forwards on a track between two waypoints. While the AUV was doing this, the support ship crossed the navigated track with the air curtain in tow. It was difficult to synchronize the timing between the AUV and the ship but by the end of the day a number of examples of successful Autosub collision and obstacle avoidance responses were logged.

The sea trials demonstrated a working collision and obstacle avoidance solution. However, problems were encountered with false triggers from the forward-looking echo sounder. Section 4.3 discussed the processing of the ‘object ahead’ indication and the need to allow for vehicle pitch and sensor noise. During the trials, further work was required to tune the avoidance trigger in order to prevent false alarms from causing the vehicle to make unnecessary and time-consuming avoidance manoeuvres.

5.2 In operation

The collision and obstacle avoidance systems were triggered many times during the course of the Autosub under-ice science campaigns. The most striking example is presented here.

The science campaign [16] took place off the northeast Greenland coast over an area known as the Northwind Shoal. The science requirements were for a mission that consisted of a 72 km return transect between two waypoints taking the Autosub under extensive sea-ice fields. Sensors on board were used to create a sonar map of the underside of the sea ice, to record temperature and salinity data, to take water samples, and to collect current information using the ADCPs. Icebergs and deep ice keels featured strongly in the region and during the course of the approximately 24 h, 144 km mission it was expected that the sea and ice conditions would change.

On the return leg the Autosub encountered a change in conditions. A small iceberg or series of ice
keels had drifted across the track that had been clear on the outbound leg. Triggered by the 'headroom limited' signal the Autosub then turned and retreated for the predefined safe distance before attempting a new offset track (navigation plot in Fig. 11). At the same time the safe depth, altitude, and overhead clearance limits were enabled, resulting in the undulating terrain-following depth profile (depth plot in Fig. 11). On the third attempt the Autosub successfully circumnavigated the obstacle and continued to the end of the mission and rendezvous with the support ship.

The story of mission 365 did not end with this successful obstacle avoidance, however. When the Autosub arrived at its assigned rendezvous position, several hours late owing to the extra distance covered by the avoidance behaviour, it was found that conditions in this area had also changed for the worse. A drift of sea ice covered the area and the homing system had to be used to lead the AUV to a safe recovery location (Fig. 12).

6 CONCLUSION

A collision and obstacle avoidance solution was successfully developed and integrated in an upgrade to the Autosub-1 AUV. The system effectively kept the vehicle safe, preventing collisions on numerous occasions throughout the campaigns of the Autosub under-ice science programme. There were many lessons learned during the development test and operation of the vehicle. Probably the most important lesson was the need to guard constantly against any unnecessary increase in the complexity of the specification and implementation. It was also demonstrated that a multi-faceted approach to the avoidance problem, including improvements to navigational accuracy, the addition of a homing system, and the careful application of tried and tested mission preparation and launch and recovery procedures, was vital to a successful outcome.

On the operational side it was found that there was considerable complexity in configuring the avoidance systems for a given work area. Section 4 referred to many ‘preconfigured values’ and, while these were preset during trials, it was frequently found to be necessary to adjust these for different

![Fig. 11](image1) A depth and navigation plot of the mission 365 return leg. Note that the depth plot is time-based and so the three repeated attempts evident in the navigation plot appear sequentially. Also note the transition from constant depth to terrain-limited control in the highlighted area.

![Fig. 12](image2) Autosub-2 recovery
mission profiles and work areas. This task was complex and prone to operator error and thus required careful and time-consuming checking by skilled personnel.

On various science missions, in particular in the confined waters of the Kangerdlugssuaq Fjord on the Greenland coast, the collision avoidance system was found to be insensitive to small-scale features when working in close proximity to obstacles. In such situations, more sensory information would be needed to enable the AUV to optimize its avoidance behaviour, e.g. to be able to turn away from an obstacle in the direction of the clearest waters.

In summary, the following points should be made.

1. The solution was dependent on the operator's domain knowledge and involved prescribed large-scale responses. This was largely because of the limited sensory information available.

2. This solution was useful and successful for large-scale obstacles but was susceptible to being confused by cluttered small-scale objects in relatively confined waters. However, this may be seen as an indication that Autosub-2 should not have been operating in these areas.

3. The Autosub-2 solution was also limited in not implementing a means of determining the best direction to turn away from an obstacle, apart from the mission preset turn bias (section 4.4).

It will be apparent that the collision and obstacle avoidance solution presented in this paper was highly optimized for the under-ice conditions that were expected to be encountered by the Autosub. The wider problem of collision avoidance for AUVs is significant and related to the availability of suitable sensor information. In the case of large-flight-class AUVs the problem is one of collecting sufficient detail, without a high incidence of false alarms, from far enough ahead to allow the vehicle enough space to manoeuvre. It is not necessary to identify an obstacle; it is necessary to detect its presence and context. A particular avoidance problem faced by all AUVs that are working unescorted is the detection of surface obstacles prior to surfacing themselves.

This paper has presented the successful implementation and operation of a systems-oriented approach to collision and obstacle avoidance. It has been demonstrated from operational experience that the problem of AUV safety requires a multi-faceted approach to systems design. The detection and algorithmic response to an obstacle is only one aspect of the problem. Other components of a fully operational AUV such as accurate navigation are equally if not more important.

ACKNOWLEDGEMENTS

The Autosub AUV programme is ongoing and has been realized by the team members, all of whom have worked extensively on every aspect of the vehicle design and operation: Maaten Furlong, Andrew Harris, Stephen McPhail, Nick Millard, Miles Pebody, James Perrett, Peter Stevenson, Andrew Webb, and David White. Other personnel involved in the Arctic science campaign were Gwyn Griffiths, Peter Wadhams, and the Master and the crew of the R.R.S. James Clark Ross.

REFERENCES


