AUTONOMOUS INITIAL CAPTURE SYSTEM FOR AUV RECOVERY

Sagar Pai[a], Piero Guerrini[b], John Potter[a,b], Alain Maguer[b], Mandar Chitre[a] & Stefano Biagini[b]

[a]Acoustic Research Laboratory, Tropical Marine Science Institute, National University of Singapore, 14a Kent Ridge Road, Singapore 119223.
[b]NATO Undersea Research Centre, Viale San Bartolomeo, 400, La Spezia 19026 Italy.

Contact Author: Sagar Pai, Acoustic Research Laboratory, Tropical Marine Science Institute, National University of Singapore, 14a Kent Ridge Road, Singapore 119223. Fax: +65 68748325 Email:sagar@arl.nus.edu.sg

Abstract:

As Autonomous Underwater Vehicle (AUV) technology matures and applications become more widespread, it is becoming clear that AUVs will be deployed in fully autonomous scenarios (that is, without direct human intervention at any point in the mission, including launch and recovery) and in collaborative 'swarms'. With multiple AUVs in the water at the same time, or for fully-autonomous operation, the efficient, reliable autonomous launch and recovery of AUVs becomes an as-yet unsolved challenge. There are several areas in which current launch and recovery techniques need to be advanced to meet this challenge, including all-weather operation, recovery in reduced visibility (e.g. at night) and automation of the recovery.

The next generation of automated recovery systems will need to provide a reliable method to achieve first contact between the support platform and the AUV to support the subsequent recovery, recharging, data exchange, etc. This is perhaps the hardest step. We propose a generic capture device that would provide this initial contact for a wide range of AUVs, including those without homing or Ultra-Short Base Line (USBL) capabilities.

One of the key features of the design is to minimise assumptions and requirements on the AUV so that the system has wide application to a range of AUVs, including simple AUVs that might be used in 'swarms' and recovery by surface ships, Unmanned Surface Vessels (USV), bottom-mounted data/power hubs, etc. It is assumed only that the AUV can be programmed to proceed from a predetermined 'Start' waypoint to an 'End' waypoint along a 'recovery track' at a nominally-constant depth and speed, ignoring any internal collision avoidance warnings.

This leads into another novel feature; the homing is performed by a mobile Tethered Initial Contact Hoop (TICH) rather than the AUV. This design choice in turn demands that there should be a mobile and a 'fixed' part of the system; in our case connected by an umbilical tether cable. The Tethered Initial Contact System (TICS) then consists of a wet-end mobile TIC Hoop (TICH) coupled via an umbilical to a dry-end (though this could be sub-surface) signal processing TIC Intelligence Unit (TICIU). The TICS additionally requires two small self-contained transponders to be attached to the AUV, perhaps housed on a jacket, collar or internal to a flooded AUV fairing.

The TICH is equipped with an interrogating transducer and three acoustic receivers (forming an USBL for the AUV-mounted transponders), depth, heading and IMS sensors. Data from these sensors are fed from the TICH to the TICIU over an ethernet backbone via the umbilical. Control data are, in return, supplied by the TICIU, housed on the support platform. The TICH has thrusters so that it can move autonomously within the range of its umbilical tether, following TICIU commands. TICH power may be on-board (using high energy-density batteries) or supplied via the umbilical.

While the TICH is concerned only with its position relative to the AUV, an optional transponder on the TICIU would permit the position of the TICH relative to the TICIU to be estimated, which may prove useful in limiting attempted motion at the limits of the umbilical reach.

The TICH will initially be deployed close to the anticipated rendezvous point (towards the end of the recovery track), manoeuvring itself to the planned intercept point while seeking reliable acoustic contact with the AUV transponders. Once the AUV is detected and its bearing estimate has stabilised, the TICH will switch to a predictive pursuit mode of homing, positioning itself in an anticipated capture pose given the known nominal recovery track and estimated AUV bearing, allowing for AUV navigational errors and water currents. As the AUV closes and the signal to noise ratio improves, near-field USBL range estimation will become available for final fine-tuning of the homing motion. The TICH will be fitted with a mechanical guidance cone of flexible staves, entering into a tube, in which a grappling mechanism will physically engage the AUV for capture.

Keywords: *Autonomous Underwater Vehicle Recovery Homing Navigation Acoustic Transponder USBL AUV LARS*

1. INTRODUCTION

With interest in exploiting marine resources moving into ever deeper water and distributed sensing networks coming to the fore, the Autonomous Underwater Vehicle (AUV) with diverse and modular sensing payloads will play an increasing role in the exploration, detection, classification and tracking of marine phenomena. In addition, the prospect of using many AUVs simultaneously in a 'swarm' is gaining momentum. As AUVs become commonplace and with the expectations of exploiting collaborative behaviour, the technical demands of efficient handling of AUVs is brought to the fore, both in terms of the launch and recovery and also in operations like data download, mission upload, and power recharging to extend the autonomous endurance of the AUV. In addition, there is considerable interest in being able to operate AUVs from unmanned surface vessels (USVs), in high sea states and at night.

AUVs, with limited endurance, need to rely on a support platform to provide power and data exchange between missions. Given the desire to be able to recover AUVs in all weathers, day and night, the natural way forward is to recover the AUV sub-surface. For an USV to provide this support, there is, in addition, a need for the entire operation to be automated.

2. CURRENT RECOVERY STRATEGIES FOR 'TORPEDO-TYPE' AUVS

Generally, a 'torpedo-type' AUV (defined here as having small frontal area compared to its length whose control requires external surfaces deflecting the water flow around the vehicle while underway) is recovered by either coming to a standstill at the surface and/or by ejecting a capture line from the nose. In the former case (applicable to smaller AUVs) the AUV is generally recovered by personnelle operating from a small boat close to the waterline (such as from a Rigid Hull Inflatable) and in the latter the AUV may be recovered by snagging the recovery line with a grappling hook and drawing the AUV onto some type of recovery sled lowered from the support platform to the water surface. Cocoons are often used for AUVs with payloads that cannot directly handle ramp contact, intended to sheath and protect the AUV during the recovery process [3].

In all these cases, human intervention is required for the initial contact and the operation is unsafe and/or unreliable during high sea state and in limited visibility, such as at night, during rainstorms, etc.

Some AUVs like the Remus 100 series, and more recently a 21" Bluefin, have demonstrated the capability to navigate and home into a fixed bottom mounted docking station using an onboard USBL system homing into a static hoop [1,2]. This requires that the AUV has an USBL receiver array, sufficiently responsive motion control to home effectively and software to implement homing signal processing and real-time 'externally-determined' control. While some AUVs can home into dedicated stationary docking stations, the majority do not posses all of the required hardware and software, or perhaps even the manoeuvrability, required. This technique is also not directly applicable to recovery by surface ships. In addition, with heterogeneous 'swarms' of co-operating autonomous assets, it is likely that more than one type of AUV will be deployed at once.

For a generic baseline AUV we permit ourselves only to expect that the AUV can be programmed to proceed at a specified depth and speed from a 'Start' waypoint along a 'recovery track' towards an 'End' waypoint and then to stop. If the AUV has a collision avoidance system, this would obviously need to be disabled during the recovery phase. This project addresses the need to autonomously handle AUVs of this nature in a generic fashion.

3. TETHERED INITIAL CONTACT SYSTEM (TICS)

The first step in defining the design constraints for our problem is in recognising that the homing and manoeuvrability requirement to have a generic AUV intercept a support-platform must be transferred from the AUV to the recovery system. This means that the recovery system must not only implement the homing (USBL array and signal processing) but also have at least some movable element, to react to homing estimates and close the control loop. Since the support platform is assumed essentially fixed (or at least unlikely to be able to move with sufficient agility to adapt to capturing the AUV in surge and currents), this implies that the recovery system must consist of at least two parts, one mobile and agile, the other 'fixed' to the support platform. We choose to connect these two components by an umbilical cable that supports an ethernet backbone data communication link.

The proposed approach automates the first physical contact with a returning AUV. A Tethered Initial Contact (TIC) capture device that we call a 'Hoop' (TICH) provides the agile mobile element of the recovery system. The TIC Intelligence Unit (TICIU) takes the sensor data from the TICH, computes the thruster activation for the TICH to home onto the approaching AUV and, optionally, provides power to the TICH. The TIC System (TICS) then consists of the mobile TICH and fixed TICIU, connected by an umbilical cable, with transponders mounted on the AUV and possibly also the support platform.

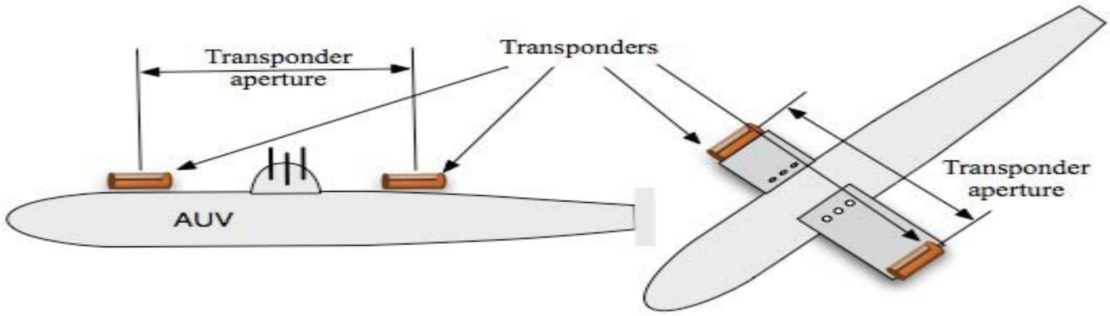

Fig. 1. Schematic of possible AUV transponder arrangements

The separation of the system into two main parts, necessitated by the homing and agile mobility requirements, has a collateral advantage. For recovery from surface platforms, the TICH can be allowed to descend typically 2-20 metres below the sea surface, away from surface wave action, greatly reducing the impact of wind and wave on the motion of the AUV and initial contact component of the recovery system. This greatly reduces the all-weather problem experienced by surface vessels.

1. Functionality

The basis of the homing control is an acoustic estimation of the AUV position and orientation by means of an Ultra Short Base Line (USBL) array, formed by three receiving hydrophones arranged round the outer edge of the receiving funnel of the TICH. This requires that two self-contained transponders, operating at slightly different frequencies, be attached to the AUV. The transponders may be housed in an external jacket or collar, attached to the outer hull or incorporated internally in a flooded design.

The geometry and positions of the transponders is not critical, providing they generate as large an aperture as possible and that their positions with respect to the leading point of the AUV are input to the TICIU software as parameters. The transponder aperture is used in the closing stages of the interception, when the AUV is in the near field of the USBL, to estimate the heading orientation of the AUV independently of its track to improve estimates of drift due to water currents. Fig. 1 shows a cartoon of possible AUV transponder arrangements that might be used. Note that the 'glider-like' AUV on the right would have to be a hybrid to satisfy our requirement of proceeding between waypoints at constant depth.

In addition, an optional transponder may be attached to the support platform to provide platform-centric navigation information on the TICH position. This is useful both for navigating the TICH to the nominal intercept position and for managing manoeuvrability at the limits of the umbilical tether.

The AUV mission will end with instructions to move first towards a specific ‘Start’ waypoint and from there to proceed on a constant heading, thrust and depth to a designated ‘End’ waypoint some 500 m distant, then coming to a halt (at which point it would normally float to the surface if not captured). Depending on the sophistication of the AUV navigation system, it may or may not be instructed to adjust its heading to remain on the nominal track between Start and End waypoints. To improve navigational accuracy and establish pre-recovery contact, the AUV may surface at the Start waypoint prior to starting its recovery run. The Start and End waypoints would normally be chosen at the beginning of the mission (before the AUV is launched if no contact is possible afterwards), aligned with anticipated water currents at the planned time of recovery. The depth of the recovery track would be chosen to insulate the AUV and TICH from surface wind and wave action and to remain clear of the support platform’s own draft. If the support platform were bottom-mounted, the arrangement would be inverted, with the TICH now above the TICIU at sufficient altitude above the bottom and TICIU to minimise collision risk.

The TICH would be launched from the support platform adjacent to the recovery track, near the ‘End’ waypoint. The TICH would be controlled by the TICIU on board the support platform in the following four stages:

1. Descend/ascend to nominal intercept depth and proceed to the intended recovery intercept point on the recovery track.
2. Maintain position while orienting the USBL perpendicular to the anticipated arrival track of the AUV and interrogating the transponders to establish acoustic contact.
3. Once reliable acoustic contact has been made and the AUV range and bearing estimates are steady, estimate the AUV actual track deviation from the intended recovery track (by the temporal derivative of the azimuthal and elevation bearings) and proceed to the updated estimated intercept point. Repeat as necessary.
4. Once the AUV is in the near field of the USBL, use the independent range and bearing information from the two AUV transponders to improve AUV heading versus track estimates and refine homing motion to intercept.

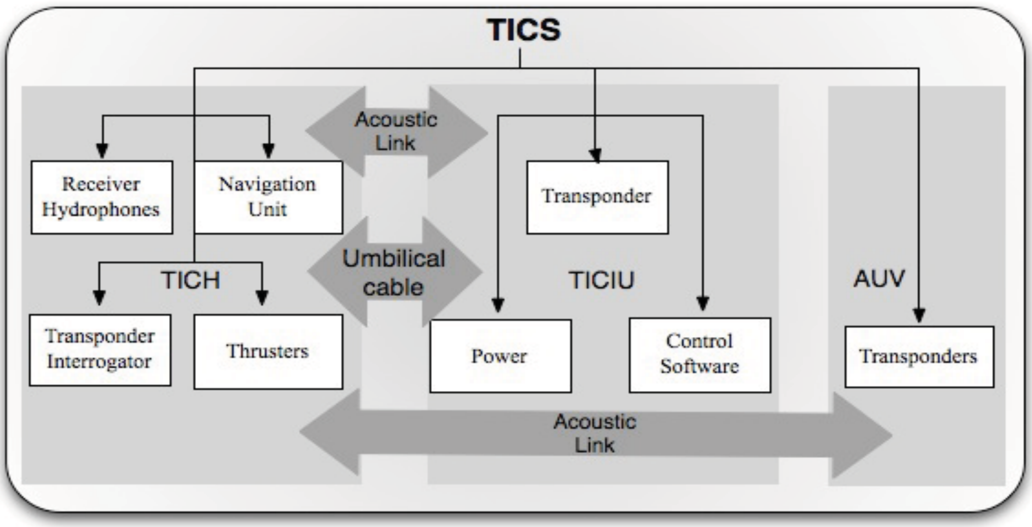

Fig. 2: *TICS Components*

The TICH would feed the TICIU control software with USBL acoustic data, TICH heading and depth. The TICIU then estimates the state space parameters and computes the control input for the thrusters to position the TICH. By keeping the TICH sensors simple and the computational load on the TICIU, the size and inertia of the TICH can be kept to a minimum, improving manoeuvrability.

2. TICS Components

The Tethered Initial Capture System comprises the Tethered Initial Capture Hoop (which is immersed and mobile), the Tethered Initial Capture Intelligence Unit (which may be above the surface) the ethernet umbilical connecting these two modules and the COTS transponders fitted to the AUV. These components are depicted in Fig. 2.

5. TICS ARCHITECTURE

1. Tethered Initial Contact Hoop (TICH)

The TICH is the physical hoop that will navigate to intercept the AUV; an umbilical cable connects the TICH to the TICIU. The TICH will have a transponder interrogator to trigger the AUV transponders. The rim of the capture guidance hoop will have a set of three receiving hydrophones spaced at 120 degrees. Fig. 3 shows a schematic of the hydrophone geometry on the rim of the TICH and the interrogation of transponder 2 by the TICH. Here δt_i is the time delay to propagate from the transponder on the AUV to receiver hydrophone i.

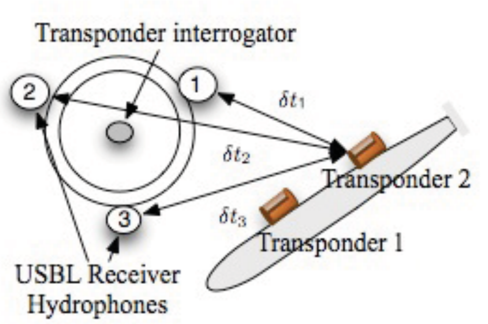

Fig. 3: *Transducer placement*

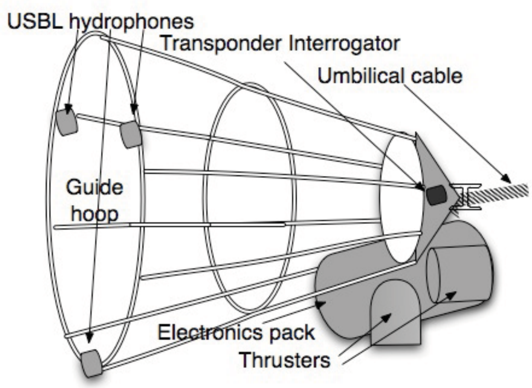

Fig. 4: *TICH*

The hydrophone data will be pre-processed and sent to the TICIU on the Ethernet backplane via the umbilical tether.

The TICH's navigation unit will have a solid-state compass, depth sensor (pressure) and possibly an inexpensive IMU. The outputs from the navigation unit will also be sent over ethernet to the TICIU. The TICIU will then estimate the bearing (and at closer range the range) of the AUV and generate control outputs for the TICH thrusters. The TICH's physical dimensions will be designed to accommodate the Nose and a section of the hull of the AUV as it approaches the TICH. Obviously, larger guidance hoops and docking tubes will be required for larger AUVs, but in principle these could be interchangeable

TICH modules, selected for the mission underway. A sketch of the TICH layout is shown in Fig. 4.

2. Tethered Initial Contact Intelligence Unit (TICIU)

The TICIU accepts inputs from the TICH sensors and controls the thrusters on the TICH. If a support platform transponder is deployed the TICIU can also calculate the distance and bearing of the TICH from the support vessel. The TICIU can then use this information to manage the range of operation of the TICH based on the available length of the umbilical tether. The TICH thrusters provide for heave, sway, surge and yaw degrees of freedom. The block diagram in Fig. 5 outlines the main steps taken by the TICIU to navigate the TICH to intercept the AUV.

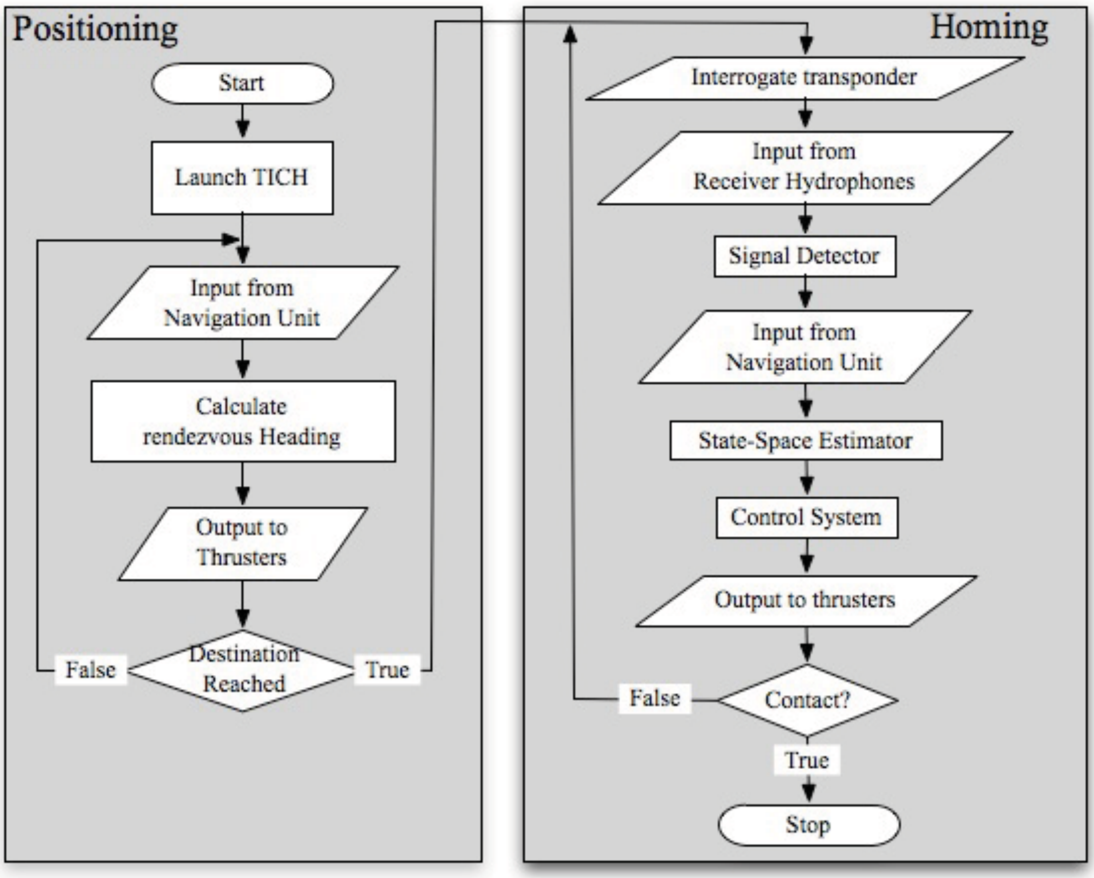

Fig 5: *TICIU Control Flow*

The TICIU will execute the interception process in two main phases, the ‘Positioning’ phase and the ‘Homing’ phase. In the ‘Positioning’ phase, the TICIU will navigate the TICH towards the nominal intercept position. This position is on the line connecting the Start and End waypoints at the proscribed depth. The co-ordinates of the TICH at launch are known to the TICIU from GPS data on the support platform. At this point the control system of the TICIU operates on the support platform transponder data (if available) combined with the data from the compass and IMU in the navigation unit on the TICH.

After reaching the nominal intercept position the TICIU will shift to the second 'Homing' phase. In this phase the TICIU controls the TICH in response to the positioning data from the interrogation of the transponders on the AUV by the TICH. This homing phase is itself composed of an initial long-range traditional pure pursuit algorithm, followed by an anticipatory intercept homing sequence as the signal to noise ratio improves and the AUV moves into the near field of the TICH. Pure pursuit is a special case (unity gain) of the well-known proportional navigation algorithm [4]. In the final stages of approach, higher gains may be appropriate to have the TICH lead the AUV estimated track to account more effectively for cross-drift. The TICIU will also need to keep track of the acoustic channel conditions to dynamically adapt the interrogation interval and track error estimates on the bearing and range. The state-space estimator uses these error estimates, the position returned from the signal detector and the data from the navigation unit of the TICH. This data is used to orient the TICH towards the approaching AUV.

3. AUV transponders

The AUV will be fitted with two COTS transponders which may be jacketed to provide a hydrodynamic profile to the AUV. As the transponders will only operate when the transducer on the TICH interrogates them they are not expected to interfere with the normal operation of the AUV during its mission.

6. CONCLUSION

This project outlines a design solution to the generic problem of autonomously capturing a returning AUV by a support platform, assuming only minimal capability on behalf of the AUV. The subsequent docking and recovery is not addressed, there being a number of established solutions to this part of the recovery problem. The conceptual solution can be applied to both surface and bottom-mounted support platforms, including both manned and unmanned surface vehicles. The solution is valid for zero visibility and high sea state conditions, since it relies on acoustic rather than visual homing and the initial contact can be arranged to occur well below the sea surface. The next planned phase of this project is to develop a TICS system for trials with small torpedo-type AUVs such as the REMUS 100 series.

7. REFERENCES

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