AUTOMATIC RECOVERY SYSTEMS FOR AUTONOMOUS UNDERWATER VEHICLES

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Abstract

Autonomous Underwater Vehicles (AUVs) can be used for a wide range of applications, such as bathymetry, environment monitoring, and mine countermeasures. However, as their range is limited by battery life, they are often carried on larger ships to effectively extend their reach. Launching and recovering AUVs from these ships tends to be a manpower intensive process, and highly dependent on ambient conditions and operator skill. Implementing an automatic recovery system would greatly reduce these limitations. This paper explores the creation of such a recovery system, with recovery taking place over four phases, based on the distances between the recovery system and the AUV. The proposed recovery system is also able to accommodate different sizes of AUV with only minor modifications to the recovery system. Improvements to the proposed system to address potential limitations have also been suggested.

1. Introduction

An Autonomous Underwater Vehicle (AUV) is a robotic device containing its own power that has six degrees of freedom (DOF) and can travel through water independent of its operator [1]. Equipped with a multitude of sensors such as stereo vision cameras, satellite navigation, and sonar, AUVs are utilised in many applications such as marine research, oceanographic surveys, and military mine countermeasures (MCM) [2]. However, as most AUVs have a limited battery life, they are often carried aboard surface vessels and brought to the mission site, therefore increasing their operational effectiveness.

1.1 Motivation

In Singapore, AUVs are used by the Republic of Singapore Navy (RSN) for purposes such as MCM. While the recovery of AUVs is crucial in maximising their usage, the following limitations have been identified:

1. Recovery systems can usually only recover one specific type of AUV
2. Existing systems require multiple people to operate
3. Successful recovery of the AUV is dependent on operator input and skill
4. The recovery system and AUV are affected by environmental conditions (ship wakes, wave effects, sea states, ambient lighting)
5. Modification of the AUV is typically not desirable, as this may impede their effectiveness in their original applications

1.2 Aim

This research aims to combat the existing problems of recovery systems by developing a novel recovery system for AUVs to increase the reliability of AUV recovery, and to reduce manpower required during AUV recovery, by automating the recovery process and making use of a moving cradle.

1.3 Constraints

AUVs come in many types of shapes and sizes; however, due to the limited resources and time available in this study, the focus will be on recovery systems for torpedo-shaped, positively buoyant AUVs, with diameters between 200mm and 600mm, and weighing less than a tonne. Additionally, as AUVs can have many different types of protrusions, the proposed solution will take into account the sonar arrays as well as the Doppler velocity log.

2. Design of Recovery Cradle

2.1 Phases of Recovery

When designing the recovery cradle, the entire recovery process was broadly broken up into four phases. Phase 1 occurs when the AUV is 100m or further away from the recovery cradle, and is heading towards the recovery cradle. Phase 2 occurs when the AUV is between 1m and 100m distance away from the edge of the recovery cradle. Phase 3 describes the period where the AUV is between 0m to 1m away from the edge of the recovery cradle. Phase 4 describes the terminal period where the AUV is within the cradle. Throughout the entire recovery process, the cradle is towed by the moving mothership, while the AUV is moving at a speed higher than that of the cradle, and all sensor information is processed taking the cradle as a reference point.

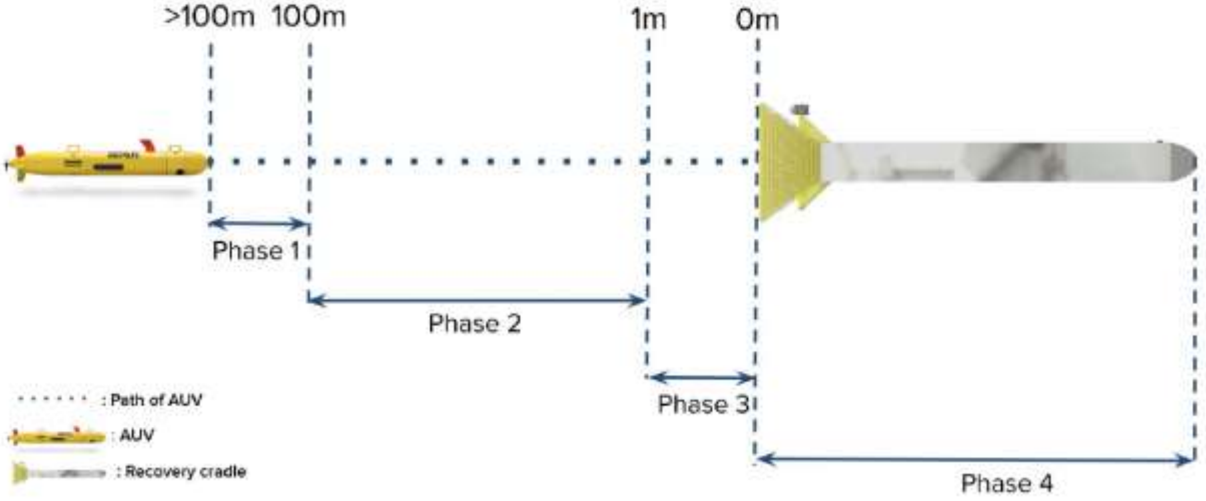

Fig 1. Diagram illustrating the 4 phases of recovery

2.2 Overview of Design

This design of the recovery cradle features GPS and LIDAR sensors, a funnel-shaped entrance nozzle, rollers, an aluminium frame and rubber strips mounted within, as well as an ogive head.

Fig 2. Labelled diagram of AUV recovery cradle

2.3 Phase 1- GPS Sensor

In phase 1 of the recovery, the cradle provides the AUV with the cradle's location to direct the AUV towards it. This is done via a GPS sensor mounted on a position which corresponds to the final docking position of the nose of the AUV. This provides a reference location for the AUV to home in on during this phase. As the recovery cradle is constantly floating at the water-air interface with the GPS sensor above the water level, it is able to obtain its GPS fix via radio waves at 1s intervals, which would be communicated to the AUV via radio frequency communication.

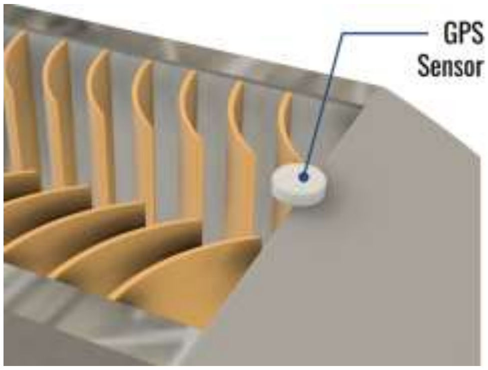

Fig 3. Mounting Location of GPS Sensor

While there are other types of navigation sensors available, such as INS and underwater acoustic positioning systems, the GPS sensor is chosen due to its low cost, low error of roughly 1m, and commercial availability. The inertial navigation sensor, while being able to calculate a wider range of data, such as orientation, velocity and acceleration, suffers from integration drift, as errors in integration are compounded when calculating position from acceleration, thus leading to errors of up to 50m in 17 minutes [3]. The underwater acoustic positioning system is also unsuitable as it tracks its position by acoustic signals, which is unreliable at the water-air interface, as acoustic signals are unsuitable to be used in air, and the presence of waves would disrupt the signals, thus leading to high frequency of disruption [4]. While there are concerns that the GPS sensor is not the most precise sensor available, as the AUV is 100m or further away from the recovery cradle, precision is not crucial, and an error of a few meters is tolerable as correction would be performed in phase 2.

2.4 Phase 2- LiDAR sensor

In phase 2 of the recovery, the cradle provides the AUV with specific course commands to accurately guide the AUV into the cradle for recovery. This is done via a Neptec OPAL™ LiDAR mounted on the entrance funnel of the recovery cradle.

The Neptec OPAL™ LiDAR was chosen due to its unique cone of coverage. While there are other types of LIDARs such as the Velodyne™ HDL-64E and Puck™, these LiDARs offer a 360° surround view, which is more suitable for all-round situation awareness; the Neptec OPAL™ LiDAR, however, has a rosette-type scan pattern that generates high data density around a focal area [5], which is more suitable for this application, as the AUV would be coming from a known direction that the LiDAR can focus on.

Using the Neptec OPAL™ LiDAR, the exact position of the AUV is detected with reference to the LiDAR. However, as the LiDAR is located on the entrance nozzle, the position of the AUV with reference to the LiDAR is inaccurate with reference to the actual homing position. Parallax correction is then performed with known values of distance and bearing of AUV to the LiDAR and from LiDAR to the actual homing position, and the position of the AUV with reference to the homing position is calculated.

Through vector field path following, using the algorithm for straight line path following, the cradle pre-calculates a vector field where the vectors in the field are directed towards a straight path for the AUV to follow in order to home in. The position of the AUV corresponds to a single vector in the vector field, while individual vectors represent the desired direction of travel of an AUV in that position to serve as course commands to the AUV, in terms of unique heading and velocity in the 3 planes. When the AUV is far away from the path (i.e. lateral distance greater than 2 or 3 times the minimal turn radius), the objective of the AUV is to travel towards the path at a constant heading. When the AUV approaches the path and enters within the transition range, the desired heading then transitions to travelling along the path [6][7][8]. As the Neptec OPAL™ LiDAR has a conical field of regard (FOR), when the AUV is beyond the FOR, it is given the course commands to stop momentarily until it enters the FOR once again, where the cradle can communicate course commands to it.

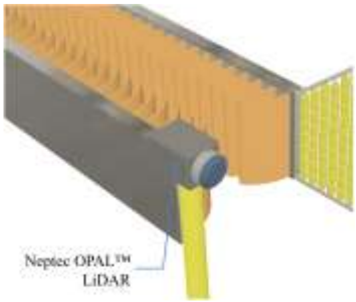

Fig 4. Diagram illustrating position of LiDAR on recovery cradle

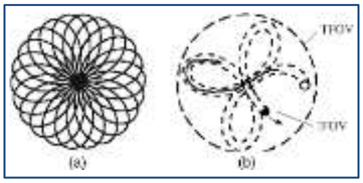

Fig 5a. Rosette-type scan pattern [9]
Fig 5b. Instant versus Total Field of View (FOV) of LiDAR [9]

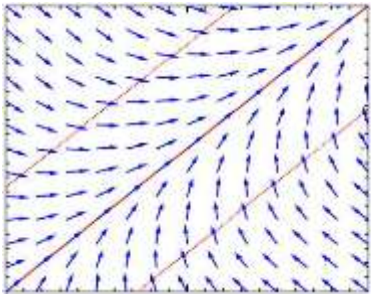

Fig 6. Example of straight line vector field path following [10]

2.5 Phase 3

In phase 3 of the recovery, the cradle directs the AUV into the body of the cradle for successful recovery. This is achieved by a funnel-shaped entrance nozzle, as well as ethylene-vinyl acetate rollers mounted on the nozzle.

2.5.1 Funnel-shaped entrance nozzle

Commonly seen in the docking stations for AUVs, such as MBARI's docking station for a 21" AUV [9] and WHOI's docking station for REMUS 100 [10], the funnel-shaped docking station is one of the most common structures for unidirectional approach in the docking of an AUV [11]. The funnel helps in proving the cradle with a tolerance of 700mm at the sides to reduce the chances of the AUV missing the recovery cradle due to unexpected sea conditions (e.g., waves) and increases reliability of AUV recovery.

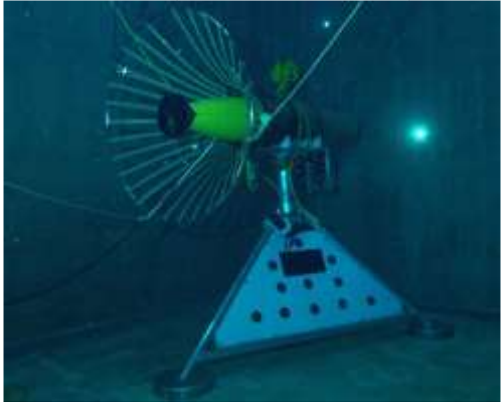

Fig 7. MBARI's docking station for 21" AUV [9]

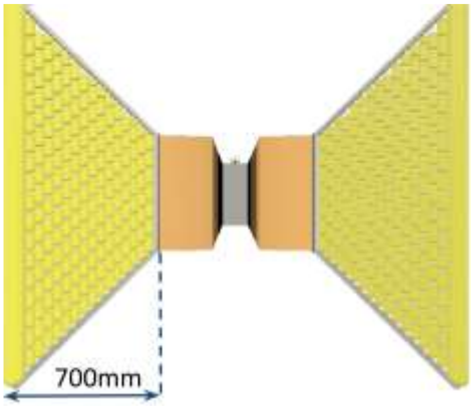

Fig 8. Funnel-shaped entrance nozzle

2.5.2 Rollers

The rollers help to absorb the impact energy should the AUV come into contact with it, and help to redirect the energy into the rotational movement of the rollers to facilitate forward movement of the AUV into the recovery cradle [12], instead of exerting equal amounts of force in the opposite direction of impact onto the AUV, hence reducing potential damage to the AUV. This is especially important as the nose of the AUV is where most of the AUV sensors, which are both fragile and expensive, are housed, thus the recovery process should eliminate any damage that could be sustained in this area. Additionally, in guiding the AUV forward, the rollers also help to prevent the AUV from veering off sharply in the opposite direction, thus preventing a second collision of the rear of the AUV.

Designed as small individual units of diameter 55mm and height 80mm, the rollers are better able to guide the AUV into the cradle due to increased manoeuvrability, and are also easily replaceable in case of wear and tear, hence increasing the cradle's cost efficiency.

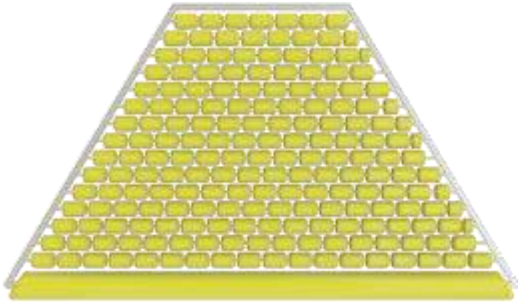

Fig 9. Diagram of rollers mounted on frame of entrance funnel

Fig 10. Diagram of a single roller unit

2.6 Phase 4

In phase 4 of the recovery, as the AUV is recovered in the body of the cradle, the main purpose of the cradle is to securely recover the AUV within the recovery cradle and ensure that the AUV does not fall out of the cradle when lifted out of the water.

2.6.1 Rubber

The rubber strips located within the boy of the cradle help to slow the AUV as it enters the cradle, while also distributing the load across the hull as the rubber strips deform elastically. This latter portion is especially useful for AUVs with hull relatively fragile hull protrusions, such as sonar arrays.

These rubber strips are angled forward to facilitate inwards movement of AUV during recovery; at the same time, backwards movement of the AUV is minimised due to the increased normal, and therefore frictional, forces associated with this direction. This increases reliability of recovery by reducing the chances of the AUV sliding out of the cradle during the final phase of recovery.

The rubber strips are mounted on a removable 5052 aluminium frame via a sliding connection in the z-axis. 5052 aluminium was chosen due to its light weight to aid in buoyancy of the cradle and its high corrosion resistance in seawater [13]. The removable nature of the aluminium frame housing the rubber strips allows for the recovery cradle to cater to a range of AUV sizes in terms of diameter, by having specific aluminium frames with rubber strips to cater to a specific dimension of AUV, and mounting the corresponding frame during AUV recovery. This eliminates the need to utilise different recovery systems when recovering different sizes of AUV, thus increasing cost efficiency as different recovery systems do not need to be purchased.

Each rubber strip is attached to the aluminium frame via a sliding connection in the y-axis, thus making it removable within the aluminium frame. This facilitates the replacement of damaged rubber strips during repeated recovery processes, as large amounts of friction between the rubber strip and the AUV to secure the AUV may lead to wear and tear of the rubber strip. As each strip is replaceable, this increases cost efficiency, as only individual strips need to be replaced instead of the entire stretch of rubber strips.

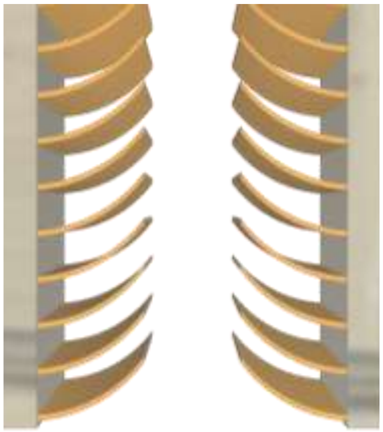

Fig 11. Diagram illustrating inwards angling of rubber strips

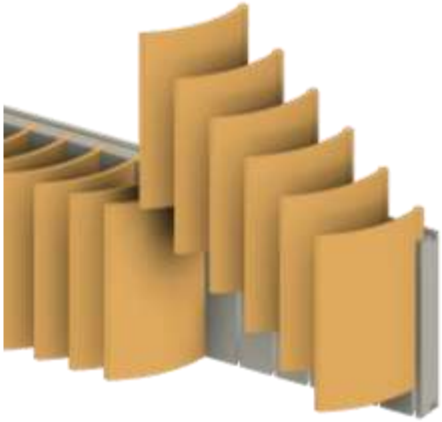

Fig 12. Diagram illustrating removable aluminium frame

Fig 13. Diagram illustrating removable rubber strips

2.7 Limitations

There remain potential limitations to this research. While materials were chosen with corrosion resistance to seawater in mind, actual interaction of the recovery cradle in seawater was not tested for, thus further design modifications and testing are needed in order to accommodate for the behaviour of cradle in seawater. Furthermore, due to cost limitations, a prototype of the recovery cradle was unable to be built due to sheer size and cost of materials, and launch and recovery of an AUV was unable to be held, thus no sea trials were able to be conducted.

3. Conclusions and Future Work

3.1 Conclusions

This research has identified a novel design of a recovery cradle for AUVS ranging from diameters 200mm to 600mm, length of up to 7m and weighing up to a tonne. The design has achieved its aim of increasing the reliability of recovery, while reducing the manpower required.

3.2 Future Work

While this research has identified a novel design of a recovery cradle for AUVs, it still remains in the conceptual phase. Further testing, such as online simulation of the recovery process and scale model testing, are required in order to obtain results on actual interaction of the cradle with AUVs in order to validate the design. Testing is also required to validate the vector field path following algorithm utilised in phase 2. Additionally, the recovery cradle proposed only accounts for the phases of recovery in which both the cradle and the AUV are in water, thus further work is required to account for final recovery process, where the recovery cradle with the AUV is winched onto the mothership.

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