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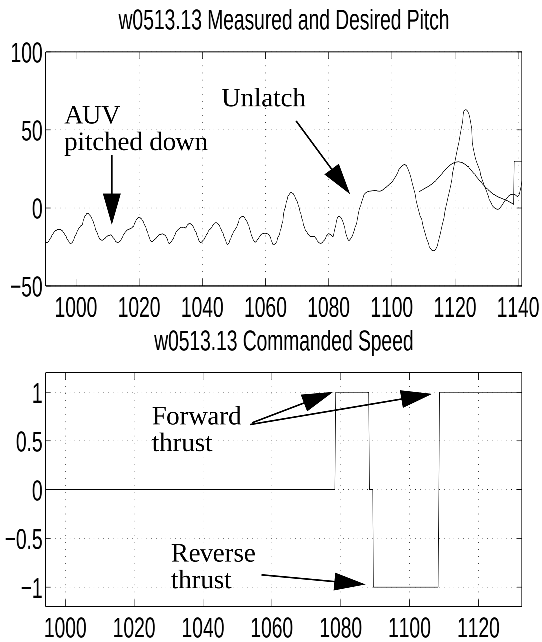

Figure 7. Undocking

ANALYSIS OF A SERIES OF MISSIONS

Table 1 summarizes the results from seven consecutive runs that were made by the AUV. Each mission took the vehicle away from the ship on a specified heading. The vehicle then went into its homing behavior. It was commanded to home until it docked and then stayed docked for a fixed period of time. During this fixed period an operator ran a program on the dock which brought the inductive cores on the AUV and the dock into alignment. Power transfer between the dock and the vehicle was then initiated for typically several minutes. The carriage on the dock was then brought down prior to the vehicle undocking.

Our engineering trials were carried out in a relatively shallow water environment that was much harsher than what we expect to see in an actual deep water deployment at the Labrador Sea. Wind induced motion of the ship, from which the dock was suspended, presented a moving dock for the AUV to home in on. A qualitative examination of the wind strength during these missions shows the wind strength decaying from 15 knots to 10 knots. As wind speed and sea state lowered, the ship swinging at anchor lessenedand the dock suspended over the side was less of a moving target. This might explain why there were a relatively large number of misses in the first few missions as opposed to the latter ones. An opposite trend in the number of attempts required to align the cores was exhibited as the wind died, which seems to suggest that the motion of the dock was helping us to align the cores. However, in dockside tests of core alignment carried out before this cruise very good alignment of cores was obtained in calm conditions. These two facts taken in concert lead to the conclusion that wind induced motion of the dock was actuall helping as well as hurting our performance. Overall for both, calm as well as moderate seas, the performance was more than satisfactory.

For undocking we saw one failure of the vehicle to leave the dock which occurred during the last mission. This was due to the batteries of the AUV being in a low state of charge. The current spike associated with the firing of the solenoid, although short-term, is the largest current demand on the AUV. This makes undocking a good test of the conditions of the battery and we consider, from a global system perspective, the failure to undock under these circumstances a favorable attribute.

CONCLUSIONS

Overall we can see that six of the seven missions were complete successes and that the last failure to undock could also be considered a success because of the low state of the battery charge.

There are some issues that need to be resolved that pertain to the autonomous operation of the dock, the interaction between the dock and the vehicle, and the interaction of the dock/AUV with operators that are connected to the dock via a very small bandwidth link.

We are well on our way to building up confidence in our ability to dock an AUV to a mooring for the purpose of data and power transfer to support long term missions in remote areas. While overall system reliability is quite high we still need to run a more exhaustive set of tests to quantify these qualitative observations and more definitely identify future modifications that may be needed.

ACKNOWLEDGEMENTS

We would like to thank the crew of the R/V Cape Hatteras; Jim Bellingham, Jim Bales, Brad Moran, Robert Grieve and others of the MIT SeaGrant Program; and Mike Feezor and Paul Blenkinship of EDC for their time, work, and companionship while on land and at sea.

Run #	Homing	Latching	Core Alignment	Power Transfer	Undocking
w0513.07	Miss, Miss, Yes	Yes	Yes	Yes	Yes
w0513.08	Miss, Yes	Yes	Yes	Yes	Yes
w0513.09	Yes, Miss, Yes	Yes	Yes	Yes	Yes
w0513.10	Yes	Yes	Yes	Yes	Yes
w0513.12	Yes, Yes, Miss, Yes	Grazed, Grazed, Yes	No, No, Yes	Yes	Yes
w0513.13	Yes	Yes	No, No, Yes	Yes	Yes
w0513.14	Yes	Yes	No, No, Yes	Yes	No

Table 1. Seven Consecutive Missions

and the dock into alignment. Magnetic switches associated with the pucks provide an independent mechanism for determining when the pucks are in alignment. The magnetic switches are tripped only within a radius of a quarter of an inch. To achieve this tight tolerance it is sometimes necessary to cycle the carriage up and down the pole more than once.

Power Transfer — Once the pucks are in alignment, power may be transferred between the dock and the AUV. In the runs described here we would typically transfer power for about ten minutes. We saw efficiencies of about 80% when transferring power across the whole system. A systematic description of the factors that affect the efficiencies obtained across the inductive cores and the charging system as a whole, as well as how they are affected by our particular dock design, may be found in [5].

Undocking — Unlatching from the dock is carried out in the following manner. As shown in Figure 7, the vehicle is first commanded to thrust forward for ten seconds. During the last second of forward thrust, the solenoid is energized. Reverse thrust is then commanded for 20 seconds, during which the latch solenoid is held energized for the first five seconds. In the preceding sequence of events, we apply a large elevator deflection such that during the reverse thrust, the tail is forced down, countering the normally positive flotation of the vehicle effectively powering the vehicle downward with a nose-up pitch, away from the dock.

The pitch plot for undocking, shown on the same scale as commanded speed in Fig 6, is interesting to examine. We note here that when the AUV is not constrained within the two carriages the only point of contact between it and the dock is the latch. As the vehicle is ballasted slightly positive during its operations, and the centre of buoyancy is well aft of the pivot point on the latch, the vehicle tends to pitch down. We can see this phenomemenon in Figure 6. However, a pitched vehicle has a greater tendency to bind with the pole and we would like the vehicle to ideally be level when unlatching. The pitch oscillations induced by the sequence of undocking are such that the latch is energized just as the pitch approaches zero. This frees us from the effect of any binding between the latch and the pole that may occur. Once the latch is energized we simply reverse for a sufficient duration to prevent ourselves from relatching onto the pole.

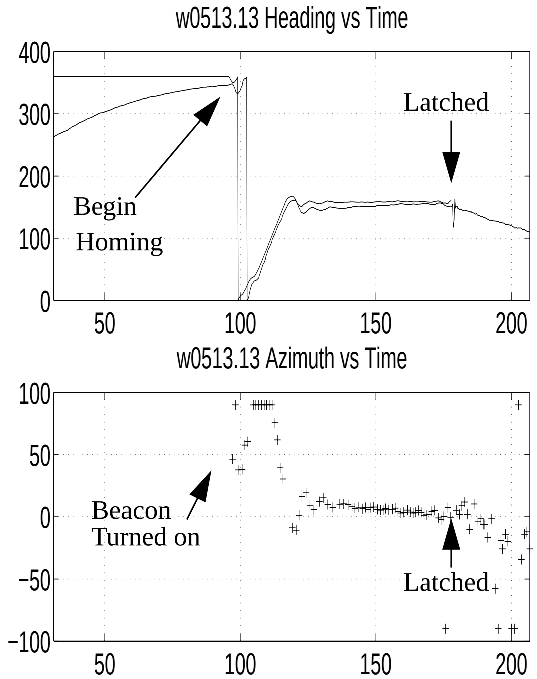

Figure 4. Homing into the Dock

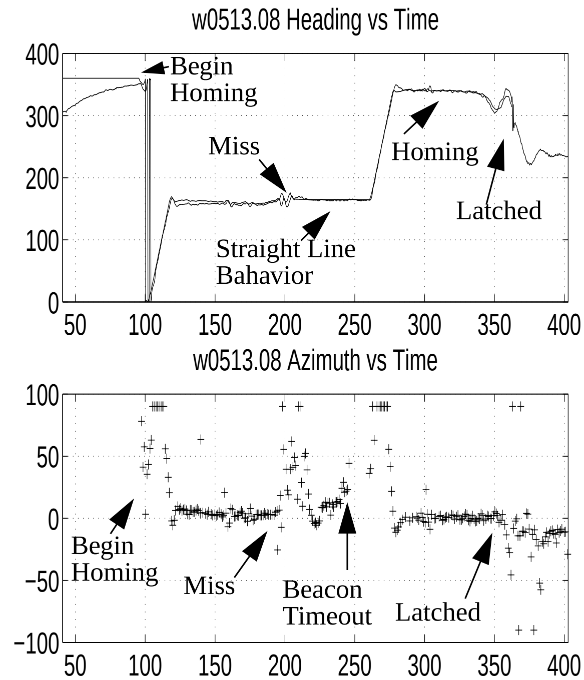

Figure 5. Homing: Miss, Dock

vehicle on its first approach.

On determining a miss the vehicle drives in a straight line for a fixed interval (in our case we chose 45 seconds) so that the AUV has room to maneuver without being caught in a spiral around the dock. It then reacquires the beacon and begins the process of homing again.

Figure 5 shows another run where the AUV did not successfully latch onto the dock on its first attempt. However, it did determine by looking at its range rate estimate that it had missed and went into a straight line behavior. At this juncture the beacon timed out but the AUV restarted the beacon, reacquired, and homed successfully in to the pole. *Docking* — The AUV goes into its docking behavior when its latch is tripped. The latch, a picture of which is shown in Figure 6, is designed after the working of a common door hinge and is mounted on the bow of the vehicle.

The latch consists of a vee-shaped, bilaterally symmetrical, titanium latch body with two fixed tines and a pivoting titanium capture bar. The docking pole on the mooring enters the latch anywhere between the two fixed tines of the latch body and is directed toward the AUV centerline, taking advantage of the forward motion of the AUV. The pole then pushes the capture bar aside and enters a nest in the latch body, where an extension spring closes the capture bar around the pole. The AUV may latch onto the pole anywhere within a one-meter length. When latched, the geometry of the capture bar ensures that the AUV remains safely mated to the pole and is unable to force its way out. To unlatch, a solenoid briefly opens the capture bar, allowing the pole to escape the latch.

Figure 6. The Docking Latch

Core Alignment — The cores are aligned by driving a motorized carriage up the pole so that it forces the vehicle to slide up the pole. Guiding struts on the top assembly force the pucks on the vehicle

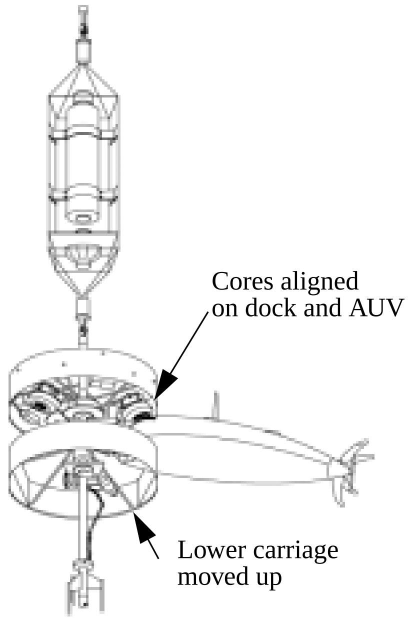

Figure 2. A Docked AUV

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THE DOCKING SYSTEM

The whole task of undocking from a mooring, carrying out a specific mission and then redocking may be defined functionally by breaking it up in the following manner.

Homing — On the dock a homing beacon sends out a barker code at 2Hz. An ultra-short baseline system[2][3][4] on the vehicle uses this signal to calculate an azimuth and elevation to the dock which it uses to home in on the dock[2]. In addition the free-running Barker code being emitted by the beacon has a very precise inter-ping interval, knowledge of which at the AUV end, allows us to obtain a range rate estimate of the AUV as it approaches the dock. This range rate may be integrated to yield a range to the dock as long as we have an initial position obtained by some other means such as long baseline navigation. We note here that the range rate by itself allows us to decide whether we are approaching the dock that is, we are homing, or moving away from it which may signify a miss.

The process of homing is initiated when the computer on the AUV, using long baseline navigation decides that the vehicle is in the vicinity of the dock. We typically begin homing from 100m-200m away though much longer ranges of up to 1 km in shallow water were obtained. The AUV starts the homing beacon by transponding on it more than four times in a ten second interval. The beacon once turned on, remains on for a period of 150 seconds. When the vehicle hears the homing beacon through its USBL system it attempts to null the bearing to the dock. It continues homing until either of the following happens — its latch trips indicating that it has docked; or the range rate to the dock undergoes a sign reversal telling us the AUV has missed on this approach. Once the latch trips, the homing portion of the behavior turns over command to the behavior that deals with the docked vehicle.

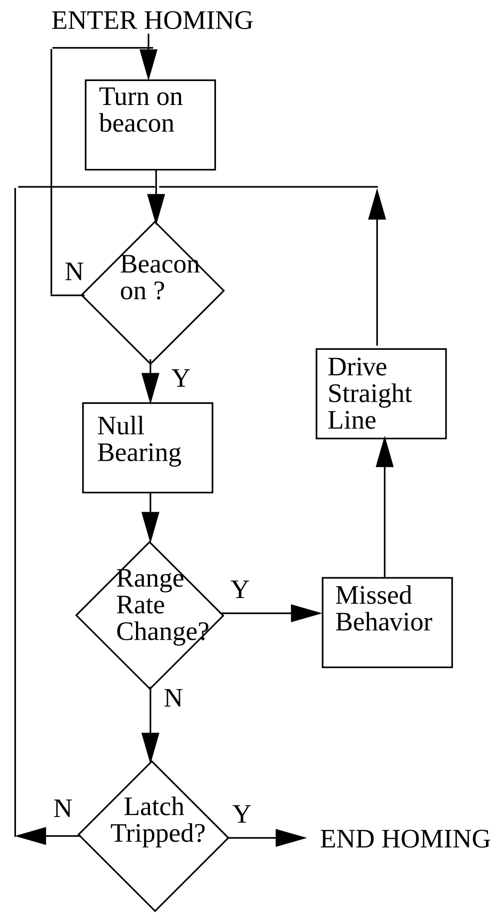

Figure 3. The Homing Behavior

Figure 3 is a simplified version of the flow chart that determines vehicle behavior during homing. It outlines the flow of the algorithm for homing onto the dock and the manner in which the vehicle deals with conditions which arise in the interaction with the homing beacon. This flow chart is executed at 5Hz corresponding to the vehicle control cycle.

Figure 4 shows one run where the vehicle turned on the beacon, acquired it almost immediately, turned around from its initial heading of 350° to a heading of 150° and then successfully docked to the

Intelligent Docking for an Autonomous Ocean Sampling Network

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ABSTRACT

In this paper we examine the complexities associated with docking for autonomous underwater vehicles (AUVs) operating within an autonomous ocean sampling network. By looking at the different stages in a typical mission profile for a number of actual runs, we can qualitatively estimate failure rates for each of the different stages of docking. We examine statistics for the following stages - undocking and launching the vehicle; completing the mission; returning to the vicinity of the dock; turning on the homing beacon; homing into the dock; latching onto the dock; and finally aligning inductive cores for power transfer. Despite differing probabilities of success for the individual stages, we show that the redundancy associated with retrying each stage until the exit condition is met, is sufficient to yield a very high overall sytem reliability.

INTRODUCTION

One of the basic tasks actively being pursued under the autonomous ocean sampling network[1] multi-disciplinary university research initiative is the ability to do repeated missions with an autonomous underwater vehicle at a remote site. A demonstration of such a capability to study convective overturning in the deep ocean is planned for the Labrador Sea over the course of the winter of 1997-1998.

The Labrador Sea deployment envisages two moorings and three MIT Odyssey IIB class vehicles being deployed onsite. Surface expressions from the moorings will provide limited data access via satellite to sites onshore. The harsh environment one expects to see at such a site, coupled with the high degree of autonomy that is required to accomplish such a task necessitates a complex mechanical, electronic and computation system for dock and vehicle systems. Our approach to the design of the docking system is to decouple individual components functionally into simpler self contained subsytems.

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In this paper we outline the entire docking system functionally and algorithmically. We describe the results of trials that were conducted off of the *R/V Cape Hatteras* in May of 1997 that tested each of the individual components as well as the overall system. The system was seen to be remarkably robust and reliable in the face of wind induced current and associated dock motion.

Figures 1 and 2 are an artist's rendition of the docking system as it exists today. The AUV drives into a pole on the dock such that a latch mounted on the bow of the AUV trips and ensures that it is captured by the dock. The lower moveable carriage on the dock is then driven up to force inductive cores on the AUV and the dock into alignment.

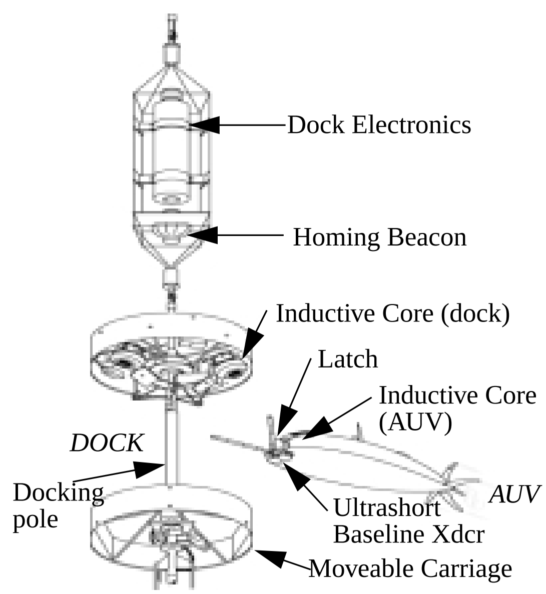

Figure 1. The Docking System