AUTONOMOUS UNDERWATER VEHICLE HOMING/DOCKING VIA ELECTROMAGNETIC GUIDANCE

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Abstract

Central to the successful operation of an Autonomous Undersea Vehicle (AUV) is the capability to return to a dock, such that consistent recovery of the AUV is practical. A number of homing technologies have been proposed and tested, with acoustic homing generally the most prevalent. Accurate acoustic homing requires systems with high update rates, and extensive signal conditioning if AUV orientation is required, as well as, bearing and distance to the dock. Vehicle orientation becomes increasingly important in the final stages of the docking, as large changes in orientation near the dock are impractical and often not possible. An Electromagnetic Homing (EM) system is one alternative that can provide accurate measurement of the AUV position and orientation to the dock during homing. This system offers inherent advantages in defining the AUV orientation, when compared to high frequency acoustic systems. The design and testing of an EM homing system is given, with particular attention to one can be adapted to a wide class of AUVs. The EM homing system consists of a dock with EM coils that provide the homing signal, and set of sensing coils that are mounted in the AUV. The present tests used the MIT Sea Grant Program Odyssey AUV as the test vehicle. A number of homing, docking and latching trials were successfully performed with the design. Homing data include dead reckoning computation and acoustic tracking of the homing track, and video documentation of homing into the dock.

I. Introduction

Available sensors for oceanographic measurements have increased in number and capability with recent advances in microprocessors, communications, microelectronic machining, and the ability to integrate smaller components into multiple sensor packages. Unfortunately, this increase in sensor capability has been accompanied with increased sensor costs. In addition, techniques such as burst sampling and digital signal processing have greatly increased the capability to obtain and use, and consequently the desire to acquire much larger amounts of data. This ability to acquire and use large data bases has lead to a need to obtain data on a scale that continues to expand. Acquisition and storing of large amounts of data has also increased the costs associated with oceanographic sensor packages. Efforts to reduce these costs by increased sensor utilization, and/or by common or lower cost data acquisition/storage systems is a current objective. There have been several approaches toward this objective, and this paper addresses one such approach.

With increasing complex and expensive sensor suites and data systems, one approach to maximize their use is to mount sensors and data acquisition system on a moving platform. This provides maximum flexibility as well as utilization of an integrated system. This approach was adopted by Light and Morison (1989), who used a modified Mk-38 target torpedo with conductivity and temperature sensors. Utilization of this sensor platform, or autonomous underwater vehicle (AUV), for under-ice CTD measurements was described by Light (1993). In this operation, the AUV was recovered by acoustic homing into a capture net.

Recently, Curtin, Bellingham, Catipovic, and Webb (1993) proposed a system of AUVs to form a spatially and temporally dense network of sensors for a variety of oceanographic observations. The focus of this application is on data for hypothesis testing and long term monitoring. Multiple AUVs form a network for oceanographic sampling, and the system is called an Autonomous Oceanographic Sampling Network (AOSN). For full autonomous operation, the AUV must not only transport the sensors to the desired location(s), but also return to a buoy/dock, with the data taken in the prior mission downloaded to the buoy, and the energy system of the AUV recharged. The AUV would then be released for the next mission. Plans call for a satellite up-link from the buoy for "real-time" transmission of the data to a home base.

Much of the work to date has been on a suitable platform to transport the sensor and data acquisition systems. This was addressed by Curtin et. al. (1993) and more recently in an article on the MIT Odyssey AUV by Altshuler, Vaneck and Bellingham (1995). However, for autonomous operation, the AUV must not only transport the sensors to the desired location(s), but must also return to and home into the dock. This homing/docking

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0-7803-4108-2/97/$10.00 ©1997 IEEE

function requires a homing system, consistent with the AUV dynamic response, to provide guidance into the dock, and a method of securely "locking" the AUV in the dock. Finally, after being secured in the dock, the AUV and the dock must have communication with each other, so that the data obtained by the AUV can be transferred to the dock, and method for power transfer from the dock to the AUV. This paper describes an electromagnetic homing system that has been used to home and dock the Odyssey AUV. It has been used with an inductive power and communication interface, however, the primary focus of this paper is the homing and docking system.

II. Homing Guidance Options

The primary requirement of the homing system is that it provide guidance for the AUV to return to, and maneuver into the dock. This system must be consistent with the AUV dynamic response capabilities, in that it not require maneuvering which is frequently at the edge of the AUV's ability to respond. There are a number of available technologies for underwater guidance including, optical, acoustic and electromagnetic (EM) systems. Optical systems provide good response in non-turbid environments, but may be limited over a wide range of background lighting and water turbidity conditions. In addition, with an optical system, the optical sensors must have "line of sight" access before homing can be initiated. Acoustics are proven for position finding at distances to less than 1 meter, and under a wide variety of oceanographic conditions. However, the orientation of the AUV to the direction of the acoustic signal is difficult to precisely define in real time. Moreover, successfully homing when the AUV is very close to the dock, requires precise spatial measurements with fairly rapid temporal resolution. It is in the last stage of docking, where the AUV is close to and approaching the dock, that is the most critical and difficult in the docking operation. For an acoustic system, this translates into a system with a high up-date rate, which often means the homing system must be dedicated to this operation. Finally, an acoustic system will have increased complexity if it must operate near the surface, bottom or other sources of reflected acoustic signals.

The design or configuration of the Dock will also set constraints on the homing system. Generally there are two types of docks. One is a conical system which requires the AUV to enter into the dock from a single direction. The other is a omni-directional system, where the AUV can approach the dock from any direction. The conical system clearly puts increased constraints on the homing system, but offers a simplified dock design and docking procedure, as well as possibly better access to and more robust protection of the AUV. The omni-direction dock requires less of the homing system, at the expense of increased dock complexity. Thus, the choice of homing system is integral with the dock configuration. As might be expected, there are differing views as to which integrated dock/homing configuration is likely to provide the optimum system. The present approach has adopted the conical dock, and thus a homing system that is compatible with this dock is required. This translates into the requirement that the homing system sense both the angle to the dock entrance, as well as the bearing to the dock.

Given the requirements of a dedicated system for near field homing, a precise (less than 20cm) position location near the dock, and the desirability of sensing not only the AUV bearing to the dock, but also the orientation of the AUV relative to the entrance of the dock, an electromagnetic (EM) system was selected for the homing application. This EM system operates with a dipole magnetic field generated at the dock, and sense coils in the AUV to measure the bearing and orientation relative to the dock entrance. For this application, the dock is a cone, with a 1 m dia base. The base is open and serves as the entrance into the dock. A schematic diagram of the system is shown if Fig. 1. In operation, magnetic field sensors in the AUV identify a magnetic field line emanating from the dipole on the dock, and the AUV simply follows the field lines into the dock entrance. A straightforward PID control loop supplies the control response of the AUV. The system has been implemented in the dock described above, which has an opening or capture dia of 1 m. The AUV used here was the Odyssey AUV from the MIT Sea Grant program, with the addition of magnetic field sense coils installed in the nose, and a modification to the control algorithm used during homing. A number of tests of the system were conducted, and the results are given. These include the near field position accuracy and limitations on the range of the homing system.

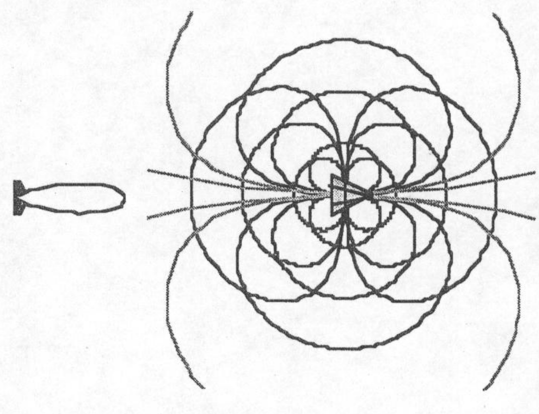
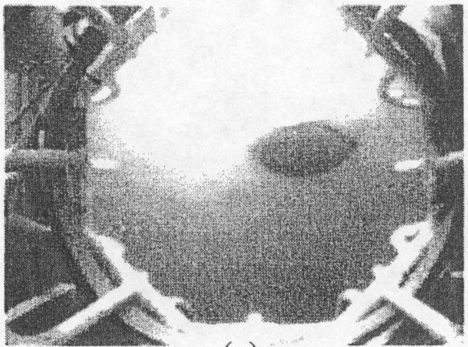


Fig. 1 Schematic of EM homing system showing field lines and the dock

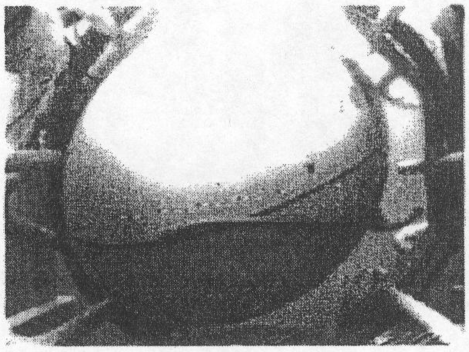
III. Description of the EM Homing System

The EM homing system consists of a transmitter located on the dock and the receiver located on the AUV. The transmitter generates orthogonal magnetic dipole fields from the docking location. Both fields are oscillatory, the horizontal dipole field at 2kHz, and the vertical dipole field at 1kHz. The horizontal field is used for directional control and the vertical field primarily for synchronization. The receiver in the AUV senses both of the

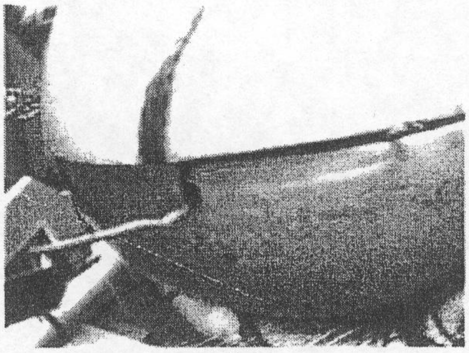
Three frames from the video camera mounted on the dock are shown in Fig. 4. In the first frame, the AUV is just coming into view of the camera. The top of the vehicle is barely visible because of light from the surface. The second frame given, is just as the vehicle is entering the dock. The last frame is after the AUV has fully entered the dock, and the latch has hooked onto a cable from the nose of the AUV. The latch is remotely operated. This frame is from a different test than the first two frames. In the first two the latch was not operating, and hence the wire cable is not present in the nose of the AUV. The video system removes any ambiguity at to successful docking or not, and if the latch is present, if the latch has fully captured the vehicle.



(a)



(b)



(c)

Fig. 4 Sequence of frames from the video camera mounted on the dock, as the AUV approaches the dock (a), enters the dock (b), and is captured by the latch mechanism (c)

As mentioned, the long range goal of the AOSN system is for autonomous monitoring. The present Odyssey was used in this mode to perform a survey of the magnetic field supplied by the coils on the dock. In this mode, the AUV was programmed to travel in a search mode, which is a series of loops that search the region of interest. These loops were approximately 100 m long in the North-South direction, with each path programmed to be 10 m further toward the East than the previous path. Because of the sea current some of the programmed paths overlapped. The actual path was monitored with the acoustic range finding system. The magnetic field sense coils in the AUV, which are a part of the homing system, were used to measure the magnetic field produced by the dock. These data are of interest, not only to demonstrate the concept of using an AUV for monitoring oceanographic data, but also to measure the strength of the magnetic field in the region of the dock. This data can then be used to predict the range of the EM homing system. The results of the magnetic field survey are shown in Fig. 5. The dark regions, are the regions in which data was not obtained, either due to low field strength, noise or simply missing in the data acquisition system. The data show the high spatial resolution that can be achieved using this technique. Based on these data the effective range of the EM homing system in sea water is estimated to be around 25-30 m.

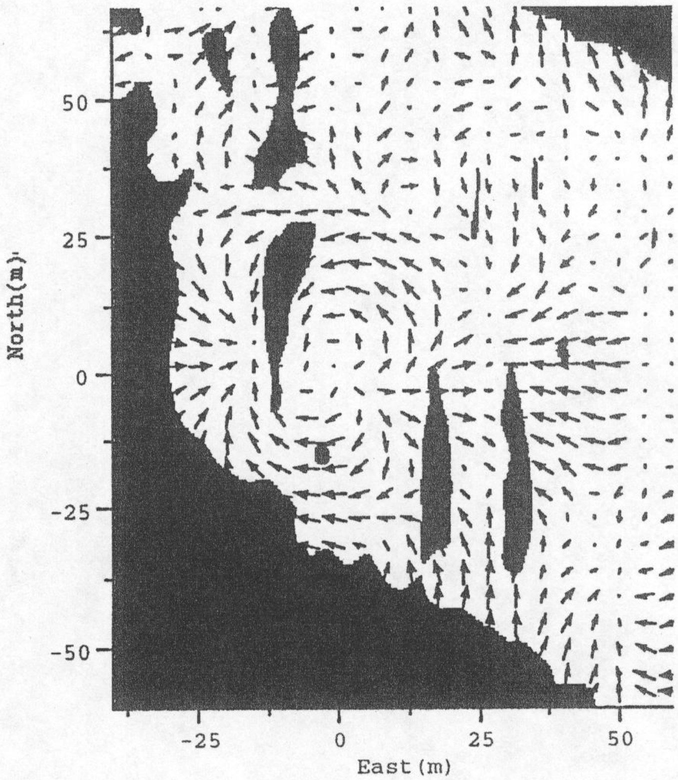


Fig. 5 EM field lines measured using the homing sense coils mounted in the AUV

become reversed. If the homing system is allowed to assume control in this region, the AUV will actually turn away from the dock. In principle, this effect could be eliminated, and the useful homing range increased, by using the field strength to estimate AUV-to-dock distance, and then correcting the phase shift based on the conductivity of the sea water. An alternative to this would be to use two frequencies for the horizontal and vertical coils that are closer to each other. In that way the relative phase lag between the two signals would be less. At this time neither of these techniques to increase the range of the homing system has been attempted.

Because most fouling substances in the ocean have nearly the same magnetic permeability as sea water, fouling does not change the magnetic field distribution. Thus, the EM homing system is robust to fouling of both the transmitting coils on the dock, as well as the sensing coils on the AUV. About the only thing that will change the field distribution is a relatively large (to the coil diameter) volume of material with different magnetic permeability located directly in or near the homing field. Therefore the EM homing system is not significantly perturbed by some of the factors that effect other systems, such as mists or clusters of bubbles, floating organic matter, or air/sea and/or bottom/sea boundaries. Because the field lines in a dipole are closely bounded, in order to alter the field lines, a magnetic disturbance must be directly in the homing path. This have been verified by successful operation in the presence of a large metal ship located only 5 meters behind the dock. There is the possibility of a sharp salinity gradient, with corresponding gradient in conductivity, altering the magnetic field distribution. In order to alter the field enough to effect the homing, this would have to occur on a length scale about the same as skin effect characteristic length. This is extremely unlikely in oceanographic conditions. Thus the EM homing system has the capability of robust operation over a wide range of oceanographic conditions and parameters, and is unpertubed by virtually all of the common phenomena that occur in the ocean.

IV. Results from Field Trials.

A number of shallow water tests in fresh water were made to de-bug the system and establish the optimum control gains. After this was a series of test in Buzzards Bay, near Woods Hole Oceanographic Institution, in April 1996. These tests not only included the control system response, but the dead reckoning computations and acoustic tracking of the path into the dock. The results given in this section are a sub-set from the Buzzards Bay trials.

For the Buzzards Bay field trials, the dock was suspended by a crane from the Diane G, which is an approximately 100 ft steel vessel. The AUV was launched from a small work boat attached to the side of the Diane G, and about 10-20 ft away from the dock. The AUV was programmed to travel outbound from the launch point for 60 sec, execute a 180 deg turn, and travel back toward the ship and dock. The AUV remained under internal computer control until the magnetic field sense coils detected a predetermined magnetic field strength. At this point, control of the AUV was shifted from the compass and depth sensors to the homing system. The AUV propulsion system was programmed to shut down or to reverse the direction of the thrustor 60 sec after the 180 turn. Thus shortly after the AUV docked or missed the dock, the power was shut down, or the AUV attempted to back out of the dock. After series of trials to assure that all sub-systems were working properly, a total of 8 homing tests, with all systems functional, were conducted. All tests were with 60 sec outbound and then the return, and were over a two week period. The speed of the AUV varied between 1.5 and 2 m/s and the prevailing currents were from 6 to 30 cm/s. The direction of the pervalling current was typically at 350 °. Of these eight tests, five produced successful homing into the dock.

The tests were monitored with an underwater video camera mounted on the rear of the dock, and looking toward the entrance of the dock In addition, the AUV position was monitored with an acoustic range finding system. After docking, the data taking during the mission was also recorded, and could be used to provide a dead reckoning path of the AUV. These data are given for one of the successful homing tests. The tracks for both the dead reckoning path and the acoustic range finding track are shown in Fig 3. The top path is that computed by dead reckoning, that is by using the compass heading, AUV speed and time. The lower track is that from the acoustic range finding system. The two tracks have been offset, to enable a better view. For both cases, the outbound track is solid and the inbound track is dashed. The acoustic track has considerable scatter and thus it provides only an approximate path as the AUV homes toward the dock. However, there are some real oscillations in the path as the AUV nears the dock, because of the system response during homing.

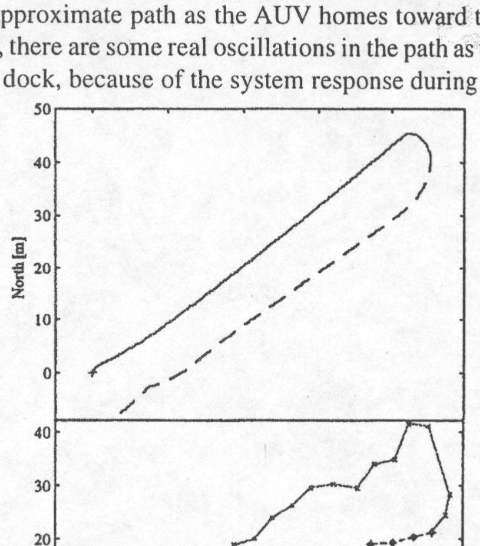


Fig. 3 Horizontal path of the AUV for a homing trial. The top track is the dead reckoning path and the bottom track is measured by acoustic range finding

two fields. A synchronous detector derives x and y field direction from the horizontal field using the phase information from the vertical field. The magnetic dipole fields are generated by two coils mounted on the dock. One coil generates the 2kHz horizontal or directional field, and spans the entrance of the dock. This is shown in Fig. 2. The other coil is wound in the horizontal plane of the dock and generates the sync field. This coil is horizontal, and is two coils, as shown in Fig 2. In this configuration the ends of the coils toward the dock opening are slanted up-ward, to entrance into the dock. This field has its predominate component perpendicular to the horizontal plane containing the dock at all points near this plane. The complete dock and coil configuration are shown in Fig 2. Both coils are 64 cm in diameter and have 24 turns of #12 wire. The power output into each coil is approximately 15 watts.

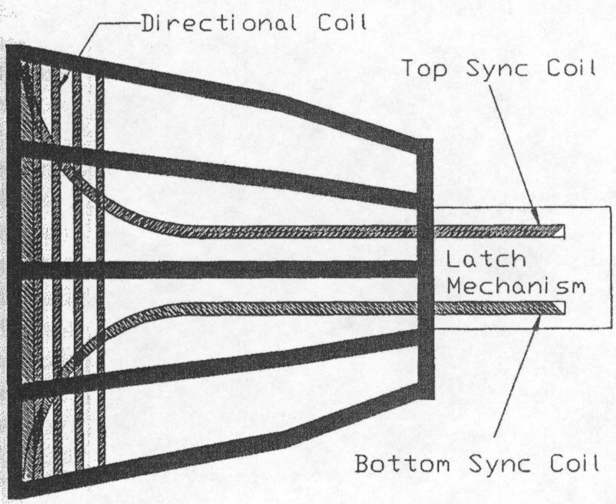


Fig. 2 Drawing of dock showing the coils that generate the horizontal and vertical magnetic fields

Two frequencies are used to avoid confounding the fields when the ship is out of the horizontal plane containing the dock, or when the dock rolls or pitches. The changing attitudes result in some vertical signal appearing in the horizontal channel and some horizontal signal appearing in the vertical channel. Because the two signals are at different frequencies, the undesired component in each is removed by filtering out the other signal.

The transmitter employs a resonant topology to generate a large circulating current in the dock coils with a minimum of power loss and a minimum current in the feeder lines. The resonant topology also minimizes radiation of acoustic and magnetic components at frequencies other than the 1 and 2kHz frequencies. The transmitter frequency is quartz crystal controlled, with the 1 kHz frequency component derived from the 2 kHz signal using a digital divider. This ensures proper relative phasing of the two signals.

The field sensing coils in the AUV consists of three orthogonal coils, 9 cm in diameter, each with 25 turns of small gage magnet wire. One of the coils in the horizontal plane, and the other two coils are in the vertical plane, and perpendicular to each other. The horizontal coil picks up the vertical field component and is used to synchronize a synchronous detector. The two vertical coils are used to measure the direction field and to resolve it into two orthogonal components. These three signals each pass through three-stage automatic gain control (AGC) circuits which effectively normalize the signals with respect to one another, and limit the dynamic range seen by the detector. It also normalizes the demodulated directional signals.

The demodulated directional signals provide the sine and cosine of the angle of the local horizontal magnetic field component with respect to the axis of the ship. This gives the number of degrees that the ship must turn in order to follow the local field. The 2kHz or vertical component of the magnetic field is used to estimate the vertical angle of the local horizontal dipole field. The homing circuit derives a pitch error signal from this component which is the angle that the ship must pitch to follow the field. Because the horizontal field emanates from a coil spanning the dock, Fig. 2, all field lines generated by this coil must enter the dock. In order to home or enter into the dock, the AUV only has to follow one of these field lines as it approaches the dock.

The AGC circuits each use three stages of variable gain control. The control signal is derived by combining the outputs of the synchronous detector. In a non-conducting medium, the field strength varies as the cube of the distance from the dock, and the AGC gain varies as the cube of the AGC voltage. Thus with a non-conducting medium, the AGC voltage provides a linear estimate of the distance of the ship from the dock. The fact that the dipole field strength varies by a factor of 2 between the axis of the dipole and a point abeam the dipole results in about a 20% error in this estimate when the ship is abeam the dock. This variation applies to the directional field, and not to the sync field, since in a normal homing scenario, the AUV is always nearly abeam the sync field. In air the directional signals are usable to a distance of about 100 meters with the AUV computer operating, but without operating the AUV servos. The magnetic noise generated by the servos limits the usable range to about 75 meters.

In a conducting medium, such as salt water, there is an additional attenuation due to the "skin" effect. The skin effect is a function of frequency, and results in differential attenuation of the 1kHz and 2kHz signals, in addition to a differential phase shift. The differential attenuation thus reduces the useful range of the homing system. The differential phase shift causes the authority of the directional control to weaken with distance from the dock, and to eventually reach a null. At typical sea water salinity and temperatures, this reduces the range to approximately 25-30 meters. This is determined experimentally, and the data are given in the next section. Beyond this range, the magnitude of signals is such that they are readily detectable, but because of the different phase lags at the two different frequencies due to the conductivity of the sea water, the sense of the signals will

V. Summary

An EM homing system that uses a magnetic field generated by coils on the dock, and sensed by smaller coils in the AUV has been developed and tested. The system provides precise, better than 20 cm, homing position into the dock. The EM homing system supplies not only the bearing to the dock, but in addition the angle of the AVU relative to the field lines, and thus the angle relative to the dock entrance. This provides for more precise control of the AUV in final stages of homing. The major advantage of the capability to sense relative angles is that entrance into the dock is from a single direction, and thus a single direction dock can be used. A further advantage is that common oceanographic phenomena, such as turbidity, bubbles, floating organic materials, and boundaries at the surface of bottom do not alter the field lines. Thus the system is quite robust under almost all conditions encountered in the ocean environment.

The range of the present system is limited to 25-30 m, although two options to increase this range are suggested. Because of this, the system as viewed as being most applicable to the final stages of homing by an AUV into a dock that has a single angle for entry. This type of dock offers inherent advantages, and the EM homing system integrates bearing and orientation required by this type dock with a precision that is difficult for other systems to provide. Because of this the EM homing system has the potential for improved homing under adverse conditions.

VI. Acknowledgment

This work was supported by the Office of Naval Research, through Grant No. N00014-95-1-0826.

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