

Docking for an Autonomous Ocean Sampling Network

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Abstract—In this paper, we examine the issues associated with docking autonomous underwater vehicles (AUVs) operating within an Autonomous Ocean Sampling Network (AOSN). We present a system based upon an acoustic ultrashort baseline system that allows the AUV to approach the dock from any direction. A passive latch on the AUV and a pole on the dock accomplish the task of mechanically docking the vehicle. We show that our technique for homing is extremely robust in the face of the two dominant sources of error—namely the presence of currents and the presence of magnetic anomalies. Our strategy for homing is independent of the initial bearing of the dock to the AUV, includes a method for detecting when the vehicle has missed the dock, and automatically ensures that the AUV is in a position to retry homing with a greater chance of success. Our approach is seen to be extremely successful in homing the vehicle to the dock, mechanically attaching itself to the dock, aligning inductive cores for data and power transfer, and undocking at the start of a fresh mission. Once the AUV is on the dock, we present a methodology that allows us to achieve the complex tasks with ensuring that the AUV is securely docked, periodically checking vehicle status, reacting to a vehicle that requires charging, tracking it when it is out on a mission, archiving and transmitting via satellite the data that the AUV collects during its missions, as well as providing a mechanism for researchers removed from the site to learn about vehicle status and command high-level missions. The dock is capable of long-term deployments at a remote site while respecting the constraints—low power, small size, low computational energy, low bandwidth, and little or no user input—imposed by the amalgamation of acoustic, electronic and mechanical components that comprise the entire system.

Index Terms—Acoustic ultrashort baseline system, autonomous underwater vehicles, AUV docking, homing strategies.

I. INTRODUCTION

THE AUTONOMOUS Ocean Sampling Network (AOSN) [1] concept envisions a number of autonomous underwater vehicles (AUVs) deployed at a site of oceanographic interest for conducting adaptively sampled spatio-temporal surveys. A

number of systems are actively being deployed or tested that are aimed at providing a long-term presence in the ocean environment through the use of AUVs and docking nodes. One such system uses the Remus AUVs and has been deployed at the LEO-15 site off of New Jersey [4]. Another system utilizing the Florida Atlantic University's fleet of AUVs is being built for use off of the Florida coast [7]. Still another system, the Eurodoker, is being tested off of a ship but with longer term deployments in mind [6]. What is unique about our system in comparison to other systems that are currently being deployed or developed [4], [6], [7] is the requirement for operations at remote sites with the consequent low-bandwidth connection between dock and remote users. Essentially, this has dictated a dock that operates autonomously. The various components of the docking system are illustrated in Fig. 1. The dock consists of battery housings, an electronics housing that contains a PC-104 based computer, a homing beacon, and a pole along which a motorized carriage can ride, based on commands from the dock's computer. The dock computer can talk to the AUV via an inductive link as well as via an acoustic modem. It is also connected via electromagnetic conductors to a buoy on the surface. The surface buoy is powered independently and contains its own PC-104 computer. Besides communicating with the dock, it provides a link to remote users via satellite as well as a more immediate link to users on a ship in the vicinity via an RF modem.

The AUV homes into a beacon on the dock using an ultrashort baseline (USBL) system. It 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. Once the AUV is securely latched, it communicates with the dock via its acoustic modem and the upper movable carriage on the dock is driven down to force inductive cores on the AUV and the dock into alignment. Magnetic switches confirm that the cores are indeed aligned. These cores can then be used for power and data transfer between the dock and AUV.

The basic required algorithmic structure for autonomous docking can be described by a flowchart, as shown in Fig. 2. After an AUV latches onto the dock, the dock detects the presence of the AUV and runs its motorized carriage to align the inductive core on the AUV with the inductive core on the dock. Once the inductive cores are in alignment, the data from the AUV's mission is transferred and archived and then suitably compressed and relayed by satellite back to remote users on shore. The dock then begins the longer process of recharging the AUV's batteries. Once the vehicle is ready, the dock waits until it is time to send the vehicle on its next mission. While the vehicle is on its mission, the dock communicates with the AUV

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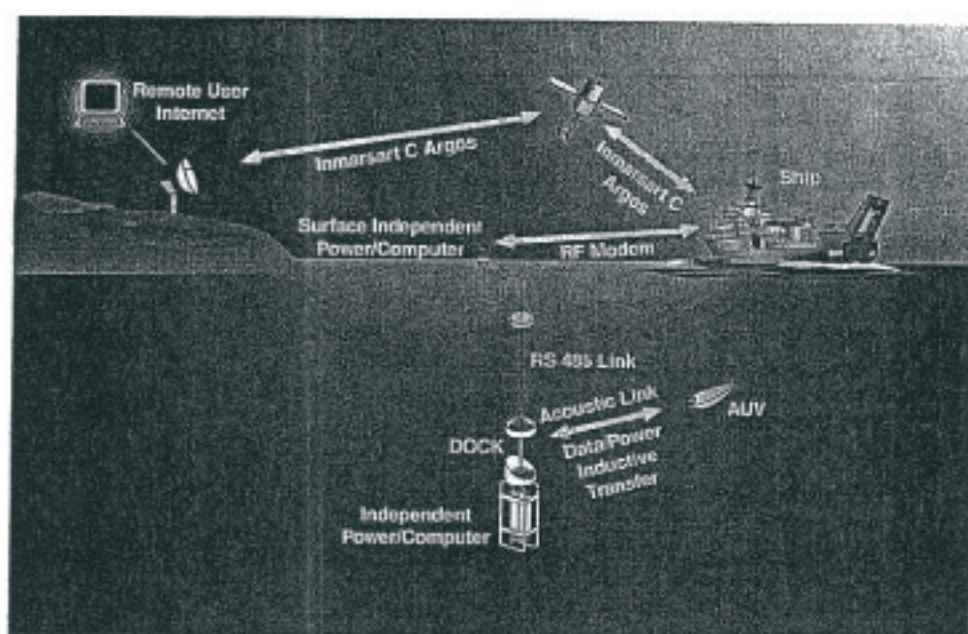


Fig. 1. Implemented data paths between the dock, AUV, and remote users.

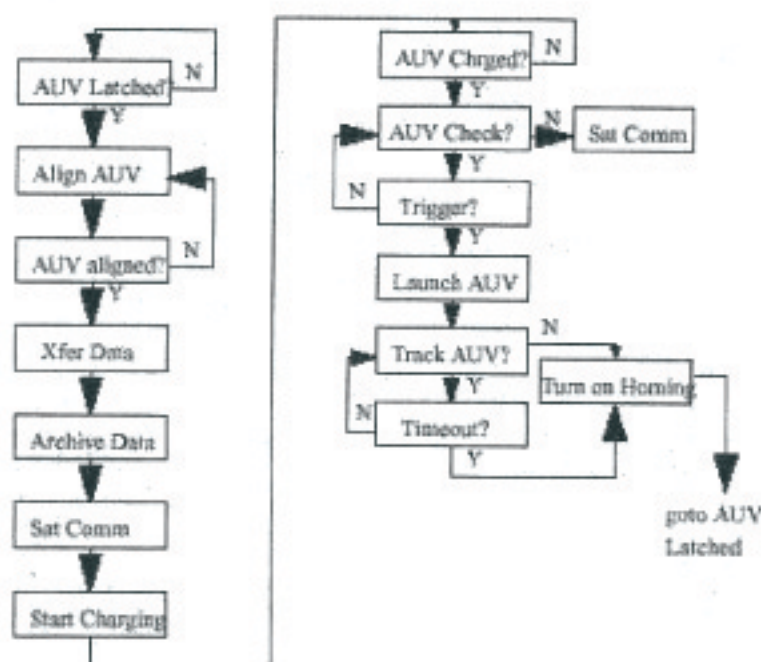


Fig. 2. A simple flowchart for autonomous docking operations.

via an acoustic modem and tracks the vehicle until it returns safely. For multiple missions, this cycle continues.

From a docking perspective, we can divide the tasks into two distinct categories. The first category of tasks are AUV-centric and relate to physically navigating the AUV into proximity of the dock, or homing, while the second category of tasks are more dock-centric and deal with autonomously servicing the needs of the AUV in terms of data and power transfer as well as the needs of remote users to interact with the AUV to enable adaptive surveys.

If we look at the tasks associated with homing, a number of docking systems have been proposed, are actively being de-

ployed in tests, or are currently being designed and built. These are based on electromagnetic (inductive coil) sensors [5], optical sensors [3], and acoustic sensors [4], [6], [11], [12] and aim to dock the AUV to a cone [3]–[5] or cage [6]. Another system being developed uses a tailhook to dock to a bottom-mounted assembly [7].

The tradeoff between the electromagnetic (both optical and inductive) and the acoustic systems is that between range and update rates. The acoustic systems provide the capability to begin homing at distances as far as 200 m away in shallow water, but only at update rates of a few hertz. The performance of transponder-based systems, in terms of update rates, can be

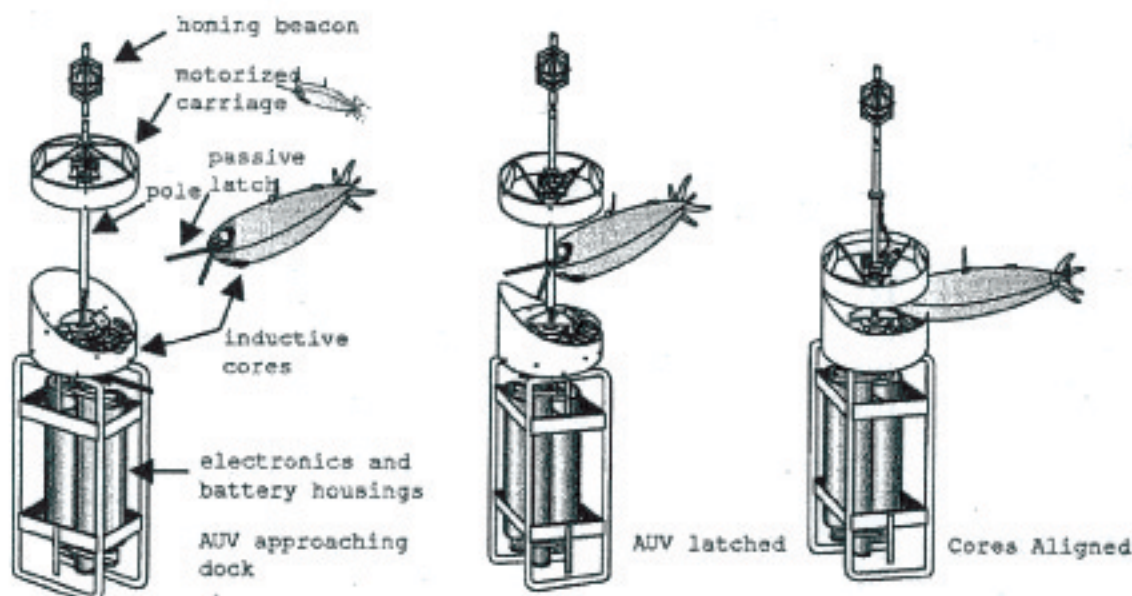


Fig. 3. The AUV-centric components of the docking system. The AUV passively latches onto a pole and a aligning inductive cores on the AUV and the dock to enable data and motorized assembly drives down power transfer.

much worse due to finite travel times associated with the velocity of sound in water. The electromagnetic systems on the other hand, can provide very high update rates, far higher than the intrinsic control cycles (of the order of 10 Hz) of most AUVs but are limited in their range of initial acquisition to distances of 10 to 20 m due to the rapid attenuation of electromagnetic radiation in sea water. With the exception of the bottom-mounted tailhook system [7], all the systems described above dock to a cone or cage, a geometry that is also limited with respect to the angle from which the AUV may approach the dock. Such a geometry may be acceptable in areas where the dock is fixed on the bottom and the environmental conditions are well known, but it is not generally amenable to use on an oceanographic mooring where weather vaning of the cone or cage would complicate the process of docking. As we elaborate later in this paper, our approach is based on a methodology for omnidirectional docking of an AUV that is capable of being deployed in both shallow and deep water.

If we look at the dock-centric issues associated with an AOSN, the flow chart in Fig. 2 captures, at a simplistic level, the essence of all the tasks that are required of the dock. However, it does not address all the issues that are necessary for reliable long-term operations. The most important of these issues include the asynchronous nature of autonomous operations; fault detection and tolerance, that is, the reliability of the system in the event of subsystem failure; the low-bandwidth, significant delay link associated with satellite communications; the power budget associated with a deployment that lasts several months; the protocols for dock, AUV interactions; and the precise nature of remote access for users onshore. In this paper, we look at each of these issues in turn and their combined effect on the overall system design. We should point out that two of the major components of the docking design, namely, the battery technologies and inductive data and power transfer and the issues associated with mooring design, are detailed separately in related papers in this issue [13], [14].

In the succeeding sections, we provide an analysis of the major sources of error involved in docking small AUVs with solutions for these sources of error (Section II). We look at the tasks related to system requirements for autonomous operations (Section III) and our system design (Section IV) and provide a discussion of failure modes and reliability (Section V) and the results of using our entire system and future directions of research (Section VI).

II. THE HOMING SYSTEM

Fig. 3 is an artist's rendition of the homing components of the docking system. In the context of the other systems discussed in the introduction this system offers the advantage that it is omnidirectional and that the range of acquisition for the homing is easily 200 m in shallow water and far greater (measured at 1 km) in deep water. Moreover, instead of a transponder based system we utilize a synchronous pinger that ensures a high update rate (3 Hz) independent of the range of the AUV from the dock. Also our system is capable of being deployed and has been demonstrated in depths as shallow as 5 m and as deep as 3500 m. We point out that the simplicity in design of our docking mechanism, a pole as opposed to a dock, is offset somewhat by the complexity of mounting an additional assembly, a latch, on the AUV.

Our approach to the design of the docking system is to decouple individual components functionally into simpler self-contained subsystems. This allows us to focus on the critical issues for each subsystem as outlined in the next section and yields a very high degree of overall system reliability. The whole task of undocking from a mooring, carrying out a specific mission, and then redocking may be defined functionally by breaking it up into subtasks associated with homing, latching, aligning cores, and undocking. We now look at each of these issues in turn.



Fig. 4. Vehicle angle ϕ and θ used in stability analysis.

A. Homing

On the dock, a homing beacon transmits a coded waveform (a barker code) [2] which is optimized for multipath discrimination common in the underwater environment. An ultrashort baseline system [2] on the vehicle uses this signal to calculate an azimuth and elevation to the dock. Our algorithm for homing works by nulling the bearing to the dock. The heading control law is of the inner-outer loop type, wherein a traditional PID (the inner loop) ensures that the actual vehicle heading ϕ follows the desired heading ϕ_{des} , but the desired heading is generated by an outside mechanism. For homing, we use as the outer loop

$$\phi_{des} = \phi + \theta \quad (1)$$

where θ represents the bearing angle from the vehicle to the beacon, as shown in Fig. 4.

This algorithm is seen immediately to be insensitive to slowly-varying magnetic anomalies as whatever deviation appears in the measured ϕ is transferred directly to ϕ_{des} .

The achievable performance of the inner-loop controller is written as $\phi(s)/\phi_{des}(s) = G(s) = \overline{G}(s)/\underline{G}(s)$ where $G(s)$ denotes the closed-loop transfer function (with s the Laplace variable), and $\overline{G}(s)$ and $\underline{G}(s)$ are the numerator and denominator of $G(s)$, respectively. Incorporating the outer loop above, we have

$$\frac{\phi(s)}{\theta(s)} = \frac{\overline{G}(s)}{\underline{G}(s) - \overline{G}(s)}. \quad (2)$$

Next, we consider the evolution of θ in the absence of outer-loop control, that is, with the vehicle traveling in a straight line at heading ϕ . Some geometry and manipulation shows that

$$\tan \theta(t + \delta t) = \frac{\tan \theta(t)}{1 - \delta t(U/L)} \quad (3)$$

from which, with a small angle assumption for θ , we have

$$\frac{d\theta}{dt} = \frac{U}{L} \theta. \quad (4)$$

Here, U is the speed of the vehicle and L the distance to the beacon. This distance obviously decreases with time; we shall make the assumption, however, that L changes slowly and that letting L be constant is adequate for a local stability analysis, far from the beacon. This simplification is invoked several times below.

The effects of the outer control are assessed by observing that, if the vehicle is in fact allowed to yaw, the above is augmented to become

$$\frac{d\theta}{dt} = \frac{U}{L} \theta - \frac{d\phi}{dt}. \quad (5)$$

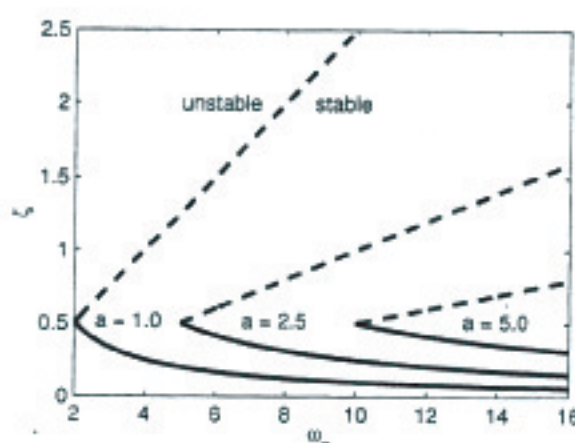


Fig. 5. Regions of stability for a second-order closed-loop response for the inner loop, parametrized with $a = U/2L$.

Inserting the inner-loop dynamics for $d\phi/dt$ gives a homogeneous equation in θ , for which the characteristic equation is simply

$$\frac{U}{L} (\underline{G}(s) - \overline{G}(s) - s\underline{G}(s)) = 0. \quad (6)$$

Two special cases help illustrate the dependence of the bearing response on $G(s)$. Note that, in still water, stability of θ is generally equivalent to stability of ϕ .

Case 1) First-order lag, no zeros.

With the approximation

$$G(s) = \frac{\lambda}{s + \lambda} \quad (7)$$

we find a simple (necessary and sufficient) condition for stability: $\lambda > U/L$, indicating that a high-bandwidth inner control is preferred and would probably enhance stability when L is small.

Case 2) Second-order lag, no zeros.

If we have the approximation

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (8)$$

the characteristic equation is

$$s^2 + (2\zeta\omega_n - U/L)s + (\omega_n^2 - 2\zeta\omega_n(U/L)) = 0. \quad (9)$$

Thus, defining $a = U/2L$, we have two conditions to meet, as follows:

$$\zeta\omega_n > a \quad (10)$$

$$\omega_n/\zeta > 4a. \quad (11)$$

In this case, stabilizing values for damping ratio ζ and undamped natural frequency ω_n are restricted to a region, as shown in Fig. 5.

The inner-loop control should have a damping ratio of around 0.5, and a high bandwidth. The first-order requirement above is consistent with $\lambda > 2a$.

We consider lastly the effects of a cross current. With the present strategy, the vehicle is continually swept downstream. The effect on bearing of a cross-track velocity c , perpendicular to

the distance line, is (with linearization) $d\theta/dt = c/L$. A transfer function taking c/L to θ is, for the case of first-order $G(s)$,

$$\frac{\theta(s)}{[c/L](s)} = \frac{1}{s + \lambda - U/L} \quad (12)$$

A steady or slowly-varying value of c/L leads to a bearing value of $\theta = c/\lambda$; as the vehicle approaches the beacon, the bearing will increase rapidly as L shrinks. The vehicle heading itself is governed in this case by

$$\frac{\theta(s)}{[c/L](s)} = \frac{\lambda}{s} \cdot \frac{1}{s + \lambda - U/L} \quad (13)$$

At large L , we have for steady c/L beginning at time $t = 0$

$$\phi(t) = \frac{c/L}{\lambda} (\lambda t - 1 + e^{-\lambda t}). \quad (14)$$

Thus, heading has the long-term form $\phi = tc/\lambda$; it varies inversely with L like bearing, but not with λ . In strong currents, the vehicle may successfully approach the dock from downstream using our procedure. In this case, stability is enhanced because the effective vehicle speed is reduced, while controllability (scaling with water flow over the control surfaces) is preserved.

In summary, the behavior of a vehicle under even a very simple homing algorithm is complex. We have motivated our approach through a purely linear analysis, which holds mainly at large distances. Near the beacon, the terms U/L and c/L increase rapidly, complicating the response, but can also be seen intuitively to destabilize the vehicle.

While the preceding analysis applies to nulling the bearing to the dock, we point out that, in addition, the free-running 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 when combined with an estimate of the initial position obtained by long baseline navigation. The entire process associated with homing is illustrated in Fig. 6. Homing is typically initiated from 100 to 200 m away, though much longer ranges (up to 1 km) have been obtained. In case the AUV does not pick up the signal from the beacon when it starts homing, it continues toward the beacon based on its long baseline fixes for a fixed period of time, set up in our case to be 45 s. If it still does not hear the beacon, it circles in place until it can pick up the homing signal.

When the AUV picks up the homing beacon, 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. The strategy for a missed approach is detailed later. Once the latch trips, the homing portion of the behavior turns over command to the behavior that deals with the docked vehicle.

Fig. 7 shows one of the simplest examples of a successful homing run. The vehicle turned on the beacon, acquired it almost immediately, turned around from its initial heading of 350° (pointed away from the dock) to a heading of 150° , and then successfully docked to the vehicle on its first approach.

This example highlights an interesting feature of our USBL system in that it has an effective 360° field of view particular to the task of homing. The processing in the USBL system can

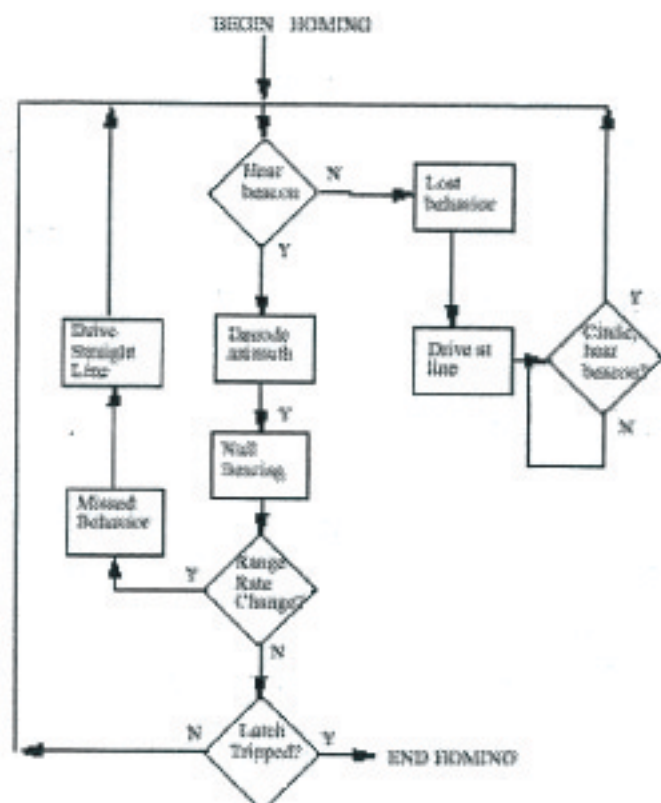


Fig. 6. The homing behavior.

detect signals arriving from the rear of the baffled hydrophone. Although ordinarily we could not process these arrivals to calculate an azimuth with any reliability, we simply assign them an arbitrary high value (95°) for the purposes of homing. As the homing algorithm responds to this value by turning the AUV to null the bearing, we eventually receive signals from the front of the hydrophone which in turn allows us to calculate and home to the true azimuth.

B. Effect of Currents

We have already presented an analysis for the case of homing in a cross current in the previous section. We now illustrate this effect with an example (Fig. 8). Although this run was successful, we see the angle to the dock increasing rapidly as we approach with the vehicle having to turn 30° in the last 25 s. It is interesting to look at the dead reckoned plots of the AUV trajectory while homing in a current (Fig. 8) as opposed to the simple homing run illustrated in Fig. 7. The cross current essentially implies that the AUV needs to fly at a progressively greater crab angle as it approaches the dock. The vehicle trajectory describes a j-hook. Eventually, as the current increases, the dynamics of the vehicle could preclude it turning fast enough so that the vehicle could conceivably miss the dock.

C. Missed Approach

There are two important issues that one must address in setting up for another homing run after an unsuccessful attempt. The first concerns a reliable means for detecting the miss. In the absence of such a mechanism, the AUV can become trapped in an endless spiral around the dock. In our case, this can be handled quite

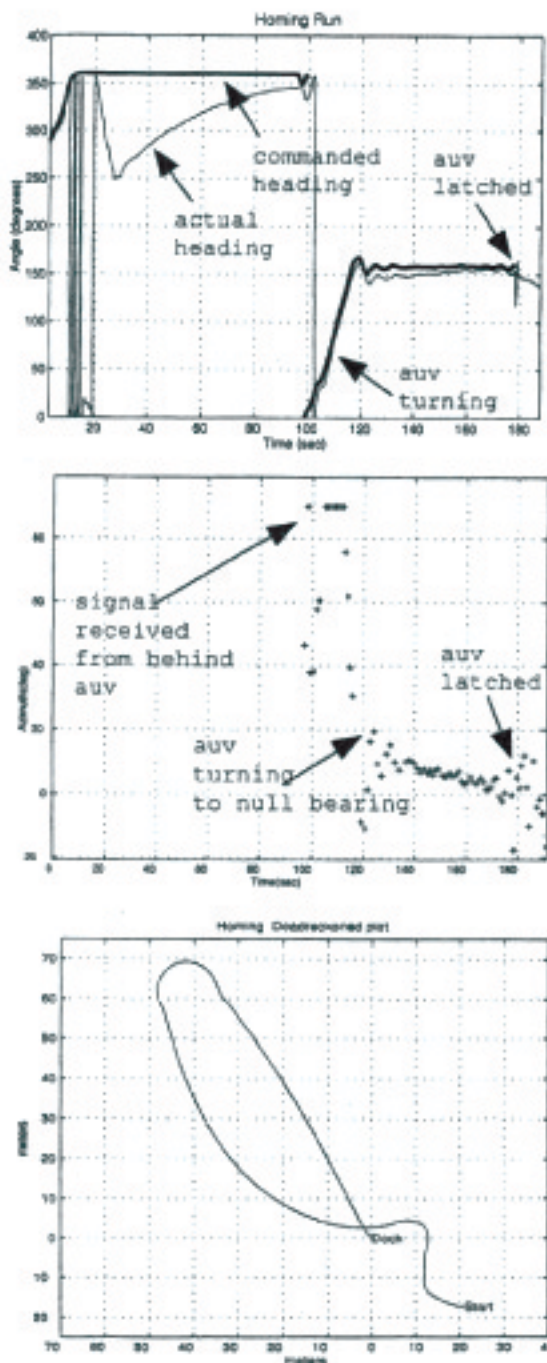


Fig. 7. Homing into the dock—heading, azimuth, and a deadreckoned plot.

easily, by looking at the range rate that can be derived from our synchronous beacon. A change in sign from positive to negative in range rate corresponds directly to a missed docking attempt. The second issue that needs to be addressed is understanding the most probable cause of the miss and ensuring a higher probability of success on the next approach. Our strategy for dealing with a miss is to have the vehicle drive in a straight line for a fixed interval (in our case, we chose 45 s) and then have it reacquire the beacon and begin the process of homing again.

The straight-line maneuver ensures that the vehicle is not limited by its turn dynamics to a spiral around the dock but gives it

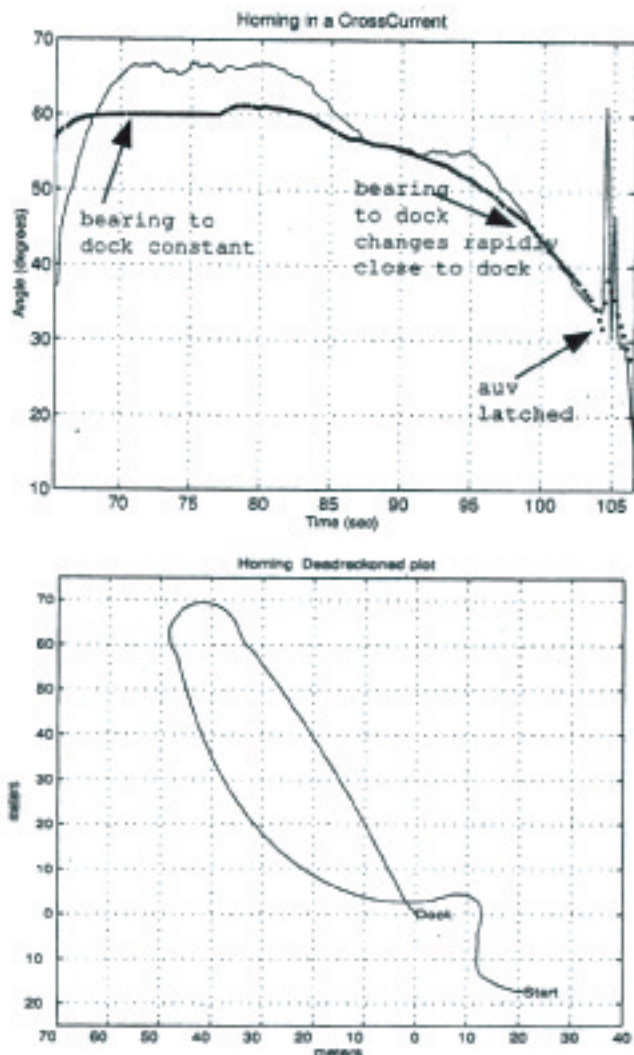


Fig. 8. Homing in the presence of a strong cross current. Notice that the AUV changes bearing rapidly as it approaches the dock.

room to maneuver for its next attempt at homing. It also serves another important purpose in that it ensures a higher probability of success for the next attempt in the case of a cross current. We have already pointed out that the worst-case direction of approach in such a case is cross current. We should add, however, that the optimum approach is to drive the vehicle upstream against the current. The straight-line maneuver that we drive after a miss pushes the AUV downstream and, thus, on the next attempt it aligns the direction of approach to a more upstream direction, thereby increasing the probability of success. In practice, this works extremely well and seldom do we see the occurrence of more than a couple of attempts before the AUV successfully docks.

Fig. 9 shows a run where the AUV did not successfully latch onto the dock on its first attempt. However, it did determine by looking at the range rate estimate from the synchronous beacon that it had missed and went into a straight-line behavior and on the second attempt was successful in docking. An interesting phenomenon illustrated in this run, the effect of magnetic anomalies is described next.

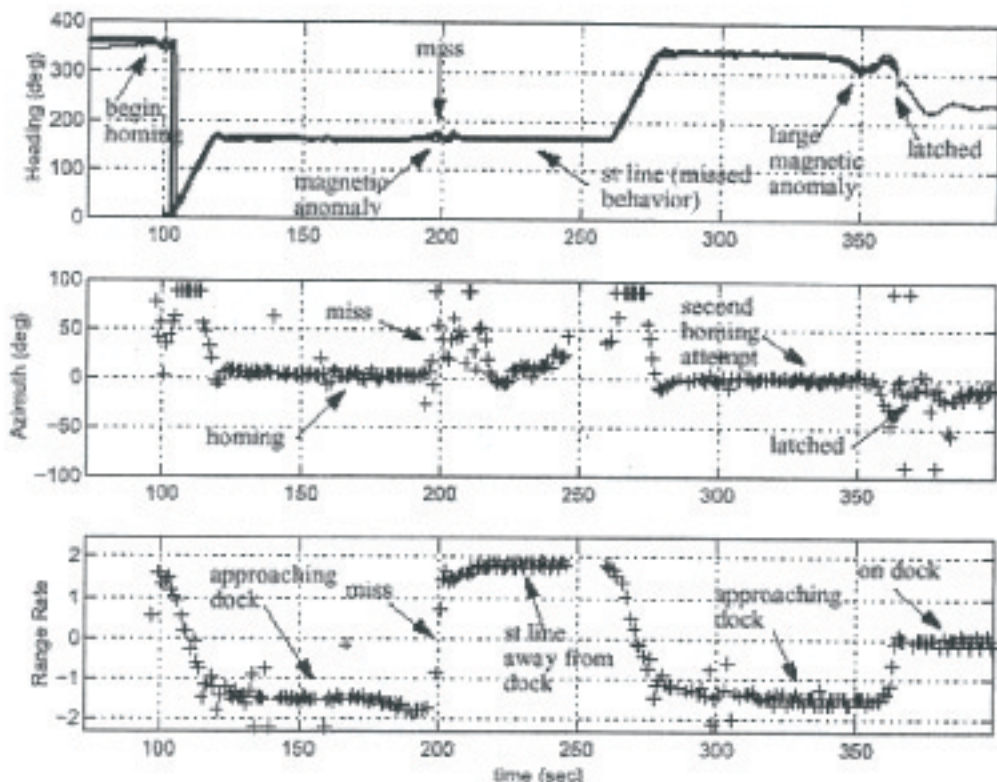


Fig. 9. Homing. A missed attempt, followed by a successful dock.

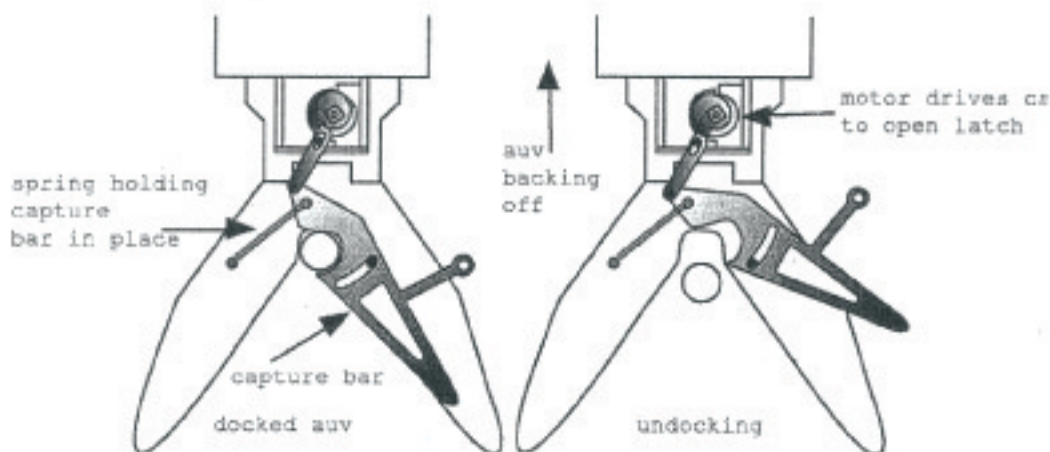


Fig. 10. The latching mechanism.

D. Magnetic Anomalies

Most small AUVs use a magnetic fluxgate compass as a heading reference which is very susceptible to the influence of external static or dynamic magnetic fields. In particular, if the dock is hanging off a pier, or as in the case of Fig. 9, hanging off the side of a ship, this influence can cause large-scale swings of the AUV's compass. As our analysis in Section II-A showed, our algorithm relies solely on nulling the bearing so that a magnetic anomaly does not affect the homing performance. While the absolute value of the compass is affected, the bearing reported by the USBL system is unchanged and thus the homing performance is unaffected. Fig. 9 shows a dramatic example of this. The first homing attempt was unsuccessful (due to a cross current) while the second homing was successful even

though we were driving underneath the ship and along it in the presence of a very large magnetic anomaly.

E. Latching

The AUV goes into its docked behavior when its latch is tripped. The latch, shown schematically in Fig. 10, is mounted on the bow of the vehicle and 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

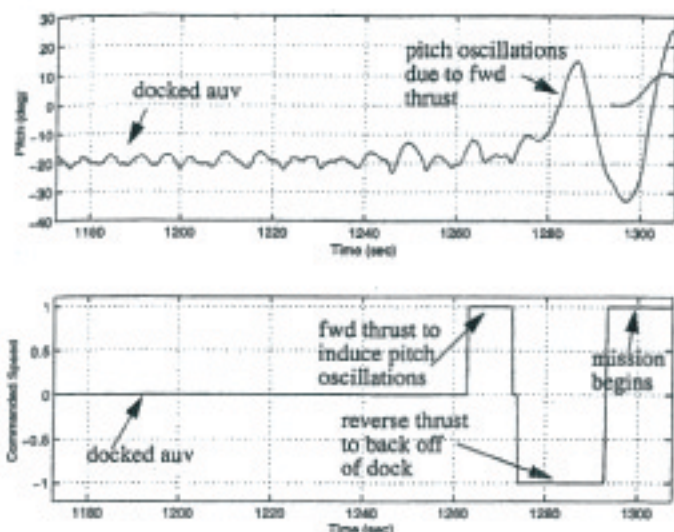


Fig. 11. Undocking.

an extension spring closes the capture bar around the pole. The AUV may latch onto the pole anywhere within a 1-m 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 motor moves a cam that opens the capture bar, allowing the pole to escape the latch.

F. Core Alignment

The cores are aligned by driving a motorized carriage down the pole so that it forces the vehicle to slide down the pole where a tapered bottom assembly force the pucks on the vehicle 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.

G. Undocking

Unlatching from the dock is carried out in the following manner. A motor on the dock starts opening the latch, which is fully open after 10 s and remains open for a further 20 s. As shown in Fig. 11, the vehicle is first commanded to thrust forward for 10 s. Reverse thrust is then commanded for 20 s during which a large elevator deflection is applied such that the tail is forced down, countering the normally positive flotation of the vehicle and 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 the commanded speed in Fig. 11, 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 center of buoyancy is well aft of the pivot point on the latch, the vehicle tends to pitch down. We can see this phenomenon in Fig. 11. Unfortunately, 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 open when the pitch approaches zero. This frees us from the effect of any binding between the latch and the pole that may occur. Once the AUV is free from the pole, we simply apply reverse thrust for a sufficient duration to take us away from the dock to prevent ourselves from relatching onto the pole.

H. Results

Our most recent docking exercises were conducted off of the R/V Gyre, a few miles off Gulfport in Mississippi. During the week-long 1998 UUVFest activities, we ran several missions everyday and demonstrated 18 successive missions with homing, latching, aligning cores, and undocking. These exercises were conducted in shallow water (6 to 10 m of water depth with a ship draft of 2 m) with a deployment scenario that had the dock hanging off of the side of the ship with the vehicle often transiting underneath the ship in its docking attempts. Besides this specific cruise, we have also conducted several hundred missions on other cruises and working off of the Woods Hole Oceanographic Institution's dock facility. Our missions have been interspersed with various surveys and we have also the ability to do repeated dock-undock cycles without human interference as would be required for a real AOSN deployment.

III. AUTONOMOUS DOCKING SYSTEM DESIGN

The requirements for our autonomous dock are summarized in Table I. Examining these requirements for long-term deployments with a low duty cycle, multiple data paths between AUV, dock, surface and remote users, a fixed power budget and the requirement for remote reconfigurability all contributed to the overall system design. In the succeeding sections, we elaborate on our rationale and the actual implementation of our autonomous docking system.

A. Handling Asynchronous Events

One of the first questions that arises is how one would structure the software to implement such a system. A single process executing the flow chart in Fig. 2 is too inflexible to handle events that require immediate attention. Multiple processes, on the other hand, yield a paradigm that is complex and hard to debug, especially for remote users with limited bandwidth access. Thus, we chose to implement our design by means of a finite state machine model [15]. As shown in Fig. 12, this considers the dock to be in one of three states. The three states, not including power on/off sequences, are associated with the AUV being deemed ready for a mission, the AUV out on a mission, and the AUV back on the dock being serviced with respect to data transfer and/or battery charging. This finite-state machine approach serves two fundamental purposes. It allows us to easily and quickly check consistency of behavior over time and, as explained later, provides a mechanism for remote users to understand and debug the state of the dock over the low-bandwidth link associated with satellite communications.

B. Fault Detection and Tolerance

From a hardware standpoint, the overriding concern is to check for and detect low-level hardware faults. In this context,

TABLE I
REQUIREMENTS FOR AN AUTONOMOUS DOCKING SYSTEM

Requirement	Comments
Deployment	4 months
Duty Cycle	Awake every two hours for system check or when AUV is on mission
Charging Rates for AUV	100-300 W
Data Transfer	AUV-Dock (acoustic modem @300 baud; inductive link @10Mbps) Dock-Surface (RS-485 @19200 baud via electromagnetic cable) Surface-Ship (RF Modem @19200 baud) Surface-Shore (satellite ~1kbyte every 6 hours)
Data Storage	2 Mbyte per hour when AUV is on mission; 4kbyte per hour otherwise
Power Budget	60 kWh distributed over 4400 alkaline D-cells in battery housings on mooring
Remote reconfigurability	Required to adaptively trigger AUV missions based on sensor information and remote user input

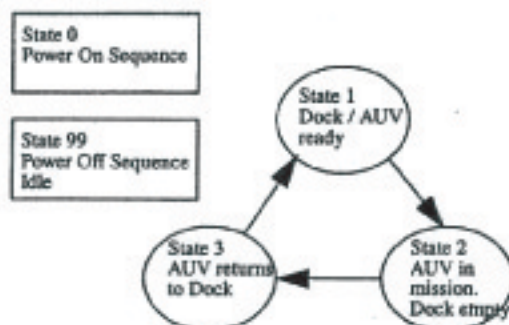


Fig. 12. The finite-state machine model for autonomous docking.

power-on sequences exercise the different subsystems with the explicit aim of providing hardware health status. The flowcharts for the consistency checks for the dock and the vehicle are shown in Fig. 13.

For the dock, the check includes basic tests of hard disks and system time, a test to ensure that the AUV is securely docked, a test of the motorized carriage and the magnetic switches (labeled MIO in the flow chart) which are used to check for dock-AUV alignment, a sanity check on the various sensors on the dock, satellite communications capabilities, and finally the inductive communications link to the AUV, which is then used to obtain AUV status. The AUV status is returned by the vehicle which performs tests on its own subsystems and returns a message that can be parsed by the dock about the vehicle's readiness to run a mission. These tests allow us to examine and report on system performance at a very basic level before attempting the more complex operations associated with autonomous dock operations.

C. Low-Bandwidth Satellite Link With a Large Inherent Delay

One of our driving concerns has been for a system that is capable of being deployed in deep water at remote sites in any of the world's oceans. Given satellite footprints and availability, this only allows us to receive a few messages a day of limited

size and precludes any real-time feedback from human operators. Our surface connection included an Inmarsat-C link which reliably allowed us to transmit a kilobyte of data every 6 h, as well as four Argos IDs.

We chose Inmarsat-C as our primary satellite system because its capabilities are well known and reliable although generally perceived as unsuitable for battery-powered oceanographic applications. This provides a 600-b/s bidirectional subscriber system commonly used for text messages between vessels at sea and shore facilities at a commercial rate of roughly one cent per byte. A small omnidirectional antenna can be used with transparent error detection and correction. Coverage to 1 of 4 geosynchronous satellites extends to about 70 degrees latitude. Despite its reputation as being power hungry, we note that an Inmarsat-C transceiver that is powered only as needed, yields a cost and power per byte that is comparable (and more reliable) than ARGOS transmitting at a 90-s period.

Moreover, for situations where the dock is within RF range of shore, or a ship is in the vicinity of the dock, we wanted to support real-time access and control of the dock and so also built an RF link into the dock's basic capabilities. Thus, based on the circumstances, the dock can be run completely autonomously with little or no feedback via human operators interacting via satellite as well as support completely manual operations via its RF link.

D. Remote Interactions and Reconfigurability

There are a number of mechanisms that link the AUV to the dock and the dock to remote users. These communications links are based on the following components—a radio frequency and satellite link between the surface expression of the dock and users on shore or on a ship, an electromagnetic cable that links the dock to the surface expression via an RS-485 protocol, an inductive data link that connects the dock to the AUV that supports TCP-IP, and an acoustic modem between the dock and the AUV which allows communications with the AUV when the AUV is on a mission.

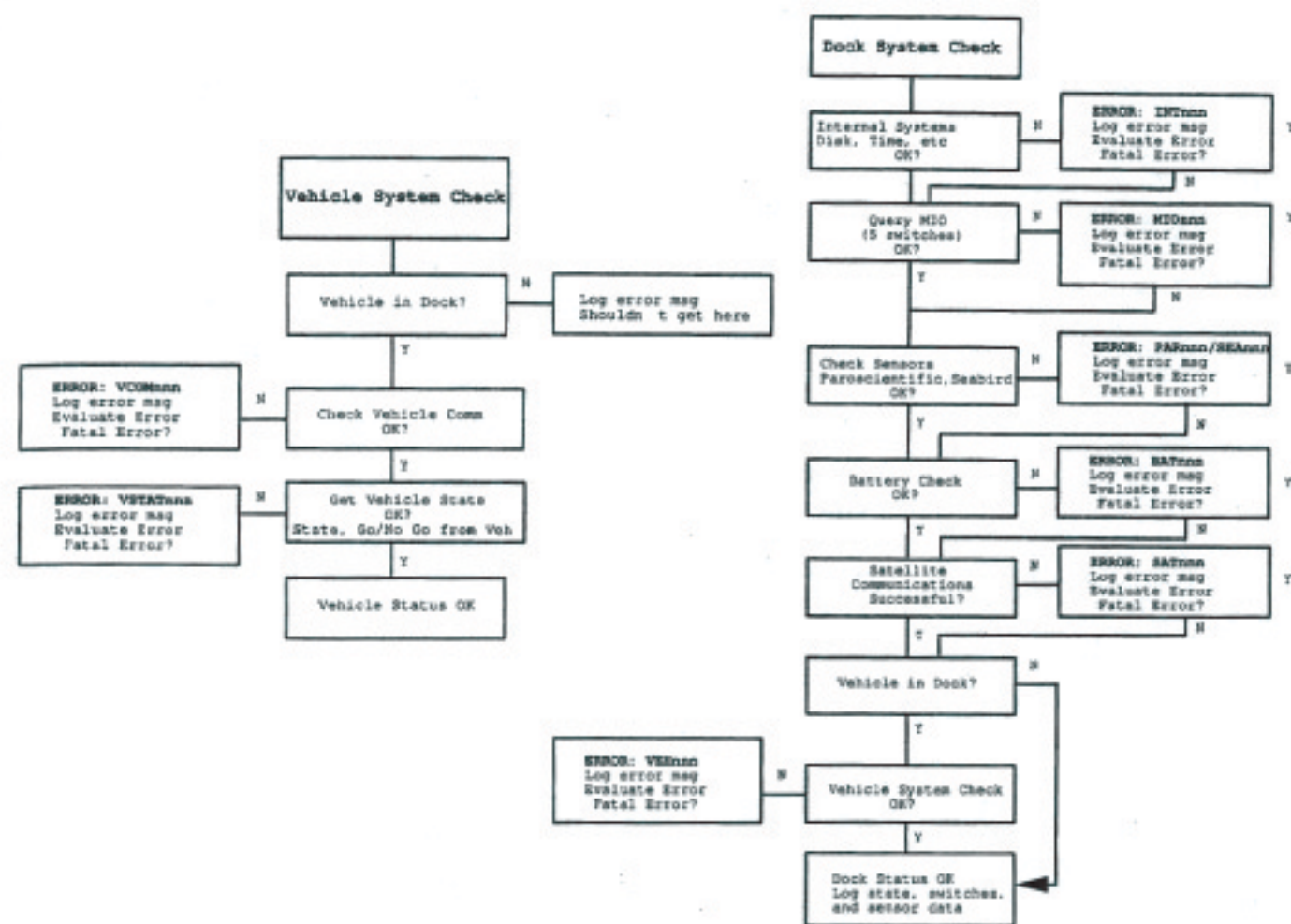


Fig. 13. Basic vehicle and dock system checks.

The incoming messages from the satellite link may be of several types. They may consist of mission files which the dock keeps before passing onto the vehicle, they may be specific files destined for a particular directory on the dock, or they may be files that are specific to the vehicle which the dock passes on. The dock transmits a highly compressed data packet for transmission over the Argos link as well as short snapshots of status and data for transmission over the Inmarsat-C link.

The RF modem provides a 19 200 baud link to the surface expression when a remote user is within RF range. This connection is then linked via RS-485 cable to the dock so that a remote user sees a console on the dock. This console can be used to access the acoustic modem on the dock, which is connected to it via a serial port, as well as an ethernet connection which is run transparently through the inductive cores. The acoustic communications link that exists between the dock and the AUV serves to keep the dock informed about vehicle position and sensor data when the AUV is on a mission as well as lets the dock know when the AUV believes it has latched onto the docking pole. All these data paths are illustrated in Fig. 1.

E. Low-Power Constraints

Power for the dock is supplied by two housings containing 4400 alkaline D-cells. We chose alkaline D-cells as they were

a cheap, readily available, low-risk option that could support our power requirements. Our power source is required to run the dock, its computing engine an i486 based PC-104 system, additional science sensors connected to the dock, as well as provide energy for recharging the AUV. The deployment scenario called for extended four-month-long deployments to support 12-h missions. Looking at this scenario, it becomes obvious that for the majority of the time the dock and vehicle are idle. From a purely power budget standpoint (Table II), we could not afford to leave the dock running continuously. Trading off idle time with a need to check the health of the dock as well as log the data from the sensors on board the dock, we settled on a cycle such that the entire system would wake up and then shut down every two hours, assuming a mission was not scheduled for the next time period. The typical time to boot up, make contact with the subsystems, and transfer data between them was of the order of two minutes. With the entire suite of sensors running, the dock uses 35 W of energy. However, in the sleep state, it uses only 100 mW.

F. Mission Triggers

There are currently three mechanisms for scheduling an AUV mission. It may be scheduled *a priori*, downloaded by operators on shore via the satellite link, or it may be triggered based on

TABLE II
THE POWER BUDGET FOR THE DOCKING SYSTEM

Power Requirements	Comments
Total Power Req'd	4 months deployment w/ 12 missions each of 12 hour duration
Actual Power on Mooring	4400 alkaline D-cells @13.5Wh each = 59.4 kWh
Power Req'd during Missions	AUV + Dock (and associated sensors) utilize 300W while running. 12 missions for 12 hours each = 43.2 kWh
Power Req'd while AUV is idle and latched on dock	300W for 2 minutes every two hours for four months = 14.4 kWh 100 mW for 4 months running continuously = 0.28kWh
Excess Power	59.4kWh - (43.2kWh + 14.4kWh + 0.28kWh) = 1.52 kWh

sensor input on the dock. The *a priori* mission schedule is an ASCII file that resides on both the dock station and the vehicle. This file contains the time to start a mission, the name of the mission, and its duration. This allows the dock to prepare for launching the vehicle at the right time as well as lets it know when to expect the return of the vehicle. Additionally, this is a fall-back mechanism should communication between remote users and the dock fail for any reason. The downloadable mission schedule is identical to the *a priori* mission schedule except that the ASCII mission file has been sent by remote operators via satellite to the dock and then to the vehicle. Finally, the dock also monitors sensors located on the dock and may make a decision to start a vehicle mission based on its input. This protocol has a mechanism built in so that it may be armed or disarmed by users on shore.

G. Hardware in the Loop Simulation

Physically assembling the components that form the assembly of AUV, dock, and mooring is in itself a daunting task. In order to decouple software development from the actual hardware, we built a sophisticated hardware in the loop simulator. This allowed us to use the actual hardware components or to simulate them transparently as the need dictated. The simulator was able to support simple operations such as the magnetic switches on the dock to the complex asynchronous timing patterns associated with the AUV leaving the dock on a mission and returning.

H. Operational Paradigm

Based on the constraints imposed by the factors outlined above we can now look at the entire system design. Fig. 14 shows the flowcharts at a high level of abstraction for the individual states of the finite-state machine model.

State

- 0 Every two hours the AUV wakes itself up a few minutes before the hour and goes through a self check, the results of which it stores locally. On the hour, the dock wakes up and, as part of its check, communicates to the vehicle via FTP. It goes to the data directory on the vehicle and checks for the existence of a specific file which it transfers over and parses. Contained in

this file is a running list of mission data files to be transferred. At this point, the dock initiates the FTP session to transfer the data files, estimates how long the transfer will take, and puts a lock file on the vehicle. After the transfer is completed, the lock file is removed. The lock file, which contains a time stamp from the dock, serves the dual purposes of synchronizing the time between the AUV and the dock as well as providing a mechanism for dock and AUV handshaking.

The data from the AUV consists of archival data that is logged on the dock, highly compressed data that is transferred back to remote users via InmarsatC, as well as vehicle status information that the dock concatenates with its own status information into a bit stream suitable for Argos transmission. As part of its wakeup cycle, the dock also communicates with the surface expression. It queries the surface expression for sensor data and GPS time for synchronization, as well as for any incoming messages that the surface may have received via its satellite link.

It then checks to see if the AUV is in the dock (as it should be), is charged (as it should be), and then goes to the appropriate state based on these checks.

State

1

The dock again checks dock and AUV status before checking mission trigger status based on which it can decide to power up if a mission is imminent, or go back to sleep until the next (two-hour) cycle. If a mission needs to be launched, the dock checks the status of the homing beacon that is required for bringing the AUV back to the dock and then, by transferring a file to the AUV, tells the vehicle to launch a mission at a specified time. The dock checks to see if the vehicle actually left the dock and transitions to State 2.

State

2

The dock checks its own status, checks to see that the AUV is not docked, checks to see that the AUV is on a real mission (as opposed to missing from the dock), and then waits for the mission timer to expire while trying to keep track of the AUV via its acoustic modem. As the mission timer expires, it waits for the AUV to

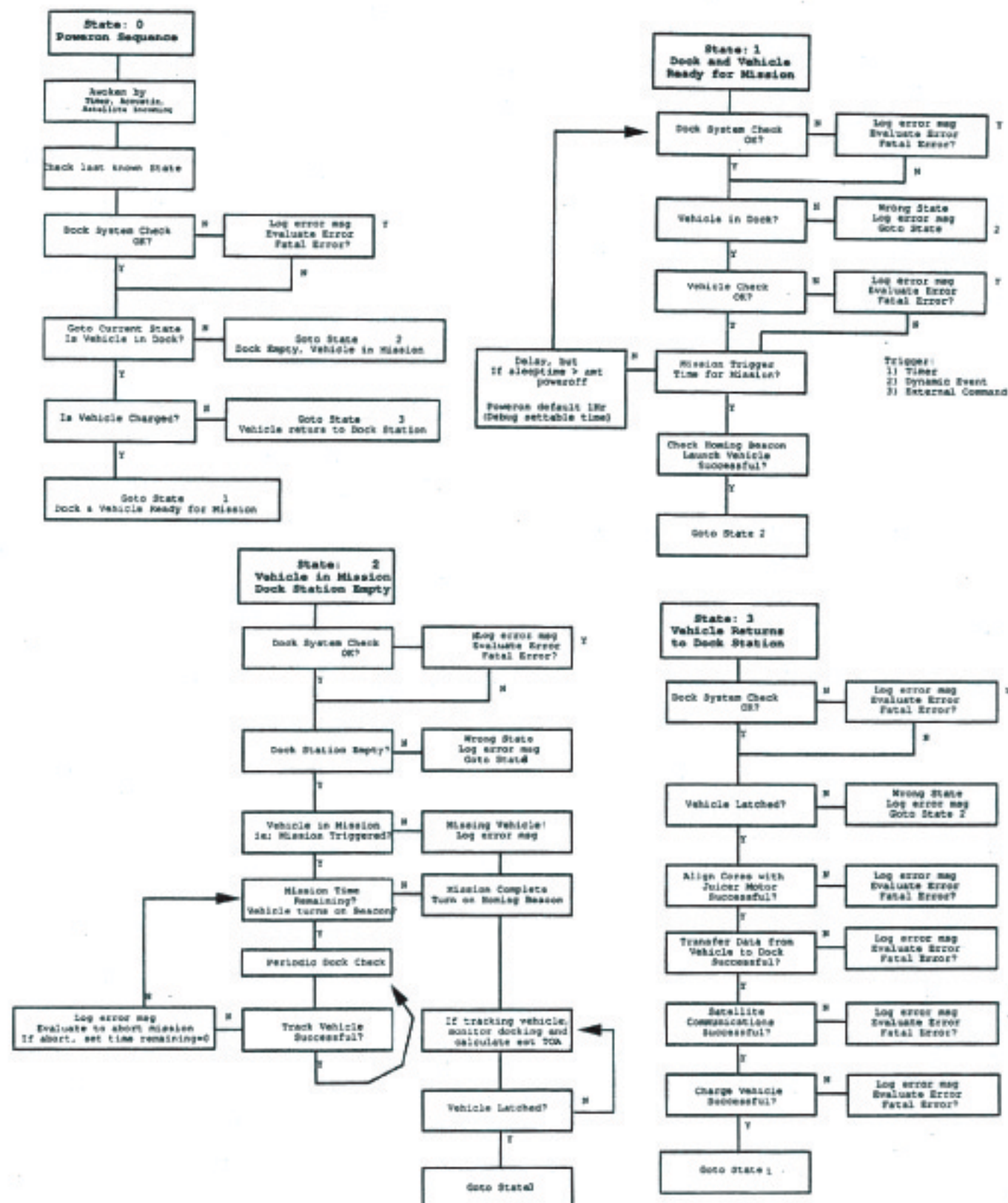


Fig. 14. Flowcharts for the individual states of the finite-state machine model for autonomous docking.

turn on the homing beacon and return to the dock. In the event that the homing beacon is not turned on by the AUV, the dock turns on the beacon itself. After the AUV is latched, it transitions to State 3.

State

3

After the AUV returns to the dock, the dock checks its own status, makes sure that the AUV is indeed latched, aligns inductive cores between the dock and AUV, and


```

1 2041410
2 MSG SIZE ALERT, 559 bytes, only 512 sent
3 COMCON T 2.94 P14.33 D5 M25.7 A10.6 S27.9 L10.3 @02041218 56 42.28
- 052 46.409W -
4 D1 98/02/04 11:02:55 3 Charging auv...timeoutVal 2 min (mdur=0)
5 D1 98/02/04 11:04:55 3 charge timeout
6 D1 98/02/04 11:04:57 1 No valid mission scheduled
7 D1 98/02/04 11:04:57 1 ***Power Off - alarm=6900secs (115min)
8 D1 98/02/04 13:00:30 0 Power-on State=0 WakeupSource=0x01
9 D1 98/02/04 13:00:37 3 FTP files...
10 D1 98/02/04 13:01:45 3 FTP: Getting 0 files (nbytes=0)...
11 D1 98/02/04 13:01:45 3 FTP: Putting 2 files to vehl

```

Fig. 15. An InmarsatC e-mail message detailing autonomous operations with a simulated AUV. Line numbers were added to this message, otherwise taken verbatim from the satellite transmission to facilitate discussion.

then transfers mission data from the AUV to the dock. It then sends off compressed data to remote users via satellite and recharges the AUV before going back to State 1.

Errors can occur during execution of any of the different states. We examine the failure modes at length later in the paper (Section V).

IV. SYSTEM OPERATION

A. A Simulated AUV on a Real Dock

We now present two examples of the autonomous docking system in operation. Fig. 15 shows the complete text of a message sent via Inmarsat C during a deployment of the dock in the Labrador Sea. At this stage, we were simulating the presence of an AUV on the completely functional dock.

Lines 1 through 3 are used by the surface expression of the mooring to denote satellite message number, size, as well as the values of conductivity, temperature, battery status, and GPS location on the surface expression. Lines 4 through 11 represent the latest message sent by the dock. Each line consists of a unique ID (D1) for the dock, the date and the time associated with the message, the State of the dock (for example, the dock was in State 3 in line 4) and a descriptive message. Lines 4 and 5 show that the dock attempted to charge a simulated vehicle for two minutes (the default charge time-out), it then transitioned (line 6) to State 1 where examining its mission triggers it concluded that no missions were scheduled for the next two hours and shut itself off (line 7). Two hours later, on the hour, the dock awoke (line 8) and attempted to talk to a simulated AUV (lines 9 through 11).

What is interesting about this example is the amount of information contained in the relatively small-sized (512 byte) satellite message. A quick perusal of the text provides significant information about all the complex subsystems that go to form the autonomous dock.

B. A Complete Autonomous Docking Mission

We now present an example mission handled autonomously by the docking system. Fig. 16 is the log file associated with a 10-min-long mission run off of the Woods Hole Oceanographic Institution's dock. As in Fig. 15, we have added line numbers to facilitate discussion. Additionally, blank lines indicate where we edited repetitious messages that do not contribute to the overall explanation. Each line for dock D1 contains a date and time

string, followed by a number denoting the FSM state that the dock is in and a descriptive string identifying the stage of the operations. Line 1 shows that the dock is ready for a mission (in state 1—ready for mission) and is aware of a mission scheduled to start in 1 min. A minute later (line 3), the dock (in state 2—AUV in mission) opens the motorized carriage to allow the AUV to proceed on its mission. It checks to see that the AUV did indeed leave the dock (lines 4, 5) and then waits until the AUV returns after completing its 10-min-long mission. When the AUV returns (line 6), the dock (in state 3—AUV returned from mission, being serviced) closes the motorized carriage to align inductive cores (line 6), sends via ftp the data files associated with the AUV mission (lines 7 through 15) and also transfers a copy of these files to the surface buoy for transmission via InmarsatC and Argos (lines 16 through 27). It then attempted to charge the AUV's batteries (lines 28 through 31) but was overridden by a remote user flag which had disabled charging. So far, we have been unable to demonstrate *in situ* charging of AUV batteries though we have transferred power into a dummy resistive load located in the AUV. From the standpoint of autonomous docking, however, our system is ready to charge the AUV autonomously as that system comes on line. At this point (line 32), the dock was ready to run a new mission (state 1) and the cycle of autonomous remote operations could continue.

V. FAILURE MODES AND RELIABILITY

So far, we have outlined the factors that guided our system design and demonstrated how the overall system works within these constraints. In this section, we look at the most probable failure modes and how our design tries to achieve reliability for the complex collection of individual subsystems that go to form the overall system.

A. Failure of a Task to Complete

One of the basic kinds of failure is when a task fails to complete. An example of such a task might be when the motor driving the carriage on the dock fails to successfully align the inductive cores on the vehicle and the dock. The normal mechanism for dealing with such a failure is to repeat the task a finite number of times, noting the error condition, and reporting it back to users on shore. In the case of repeated failures, the dock also continues down the task list based on the assumption that the failure of the previous task may only partially (or perhaps only from an efficiency standpoint) affect the succeeding tasks. For example, if the inductive cores fail to align, the dock still


```

1 D1 97/12/31 22:49:58.63 1 MSG MTime:97/12/31 22:50 CTime:97/12/31
22:49 Delta: 1min
2 D1 97/12/31 22:50:05.72 1 MSG Vehicle ready for mission - launching...
3 D1 97/12/31 22:50:05.77 2 MSG Opening juicer...
4 D1 97/12/31 22:50:27.03 2 PRI SW=11110001 ET=01 [latch=1 range=0]
5 D1 97/12/31 22:50:27.08 2 MSG Waiting for vehicle to leave dockstation

6 D1 97/12/31 23:02:28.04 3 MSG Closing juicer...
7 D1 97/12/31 23:02:28.09 3 MSG Enable Transfer data from vehicle
8 D1 97/12/31 23:02:30.23 3 MSG FTP: Moving auv2dock to previous auv2dock
9 D1 97/12/31 23:02:30.95 3 MSG FTP: getting auv2dock
10 D1 97/12/31 23:02:31.06 3 MSG d_chg=3 d_time=60 amps=0.00
11 D1 97/12/31 23:02:34.46 3 MSG nbytes=0.04MB, xfr=1.00mb/s, Est Time=1.0min
12 D1 97/12/31 23:02:34.74 3 MSG FTP: sending lockfile
13 D1 97/12/31 23:02:37.48 3 PRI FTP: Getting 3 files (nbytes=45163)...
14 D1 97/12/31 23:02:41.27 3 MSG FTP: Putting 4 files to vehicle...
15 D1 97/12/31 23:02:45.01 3 MSG FTPing finished
16 D1 97/12/31 23:02:45.12 3 MSG Scanning Dock/AUV data dir:
c:\aon\auvdata
17 D1 97/12/31 23:02:45.23 3 MSG FTP: Moving W9736502.D to doccom outbound
18 D1 97/12/31 23:02:46.44 3 MSG Send data via satellite comms
19 D1 97/12/31 23:02:48.25 3 MSG DOCCOM: sending doccom wakeup...
20 D1 97/12/31 23:02:59.07 3 MSG in DoccomGetAck <#Y

21 D1 97/12/31 23:03:17.25 3 MSG Doccom: Sending DOCKSTAT.D dest='D'

22 D1 97/12/31 23:03:19.67 3 MSG Doccom: File sent successfully
23 D1 97/12/31 23:03:19.83 3 MSG Doccom: Sending W9736502.D dest='D'

24 D1 97/12/31 23:04:18.82 3 MSG Doccom: File sent successfully

25 D1 97/12/31 23:04:21.24 3 MSG Doccom: Sending DCOMDATA.A dest='A'
26 D1 97/12/31 23:04:22.01 3 MSG in DoccomGetAck <#Y

27 D1 97/12/31 23:04:22.94 3 MSG Doccom: File sent successfully

28 D1 97/12/31 23:04:30.24 3 MSG d_chg=3 d_time=60 amps=0.00
29 D1 97/12/31 23:04:31.01 3 MSG Charging auv...timeoutVal 2 min (mdur=0)
30 D1 97/12/31 23:04:31.12 3 WNG Disable Charging flag set in dockctl.clg
31 D1 97/12/31 23:04:31.23 3 MSG ***Bypassing Charging***
32 D1 97/12/31 23:04:31.29 3 MSG Vehicle charged and ready -> State 1
33 D1 97/12/31 23:04:31.40 3 MSG Turning power core off
34 D1 97/12/31 23:04:31.51 1 PRI SW=11110001 ET=01 [latch=1 range=0]

```

Fig. 16. A log file illustrating autonomous dock operations for an AUV mission. Line numbers were added to facilitate discussion. Blank lines represent edits in the log file.

tries to establish a data and power connection anyway because, while improper alignment may make the data connection slower and the power connection far less efficient, it may be still possible to accomplish these tasks.

B. Conflicting Sensor Data

Another kind of failure occurs when sensors yield conflicting data. One example might be the case of the magnetic contact switches in the dock which might be telling us that the dock is both open and closed at the same time. In this case, a decision tree is followed to resolve such conflicts in the best *a priori* manner possible. Remote users also can watch the history of different sensors and, based on this data, instruct the dock to ignore particular sensors deemed unreliable.

C. Mechanical Failures

The deployment of instrumentation and moorings in the deep ocean is inherently a difficult task. In the case of our dock mooring, the surface expression was the most vulnerable component due to the effect of wind, sea state, etc. We addressed this issue at two levels. Mechanically, the tether from the surface expression to the subsurface buoy is designed to be the

weakest part of the system and, thus, in the event of greater than designed stresses was meant to break away while allowing the rest of the mooring to support itself. From an algorithmic viewpoint, the dock was designed to continue functioning in the absence of the surface expression. The major tasks associated with the surface expression—providing GPS time, providing sensor data and remote access to human operators—would of course not be possible, however the dock and AUV would continue to run missions and collect scientific data that could be processed when the mooring was eventually recovered.

D. Missing AUV

Should the dock wake up and discover that the vehicle is not in the dock and not on a mission, it has the ability to send an abort sequence via the acoustic modem to the AUV. This scenario is also the fallback position in case the AUV were to latch onto any part of the dock—mooring wire, electromagnetic cable—other than the docking pole itself. If the AUV receives an abort sequence, its first action is to unlatch and then to try and home to the dock. After sending the abort sequence, the dock also turns on the homing beacon, a task usually carried out only by the vehicle, to ensure that the AUV could home and return to the dock even if it was not able to turn on the homing beacon.

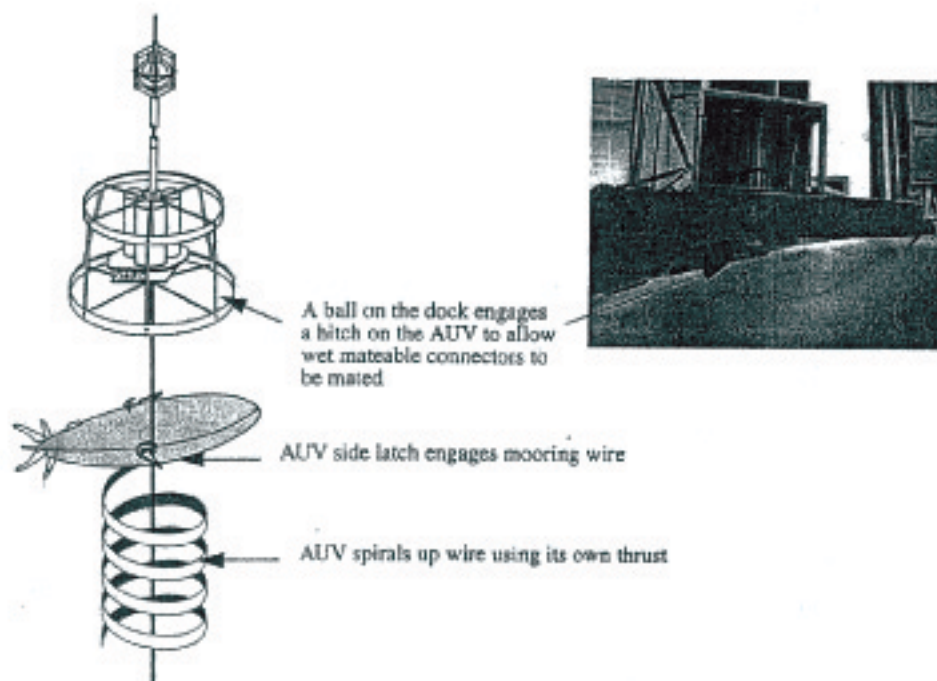


Fig. 17. A schematic view of the second-generation docking design.

E. Communication Failures

Another possible scenario is that the acoustic modem, the primary communication link between the dock and the AUV when the AUV is on a mission, were to fail to send data back to the dock. The major impact in this case would be that the dock would have no way of knowing when the vehicle had returned from its mission. To guard against this eventuality, the dock implicitly waits for a user-specified interval past the time that the vehicle was expected back before forcing the alignment carriage to be run up the pole. Thus, if a vehicle was present, the magnetic switches that are used to check for alignment of cores would determine the presence or absence of a vehicle.

F. Software Lockups

Finally, in the case of an irrecoverable lockup on the dock, a mechanism exists for sending a reset sequence to the dock computer that would cause it to reboot. By manipulating the files on the dock, we can also replace source code and configuration files on the dock as well as recompile code remotely. Besides the ability for remote users to send the reboot sequence, the computer on the surface expression is also programmed to send this command to the dock if the dock fails to communicate to it for more than a day on its normal 2-h cycle.

VI. CONCLUSION

We have now run several hundred successful missions to demonstrate our ability to home an AUV omnidirectionally back to its dock. Our work in this regard is now being transitioned to industrial users. In particular, the Marconi AUV [16], developed by British Aerospace Engineering Systems for military applications, and the Apogee AUV [17], being developed by Bluefin Robotics for scientific work under the ice in the Arctic ocean, have both chosen our USBL hardware system and our algorithmic implementation for their respective applications.

We believe we have a robust and functional software implementation based on the constraints associated with deploying an AOSN for extended periods at remote sites in the world's oceans. While we do not have as much experience in deploying the entire autonomous docking system, we are in the process of continuing to test and modify the software as appropriate.

From the standpoint of mechanical design, our first-generation dock (as presented here) taught us some interesting lessons that are being incorporated into our second-generation dock design. Our experiences are being translated into both design considerations and functional requirements. From a design perspective, we are striving for a simpler and smaller dock with a smaller complement of docking related sensors and actuators. From a functional standpoint, we would like the dock to: 1) accommodate multiple AUVs of different shapes and sizes within the same dock; 2) minimize the footprint of the latch that must be integrated on the AUV without compromising the performance of our homing algorithms; and 3) allow us to be able to support much higher charging rates such as those associated with the new generation of lithium ion chemistries that are currently being incorporated into AUVs.

While we are just beginning our design efforts in this regard, our second-generation prototype dock is shown in Fig. 17. This prototype can easily be carried by two people and can be readily attached to a standard 3/8-in in oceanographic mooring wire in-line at any spot on the cable as required. We have done away with the pole and the carriage that was used to bring the AUV and dock into alignment and the docking latch has been moved from the front to each side of the AUV. We now dock to the oceanographic mooring cable using our side latch with the idea that the AUV continues to thrust after latching. The asymmetry between the thrust and the side latch forces the vehicle to spiral up (or conceivably down) the cable. Eventually the AUV rises up to the level of the dock where a ball on the dock engages a

hitch on the vehicle. The ball can then be retracted so that wet mateable connectors on the dock can be mated to similar connectors on the AUV. Our initial experiments with this prototype have been extremely encouraging. We have demonstrated that we can reliably get the vehicle to latch, climb the wire, engage the ball and socket, align our wet mateable connectors, and complete the link between dock and AUV. Plans are underway to deploy such a system untended and for longer periods of time.

To sum up, we believe that this paper presents a thorough analysis and description of AUV homing and the software and hardware required for an autonomous docking system for an AOSN.

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Dana Yoerger received the S.B., S.M., and Ph.D. degrees in mechanical engineering from the Massachusetts Institute of Technology, Cambridge.

He is currently an Associate Scientist at the Woods Hole Oceanographic Institution (WHOI), Woods Hole, MA, where he designs and implements robotic control systems for telerobotic and autonomous underwater vehicles. These include the full-ocean depth Jason remotely operated vehicle, the autonomous benthic explorer (ABE). He has gone to sea on over 30 oceanographic expeditions, including the 1985 Titanic discovery cruise. Other expeditions include archaeological surveys of ancient shipwrecks, a forensic investigation of a modern shipwreck, and scientific surveys of sites along the Mid-Ocean Ridge. He is currently head of WHOI's Deep Submergence Laboratory (DSL).