

DOCKING CONTROL SYSTEM FOR A 21" DIAMETER AUV

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Abstract—The Monterey Bay Aquarium Research Institute (MBARI) has developed a 21-inch (54 cm) diameter docking AUV and companion docking station. This program resulted in four consecutive successful autonomous homing and docking events in the open ocean, which included downloading data, uploading a new mission plan, recharging the battery, and complete power cycling of the AUV. We describe the design, simulation, and at-sea test of the homing and docking control system.

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are playing an growing role in the ocean sciences. At MBARI, a 6 km depth-rated mapping AUV is routinely generating bathymetry maps with unprecedented precision, resolution and speed, and a second AUV routinely performs physical, chemical, and biological measurements in Monterey Bay. Both of these AUVs are characteristic of a class of vehicles carrying sophisticated, but power-intensive instrumentation. The high power draw of the instrumentation limits today's AUVs to endurances of roughly one day. This means that for all but near-shore operations, the vehicles must be attended by a ship. As a consequence, the fundamental utility of the AUV is limited by ship support requirements. In some cases, the issue is cost. In other cases, the need for ship support makes activities impossible, for example in high sea states, or when events cannot be predicted in advance for scheduling ship time.

Our docking station is designed to link to the power and communication infrastructure of a seafloor observatory, enabling the AUV to operate independent of a surface vessel for extended periods. In effect, the docking station allows the vehicle to connect to a mooring or a cabled instrumentation node. Once attached, the AUV can recharge its batteries, download data, upload new



Fig. 1. AUV in the Dock in a Seawater Test Tank

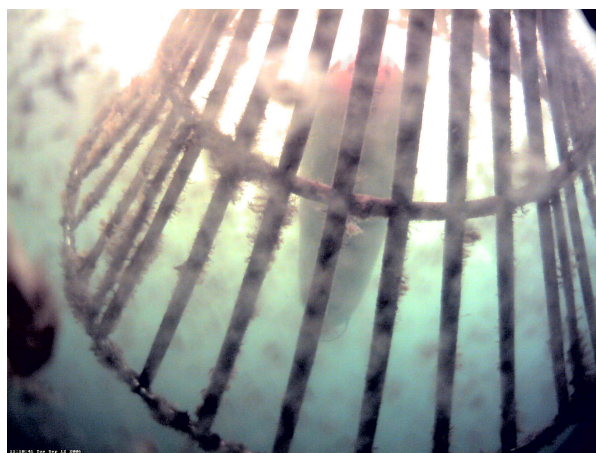


Fig. 2. AUV Entering the Dock in Monterey Bay

instructions, and safely park until the next mission. Once its batteries are recharged, the AUV can be deployed nearly instantaneously. Instead of being limited to studying static or repetitive subjects, the AUV can be quickly dispatched to record episodic events such as canyon turbidity flows or plankton blooms, greatly increasing the scientific utility of an AUV.

The move toward seafloor observatories is in-

ternational in scope, and creates the possibility that power and communication infrastructure will be available on the seafloor in a variety of interesting regions. At MBARI, the focus has been the development of the Monterey Accelerated Research System (MARS) cabled observatory and the Monterey Ocean Observing System (MOOS) mooring-based observatory. MARS is a testbed for subsequent cabled observatories, and provides an early opportunity to develop and demonstrate the AUV docking capability in a logistically benign environment. The compatibility of MARS and the docking system should ensure that the system is well suited to being deployed on future Regional-scale Cabled Observatories (RCOs). The MOOS mooring system is also capable of supporting docking, and while MOOS is unable to supply as much power to a docking station as a shore-cabled observatory, it has the advantage of being much more easily relocated and deployed in regions of interest.

In the tests described below, the AUV was able to successfully dock and undock repeatedly in the open ocean, without assistance from the surface. Shore operators downloaded mission data and uploaded the next mission through an underwater Ethernet link, charged the battery, and completely powered the vehicle down and back up. Figure 1 shows the dock and vehicle in a test tank.

Figure 2 shows the vehicle entering the dock in the Monterey Bay where the AUV was tested in a near-shore, disturbance-intensive environment. The dock worked well despite the fact that it was designed for a permanent deployment in a deeper more benign environment at the MARS cabled observatory at 900 m depth in Monterey Bay. This deeper MARS site is free from surface wave motion and the intensive bio-fouling evident in Figure 2.

II. DOCKING SYSTEM OPTIONS

In past years, various research groups have developed different and innovative dock designs. Some of these require a hovering vehicle, such as the intervention-style grappling system described in [1]. Another hovering vehicle has a tail hook and wire arrangement, where the vertical thrusters lower the vehicle into a cradle [2]. The designs of

docks for flying vehicles, which rely on sustained forward motion for control, generally rely on either a pole or funnel. In the pole design [3], the vehicle carries a latching mechanism that grabs on to a vertically moored pole or cable. In the funnel or cone design, the vehicle enters a circular funnel and is channeled into a tube where it is captured. There have been several designs of this type for smaller vehicles; the Remus/LEO15 system [4], [5], the Flying Plug [6], and the KRISO-KORDI [7]. To the best of our knowledge, there has never been a cone dock for a 21" (54 cm) vehicle that worked in the ocean.

We considered three classes of dock for MBARI's torpedo-like flying vehicle: the pole, the weathervaning cone, and the fixed cone. The pole is omni-directional, and eases the constraint on depth control, but requires the vehicle to carry an external, complex, motorized latching device. Establishing the power and data connection is difficult since the docked vehicle is not rigidly attached to the pole. A weathervaning cone is also omni-directional, but securely captures the vehicle, making power and data connections easier. However the dock must communicate its heading to the vehicle prior to docking, requiring a communication system. This dock must also transfer power and data across a moving interface, most likely using a slip-ring.

III. THE AUV

The Docking AUV is a Dorado/Bluefin 21" (54 cm) diameter type, which has a Gertler body shape, Series 58 Model 4154, with a cylindrical midsection inserted at the point of maximum diameter, and a ring-wing tail [9], [10]. The vehicle is 358 cm long, and weighs 640 kg including entrained water. The vehicle has the capacity to carry three batteries, although during the short duration docking sea-trials, it typically carried only one. Each battery provides 2 kWh of energy, giving a maximum range of approximately 70 km at 1.5 m/s with all three batteries present. The vehicle must maintain a minimum speed of approximately 0.8 m/s for controllability and to counteract the static buoyancy.

The ring-wing propulsion unit, shown in Figure 3, generates 52 N of thrust at 300 rpm. The

outer ring is attached to the body by 8 equally-spaced struts, which are small foils with a twist or pre-swirl. See Tables III and IV for numerical values, and [10] for a photograph and a mathematical model. Both the ring and the struts are based on a NACA 0015 foil profile.

The propulsion unit has a fractional horsepower DC brushless motor with a 10:1 reduction gear box. A 2 degree-of-freedom gimbal provides control in both vertical and horizontal directions.

The control system consists of outer and inner proportional-integral-derivative (PID) loops for both heading and depth. The nominal horizontal-plane cross-track control loop is similar to the docking control presented in Figure 8. A full explanation of the control system in both vertical and horizontal planes is in [10].

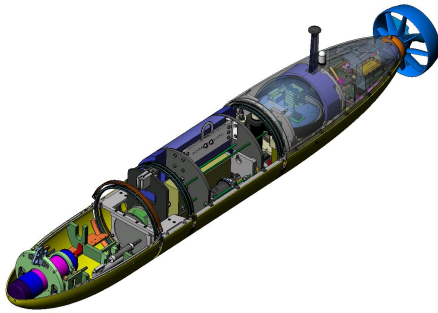


Fig. 3. Solid model of the docking AUV showing USBL homing system as magenta cylinder in the bow.

The vehicle navigation system is essentially Doppler velocity log (DVL)-aided dead reckoning, with periodic global positioning system (GPS) updates, which require surfacing. The expected accuracy is 4% of distance traveled (DT), circular error probability (CEP) with the navigation and control sampling rate of 5 Hz.

The AUV homes to the dock using an USBL sonar transceiver mounted in the vehicle nose, as shown in Figure 3. MBARI selected an Sonardyne Scout inverted Ultra-Short Base Line (USBL) homing system, although other types of homing systems have been proven, such as an electromagnetic system [8], and optical systems [6] and [7]. The USBL has the advantage of much greater range, and is also reliable, mature, and commer-

cially available. The only drawback is that the Sonardyne Scout USBL selected is relatively large and takes up valuable space in the nose of the AUV. The USBL provides a bearing to its beacon in both the horizontal and vertical planes with a specified accuracy of .28 degrees root mean square (RMS). The maximum sampling frequency of the USBL is 1 Hz due to mostly to the beacon turn-around time and subsequent beacon lockout, which are 300 and 600 ms respectively. A faster beacon firmware design is under consideration, which assumes a single, nearby vehicle. This sampling rate may go as high as 3 Hz.

MBARI has already placed and surveyed over 100 USBL beacons in the Monterey Bay and the USBL can home to any of the appropriate beacons. The USBL is useful as a navigation instrument, since it provides position fixes much like GPS, but without surfacing or stopping.

IV. THE DOCK

The MBARI design approach keeps the dock as simple as possible and puts the complexity on the vehicle, since it is easier to retrieve the vehicle for maintenance than the dock. The dock is a benthic, fixed-heading cone that minimizes moving parts and electronics on the dock, and does not require the vehicle to carry an external latching mechanism. It also provides secure parking and a rigid data/power connection. The drawback is that the vehicle must fly a near-bottom precision approach along a fixed flight path, possibly in a cross current, and must therefore contain the necessary electronics and algorithms. The body of the dock is a fiberglass tube of diameter 57 cm, 3 cm wider than the vehicle's diameter.

The dock's entry is conically shaped, built of fiberglass staves held in place by two tubular stainless-steel rings with an entrance diameter of two meters. This entrance diameter was selected based on:

- 1) Observations that the vehicle was passing well within two meters of the transponder during initial homing tests [11].
- 2) The predicted position deviation of the vehicle described in Section VIII using the data from Section X.
- 3) Personal communications from local divers familiar with bottom currents in that area.

The dock body, consisting of the cone and tube, is mounted on a 3 m tall aluminum tripod (Figure 1). It contains a pressure housing with the electronics necessary to support power and data transfer between the vehicle and the cable, and a sonar beacon for AUV homing. Although the dock body is fixed in heading, it gimbals in pitch and roll, due to a self-leveling pendulum designed for deployment at MARS. The forces exerted by the short-period wave motion caused the dock to continually pitch up and down with an amplitude of approximately 10 degrees. This motion proved to be helpful in preventing the AUV from binding during entry. A next-generation dock design will likely take more deliberate advantage of this pitching motion to prevent binding, as well as employing other aids such as mechanical rollers.

Power transfer and mechanical latching were both accomplished by having a peg inserted into the AUV from the dock. The peg has an inductor embedded in the tip, as does the receptacle. The system then transfers power inductively through the sea water without a metal-to-metal connection. The measured power transfer rate was 416 W of power shore-side, with an efficiency of 48%. The peg and receptacle mechanism and electronics were a slightly-modified version of a previous design [12].

We expect that a next-generation design will reverse the peg and receptacle, placing the moving peg in the vehicle, in keeping with our design philosophy of an uncomplicated dock. Even with the peg located in the dock, the entire docking system has only a single moving part with an associated drive motor.

The AUV transfers data to the dock using modified off-the-shelf wireless Ethernet antennas. One is embedded in the top of the vehicle, with its mate correspondingly located in the top of the docking tube. The static vehicle buoyancy holds the antennas nearly in contact, with the peg aligning the vehicle fore and aft. Seawater tank tests conducted at MBARI achieved a transfer rate of 10 Mb/second in seawater with a 2.5 cm antenna separation. The system also worked very well in the ocean trials.

V. HOMING AND DOCKING SEQUENCE

The general homing and docking sequence consists of the following steps:

- 1) Locate and home to the dock. The vehicle uses its on-board navigation to transit within USBL range of the beacon, about 2 km. The USBL is directional with a ± 85 degree field-of-view. The vehicle then homes to the dock using pure pursuit guidance, where the heading control system simply keeps the vehicle pointed at the beacon. This guidance strategy does not compensate for ocean current and thus the vehicle can be blown downwind while approaching. Pursuit guidance has the advantage of keeping the USBL pointed right at the beacon for maximum signal strength.
- 2) Compute a position fix. When the USBL attains good signal strength, the vehicle uses its compass heading and the USBL bearing and range to compute a position fix. Based on previous testing this occurs between 1000 and 200 meters away from the dock. Since the homing control does not use compass heading or propagated position, a jump in the propagated position caused by the fix does not affect the vehicle control.
- 3) Fly to the start of the final approach path. The approach path is along the cone centerline, about 300 meters out. The approach may require the vehicle to turn away from the dock and temporarily lose USBL contact.
- 4) Execute final approach. The vehicle approaches along the cone centerline using a cross-track controller instead of pure pursuit. This means that the vehicle will track the approach path to the cone, and acquire a drift correction angle (crab angle) if the ocean current has a lateral component. This type of control uses both range and bearing from the USBL at 1 Hz, and uses the DVL and compass to dead-reckon between USBL updates. The vehicle slows to 1.0 m/s about 200 m from the dock. This allows time for the control loop to zero the cross-track error, and also prevents the vehicle from hitting the dock with too much force.

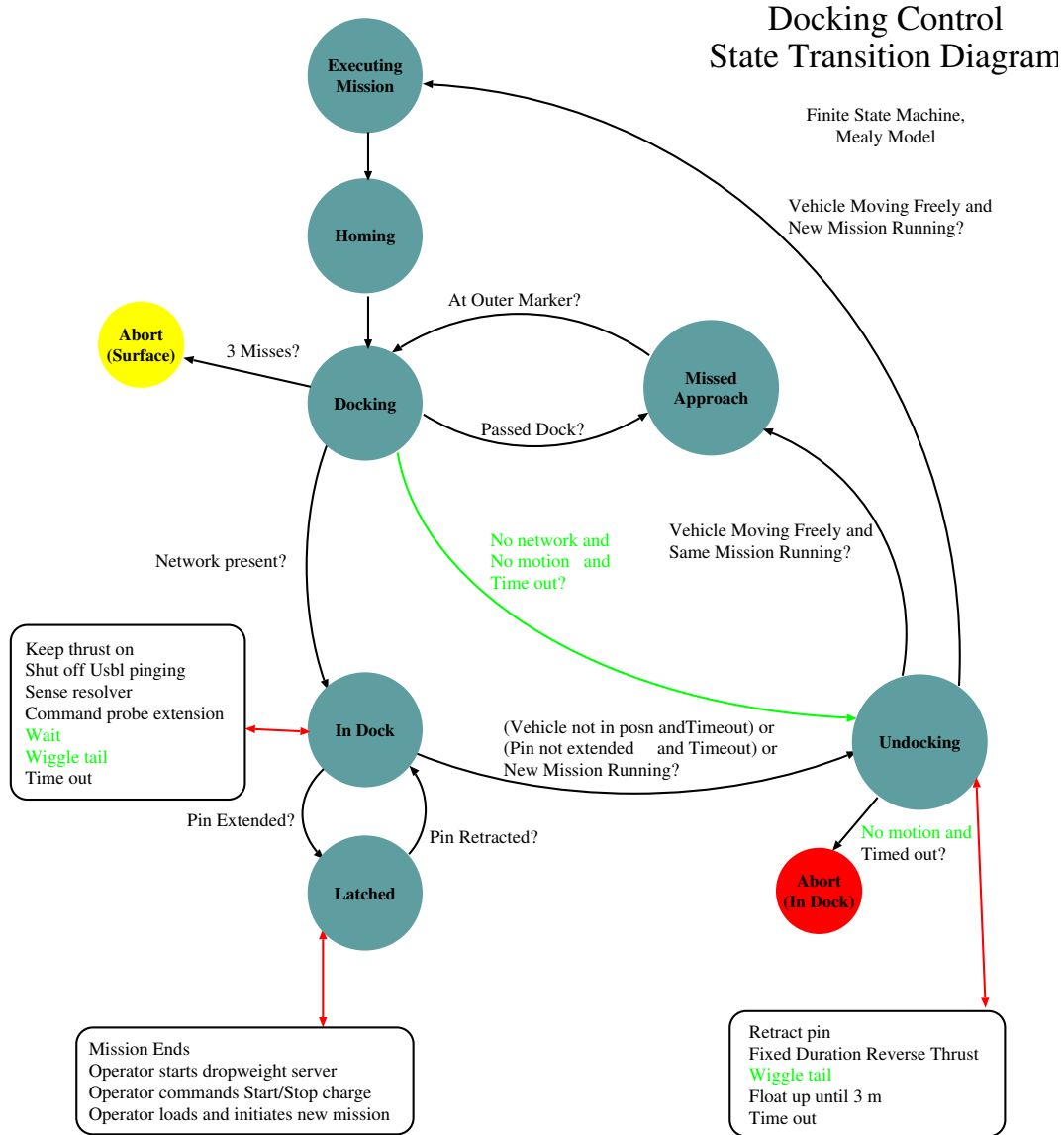


Fig. 4. State diagram of the mission, homing and docking sequence

- 5) Latch. The vehicle uses the inductive position sensor and Ethernet contact to determine if it has fully entered. The code then raises the peg and latches the vehicle. This code was not fully debugged, but worked about half of the time in test tank tests. In the open ocean tests, shore operators raised the pin remotely while watching the vehicle enter the dock on camera.

Figure 4 shows the various possibilities during the homing and docking sequence in state-diagram form. Items shown in green text were planned

but not implemented at the time of these tests. The ability of the vehicle to sense a deceleration without network presence, that is, to sense that it is stuck either partially in the dock, or somewhere else, is important and planned for later development. In the meantime, if the AUV becomes stuck, we plan to wiggle the rudder/elevator, and pulse the thruster to free the vehicle.

If the vehicle enters the dock, but cannot achieve acceptable fore/aft alignment, it executes an undocking maneuver, returns to the waypoint, and retries. After three unsuccessful tries, the AUV

aborts the mission and surfaces.

The homing and docking steps were tested separately. Homing was tested in the fall of 2005 in central Monterey Bay off Moss Landing. Docking was tested during the summer and fall of 2006 at the Monterey Inner Shelf Observatory (MISO), operated by Naval Postgraduate School (NPS) [16] and Associate Professor Tim Stanton, who generously allowed MBARI full access to the facility. MISO is a cabled facility that provides power and Ethernet 600 meters offshore, in 12 meters of water. The shallow depth makes this site subject to 9-12 second short-period wave motion, as well as 12 hour tidal currents. The observatory has an upward-looking ADCP, and NPS maintains an archive of current measurements stretching back for many years.

The docking flight pattern was a rectangle of 300×50 meters. The approach to the dock at MISO was a corridor about 150 meters wide, defined by kelp beds on either side, with a flight pattern through this corridor.

The position fix update in step 2 was not implemented for the sea-trials described here due to time limitations. However, it is simple code to add, and would eliminate surfacing the AUV for a GPS fix close to the dock, which increases risks at MISO due to the proximity of the shore, kelp, and recreational boating traffic.

VI. UNDOCKING

The vehicle was designed to undock by lowering the peg and reversing the thruster. The vehicle is unstable in reverse, and therefore thrusts with a fixed elevator angle and duration. After the thruster shuts off, the vehicle floats up until reaching a depth of 3 meters, well above and clear of the dock. The vehicle then begins a normal mission with ahead thrust, which consists of a U-turn and a transit down the corridor to the outer waypoint.

During the sea-trials the shore operators manually lowered the peg and initiated the undocking mission while watching on the camera, because the peg control code was not yet reliable. The Ethernet path from the main vehicle computer to the peg PIC passed through four Wireless Access Points (WAPS), and we believe the source of the problems lay in the four routing tables.

A planned, but unimplemented feature, was undocking behavior that would pulse the thruster forward and backward to break loose if the vehicle had difficulty backing out. Should the vehicle become permanently stuck, the positively buoyant dock would contain an acoustic release at the top of the base. A support ship could then trigger the release and recover both the vehicle and the dock.

VII. HOMING CONTROL LOOP

This section explains the homing control loop that operates in step 1 above. Section VIII explains the docking control loop of step 4.

Figure 5 shows angle and reference frame definitions used in the following homing analysis. Angles are defined to be positive clockwise.

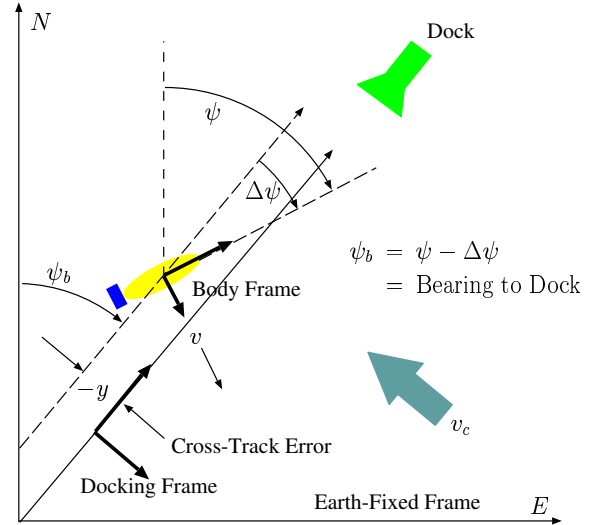


Fig. 5. Angle and reference frame definitions

The design and analysis of the homing and docking control loops are fundamentally based on the dynamics of the vehicle, described by coupled nonlinear equations of motion (EOM) such as those in [13]. The vehicle travels most frequently in straight and level flight, with small angular and translational deviations, in which case the horizontal-plane and vertical-plane dynamics decouple. Equation 1 is the horizontal-plane, or sway-yaw dynamics linearized about straight and level flight. It is fourth order and consists of $\Delta\psi$, heading deviation; y , cross-track displacement; v , lateral velocity component in the body frame; and finally r , which is heading rate. See [14],

$$\begin{aligned}
& \begin{bmatrix} m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} & 0 & 0 \\ mx_G - N_{\dot{v}} & I_{zz} - N_{\dot{r}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{y} \\ \Delta\psi \end{bmatrix} \\
&= \begin{bmatrix} (Y_v - Y_{RF} - Y_A)U & (Y_r - m - x_R Y_{RF} - x_A Y_A)U & 0 & 0 \\ (N_v - x_R Y_{RF} - x_A Y_A)U & (N_r - mx_G - x_R^2 Y_{RF} - x_A^2 Y_A)U & 0 & 0 \\ 1 & 0 & 0 & U \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ y \\ \Delta\psi \end{bmatrix} \\
&+ \begin{bmatrix} Y_R U^2 + T_P \\ (Y_R U^2 + T_P)x_R \\ 0 \\ 0 \end{bmatrix} \delta_R - \begin{bmatrix} (Y_v - Y_{RF} - Y_A)U \\ (N_v - x_R Y_{RF} - x_A Y_A)U \\ 1 \\ 0 \end{bmatrix} v_c
\end{aligned} \tag{1}$$

p. 117, and [10] for derivations. Tables I-V in the appendix define the symbols and numerical values of the constants.

The depth control did not require any special modifications for docking, and so discussion of the vertical-plane dynamics and control [10] are not repeated here.

The origin of body-fixed coordinate system assumed by Equation 1, and the values in Tables I and II, is amidships, that is, along the centerline at half the overall length. It is *not* at the center-of-mass or the center-of-buoyancy.

In Equation 1, Y_{RF} is the sway force coefficient due to the rudder fixed (RF) in the neutral position,

$$\begin{aligned}
Y_{RF} &= \frac{1}{2}\rho A(C_{L\alpha} + C_{Do}) \\
&+ \frac{1}{2}\rho A_S(C_{SL\alpha} + C_{SDo}). \tag{2}
\end{aligned}$$

A is the area of the ring, defined as chord $\times$ diameter, that is,

$$A = \bar{c}_R d_R. \tag{3}$$

A_S is the equivalent strut area, defined to be

$$A_S = 2(1 + \sqrt{2})\bar{c}_S b_S. \tag{4}$$

$C_{L\alpha}$ is the slope of the coefficient of lift of the ring, and C_{Do} is the coefficient of drag. Similar symbols with subscripts S and F refer to the struts and RF/GPS fin, respectively.

It is common to subsume the rudder-fixed portion of the force, Y_{RF} , into the stability derivatives. In this presentation Y_{RF} is added explicitly in

Equation 1, and so the stability derivative values in Table II are for the fuselage only.

Y_A is the sway force due to the RF/GPS antenna fin,

$$Y_A = \frac{1}{2}\rho A_F(C_{FL\alpha} + C_{FDo}). \tag{5}$$

A_F is the area of the RF/GPS antenna fin.

Y_R is the sway force coefficient due to a deflected rudder,

$$Y_R = \frac{1}{2}\rho A C_{L\alpha}. \tag{6}$$

The homing control loop implements pure pursuit guidance, which requires that the vehicle's nose continuously point at the beacon during the approach. Pure pursuit is a special case of the well-known proportional navigation technique used for missile guidance [15]. Pure pursuit is proportional navigation with a navigation gain of unity. Larger gains will cause the pursuing vehicle to lead the target and intercept faster, but the algorithm is more complicated. Proportional navigation is unnecessary in our case because the time-to-intercept is unimportant, and also because the vehicle does not come directly into the dock, but must first transit over to a fixed approach path after it gets to within several hundred meters. The dock has a fixed heading and the vehicle must line up with it, much like an airplane approaching a runway.

When the homing loop is first initiated it uses cross-track waypoint control to fly toward a pre-programmed dock location until the USBL receives a response from the beacon. From that

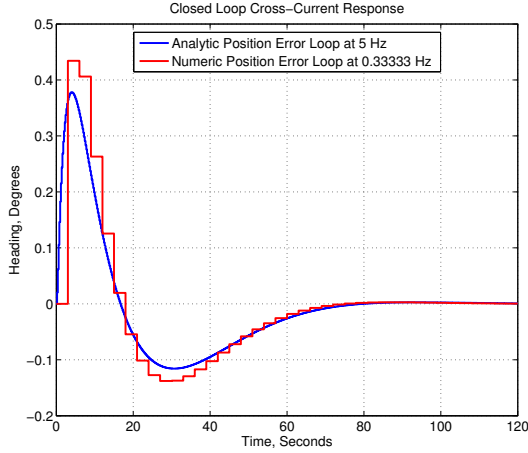


Fig. 7. Closed-loop heading Response to a 25 cm/sec. step disturbance

center-of-mass. Equation 1 models this, as shown by the N_v term in the disturbance (v_c) input matrix.

The red curve shows the response assuming the outer USBL loop has a sampling period of 3 seconds, which it does at the outer limit of its range. The inner gyro feedback loop still runs at 5 Hz. As the vehicle approaches, the USBL sampling period drops to one second. Figure 7 shows that the slow outer loop does not significantly degrade the performance.

Between USBL sample periods, the 5 Hz heading loop maintains the last bearing determined by the USBL and the compass.

The control gains were empirically chosen and resulted in a dominant pole pair with a damping of .77 and a time constant of 17 seconds. This means that the vehicle will travel about 75 meters before transients induced from step disturbances die out. Since we expect this loop to be in operation from 1-2 km out, these time constants are acceptable. Gain values are in Table VI.

The eigenvalues were determined by substituting analytically-determined stability-derivative values into Equation 1, and combining the result with the control loop shown in Figure 6. Numerical values are shown in Tables I-V.

VIII. DOCKING CONTROL LOOP

Figure 8 shows the docking control loop. It differs from the homing control loop because

now the cross-track error state is computed from the USBL and fed back. The vehicle will now fly down a fixed approach path and will not be blown downwind by ocean currents. The integrator, which has been moved to cross-track error, will crab the vehicle into any current so as to keep the cross-track error at zero.

In Figure 8 there is a smoothing filter after the waypoint control, which has a time constant of 2.5 seconds. This filter was neglected in the analysis below since it is much faster than the slowest roots of the closed-loop characteristic equation.

Since the vehicle position is now computed from the USBL, the navigation is free from the accruing odometry error inherent in dead reckoning. The error is proportional to the range, and thus decreases as the vehicle closes on the dock. This is fundamentally what makes the docking system work, and is the reason for having a homing system.

The heading of the dock, ψ_b , was measured after deployment, and is a known constant. It is used inside the USBL feedback loop to convert heading deviation to cross-track error.

As in the case of the Homing Controller, this control has a fall back in case the USBL drops out. It latches the last dock position measured by the USBL, and continues by DVL-aided dead reckoning.

Control gains were again empirically determined, with K_v kept at zero. Values are in Table VII. The cross-track error step response is dominated by a closed-loop pole pair with damping .29 and a time constant of 55 seconds. Figure 9 shows simulated cross-track error response to a 25 cm/sec current step.

Although the transients damp slowly, the error is well below the one meter dock aperture radius after 100 seconds, while the vehicle has 100 meters yet to travel before encountering the dock. This assumes that the docking control is initiated 200 meters from the dock on the approach path, and the vehicle has also slowed to 1.0 meter/second. The thrust is also reduced to 22 N. These two values were used in Equation 1 along with the gains in Table VII to produce Figures 9 and 10.

In addition to crabbing into a constant tidal cross current, the control loop must perform in

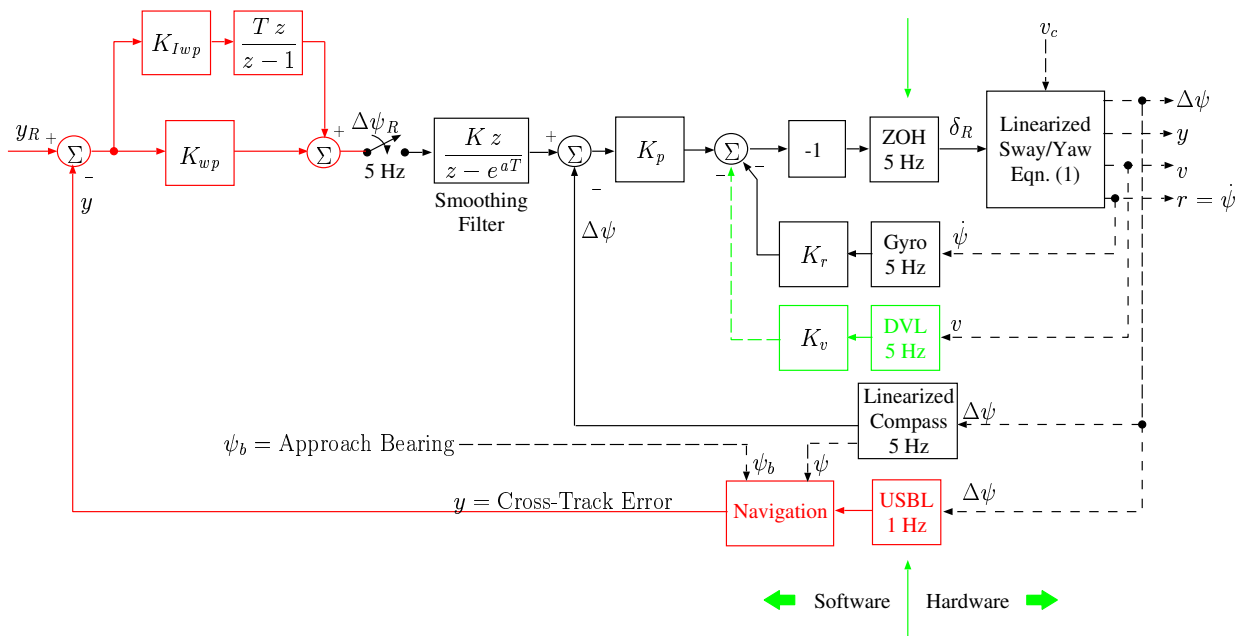


Fig. 8. Cross-track docking control loop

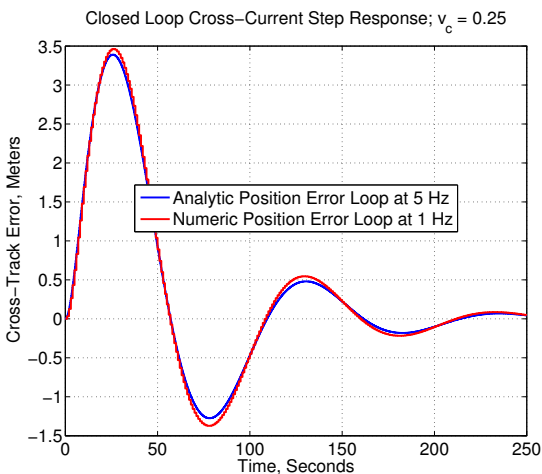


Fig. 9. Cross-track error response to a 25 cm/sec step current

the presence of 8-12 second wave motion. The green curves in Figure 10 show the steady-state sinusoidal response of cross-track error to lateral current. The frequency region bounded by the vertical magenta lines represents the wave energy. The black curve is the open-loop transfer function, which is coincident with the closed loop transfer function at the wave energy, showing that the control loop has rolled off there and has no effect. At the low end of the wave spectrum the closed-

loop gain is a factor of 2.5, and decreases to less than one at the high end. Typically the wave period is close to ten seconds, where the loop gain is near unity, implying that a 30 cm/sec wave motion will deviate the vehicle less than 30 cm from the flight path. ADCP data taken during the docking trials, plotted in Fig 15, showed that the wave period was 9.3 seconds with 3σ amplitude of about 30 cm/sec, and this is shown in Figure 15.

The dotted lines show the multi-rate transfer function with the outer USBL loop at 1 Hz, in comparison to the solid lines where 5 Hz was assumed. The 1 Hz sampling doesn't appreciably degrade the performance.

IX. SEA-TRIAL RESULTS

The MBARI team conducted the first at-sea homing trials on 11 December 2005. The test area had a flat bottom about 15 meters deep, without any nearby obstructions or kelp beds. The transponder was moored about 5 meters off the bottom. The vehicle was acquiring the transponder at distances exceeding 2 kilometers, and homing to within 50 cm. See [11] for details.

The USBL performed well during the homing trials, with little noise and few dropouts, leading us to conclude that little filtering was necessary.

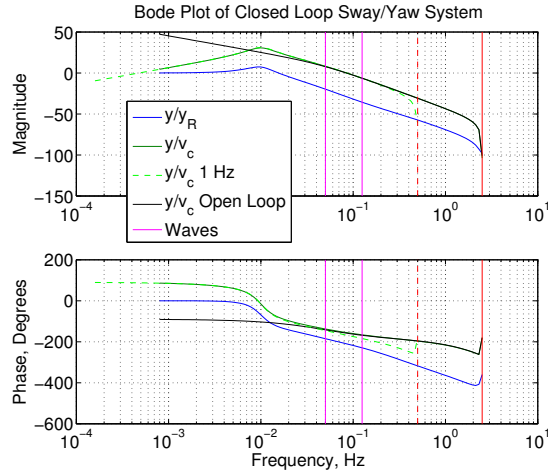


Fig. 10. Bode plot of cross-track docking control loop

However the noise environment at the MISO docking site was much worse, due perhaps to the proximity of the shoreline, the surf, and nearby kelp beds.

The noisy USBL data at MISO was significant in that it was causing the vehicle to consistently miss the dock by 3-10 meters. This led to the design of a moving-window median filter which proved to be very effective. The vehicle made the first controlled dock after implementing the filter, and successfully docked on every attempt thereafter. There were four consecutive dockings.

A median filter can be effective for sonar applications because it rejects multipath, as long as the number of measurements corrupted by multipath are fewer than the uncorrupted ones.

Before median filtering, the USBL measurements were passed through simple outlier rejection tests. The data had to pass all of the below to be considered valid:

- 1) There must be a preset number of good consecutive samples.
- 2) The vehicle must not be turning too fast.
- 3) The measured bearing must not be too great.

These tests are not switched on until the vehicle is near enough to the transponder that the signal is strong.

The median filter then consists of taking the last 11 valid USBL measurements, and computing the median of each axis individually. The navigation first converts the measurements to UTM locations,

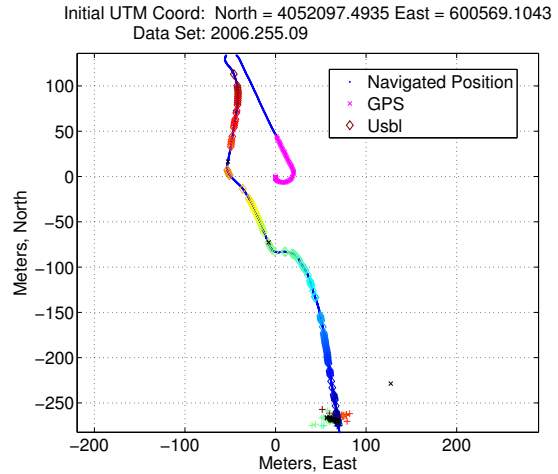


Fig. 11. Vehicle track during a docking trial. The + points are USBL measurements of the dock location, color coded by distance.

so that each measurement appears as a fixed location on a map, such as those in Figures 11 and 12. Median filtering the eastings and northings separately has the interesting effect of producing a location that is not the same as any of the measurements, yet is contained within the largest cluster.

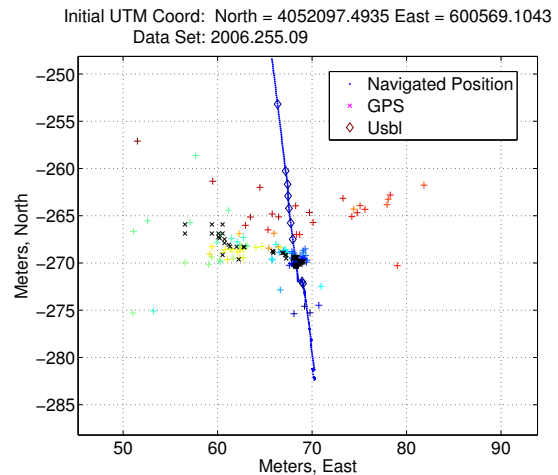


Fig. 12. Enlargement of the USBL dock hits. The +'s are raw data, and the x's are the filtered result.

Figure 11 shows the vehicle path, as seen from above, of the second docking mission. The axes are eastings and northings (UTM) in meters. The magenta points at the start, near (0,0), are GPS hits. The vehicle submerges, turns and flies north

to the first waypoint, then turns again to the south and passes through two more waypoints. The color-coded diamonds overlaying the path show the location of the vehicle at each USBL measurement. The color shows the distance from the transponder, and corresponds to the color of the measured location indicated by a +. Black $\times$'s show the location of filtered points.

Figure 12 shows a zoom of the dock location in Figure 11. There is a distinct cluster of points about 8 meters to the west of the dock, detected by the USBL when the vehicle was around 200 meters out. The error is presumed to be due to a bounce (multipath). This cluster contains many valid hits. As the vehicle closes, however, this cluster is discarded by the moving window and the valid hits then cluster at the dock, precisely as desired.

The position error of the vehicle when it enters the dock, as viewed on the video, is nearly undetectable, appearing less than 5 cm.

The jog after the third waypoint, at (0,-70), is caused by the initiation of the docking control loop. It turns the vehicle to the east to bring it onto the fixed flight-path heading of $\psi_b = 171$ degrees. From that point in, the cross-track error is computed directly from USBL measurements, and not from propagated position.

The top strip of Figure 13 shows yaw commands during the approach to the dock. The green line is commanded bearing to each of the three waypoints, followed by a flight path approach of 171 degrees, beginning at 291 seconds. The approach bearing is labeled ψ_b in Figure 8. The red line in Figure 13 is the filtered heading command, and the blue is the measured. They correspond to $\psi_R = \Delta\psi_R + \psi_b$, and $\psi = \Delta\psi + \psi_b$, respectively. The commands to turn the vehicle from each waypoint to the next are clearly visible at 128 and 227 seconds, with ψ tracking as expected. The maneuver at 291 seconds is interesting, where ψ_R increases, but the vehicle commanded heading appears to turn the opposite direction. This is because the docking controller has activated and must now slew the vehicle not only onto the specified bearing of $\psi_b = 171$ degrees, but must do so on the approach path. To do this, the docking controller must first turn the vehicle in the opposite

direction to get onto the line, before turning back to the specified bearing.

The middle strip of Figure 13 shows heading deviation $\Delta\psi$, which corresponds directly with the same symbol in Figure 8. The green curve is the crab angle, commanded by the integrator. It is apparent that there is little cross current during this approach, since the crab angle approaches zero as the control reaches steady-state just before each of the two waypoint changes.

The character of the blue $\Delta\psi$ curve changes when the waypoint control activates at 291 seconds. This is because the cross-track error was previously computed from the propagated position, determined from DVL-aided dead reckoning. After 291 seconds the cross-track error is computed from the filtered USBL measurements and the compass. Several jumps in heading deviation are apparent between 320 and 450 seconds due to USBL noise.

The bottom strip shows the cross-track error. It is converging to under a meter after 400 seconds. Interestingly, the USBL apparently got some hits that took the vehicle almost a meter off-track at 490 seconds, but then the measurements improved until the vehicle had zero measured cross-track error only about 4 seconds before contact. The measured error at the moment of contact, at 519 seconds, was 10 cm, slightly larger than was apparent in the video.

There were three additional docking events, each appearing much like this one, indicating that the docking control is repeatable, at least in the cross-current conditions shown in Figure 15

Depth control is unchanged from the standard algorithm as described in Ref. [10]. The vehicle flew at 12 meters depth during it's final approach, until about 50 meters out, where it transitioned to a 3 meter altitude track. The dock is located on a slight slope and is 3 meters high in 12 meters of water.

X. DOCK TEST ENVIRONMENT

Figure 14 shows statistics of cross-shore and along-shore currents at the MISO docking test site during July and August 2005, which is a representative period for the docking trials. The measurements are at 1.8 meters altitude. The along-shore current is of primary concern because

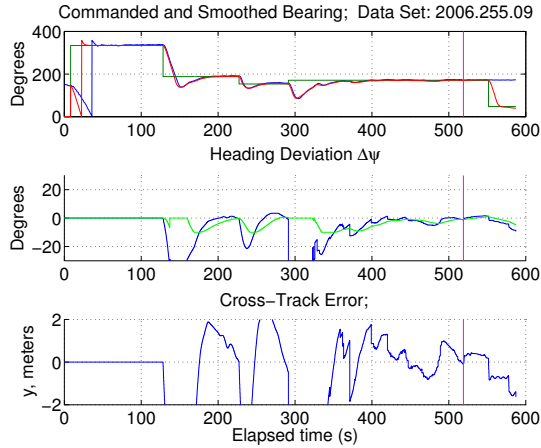


Fig. 13. Cross-track error, heading deviation, and heading during the docking event

it is perpendicular to the approach path, and will tend to carry the vehicle off track. The vehicle approach altitude was 3 meters, where the current was expected to be larger, and so the design had to allow for currents greater than shown.

Blue points are the mean current over a six-hour period, which shows the tidal component with wave motion averaged out. The sampling period was between 1 and 2 seconds. Tidal currents act as a constant during a docking approach since an approach takes only a few minutes.

The standard deviation of the tidal component is 3.8 cm/sec, with a maximum surpassing 5 cm/sec. The constant-current design specification was consequently taken to be 25 cm/sec, keeping in mind that the currents tend to be faster further above the sea bed, and allowing a margin.

Figure 15 shows a 3 minute segment of the full 1 second data set of along-shore current measurements. This data was taken on the day that the AUV docked. At 3 meters altitude, the tidal (average) current was 2.0 cm/sec to the north, with a 9.3 second wave component, with standard amplitude deviation of $\sigma = 9.4$ cm/sec.

The figure shows that the short-period wave current tends to increase with altitude, justifying a design margin for current greater than what was measured at 1.8 meters in Figure 14.

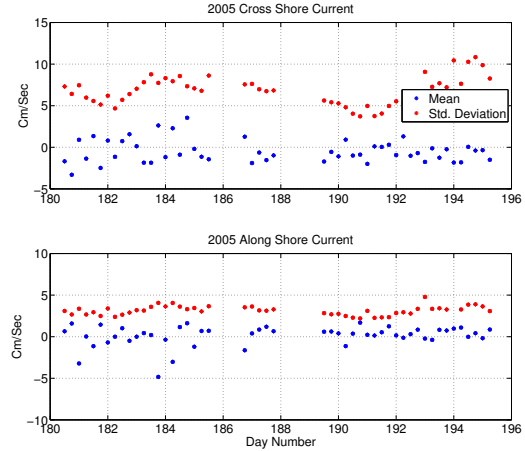


Fig. 14. 6 Hour Current Statistics at 1.8 Meter Altitude

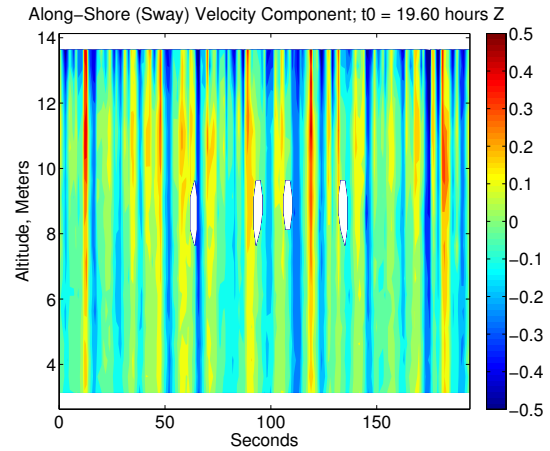


Fig. 15. Along-shore current as a function of altitude at MISO on the moment of the docking event in Figures 11-13, 12 September 2006 (day 255)

XI. CONCLUSIONS

A prototype AUV docking system has been designed, built and tested at sea. The dock was attached to the MISO cabled observatory in southern Monterey Bay, and used to support docking operations with a Dorado 21" (54 cm) diameter AUV. All the of the capabilities required for a docking capability for seafloor observatories has been demonstrated, including:

- 1) homing and capture of the AUV in the docking station
- 2) establishing an Ethernet connection between the vehicle and the dock using a short range radio frequency communication system

- 3) complete interactivity with the vehicle including recovering mission data to shore, downloading new missions to the vehicle, and even adding new code to the vehicle and compiling in situ
- 4) inductive transmitting power to the vehicle
- 5) charging vehicle batteries from observatory power
- 6) turning the vehicle off, and then waking it up from the dock
- 7) undocking the vehicle from the dock, and commencing missions.

ACKNOWLEDGMENTS

This work would not have been possible without the sustained effort of the entire MBARI Docking team, including Jon Erickson, Lance McBride, Thomas Hoover and Farley Shane, as well as important contributions from Hans Thomas, Rich Henthorn, Judith Connor (MBARI), Steve Rock (Stanford University), and others. We would particularly like to thank Tim Stanton (Naval Postgraduate School) for allowing us full and unrestricted access and use of the Monterey Inner Shelf Observatory, which provided the undersea power and data cable, and infrastructure required to support the dock. We gratefully acknowledge the support of the Packard Foundation. This work was supported in part by the National Science Foundation under NSF-OPP 9910290. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the National Science Foundation.

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APPENDIX

m	640.3	kg	Mass
I_{zz}	475.0	kg-m ²	Inertia
x_G	.119	m	CG offset
x_R	-1.79	m	Dist. to rudder
x_A	-1.03	m	Dist. to antenna
U	1.54	m/s	Speed
T_p	52	N	Thrust
ρ	1025	kg/m ³	Density of seawater

TABLE I

GENERAL PARAMETERS AND MASS PROPERTIES IN
EQUATIONS 1-6 FOR THE HOMING CONTROL

$Y_{\dot{v}}$	-595.0	kg	Added mass
$Y_{\dot{r}}$	-57.91	kg	
$N_{\dot{v}}$	-57.91	kg-m ²	Added Inertia
$N_{\dot{r}}$	-381.4	kg-m ²	
Y_v	-106.0	kg/m	Force deriv.
Y_r	37.90	kg	
N_v	-494.9	kg	Munk moment
N_r	-288.1	kg-m	Torque deriv.

TABLE II

STABILITY DERIVATIVE VALUES IN EQNS. 1-6

d_R	.381	m	Diameter
c_R	.127	m	Chord
$C_{L\alpha}$	4.80	radians ⁻¹	Coef. of lift slope
$C_{D\alpha}$	.012	none	Coef. of drag

TABLE III

HYDRODYNAMIC VALUES FOR RING WING IN EQNS. 1-6

b_S	.127	m	Span
$\bar{c}_S$	.043	m	Chord
$C_{SL\alpha}$	6.28	radians ⁻¹	Coef. of lift slope
$C_{SD\alpha}$	.012	none	Coef. of drag

TABLE IV

HYDRODYNAMIC VALUES FOR RING WING STRUTS IN
EQNS. 1-6

b_F	.254	m	Span
$\bar{c}_F$	.0762	m	Chord
$C_{FL\alpha}$	4.4	radians ⁻¹	Coef. of lift slope
$C_{FD\alpha}$	.005	none	Coef. of drag

TABLE V

HYDRODYNAMIC VALUES FOR GPS/RF ANTENNA FIN IN
EQNS. 1-6

K_p	0.4	none	Position gain
K_r	2.0	seconds	Rate gain
K_v	0.0	radians/meter/second	Lateral speed gain
K_I	.02	seconds ⁻¹	Integral gain
T	.2	seconds	Sampling period

TABLE VI

HOMING CONTROL GAINS IN FIGURE 6

K_p	1.0	none	Position gain
K_r	2.0	seconds	Rate gain
K_v	0.0	radians/meter/second	Lateral speed gain
K_{wp}	.05	radians/meter	Wpnt. posn. gain
K_{Iwp}	.003	radians/second/meter	Wpnt. intgrl. gain
T	.2	seconds	Sampling period
a	1/2.5	seconds ⁻¹	Filt. nat. freq.
K	$1 - e^{aT}$	none	Filt. gain

TABLE VII

DOCKING CONTROL GAINS IN FIGURE 8