The Development and Ocean Testing of an AUV Docking Station for a 21" AUV

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Abstract-**The Monterey Bay Aquarium Research Institute (MBARI) has developed an AUV docking station for a 21-inch (54 cm) diameter AUV. The system was designed for operation with cabled undersea observatories in water depths up to 4km deep and has been demonstrated in the open ocean, though at much shallower depths. The program demonstrated successful autonomous homing and docking, data downloads, uploading of new mission plans, battery recharging, and complete power cycling of the AUV. We describe the design, and at-sea tests.**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are playing a 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 performs weekly missions to measure the physical, chemical, and biological measurements of the upper water column 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. The docking station allows the vehicle to connect to either a mooring or a cabled instrumentation node. Once attached, the AUV can recharge its batteries, download data, upload new instructions, and safely moor 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 or other event response applications, greatly increasing the scientific utility of an AUV.

The move toward seafloor observatories is international 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.

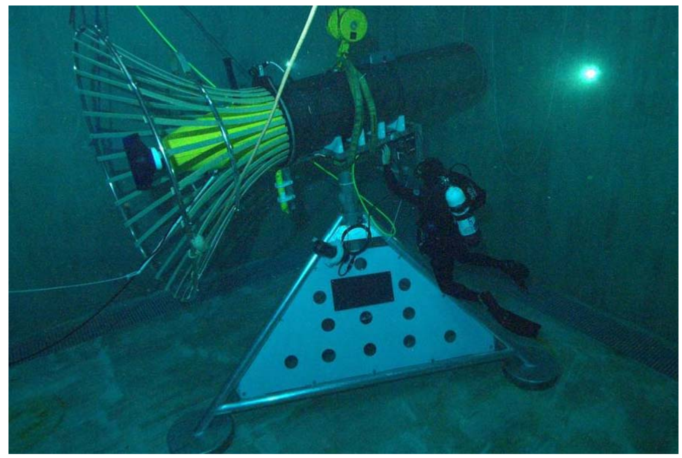

Figure 1: AUV in the dock during testing in MBARI's 1.4 million liter seawater test tank

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.

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.

Figure 2: Dock being recovered after 5 months in Monterey Bay

II. DOCKING SYSTEM DESIGN

AUV docking stations are a multiplier for one of the fundamental features of AUVs that make them so powerful for ocean sampling: long-term, un-attended operations. Therefore, people have been proposing and demonstrating AUV Docking for almost as long as AUVs have been operational. The Remus operations from a docking station deployed on the Leo 15 cabled observatory in the mid 1990s, described by Stokey in [1], demonstrated the feasibility and scientific utility. Since then, many designs have been proposed and several groups have demonstrated basic functionality, but to the best of our knowledge, nobody has conducted sustained operations of an AUV from a docking station for science or industry applications.

The designs put forth so far either hook to a cable or pole or fly the AUV into a tube or garage. Lambiotte [2] and Fukasawa [3] demonstrated a hook capture mechanisms for the Morpheus and Marine Bird respectively, and a nose hook was used for an Odyssey by Singh et al. at WHOI [4]. The Remus dock at Leo 15 used a cone to align the vehicle for docking in a tube. Cowen also used a cone dock for the Flying Plug [5]. A variation of the cone dock, the weather-vaning cone described by Coulson in [6], employs a rotating joint that allows the cone and tube to align itself with the ambient current. Another variant of the cone dock is a grappling system described in [7] and [8] that requires an AUV capable of precise hovering.

We considered three classes of dock for MBARI's torpedo-like flying vehicle: the pole, the weather-vaning 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 weather-vaning 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.

Guided by the research interests of MBARI scientists and the opportunities afforded by the MARS observatory we focused on development of a dock for deep ocean deployments. From previous experiences of developing, deploying and maintaining complex equipment in the deep ocean it was clear that the dock must be as reliable as possible. The easiest way to ensure reliability was to design a dock that was as simple as possible; therefore we chose the fixed cone design.

III. THE AUV

The AUV used for our docking work 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 AUV docking configuration of this vehicle is 358 cm long, and weighs 640 kg including entrained water. Power storage is provided by a single, 2 kW-hr pressure tolerant lithium polymer battery pack that provides a maximum range of approximately 30 km at 1.5 m/s. The vehicle must maintain a minimum speed of approximately 0.8 m/s for controllability and to counteract 3.5 kg of positive buoyancy. The ring-wing propulsion unit, shown in Figure 3, generates 52 N of thrust at 300 rpm using a fractional horsepower DC brushless motor with a 10:1 reduction gear. 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 vehicle navigation system is essentially Doppler velocity

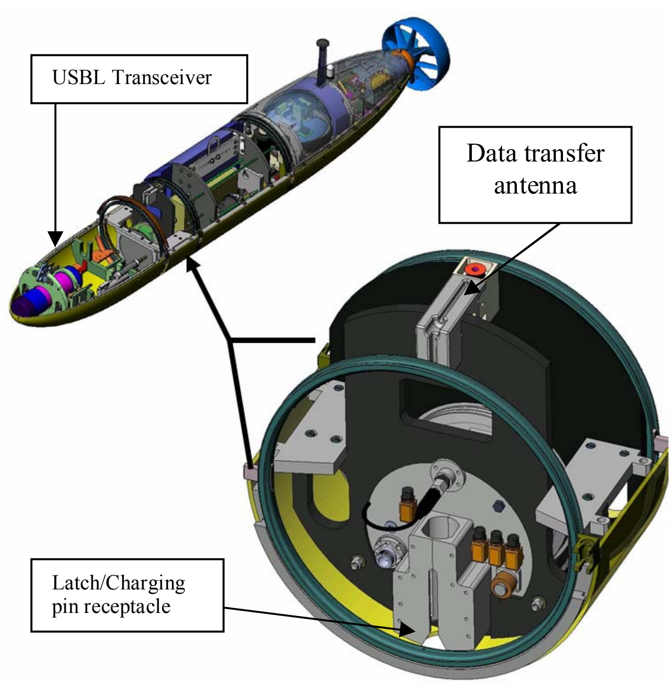

Figure 3: Solid model of Docking AUV with 10" long Docking Section

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.

A. Homing System

The AUV homes to the dock using an Ultra-Short Base Line (USBL) sonar transceiver mounted in the vehicle nose, shown as the magenta cylinder in Figure 3. MBARI selected a 4 km rated Sonardyne Scout USBL homing system, although other types of homing systems have been proven, such as an electromagnetic system [11], and optical systems [5] and [7]. The USBL has the advantage of much greater range, and is also reliable, mature, and commercially available. The only drawback is that the 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, its maximum range was about 2000 m and the field of view was ±85- degrees. Another factor in the selection of the Sonardyne Scout is that MBARI has already placed and surveyed over 100 acoustic beacons in the Monterey Bay that are compatible with this system. In addition to AUV docking, the USBL is useful as a general navigation instrument; since it provides position fixes to bound steadily growing error of DVL aided dead-reckoning navigation, much like GPS, but without surfacing or stopping.

B. Data Transfer

The AUV transfers data to the dock using modified off-the-shelf wireless Ethernet (802.11b) radios. This thru-water, contact-less system uses one antenna that is embedded in the top of the vehicle and a mate correspondingly located in the top of the docking tube. 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.

C. Power Transfer

Power transfer and mechanical latching were both accomplished by having a latch/charge pin inserted into the AUV from the dock. This system is a slightly modified version of the system developed by Florida Atlantic University (FAU) [7]. The system works just like many of the popular electric toothbrush charging stations. When the latch pin is inserted into the AUV, an inductor coil that is embedded in the tip of the pin is engaged between two mating inductor coils inside the docking payload section of the AUV. The system then transfers power inductively through the sea water without a metal-to-metal connection. This system was demonstrated to transfer up to 1 kW at efficiencies as high as 88%.

While we retained FAU's original design for the prototype demonstration described here, in the future we plan to reconfigure the system so that the moving parts and actuator are in the AUV. This change will retain our design philosophy of keeping the dock as simple as possible. Even with the latch/charge pin located in the dock, the entire docking system has only a single moving part with an associated drive motor.

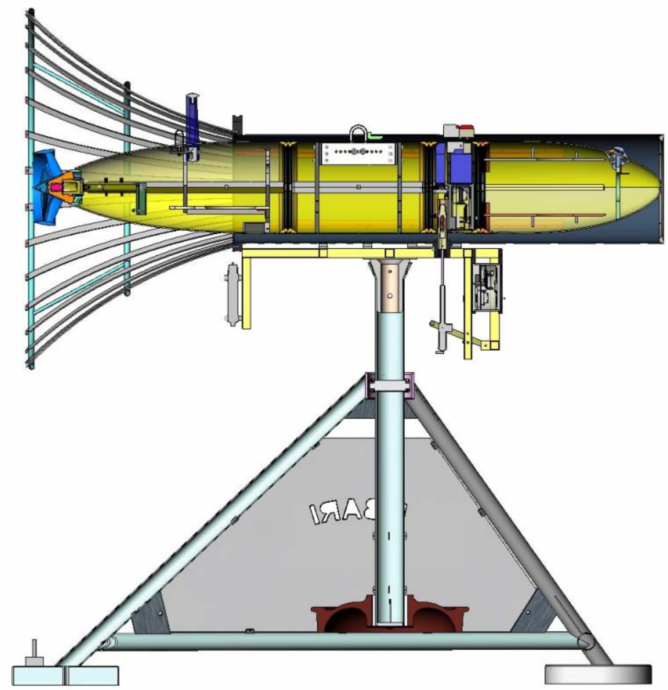

Figure 4: Cross section of AUV Dock

III. 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 for maintenance or repair. The dock is a benthic, fixed-heading cone design that provides secure parking and a rigid data/power connection. The drawback to this design 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 control 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 a compliant, open frame cone, 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 observations that the vehicle was passing well within two meters of the transponder during initial homing tests [12], and the predicted position deviation of the vehicle based on simulations that used historical current data for the near-shore area we planned to conduct tests. The cone and tube are mounted on a 2 m tall aluminum tripod (Fig.4). A pressure housing with the electronics necessary to support power and data transfer between the vehicle, dock and cable is mounted below the tube, along with the acoustic transponder used in homing. A 2 M-pixel Ethernet camera is positioned below the cone (not shown in Fig. 4), looking up at about 45 degrees to allow shore-side operators to monitor the approach, and confirm the vehicle is present and fully aligned inside the dock. An important feature of this design is the compliance that is built into the cone that helps absorb energy as the AUV quickly decelerates as it enters the opening of the tube. In the event of a direct hit where the AUV bypasses the compliant cone and enters the tube at full speed, a series of vent holes in the tube restrict water exiting from the tube, limiting the AUV's deceleration rate before hitting the end-stop.

A. Gimbaled Base

The seafloor around MARS, the planned deployment site, slopes toward the abyss at about 8 degrees. We plan to deploy the dock at this site by lowering it on a cable, touching down and firing an acoustic release to separate the dock from the lifting wire. As we'd have little control over the orientation, we were concerned the docking process could be complicated by the tilted tube. Therefore, we implemented a two axis gimbal between the dock tube and tripod base to allow the tube to self-level, Fig 4. A 275 kg railroad wheel at the end of the pendulum provides a strong righting moment, leveling the dock. In addition to self- leveling, this system provided additional dampening to help reduce accelerations during the docking sequence. Since we did our initial testing in 12 meters of water, surface waves rocked the dock, forcing us to disable the gimbal motion with cable stays to the three legs of the frame.

IV. 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, which is about 2 km. 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 final 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 and begins 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. 5) Alignment. The tapering cone and tube align the AUV in all axes except roll and surge. A V-groove entrance and axial slot cut in the top of the tube force the vehicle's lifting eye that protrudes from the top of the AUV, into alignment. A hard urethane bumper at the end of the axial slot arrests the AUV's surge axis. 6) Latch. The vehicle monitors an inductive position sensor and the status of the data transfer Ethernet connection to determine when to command the insertion of the locking pin. Once in position, the locking latch/charge pin is raised and the vehicle is locked in place. In the open ocean tests, shore operators raised the pin remotely while watching the vehicle enter the dock on the camera. If the AUV is unable to fully align, it backs out and re-enters the approach pattern to attempt docking again. The vehicle undocks by lowering the latch/charge pin 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 positively buoyant vehicle floats up above the dock and begins a normal mission with forward thrust. A more detailed description of the control system used can be found in [13].

X. SEA-TRIAL RESULTS

The AUV and docking station were tested in MBARI's 1.4 million liter seawater test tank before going to sea (Fig. 1). Because the MARS observatory was not operational in time for our initial tests, we accepted an invitation from Tim Stanton at the Naval Postgraduate School to use the Monterey Inner Shelf Observatory (MISO). MISO provides power and Ethernet connectivity to a node in 12 meters of water about 600m off the beach near Monterey California. The dock was installed in early June 2006 and was recovered five months later (Fig. 2). Bio-fouling and wave motion were two challenges that we hadn't anticipated for the planned 900 meter deep deployment on MARS. Based on historical records from an upward looking current profiler (ADCP) installed at MISO we anticipated wave induced reversing currents of 0.25 m/s, which were within the 0.5 m/s limit we had in mind during the development of the AUV docking control system. To reduce the chance of MISO being damaged by fishing trawlers the instrument frame and connector ports were installed in a 100m wide sand channel between two large kelp beds. We defined navigation waypoints to guide the AUV in from open water, down the channel and into the dock. When the AUV left the dock, or missed an approach, it would make a U-turn and head out the channel to a waypoint in open water.

During the early trials at MISO the AUV made several unplanned excursions into the kelp due to erroneous data from the USBL. A moving-window median filter was developed to filter the USBL. A median filter can be effective for sonar applications because it rejects multi-path errors, as long as the number of measurements corrupted by multi-path is fewer than the uncorrupted ones.

Fig. 6 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. During this mission, 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 +, and the black ’s show the location of filtered points. The second chart in Fig 6 shows a zoom of the dock location. 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 repeatable bounce (multi-path). 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 and in Fig. 5, is nearly undetectable, appearing less than 5 cm.

A shift in priorities at MBARI caused an abrupt end to testing. On the last day of testing we ran four missions and were able to demonstrate the complete docking sequence on the first attempt for each of the four missions. Automatic detection of the dock by the AUV was intermittent, but shore-side operators were able to watch the AUV fly into the dock, confirm alignment and manually raise the latch/charge pin. Power was transferred to the battery at a rate of 416 watts with a measured efficiency of 48%. Mission data was transferred off the AUV at 10 Mb/sec and the AUV was completely powered down and then powered up, and a new mission was downloaded. The new mission was started, the pin was lowered, and the vehicle backed out, cleared the dock and ran the next mission.

XI. CONCLUSIONS

A prototype docking station for a 21” (54 cm) AUV has been designed, built and tested at sea. The AUV and dock was ocean tested while connected to the MISO cabled observatory in Monterey Bay. All the of the steps required for docking a 21” AUV to a seafloor observatory 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. MBARI plans to refine this prototype system and install and operate an AUV for science missions from the MARS cabled observatory.

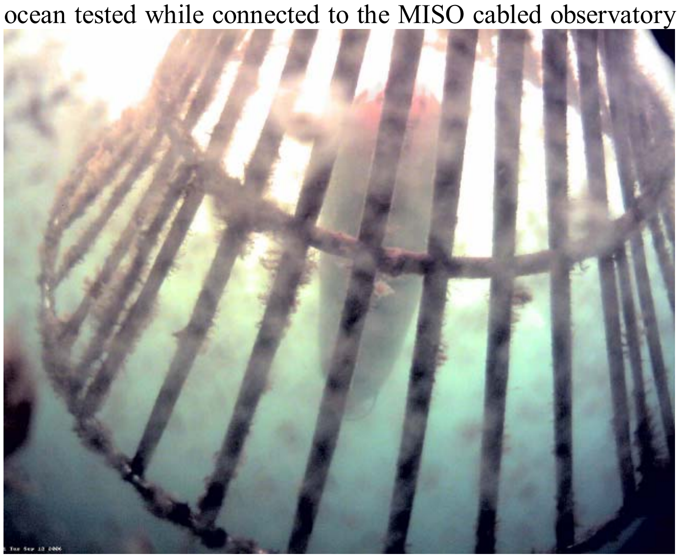

Figure 5: Screen capture image from dock camera showing AUV entering the dock

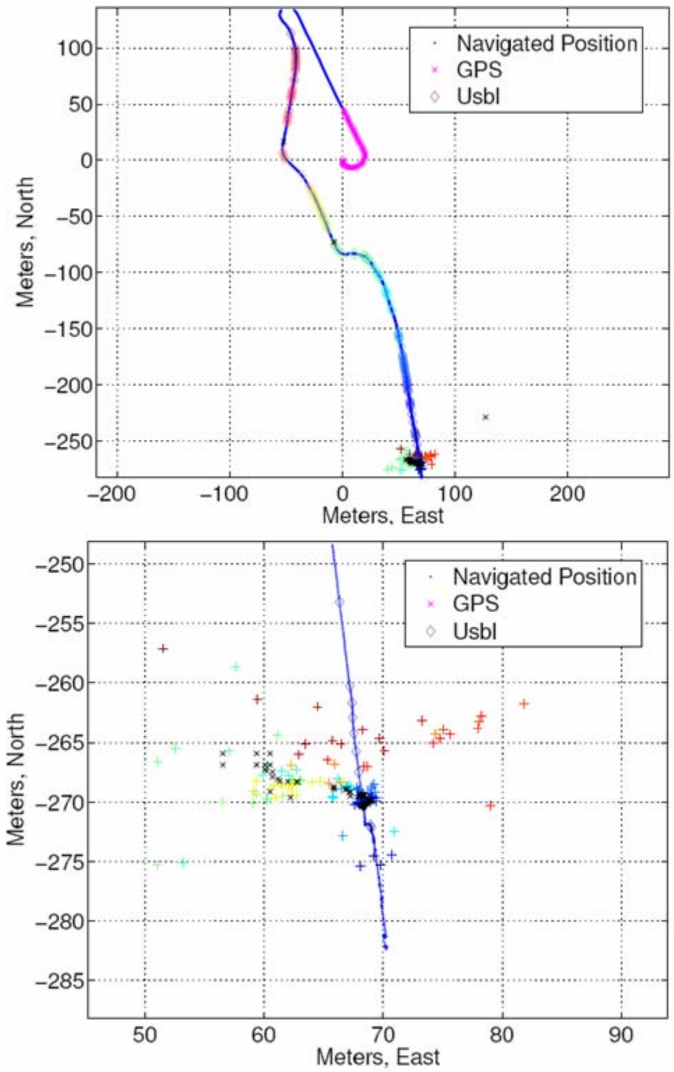

Figure 6: Image above shows a post mission plot showing AUV position track on a docking mission, and a zoom in image below that shows the position estimates of dock based on USBL positioning.

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