Enabling Technologies for REMUS Docking: An Integral Component of an Autonomous Ocean-Sampling Network

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***Abstract*—A dock for an autonomous underwater vehicle (AUV) allows the vehicle to be left on station ready for deployment. However, it represents a significant engineering challenge, as docking requires an accurate navigation system so that the vehicle can find the dock, and complex mechanics to make the required underwater power and data connections. This paper describes the docking system built for the REMUS AUV. It outlines the basis for the design decisions, the as-built configuration, and its performance once deployed. It also delineates the lessons learned from the deployments, and the refinements in the vehicle that have been made since that time, that will improve the system's utility and reliability.**

***Index Terms*—Autonomous ocean sampling network, AUV, docking.**

I. Introduction

THE industrial revolution was largely powered (literally and figuratively) by the steam engine. This invention is generally credited to Scottish engineer James Watt, but in fact its creation predates Watt. His contributions were a separate condenser that made steam engines vastly more efficient, and other improvements that made them practical. Like most complex systems, it was not one single development that made steam engines *possible*, but rather a series of advances: improvements in metallurgy, machining, and a deeper understanding of thermodynamics were all fundamental. It was a convergence of technologies.

In a similar vein, a series of advances have made autonomous underwater vehicles (AUVs) a practical alternative to other types of systems, and these AUVs are fostering a revolution in oceanographic data collection. To the uninitiated, it seems a remarkable act of faith to calmly watch an AUV slip beneath the waves and vanish from sight for an extended period of time, when it would seem entirely possible that this expensive piece of hardware will never be seen nor heard from again. However, advances in systems and technologies have made these vehicles extremely reliable and more cost effective than competing systems and have given them the ability to collect data simply not possible via other methods.

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Robotic systems such as AUVs succeed where they result in decreased costs, improved safety, or better performance. In the case of AUV operations, all three aspects play a factor in their increasing acceptance. Nonetheless, a significant cost of operations is the ship and personnel time required to get a vehicle on station to begin a deployment and to recover it at the end of a mission. In addition, for AUV missions under a few hours, it is effectively required that the operators linger in the vicinity during the mission. A docking system allows an autonomous vehicle to remain at the site waiting for deployment, thus significantly lowering the cost, and increasing the efficiency of AUV operations. Additionally, deploying vehicles in rough weather unnecessarily risks personnel and equipment; however, often those are precisely the situations when it is desirable to make measurements.

For these reasons, the Oceanographic Systems Laboratory (OSL) of the Woods Hole Oceanographic Institution developed a docking system for REMUS [1], [2], allowing it to remain on-station ready for deployment under the command of shore-based operators. However, a dock alone is not sufficient to meet the goal of long-term, on-station vehicle deployment. Advances in the state-of-the-art of dock and vehicle design as well as vehicle tracking are all necessary. Thus, it is not one single technology that allows a docking system to be successful, but many.

An effective system requires careful design of a number of different subsystems to meet the complex requirements. It must have:

1) an accurate navigation system that enables the vehicle to locate and navigate to the dock;
2) a mechanical system that clamps the vehicle in place, provides protection from storms, and allows power and data connections to be made while submerged;
3) a system for recharging batteries that optimizes power transfer and avoids gas generation;
4) two-way communication with the vehicle while docked to allow:
   - downloading of mission data;
   - uploading of new instructions to the vehicle;
   - real-time vehicle diagnostics;
5) the ability to track and verify the performance of the vehicle while it is on a mission.

II. Design Overview

There are several approaches that have been created for AUV docking systems. One example is the system developed for the

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Odyssey vehicle [3] by a group from MIT and WHOI. [4] In this design, the vehicle navigates to the dock using an ultra-short baseline (USBL) acoustic array to determine range and bearing to a transponder mounted on the dock. Once the vehicle reaches the dock, it latches on to a pole using scissor-shaped appendages added to the front end of the vehicle. The power and data connections are made using an inductive link. The advantage of this technique is that it is omni-directional: the dock can be approached from any angle, thus problems with cross currents can be avoided by aligning the approach with the current.

A different method was used by the SPAWARS (San Diego, CA) with their "Flying Plug" [5] and later with a modified Odyssey vehicle [6]: the vehicle navigates to a conical dock entry using an optical tracker for terminal guidance. Once inside the dock, the vehicle is latched into place using movable pins. Data are transferred optically.

Still another approach used for homing is electromagnetic guidance [7].

The approach chosen for the REMUS dock was a combination of the first two methods described. REMUS already possessed USBL navigation capability, so using acoustics for terminal guidance required few modifications. Since the dock was to be installed in shallow water at LEO-15 (Long Term Environmental Observatory15-m depth) [8] off of Tuckerton, NJ, it was desired to shelter the vehicle from the grave risk of storms and wave surge present in any shallow-water installation. For this reason, a design based on a fixed cone leading into a tube (effectively a horizontal funnel) was selected, thus providing a protective garage for the vehicle. This garage also allows the incorporation of biocides, useful for minimizing marine growth over long-term deployments (Fig. 1).

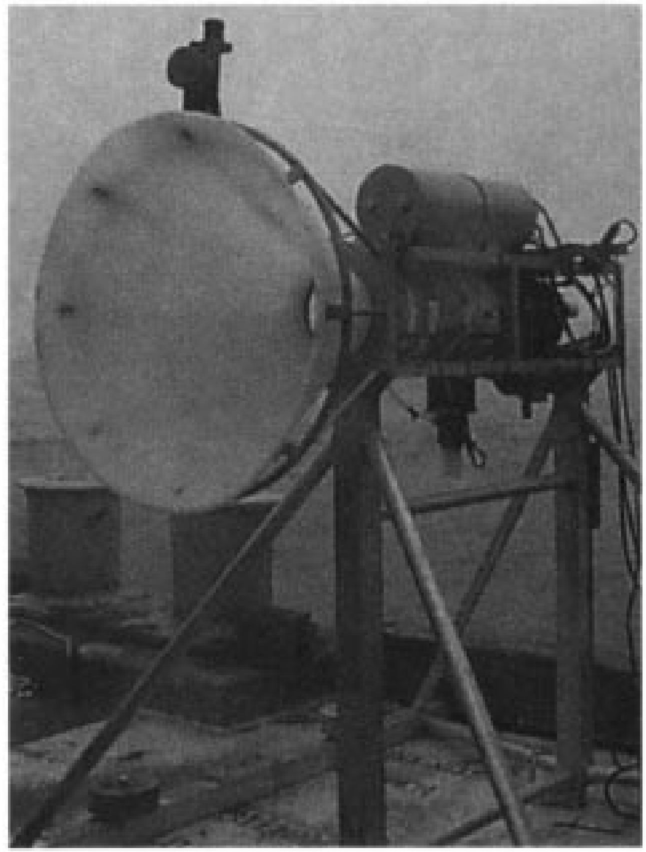

Fig. 1. The REMUS dock at Woods Hole.

A benefit to the design is that it minimizes external modifications to the vehicle and requires no moving parts on the vehicle, thus the impact on acoustic navigation, stability, control, and drag is negligible. Avoiding significant hardware additions also eliminates the need to increase length to create additional buoyancy and, since few alterations are required, more vehicles are readily available for deployment in the dock.

The design also has its disadvantages. It presents a more difficult navigational problem, since the vehicle cannot merely head toward the dock. It must orient itself on a proper glide path, much as an airplane must align itself with a runway. However, because USBL is extremely accurate at short range this was not considered a serious problem. Another difficulty is that this approach requires *a priori* knowledge of the dock's orientation. i.e., which way it is facing. This can be accomplished with either a compass on the dock and/or calibration at installation. One approach is to simply install the dock with a vehicle inside and determine the orientation from the vehicle's heading. The docking method also presents a greater challenge in high current environments, which may move the vehicle off its desired approach path. It is easy to overstate this problem, since it is generally easy to align the dock with the prevailing current direction so as to avoid cross currents, and even so, by crabbing, a vehicle can maintain a desired glide path, much as an airplane is able to land in a cross wind.

Wave surge is a more significant problem, even at depth, because the waves' relatively short period make it difficult for the vehicle to stay on its three-dimensional (3-D) glide path, and over time, the wave surge can come from any direction, thus the dock cannot be oriented to minimize the cross-track component.

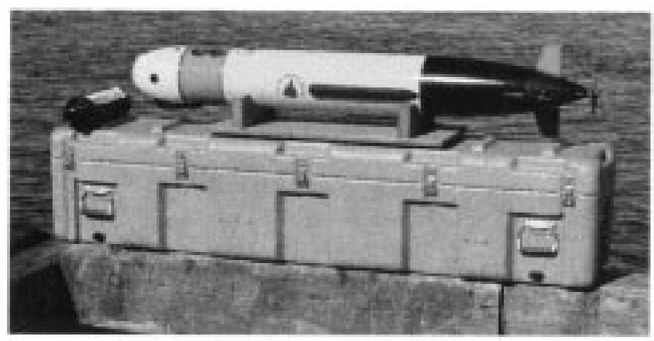

Fig. 2. REMUS and its case weigh less than 68 kg (FED-EX shippable).

A number of options were explored for making the power/data transfer between dock and vehicle. The use of inductive coupling was already being well researched by the Odyssey/MIT/WHOI team. There was a conscious desire to use a dissimilar method, so as to explore different alternatives and provide an effective comparison. The weight of the inductor in a small vehicle such as REMUS (Fig. 2) was also a concern. Optical transfer was rejected as being susceptible to fouling and misalignment. Based on these concerns, it was decided to pursue a direct electrical connection technique. The pin and socket techniques used in commercially available underwater

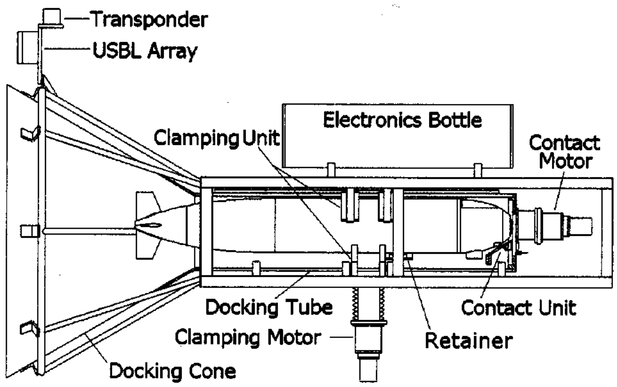

Fig. 3. Docking system components.

mateable connectors were considered, but these require excellent rotational alignment, and the socket, located on the vehicle, would be very susceptible to fouling. The selected design consisted of one butted connection in a sealed environment and one spring-loaded sliding connection in sea water.

III. Hardware Implementation

The dock consists of an entry cone, a docking tube, a clamping assembly, and control electronics. The most visible component is the 1.0-m-diameter docking cone, used to guide the vehicle into the docking tube (Fig. 3). This size was based on the measured accuracy of the REMUS USBL navigation system in conjunction with the expected vehicle offsets due to surge. The docking tube holds the vehicle between missions while it is being recharged. It is made from clear acrylic and has an inner diameter of 0.25 m, with openings for contact assemblies. A coil of 16 AWG wire is spiraled around the docking tube and forms the tuning element of an oscillator circuit. As the vehicle moves in or out of the docking tube, the frequency of the oscillator varies in proportion to the distance REMUS has moved into the coil. A Intel 87C51–based frequency counter allows motions of less than 3 mm to be resolved, thus vehicle entry into the dock can be automatically detected and latching initiated.

The vehicle is held in the garage by the clamping unit. It consists of a fixed two-part cradle mounted to the top of the docking tube and a motor-driven cradle mounted to the bottom of the docking tube. All of the cradle clamping components are fabricated from PVC plastic. A clamping force of 333 N is effective in holding the vehicle, but occasionally a good electrical connection could not be made because the vehicle would slip. To limit slippage, a keel-mounted retainer was added to the vehicle [9].

The data and power connections are made via the contact unit (Fig.4), which consists of the contact assembly and a motor unit that drives it against the vehicle. Both the dock and vehicle contacts are made from 316 stainless steel. The dock centerline contact, a 1.9-cm-diameter disk, connects to the vehicle centerline contact in a sealed cavity created by pressing a polyurethane ring against the face of the navigation array. The required force for a reliable seal is 130 N. The dock lower contact consists of two torsion spring-mounted disks that are pressed against the vehicle lower contact surface. This outer connection takes place

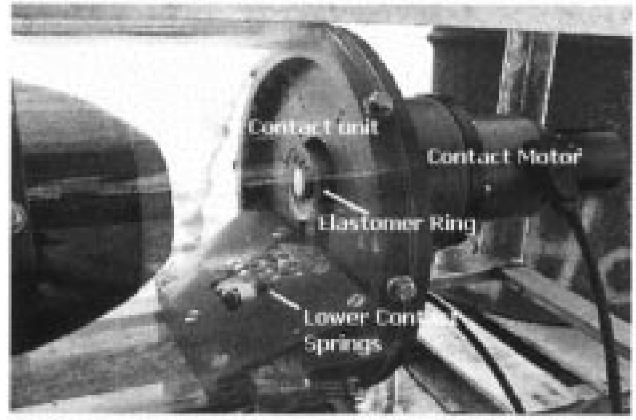

Fig. 4. REMUS in the docking tube.

in water. Only the center contact is sealed, thus simplifying the design. Compression of a spring between the motor unit linear drive and the contact assembly closes a microswitch when the required sealing force is achieved, which turns off the motor. This system will make a good contact if the vehicle forward face is within 2 cm of the docking tube end plate. A linear potentiometer provides feedback on contact motor position and prevents excessive travel. Once the mechanical connection is made, a series of electrical tests are performed to verify that the link is properly isolated before full power is applied to the vehicle, as follows.

1) Reverse voltage is applied to the nose contact and the leakage current is measured. All internal paths in the vehicle are blocked by open relays or reverse biased diodes. If there is not a good seal, then leakage current will be detected. A good seal of the elastomer ring is assumed if there is less than 150-μA leakage with a 12-V bias.
2) A forward voltage is applied through a limiting resistor to the nose contact and the current is measured. This test verifies continuity to the vehicle and the absence of a short circuit by looking for the expected resistance of the coils of a pair of isolating relays.
3) After application of the full power to the vehicle, the current is monitored for normal values. There are two return current paths: one through the seawater exposed spring contacts on the lower contact of the vehicle, and one through a large zinc anode placed near the nose of the vehicle. The current is measured for each of these paths, and, if negligible current returns from the zinc, then the spring contacts are determined to be making good contact.

If at any time after full power is applied excessive leakage currents are detected, power to the vehicle is automatically shut down.

The electronics hardware necessary to control and monitor dock performance are located in a pressure housing mounted to the docking tube frame. The core of the hardware system is a PC-104 computer system with a flash disk, a four-channel serial card, and a digital I/O board. The clamp and contact motors are controlled with a 68HC11-based controller board. A dedicated digital signal processing system supports tracking of REMUS using USBL tracking. This allows remotely located observers to

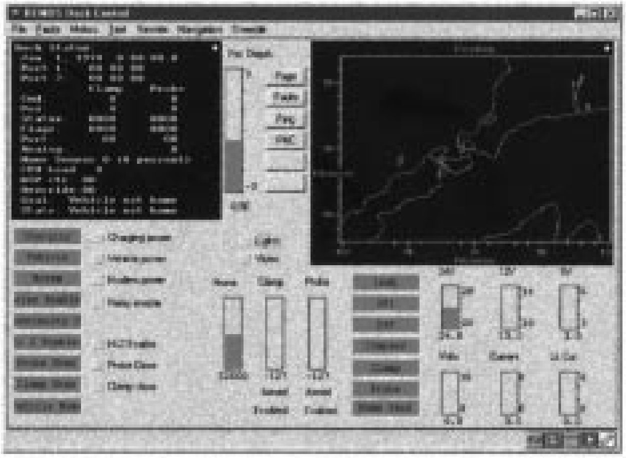

Fig. 5. The REMUS dock control program.

view the vehicle's progress toward the dock during the docking maneuver.

Data are transferred between the dock and vehicle on the same connections as the charging power. A pair of short-haul modems, one in the vehicle and one in the dock, modulate the data to a 10-kHz–300-kHz band. LC power separation filters in the dock and the vehicle isolate the high-impedance telemetry circuit from the low-impedance power circuit. The dock status is monitored from shore via the dock control program (Fig. 5), which communicates with the dock electronics CPU via a dedicated RS-232 link. This provides capability for round-the-clock monitoring of dock status. Controlled subsystems include: current, voltage, leak, and ground fault monitoring systems, compass, and attitude sensors, "home" sensor, and clamp and contact motor tracking systems.

A second serial link is used to monitor the vehicle, with its own dedicated program [10].

IV. Navigation

The REMUS vehicle is capable of navigating using dead reckoning (with and without Doppler assist), long baseline navigation (using two or more transponders), or using a forward-looking USBL array to home on a single transponder. The accuracy of these systems is indicated in Table I. For completeness, this table shows the capability with Doppler-assisted dead reckoning; however, this capability was not present on the vehicle used in the docking experiments.

For docking, use of the USBL navigation is the most practical, as it is the most accurate at short ranges. Its errors are primarily angular in nature, and the relative accuracy increases as the vehicle approaches the dock.

While docking, REMUS acoustically interrogates a transponder mounted at the dock. The USBL receiver computes the range based on the round-trip travel time and bearing in azimuth and elevation based on the relative phase differences detected across a four-element planar array located in the vehicle's nose (Fig. 6). Vehicle heading and attitude are also included in the calculation, resulting in an actual geo-referenced, acoustically determined position. Wide-band coded signals are used to improve the range and resolution of the system [11],

TABLE I
Navigational Performance (Note: Docking Vehicle did not Have Doppler)

Navigational Performance with Respect to the Dock		
Method	Error	Primary Sources
Dead Reckon	10% distance traveled + 1 to 5 degrees	Currents, Compass, Propulsion unknowns
Doppler Assisted DR[1]	0.2% distance traveled + 1 to 5 degrees	Compass
Long baseline	15 Meters	Transponder Positioning
USBL	+/-0.5 meters + 1 to 3 degrees from endpoint	Compass

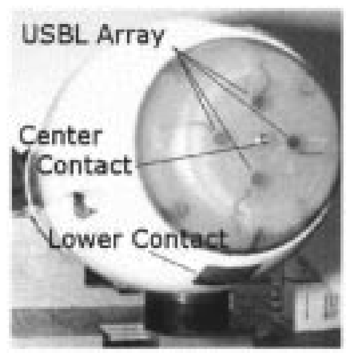

Fig. 6. USBL array with electrical.

[12]. REMUS uses this geo-referenced position information to navigate to and remain on a trackline leading into the cone.

In the 20–30-kHz frequency range in which the REMUS USBL system operates, acquisition and tracking can occur at ranges of up to 2000 m from the dock. Absolute accuracy is limited by static errors in the magnetic compass, typically 1–3 degrees. However, minor heading biases will not hinder the homing operation. Noise, and to a lesser extent, resolution, have a more significant impact on performance.

V. Docking Algorithms

A REMUS mission consists of a sequence of objectives, which are high-level building blocks from which complex missions can be created. One such objective is "Dock." When the vehicle is instructed to dock, it first navigates to a point 50 m in front of the docking cone. It then navigates toward the cone using USBL. The docking objective requires REMUS to follow the trackline, so, if necessary, it will crab to stay on the line. Once REMUS has closed within 2 m of the dock, the vehicle straightens its fins and continues to drive itself toward the dock for 10 s (Fig. 7). This procedure is designed to allow REMUS to ignore the compass, which may be unreliable due to ferrous metals in the vicinity and due to accelerations associated with the impact with the dock. It also forces the vehicle into the cone

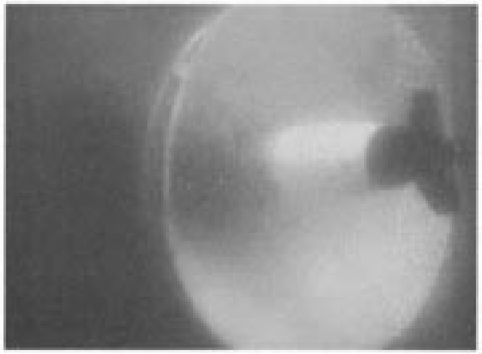

Fig. 7. REMUS entering the dock.

and docking tube. After this period has elapsed, the vehicle puts the rudder hard over, while continuing to thrust. If the compass indicates the vehicle has turned 90 degrees, then the vehicle determines that it has missed the dock and navigates back out to the start point for another attempt. If the vehicle does not turn, then it continues to thrust until the dock clamps it in place and applies external power. The presence of the higher voltage of external power is REMUS's cue that it can shut down the thruster.

The dock has its own procedure that it follows during the docking sequence. Once the dock has been "armed," the docking sequence is entirely automatic.

1) The dock detects the entry of the vehicle by changes in the tuning frequency of the oscillator formed by the coils around the tube.
2) The clamping motor is started.
3) The dock waits until clamping motor is closed.
4) The probe motor is started.
5) The dock waits until probe motor is closed.
6) Electrical checks are performed as described in Section III.
7) Full power is applied.

Undocking is essentially the same process in reverse. The dock removes external vehicle power, backs away the probe contact, and then releases the clamping motor, freeing the vehicle. Meanwhile, the vehicle's "Undock" objective requires the vehicle to thrust hard in reverse with the rudder hard over. When the vehicle detects that it has turned 90 degrees, it assumes that it has backed out and cleared the dock, and executes the objectives that form the rest of the mission.

VI. Performance and Results

During the summer and fall of 1998, the OSL successfully demonstrated the dock at Woods Hole, at the LEO-15 Observatory off of Tuckerton, NJ, for 17 days in July, and in November, at the AUV-Fest off of Gulfport, MS [13]. During that time, it developed a significant body of statistics regarding reliability.

During early testing at LEO-15, the vehicle docked successfully on only 21% of all approaches. However, because the vehicle retries after a missed approach, it may succeed in subsequent attempts. In this early testing, it succeeded in 47% of all missions.

TABLE II
Docking Results

Results	Attempts	%	Missions	%
LEO-15	20/97	21%	20/43	47%
Woods Hole	13/19	68%	13/16	87%
Gulfport	30/50	60%	30/33	91%

As the software and hardware were improved, performance also improved. During later testing back at WHOI, the vehicle successfully docked in 87% of all missions, and at the final testing off the R/V Gyre the vehicle successfully docked on 30 of 33 missions, a 91% success rate. Table II shows the docking results of these three tests. The attempts column indicates the number of times the vehicle successfully docked, compared to the total number of approaches. The mission columns are the same number of successes divided by the total number of missions. This is the more meaningful figure of merit because the vehicle circles back around and makes another attempt at docking when it misses, and docking is sometimes successful on second, or later attempts. The number of attempts was typically limited to five per mission.

Since the dock rests on the seafloor, depth cannot always be used to determine the correct vertical position for the approach. Tidal change causes variations in the depth of the dock. For this reason, acoustics were sometimes used to determine the proper vertical approach. In tests, both direct depth control and acoustic homing were used for controlling vehicle vertical position. At Gulfport, constant depth was successful in 24 of 36 approaches, and acoustic in 6 out of 14. While the constant depth results are better, it should be noted that five of the missed acoustic approaches occurred during one mission with a significant acoustic multipath problem. If this is discounted, the performance with the two techniques is comparable.

When using acoustics to determine depth, the vehicle is given a maximum and minimum depth window, typically somewhat larger than the expected tidal range. This window size was typically about 3 m. When the vehicle calculates an acoustic fix, it uses vertical bearing angle, vehicle pitch, vehicle depth, and range to estimate the depth of the transponder. From this, the depth of the center of the cone could be determined. Results that were outside the window were thrown out as being corrupted by multipath off the surface or bottom.

The docking vehicle was not equipped with an ADCP, however, recent reductions in size and cost of the REMUS ADCP result in that item being essentially a part of the "standard" vehicle configuration. The Doppler navigation capability made possible by this instrument improves navigational accuracy, and it also serves as an altimeter, thus providing a much more accurate method of vertical control while docking.

VII. Improvements

Despite the system's success, it was apparent that there was significant room for improvement. Clearly anything less than near 100% mission reliability is unacceptable. However, docking statistics alone are an insufficient metric. The vehicle, dock, and other hardware must provide a complete end-to-end

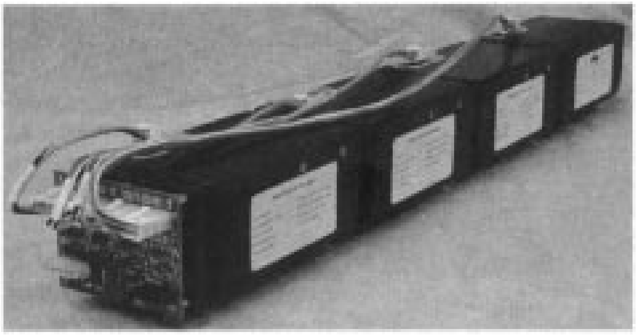

Fig. 8. A 1000-Wh lithium ion pack with smart battery bus interface.

solution for long term deployments. Consequently, OSL improved a number of subsystems to improve performance of the entire docking system.

A. Battery Technology

Lead Acid batteries present significant limitations because they vent hydrogen, which limits the number of recharge cycles that can be safely accomplished, because of their limited volumetric efficiency (44 Wh/kg), and because even with careful maintenance they rapidly lose capacity over time. This loss of capacity, combined with their large self-discharge rate, makes it difficult to reliably estimate available power.

Tests have shown that the amount of hydrogen released during a single charge of the REMUS lead acid batteries is significant and may raise the hydrogen content in the enclosed 19-L free air volume of REMUS to the 4% Lower Explosive Limit (LEL) of hydrogen in air. To alleviate this problem, a platinum catalyst was installed in REMUS. Laboratory experiments have shown that these devices reliably combine hydrogen and oxygen to make water, even at concentrations well below the 4% LEL. A desiccant was used to trap the water and thus avoid condensation inside the vehicle. Since the vented hydrogen is primarily reacting with the ambient oxygen both the oxygen content and internal pressure decrease. Data from tests with one battery suggest that REMUS can be recharged 4–6 times before all the oxygen is consumed. REMUS uses temperature and pressure sensors to measure the total gas content of the vehicle, and thus track the approximate amount of oxygen available. Other technologies, such as nickel cadmium and silver–zinc also exhibit problems with gas venting.

One of the most significant improvements in REMUS is the development of rechargeable medium capacity lithium ion battery cells for the vehicle by Saft America, Inc. (Cockeysville, MD) (Fig. 8). While lithium ion technology is reasonably energy efficient at 140 Wh/kg, its real benefit for AUVs is that the cells are hermetically sealed, so no gas is transferred between the cell and the atmosphere during charge or discharge. This means there is no limit on the number of charge/discharge cycles that can be achieved without opening the vehicle housing [14]. The nongassing characteristic of the batteries is essential for any battery-powered vehicle that will recharge at a dock. Without this capability, the vehicle/dock system cannot be deployed for extended periods or in remote areas, as frequent service will be required to vent gas buildup. Not only does lithium ion technology enable long-term deployments, it also results in improved reliability and reduced labor. Also, these new lithium ion batteries have a projected life span of more than 500 cycles (significantly greater longevity than lead acid), and the self discharge rate of the battery is significantly lower than that of lead acid.

The batteries in REMUS are interfaced to a "smart" battery bus, a standardized data collection and control scheme for batteries used on laptop computers and based on the I^2C bus [15]. It permits the function and capacity of individual batteries to be monitored. This is important for long-term deployment of an AUV from a dock because batteries are historically low-reliability devices, and yet their proper function is essential for the return of a vehicle from a mission. While the ability of a vehicle to find and connect to a dock is critical, failure of the vehicle to return renders the dock superfluous. Thus, it is essential that a vehicle be capable of accurately assessing its available power at all times.

The Texas Instrument/Benchmarq bq2040 smart battery chip, built into the Saft batteries, is essentially a charge counter, a clock, a voltmeter, and a thermister. The counter integrates coulombs into and out of the battery, and the temperature and time data are used to estimate self discharge. Full and empty voltage thresholds are programmed into the chip, and a full-to-empty discharge cycle allows the chip to learn the battery capacity in milliampere-hours. Each new cycle allows it to relearn the capacity, thus as the battery ages, it updates the estimates.

The IC provides available milliampere-hours, relative to its estimate of full charge milliampere-hours. Since watthours is a far more useful unit, the typical discharge curve at 0 °C (percent of full capacity versus volts) was curve fitted to a cubic equation. By integration, this can be used to derive available power, using the following equation:

$$\text{power avail} = \left(3.8C^4 - 8.25C^3 + 7.8C^2 + 22.1C\right)^* AH$$
$$\text{where } C = \text{normalized available charge } (0.0\text{–}1.0)$$
$$AH = \text{battery ampere-hours at full charge.}$$

The increased energy capacity of the lithium ion batteries allows longer missions. The typical REMUS lead acid packs provided about 380 Wh of energy when new and a range of about 21 km at top speed. However, they degraded fairly quickly and, at the end of two years, had about 75% of their original capacity remaining. Some packs that were not properly maintained by regular charge and discharge cycles had even less capacity remaining. The newest lithium ion packs delivered from Saft are rated at 1000 Wh, but exceed that value by about 10 percent, since that rating is the estimate of available capacity *after* 500 cycles.

Longer mission times fundamentally change the potential mission profile for a docking vehicle. It takes REMUS a little under 3 h at 2.5 m/s to achieve 100% insonification of a one square kilometer area at 30-m sidescan range. Thus, the 4-h battery life provided by lead acid batteries essentially restricted vehicle operations to the immediate vicinity of the dock. The lithium-ion battery life of eight hours at 2.5 m/s allows for a 2-h transit to and from the survey area, meaning the vehicle could effectively perform these surveys anywhere along a

35-km beach front. Alternatively, REMUS could do a very low-resolution patrol of a large area, then dynamically alter its mission to do a local high-resolution survey when it detects an anomaly, afterwards resuming its original mission. REMUS has already demonstrated this redirect capability via an external command sent by acoustic modem.

B. More Efficient Prop and Reduced Drag

Mission duration was also limited by high vehicle drag and low prop efficiency of the vehicle. Improving efficiency in this area is more effective than increasing battery energy because power consumption increases as velocity is cubed.

An extensive study of the vehicle hydrodynamics was undertaken, including tow tank tests. These were necessary because it is not possible to determine the difference between the effects of hull drag coefficient and propeller efficiency in open water vehicle tests when neither the actual vehicle drag coefficient nor propeller efficiencies are known. Therefore, the first step in the design process entailed quantifying the sources of drag in a tow-tank on an existing vehicle, and then determining what improvements were possible.

Based on these tests, the following changes were made: the sensor pockets in the nose cap were removed; the blunt nose was extended to a full ellipse; the long baseline (LBL) transducer was cast into a foil section potting (NACA 0024), and the sidescan sonar transducers were streamlined to reduce drag. The effect of all these changes reduced the drag coefficient of the existing vehicle with sidescan sonar and ADCP from 0.42 down to an estimated 0.20 for the new vehicle similarly configured [16].

The second step was to maximize the efficiency in delivery of power to the propeller shaft by selecting a more efficient motor and by eliminating as many power losses as possible. REMUS operates over a range of speeds from 1 to 2.5 m/s. A source of friction at low speeds, and hence power loss, are the wear surfaces associated with a rotating shaft seal. This dynamic shaft seal is also a challenging seal to maintain and keep reliable for extended periods of time in turbid coastal waters.

A primary power loss on the existing design is the brushed dc motor which operates in an air filled compartment at an estimated 65% efficiency at 80 W. Other sources of power losses include the coupling and bearings of a conventional drive system. Therefore, the main propulsion system was modified to use a brushless dc motor with magnetic torque transfer through a plastic collar as a mechanism to eliminate a rotating shaft seal. The elimination of the shaft seal means that longer deployments in the dock are possible without maintenance.

After drag was reduced and the propulsion system modifications were in place, a propeller design tradeoff analysis was conducted based on the results of tow tank tests and motor performance values. This analysis led to the selection of input parameters for a final design for a propeller for REMUS. The design selected from this study was a 14-cm-diameter 3-bladed propeller based on NSMB B-series propeller modified with increased chords toward the hub and reduced chords between 0.4R and 0.8R with an expended area ratio of 0.307. The principal characteristics are shown in Table III.

TABLE III
PROPELLER PRINCIPAL CHARACTERISTICS

Parameter	*Value*
Diameter	14 cm
Number of Blades	3
Expanded Area Ratio	0.306
Blade Pitch/D @ .7R	0.718
Blade Max. Thickness/D @ .7R	0.0103
Propeller	1525 RPM
Vehicle Speed	2.3 m/sec.
Thrust	16.0 Newtons
Torque	0.286 Newton-meters
Developed Power	45.7 watts
QPC (efficiency)	81 percent

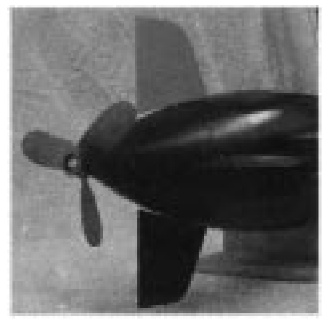

Fig. 9. Tail section with improved prop.

TABLE IV
BATTERY/PROPULSION COMPARISON

	Original Design	*New Design*
Batteries new	380 watt-hrs	1100 watt-hrs
Batteries at 2 years	300 watt-hrs[1]	1000 watt-hrs[2]
Hotel load[3]	29 watts	29 watts
Volumetric efficiency	44 watt-hr/kg	140 watt-hr/kg
Maximum speed	1.7 m/sec.	2.9 m/sec.
Propulsion at max	80 watts	110 watts
Range at max speed[4]	16-21 km	75-82 km
Duration at max speed[4]	2:45-3:30	7:00-7:55
Propulsion at 1.5 m/sec	60 watts	15 watts
Range at 1.5 m/sec[4]	19-24 km	126-139 km
Duration at 1.5 m/sec[4]	3:20-4:15	22:45-25:00

Notes: 1. Estimate based on experience with average maintenance.
2. Based on SAFT estimates of capacity after 500 cycles.
3. Hotel load includes ADCP and Sidescan power.
4. Based on both new and used batteries.

These data were used to develop a propeller geometry which was manufactured, installed, and tested to determine the final improvements in efficiency.

With these improvements, the vehicle consumes 15 W of propulsion power at 1.5 m/s while the previous design consumed about 65 W at 1.6 m/s. The improved vehicle has a top speed of 2.9 m/s drawing 110 W of propulsion power, while the previous design had a top speed of 1.7 m/s drawing 80 W of power.

The performance improvements combined with a battery change from a 380 Wh lead-acid pack to a 1000-Wh lithium-ion pack bring the maximum endurance of this design up to more than 22 h at 1.5 m/s. The results of these improvements are outlined in Table IV.

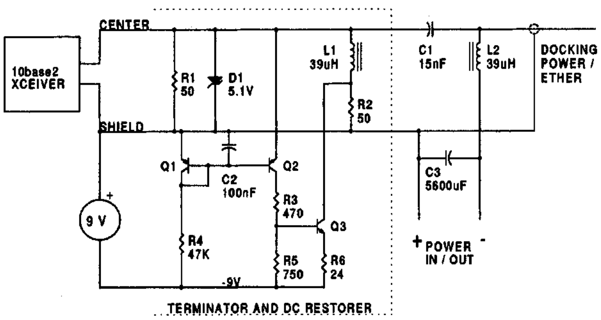

Fig. 10. Schematic of the Ethernet interface.

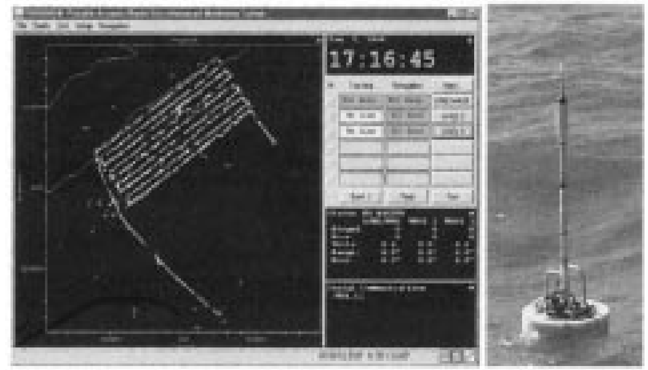

Fig. 11. PARADIGM tracking system and radio buoy.

C. Network Interface

In its original design, the REMUS vehicle used a simple RS-232 interface to allow the vehicle to communicate with its laptop based host program for mission programming and data download. For connection while docked, a simple short haul modem was used to modulate the serial stream up to 10–300-kHz band, while the dc portion carried the power. This approach allowed direct connection with the main vehicle CPU, but not other CPU based subsystems, for example the sidescan sonar. Also, the design was limited to 38 400 baud, which while not a serious limitation did slow the transfer of data.

REMUS has now been upgraded to support an Ethernet interface, which allows the vehicle to carry power and data in a simple two-wire interface. Ethernet is faster than the serial link and allows multiple CPUs to be connected. For a sidescan equipped system, with its separate CPU and hard disk, it allows a single connection to serve both the main CPU and the sidescan.

The two-wire power/network interface is based on the coaxial implementation of Ethernet (10base2/10base5). This hardware was chosen because it is already configured to send bi-directional data on a single medium, standard hardware is available to support it, and its signaling rate of 10 MHz is compatible with the short span of uncontrolled-impedance wiring that exists in the docking apparatus.

Due to the coding of the standard Ethernet signal, all of the information content is contained in the ac portion of the signal, generally above 5 MHz. However, the standard signal is dc coupled and the dc component is required by the collision detection scheme. Because the dc and low-frequency components of the docking connection are reserved for the power transfer, the dc component of the Ethernet signal must be stripped from the connection and restored at each end, prior to connection to standard 10base2 transceivers.

The circuit in Fig. 10 implements the mixing of the power and network signals for one end of the interface; the other end is identical. $L2$ and $C3$ form a lowpass "pi" filter (when paired with the other end) for the power connection with a cutoff frequency of 340 Hz. $L2$ and $C1$ form a highpass "T" filter (when paired with the other end) for the data connection with a cutoff frequency of 200 kHz.

The remainder of the circuit, within the dashed box, is a pair of terminators and a dc restorer to make the whole arrangement appear to the 10base2 transceiver as if it were connected to a dc coupled coaxial cable. The transceiver expects to drive a 25-ohm load, consisting, in general, of two lengths of terminated 50-ohm coaxial cable. $R1$ provides one termination; but, as the termination at the other end is ac coupled by $C1$, an additional dc termination at the local end is provided by $L1$ and $R2$.

The 10base2 signaling alternately drives the center conductor negative with respect to the shield, and then allows it to float back to zero. To restore the dc level inherent in this signal, the charge on $C1$ is altered by the action of $D1$ and amplifier $Q2/Q3$ to prevent pulses from going more positive than the shield. $D1$ borrows charge from the first few pulses of the preamble (the leading pulse train in a packet, prior to the start of real data) while a steady bias from the amplifier is established through the filter action of $L1$. $Q1$ provides bias for $Q2$. While the first few pulses of the preamble may be attenuated by this circuit and not detected by the transceiver, this does not cause any problem for the Ethernet protocol.

The amplifier can be implemented in a variety of ways, but this discrete version was simpler to apply than an operational amplifier due to common-mode range requirements and available power supplies. The restorer can operate from any supply more negative than –5 Vand draws little enough power that when the network is idle, it can stand by for weeks on a single 9-V battery (MN1604).

The dock will see a similar upgrade in the near future so that it will also communicate via network protocols to the dock control program. Network-ready cameras, used to observe the vehicle while docking, can also be connected via this same interface. The result is a much simpler interface with significantly reduced wire count.

D. Mechanical Improvements

During a docking event, REMUS effectively crashes into the docking cone. Early testing identified areas of weakness in the REMUS vehicle design. These included the internal chassis, mounting of some internal circuit cards, which loosened, and the fin shafts, which were bent. The chassis has been strengthened significantly and the REMUS motherboard and daughter boards redesigned to provide a solid mounting for all cards and components. The fin shaft diameter has been increased from 0.25 to 0.38 in. The latest REMUS vehicle design has been subjected to extensive shock and vibration testing at a commercial lab. The vehicle was tested with a 6G RMS random input from 20 to 2000 Hz, as well as 1800, 4G, 40 ms shock pulses. Also, inside its shipping case, it was repeatedly dropped from a height of 60

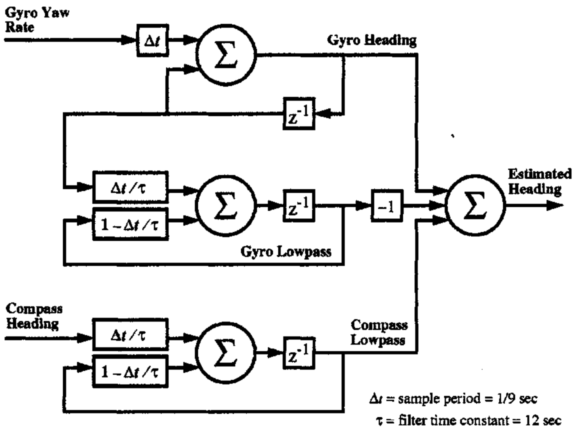

Fig. 12. Heading estimator block diagram.

cm onto all of its axes. The performance in these severe tests indicate that with these improvements, the vehicle will withstand impacts associated with docking without problems.

E. PARADIGM System for Vehicle Tracking

The docking system was originally designed with a USBL system for tracking the vehicle. This used a planar array mounted on the front of the dock to determine vehicle location as it approached the dock. This was adequate when the vehicle was inside a 45 degree cone up to 1500 m in front of the dock, but outside that area tracking was degraded or unavailable.

The Portable Acoustic/RADIo Geo-referenced Monitoring (PARADIGM) system [17] uses multiple radio buoys to track the vehicle and is significantly more accurate (Fig. 11). This system has been routinely used to track the vehicle as it ran 20-km transects at the LEO-15 site. The reality with any complex system is that malfunctions do occur. Remote tracking of the vehicle is essential, unless possible loss of the vehicle is considered an acceptable risk.

F. Quartz Rate Sensor

REMUS has suffered from reduced heading accuracy in dynamic situations due to its sole reliance on a magnetic compass. These are susceptible both to magnetic anomalies and the effects of acceleration during turns. Ironically, the dock itself is one potential source of these anomalies, although it is made from largely nonmagnetic materials where possible. Also, as the vehicle navigates to the dock, the accelerations of the turns it makes to get on a proper glide path themselves cause errors. To minimize these heading error sources, a Systron Donner quartz rate sensor aligned with the yaw axis was combined with the raw compass output to provide a heading reference that has greater immunity to short term interference.

This is accomplished by low pass filtering the raw compass output using a recursive filter with the transfer function of

$$H(z) = \frac{\left(\frac{\Delta \mathrm{T}}{\tau}\right) z^{-1}}{1.0 - \left(1.0 - \left(\frac{\Delta \mathrm{T}}{\tau}\right)\right) z^{-1}}.$$

The heading rate output of the rate sensor is digitized, integrated, and also low-passed, using an identical filter. By subtracting this output from the integrated heading rate, a high-pass

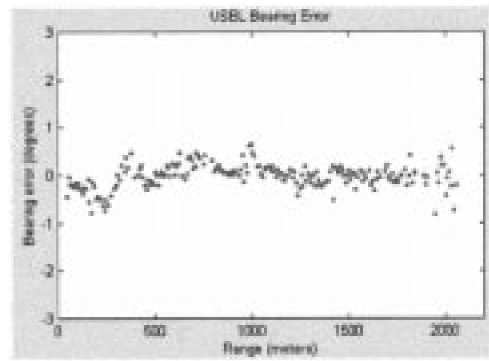

Fig. 13. USBL bearing error (with rate sensor).

filter with the inverse response results. The sum of these two outputs results in a heading output with the advantages of both systems.

Because REMUS carries only a yaw rate sensor, and not a pitch or roll rate sensor, it is not possible to correct the vehicle referenced yaw sensor to yaw in an inertial frame of reference. Therefore, the yaw response is treated as if the vehicle does not pitch or roll, which is a good approximation in the mission modes where accurate heading is important.

Because dc offset in the rate sensor results in a ramp after integration, the rate sensor high-pass filter does not completely remove the offset. However, over a long period of time, any difference in the heading delta of the rate sensors integrated output and the heading delta of the compass will be due primarily to rate sensor offset, and thus the offset can be computed and subtracted from subsequent rate sensor measurements.

During closure to the dock without the rate sensor, there is about 1.0 degree rms of noise, which means that, even at 5 m, the range where REMUS typically obtains the final fix, there is an error of nearly 20% of the cone radius. The addition of the rate sensor improves the rms noise to 0.3 degrees, thus reducing the error in that final fix to about 3 centimeters. This may allow a smaller cone on the dock, while increasing docking reliability. Fig. 13 shows a plot of USBL bearing error as a function of range when using the rate sensor, in water about 6 m deep.

G. Trackline Following

The ability to transit between two waypoints and stay on the line connecting those two points is an essential capability of any AUV. When searching, minimizing the distance from this line (cross track error) is necessary in order to ensure 100% coverage of the search area. While docking, it is necessary in order to maintain a proper glide path toward the cone. USBL navigation presents a problem because heading noise translates directly into cross track error noise, and thus the latter (measured in meters) grows in proportion to the range from the dock. To avoid instability at longer ranges, REMUS formerly used an algorithm that aimed the vehicle at the track line some user-defined percentage toward the final destination. For docking, this value was 40%. This approach, while having the advantage of stability, also had the disadvantage that in a cross current there would always be some residual error.

The improvements in the heading sensor now allow the system used for long baseline navigation to also be used for

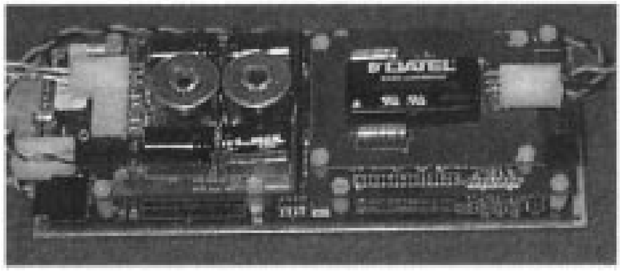

Fig. 14. The UAM.

USBL. The technique determines the cross track error and offsets the heading goal (nominally the bearing between the two waypoints) based on that error. When the error drops below ten meters, an integrator is applied that drives the residual term to zero. This integrator is zeroed for each new leg because the effect of a cross current (the primary cause of static cross track error) is typically opposite on each leg of a survey. A derivative term is not used because acoustic fixes may cause minor step changes in the cross track error and a rapid response to these errors is not desired so as to avoid corrupting sidescan data.

H. Acoustic Modem

For the 1999 AUV Fest, and then in June of 2000 in Fort Lauderdale, the utility acoustic modem (UAM) was integrated into the REMUS [18]. In these demonstrations, the vehicle sent back in real-time position, bathymetry, and CTD information which were plotted as they arrived on a laptop. In April of 2001, two-way communication was demonstrated. The transmission to the vehicle was used to dynamically instruct the vehicle to temporarily alter its mission and perform a high-resolution survey over an assigned area. For longer surveys, the ability to redirect the vehicle is a powerful feature because conditions may change during the course of a mission, thus requiring modification of the mission plan. Real-time data from the vehicle also enable operators to verify that the vehicle is functioning correctly and provide information that the operators may use to modify the mission plan. Lastly, by equipping the vehicle with a modem, the dock could be allowed to pivot so as to be always aligned with the current. The dock would then telemeter its orientation to the vehicle, which would navigate accordingly.

VIII. Tests and Demonstrations

Many of these subsystem improvements were demonstrated in the summer of 2000 at LEO-15 during the ONR-sponsored Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE). During these operations, the REMUS vehicle conducted a daily 40-km mission. Each day the vehicle was launched at about 9 a.m. near node B at LEO-15, and headed 20 km out to sea, along a line of six low-frequency PARADIGM radio buoys. As the vehicle conducted its transect, it ascended and descended through the water column (yo–yo), effectively performing about 80 profiles during the course of the outbound leg. At the end of that leg, the vehicle turned around and returned to its launch point, again profiling, and was picked up and returned to shore for recharge. This was done without opening the housing. For the duration of the mission operators

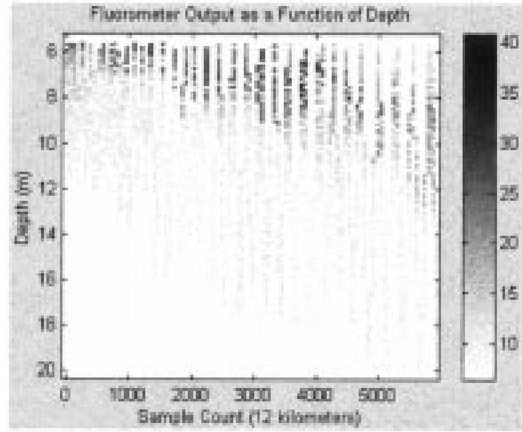

Fig. 15. Fluorometer data collected July 2000 at LEO-15.

remained on shore, only returning when PARADIGM indicated that the vehicle was approaching the recovery point. Fig. 15 shows the fluorometer output, grayscale indicating intensity, the X axis depth, and the Y axis the distance along the transect. Other data collected included temperature, salinity, radiance, and irradiance data, as well as ADCP water current data (using an up- and down-looking ADCP). For these tests, the profiling mode allowed the gap around the immediate vicinity of the vehicle to filled in by averaging adjacent ensembles [19].

This is an ideal example of a mission that could be performed more efficiently using the dock. Using the dock would allow a vast reduction of operator and boat support, since the twice-daily, 1-h round-trip transit to the launch and recovery point would be eliminated. Unfortunately, logistics made this impossible, however, there is no technical reason this could not be done in the future.

IX. Future Improvements

Additional deployments are required to demonstrate the results of these improvements in an integrated manner with the dock; however, further improvements to the dock are also anticipated.

To decrease the possibility of the vehicle getting hung up underneath the dock, the next-generation dock will use a single pedestal for support. The dock will also incorporate the latest UAM, allowing the vehicle to telemeter back data in real time, and modification of the mission plan. The two-motor system will be replaced by a single motor that both clamps the vehicle and makes the electrical contacts. These contacts will be moved from the nose of the vehicle to make them less susceptible to damage during collisions with the dock or other objects.

Eventually a battery-powered dock that can be deployed anywhere will also be built, equipped with both an acoustic modem and a vertical profiler. The latter will have a radio antenna for transmitting data back to a central source.

X. Conclusion

Autonomous docking of an AUV presents significant engineering challenges. For this reason there are very few successful examples. However, the benefits to be achieved by this technology are enormous and will enable AUVs to play an even greater role in an autonomous ocean sampling network. Continued incremental improvements are vital, and bring the day closer when a dock can be permanently deployed for AUV operations.

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Ned Forrester, photograph and biography not available at the time of publication.

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