Autonomous Docking Demonstrations with Enhanced REMUS Technology

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***Abstract*- As autonomous underwater vehicles (AUV's) become more pervasive and enter common usage, systems that expand their capabilities, extend their range, and/or permit operation in denied areas become essential. A dock is one method of achieving these goals. An autonomous dock for an AUV provides the capability to greatly increase the duration and extent of AUV operations, provided the dock has a substantially greater energy supply than the AUV. Other docking station applications include the possibility of installation onto a cabled oceanographic observatory, thus providing unlimited power for battery recharge and continuous data communications. This paper presents the design, development, testing, and results of recent field demonstrations of a compact bottom-mounted docking station for a modified REMUS-100 series AUV.**

In addition to the dock development, the REMUS vehicle was enhanced with a new, modular endcap to facilitate the installation of modular sensors to the vehicle for the docking program. These sensors include a new digital ultra-short baseline (USBL) acoustic homing array and a periscope camera for sea-surface observations. The USBL homing array along with DVL velocity and altitude information provided the capability of the AUV to reliably navigate along a pre-programmed glidepath into an entrance nozzle of the dock. A unique challenge of this second generation docking system was the requirement for small size and near-bottom entrance into the dock.

I. INTRODUCTION

Recent developments AUV performance and reliability over the past several years in have led to the need for extended duration of AUVs at a particular site. Reasons vary for this need, but all include extensive data gathering, data downloading and recharge of batteries [1]. Autonomous docking systems fulfill these needs and in addition provide a means, when coupled to a shore-side communications link, to allow the uploading of new mission objectives based upon analysis of data collected by the AUV.

Advances in AUV technology systems depend upon the successful integration of several individual components. Some components are newly developed while others are incremental improvements of existing designs. The bottom mounted, low profile REMUS docking station presented here is a good example of such an advance in AUV technology. The docking system presented (see Figure 1.) is a second generation design relying on lessons learned from previous design efforts [2],[3],[4].

The REMUS-100 AUV is a 100 meter rated vehicle 19cm (7.5 in.) in diameter and has seen wide use in recent years [5], [6]. A standard vehicle is nominally 158 cm (62 in.) long. The vehicle developed for docking has a configuration that includes an additional inertial navigation system, modular front endcap, and digital Ultra Short BaseLine (USBL) acoustic homing sensor on the nose and is 174 cm (68.5 in.) long. See Figure 2.

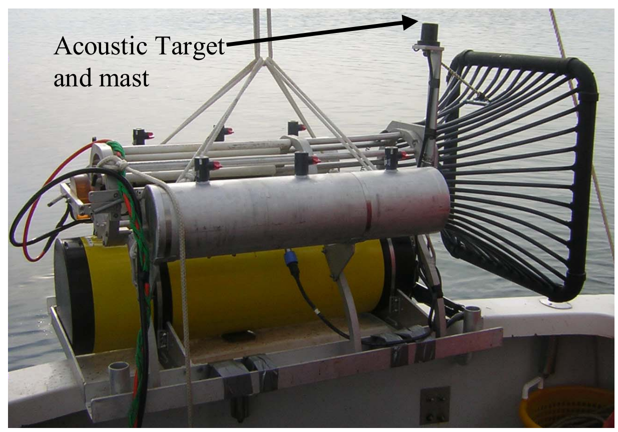

Figure 1. REMUS Dock on transom of research boat near Woods Hole

Figure 2. REMUS 100 in Docking Configuration

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The docking entrance nozzle is approximately 4 vehicle diameters wide and high, and guides the vehicle into an open tubular frame for securing the vehicle. Figure 3 shows the vehicle inserted into the dock in the position when docked underwater. Also shown is the communications buoy and cabling to the dock station.

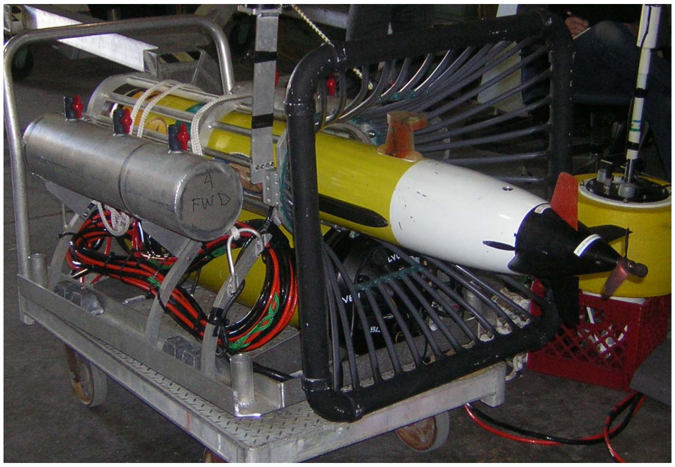

Figure 3. REMUS 100 in docking station.

II. DOCKING SYSTEM DEVELOPMENT

A. *Initial Design and Overall Configuration*

One goal of this design effort was to minimize the number of electromechanical actuators and keep the design as simple as possible. An actuator, whether linear or rotary, is the general term we use for a device that includes an electrical motor or solenoid coupled to some sort of mechanical linkage all enclosed in a water tight housing suitable of deployment in seawater. Complexity can add unnecessary risk; therefore it is desirable to use only one actuator. Initial experimentation with self-centering alignment with single pin underwater connectors was encouraging. This led to the decision to proceed with a single actuator to both electrically connect to the vehicle and clamp the vehicle in place inside the dock frame. As a backup, a second clamping station with actuator was designed and fabricated, but to date, it has not been used.

Due to the space limitations of a delivery vehicle for the dock, the entire docking station had to be very compact for transport and installation on the seafloor. The consequences of this requirement resulted in a configuration of the dock that is an overall small profile, and by using a pop-up acoustic target mast and detachable entrance nozzle. Figure 1 shows both the deployed acoustic target and mast assembly and the assembled entrance nozzle.

An LVDT sensor is used to measure the position of the AUV in the dock. Communications to the dock controller is provided via an attached surface buoy and cable. An Ethernet video camera provided real-time observation of the AUV entering and departing the docking station.

The Docking station also includes twin open-bottom buoyancy tanks to assist with diver deployment. The diver's air supply is used to fill the tanks to near neutral buoyancy to ease the maneuvering of the docking station in water. Lead weights at each corner are used in higher current environments. See Figure 4.

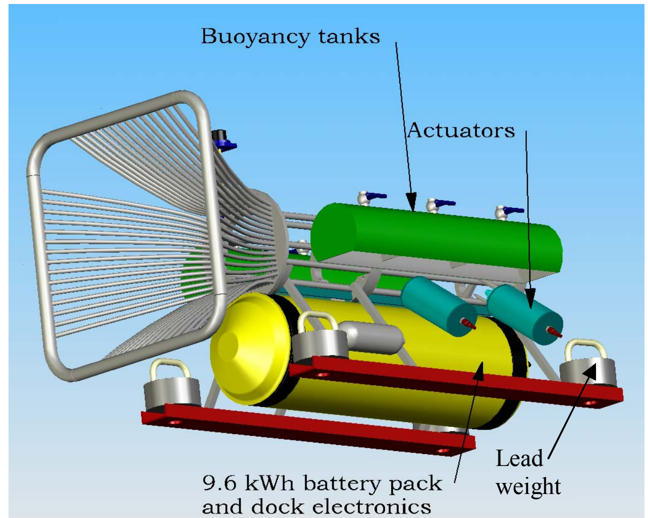

Figure 4. Docking Station showing Entrance Nozzle and Buoyancy Tanks

Other design considerations included preventing problems associated with sediment accumulation, corrosion and bio-fouling. The open frame design is intended to eliminate pockets for sediment accumulation. Appropriate placement and mass of zinc anodes can efficiently suppress corrosion of dock components.

B. *Single Pin Connector and Clamping Mechanisms*

A novel underwater docking connection system was developed and demonstrated. This connection allows the recharging of AUV batteries from the dock supply, upload of AUV data and download of a new mission. Figure 5 shows the linear actuator on the dock frame engaging into the docking connector on the vehicle. Figure 6 is a close-up view of the stab connection showing the long (lower) and short (upper) guide pins. The electrical connector is inside the shortest pin in the middle.

Figure5. Linear Actuator on Dock Frame.

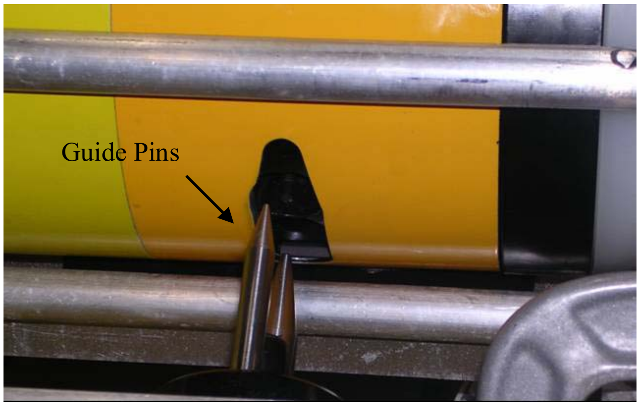

Figure 6. Guide Pins and Underwater Electrical Connector.

C. Detachable, Complaint Entrance Nozzle.

The entrance nozzle shown in Figure 3 is detachable from the main frame of the dock via a 4-pin breech-lock connection. This feature allows the assembly to fit into a compact space and allows ease of assembly and disassembly by divers.

D. Docking Control Assembly

The architecture of the REMUS dock is similar to that of the vehicle itself. A central computer is connected to distributed sensors via a simple RS-232 communications link or through a 10BaseT Ethernet network. Power for the sensors and processor is derived from the battery bus after it has passed through a main power switch. Before reaching the sensors, the various voltages and communications are passed through a "guest switch" that provides current limiting and isolation in the event of a sensor fault. All of the external electrical sub-assemblies are connected to the central computer through a guest port, which provide a common interface for all systems. Even the REMUS vehicle itself is connected to the dock electronics through a guest port. See Figure 7 for a layout view of the controller and endcap assembly.

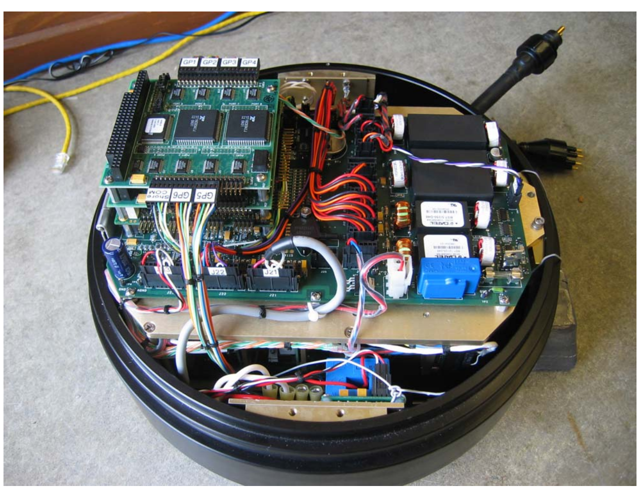

Figure 7. Dock Controller Assembly inside Battery Housing Endcap

E. Dock Batteries

The dock is designed to operate from external power, as when cabled directly to an observatory, or from batteries that are installed in the dock. For battery operation, one or two battery assemblies can be installed. Each battery assembly provides 5.4KWh energy at 23-29VDC. Allowing for the efficiency of re-charging REMUS from the dock, 10.8kWh allows the REMUS vehicle about 65 mission hours (at 5 knots) or significantly longer at reduced speeds. Each battery assembly contains 10 lithium-ion battery packs, each with an electronic controller that provides fault protection and an integrated charger. See Figure 8. Each battery pack contains 63 2.4Ah, 18650-size, lithium-ion cells, arranged in a 7-series by 9-parallel configuration. Data from all packs in the assembly are provided on two RS-232 ports.

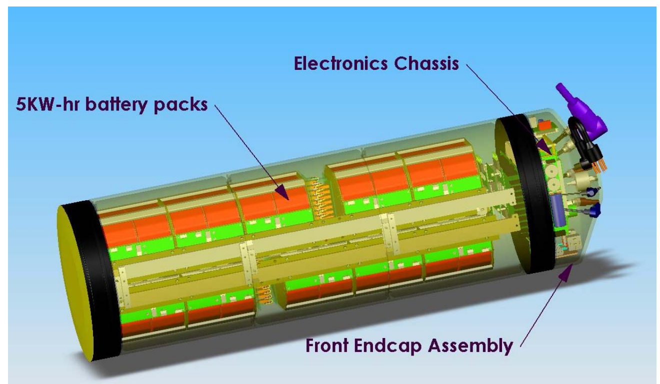

Figure 8. Battery Housing with Electronics Chassis and Endcap Assembly

F. Dock Software Control

The embedded software that operates the dock was designed to accomplish monitoring, telemetry, as well as simple operations, such as operating the motor that engage the power/data connection. It is capable of putting itself to sleep for extended periods of time so as to preserve battery power. The user interface was designed as a DLL extension to the REMUS 32 bit VIP (Vehicle Interface Program). The dock itself is made to appear as another vehicle. Thus the operator can easily switch between communicating with the dock and the vehicle within the same application. This provides voltage, current, and battery monitoring in a manner exactly like the vehicle, thus additional operator training is not required.

Because the dock is made to "look" like a vehicle to the user interface, a lot of the existing development and operational capabilities of the REMUS system are available. This not only speeded development, but simplifies the operator training.

G. Dock Surface Communications

Since power and network communications with the dock are directly available through the guest ports, a guest buoy was designed to provide a link to an operator's console for the testing phase of the project. A custom cable with category 5 twisted pair network cable and power wires connects the buoy to the dock. A WiFi radio system in the buoy allows operators in a nearby boat to observe and interact with the dock during deployment. To observe the REMUS vehicle swim into and back out of the dock, a small video camera is mounted behind the docking cone, where it has a good view. Analog video data is passed to the buoy and into a networked video server for transmission via WiFi.

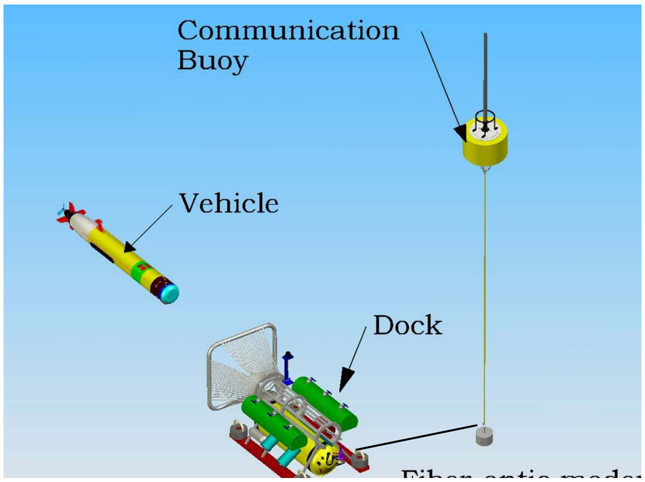

Figure 9. Docking System Assembly showing Communications Buoy.

III. DOCKING VEHICLE ENHANCEMENTS

The REMUS docking vehicle was modified in preparation for these docking efforts. The modifications include significant enhancements to the performance and flexibility of the vehicle for docking. These modifications, shown in Figure 10, are discussed below.

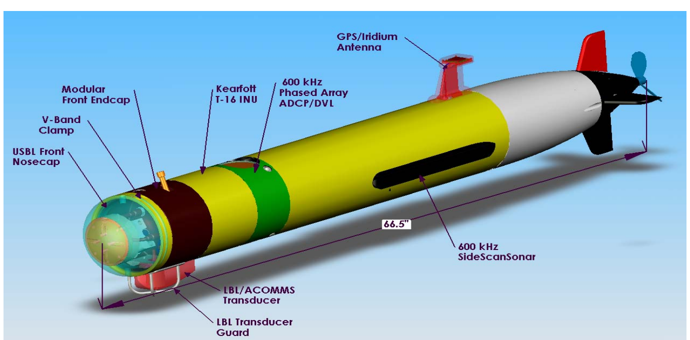

Figure 10. REMUS 100 Docking Vehicle.

A. *Ultra Short BaseLine (USBL) acoustic navigation*

WHOI has developed a nose mounted Ultra-Short Baseline Receiver Array/Processor for range and bearing estimation of an incoming acoustic signal. This small, potted unit mounts on the nose of the AUV, (see Figure 11) and contains a planar array of four hydrophone elements, spaced optimally for signals in the 20-30 kHz range. An integral receiver/processor board is potted in with the hydrophones, making it a convenient, stand-alone unit, requiring only power and a serial interface. This is notably different from an existing analog USBL system on most current REMUS vehicles. This digital USBL is a stand-alone guest port device on a modular nosecap as shown in Figure11.

Signals from the hydrophones are conditioned and digitized. An embedded digital signal processor then receives the digitized samples from the four hydrophone channels, performs complex demodulation and matched filter detection, then follows with a 2-D spatial beamforming algorithm which computes the estimated bearing in both azimuth and elevation. The resulting range and bearing estimates are reported via the serial interface to the AUV controller in the vehicle. Wide band signals are used to increase the range and bearing resolution, while maintaining the long range capability [9] [10]. This acoustic system is capable of acquiring a dock mounted transponder at ranges of 3000 meters or more. Its maximum update rate is 1 Hz. Its DC bearing estimation accuracy is +/- 2 degrees without calibration, and its resolution is 0.5 degrees or less [11].

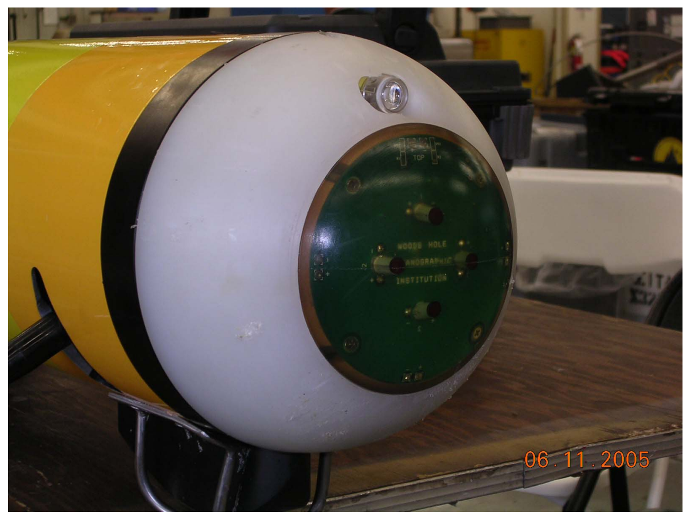

Figure 11. Digital USBL Nose Array.

B. *Docking Modular Endcap Modification*

A standard modular front endcap for REMUS was modified to have the power and Ethernet data connector rotated from the top of the vehicle to about 40° down from the horizontal on the starboard side of the vehicle. This change allows the installation of a clamping and connecting actuator at a similar angle on the dock station to keep the dock compact. See Figure 5.

The front endcap was further modified to include a double guide pin receptacle block as part of the centering mechanism for the electrical connection and as part of the final mechanical clamping of the AUV against the far wall of the tubular frame. The guide pins on the actuator were used to pre-center the electrical pin of the underwater connector and fit inside the openings of the receptacle block. Figure 12 is

CAD solid model of the modular front endcap assembly, and Figure 13 shows the details of the guide pins and underwater connector halves.

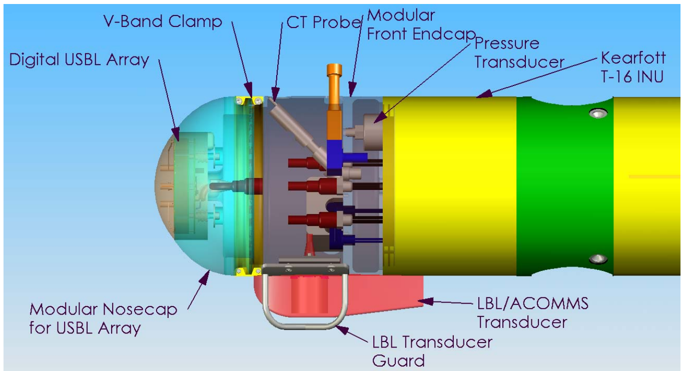

Figure 12. Modular Endcap Features.

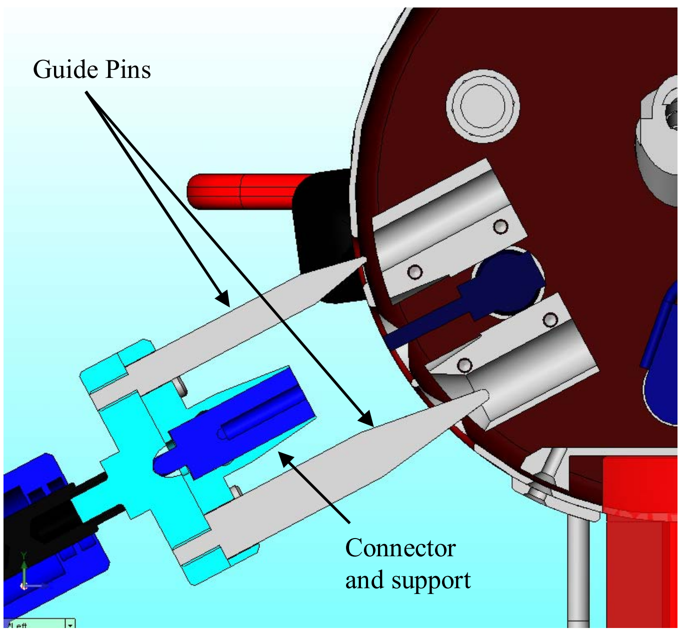

Figure 13. Guide Pin Connector Detail (partial engagement).

C. *Inertial Navigation System and ADCP/DVL*

The vehicle used for docking was equipped with a Kearfott inertial navigation system; however for the approaches to the dock, it is only used as an attitude-heading reference system. This allows tighter control of position based on the USBL acoustic navigation system. The vehicle docks by setting up on a glide path 100 meters away from the cone. Because the cone entrance is only 0.35 meters above the sea floor, the vehicle starts at an altitude considerably higher than that, and descends as it approaches the cone, much as an airplane descends when landing. During final approach, the ADCP on board typically loses bottom lock, however the vehicle handles that situation without problems. Once the vehicle enters the dock, it puts the rudder hard over and climbs. If the vehicle turns, that means that it has actually missed the dock, and it automatically resets itself for another approach, much the same as an airplane would.

Undocking works by having the vehicle thrust in reverse with the rudder hard over. When the vehicle determines it has turned 90 degrees and risen a few meters in depth, it commences its mission.

D. *WiFi Antenna*

The vehicle is equipped with an on-board 802.11B wireless Ethernet capability. A fixed fin contains both a GPS/Iridium receive antenna as well as the 2.4 MHz wireless networking antenna. A wireless access point is installed in a waterproof box on the operator's vessel. This capability provides great convenience to the vehicle operators by allowing them to perform all normal checkouts, mission planning, and data off-load functions remotely between missions, without the need to recover the vehicle. The same wireless network can connect with the dock electronics and video systems via a surface buoy which is connected to the docking station via a subsea cable. A video camera on the docking station is connected to the buoy. Its video signal is routed to the operators console using an Ethernet video server, also connected to the wireless network. Figures 10 and 14 show the GPS/Iridium/WiFi antenna on the vehicle.

E. *Periscope Camera*

A periscope camera for sea-surface observations was developed and tested on the AUV. The camera module is a vehicle guest instrument mounted between the forward endcap and the USBL nose. A low light, miniature surveillance video camera, with a 1/3 inch CCD and a 6mm lens, is installed in the small periscope housing. The housing is deployed, and retracted, with a scissor-jack assembly driven by a small electric gear motor to a height of 23 cm above the AUV body. See Figure 14. The vehicle provides a stable platform for camera operations at all operational speeds. A video digital recording system is housed, along with the gear motor and motor controller electronics.

Figure 14. Periscope Camera in "Extended" Position.

IV. RESULTS

Docking runs with the vehicle evolved over the summer and fall of 2005, with a successful demonstration during the winter of 2005/2006. A docking run consists of the vehicle approaching the dock to establish its glidepath approach. A run is considered successful if the vehicle enters the dock within five glidepath docking attempts. During the final two testing sessions in Woods Hole and the demonstration in Florida, the vehicle made 17 successful (out of 29) glidepath attempts with the following results:

8 entered the dock on the first attempt
7 entered the dock on the second attempt
1 entered the dock on the third attempt
1 entered the dock on the fourth attempt

Each time the vehicle entered the dock, the docking controller successfully detected the presence of the dock with the LVTD sensor, and the linear actuator engaged into the vehicle connector to allow electrical communications between the vehicle and dock 100% of the time. Each docking connection was then followed by a short battery recharge, upload of the previous mission data and download of a new mission objective.

The periscope camera module, when mounted on the vehicle, adds 33 cm (13 inches) to the length of the vehicle and did not affect the flight stability of the vehicle. The resultant movies from the camera were adequate to resolve large objects in view of the camera, and image stability was good, but quite dependant upon sea state.

V. CONCLUSIONS

The low profile, bottom mounted docking station presented many developmental and engineering challenges; however the successful repeated docking in the final stages were very encouraging. During these tests, the effects of tidal current and waves were overcome. Sedimentation, corrosion were not an issue and the dock was not in continuously long enough to see effects of bio-fouling.

Since the value of docking stations depends upon their ability to function when needed after potentially long periods of dormant use, future efforts will be focused on developing long-term reliability of the docking station and vehicle.

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