Development of A Modular Docking Sub-System for 12" Class Autonomous Underwater Vehicles

R. Coulson, J. C. Lambiotte, G. Grenon, T. Pantelakis, J. Curran, E. An
Department of Ocean Engineering
Florida Atlantic University, 777 Glades Rd., Boca Raton, FL 33431

Abstract This paper reports on the progress of our current docking design for the 12 ¾ inch class autonomous underwater vehicle (AUV) to be built by Bluefin Robotics Inc. While there are existing docking systems demonstrated during a limited number of at-sea trials, and shown to have limited success as "proof of concept" research prototypes, the main objective of this docking design project is to design and build a docking system that is rugged and operable over a long duration. That means, cycle stress, corrosion, and bio fouling growth will be considered in the overall design. In this paper, different design options will be presented and compared, followed by our docking design concept which combines the best features of all the existing options.

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are unmanned and untethered submarines. They provide marine researchers with a simple, long-range and low-cost solution with which to gather oceanographic data. Common applications for deploying AUVs include oceanographic sampling, bathymetry profiling, underwater system inspection, and military mine counter-measure (MCM) operations. Some of these missions require long survey operations, and/or some triggering events for starting the missions. These events can be related to environmental conditions, or man-in-the-loop decision making. An example of such a situation is making oceanographic measurements just before, during, and just after a storm front passes an area. For these missions, long endurance and readiness are important capabilities for AUVs.

The ability to dock an autonomous underwater vehicle (AUV) is a key component in extending the endurance capability for AUVs. A docking system consists of a docking station, which is commonly situated on the ocean floor, and a docking payload, which is situated on a docking vehicle. This terminology will be used throughout this paper. Docking allows an AUV to recharge batteries, download collected data, and upload new mission plans. The use of a dock in an AUV mission could create an enormous saving in manpower and ship time for the collection of spatial and temporal data, limited only to deployment and recovery of the vehicle and dock. In other situations, operating an AUV without a dock could be difficult or impossible. Florida Atlantic University (FAU) and South Florida Testing Facilities (SFTF) are currently designing and developing a docking system for a new class of 12 ¾ inch AUVs developed by Bluefin Robotics Inc. (referred to as SFOMC[1] AUV in this paper). The general characteristics of the system are modular, small, portable, reliable, and durable. Specifically, the docking payload will be completely embedded in a detachable nose section.

The paper is organized as follows: Section II describes the design options in terms of mechanical capture, navigation, power and data. Specifically, advantages and disadvantages of these options will be compared in each of the categories. Section III presents our docking design concept that was derived by combining the best features of all the existing options. The final section provides a summary of important design concepts.

II. DOCKING DESIGN OPTIONS

There are four main areas of design that address the interface between the station and payload of a docking system: mechanical capture and retention of the vehicle, navigation and control of the vehicle to the capture window, power transfer from the docking station to the vehicle for battery charging, and a communications link for data transfer between the docking station and the vehicle. In this section, different design options, including those that exist, will be presented for each of the four categories. Some design choices will be somewhat dependent on choices in the other categories, but in general they are independent. Details of the comparison of the design options can be found in [8].

II.1 Mechanical System

The design consideration consists of docking window size, vehicle capture method, vehicle safety, size of the docking payload, approach direction, corrosion and bio-fouling growth, and versatility. In particular, five different design options are described and compared: 1) Buoy Vertical Pole (BVP), 2) Stinger & Puck (S&P), 3) Dual Horizontal Wire (DHW), and 4) Funnel Docking Station (FDS).

BVP This type of docking system was developed by the Woods Hole Oceanographic Institute for the Odyssey AUV with the "Juicer" docking station [5]. The

[1] South Florida Ocean Measurement Center

0-7803-8669-8/04/$20.00 ©2004 IEEE.

docking station in this system consists of a vertical pole as a capture point between a "bottom assembly" below and a motorized "carriage" above. The docking payload has a nose mounted vee-shaped latch body.

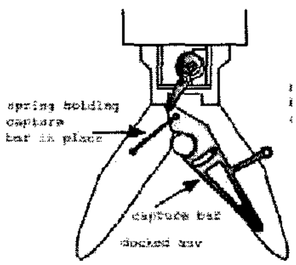


Figure 1. "Latch Body" (picture duplicated from

When the vehicle reaches the docking station, the latch body guides the vertical pole to the center of the latch body. The capture bar at the center of the latch body is pushed aside to allow the pole to enter and then closes behind. At this point, the carriage moves down, forcing the vehicle to slide down the pole to the bottom assembly. The bottom assembly is tapered so that the vehicle rotates around the pole to line up its part of the charging and data transfer system with the part on the docking station. To undock, the carriage moves back up, the latch is opened (this requires some vehicle thrust and fin actuation because the positive buoyancy of the vehicle causes it to negatively pitch on the pole which can bind the latch), and the vehicle backs away by reversing its thruster.

FDS The following funnel docking system was developed by Woods Hole Oceanographic Institute for the REMUS AUV [6][7]. The design of this docking station mechanically consists of a large funnel that leads to a tube. The nose of the vehicle hits the funnel and is guided to the tube. Once in the tube and the

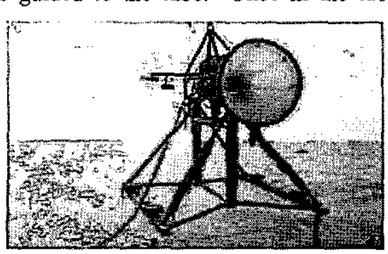


Figure 2. REMUS Dock [picture from http://www.mit.edu/~tprester/thesis.htm

docking station detects the vehicle is in position, a clamp traps the vehicle in the docking tube. Once held in place, a motor moves charging and data elements to the corresponding elements on the vehicle. To exit the docking station, the clamps are released and the vehicle reverses out of the docking station.

S&P The stinger docking system was developed and partially tested at Florida Atlantic University [3][4].

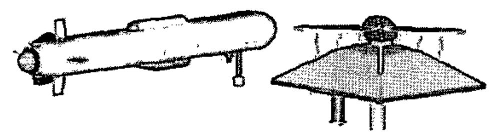
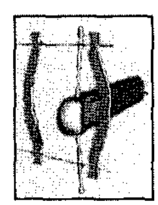
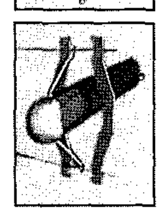


Figure 3. FAU stinger docking system

The docking payload consists of a "stinger" that hangs below the bottom of the AUV. The docking station has four sides, each with a ramp and two horizontal guides. Having four sides allows the vehicle to choose an approach direction into any existing current. When the stinger hits the docking station, the "puck" at the end of the stinger is funneled to the center of the docking station where it passes through a set of one-way gates. At this point the vehicle is securely captured. The charging contact is then driven up into the bottom of the puck. To release the vehicle, the four guides are driven away from the center of the docking station, which releases the puck and allows the slightly positively buoyant vehicle to float up away from the docking station.

DHW This docking system design concept was developed at Florida Atlantic University [3]. This design consists of a pair of "hooks" on the vehicle, one on the top and one on the bottom, that would lie back along the hull or be withdrawn into the hull of the AUV during normal operations. When the vehicle is ready to dock, the hooks would be deployed to reach out nearly perpendicular to the hull. The docking station consists of a pair of "clamps" mounted on two cables stretched horizontally between two vertical poles. One of the clamps is attached to the cables and one allows the cable to slide freely through it. The cables are attached to a winch system. In order to dock, the vehicle, flies between the cables. As the vehicle moves through, the cables slide up through a latch at the end of the hooks to catch the vehicle. The winch is then turned on, moving one of the clamps over to the other, sandwiching the vehicle securely between. To release the vehicle, the clamp retracts, the latches at the end of the hooks are opened, and the vehicle reverses its thruster to back out. Table 1 summarizes the advantages and disadvantages of the four methods.





II.2 Navigation System

The design considerations consist of accuracy and range requirements, size and mounting constraints, navigation filtering, and choice of a navigation system. Table 2 compares the advantages and disadvantages of five different navigation systems: Ultra-short baseline acoustic system (USBL), Short baseline acoustic system (SBL), Optical-based system, Magnetic based system, and dead reckoning system (DR).

II.3 Power Transfer

The design power requirement for the Docking Station is that it must transfer up to 1000 watts of power to the SFOMC AUV at 36VDC and 30 Amps. Three different design options are considered: direct electrical contact (**DEC**), inductive transfer (**IT**), and motor generator (**MG**). **DEC** uses an Isolating DC to AC Inverter on the Docking Station and an isolating AC to DC Converter on the AUV. The power is transferred across the contacts with transformer-isolated alternating current. **IT** uses an Electromagnetic Transformer with the primary winding on the docking Station and the secondary winding in the AUV. The transformer core is split into two sections, one for each winding. The power is transferred across a magnet gap between the two core sections. The power in **MG** is transferred from the Docking Station to the AUV by a rotating shaft. A DC motor in the Docking Station turns a shaft that is coupled to a DC generator or alternator located in the AUV. The AUV's thruster motor could be redesigned to also act as a generator. Table 3 summarizes the design comparison among three options.

II.4 Data Transfer

The design options for data transfer consists of 1) very high frequency RF LAN modules and loop/patch antennas, 2) Inductive Transfer with no additional modulation, and 3) Direct electrical contact of data link. Table 4 summarizes the design comparison among these options.

III. PROPOSED DOCKING DESIGN

This section presents our docking design for the SFOMC AUV in the four mentioned categories. It is important to note that while the existing docking systems [1-7] have been demonstrated during a limited number of at-sea trials, and have been shown to have limited success as "proof of concept" research prototypes, the main objective of this docking design project is to design and build a docking system that is rugged and operable over a long duration. That means, cycle stress, corrosion, and bio fouling growth will be considered in the overall design.

III.1 Mechanical Capture: Funnel Type

A funnel type docking station satisfies most of the requirements and is the most simple and robust in terms of capture mechanisms and protrusions required on the vehicle itself. Trapping the vehicle inside the funnel tube not only protects the vehicle during its visit, but also facilitates easy alignment of the data and power transfer systems, which can also be used to hold the vehicle in place; eliminating the need for additional latches and their inherent release mechanisms. A funnel style docking station can be easily rotated and aligned so that the vehicle can approach at a minimum speed into any ambient current. Orienting the funnel entrance downstream also minimizes the build-up of flotsam within the tube, and allows debris to more easily wash over the entire docking station. Any floating matter that is caught on the station will likely be on the exterior and thus not interfere with the function of the capture, or power and data transfer systems. Additionally, a funnel type system is relatively compact and hence easily deployable, and is readily suited to adaptation to ship or submarine tube mounted configurations.

We believe that these favorable characteristics make a funnel type docking station the most practically attractive and achievable given the resources and available time, however we acknowledge that there could be a significant drawback in that the vehicle nose section impacts with the dock. However, by designing the docking payload as a stand-alone unit with navigation, power/data transfer systems that are essentially independent of the capture mechanism, it would be relatively easy to investigate future modifications to the docking station that would not require significant interaction with the vehicle nose section and hence allow for a more varied instrumentation suite.

III.2 Navigation: USBL

An ultra-short baseline navigation system is ideal for this application. USBL offers long-range performance, and its accuracy increases as the separation of the vehicle and docking station decreases which is ideal. Modern microelectronics and a small array size also allow for a compact footprint that can relatively easily be incorporated into the vehicle payload. Having the USBL system on the vehicle itself, reducing the time between fixes and errors due to the vehicle translation. Florida Atlantic University is currently building a small USBL system based on its new multi-purpose acoustic modem. We plan to incorporate this system into our docking payload in order to provide the navigation necessary to enter the docking station and an inherent communication channel between the dock and/or support vessel.

III.3 Power Transfer: Inductive Coupling

The proposed method is based on some of the same conclusions that are in [1]. The Inductive Power Transfer in [1] was 180 to 220 watts but the new 12-inch diameter AUVs require over 1000 watts for battery charging and vehicle operations. This is primarily due to higher capacity batteries, which need to be charged in the same amount of time. The weight and size of the transformer, in the previous Inductive Transfer System, was over 11 lbs and 6.5 inches in diameter, so increasing the size and weight to accommodate the extra power would not be very practical for a 12-inch diameter AUV. However to accommodate the increased power some compromises must be made. Using some of the best features of inductive transfer and direct electrical contact methods will yield a hybrid that can meet the goals:

- The main advantages of Inductive Power Transfer are:
  - no physical electrical contact.
  - the surfaces are tolerant to inaccurate mating and bio-fouling.
- A Probe Inserting System will provide wiping action and cover protection to the magnetic gaped surfaces. The decrease of bio-fouling and foreign objects allows the magnetic gap to be minimized. This smaller gap than in previous designs will provide a means to transfer higher power without increasing the transformer size. With the end of the receiving section open, all foreign objects will be pushed out and not trapped in the magnetic gap. The probe may also be used to lock the AUV in the Docking Station. The Spring Loaded Cover on the AUV's Docking Payload prevents drag and protects the unit from bio-fouling.

To aid the alignment of the magnetic surfaces the Probe will have 4 flat sides. Each side will have an inductive transferring surface. The flat surfaces will also enable the transformers to be constructed with standard off the shelf EE Ferrite Cores. Each transformer will transfer over 250 watts, which totals over 1000 watts.

The Probe size will be approximately 2 inches square by 4 inches long and weight about 5 lbs. The AUV transformer section will be approximately 5 inches square by 5 inches long and should weight less than 5 lbs.

As the Probe moves from side to side in the AUV, the effective average gap between the 4 surfaces will remain relatively constant. As one gap gets larger the opposite gap gets smaller. A relatively constant gap will in turn keep the leakage inductance constant and that will enable a simple and highly efficient over all design.

A special feature will be added to the electronic circuit, which will degauss the Ferrite Cores at the end of each Power Transfer Cycle. This will prevent residual magnetism from causing an error in the AUV compass readings.

The inverter section of the Power Transfer System will have a pulse-skipping mode to keep the efficiency high during small loads. This will be useful when the Docking Station is being powered by batteries.

III.4 Data Transfer: RF LAN Coupling

Data will be transferred from the Docking Station Probe to the AUV with standard RF LAN modules using either loop or patch antennas. The RF frequency can be as high as 2.4GHz. The interference between the relatively Low Frequency Power Transferring Circuit and the Very High RF LAN frequency should be low. Also the antennas may be positioned in a location where the power transformer magnetic fields are lowest. It is assumed herein that the docking payload will generate navigation commands, such as heading, speed and height (from surface and from bottom), to the vehicle, and the vehicle motion to achieving the navigation commands will be controlled by the onboard vehicle software. This is believed to be a better option since the software interface between the payload and the vehicle can be managed at a high level.

IV. SUMMARY

In this paper, different design options were presented and compared with regard to the docking design for the SFOMC AUV. The overall docking design concept was presented which combines the best features of the design options. The assembly effort is currently underway, and details of the docking design will be presented at the conference.

ACKNOWLEDGEMENTS

This research was supported by the Office of Naval Research under the grant N000149810861.

REFERENCES

[1] Albert M. Bradley, Michael D. Feezor, Hanumant Singh and F. Yates Sorrell, "Power Systems for Autonomous Underwater Vehicles," IEEE Journal of Oceanic Engineering, Vol. 26 No. 4, October 2001.

[2] M. Feezor, P. Blankinship, J. Bellingham, F. Sorrell, "Autonomous Underwater Vehicle Homing/Docking via Electromagnetic Guidance", IEEE 1997

[3] Lambiotte, Joseph, Implementation of the Ocean Explorer AUV Dock for Use With the Morpheus

AUV, Florida Atlantic University Thesis, May 2001.

[4] Rae, Graeme "Final Report for SFOMC: SBL Docking System for FAU Ocean Explorer Class AUVs Using a Low Cost, High Accuracy Short Baseline Positioning System; Phase I – Navigational Accuracy", Report for South Florida Ocean Measurement Center, September 1999.

[5] Singh, Hanumant; Bellingham, James G.; Hover, Franz; Lerner. Steven; Moran, Bradley A.; von der Heydt, Keith; Yoerger, Dana, "Docking for an Autonomous Ocean Sampling Network", IEEE Journal Of Oceanic Engineering, Vol. 26, No. 4, October 2001.

[6] Stokey, Roger; Allen, Ben; Austin, Tom; Goldsborough, Rob; Forrester, Ned; Purcell, Mike; von Alt, Chris, "Enabling Technologies for REMUS Docking: An Integral Component of an Autonomous Ocean-Sampling Network", IEEE Journal of Oceanic Engineering, Vol. 26, No. 4 October 2001

[7] Stokey, Roger; Purcell, Michael; Forrester, Ned; Austin, Thomas; Goldsborough, Rob; Allen, Ben; von Alt, Christopher, "Docking System for REMUS, an Autonomous Underwater Vehicle", Oceans Conference Record (IEEE), Volume 2, 1997, Pages 1132-1136.

[8] Feasibility Study for 12 Inch Class AUV Docking System Design, FAU internal report, June, 2003.

TABLE 1	Advantages	Disadvantages	Versatility
Stinger & Puck	Multi-Directional Docking No Nose-Payload Interference Protrusion Absorbs Impact Release Mechanism on Docking station Stinger/Puck Facilitates Hard-wire Connection	Requires significant protrusion on Vehicle Inductive Coupling more difficult Vehicle Windmilling Issues Complex Release Mechanism	Not Conducive to Shipboard Recovery, deep water, or Submarine Docking. If inverted, could be used to dock with ship.
Dual Horizontal Wires	Multi-Directional Docking Reduced Vehicle Pitching on Capture No Nose-Payload Interference Low Impact - Wires Absorb Impact Horizontal Docking Window Easily Increased	Requires significant protrusions on Vehicle Complex Reeling/Capture Mechanism(clamp) Complex Release (hook latches) Cable Fouling Issues 2-Part Deployment Possibility of Catching Wrong Wire	Not Conducive to Shipboard Recovery, deep water, or Submarine Docking. Could be used to dock with ship.
Buoyed Vertical Wire/Pole	Omni-Directional Docking Vertical Docking Window Easily Increased Release Mechanism on Dock	Smaller Horizontal Docking Window Large Protrusions on Vehicle Nose Significant Nose-Payload Interference	Not Conducive to Shipboard Recovery or Submarine Docking. More conducive to deep water docking, or to dock with a ship.
Funnel Docking Station	No protrusions on vehicle Latching/Capture built into Dock	Vehicle Nose Section Utilized Impact of Vehicle with Dock Docking Station Needs Customization for Vehicle Protrusions	Could be adapted for ship recovery and docking, & deep water applications. Most conducive to submarine torpedo tube adaptation.

TABLE 2	Advantages	Disadvantages	Versatility
USBL	Robust to oceanographic conditions. Accurate to less than a meter. More accurate at close range. Wide range (2000m) Current system in development at FAU.	Direction difficult to establish precisely in real time. Increased complexity near surface, bottom, or other sources of reflected acoustic signals.	Can be used for any type of docking system. Environment insensitive.
SBL	Relatively precise and simple to operate. Existing unit at FAU. Wide range.	Complex and cumbersome deployment. Increased accuracy obtained by increasing the size of deployment.	Can be used for any type of docking station platform. Environment insensitive.
Optical	No acoustic or electromagnetic noise.	Very sensitive to oceanographic conditions (lighting, water turbidity) Limited range (10-30m)	Practical only when entrance from a single direction (funnel type).

			Use only in clear, well-lit water.
Magnetic	Accurate positioning and guidance (20cm)	Relatively short range (25-30m). Magnetic interference not desirable for onboard flux-gate compass. No experience at FAU	Practical when entrance into docking station from a single direction (funnel type).
GPS/dead-reckoning	Potentially very accurate navigation. Potentially large range (depending on navigation system drift)	Need to surface to acquire DGPS fix. Need to have very accurate (expensive) IMU as part of the navigation system	Environment insensitive.

TABLE 3	***Direct Electrical Contact***	***Inductive Transfer***	***Motor Generator***
Environment Insensitivity	Poor	Medium	Medium
Maintenance Free	Poor	Medium	Poor
Efficiency	Medium	Medium/High	Low
Probe/Coupling Size	Smallest	Medium	Medium
Transformers (1000W)	8 Transformers	4 Transformers	2 large motors
Weight	Medium/High	Medium	High
Size	Medium	Medium	Large
Residual Magnetism	Low	Low	Medium
Isolation from Sea Water	Poor	High	Medium
AUV Drag	Low	Low	Low
Electrical Interference	Low/Medium	Low/Medium	Medium

TABLE 4	***Direct Electrical Contact***	***Inductive Transfer***	***RF LAN Modules***
Environment Insensitivity	Poor	Good	Good
Maintenance Free	Poor	High	High
Probe/Coupling Size	Small	Medium	Small/Medium
Transformers/Antenna	none	Two 1/2 Transformers	2 antennas
Weight	Low	Medium	Low/Medium
Size	Small	Medium	Small/Medium
Residual Magnetism	none	None/Low	none
Isolation from Sea Water	Poor	High	High
AUV Drag	Low	Low/ Medium	Low/Medium
Susceptible to Interference	Low	Medium	Low

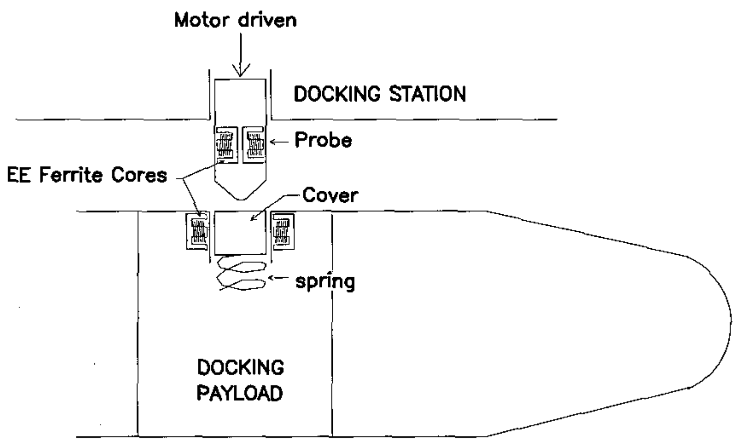


Figure 5. Inductive charging

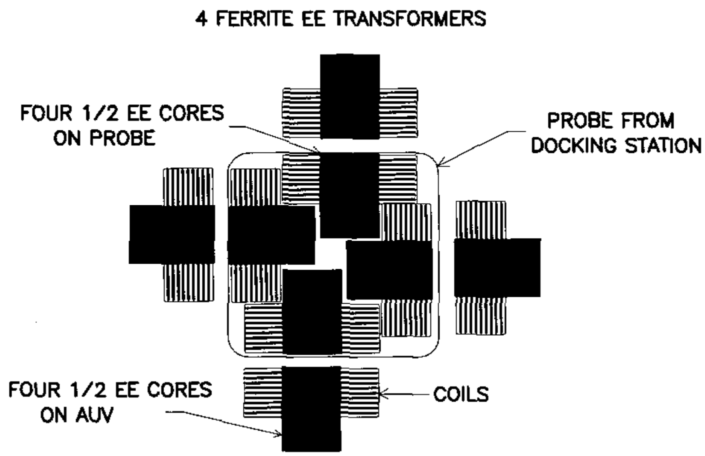


Figure 6. Cross section of inductive charging

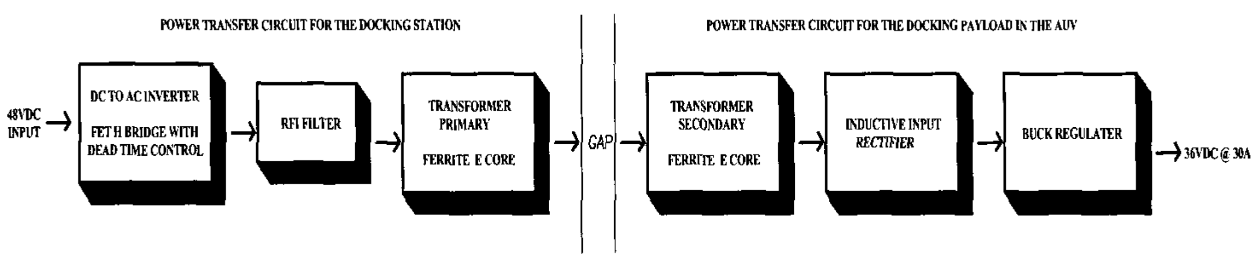


Figure 7. Circuit for inductive power transfer system.