THE UNDERWATER DOCKING AND TRANSFER OF HIGH BANDWIDTH DATA BETWEEN AN UNMANNED SUBMERSIBLE AND A REMOTE UNDERWATER PLATFORM.

Dale Bryan, Brenda Gillcrist, and Ron Reich

Naval Ocean Systems Center
Undersea Al and Robotics Branch, Code 943
San Diego, CA 92152-5000

ABSTRACT

An underwater docking and data transfer technique between an unmanned robotic submersible and a remote data-gathering platform was developed and demonstrated. A docking mechanism was developed that progressively reduced the three dimensional positioning plus rotational aspects of the docking task to a simple one dimensional translation task. Docking was completed by the mating of anunderwaterfiberoptic connector. After docking was achieved, high bandwidth data was transferred from the remote site back to the vehicle launch platform. For demonstrationpurposes,realtimefrequencymodulated (FM) video was transferred through the channel and displayed at the vehicle launch platform. The channel was established using two fiber optic links; the docking link, between the remote platform and the vehicle; and the vehicle link, between the vehicle and the vehicle launch platform. The vehicle was guided to the remote platform by a vehicle based acoustic homing subsystem. The vehicle tracked the relative range and bearing of the remote platform by interrogating a transponder mounted on the remote platform. The vehicle's deployable grabber arm and hover capabilities assisted in the docking task.

INTRODUCTION

The Naval Ocean Systems Center (NOSC) has an extensive background in the research and development of undersea technology. Since 1979, the Free Swimmer Testbed Program has been used as one of the mechanisms at NOSC for demonstrating and evaluating new concepts for undersea applications. The ongoing technology development efforts targeted for this platform include the following areas: autonomous control, navigation, alternative power sources, fiberoptics, image processing, parallel distributed processing, and undersea sensor development. There are three unmanned robotic vehicles that make up the Free Swimmer Testbed Program (1]-[3]. Vehicle configuration is different for each but an equivalent modular electronic architecture is used by all three. Initial work involved demonstrating autonomous vehicle operation [4]. In 1980, an expendable fiberoptic link was developed to demonstrate a unique way of maintaining high bandwidth communications through supervisory control of a vehicle while maintaining vehicle maneuverability equivalent of autonomous operation [5]-[7]. More recent work has demonstrated the feasibility of long distance high bandwidth communications with an unmanned vehicle using fiberoptics [8]. Alternate power sources to support long duration missions of underwater vehicles has been researched [9]. In 1986, a vehicle-based acoustic homing sensor was developed to aid an autonomous vehicle in locating and maneuvering to a target destination. This system was further developed to include a vehicle cable recovery system using a vehicle-based grabber arm [10]. In 1988, a vision-based cable detection and tracking system was developed for aiding an autonomous vehicle in a cable recovery task [Ill, [12]. TheFree Swimmer computer architecture has continually evolved and developed with advancing technology. Ongoing research in parallel distributed processing architectures is being applied to command, control, and sensor subsystems on the vehicle [13]-[16].

The NOSC Free Swimmer Testbed (Fig. 1) with its fiberoptic link provides a unique capability for offboard sensor applications. One mission scenario is depicted in Fig. 2. Here, the vehicle is used to establish a high bandwidth communications channel between the launch platform and a remote underwater data-gathering platform. In this scenario, the vehicle is deployed from the launch platform and maneuvered to the vicinity of the remote platform. Once in the vicinity of the remote platform (<I km), the vehicle acoustic homing sensor is activated to navigate to a transponder at the docking site. At the docking site, the vehicle operator performs the underwater docking maneuver utilizing the vehicle's underwater TV camera, deployable grabber arm, and vertical thruster. When docking is completed, the data is transferred from the remote platform through the fiberoptic docking and vehicle links to the launch platform where it is stored and displayed. The vehicle acts as an electro-optical repeater/multiplexer in the data transfer operation. After data transfer has completed, the vehicle separates from the docking mechanism and returns to the launch platform.

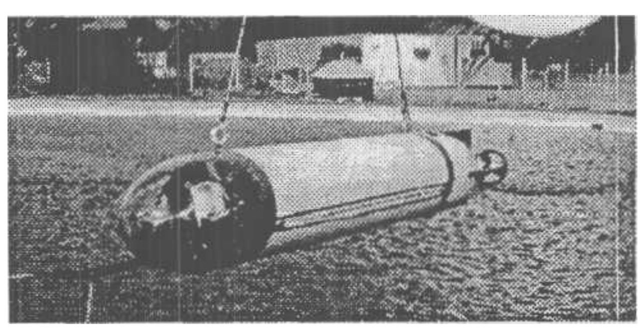

Fig. 1. Free Swimmer Testbed.

0-7803-0202-8/91/0000-1275$1.00®1991 IEEE

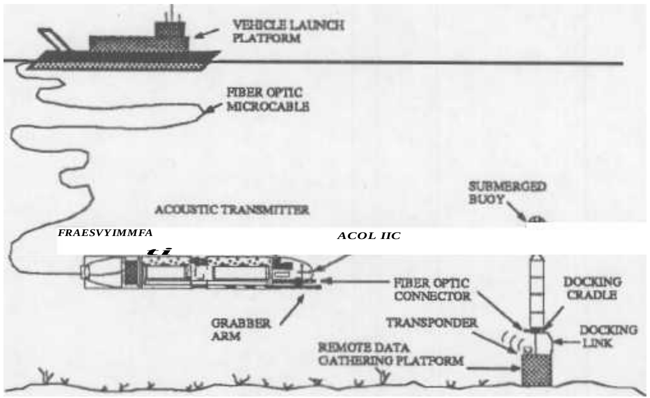

Fig. 2. Mission scenario.

PROGRAM GOALS

The goals of this program were to (1) develop an underwater docking capability, (2) demonstrate the docking of an unmanned robotic submersible with a remote data-gathering platform, and (3) transfer high-bandwidth data in real time from a remote site back to the vehicle launch platform.

DOCKING HARDWARE

The ocean environment acts on a vehicle in all six degrees of freedom (x-, y-, z-translation, pitch, yaw, and roll) while a vehicle may only be able to actively control a restricted set of these degrees of freedom (Fig. 3). The Free Swimmer Testbed can actively control x-, z-translation, and yaw using its three thrusters. Passive pitch and roll stabilization is achieved for a static environment by locating the center of buoyancy above the center of gravity [2]. During a docking task, the vehicle needs mechanical assistance to restrict uncontrollable degrees of freedom. Docking mechanism hardware and vehicle grabber arm modifications are developed to provide the mechanical advantage necessary for the Free Swimmer Testbed to accomplish the underwater docking task.

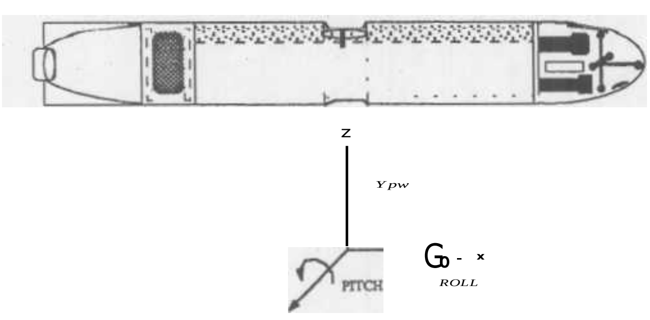

Fig. 3. Coordinate frame.

Docking Technique

The docking technique is based on a progressive degree of freedom reduction between the vehicle and docking mechanism during the docking maneuver. After the vehicle is guided to the docking assembly by its acoustic homing sensor, the grabber arm is deployed to capture the docking mechanism guide cables visible on the vehicle camera's surface monitor. The grabber arm is commanded to capture the guide cables. This compliantly restricts the vehicle in all degrees of freedom except z-translation (vertical). The vehicle is then maneuvered down the guide cables into the docking cradle using its vertical thruster. Once in the docking cradle, continued downthrusting eliminates relative movement between the docking cradle and the vehicle. The grabber arm is retracted to capture the docking cradle. The docking cradle and grabber-arm gripper are designed to fit together in a way that aligns the underwater mateable connector halves. At this point, connector alignment is achieved and all relative uncontrolled motion between connector halves is eliminated. This action also eliminates the need for continued downthrusting to keep the vehicle's grabber arm in the docking cradle. Docking is completed by further retracting the grabber arm until the underwater connector is mated. Upon completion of the data transfer, the commanded grabber arm demates the underwater connector and releases the docking cradle. The captured docking mechanism is illustrated in Fig. 4.

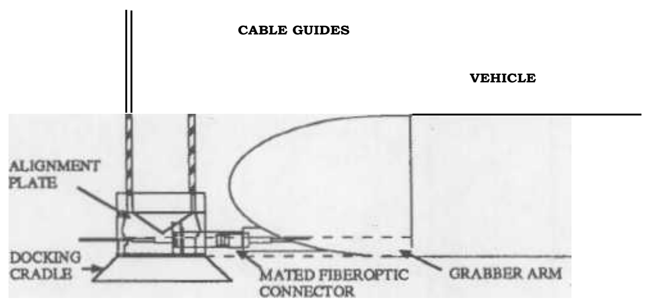

Fig. 4. Captured docking mechanism.

Docking Mechanism

The docking mechanism consists of the guide cables and the docking cradle. The guide cables are 4.8 mm wire ropes. They are attached to the docking cradle's alignment plate. One of the guide cables is marked indicating the forward position for cable capture by the vehicle. The use of two guide cables prevents relative rotation between the vehicle and the docking cradle. The docking cradle has a W-shaped design (Fig. 5). The two outside sections of the docking cradle have tapered lead-in edges to assist gripper guidance onto the center section alignment plate. The alignment plate has edges that are both tapered and notched to compliment the grabber-arm gripper design. The male underwater fiberoptic connector is attached to a section that is slot mounted on the outer left side of the docking cradle. This section slides up and down for connector vertical fine adjustments.

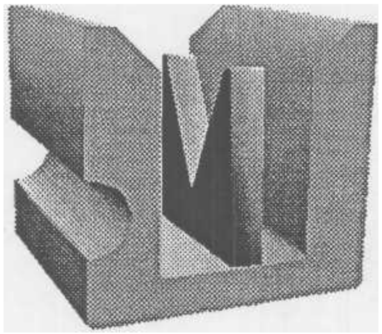

Fig. 5. Docking cradle.

Vehicle Modirications

Modifications to the vehicle are focused on changes to the nose cone and grabber arm (Fig. 6). The vehicle nose cone has a hole drilled through it for mounting the female underwater fiberoptic connector. This hole is precisely placedrelative to the grabber arm to ensure correct positioning for connector mating. The grabber arm was originally designed to capture a cable for a vehicle recovery task [10]. Its end effector was a pair of one meter rods used to contain and guide a recovery cable into a latching mechanism located at the grabber arm/rod attachment site. For this project, a gripper type end effector was designed. The gripper is used to perform three functions: capture, containment, and alignment. Capture and containment are performed on the guide cables during initial docking steps. The open gripper is commanded to close around the guide cables by the vehicle operator when the vehicle is in position. The closed gripper forms an enclosed slot that contains the guide cables during vehicle downthrusting. The closed gripper also slides over the docking cradle's alignment plate with minimum clearance. Tines are fabricated on the inner face of each gripper appendage to fit snug with the docking cradle's alignment plate providing connector alignment during docking cradle capture.

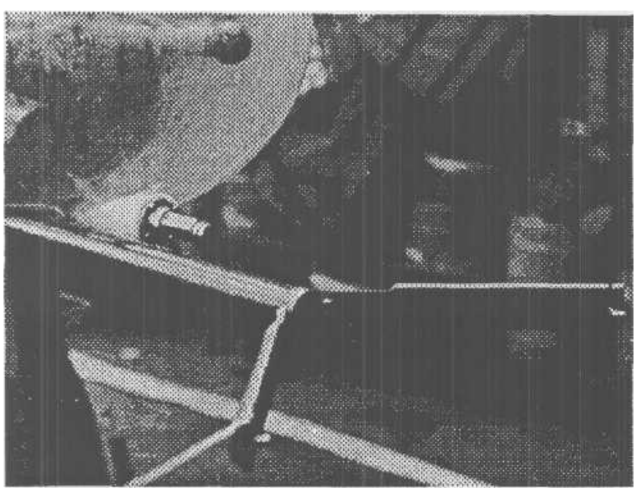

Fig. 6. Nose cone mounted connector and extended grabber arm (gripper open).

DATA CHANNEL

The purpose of performing the docking task is to create a communications channel for high bandwidth data transfer between a remote platform and the vehicle launch platform. The overall data channel consists of two data links coupled together, the docking link and the vehicle link. A high channel capacity is achieved by using single-mode fiberoptics for these links. A fiberoptic channel can provide high bandwidth over long link distances [8]. Channel components include a color-video camera, electro-optical modulators/demodulators, single-mode fiberoptic cables,underwater mateable fiberoptic connector, fiberoptic pressure penetrators, video switch, and monitor/VCR (Fig. 7). The data channel is completed by mating the underwater fiberoptic connector during the docking task. Data is transmitted from the remote platform to the vehicle launch platform through the docking link and vehicle link combination. The vehicle acts as an electro-optical repeater/multiplexer in the data transfer operation. The data is displayed and stored at the vehicle command and control console on the launch platform. The high bandwidth data transferred during these tests is frequency modulated color video.

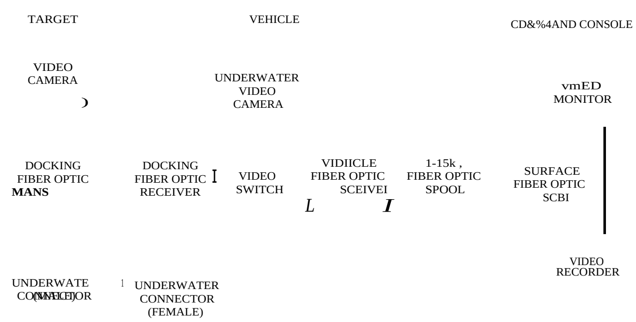

Fig. 7. Overall data channel.

DOCKING LINK

The docking link provides a unidirectional data path from the remote platform to the Free Swimmer Testbed when docking is completed. This link is divided into remote platform components and vehicle components. On the remote platform side, a color video camera provides the source for data transfer. The video signal is coupled into a FM video fiberoptic transmitter. The fiberoptic transmitter converts the 6 MHz electrical video signal into a 220 Mb/s optical pulse stream. The optical signal is fed into a 0.5 km single-mode fiberoptic cable. The single-mode fiber is terminated at the target docking site with the male side of the underwater mateable fiberoptic connector. This connector is mounted on the docking cradle. At the vehicle, the female side of the underwater mateable connector is mounted to the nose cone at the position necessary for docking. This female connector is attached to a single-mode fiberoptic cable. The optical signal enters the vehicle's electronics bottle through a pressure penetrator mounted on the bottle end cap. Inside the electronics bottle, the optical fiber is coupled to the FM video fiberoptic receiver. This receiver converts the optical pulse stream back into electrical video. The fiberoptic receiver output is connected to a video switch. The video switch is used to couple the video signal between the docking and vehicle links.

Loss Budget Analysis

A fiberoptic link design is based on both a loss budget and bandwidth budget analyses [17]. The bandwidth budget analysisfor the docking link is not needed due to the short link distance (0.5 km) and fast optoelectronics used. The loss budget analysis drives the design of the docking link. These losses are represented below for a wavelength of 1.3 gin.

connectors (2)	2.0 dB
splices (2)	1.0 dB
penetrator	1.0 dB
underwater connector	1.0 dB
0.5 km fiberoptic cable	0.25 dB
safety margin	5 Q dB
TOTAL	10.25 dB

Components were developed and selected for the docking link which met or exceeded these design criteria.

Fiberoptic TransmitterlReceiver

Fiberoptic video transmitter/receiver pairs were investigated that would meet the constraints of the docking link design. These constraints included sufficient optical dynamic range, compact size, and compatibility with existing vehicle power supplies. Force Incorporated's Model 2498 FM video laser transmitter and Model 2290 FM video receiver met these constraints. This pair operates at a wavelength of 1.3 gm. The transmitter optical power output is -13 dBm and the receiver sensitivity is -34 dBm. These parameters allow for an optical link budget of 21 dB. The design losses of 10.25 dB for the docking link are well within the link budget of this transmitter/receiver pair. The units' 3.75 in x 3.00 in x 1.125 in compact form factor is easily integrated with existing vehicle hardware. Power requirements (+12 V) of these units are compatible with vehicle power sources.

At the transmitter, the video signal is frequency modulated onto a 70 MHz carrier. The FM signal is then squared up by a comparator. The comparator output drives a 220 Mb/s fiberoptic digital transmitter. At the receiver, a 220 Mb/s fiberoptic digital receiver converts the optical pulse stream into an electrical one. This converted signal is fed into a FM demodulator with a center frequency of 70 MHz. The demodulator output signal is amplified and lowpass filtered resulting in the video signal at the receiver output.

Fiberoptie Cable

Several factors were involved in choosing a fiberoptic cable for the docking link. These factors included cable ruggedness, termination compatibility with underwater mateable connector, and single-mode cable availability. Seicor's single-mode fiberoptic cable (P/N SG100-153E) met these requirements and was chosen for the docking link. The Seicor cable is armor reinforced and therefore rugged enough to endure handling on the docking assembly. Specifications of dispersion and attenuation for this cable are 3.5 ps/nm-km and.45 dB/km, respectively. Each half of the underwater mateable connector is terminated with this cable.

Underwater Mateable Fiberoptic Connector

The underwater mateable fiberoptic connector is a critical component of the docking link design. This connector has to provide consistent performance during repeated matings at depth. A modified version of the Lockheed underwatermateable fiberoptic connector is used in these tests. The modifications to this connector included removal of the latching mechanism and alignment key. This connector is rated for operation at full ocean depth.

The underwater mateable fiberoptic connector consists of two halves, a female receptacle and a male plug. When the connector is mated, a fiber-to-fiber butt splice joint is made by direct mechanical alignment of the prepared fiber ends within each connector half. This fiber-to-fiber joint is contained in a fluid-filled pressure-compensated environment within the mated connector. Attenuation of less than 1 dB was measured for the mated connector.

Video Switch

The video switch consists of an electrical circuit designed to switch one of two input signals into the vehicle's uplink channel. The input signals to the video switch are the vehicle's underwater video camera and the docking link receiver's video output. The vehicle's underwater video camera is connected to the uplink channel under normal vehicle operating conditions. The video switch is controlled by keyboard command from the surface console.

VEHICLE LINK

The Free Swimmer Testbed uses a deployable fiberoptic link for bidirectional communications between the vehicle and a launch platform. The advantages of this type of link are its high bandwidth, deployability, and expendability [5]. A high bandwidth channel enables large amounts of data to be transferred across the fiberoptic link in realtime. The vehicle deployment scheme enables maneuverability consistent with that of an autonomous vehicle. Link expendability eliminates the need for a tether management system aboard the vehicle launch platform.

The vehicle link (Fig. 9) combines two optical channels, an uplink and a downlink, onto a single fiber using wavelength division multiplexing. The uplink and downlink channels operate at wavelengths of 1.3 gm and 1.55 μm, respectively. The uplink channel is used to transmit two frequency division multiplexed sensor channels to the surface console. The two frequency division multiplexed sensor channels include a pulse frequency modulated (PFM) video signal and a Manchester encoded digital signal. Further, the signal driving the Manchester encoder represents a time division multiplexed waveform of five 9600 Bd RS 232 channels. The downlink channel is used to transmit a Manchester encoded version of the time division multiplexed waveform containing the complimentary five RS 232 channels. The vehicle link provides operation of five bidirectional 9600 Bd RS 232 channels and a unidirectional high bandwidth channel between the vehicle and the surface console over a link distance of 15 km using single-mode fiber. One of the five RS 232 communication channels is used for command and control between the surface console and the vehicle computer. The high bandwidth channel is used to feed realtime video from the vehicle's underwater video camera to the surface viewing monitor.

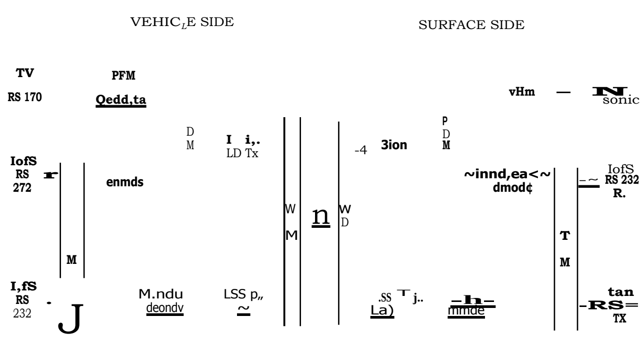

Fig. 9. Free Swimmer fiberoptic link.

Only a part of the vehicle link is needed to transfer the docking link data from the vehicle to the launch platform. The PFM uplink channel is time shared between the vehicle underwater video camera and the docking link signal through a video switch.

Fiberoptic Transceivers

The vehicle's fiberoptic transceiver is used to transfer the docking link receiver output data from the vehicle to the vehicle launch platform on its uplink channel. The docking link receiver output video signal is pulse frequency modulated (PFM) onto the 36.8 MHz uplink carrier. The PFM signal drives a 1.3 μm laser transmitter with an optical power output of -10.3 dBm. At the surface console, the complimentary transceiver converts the optical pulses back into an electrical PFM signal. The optical receiver has a sensitivity of -35 dBm at 1.3 μm. The PFM signal is then directed into a PFM demodulator. The output of the demodulator is the realtime signal of the video camera sourcing the docking link data.

Expendable Fiberoptic Spool

The vehicle link consists of an expendable fiberoptic microcable 30 mils in diameter. This microcable consists of an optical fiber surrounded by a fiberglass jacket. The small size enables winding of tens of kilometers of fiber into compact spools (Fig. 10). During winding, an adhesive material is applied to the microcable to maintain the spool shape.

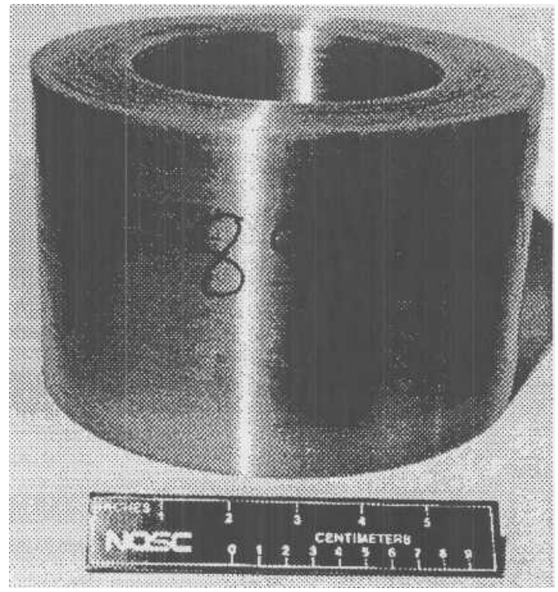

Fig. 10. 20 km expendable fiberoptic spool.

The fiber spool is placed in a canister that is mounted in the vehicle aft section (Fig. 11). The expendable fiber pays out of the canister and lays motionless in the vehicle track as the vehicle transits. The payout occurs with less than 1 lb of tension. This causes minimal drag to the vehicle, which allows maximum vehicle maneuverability during its mission. This payout scheme coupled with link expendability alleviates the need and reduces the impact of a bulky, complex tether-management system aboard the vehicle launch platform.

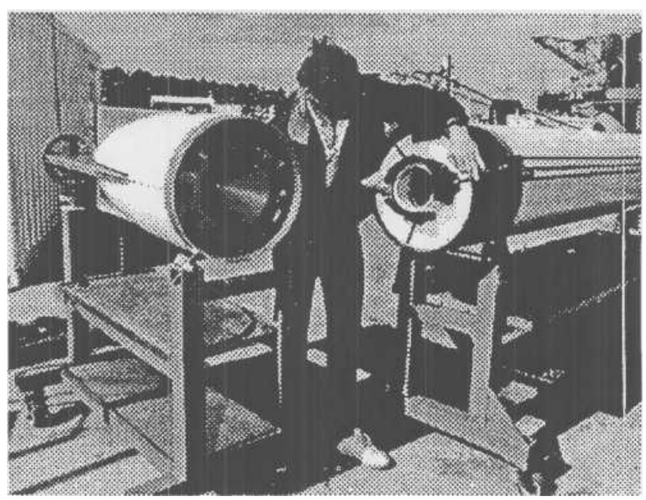

Fig. 11. Fiberoptic cannister mounting.

Video Monitor/Recorder

The surface console video monitor and video recorder are normally used to display and document mission video data from the vehicle underwater video camera., This equipment is also used to display and store video transferred over the data channel when docking is established.

TEST RESULTS

TRANSDEC Tests

The NOSC Free Swimmer System was moved to the NOSC Transducer Evaluation Center (TRANSDEC) pool for initial inwater tests. During these tests, the vehicle made 20 successful dockings with realtime video data transferred over the link. All phases of the planned sea tests were performed at TRANSDEC including: acoustic-homing acquisition of docking assembly, vehicle-homing maneuvering, visual siting of underwater remote platform, grabber-arm deployment, guide cable capture by grabber arm, vehicle maneuvering to target docking cradle, grabber-arm/docking-cradle alignment, underwater connector mating, video switch transfer of docking link data into vehicle uplink, connector demating, grabber-arm/docking-cradle release, and vehicle separation from docking assembly. A modification was made to the remote platform docking hardware as a result of these tests. The underwater mateable connector mounting was made adjustable to allow horizontal alignment fine tuning.

Sea Tests

In preparation for the sea tests, a docking assembly was constructed to simulate the underwater remote platform. A diagram of the docking assembly used for these tests is illustrated in Fig. 12. The docking assembly included the docking mechanism hardware, station-keeping hardware, half of the docking data link, an acoustic homing transponder, surface support electronics, and surface support craft.

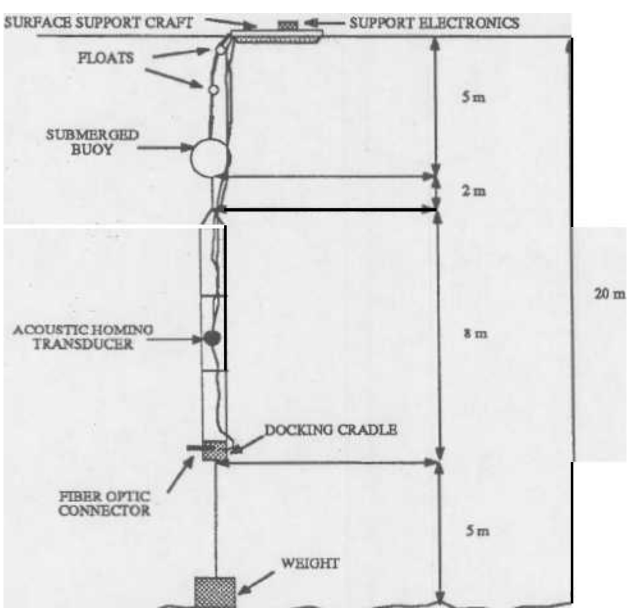

Fig. 12. Docking assembly.

During September 1990, the NOSC Free Swimmer System successfully demonstrated the underwater docking and data transfer task at sea. Both the vehicle launch platform and surface support craft were anchored in approximately 20 meters of water. Divers assisted in the deployment of the docking assembly. Test runs were performed from initial standoff distances of between 100 to 400 meters, all within the acoustic window of the vehicle homing sensor. The vehicle was deployed and maneuvered to midwater depth. The vehicle was guided to the docking assembly location by the vehicle operator based on vehicle homing sensor data displayed at the command console. The docking assembly was visually sited on the vehicle operator's video monitor at a range of 8 meters. The vehicle operator maneuvered the vehicle's final approach to the docking assembly using the video monitor. During final approach the vehicle grabber arm was deployed through the nose cone. The commanded grabber arm captured the docking-mechanism guide cables once the vehicle was maneuvered into position. The vehicle was maneuvered down these cables into the docking cradle. The commanded grabber arm was retracted to align the connector halves for mating. Once aligned, the grabber arm was further retracted until the connector halves were mated. The vehicle underwater-video camera was switched out of the vehicle uplink causing the docking-link video to be switched in. This realtime video was transferred from the surface support craft through the docking and vehicle links to the command-console video monitor aboard the vehicle launch platform. This video was further recorded on the vehicle camera VCR at the command console.

CONCLUSION

The goals of this program were to (1) develop an underwater docking capability, (2) demonstrate the docking of an unmanned robotic submersible with a remote data-gathering platform, and (3) transfer high-bandwidth data in real time from a remote site back to the vehicle launch platform. The accomplishment of these tasks are briefly described below.

A docking technique was developed based on a progressive degree of freedom reduction between the vehicle and docking mechanism during the maneuver to accomplish docking. A docking mechanism was designed and fabricated based on this method. Modifications were made to the vehicle to allow implementation of the docking technique. These changes were focused on the nose cone and grabber arm.

The acoustic homing sensor was used to navigate the vehicle to a transponder at the docking site. Docking was achieved through supervisory control of the vehicle and was completed by mating the underwater fiberoptic connector. Once docked, the vehicle acted as an electro-optical repeater/multiplexer in the data transfer operation. The overall data channel consisted of two data links coupled together, the docking link and the vehicle link. High channel capacity was achieved by using single-mode fiberoptics for these links. The high bandwidth data transferred was frequency modulated video.

Future work in this area will be directed toward the design and demonstration of an autonomous underwater docking and data transfer capability. In order to make the transition to autonomous operation, the system will be enhanced in several t chnological areas. The vehicle acoustic homing sensor will be improved to enhance operation in multipath environments and to compensate for vehicle pitch and roll during docking approach. The docking mechanism hardware and vehicle capture scheme will be modified to allow position independent docking between the vehicle and docking mechanism. The final approach phase of target capture will be implemented by integrating a vision based homing sensor to the system [12]. Both the acoustic and visual homing sensors will be used in conjunction to capture the target. A dock sensing capability will be developed to indicate docking completion.

By enhancing several technological areas of the system, an autonomous underwater docking and data transfer capability between an unmanned submersible and a remote underwater platform will be realized.

REFERENCES

[1] P.J. Heckman, Jr., H. McCracken, "Untethered, Unmanned Submersible," in *OCEANS 79 Proceedings, pp.* 733-737, 1979.

[2] D.M. Ladd, "Free-Swimming Submersible Hydrodynamic Fairing Design," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TR 878, 1983.

[3] B.W. Gillcrist, "Conversion of a Mine Neutralization Vehicle to a Free-Swimming Mine Neutralization Vehicle," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TD 1653, 1989.

[4] P.J.Heckman,Jr., "Free-SwimmingSubmersibleTestbed (EAVE WEST)," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TR 622, 1980.

[5] S.J. Cowen, P.J. Heckman, Jr., M. Kono, "Fiber-Optic Communication Links for Unmanned Inspection Submersibles," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TR 652, 1980.

[6] M. Kono, M.R. Brininstool, S.J. Cowen, "Fiber Optic Telemetry for the REGAL Torpedo," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TR 920, 1984.

[7] W.R. Ferrell, T.B. Sheridan, "Supervisory Control of Remote Manipulation," *IEEE Spectrum, vol.* 4, pp. 81-88, October 1967.

[8] M.R. Brininstool, S.J. Cowen, W.H. Marn, M.C. Scallon, "Long-Distance Repeaterless Duplex Fiber-Optic Demonstration System," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TR 1411, 1991.

[9] A.W. Westerman, P.J. Heckman, Jr., "Seawater Battery for Autonomous Submersibles," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TR 1248, 1988.

[10] D. Bryan, "An Autonomous Homing and Recovery System for an Unmanned Submersible," Naval Ocean Systems Center, San Diego, CA, Tech. Rep. TD 1191,1988.

[11] H.G. Nguyen, P.J. Heckman, Jr., A.L. Pai, "Real-time Pattern Recognition for Guidance of An Autonomous Undersea Submersible," *Proc. 1988 IEEE International Conference onRobotics andAutomation, pp.* 1767-1770.

[12] H.G. Nguyen, P.K. Kaomea, P.J. Heckman, Jr., "Machine Visual Guidance for an Autonomous Undersea Submersible," *SPIE Proceedings 980, pp.* 82-89, 1988.

[13] . J.T. Durham, P.J. Heckman, Jr., D. Bryan, R. Reich, "EAVE-West: A Testbed for Plan Execution," *Proceedings of the Fifth Internatinal Symposium on Unmanned Untethered Submersible Technology, pp.* 33-43, 1987.

[14] J.T. Durham, "Engineering Intelligent Undersea Vehicles," in *OCEANS '89 Proceedings, pp.* 788-792,1989.

[15] M.R. Blackburn, "Biological Model of Vision for an Artificial System that Learns to Perceive Its Environment," *Proceedings of the International Joint Conference on Neural Networks, pp.* 219-226, 1989.

[16] M.R. Blackburn, "A General Architecture for Classical Conditioning of Perceptual-Motor Sequences," *Proceedings of the International Joint Conference on Neural Networks, pp.* 293-298,1990.

[17] J.C. Palais, *Fiber Optic Communications,* New Jersey: Prentice-Hall, 1984.