

UNDERWATER DOCKING OF AUTONOMOUS UNDERSEA VEHICLES USING OPTICAL TERMINAL GUIDANCE

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Missions in which an autonomous undersea vehicle docks with an underwater node for the purpose of battery recharging and/or data transfer greatly increase the scope of potential applications possible with UUV's. Robust and accurate vehicle guidance to a small, simple and reliable docking structure is a critical capability which must be developed in order to achieve this end. This paper describes a simple but highly effective underwater vehicle guidance scheme which is based upon an optical quadrant tracker which locks onto a visible light source located at the dock in the same manner as a Sidewinder air-to-air missile tracks its target in air. An optical terminal guidance system based upon this concept was developed by NRaD. Optical guidance and docking was demonstrated using two autonomous underwater vehicles: a SeaGrant Odyssey IIB and the NRaD Flying Plug. The optical docking system was demonstrated to be accurate and robust for vehicle terminal guidance during field operations and provided targeting accuracy on the order of 1 centimeter under real-world conditions, even in turbid bay water. Such a system is projected to provide reliable terminal vehicle guidance to an underwater dock from a maximum acquisition range of approximately 100 meters in typical continental shelf ocean water.

I. Background

A critical capability for a network of autonomous undersea unmanned vehicles is the ability to dock for the purpose of sleeping, recharging batteries and transferring data. As part of the Autonomous Ocean Sampling Network¹ project sponsored by the Office of Naval Research, three terminal guidance schemes were developed and evaluated during 1996. These systems employed acoustic, electromagnetic and optical sensing^{2,3,4,5}. Terminal guidance can be loosely defined as the final 10-100 meters of the vehicle's docking maneuver. A combination of GPS and long-baseline acoustic navigation is assumed in order to position the vehicle within terminal guidance range of the docking station. This paper describes the optical terminal guidance technique developed by NRaD and describes results which were obtained during field tests which were performed in San Diego Bay and Buzzard's Bay.

II. Optical Considerations

The approach which we describe here for terminal guidance of an unmanned underwater vehicle is roughly analogous to that which is employed by a heat-seeking air-to-air missile when locked onto a target. In this case our target is a light emitter which is located at the underwater dock. When light

propagates in an absorbing, scattering medium such as seawater and is subsequently imaged by a lens located at a distance the photons emitted by the source will experience four general outcomes: some are absorbed by the medium, others are scattered outside of the field-of-view of the detector, still others are scattered into the detector's field-of-view and a few photons remain unscattered. Light in the first two categories never reaches the tracker and represents attenuation which can be overcome by simply using a brighter beacon. Scattered light within the field-of-view is imaged almost equally into each of the four quadrants of a photodetector located near the focal plane of the objective lens, illuminating each quadrant fairly uniformly. Most importantly, the unscattered light focuses to an image exactly as if the seawater was not present. By using a signal processing algorithm which calculates the difference of the light intensities which are received by adjacent quadrants a great deal of the forward scattered light can be rejected when the signals from the four quadrants are subsequently processed. The distinct spot of light on the detector face formed by the unscattered light generates a high-quality control signal which can be employed to aim the nose of the vehicle at the light source because the illumination is equal in all four quadrants only when the tracker's optical axis is exactly boresighted with the source. Duntley⁶ reported that an incandescent light bulb

considered invalid. Roughly equal illumination in all four quadrants corresponds either to a beacon image which lies outside of the field-of-view (scattered light only) or to an exactly boresighted condition (very unlikely and soon to change, anyway).

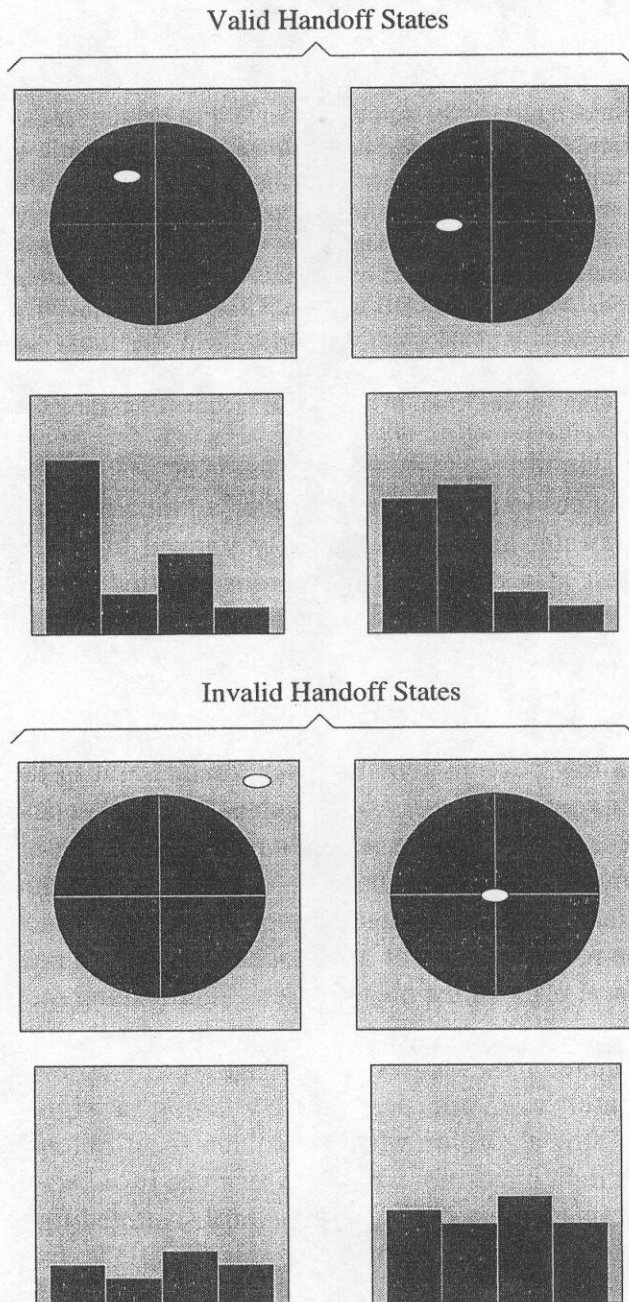


Figure 1

Possible Spatial Patterns for the Received Signal

In the latter cases the computer algorithm remains in detect mode until a valid condition actually occurs. When in track mode the computer derives left-right and up-down error signals by adding adjacent pairs

of quadrants and then calculating the respective error signals by taking the difference of the signals in the detector halves divided by the sum of the signals in the detector halves. This results in two error signals (indicating pitch and yaw errors) which will range from -1 to +1, with 0 corresponding to dead ahead, which are insensitive to changes in the relative signal strength. The horizontal and vertical control loops are identical and operate independently. The error signals are sent digitally to the vehicle control computer which converts them into proportional left-right and up-down fin commands which steer the vehicle.

V. Docking Station

Several types of docking station configurations were initially considered ranging from a vertical pole or mooring cable to a small funnel. While each configuration has its advantages the funnel concept was selected for its robustness and simplicity. Because all of our testing was conducted in shallow water the docking station was always either resting on the seafloor or multi-point moored only a few meters above it. However in deeper water it is likely that the docking funnel will actually be secured to a single vertical riser cable, making the dock free to rotate at will. We can take advantage of this geometry by designing the docking funnel so that it always rotates into a position when current is present such that the vehicle approaches the funnel mouth with its bow pointed into the current. This reduces the vehicle crabbing angle during approach and eliminates the requirement for side thrusters, even in relatively heavy currents. Additionally, once the nose of the vehicle is physically captured by the funnel it would be a relatively simple matter to latch them both together securely by mechanical means, automatically aligning the inductive power couplers used for battery charging. It has been our experience that simple ocean engineering designs without many moving parts are generally the least expensive and most reliable in practice. A small docking funnel which is free to rotate with the current is an elegant choice in this respect. The funnel does not need to be any larger than that which is required to latch onto the nose of the vehicle because the optical terminal guidance system is capable of centimeter homing accuracy.

VI. Undersea Vehicle Installation

The optical terminal guidance sensor previously developed for the NReD *Flying Plug* fiber optic guided underwater data connectivity vehicle was repackaged and installed on an Odyssey IIB⁷ vehicle furnished by the MIT SeaGrant Program. During docking tests our Odyssey was powered by a battery consisting of 120 alkaline D cells paralleled with a blocking diode and 22 nicad AA cells (which were float charged from the alkaline battery). This simple battery has comparable energy and output impedance to the AgZn battery normally used with Odyssey at a much lower cost and greatly reduced hazard level. Of course, this battery is not rechargeable, but this was not a concern for our testing since the alkaline cells in the battery pack can be replaced in much less time than it takes to recharge a AgZn battery in any case.

For practical reasons the tracker is mounted on the centerline of the vehicle and underslung slightly below its nose. This is both to facilitate ease of installation and to prevent any tracker damage from occurring due to frontal impact. To compensate for the tracker placement the docking beacon, which consists of a pair of wide-angle quartz-halogen track light bulbs and a rotating chopper wheel installed in an acrylic camera housing, is mounted in an offset location slightly below the physical center of the docking funnel. When the tracker in the vehicle is directly opposite the beacon on the dock at the time of impact the vehicle's nose is perfectly aligned with the center of the funnel. Because the capture funnel is fabricated as an open framework consisting of several identical heat-formed sections of PVC pipe it is no problem to mount the beacon so that it emits its rather broad light beam between a pair of the pipes. We have also investigated arrays of ultra-bright blue light emitting diodes as a docking beacon. An LED array has the advantage of using less energy than an incandescent lamp and can be pulsed electronically.

VII. Results

Preliminary optical docking system testing in San Diego Bay provided an opportunity to tune the vehicle's PID controller for the best transient

response and verified that optical terminal guidance acquisition ranges of 10-15 meters were possible, even in very turbid water. Water clarity in San Diego Bay during testing was such that it was sometimes not possible to discern the Odyssey from a small boat when it passed under the keel at a depth of about 2 meters. No acoustic navigation system was installed aboard our Odyssey so the vehicle had to be aimed by dead reckoning toward the submerged dock and hand-launched from a distance of about 40 meters away. Because the water depth at this location is very shallow a great deal of sunlight was always present. It was found that false detections occurred when the vehicle operated at depths of less than about 1.5 meters and simultaneously faced into the sun when it was low on the horizon in the late afternoon. Because the water in our operating location was only about 3 meters deep and no bottom avoidance sensor was incorporated on our Odyssey it was necessary to conduct testing at times when the sun was not low on the horizon in the general direction in which the vehicle was launched.

Subsequent testing performed at Buzzard's Bay in significantly deeper and slightly clearer water obtained reliable acquisition ranges of 20-28 meters. Generally, successful vehicle docking always followed beacon acquisition by the tracker; the exception being when acquisition occurred relatively close to the dock and the vehicle-to-funnel offset was on the order of the acquisition range. In these instances the small tail fins on the Odyssey were not adequate to turn the vehicle rapidly enough to cause it to actually impact the funnel hence the vehicle would attempt to turn toward the beacon, miss the docking funnel and lose the beacon almost immediately after detecting it. This would be less of a problem in clearer water because the vehicle would have increased acquisition range in such circumstances, hence more time to react to yaw and pitch corrections before it actually impacted the dock. Alternatively, the Odyssey could be outfitted with larger fins to increase its control authority. In previous work with *Flying Plug*, which has much better maneuverability than Odyssey, missed dockings after light beacon acquisition has generally not been a problem.

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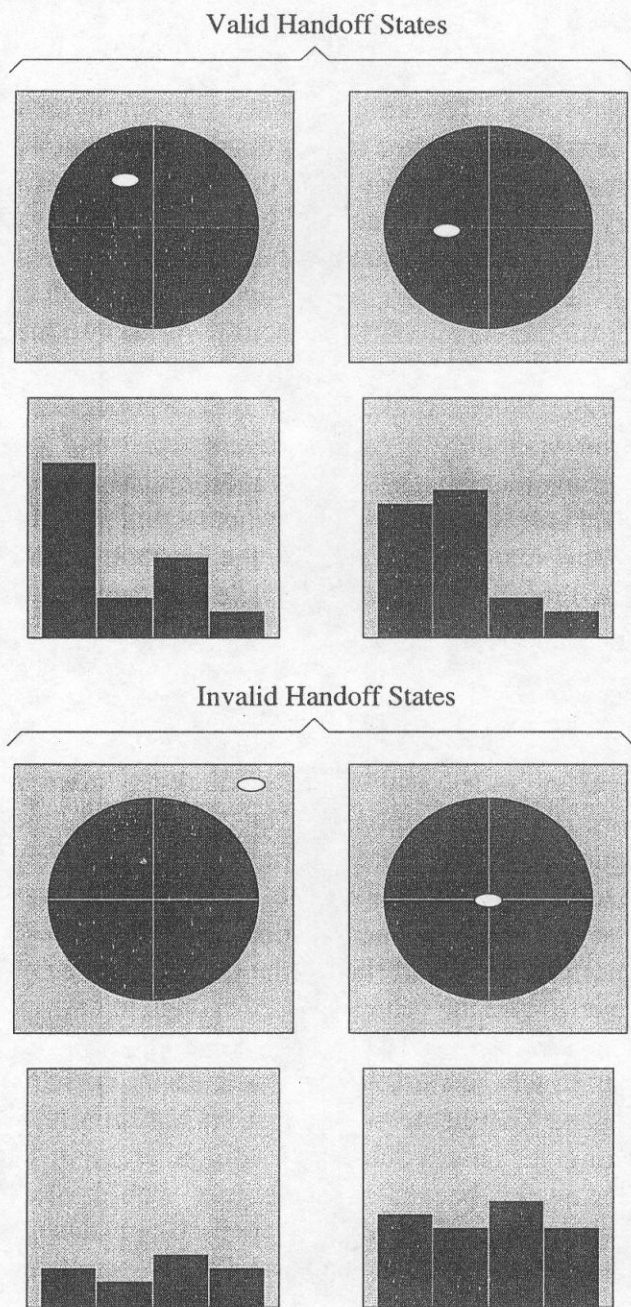


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encountered during testing in the Spring of 1996 in Buzzard's Bay were moderate and did not greatly affect the ability of our optically-guided Odyssey to dock reliably. After literally dozens of vehicle dockings no damage of any type occurred to either the vehicle or the optical tracker from impact with the dock at nominal impact speeds of 1 - 1.5 meters per second, even when the dock was resting firmly on the seafloor. This is an endorsement of Odyssey's elegant engineering design and of its very robust construction.

VII. Acknowledgements

The AOSN Optical Docking Team of the NRaD Advanced Concepts Branch would like to extend our heartfelt gratitude to Dr. Thomas Curtin of the Office of Naval Research who sponsored this effort and to all those at the MIT SeaGrant Office, especially Dr. Jim Bellingham, who provided dedicated hardware and software support for the Odyssey 2B undersea vehicle which was employed by NRaD to conduct this demonstration.

VIII. References

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