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 Network[1] 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. Duntley[6] reported that an incandescent light bulb creates a discernible image at a distance of 7-9 scattering lengths so long as its intensity is adequate to overcome the noise generated by the photodetector; so it is apparent that optical tracking for the purpose of vehicle guidance can be achieved over a much greater distance underwater than can a photographic image, which is typically only usable to a maximum range of about 2-3 scattering lengths.

III. Optical Tracker Hardware

The optical docking system employs a tracker consisting of a silicon photodiode which is diced into four equal quadrants. The photodetector is located hyperfocally (0.9 f) behind a plano-convex objective lens which gathers the incoming light and relays an out-of-focus image of the source onto the face of the detector. The increased size of the hyperfocally generated spot, compared with a sharp image, provides the gradual transition of signal from one quadrant to the next with spot movement which is necessary to implement proportional control. When the tracker is exactly boresighted with the docking beacon the light intensity is equal in all four of the detector quadrants, a condition which can be readily be employed for terminal vehicle guidance.

Because all of the tests were to be conducted in relatively shallow water it is necessary to reduce the sensitivity of the tracker to ambient sunlight which is always present during daylight hours. Typically the optical energy received by the tracker due to sunlight is several orders of magnitude greater than that received from the docking beacon when a vehicle is operating at a depth of three meters or so in murky water. Sunlight rejection is accomplished by design. The optical docking beacon is mechanically chopped by a rotating wheel at a 40 Hz rate and the preamplifiers following each photodetector quadrant in the tracker are designed to pass this frequency and reject all others. This prevents the guidance system from locking onto the sun and causing the vehicle to broach the surface. Additionally, a solar-blind optical short pass filter composed of Schott S-8612 glass is situated ahead of the objective lens which greatly attenuates all but the blue-green wavelengths. In shallow water the docking beacon is several water depths away from the tracker at typical acquisition ranges so light from the beacon is more peaked in the blue-green portion of the spectrum than is ambient sunlight. The optical filter greatly reduces DC saturation of the preamplifiers caused by the presence of high levels of ambient light in shallow water. Neither of these measures are strictly required for deep operation where insignificant sunlight is present, of course.

IV. Signal Processing

The signal processor consists of two physical parts: conditioning electronics located within the tracker's pressure vessel and a single-card computer located within the vehicle's forward pressure sphere. The former consists of four low-noise, switched gain transimpedance preamplifiers followed by a bank of four active-passive linear phase bandpass filters and a four channel delta-sigma ADC having a high-speed serial output line. The electronics, lens, solar-blind filter and photodetector are housed in an aluminum cylinder with a transparent glass window whose interior volume is approximately that of a 16 ounce beer can. The tracker and its electronics exhibit an optical dynamic range in excess of 120 dB which is necessary to provide guidance from the maximum distance which the beacon can be detected by the tracker to the point of vehicle impact with the dock.

The signal processing computer has three operating modes: *calibrate*, *detect* and *track* which are automatically sequenced by the vehicle. Calibrate mode is enabled when it is known that no docking beacon is present and is used to set a decision threshold which is above the electronic noise and shot noise caused by sunlight. Detect mode is enabled while the vehicle searches for the docking beacon. In detect mode the total energy received by the combined detector channels is compared with the threshold established during calibrate mode and when the signal exceeds this preset level the normalized energy in each channel is calculated and compared with a spatial template in the computer. If the illumination pattern indicates that a majority of the light is falling in a single quadrant or into two adjacent quadrants the computer switches to tracking mode. A spatial pattern which corresponds to high illumination levels in a pair of diagonal quadrants is 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).

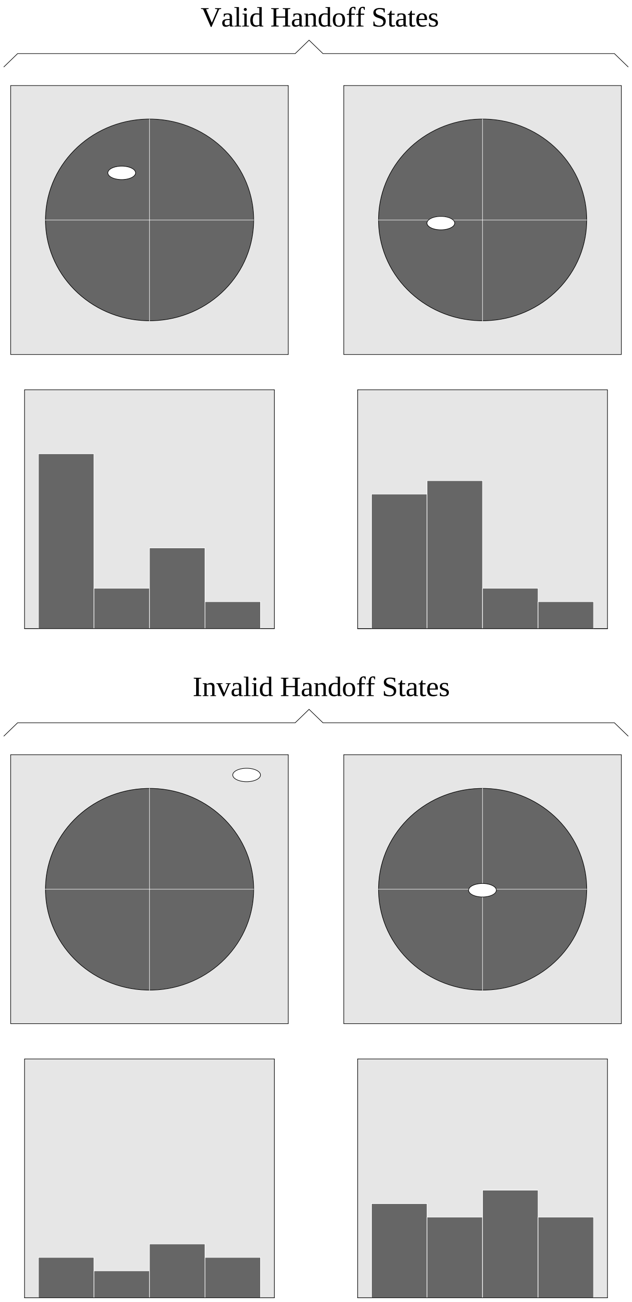

Figure 1
Possible Spatial Patterns for the Received Signal

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 NRaD *Flying Plug* fiber optic guided underwater data connectivity vehicle was repackaged and installed on an Odyssey IIB[7] 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.

Generally, the ambient currents which were 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

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