PARADIGM: A Buoy-Based System for AUV Navigation and Tracking

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Abstract- **A large variety of Autonomous Underwater Vehicles (AUVs) are currently under development or in production. These systems are beginning to show a lot of promise towards becoming useful tools supporting scientific, commercial, and military applications. However, in order for an AUV to be useful, its self-navigation capabilities must support the mission requirements. Often, underwater acoustic navigation techniques must be utilized in order to meet the navigational accuracy requirements. In addition to vehicle self-navigation, most AUV operators also require a method of tracking the vehicle while it is underway, so that its progress may be monitored, and also so that it may be located easily upon surfacing, or in the event of a vehicle failure. The Woods Hole Oceanographic Institution (WHOI) has developed a buoy-based system that simultaneously provides for both vehicle self-navigation and external tracking. This system has been used extensively by WHOI to support the REMUS AUV operations, and has also been used by the Naval Oceanographic Office to support sea-trials of the LAZARUS vehicle system.**

Long Baseline Acoustic Navigation is often the preferred subsea navigation method. It is generally accomplished by deploying two or more acoustic transponders, moored to the seafloor, near the desired area of operations. The vehicle then interrogates the transponders, determines its range to each, and finds its position using triangulation techniques. WHOI has developed a radio-controlled buoy, which can serve as a navigation transponder for the vehicle, and can also be commanded via the radio link to interrogate the AUV and report the measured travel time back to the operator. User-interface software has been developed which runs on a PC and provides the operator with a map-based tracking display, showing the vehicle's position and history, as well as other information useful in determining the mission status.

This paper describes the PARADIGM (Portable Acoustic RADio Geo-referenced Monitoring)system architecture, and presents data describing results achieved.
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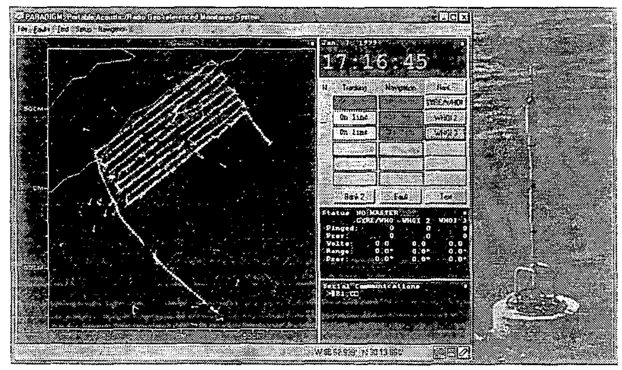

Figure 1: PARADIGM AUV Tracking/Navigation System

INTRODUCTION

The widespread use of the Global Positioning System (GPS) for surface vehicles and aircraft has created a revolution in applications and advancements of many technologies. Most people recognize that highly accurate navigation information often makes the difference between success and failure for any given program. In particular, navigation plays an extremely important role in Autonomous Underwater Vehicle (AUV) systems whose mission goals generally require large spatial area surveys and mapping. The output data quality is often as dependent on navigational accuracy as it is on the vehicle's sensor characteristics. Most vehicle systems have two navigational requirements: 1) The vehicle must be able to determine its position in order to make any necessary course and speed adjustments to remain on the desired mission track, and 2) The system operator must be able to externally monitor the vehicle's progress during the mission, whether the vehicle is operating normally or in a failed state.

Woods Hole Oceanographic Institution has developed an extremely useful system which satisfies the dual requirements of the AUV Navigation/Tracking problem. Known as "PARADIGM" (Portable Acoustic/Radio Geo-referenced Monitoring system), this system serves as a navigational reference for the vehicle, while also providing an accurate remote tracking capability for the operator on ship or on shore.

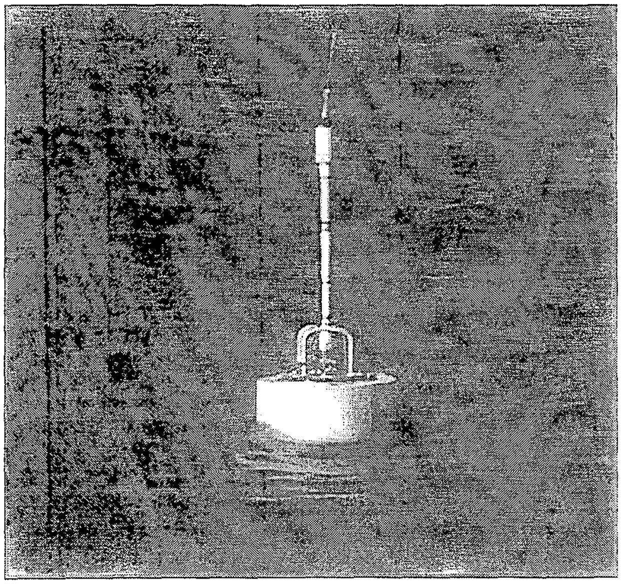

Figure 2: Mini-Buoy (0.75 meter antenna height)

SYSTEM DESCRIPTION

The PARADIGM concept is based on a "radio buoy", developed by Woods Hole Oceanographic Institution to serve as a navigation and tracking tool for undersea vehicles. The buoy combines a two-channel acoustic transceiver (developed by WHOI) with a commercially available radio modem that provides a communication link to a shore (or ship) based host computer. One of the acoustic channels acts as a transponder that may be interrogated by the vehicle for its self-navigation, and the other acts as a radio controlled acoustic ranging device, allowing the ship or shore based operator to remotely track the vehicle. When multiple buoys are deployed in known positions, simple triangulation techniques may be used to provide precise position information of the vehicle as it progresses through its mission.

Figure 3: Large PARADIGM buoys (3 meter antenna height), ready for deployment.

Source Level Output:	Greater than 192 dB re 1 uPascal @ 1 meter (9.0 – 15 kHz) Greater than 186 dB re 1 uPascal @ 1 meter (20 - 30 kHz)
Receive Signal Minimum Pulse Length:	Low frequency (9 – 15 kHz): 4 ms (recommend 10 ms) Medium Frequency (20 – 30 kHz): 2 ms (recommend 4 ms)
Detection Delay Time:	Low Frequency (9- 15 kHz): 3 ms Medium Frequency (20 – 30 kHz): 1.5 ms
Transponder Turn-around Delay:	50 ms +/- 0.5 ms
Receiver Lockout	User Selectable 50 ms to 2.56 sec (This is the time that the receiver is ignored following a valid reception.)
Transmit Signal:	One of 8 Arbitrary Signals. These signals are pre-programmed and stored in an EPROM on the transmitter board.
Receive Frequencies:	The two receive channel frequencies are hardware tuned.
Radio Modem Frequency:	900 MHz Spread Spectrum
Radio Modem RF Output Power:	1 Watt
Buoy Size:	Large Buoy: 40" diameter by 8" thick Small Buoy: 15" Diameter by 8" thick
Antenna Height above water:	Large Buoy: 9 feet Small Buoy: 2.5 feet
Shipping Weight (including Mooring and crate):	Large Buoy: 350 lb Small Buoy: 100 lb

Table 1: PARADIGM Radio Buoy Specifications

The radio buoys have been fabricated in two different sizes, large and small, depending on the application requirements. The large buoys (1 meter diameter) are used when long radio ranges are required, as they provide an antenna height of approximately 3 meters above the water's surface. The smaller buoys (0.4 meter diameter) are more convenient for short missions and small boat operations, however, they only provide an antenna height of 0.75 meters, and therefore have a relatively short radio range. Radio range is primarily limited by 'line of sight' constraints. Other than size, both systems are functionally identical.

The radio buoys have also been fabricated in two acoustic frequency ranges, the selection of which depends on the application requirements. The frequency range of 9.0 – 15.0 kHz is used where long ranges are required (up to 6 km in shallow water), and the frequency range of 20 – 30 kHz is used where more precise positioning or smaller transducers are required, at the expense of shorter range capability (2 km in shallow water).

Many aspects of the PARADIGM radio buoys are remotely programmable via the radio link. These aspects include: transmit frequencies, receive sensitivities, ping rate, and sleep mode. In addition, the buoy status may be requested in order to monitor battery voltage and the number of recent acoustic receptions on each of the two receive channels. The buoy is powered by an on-board alkaline battery pack. Because the radio modem has relatively high power requirements, the buoy is normally "sleeping" (in a reduced power state) when not in use. When sleeping, the buoy will automatically wake-up every 15 minutes and listen briefly for a radio message from the PARADIGM host computer. If none is received, the buoy will go back to sleep. Otherwise, if radio communication is established, then the buoy will remain "awake" as long as required. This method of power management allows for long life. The maximum total life of the battery is approximately 240 hours of "awake" time, or 450 days of "asleep" time, or any proportional combination of each. The battery is easily replaced, when necessary.

The buoys also have the capability to send a simple command to the vehicle during its mission. This feature is used as an emergency Abort command with the REMUS AUV. If the Abort command is received, the vehicle will stop its thruster, and float to the surface. Because its transducer is installed underneath the hull, REMUS may still be tracked by PARADIGM, even while drifting on the surface. Ranges of over 5 km to a vehicle on the surface have been achieved using the low frequency version.

Vehicle Self-Navigation: Typically two or more buoys are deployed as reference points for long baseline acoustic navigation. The vehicle is programmed to regularly interrogate the transponders, and measure the round trip acoustic travel time to each. Then the vehicle may compute its position by simple triangulation, knowing the precise coordinates of the transponders' moorings. [1]

External Vehicle Tracking: The same buoys may be used to track the vehicle by the ship or shore based operator. The PARADIGM Tracking software communicates with all selected buoys via a "point to multipoint" radio modem system (manufactured by FreeWave® Technologies), and automatically controls the buoy acoustic transceivers to repeatedly obtain ranges between all buoys and the subsea vehicle. The moored buoy positions are entered into the PARADIGM tracking software, which then computes and plots the vehicle's position in real time and in world coordinates. The spread-spectrum radio modems operate in the 902-928 MHz frequency band and do not require US FCC licensing. The modems create a "virtual" serial connection between the shore-based host computer and the buoys, as if a cable connected them. The buoys each have a unique, switch-settable address, which is known by the host computer. Serial messages are broadcast to all buoys, with the address of the desired buoy included in the message. Only the buoy that was addressed by the message will actually reply.

During the tracking operation, one of the buoys is commanded to interrogate an acoustic transponder on the vehicle. This is designated as the "Master" buoy, and is selected by the operator. Any buoy may be the Master, but generally, the buoy closest to the vehicle is selected. When the PARADIGM software commands the Master buoy to send an acoustic interrogation "ping" to the vehicle, all other selected buoys also recognize that message, and synchronize their receivers. Then, the vehicle's reply is received by all buoys, and the elapsed time is measured from the Master's interrogation ping to the reception of the vehicle's reply. The slant range between the Master buoy and the vehicle may then be directly computed from its round trip travel time. The slant range between each other buoy and the vehicle is computed by subtracting the one way range, Master–to-Vehicle from the total range measured, Master–to–Vehicle–to–Buoy. Therefore, if the Master buoy and at least one other buoy have received a reply from the vehicle, then a vehicle position may be computed. The PARADIGM software recognizes that there will be two possible solutions for the vehicle's position, and provides the operator with a button to select the correct answer. Generally, the vehicle's mission is planned to stay on one side of the baseline, however if the baseline is crossed a new selection can be made.

PARADIGM User Interface: The host program is a WHOI developed, Windows® application providing the operator with a simple to use graphical user interface (GUI) for setup and operation. This interface includes a graphical tracking display, which displays the current and previous vehicle position fixes as computed by PARADIGM, and a simple indicator panel to clearly notify the operator in the event of problems, such as no acoustic reply being detected, or a radio modem link failure occurring. Velocity filters automatically discard occasional bad-fixes. All vehicle tracking data is logged in a simple ASCII format, and may be re-displayed by the host program or post-processed by another application or spreadsheet.

RESULTS

The PARADIGM system has been used extensively by WHOI for the navigation and tracking of the REMUS AUV, a small, low cost AUV developed at WHOI for scientific, commercial, and military applications. [2] The larger radio-buoys equipped with the low frequency acoustic system have been used to support long-range vehicle operations off of the New Jersey coast for the Predictive Coastal Modeling Experiment led by the Rutgers University Institute of Marine and Coastal Studies for the National Ocean Partnership Program, during the summers of 1998 and 1999. REMUS was used to run multiple 20 km transects perpendicular to the shoreline, while collecting ADCP (Acoustic Doppler Current Profiler) and CTD (Conductivity, Temperature, and Depth) data to support the modeling experiments. Typically, the vehicle would be launched in the morning from a small boat, and would operate for 6 to 8 hours before completing its mission in the late afternoon. Most missions were 40 km (two legs) or 60 km (three legs) in length, with the longest mission being approximately 80 km. The PARADIGM system allowed the small boat to return to the dock, while the tracking system operators monitored the vehicle's progress and status throughout its mission, thus allowing the boat and crew to remain ashore.

Six buoys were deployed in a line with 4 -5 km spacing in order to provide sufficient coverage for the 20 km linear mission plan. The vehicle was programmed to proceed along a parallel line approximately 1.5 km offset from the buoy line. As the vehicle passed each buoy, it would automatically switch to the next buoy pair for the navigation algorithm. Similarly, the PARADIGM operator on shore would select the appropriate buoys to be used for tracking as the vehicle proceeded. In general, the vehicle and PARADIGM were reliably obtaining acoustic detections to ranges of 6 km or more, however in regions of extreme temperature variations, such as frontal zones, the maximum ranges were occasionally greatly reduced. The average water depth throughout the mission was 17 meters. It is interesting to note that the farthest extent of these missions was approximately 25 km offshore, thus providing a good demonstration of the radio modem capabilities as well as the acoustic tracking performance. The long radio range was achieved by installing a FreeWave® repeater module on top of a 65-meter tall tower located at the Rutgers University Marine Field Station in Tuckerton, NJ.

WHOI often uses the smaller "mini-buoy" configured with high-frequency acoustics for REMUS operations in very shallow water (3 to 7 meters depth). Figure 4 shows the PARADIGM tracking data from a survey mission that took place during the NAVO sponsored AUV-Fest, in November, 1999.

In 1999, PARADIGM was used by the Naval Oceanographic Office (NAVO) for tracking of the LAZARUS AUV during sea trials in the Gulf of Mexico. Typically, three low-frequency buoys were moored in the operations area, and the host computer was operated on the surface support ship. The PARADIGM system was used as a portable tracking range to verify the navigation and control performance of the vehicle during test runs.

CONCLUSION

Accurate navigation and tracking capabilities are key components of any AUV system. WHOI has developed a simple, low-cost, portable, buoy-based system that satisfies the dual requirements of vehicle self-navigation and external tracking, simultaneously. A complete, turn-key user interface has been developed to provide the operator with a real-time position display of the vehicle track, while underway, as well as a clear indication of the navigation and tracking status. This system has been used extensively by WHOI and NAVO for remote tracking and self-navigation of the REMUS vehicle on numerous missions in many different environments and for tracking of the LAZARUS vehicle.

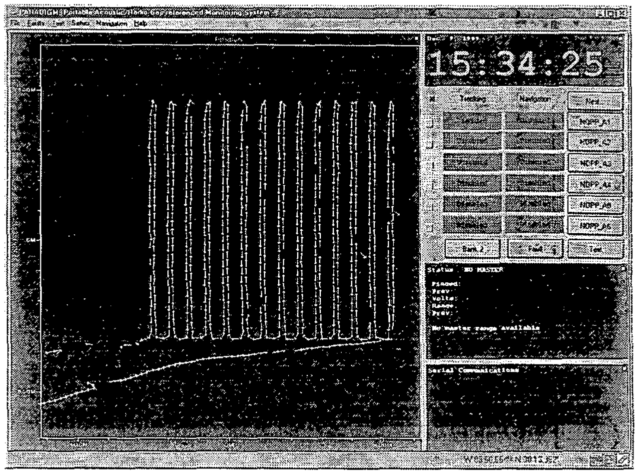

Figure 4: PARADIGM Tracking Display, AUV-Fest '99

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