Integrated Acoustic Communication and Navigation for Multiple UUVs

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Abstract—**Integrated acoustic communication and navigation for underwater vehicles provides dual functionality in a single system which reduces cost, size, power and potential acoustic interference. A combination of time and code division multiplexing is used to allow long baseline navigation and bidirectional communication for a number of vehicles operating simultaneously in the same area. The communication system uses multi-rate phase coherent modulation to maximize throughput for the uplink from a vehicle to a central node, and code-division multiple-access using a simple frequency-hopping scheme. The data rate and modulation methods are completely programmable and may be selected based on the application requirements and the propagation conditions present between the different vehicles in the network. While one or several vehicles may use time-multiplexed long-baseline (LBL) navigation, when the number of vehicles grows large, the time between fixes becomes unacceptably long. Thus in addition to LBL, a second mode of navigation is also available for use with swarms of vehicles such as the surf-zone crawlers proposed for mine counter-measure applications. This second mode employs navigation broadcasts initiated by the central controller and incorporates three additional fixed nodes that transmit in response. The time differences of arrival measured at the vehicle are used to determine its location.**

I. Introduction

This paper describes a system designed to provide both acoustic communications and navigation for autonomous underwater platforms in the shallow-water environment. The design is driven by the requirements of Navy mine countermeasure (MCM) missions that may include several different types of vehicles which carry out different tasks. Of particular interest is the use of several side-scan survey vehicles swimming in the water column accompanied at the same time or later by small bottom-crawling vehicles. The swimming survey vehicles perform wide-scale mapping and detection, while the crawling vehicles perform close inspection or investigate within the surf zone. The requirements for both the swimming and crawling vehicles are different due to the different numbers of vehicles envisioned for use in the surveys. Thus the best system will provide capabilities and operating modes that provide scalable performance with respect to the number of platforms within the network. While the MCM missions are the primary focus, the design is also applicable to science missions, for example the autonomous oceanographic sampling network (AOSN) concept [1].

The MCM mission addressed here encompasses two nearshore regions: very shallow-water (VSW), which is defined as 40 feet to 10 feet, and the surf-zone (SZ), nominally the area from 10 feet depth through breaking water to the beach. Together, a typical VSW/SZ MCM survey area is envisioned to be one to several square kilometers. The system design goal is to provide acoustic communication and navigation functions within this area.

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The communications requirements will vary depending upon the configuration of the system and the specific mission. Occasional status updates from the vehicles are necessary to make sure that the mission is proceeding according to plan, and transmission of at least some sensor data allows monitoring progress and evaluation of both terrain and detected targets. High-rate communication enables real-time examination of detailed target information such as photographs or high-resolution side-scan images.

Typical long-baseline navigation systems use the same frequency band as acoustic communication systems, and thus it is logical to merge the two into one set of hardware. This removes interference that occurs when the two systems are operated asynchronously, and provides a savings in payload space and power. Navigation modes suitable for both single vehicles or large groups have been developed in order to allow the use of the same fixed nodes for different types of surveys within the net.

The paper is organized as follows. In section II the operating concepts are reviewed and the system design is presented. In section III the acoustic communications methods are briefly outlined. Section IV includes a detailed description of the methods for both active and passive acoustic navigation. Section V includes the results of testing the integrated system.

II. System Description

The addition of acoustic communication capability to crawlers significantly enhances their MCM survey efficiency. The original "lemming" concept used a random or quasi-random search for mines in the surf zone. However, if the crawlers can be tracked and directed, then search efficiency can be dramatically increased and a large payoff in effectiveness can be attained. In addition, if the data from sensors on the crawlers can be transmitted to the base station, this information can be used by a supervisory system to direct the search. The base station can be located on a vehicle or on a small buoy with an RF link.

To convert from a random search to a directed search, the crawlers need to operate within an acoustic LBL network. However, because of the potentially large number of units it is impractical for each unit to actively interrogate the net. Instead it is proposed that the crawlers passively listen for signals from the navigation net, and then use the time of arrivals to determine their location,

The system may be used effectively in conjunction with an underwater vehicle performing a side-scan survey. The vehicle creates lists of likely targets, and then relays this information to the crawlers for closer investigation. Alternatively, the side-scan survey may be done well in advance of the crawler infusion and the number and initial placement of the crawlers can be tailored to the site based on the survey. The objective of the navigated crawler is to guarantee that the known list of targets is investigated.

Bidirectional acoustic communication with the MCM survey vehicles provides mission status information for remote observers and allows re-directing vehicles at any time. The payload capability of a survey vehicle is significantly greater than the crawler, and thus it can carry a more capable acoustic modem and transmit at higher power for longer periods. This in turn means that the modem-equipped vehicle can provide information at ranges of several kilometers, depending upon propagation conditions.

While transmitting hundreds of megabytes of high-resolution side-scan or other sensor information is impractical and unnecessary when the vehicles are to be retrieved, the acoustic modem allows selected retrieval of target lists and compressed segments of high-probability data sections to be uploaded during the mission as insurance against loss of a vehicle.

A. System Operation

The integrated system is operated as a centrally-controlled time and code-division multiplexed network. Three different types of units make up the system, one fixed Master node, one to three fixed Secondary nodes, and a number of mobile Clients. Time is broken up into individual segments called cycles, and a cycle-initialization command is broadcast by the Master node to initiate all acoustic transactions.

The cycle initialization command consists of a frequency-modulated sweep used for packet acquisition followed by the data packet. The FM sweep from the Master also triggers the Secondary nodes to respond with individual Kasami sequences [2]. The differences in the times of arrivals are used by all Clients to compute a passive navigation fix at each cycle (see section IV-B). The different network functions which may be commanded include:

1. Downlink from the Master to individual units or groups at a specified rate.
2. Uplink from any individual unit at a specified rate.
3. Uplink from a group of users using CDMA at a specified rate.
4. Unit-to-unit communication at a specified rate.
5. Active LBL navigation by any individual unit.

It is envisioned that when one or two vehicles are operating in the network they would rotate between active navigation and data upload. Command or control data for the vehicles would be transmitted on the next cycle. Regular mission status information would be requested at the low rate and not acknowledged or retransmitted in case of errors. However, target information from the vehicle is acknowledged so that its transfer is guaranteed. The ability to modify the data uplink rate on a cycle by cycle basis allows changes in the acoustic channel to be accommodated on a very short time scale and provides maximum throughput when the vehicle is close to the Master node and propagation conditions are good.

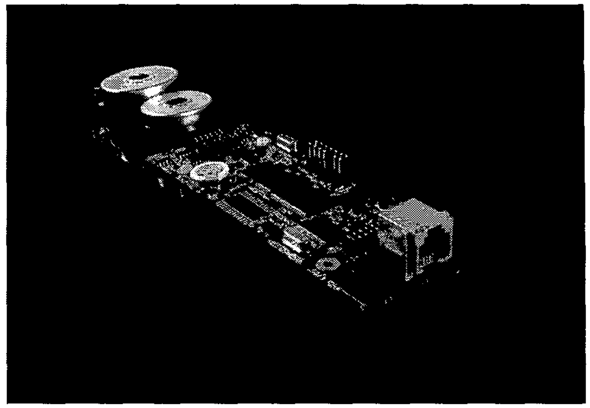

Fig. 1. The Micro-Modem main board (top) and power amplifier (bottom).

System operation when many crawling vehicles are in the network is similar. However, passive navigation is used most of the time and active navigation cycles are used only when a target is detected and the most accurate fix possible is desired. Uplink from the crawlers may be done unit by unit with single-user modulation, or in small groups with multiuser modulation. The exact mix of modes used by the system depends upon the number of units in the network and the total rate of information flow. The multiuser mode reduces the latency between updates from the crawlers. This is important for certain search algorithms that require position information and sensor data to be made available to the other vehicles at the highest rate possible.

B. Hardware Implementation

The system is implemented using two hardware platforms, the Utility Acoustic Modem (UAM) and the Micro-Modem.

Utility Acoustic Modem. The UAM, was developed specifically for use on underwater vehicles as both a communications and navigation system. It uses a floating-point processor and supports multi-channel receiver arrays which allow high-rate communication in shallow water. The main board size is 3.5 wide by 9 inches long. It operates at 4 Watts in receive mode, has a micro-power hibernate mode and transmits at 15 to 25 Watts. The UAM transmits and receives both the PSK and FSK communication signals.

Micro-Modem. The Micro-Modem (Fig. 1) uses a fixed-point processor to minimize power consumption, size and cost. The main board is 1.75 inches wide an about 5 inches long. When combined with the power amplifier the board set is just over 7 inches long and fits within a 1.8 inch inside diameter tube. The Micro-Modem requires 200 mW when in receive mode and transmits at 15 W. The Micro-Modem transmits and receives frequency-hopped FSK communications signals and has the capability to transmit PSK.

III. Acoustic Communication

In underwater acoustic communications the propagation channel dictates a trade-off between system reliability, data rate, and receiver complexity. The proposed approach provides a robust low-rate link from a central base station to a number of vehicles with the return uplink offering a range of data rates or multi-user capability. Currently four single-user data rates are used, 300, 600, 1400 and 6000 bps. These are all based on phase-coherent modulation. Two multi-user data rates, 40 and 80 bps, are also available using frequency-hopped FSK.

A. Phase-Coherent Communication

The multi-rate phase coherent transmitter and receiver are implemented on the Utility Acoustic Modem. The system is based upon work originally presented in [3]. The signaling method uses a constant bandwidth, normally 4 or 5 kHz, and varies the signal constellation density and coding rate as required to achieve reliable communication under conditions with time-varying multipath and noise. The receiver uses a small array to increase data rate in multipath environments and 5000 bits per second have been demonstrated to 5 km in shallow water. Additional information on the system and its performance may be found in [4].

B. Frequency-Hopped Communication

The frequency-hopped communications capability is based on a simple standard developed specifically to enable inter-operable acoustic communication in shallow-water environments [5]. Frequency-hopped FSK provides a simple, robust, modulation method that can be easily adapted to the underwater acoustic environment. While frequency hopping is slower than M-*ary* FSK, it is less affected by multipath, supports multiple users, and offers good immunity to impulsive noise. The hopping patterns are based on sequences that minimize the probability of a collision with another user [2]. The low data rates (80 and 160 bps raw, 40 and 80 bps coded) are not significantly affected by the Doppler shifts created by UUVs moving at 1-3 m/s.

IV. Acoustic Navigation

The navigation functions integrated into the acoustic modem use travel times from the fixed nodes with known locations that operate as transponders. Both active and passive navigation schemes are supported. Active navigation uses the fixed net locations as well as the range from the unknown point to each transponder. With three or more transponders, a linear least squares estimator is used. However with two nodes, the navigation fix is ambiguous and external information is utilized to choose between two possible solutions. The passive navigation system requires at least four transponders to produce a unique solution using time-difference-of-arrivals. This solution may be iteratively refined using a Taylor-series expansion. To compute a three node passive fix, a constrained linear least squares estimator is used which results in two possible solutions. Further refinement of the three-node solution does not produce significant improvement. To simplify the presentation that follows, the transponder turnaround time is not included in the expressions.

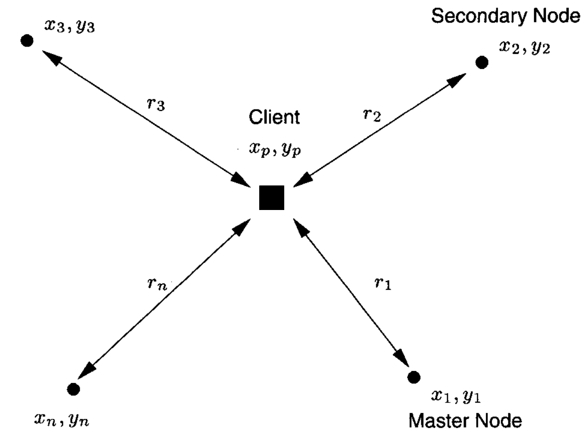

Fig. 2. Navigation geometry.

A. Active Navigation

In this section, a two-dimensional active navigational system is defined. Let us assume that there are n nodes with the two-dimensional position matrix B defined as

$$B = \begin{bmatrix} x_1 & y_1 \\ \cdot & \cdot \\ \cdot & \cdot \\ x_n & y_n \end{bmatrix}.$$

Let R be the vector of ranges from the unknown point x_p, y_p to each of the fixed nodes, then:

$$R = \begin{bmatrix} r_1 \\ \cdot \\ \cdot \\ r_n \end{bmatrix}.$$

The coordinate axes are aligned to originate at the first node, so that the relative position of point P is (x_r, y_r). Then,

$$x_r^2 + y_r^2 = r_1^2 \tag{1}$$

$$(x_r - x_i)^2 + (y_r - y_i)^2 = r_i^2, \qquad i = 2, 3, \ldots, n. \tag{2}$$

Expanding (2) and substituting (1) yields

$$[\ x_r \quad y_r\ ] = \frac{1}{2} B_r^{-1} A \tag{3}$$

where each element a_i in vector A is defined as

$$a_i = r_1^2 + x_i^2 + y_i^2 - r_i^2, \qquad i = 2, 3, \ldots, n$$

and $B_r = B[2 \ldots n]$. Solving (3) for the relative position and adding to it the origin provides the position x_p, y_p. However if $n = 2$, the system described by (3) is under-defined and y_r is computed as the two roots of a quadratic

$$C_1 y_r^2 + C_2 y_r + C_3 = 0 \tag{4}$$

where $C_1 = x_2^2 + y_2^2$, $C_2 = -Ay_2$, $C_3 = r_1^2 x_2^2$. The value x_r can then be calculated by substituting the two possible values for y_r

$$x_r = \frac{A - y_r y_2}{2x_2}. \tag{5}$$

B. Passive Navigation

In a passive system, absolute ranges from the unknown position to the nodes are unknown. Instead, the time differences between each arrival are measured (Fig. 3). If there are at least four fixed nodes, a linearized estimator based on [6] can be implemented. Node 1, the Master, always transmits first and the other nodes respond when that signal is received. The Client receives all these signals at times t_i. The network shape is known, and thus the actual time differences of arrival may be calculated.

If the unknown travel times from the n nodes to the Client are $T_i, \quad i = 1, 2, \ldots, n$, the time differences of arrival τ_i with respect to the first transponder are

$$\tau_i = T_i - T_1 \tag{6}$$

where $T_i = t_i - s_i$ and the s_i are the known travel times from node 1 to nodes $2 - N$ (Fig. 3).

The n equations written using T_1 and the adjusted time differences τ_i which describe the relation between the transponder locations and the unknown point of the Client are

$$(x_p - x_i)^2 + (y_p - y_i)^2 = c^2(T_1 + \tau_i)^2 \tag{7}$$

where c is the speed of sound in water. These relations may be formed into a system of equations that is linear in the three unknows, x_p, y_p and T_1, and then solved as outlined in [6] for the position of the Client. Note that at least four nodes are necessary to obtain an unambiguous solution for the position. With $n = 3$, the constrained linear solution gives two estimates of receiver position, of which one is chosen based on external information.

C. Refinement of the Passive Estimate

The error in position obtained with the linearized estimator is sensitive to the geometry of the system and can be large where two travel time differences are nearly equal and create an ill-conditioned system. However, this position can be used as an initial estimate in an iterative refinement scheme based on Taylor series expansion [7]. The generalized relation between the measured and true quantities is

$$f_{ki} = m_{ki} - e_i \tag{8}$$

where m_{ki} is the ith measurement of the kth quantity and e_i is the error in m_{ki}.

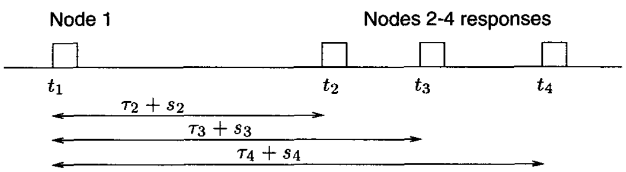

Fig. 3. Timing diagram illustrating the measured time of arrival differences τ_i with respect to the arrival times t_i and the delay from the node 1 transmission to node 2-4 transmission in the passive navigation approach.

For the specific case of passive navigation, where the measured quantities are the τ_i defined in (6),

$$f_i(x, y, T_1) = \sqrt{(x - x_i)^2 + (y - y_i)^2} - cT_1 \tag{9}$$

where x, y is the true position of point P and x_i, y_i, c, T_1 are as before. Expanding f_i in a Taylor series about the initial guess x_p, y_p, assuming that the initial guess for T_1 is zero, and keeping only first order terms [7]:

$$f_{ip} + \frac{\partial f_{ip}}{\partial x}\delta_x + \frac{\partial f_{ip}}{\partial y}\delta_y + \frac{\partial f_{ip}}{\partial T_1}\delta_{T_1} \cong c\tau_i - e_i \tag{10}$$

where

$$\delta_x = x - x_p, \qquad \delta_y = y - y_p \qquad \delta_{T_1} = T_1 - 0.$$

Assuming that the e_i terms are independent with equal variance, solving (10) for δ while minimizing the least squared error gives:

$$\delta = \left[Q^T Q\right]^{-1} Q^T z \tag{11}$$

where:

$$\delta = \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_{T_1} \end{bmatrix}$$

$$Q = \begin{bmatrix} \frac{x_p - x_1}{\hat{r_1}} & \frac{y_p - y_1}{\hat{r_1}} & -1 \\ & \cdot & \\ & \cdot & \\ \frac{x_p - x_n}{\hat{r_n}} & \frac{y_p - y_n}{\hat{r_n}} & -1 \end{bmatrix}$$

$$z = \begin{bmatrix} c\tau_1 - \hat{r_1} \\ \cdot \\ \cdot \\ c\tau_n - \hat{r_n} \end{bmatrix}$$

and

$$\hat{r_i} = \sqrt{(x_p - x_i)^2 + (y_p - y_i)^2}.$$

A new estimate of P is calculated using δ and the computation in (11) repeated until the value of δ converges to steady state.

This system is computationally simple. It requires inversion of a 3 by 3 matrix and it typically converges in 3 or 4 iterations. The error of the position estimate can be calculated using the covariance matrix $C = \left[Q^T Q\right]^{-1} \sigma^2$ as described in [7].

D. Navigation Performance Simulations

The performance of the navigation methods may be examined by computing the error for a given geometry with noisy range measurements. In actual use the error is normally dominated by noise and bias in the travel time measurements due to SNR, multipath and sound speed variability. In addition, navigation errors are increased by errors in placing or calibrating the location of the fixed nodes. In general the accuracy of GPS-reckoned transponder positions limits overall performance.

However, for comparison purposes it is instructive to examine the performance of the two methods assuming perfect network information and travel time measurements corrupted only with additive white Gaussian noise. In Fig. 4 the error map for a typical two-node active navigation solution is shown. The baseline is 1500 m and the standard deviation of the range estimates is 0.5 m. Generally the position error is the same order of magnitude as the range error, except along the baseline where the geometry is poor. In Fig. 5 the error map for an example four-node passive refined navigation solution is shown. The travel-time error is the same as in the active case, though the use of time-differences of arrival doubles the resulting range error. Within the net and a few hundred meters outside the net (but between nodes) the performance is close to that of the active solution, though performance at the corners of the net is worse.

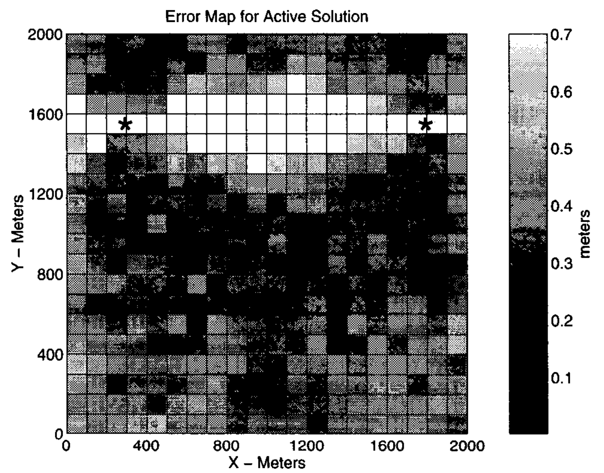

Fig. 4. Error map for the typical active navigation solution with $\sigma = 0.5$ m error in range and no other error or noise sources.

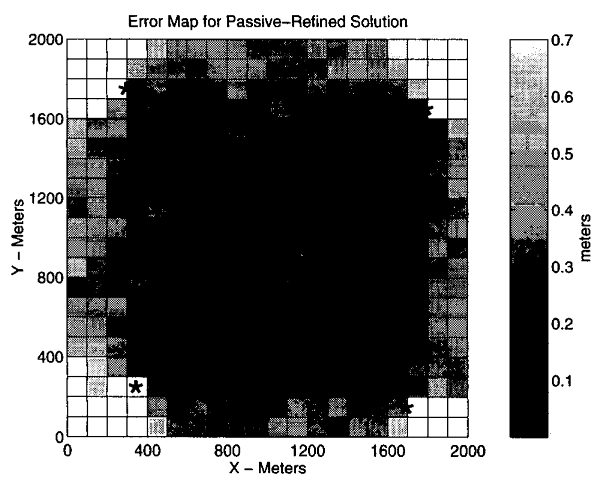

Fig. 5. Error map for the four-node passive-refined navigation solution with $\sigma = 0.5$ m error in range and no other error or noise sources.

V. Results

The initial version of the system was tested in June 2000 in shallow water off Ft. Lauderdale, Florida. Two buoys with RF links to shore were used for the fixed nodes and a mobile Client was suspended from a small boat for testing. The Utility Acoustic Modem was used for all three units. The Master buoy was commanded remotely from a lab a few kilometers away, and the different system functions were exercised. For this series of tests the lowest acoustic communication rate was used. The cycle-initialization command was used to initiate:

1. Downlink from Master to Client.
2. Uplink of status information from Client to Master.
3. Uplink of status information from the second node to the Master.
4. Active navigation by the Client using the two fixed nodes as transponders.

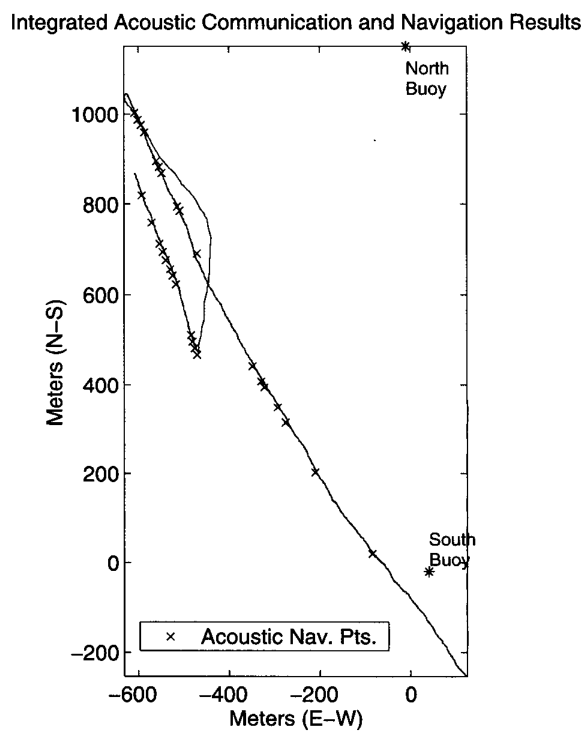

Fig. 6. Active navigation position results from a test of the integrated communications and navigation system. The typical navigation error compared to GPS was 6 m.

Results of the active navigation part of the test are shown in Fig. 6. The Master node was the south buoy located at $(0, 0)$. The solid track is from the GPS on the vessel with the Client system as it drifted Northwest through the area, then re-positioned, then drifted Northwest again. The fixed nodes were located in approximately 18 m water depth and the Client was in water 12-18 m deep during the test. The position estimates from the integrated communication and navigation system were typically within 6 m of the GPS measurements, though the actual error may be different since differential GPS accuracy is of the same order of magnitude.

An additional test was performed with the two buoys and a modem installed on one of the surf-zone crawling vehicles manufactured by Foster-Miller. The Utility Modem on the crawler operated as a communications client, and several hours of testing were performed. The geometry of the test is shown in Fig. 7. The acoustic communications link was operated at the low rate, and was successful with the crawler in water as shallow as 1.5 m with 0.3 m breaking waves. The overall performance was variable, and changed with both time and position. While normally the fixed buoys may be placed closer to shore in order to allow higher-rate communication with the surf-zone crawlers, this test showed that it is possible to communicate through the surf-zone under certain conditions.

The frequency-hopping FSK system has also been used successfully for a long-term stationary deployment in shallow water. Performance results from that work are presented in [8].

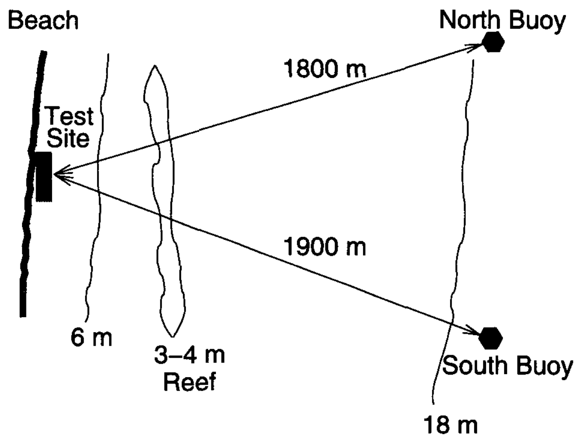

Fig. 7. Geometry for acoustic communication testing in the surf zone using a Foster-Miller crawler.

VI. Conclusions and Future Work

The integrated acoustic communication and navigation system is a small, self-contained network that provides connectivity and acoustic positioning over an area of several square kilometers. It was designed to support both individual vehicles using active navigation and variable rate uplink or large groups of vehicles with passive navigation and code-division multiple access communication. While the system was designed to support near-shore mine countermeasure operations, it is equally applicable to other scenarios such as those outlined in [1].

Areas of on-going work include in-water validation of the passive navigation system, optimizing multi-user receiver algorithms and continued refinement of the multi-rate link and related acoustic communication protocols.

Acknowledgements

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