Surf Zone Reconnaissance

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LONG-TERM GOALS

The long-term goal of this project is to develop autonomous multi-robot systems that could replace human divers that are currently performing dangerous reconnaissance and mine neutralization missions in the Very Shallow Water and Surf Zone regions. We are focusing on swarms of small Unmanned Bottom-crawling Vehicles (UBVs) for this purpose. For the purpose of reconnaissance, the swarms would augment overhead (optical) systems to provide seamless maps of littoral areas from the VSW up onto the beach. The UBV swarms could perform many additional missions, including target marking, lane marking, neutralization, and surveillance.

OBJECTIVES

The principal objective is to develop the essential supporting technologies that will make autonomous UBV swarms viable. These technologies include close-range sensors, detection-classification algorithms, and underwater communication and navigation "baseline" systems. The focus is on low-cost, low power systems that will fit within a 5000 $in.^3$ or smaller, expendable platform. Several earlier efforts have proven that vehicles of this size can have the mobility and length of life required to perform area search, neutralization and reconnaissance missions. By developing the enabling technologies rather than concentrating on one specific mission, many missions will be possible.

APPROACH

Our first year effort (FY97) included a search for existing commercial technologies and principles that could be exploited for sensing, communication, and navigation. Several investigations of specific sensor technologies and two system level studies were performed. The second year effort (FY98) concentrated on specific, promising sensor technologies, magneto-inductive signaling, and fused-sensor navigation solutions.

WORK COMPLETED

Sensing. Dr. John Stroud of CSS measured bottom scattering properties of a sand bottom using a geometry similar to a sonar mounted on the body of a small UBV. This work was an extension of an investigation into design of an ultrasonic sonar conducted in FY97 by Dr. Isaac Harris.

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An analysis of the Foster-Miller Inc. tactile sensor was completed, and a CSS-modified design was tested as well. Commercially available material-proximity and deflection sensors were also evaluated for use as additional components mounted on a contact sensor system.

A saltwater test tank was assembled for testing electromagnetic sensors and sources. Several Giant Magneto-Resistive (GMR) devices were evaluated for use on the UBV as magnetic anomaly sensors. The magnetic moment of the Lemming testbed vehicles was measured and found to be restrictive to electromagnetic sensing.

Communications. Two tradeoff studies by Magneto-Inductive Systems Ltd. (MISL) estimated the range, data rates, and power consumption for magneto-inductive communication links for long and short-range use. The first modeled system provided report-back and networking of vehicles while the second was a system for control of the search group from a battle group located over the horizon.

Navigation. Two ONR funded STTRs transitioned to phase II work, including the IS Robotics Ultra-Short Baseline Positioning System for Littoral Swarm Systems[1], a short range acoustic co-location system for robot swarms, and the Foster-Miller VLF Magneto-Inductive Signaling and Navigation System[2]. CSS represented the Navy and provided direction for these two efforts.

Dr. Everett Richards of the CSS Non-Acoustics branch investigated sensors that would support dead reckoning between sparse updates from a long baseline navigation system. The motivation for a fused approach is the assumption that underwater baseline systems, whether acoustic or magnetic, will suffer from drop outs and errors caused by anomalies in the environment. Mr. Mark Connolly has assembled Kalman filtering algorithms toward fusing tilt, compass, angular rate sensors (gyros) and a long baseline system to provide a total navigation solution. A data set will be collected in early FY99 that will include DGPS position data. Data from this set will be used to evaluate the navigation algorithms.

Search Simulation and Strategy Development. In FY97 a plan was drafted that listed a parameter matrix of sensing radii, numbers of Non-Mine Bottom Objects (NOMBOs), quantities of searchers, mission times, and sensor capabilities[3]. Monte-Carlo analysis of random search for a part of the parameter matrix was performed at CSS. A teaming arrangement with Professor Tony Healey of the Naval Postgraduate School was made to complete the study in FY97. In January 98, Lt. Jack Starr completed a master’s thesis covering this investigation[4].

Work continued during FY98 to develop the Distributed Underwater Network Evaluator (DUNE) at CSS. DUNE was used to investigate threat report frequency for reconnaissance swarms using random search in the Mission Regional Contingency (MRC-E) scenario. A full documentation package and an alpha release are nearing completion.

Standard Threat Document. Mr. Carmen Narde, Mr. John Allen, and Dr. Paul Schippnick of the CSS Mission Analysis Branch completed a review of the current obstacle and mine threat for the VSW/SZ[6]. They have identified a representative “standard threat” that includes mines, obstacles, and NOMBOs to be used for the 6.3 core autonomous vehicle program beginning in FY99.

RESULTS

Sensors. Dr. Roy Wiegert of the Non-Acoustics Branch at CSS has applied for a patent on a novel sensor that is similar to a fluxgate magnetometer. The sensor consists of a ferrite torroid with an excitation coil wound on the core. A pickup coil is wound over the core. The excitation winding is driven with a sinusoidal waveform at 1700 Hz at an amplitude level that just saturates the core. Stray fields emanating from the source interact with target objects, effecting the degree of saturation of the core. Core effects produce a second harmonic component, to which the pickup coil circuit is tuned. A lock-in amplifier compares the phase of the pickup coil's signal to that of the drive coil. The presence of a metal object near the sensor results in measurable phase shift between primary and secondary coil voltages that is dependent on the target's mass, conductivity, structure, and position relative to the sensor. A vehicle-suitable design will be developed and tested on one of the CSS testbed vehicles.

The design requirements for a passive magnetic anomaly sensor were determined. A miniature triaxial fluxgate magnetometer with triaxial accelerometers was acquired. This sensor can be mounted onto a testbed vehicle at any time. This device should enable passive detection of mine-like ferrous objects to 5 meters range.

The magnetic moment of the CSS testbed vehicles (Lemmings) was measured to be approximately 6 $A \cdot m^2$, which will severely limit the range of a magnetic anomaly sensor mounted on the vehicle. Dr. Wiegert has suggested that the vehicle moment should be reduced to 0.01 $A \cdot m^2$, which would generate a field strength of 27 nT at 0.3 m from the vehicle. The mass of metal within the vehicle also poses a problem by reducing the effective range of an inductive metal detector. An assessment of anomaly and pulse induction sensing improvement with low signature redesign is planned.

In FY98, Dr. John Stroud measured backscatter from a sand bottom at 2.25 MHz. The purpose of these measurements was to determine the severity of backscatter energy for the case of a sonar that was mounted very close (< 8 cm) to the sea bottom on the front end of a crawling robot[7]. Preliminary results indicate that the backscatter is not a problem for the case of smooth sand.

Mr. Jerry Blimbaum analyzed data from the Foster-Miller, Inc. (FMI) tactile sensor, which is composed of a grit-covered rod with a piezoelectric strain gage transducer mounted at its base[8]. The sensor was exercised using a target set comprised of different objects composed of different materials. The FMI sensor signatures indicated that a series of harmonics are produced, and that the proportion of high to low frequency harmonics could be used as an indicator of the roughness of the target. Statistics of the surface waveform could not be computed from the waveforms due to the random interaction of the grit with the target surface. The FMI sensor was modified by replacing the grit covered rod with a smooth rod, bent at the end. The bent end acted as a single point stylus. Signatures taken with the modified sensor indicated distinct differences between various textured surfaces that were clearly evident in the estimated spectra. Dr. Christopher Rahn of Clemson University developed a state model of the Foster-Miller tactile sensor structure[9] to investigate the modal properties of the tactile sensor.

Two additional contact sensors were evaluated for use in a contact sensor system[10]. One sensor was a material sensor that was obtained for less than $2.00. This sensor utilizes a small, potted transformer to measure coupling of energy from primary to secondary circuits, and produces an output voltage proportional to the degree to coupling. The sensor produces a different output voltage when in contact with different metals, provided that the volume of the target sample is much larger than the sensor head. We believe that this sensor may prove useful in identifying target materials when mounted on the texture sensor discussed above.

A second sensor that was evaluated was a deflection sensor used in virtual reality gloves. This sensor is a long strip of variable resistance material; electrical resistance varies as the strip is bent or twisted.

The sensor can be used to measure deflection of a bumper structure as the UBV encounters obstacles on the bottom, or to measure deflection of a whisker sensor for shape tracing.

Communications. Magneto-Inductive Systems Limited (MISL) continued studies on the development of magneto-inductive channel for communications. The studies were motivated by the CSS surf zone communications report[11] and a successful demonstration of magneto-inductive signaling in March 97 by MISL[12]. The two studies estimated range, baud rates, and power requirements achievable for report-back or inter-vehicle communications, and for long range command from over the horizon to the surf zone study[13, 14]. For the short-range applications, the source/receiver coil was modeled as a silicon-steel core wrapped around a 20"x14"x7" (Lemming sized) form. Six coil options were modeled, representing tradeoffs in power, weight, and working voltage. All options were determined to be suitable for use as a receiver or transmitter. The most attractive option, chosen for lowest copper loss (38W), used 120 turns of wire driven at 302 volts (tuned) at 3KHz, creating a 1200 Ampere-turn source. Coil mass was 5.15 Kg (copper) plus 0.35 Kg core mass. Assuming a 1 pT receiver sensitivity, the attainable system range along the source axis is predicted to be 1000m.

In January, MISL repeated the exercise, this time assuming no permeable core, which would minimize the effect of the communication antenna on magnetic or inductive sensors mounted on the vehicle[15]. To compensate for the original core, the number of windings increased, and copper weight more than made up for the weight of the omitted core. Of four options modeled, the lowest loss option generated the 1200 Ampere-turn source with 200 turns of wire (12.83 Kg mass) and dissipated 34W at 284 volts.

In September 1998, MISL demonstrated generation of a 100 $A \cdot m^2$ source (100nT @ 1M) using a coil wrapped around a 20"x14"x7" foam core[16]. The signal was successfully received at a range of 300m, at which field strength was measured at 0.3 pT.

It is believed that the 3KHz carrier frequency will allow data rates as high as 300 baud using true Frequency Shift Keyed (FSK) modulation. The challenge will be to perform FSK modulation with high inductance, high Q coils operating with large circulating currents. To date demonstrations of 300 baud FSK have used only small coils in the laboratory. In addition, sub-picotesla receiver sensitivity has been demonstrated using slower AM receivers with FSK-warble rate modulation, which was demonstrated at CSS in March 1997.

Search Simulation and Vehicle Control. Lt. Jack Starr, under direction of Dr. Tony Healey of the Naval Postgraduate School, completed his thesis in January 1998[4], providing full simulation results for random search in the MRC-E scenario with various quantities of NOMBOs present in the search field. Results confirmed the partial results received in FY97. The most important results were average time and numerics for 25 vehicles operating with 150 NOMBOs present in the surf zone portion of MRC-E). We have determined the sensor success rate required to provide adequate identification of mines within four, six, and eight hour mission times. The sensor success rate, or probability of classifying a detected target correctly as a threat (e.g., mine or obstacle) or non-threat (e.g., small rock), is used in the absence of real sensor performance data, which is unavailable at this time.

Mr. Mitch Gavrilash of CSS has completed final modifications toward an Alpha release of the Distributed Underwater Network Evaluator (DUNE), which is a Java and VRML based simulator for groups of robots. In FY98, DUNE code was used to develop obstacle avoidance algorithms based on a simple bump and try approach. DUNE has also been used to verify results from Lt. Starr's efforts at NPS. Statistical data collection classes have been added to DUNE to simplify collection and compilation of data from simulation runs. DUNE has also been used to explore the frequency of threat reports from a reconnaissance swarm over time to determine the messaging traffic that will have to be handled by a communication protocol in the future. DUNE will be used to develop and assess control codes written to support new close range sensors.

IMPACT/APPLICATIONS

Successful development of close-range sensors, underwater communications, and navigation technologies will make it possible for autonomous robotic systems to replace human operators performing hazardous underwater work. The greatest impact will arise from new close-range sensors, which could exploit texture, conductivity, chemical signature, underwater electromagnetic signatures, and vibratory modes of targets. Traditional long-range sonar, magnetic moment and field gradient detection, and passive and active optical systems cannot exploit these properties. We expect that close range sensing will provide automatic target classification capability, which will make it feasible to use autonomous robots to perform useful missions in littoral waters.

Low observable underwater communication and navigation systems will allow robot swarms to perform efficiently and cooperatively while reporting critical data in a real-time fashion. Additional applications for these baseline technologies include lane marking, target marking for reacquisition, remote control of minefields (RECO), precision timed detonation of ordnance, and diver communications.

TRANSITIONS

A new 6.3 core autonomous systems program has started in FY99. Under this program, a surf zone thrust will continue developing and demonstrating the supporting technologies that have been developed under the Surf Zone Reconnaissance Project. Vehicle suitable communication and navigation baseline systems, and search, detection and classification capabilities will be demonstrated. Demonstration of multiple vehicle search and mapping of a minefield is the ultimate goal.

RELATED PROJECTS

The Basic Unexploded Ordnance Gathering System (BUGS)[7] is a 6.2 effort conducted by NAVEODTECHCEN to develop small autonomous vehicles that can pick up and handle unexploded ordnance (UXO) on land. Issues common to BUGGS and the Surf Zone Reconnaissance Project include the need for communication and navigation subsystems.

The Lemmings and Sea Dog are related SBIR projects. The Lemming project, which ended in FY96, was a DARPA funded effort that developed a tracked vehicle and sensor for a mine neutralization mission. The Sea Dog SBIR project is developing a remotely operated, larger variant of the Lemming vehicle for neutralization of UXO and obstacles.

The Tactical Mobile Robots Program, managed by DARPA, is developing technologies for land-based robots for tactical use in the field and in urban environments. Technologies under development include perception (hazard detection, mapping, and position estimation), autonomy (terrain crossing, multiple-robot collaboration, autonomous mission execution), and locomotion technologies (ground, climbing, burrowing) to support urban assault, covert reconnaissance, and building reconnaissance. The effort is a combination of private sector contractors and a government team that includes the Air

Force, Marines, and Special Operations Command. System designs and a demonstration in FY99 are also planned.

REFERENCES

1. IS Robotics, Inc., 1998: "Ultra-Short Baseline Positioning System for Littoral Swarm Systems," Small Business Technology Transfer (STTR) Proposal and MIT Sea Grant, February.
2. Foster-Miller, Inc. and Autonomous Undersea Research Institute, 1998: "VLF Magneto-Inductive Signaling and Navigation System," Small Business Technology Transfer (STTR) Proposal February.
3. Multiple Autonomous Search Vehicle Modeling Plan, NSWCDD, February 1997.
4. Jack Starr, 1997: "Multiple Autonomous Vehicles for Minefield Reconnaissance and Mapping," Naval Postgraduate School, December.
5. Foster-Miller Inc., 1994: "Lemmings, A Swarming Approach to Shallow Water Minefield Clearance," February.
6. Paul Schippnick and John Allen, "Mine Threat Database - Summary of Results on Surf Zone Mines," Working Paper, Coastal Systems Station, September 1998.
7. Isaac Harris, 1997: "Acoustic Sensor for the Surf Zone Reconnaissance Autonomous Underwater Vehicle," Coastal Systems Station, October.
8. Jerry Blimbaum, 1998: "Surf Zone Contact Sensor Report," Coastal Systems Station, September.
9. S. Jaffar and C. Rahn, 1998: "Beam/Whisker Frequency Response Report," Dept. of Mechanical Engineering, Clemson University, March.
10. Jerry Blimbaum, 1998: "Proximity Sensor Evaluation Report," Coastal Systems Station, September.
11. John Sojdehei, 1997: "Communication Concept Study for the Surf Zone (Draft Report)", Coastal Systems Station, May.
12. John Sojdehei, 1997: "Magneto-Inductive Communication Demonstration Report," Coastal Systems Station, May.
13. Magneto-Inductive Systems Limited, 1997: "MI Communication System for ROVs: Preliminary Feasibility Study," U.S. Navy CSS Contract #N61331-97-M-1913, 28 November.
14. Magneto-Inductive Systems Limited, 1997: "MI Communication System Over the Horizon Signaling," U.S. Navy, 28 November.
15. Magneto-Inductive Systems Limited, 1997: "MI Communication System for ROVs: Preliminary Feasibility Study (addendum)," 26 January.
16. Magneto-Inductive Systems Limited, 1998: "Demonstration of Report-Back Magnetic Communications Trade-Off Study," CSS contract #N61331-98-M-1942, October.