Magnetic Sensors Project

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LONG-TERM GOALS

Requirements as documented in MNS-M042-85-93 (Mission Need Statement for Mine Countermeasures), MNS-M025-003-92 (Mission Need Statement for Shallow Water Mine Countermeasures), and OR 282-03-92 (Operation Requirements for Buried Mine Detector) indicate two capability gaps in mine reconnaissance of interest for this project: (1) the detection of buried mines and (2) the reduction of acoustic clutter (false alarms). These two shortcomings were addressed during the early 1990's at the CSS, using a superconducting gradiometer under the Magnetic and Acoustic Detection of Mines (MADOM) ATD [1], [2]. This sensor utilized the low critical temperature (low Tc) superconductor niobium technology and requires liquid helium for sensor cooling. Advanced sensors using new high critical temperature (high Tc) superconducting materials that operate in liquid nitrogen are being developed to transition this gradiometer technology to the Fleet.

OBJECTIVES

The current focus of this project is to develop an advanced High Tc Superconducting Gradiometer (HTSG) prototype cooled by liquid nitrogen and to demonstrate it at sea. *This development will make it possible to provide localization and classification capabilities unachieved using current Fleet magnetometers such as the ASQ-81/208 with the longer detection ranges previously reserved to low-Tc sensors.* In comparison to its low Tc counterpart, the HTSG can provide substantially reduced package sizes and minimal cryogen support requirements.

APPROACH

The technical approach for this project involves: (1) sensor development, (2) sensor evaluation in land-based motion studies simulating tow operation, and (3) sensor at-sea testing. In FY 2000, final upgrade of the sensor to a field-deployable unit and preliminary preparations were conducted for a test at sea in the 1st Quarter of FY 2001.

WORK COMPLETED

In order to circumvent the current limitations in high-T_c fabrication technology, a HTSG sensor approach is being pursued which features the three-sensor gradiometer (TSG) concept [3]. Designs of dewars for nitrogen cooling units have been established and analyzed in order to provide a range of concepts appropriate for different missions [1]. *More recently an innovative closed-cycle Superconducting-Gradiometer Refrigerator (SGR) (displayed in Figure 1) has been proposed for cooling high Tc magnetic sensors down to 77 Kelvin or below without introducing low-frequency noise into the sensor [2], [4].* If pursued, a sensor package is envisioned totally free of cryogen support and logistics with dimensions of 12 inches in diameter and 36 inches in length inclusive of the cryogenic electronics, the room-temperature support electronics, and all elements of the refrigeration unit (with the dewar length projected to be 18 inches.)

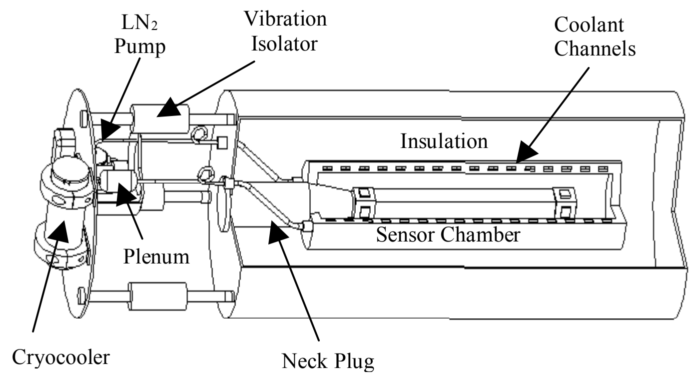

Figure 1. Concept for a compact refrigerator housing the cryogenic electronics for a 3-channel high Tc superconducting gradiometer.

The feasibility prototype for a nitrogen-cooled HTSG (displayed in Figure 2) has been developed by a team from the Coastal Systems Station, IBM, Quantum Magnetics, and Lockheed Martin and is currently being evaluated [4], [5]. This prototype features high-performance high-Tc SQUID magnetometers, 16-MHz Flux-Locked Loop (FLL) electronics developed to provide large bandwidth for electromagnetic interference immunity not possible using current commercial electronics [6], and novel field-control negative-feedback electronics to provide the resolution and dynamic range required. The HTSG has been successfully evaluated under both stationary and motion conditions in land-based testing.

The sensor has been upgraded to a field-deployable version for at-sea testing. A final system configuration and a test plan has been established for the sea test. Preliminary system preparations, including refurbishment of the tow craft, assembly of instrumentation housing, and interconnect cabling have all been completed. The localization algorithm utilized in MADOM has been optimized for high-speed operation and for GPS positioning.

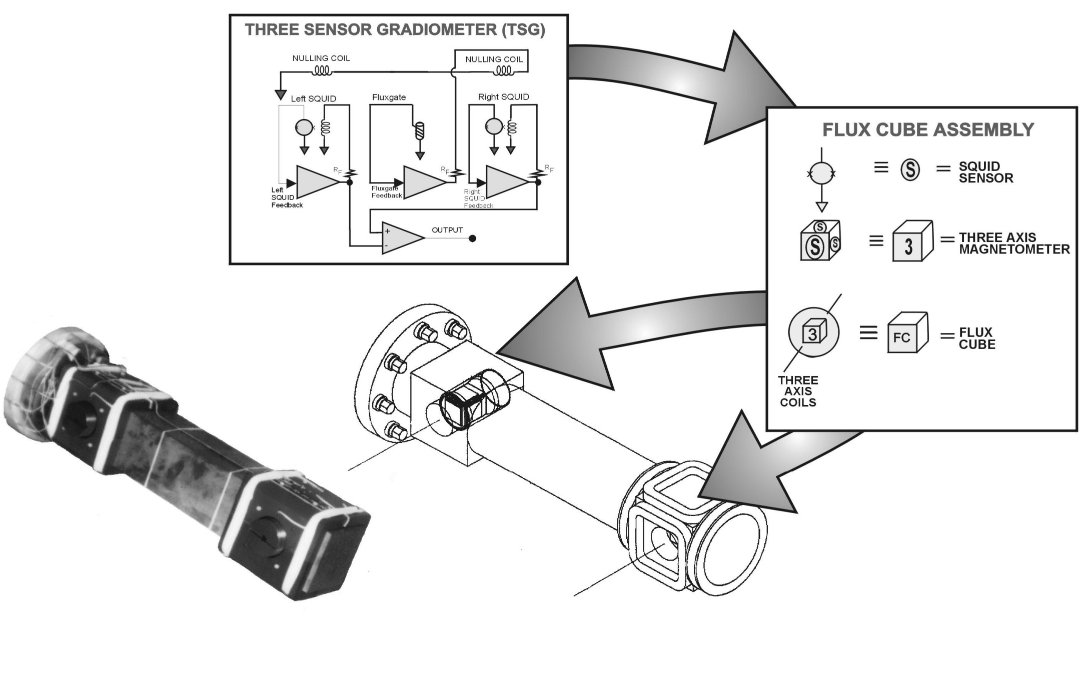

Figure 2. Concept of three-sensor gradiometer implemented in High Tc Superconducting Gradiometer (HTSG) and photograph of prototype under evaluation.

RESULTS

Sensor Development: The HTSG has now demonstrated excellent performance stationary and in motion [4], [5]. For stationary operation totally unshielded in the Earth's magnetic field, a white noise floor of 0.5 pT/m-$Hz^{1/2}$ has been measured. The corresponding magnetometer white noise in the field is 0.1 pT/$Hz^{1/2}$, essentially equal to the performance reported by the manufacturer under laboratory-controlled conditions. *Excellent performance has now been demonstrated for this sensor in land-based motion testing.* The sensitivity at 1 Hz is 5 pT/m-$Hz^{1/2}$, which corresponds to magnetometer noise of 1 pT/$Hz^{1/2}$. This result represents performance better than that attained by any conventional non-superconducting technology identified to date and is approaching that of its helium-cooled counterpart. In fact, the sensitivity of the nitrogen-cooled sensor exceeds the performance of its helium-cooled counterpart as attained in sea testing at frequencies above 3 Hertz. A 10-fold improvement in performance over results in initial motion testing has been obtained. Approaches to obtain high resolution without aliasing in the signal-conditioning electronics have been established.

Enhanced trim-coil electronics and procedures developed in FY 2000 have demonstrated an order of magnitude increase in sensor balance, a significant development to reduce the motion-stabilization requirements for sensor operation [4]. This is expected to be a critical factor when the HTSG is subjected to motions in sea testing above water, motions that may be significantly larger than would be expected with the sensor operated below water. *This development will dramatically lower the requirements for platform motion stabilization. The sensor can now operate with vehicle motions of 5 degrees per second or greater. We can envision the operation of a magnetic sensor onboard a high-speed underwater or surface tow body using at most simple mechanical-feedback stabilization, transcending the need for complex electrical motion-control assemblies that introduce performance-limiting electrical noise.*

Field-Deployable Sensor: Based on these promising results, the sensor is being upgraded to a field-deployable version for at-sea testing and demonstration. *New SQUID magnetometers with sensitivity two to three times greater than previously attained have been implemented into the sensor with the intent to realize greater performance in motion.* A room-temperature electronics subassembly for HTSG field deployment in the upcoming sea test, including new miniaturized analog SQUID control electronics featuring 16-MHz modulation for high dynamic range and the miniaturized digital electronics for remote control of the sensor, has been assembled and evaluated. The nulling-coil electronics have been upgraded to implement the enhanced trim-coil approach to provide more robust operation in higher sea states. The Vaizer-Lathrop localization algorithm developed under the MADOM project has been optimized for high-speed operation and to include GPS data for more accurate localization.

High-Speed Operation: Unlike side scan sonars for which search rate is essentially independent of speed, search rate for a magnetic sensor increases with speed. For magnetic sensing, the energy associated with target signals shifts to higher frequency as speed increases and HTSG sensitivity improves out to 10 Hertz. Hence HTSG detection range increases with speed. In fact, a 20% increase in range can be realized at 30 knots over that at 5 knots. *Hence search rate increases at a rate better than linear as a function of speed, providing one means to accelerate mine reconnaissance missions (Figure 3).* Operation at 30 knots will provide search rates on the order of 1 sq. nmi/hr in very shallow water regions, an excellent capability for reconnaissance in that region [2]. Based on this assessment, the test plan for the first at-sea demonstration of the HTSG features a configuration in which the sensor

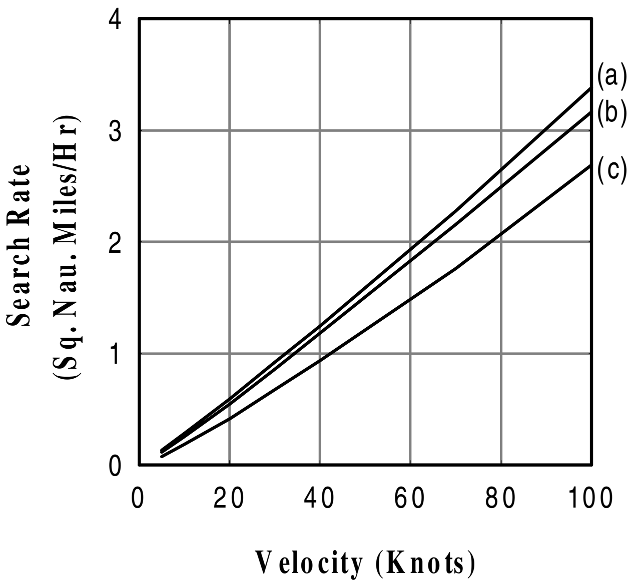

Figure 3. Nominal search rate as a function of speed for a magnetic target with moment 60 A-m ^{2} ***for a vertical offset between sensor and target of (a) 20, (b) 40, and (c) 60 feet.***

will be towed above water behind an 11m rigid hull inflatable boat (RHIB) at speeds up to 30 knots. The system prototype will be used to detect, classify, and localize mines in very shallow water and surf-zone water depths as shallow as 5 feet. Opportunities exist for subsequent demonstration towed underwater from a high-speed unmanned surface craft such as a USN RHIB with remote control (Figure 4).

IMPACT/APPLICATIONS

The U.S. Navy has pioneered the 5-channel tensor-gradiometer approach to provide localization and classification capabilities not achieved using current Fleet magnetometers such as the ASQ-81/208. The results from the MADOM ATD have provided proof of this enhanced capability. In FY 1999 the low Tc superconducting gradiometer used in MADOM was the premiere sensor in an unscripted survey to locate unexploded ordnance in the Technology Demonstration of the Mobile Underwater Debris Survey System (MUDSS) [7]. It successfully detected buried targets and was effective in an environment that limited the performance of the acoustic and optic sensors utilized in the test.

We believe that a single nitrogen-cooled magnetic gradiometer can be flexibly integrated into various platforms in order to serve in a range of littoral warfare missions. Its capability in high speed operation meshes well with emerging interest in the use of high speed unmanned surface and aerial vehicles as one means to accelerate mine reconnaissance using magnetic sensors (Figure 4). This sensing capability is of particular value in the shallow water, very shallow water and surf zone regions. Airborne operations (using either unmanned aerial vehicles or the H-60) can also provide offboard sensing for ship self defense against near-surface mines and submarines. This sensing approach can also be applied to the military missions of nonacoustic ASW, the detection of underground facilities and hidden military targets, extremely low frequency communications, and torpedo homing. It can be utilized for dual-use applications of environmental cleanup, geophysical survey, police and rescue operations for the location of sunken or buried vehicles, archeology, treasure hunting, and civil engineering for the location of underground or undersea cables, pipelines, old foundations, buried gas tanks, and well heads.

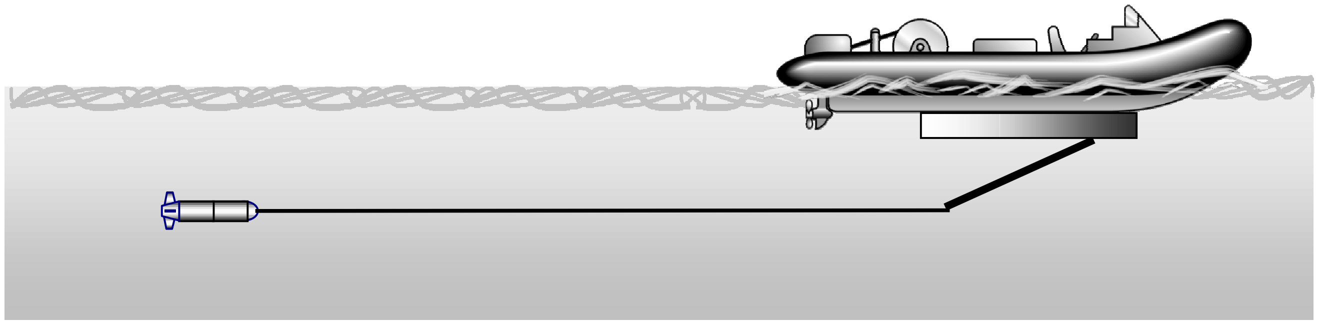

Figure 4. Operational concept for magnetic sensor deployment inside a simple tow body towed behind a RHIB at high speed operated in very-shallow water and surf-zone regions.

The HTSG represents one of the major accomplishments in the area of high T_c superconducting electronics technology initiated a decade ago. There is an excellent opportunity to commercialize TSG sensors in order to replace total-field magnetometers as the mainstay for magnetic anomaly detection in mobile applications. Advanced flux-lock loop (FLL) electronics with a modulation frequency of 16 MHz, 30 to 100 times faster than conventional schemes, have been developed to improve cryogenic signal amplification and electromagnetic immunity essential for field operation [6]. The dewar technology has also been advanced for a number of applications requiring a high degree of thermal and magnetic stability in mobile operation. It provides the basis for the concept of a high performance, compact nitrogen-cooling unit for the HTSG [1], [2], [4].

TRANSITIONS

One low-T_c sensor technology transitioned to the MADOM 6.3 ATD in FY 1989 and to the Buried Mine Detector (BMD) 6.4 Program in FY 1992. Although the BMD Program is not currently funded, the HTSG developed in this project is available for transition to support reconnaissance operations. A 6.3 demonstration proposal "Detection of Buried Mines" submitted for consideration to ONR Code 321W includes the HTSG as one candidate for buried mine detection. The low-T_c technology has been successfully demonstrated in FY 1995 and FY 1999 demonstrations of the Mobile Underwater Debris Survey System (MUDSS) Technology Demonstration of MUDSS [2], [7]. The nitrogen-cooled HTSG will be utilized in subsequent surveying for UXO cleanup and related dual-use applications. A 3-axis magnetometer prototype developed under this project is now commercially available from Tristan Technologies and is the basis of other products from that company [8]. The basic multi-channel tensor gradiometer concept pioneered under this project has been transitioned to a comparable fluxgate gradiometer, which is being pursued for demonstration for the VSW MCM mission. The HTSG technology is available if greater sensitivity is required for the VSW reconnaissance mission than can be provided by the fluxgate gradiometer.

RELATED PROJECTS

This 6.2 exploratory development project has been supported by a contract to IBM Research sponsored by ONR 312 (Dr. D. van Vechten) and by CSS Internal Research to investigate noise mechanisms in high T_c SQUID magnetic sensors [9], [10]. Projects to develop shorter-range, man-portable fluxgate gradiometers based on the sensor and signal-processing concepts initiated under this project have been sponsored by ONR 322GG and the OSD SBIR program [11], [12]. A project to integrate a fluxgate gradiometer into the Morpheus AUV developed by Florida Atlantic University was initiated in FY 2000 by ONR 321OE in conjunction with an SBIR "Integration of Advanced Magnetic Sensors into Underwater Vehicles to Provide High-Quality Spatiotemporal Magnetic Data" to Quantum Magnetics sponsored by ONR Code 322OM. The fluxgate gradiometer and the HTSG are very synergistic. They use a similar sensor design approach and essentially identical signal processing. Moreover they provide a range of solutions for high quality target localization and classification to support varying mission and operational requirements such as detection range, sensor cost, and platform compatibility.

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PUBLICATIONS

T. Clem et al., "Enhanced Magnetic Anomaly Detection using a Nitrogen-Cooled Superconducting Gradiometer," in *Information Systems for Navy Divers and Autonomous Underwater Vehicles Operating in Very Shallow Water and Surf Zone Regions II,* J. L. Wood (ed.), the International Society for Optical Engineering, Vol. 4039, pp. 70-84 (2000).

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