A PRECISION NAVIGATION SYSTEM FOR AUTONOMOUS UNDERSEA VEHICLES

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ABSTRACT

Harbor Branch Oceanographic Institution, Inc. (HBOI) and Kearfott Guidance & Navigation (KGN) Corporation have teamed to develop a low-cost inertial navigation system for autonomous undersea vehicles (AUVs). HBOI and KGN have been working together to develop such a navigation system at the lowest cost possible. The navigation system will be ideally suited for mine countermeasures missions as well as other scientific and commercial missions.

The development of the navigation system, acquisition of the inertial sensor and software development hardware have been 100% internally funded to date. HBOI has acquired the software development hardware, VX Works software and a Kearfott T-16B ring laser gyro based Inertial Measurement Unit (IMU). The Kearfott T-16B ring laser gyro system was selected partially due to the upcoming large production runs of up to 100,000 units (over the next 10 years) and partially due to its performance capability. The large production runs of this unit (beginning in late 1996 or early 1997) will reduce the cost of the IMU to less than $35,000 including the SEANAV software. The completion of this program will result in an at-sea demonstration of a precision inertial navigation system, at a mere fraction of the anticipated development cost of a purpose-built system. The navigation system will be compatible with both the F.A.U. Ocean Explorer and the M.I.T. Odyssey and could be integrated aboard either vehicle class.

INTRODUCTION

Harbor Branch Oceanographic Institution, Inc. (HBOI) has been involved in research associated with the application of oceanographic sensors and their integration and use aboard remotely operated, manned and autonomous undersea vehicles (AUVs) for many years. HBOI has invested a great deal of time and internal funds for the development of a dedicated coastal oceanographic AUV (Ocean Voyager I) and associated subsystems and sensors for collecting oceanographic data in littoral areas. For the past year, HBOI has been working closely with Kearfott Guidance and Navigation (KGN) to develop a low-cost, high accuracy, modular navigation system, based on their success with the Miniature Integrated Land Navigation System (MILNAV™), which utilizes a Monolithic Ring Laser Gyroscope (MRLG), motion sensor, GPS input and control unit.

SCIENTIFIC AND TECHNICAL ISSUES

In addressing the challenges associated with precision navigation for AUVs, the key technical issues are as follows:

- Low power
- High accuracy
- Small size (volume)
- Light weight
- Low cost
- Ability to navigate (dead reckon) between fixes (updates)

Optimal navigation performance can be attained with continuous satellite navigation (GPS, DGPS, etc.) input to the system by some means (e.g., fiber-optic link, acoustic modem, towed buoy, pop-up buoy, etc.) or transmitting its position via the LBL network. With the vehicle traveling at 2-6 knots, position updates have to occur frequently (about 1 per second). When updates are not available for what ever reason (no GPS, LBL malfunction, broken fiber-optic tether), the AUV must be capable of navigating (dead reckoning) for some time, either to continue a critical mission or to simply return home without getting lost. The ability to detect and measure speed and direction over ground is also crucial to the navigational ability of the AUV. A key to navigating under these conditions is the ability to use as many different sensor inputs as are available. This information coupled with a well designed Kalman filter will substantially increase the distance an AUV can travel without a position update.

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PROGRAM APPROACH

After many internal studies and analyses at HBOI, it has been concluded that the navigation system most suited to autonomous oceanographic data collection is a medium accuracy, inertial system coupled with a Doppler speed sensor and an acoustic modem or fiber-optic link for position updates. GPS will be used to initialize the system; and, of course, direct vehicle fixes from GPS are feasible by surfacing the vehicle. Surfacing does come with a certain amount of risk due to sea state and boat traffic and is very mission time consuming. The system architecture must be modular, enabling navigational inputs to be changed to best suit the task. This approach presents the highest accuracy system possible while maintaining the attributes listed above. The system presented here is applicable to all oceanographic AUVs.

To reduce the development cost of an oceanographic AUV navigation system to a mere fraction of the anticipated cost, HBOI and KGN have teamed to modify the Kearfott MILNAV system for AUV use. The T-16B was selected for both its performance and the fact that it will be produced in large quantities. The unit was selected for the U.S. Navy's Joint Stand-Off Weapons (JOSW), the Air Force's Joint Direct Attack Munition (JDAM) and Wind Corrected Munition Dispenser (WCMD) programs. The unit is expected to be produced in quantities of over 100,000 units over the next 10 years.

While the MILNAV as it stands today offers attractive features with respect to size, power and cost, it was not optimized for AUV use. Historically, manufacturers of inertial systems have supplied only complete systems, which included the inertial sensor and all electronics in a single chassis. This has mandated and defined a significant volume for these systems and modifying one of these systems to accommodate a new or different I/O has been cumbersome and expensive. In this light, HBOI and KGN have defined a federated navigation architecture whereby the inertial sensors and navigation electronics are separable. This approach results in two main components, the Inertial Measurement Unit (IMU) and the VME navigation processor. This modular architecture has the following key features:

- Small IMU easily packaged within the main pressure hull or in a separate pressure vessel
- Utilization of fewer power conditioning devices and lower power
- Interchangability with other IMUs with a common processor for varied performance requirements
- Easy and flexible growth potential within the VME architecture

HBOI is writing the software, developing the Kalman filter and plans to integrate the entire navigation system aboard one of our research submersibles initially. Once integrated, HBOI will take the submersible to sea and perform trials. HBOI will recompile the MILNAV software converting it from JOVIAL code to "C." Initial tests at sea, aboard a ship, showed that the MILNAV software and Kalman filter required tuning to tailor its performance for sea born motions (i.e., wind, waves and currents). HBOI and Kearfott are working to optimize the software for AUV applications which will be verified by testing in Kearfott's simulator in New Jersey via real test cases. The Kalman filter will be rewritten to operate with a sensor suite available in an underwater vehicle and the appropriate navigation solution software loaded on the VME navigator card and integrated with the vehicle controller.

All of the hardware exists to complete the navigation system including the MRLG, navigation computer, interface board which converts the serial output from the IMU to a RS 422 output, and the VX Works real time operating system running on a Silicon Graphics workstation. The navigation computer and IMU will fit in a Benthos 17-inch glass sphere or a 10-inch diameter x 20-inch long (or less) cylindrical housing.

Kearfott is modifying their existing MILNAV simulator for testing and verifying the SEANAV software. Once HBOI has delivered the software to Kearfott, they will run verification test cases and begin to optimize the Kalman filter. Kearfott will provide support for at sea testing, debugging and Kalman filter modifications during the upcoming trials off Florida.

Raw sensor data, recorded during sea trials and other operations at sea, will be used to develop the Kalman filter. This data will be used to write the Kalman filter and perform testing in the Kearfott simulator.

NAVIGATION SYSTEM DESCRIPTION

The proposed navigation system consists of three primary subsystems, the inertial measurement unit, navigation computer and navigation software. Each is described below.

Inertial Measurement Unit

The IMU is a RLG-based strap-down system utilizing Kearfott's T16-B three-axis RLG and three accelerometers as the inertial sensors. The system mechanization and the electronic configuration have been selected to minimize cost, size, weight, and power consumption and are an adaptation of the best features of existing Kearfott systems.

The IMU consists of a T16 Inertial Sensor Assembly (ISA), sensor electronic/processor Circuit Card Assembly (CCA), High-Voltage Power Supply (HVPS), and a chassis assembly. A block diagram of the IMU is shown in Figure 1, and the IMU configuration is shown in Figure 2. Key system features of the ISA are shown below:

• Size	8.6" x 6.75" x 4.4" (nominal)
• Weight	6.4 lb.
• Power	+/- 15 V, +5 V at 16 watts
• Angular rate	+/- 1000 deg./sec.
• Accelerometer capture loop	+/- 35 g
• Operating temperature	-540 deg. C to +850 deg. C

The ISA contains the 16-cm path length MRLG T16-B gyro, gyro-buffer electronics, and three accelerometers mounted on a triad. The ISA is installed in the IMU chassis using four vibration isolators located symmetrically in a principal plane. This inherently symmetrical design minimizes rocking/coning errors. The isolation system parameters (geometry-isolator spans as well as stiffness over temperature and loads) are optimized to satisfy the bandwidth requirements.

The MRLG uses a single block and six shared mirrors and offers significant size, weight, cost, and reliability advantages over three single-axis RLGs. Under development since 1981, the MRLG approach has been pursued in three sizes: 24, 16, and 10-cm path lengths for a broad range of applications. The most recent product improvement has extended the T16 to both a low-cost version, the T16-B, and a high performance model, the T16-E. The T16-B design is geared to the high volume, low-cost tactical missile market. While the T16-B shares the key features and background of the generic MRLG approach, it offers a cost advantage because of wide performance margins and design simplifications.

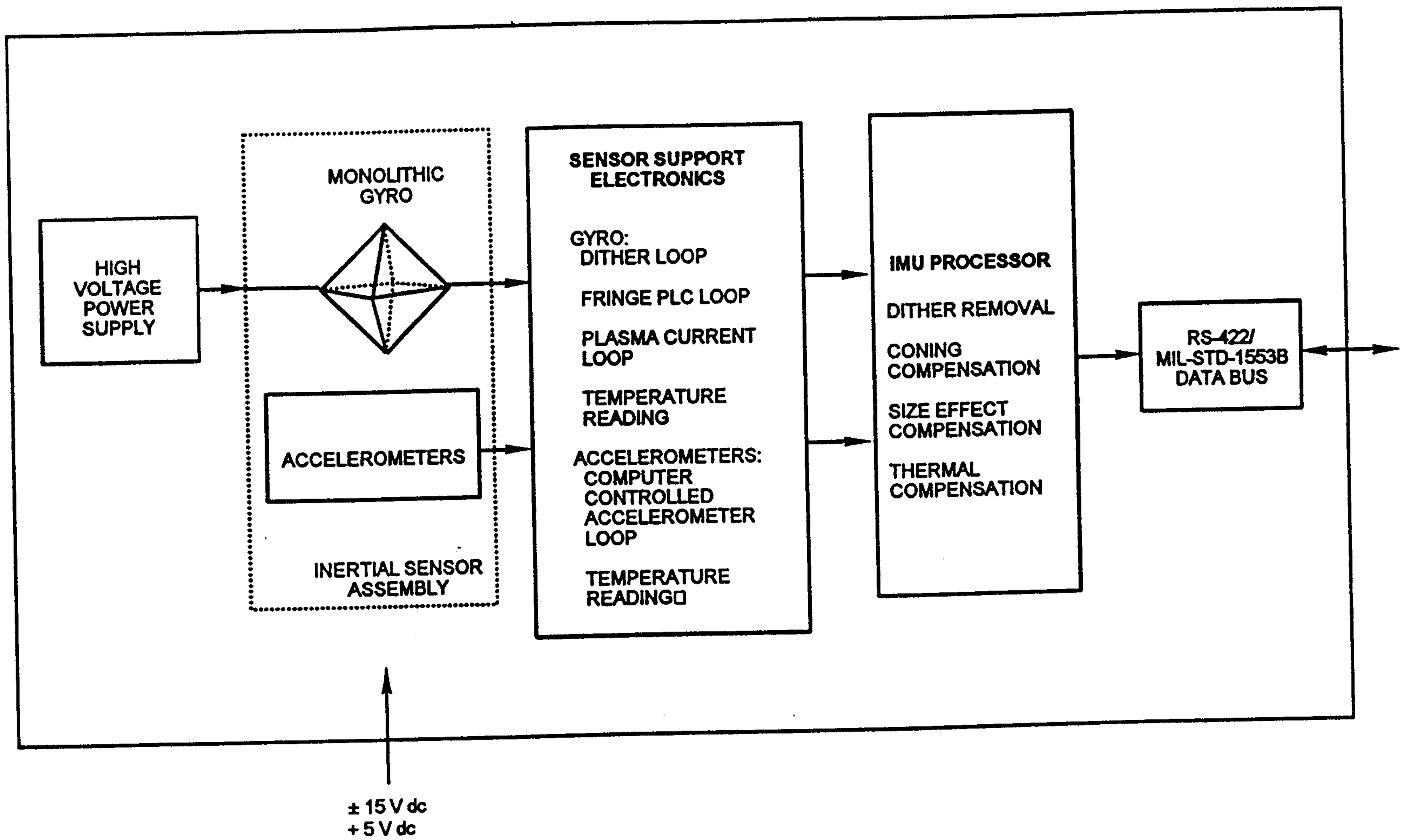
The MRLG laser assembly is based upon the same technology successfully applied to Kearfott's single-axis MOD 11 production RLG. Kearfott has demonstrated both analytically and experimentally that shared mirrors provide three uncoupled gyros in a single block. The most important part of the MRLG is its laser assembly, which consists mainly of a low-expansion, Zerodur block along with six low-scatter, low-beam, multilayer dielectric mirrors. The apertures in each cavity are elliptical in cross section to enhance single-mode operation of the astigmatic beam. The discharge path involves six anodes and a single internal cathode designed symmetrically to prevent Langmuir flow bias effects. Also, the helium-neon gas mixture has a particularly low gas-flow coefficient. The internal cathode has been designed for long life. Life test samples at this time have over 10,000 hours. The combination of gas pressure and current density are well below the level at which sputtering begins. The internal getter for the MRLG is DC-fired and is mounted on an indium step-sealed flange. In fact, all seals (mirrors, anodes, cathode, getter, and fill tube) are made by the highly-reliable indium, step-seal method pioneered at Kearfott.

The HVPS is powered by +15 V DC, and supplies DC excitation to the gyro plasma and ballast resistors. It regulates the current in the gyro to 3 mA and limits the maximum output voltage supplied to 1,750 V during no-load operation.

Extensive use of Application-Specific Integrated Circuits (ASICs) has allowed the sensor and processor electronics to reside on a single CCA. This allows for reduction in complexity, cost and weight. The sensor electronics act as the main interface between the inertial sensors and the processor. The sensor electronics consist of two gyro control ASICs, multiplexed A/D converter, ionization pulse circuitry, dither and Path-Length Control (PLC) D/A converters, and fringe comparators. The two, gyro-control ASIC's contain three PLC drivers, dither drive, and dither pick-offs. The MRLG concept permits incorporating the 16-cm path length gyro's small volume thereby providing performance margin for a smaller/lighter assembly. The housing provides space for packaging and mounting gyro electronics which need to be close to the gyro. The most significant electronic part is the fringe amplifier ASIC which provides needed amplification for the sensitive fringe signals. The electronics assembly also includes a dither transformer and a pulse start-up transformer which allow simplification of the system support electronics.

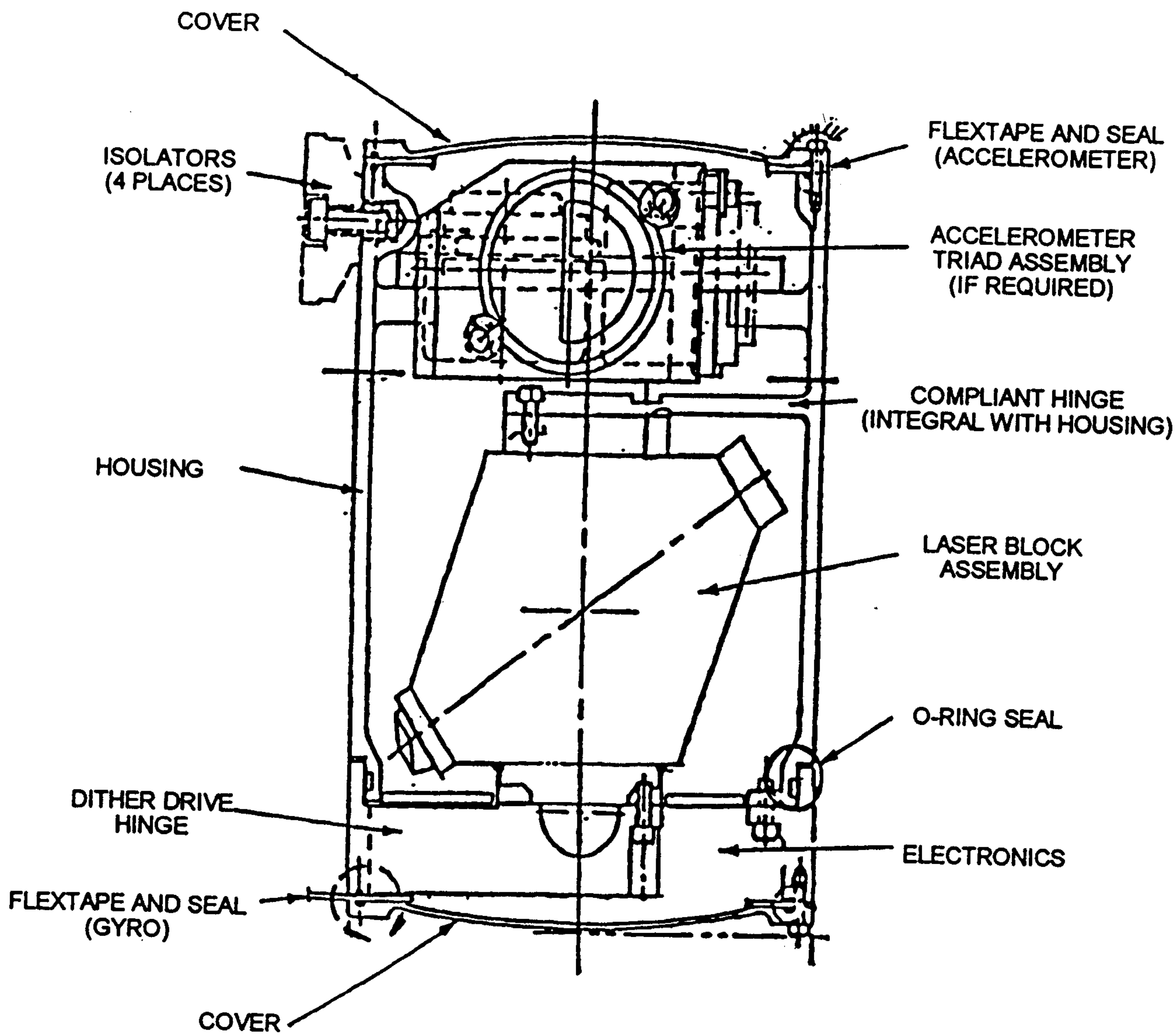
The processor electronics serve as the central control and computational element for the IMU. The processor electronics consist of a microprocessor, memory, a clock oscillator, RS-422 interface or MIL-STD-1553B interface, and a processor support ASIC. The processor support ASIC will contain processing capability which will permit it to act as a coprocessor/support chip for the system processor. The main functions of the ASIC include the following:

- Processor interface
- Fringe detectors
- Sensor bus Interface
- Serial communication interface
- Discrete Input Register (DIR)
- Discrete Output Register (DOR)
- Input/Output (I/0) decoder
- Antialiasing filters (6)



IMU FUNCTIONAL BLOCK DIAGRAM

FIGURE 1



T16-B ISA

FIGURE 2

The use of step-sealed mirrors is another part of the T16-B's low-cost technology. This feature, along with a more focused laser beam, allows polishing and angular requirements to be greatly reduced, resulting in a significant cost reduction in both the block and mirrors. Step seals have been used at Kearfott for over 10 years for installing cathodes, anodes, and fill tubes. The T16-B extends the use of this proven technology to installing mirrors on the gyro block.

The MRLG laser assembly has three PLC transducers that drive movable mirrors that keep each axis at gain center over temperature. The PLC loops are of conventional design except that, as a cost reduction measure, the loop control signal is derived from the amplitude of the fringe detector photodiode. Since in the MRLG each PLC transducer drives two axes, a simple summation process of the error signal of each axis to the transducers is used for each axis to control independently. The three output (fringe detector) signals from the laser assembly, one for each orthogonal axis, are formed by using combined optics so the cw and ccw beams form a fringe pattern. The fringe pattern is then "read" by a split photodiode so that the frequency is proportional to input rate and the relative phase of the two elements tells the direction of rotation.

As is the case with most single-axis RLGs, mechanical dither is used to eliminate lock-in. With the MRLG, there is only a single dither axis (along the diagonal of the cube) which dithers each axis at a nominal rate of 1000/s. The dither mechanism in the MRLG consists of two dither hinges, each with six spokes driven by Piezoelectric Transducers (PST). The two hinges provide equal torque and, being equally stiff, provide an inherently symmetrical dither action. This hinge design, used with the balanced block and housing, effectively eliminates any potential rocking/coning problems.

Performance of the T16-B can be assessed by both actual test results as well as scaling from a much larger production database on single-axis 32-cm path length MOD 11 RLGs. This scaling is derived from path length and beam size differences and has been experimentally verified on four different sizes of single-axis RLGs and MRLGs. Since performance margins are key to achieving high yields and low costs, the approach has been to establish conservative specification requirements that assure wide margins. These key performance parameters and supporting data on T16-B gyros are discussed in the following paragraphs.

The T16-B gyro performance is as follows:

• Bias repeatability	0.12deg./h (1 sigma)
• Random walk	0.02deg./_h, maximum
• Scale factor stability	75 ppm, maximum
• Axes non-orthogonality	150 •rad, maximum

Navigation Computer

The navigation computer is based on OR 3U VME bus cards utilizing a 32-bit 68020, 25 MHz CPU with 25 MHz FPU with 4 MB dual-ported DRAM, and two RS 232 serial ports. The existing development card cage is a 3U VMEbus sub-rack with a five (5) slot back-plane. A card cage with the greatest number of slots achievable for future expansion and/or integration with other AUVs is utilized. Currently five cards are required; however, the production (SEANAV) version will not require the IMU interface card as it will already have an RS 422 output. The five cards required are:

1. CPU
2. CMOS serial communication (Ethernet) controller
3. 8-Channel asynchronous serial communication module (8 X RS232)
4. SRAM/EPROM module
5. IMU interface card (converts the existing Kearfott IMU AMRAAM interface to RS 422)

Navigation Software

The system (SEANAV) software will be written in "C" and contains a 24 state Kalman filter. The existing MILNAV software is written in JOVIAL and must be recompiled for use aboard a seagoing vehicle. The system will have interfaces for vehicle depth, vehicle altitude, vehicle speed over bottom, vehicle speed through water, GPS, magnetic compass, vehicle reference unit (MRLG), propeller RPM, and acoustic positioning. Once the software has been recompiled, it will be verified in Kearfott's simulator in New Jersey. The existing Kearfott simulator will be modified for inputs from the AUV sensors such as the DVL, screw RPM, etc. After the SEANAV program has been verified in the lab, the system will be integrated with the HBOI submersible and additional testing and debugging performed at sea.

CONCLUSION

The navigation system will be installed aboard HBOI's submersible Clelia and fully tested at sea. The highly maneuverable and relatively fast (over 3 knots) submersible is ideally suited for evaluating the navigation system along various preplanned transects, courses and long distance runs. Ultimately, it is planned to integrate and interface the SEANAV system to the Ocean Voyager I or another AUV and perform an at-sea demonstration.