The MIT/Marine Industry Collegium

Opportunity Brief

SENSOR and NAVIGATION ISSUES for UNMANNED UNDERWATER VEHICLES

January 15-16, 1991

Cambridge, Massachusetts

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The MIT/Marine Industry Collegium
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INTRODUCTION

Continuing the format that the MIT Marine Industry Collegium Program established about two years ago, the Collegium will be joining with C.S. Draper Laboratory in sponsoring a two-day symposium on advances in underwater vehicle technology. Like the last two symposiums, "Power Systems for Small Underwater Vehicles" and "Small Underwater Vehicle Design: Motors and Propulsors," this symposium will focus on a particular engineering discipline related to underwater vehicle development. As in the past, each presenter will give a presentation of approximately 30-35 minutes in length, allowing ample time for discussion of the technology presented.

Following the natural progression that a designer may take in developing a vehicle (from power source selection to motor propulsor selection, etc.), this year's symposium will examine sensor systems and navigation strategies for UUVs. The first day of the symposium will focus on various types of sensors for UUVs, both their advantages and limitations. Due to time constraints, the sensor systems that will be addressed are primarily acoustic. However, there is one presentation that will address recent advances in laser gyrocscope research which is currently taking place at MIT.

The second day will be devoted primarily to sensor-data fusion and subsequent navigation issues for UUVs. Presentations will cover a broad range of topics, from multisensor modeling to neural networks for target recognition and building three-dimensional maps from side-scan sonar data.

In planning this symposium, I thought it extremely important to have a couple of presentations that provide perspective on those systems that are able to sense and navigate far beyond any currently developed UUV. By this I am referring to aquatic animals. One speaker will provide an overview on the different mechanisms which aquatic animals employ to sense their environment, with special emphasis on electroreception. The second speaker will present the results of current research on dolphin echolocation.

Two days is simply not enough time to cover all the advances currently taking place in this field. Yet this symposium will attempt to provide a broad overview of some of the most promising directions, striking a balance between applied and more basic research. Through this symposium the Collegium hopes to continue to provide a forum where researchers and design engineers can gather, connect and promote the active transfer of technology leading to greater advances in underwater vehicle development.

John Moore Jr.
Manager
Marine Industry Collegium

SYMPOSIUM AGENDA

Sensor And Navigation Issues For Unmanned Underwater Vehicles

January 15

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Sensor and Navigation Issues for Unmanned Underwater Vehicles

January 16

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11:15 - 12:00	**The Role of Object Recognition in Navigation** *W. Eric L. Grimson, MIT*
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1:15 - 2:00	**Three-Dimensional Modeling of Seafloor Backscatter from Side-Scan Sonar for Autonomous Classification and Navigation** *W. Kenneth Stewart, Woods Hole Oceanographic Institution*
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3:00 - 4:00	**Tour of Draper 36' UUV**

SYNOPSES of PRESENTATIONS

JANUARY 15

9:00
Navigation Requirements for A Small Autonomous Underwater Vehicle
Dr. James G. Bellingham, MIT

A primary difficulty impeding autonomous underwater vehicle development is the lack of appropriate navigation capabilities. A variety of systems have been implemented to meet the requirements of various autonomous missions. However, there exists no single solution for the navigation problem and many missions remain impossible. This is an especially difficult problem for the class of vehicles under development at MIT Sea Grant: small, inexpensive, fully autonomous survey vehicles.

This paper will discuss navigation requirements for several different mission profiles, missions considered appropriate for a small AUV. These missions comprise a variety of settings including the near shore, deep ocean, and under-ice. The trade-off between various navigation systems for these missions is described, both in terms of capabilities and in terms of vehicle requirements. A unique class of long-baseline navigation system, developed at MIT Sea Grant for supporting multiple AUVs, will also be described.

The discussion is motivated by experience with an operational vehicle, the Sea Squirt. The vehicle is small, weighing only 77 lbs, and integrates a computer and sensor complement typical of much larger vehicles into a hull less than three feet long. Designed to run totally autonomously, the vehicle requires neither a tether nor an acoustic link. The Sea Squirt is being used at MIT Sea Grant as a platform for exploring AUV technologies, especially intelligent control and navigation.

9:45
Ocean, Platform, and Signal Processing Effects on Synthetic Aperture Sonar Performance
Mr. K.D. Rolt, MIT

Synthetic Aperture Sonar (SAS), the underwater sound application of the aperture synthesis method borrowed from Synthetic Aperture Radar (SAR), is investigated by means of ocean medium effects, platform motion effects, and signal processing effects. Synthetic aperture methods for radar and sonar allow large synthesized apertures, or equivalently synthesized arrays, to be formed from the combined use of coherent signal processing and a small, real aperture transducer (*e.g.* a radar or a sonar transducer). Large synthetic apertures give rise to relatively narrow synthesized beams that allow very high resolution focused images to be formed from radar or sonar data. Thus, a small real aperture sonar fitted to one or both sides of a manned or unmanned underwater vehicle (UUV) could form a synthetic aperture that would provide sonar images with resolution far in excess of any contemporary, existing imaging sonar. The range resolution for an SAS is shown to depend on the transmit signal bandwidth while azimuth resolution is held constant (independent of range, and independent of frequency), and is on the order of the horizontal sonar length.

A relatively small UUV can benefit from having a short, multi-task, side-scan sonar: the side-scan would perform general exploration and could also be used to take SAS data for regions of interest. Upon UUV retrieval, geographical areas that warrant SAS image processing would be determined from the evaluation of side-scan images. A UUV with this capability will produce much higher resolution images than just the stand alone side-scan sonar imaging system.

While SARs have been extensively developed and used since the late 1950's, SASs are rare, except for a number of academic papers and a few experimental systems. A reason usually cited for the lack of SAS development is the instability of the ocean to support coherent aperture synthesis.

However, this notion is false, with a number of stability experiments proving the ocean to be able to support SAS operation.

To evaluate the imaging potential of synthetic aperture sonar, a computer-based model has been created at MIT. The model includes ocean refraction, spatial and temporal coherence, surface and bottom influences *via* multipath, deterministic and random platform motion, and a variety of processing options. Model verification has been performed by comparison to SAS ocean experimental data. This model is now being used to study the three dominant influences of ocean, platform, and signal processing on the performance of SAS imaging.

The ocean influence on SAS imagery is shown to depend on: the extent of spatial/temporal coherence that limits useful aperture length for sharp imaging, and the refraction profile that must be accounted for in image reconstruction to ensure a match between the real ocean and the estimated ocean in the computer model, which turns out to be a geometric matched filter.

Platform motion is also shown to degrade the imagery, and the model confirms that ideal lateral platform motion be held to within the canonical 1/8 distance found in the SAR literature. The model also suggests that this limit may be relaxed with a slight penalty in image resolution.

Finally, a number of processing effects are shown, the most important being: (1) synthetic aperture radars and sonars working exactly at the Nyquist sampling rate do not entirely null alias lobes (an assumption often made in the SAS literature); (2) the use of many sub-aperture lengths for a Nyquist sampled synthetic aperture will force the aliases to the level of the far sidelobes (hence making them invisible); (3) the bandwidth must be carefully chosen for a Nyquist-rate sampled synthetic aperture to minimize alias images; and (4) broadband operation is always useful for undersampled synthetic apertures, and a "ballpark" formula is developed to estimate the level of alias image smear.

Example images will be shown and a forecast for future work will be given. [Work supported by the C. S. Draper Laboratory].

10:50
Environmental Acoustic Concerns
Professor Henrik Schmidt, MIT

Due to the very limited propagation of electromagnetic waves, acoustics form the major mechanism for communicating information between two points. Like electromagnetic waves, acoustic waves propagate through the environment and can be used for communication, imaging and navigation, analogous to similar tasks above the sea surface, where radio and radar are the natural choices. However, there are several factors, which are listed below, that complicate high fidelity use of underwater acoustics for such purposes.

- The speed of sound is several orders of magnitude lower than the speed of light, making the time of flight of an acoustic signal much longer, measured in seconds for even a few kilometers. The effect of temporal variability therefore becomes a critical issue.

- The attenuation of sound increases with frequency, limiting the use of acoustics to frequencies lower than a few kHz, in turn affecting the obtainable resolution for imaging and navigation and the rate of information interchange.

- The spatial variation of the acoustic properties is strongly dependent on depth, making refraction in the vertical significant. Traditional imaging methods based on straight line propagation are therefore inapplicable, except for ranges within a few hundred meters.

- Although less significant, horizontal variations in acoustic properties occur at ocean fronts and eddies, giving rise to horizontal refraction.

- For acoustic propagation farther than a few water depths, the waveguide nature of the environment becomes important, with a significant multipath structure as a result. And for longer ranges, the direct path becomes insignificant.

- Due to the waveguide nature of the propagation, the interaction with the sea surface, in particular, and with the bottom become important issues. Thus, scattering from the rough sea surface or an ice cover can significantly distort the acoustic signals. Bottom interaction generates additional multipaths and attenuation effects.

- The ocean acoustic environment is contaminated with a significant component of ambient noise in all frequency regimes, significantly affecting the signal processing involved in extracting information from the acoustic signals.

These various factors complicating the use of underwater acoustics for communication, navigation and imaging will be reviewed, and their effect on signal processing performance will be discussed. Examples will be given for localizing sources of sound in realistic ocean environments in the presence of ambient noise.

11:35
Autonomous Signal Processing and Analysis
Professor Arthur B. Baggeroer, MIT

Synopsis not available at time of publication.

1:00
Sensory Guidance for Communication and Orientation by Animals in Aquatic Environments
Professor Carl D. Hopkins, Cornell University

An animal's sensory system guides its present and future behavior in two important ways: first, in a recognition role, by guiding selection of an appropriate response from a limited behavioral repertoire, and second, in an orienting role, by guiding spatial orientation of subsequent behaviors relative to an external stimulus. We have been interested in both aspects of sensory guidance in aquatic animals. One especially fruitful area of research concerns studies of localization and recognition of animal communication signals—stereotyped and species-specific signals for which receivers have become highly specialized in sensing.

Animals exploit a rich variety of sensory systems for orientation and communication, including olfactory systems, auditory, electrosensory, and vibration senses, surface wave sensors, and visual systems. A few selected examples will be drawn from each of the different sensory modalities, illustrating communication and active or passive orientation.

Our work concerns the electric sense in weakly-electric teleost fishes. Two groups of weakly-electric fish, one South American and another African, generate and receive weak electric signals. They use these signals in communication and in sensing objects in the environment. Our studies include behavioral analysis of sensory guidance, and physiological studies of peripheral and central electric sense.

Electric fish from Africa produce electric organ discharges (EODs), which are species-specific electrical signatures. EODs are sensed by a subset of electroreceptors called Knollenorgans. Knollenorgans are frequency tuned to match the power spectrum of the EOD. Knollenorgans encode EODs as a pattern of nerve spikes, for which the temporal pattern of spikes is a unique species-specific code. Temporal recognition occurs in the midbrain in a nucleus specialized for measuring time differences on the order of tens of microseconds.

Electric fish sense their own EODs for use in active electrolocation, a short-range sensory system for detecting objects in the environment as distortions in the magnitude of the electric field in the skin. Highlights of active electrolocation mechanisms will be reviewed.

Electric fish can passively locate the electric signals of other electric fish. By aligning their body axis parallel to the local electric field lines, these fish can locate any distant source of an electric field, even if it is moving.

1:45
Recent Developments in Optical Gyroscopes for Inertial Navigation
Professor Shaoul Ezekiel, MIT

The measurement of inertial rotation by optical techniques became feasible with the invention of the laser. Today, ring laser inertial rotation sensors or "gyroscopes" are already in use in many of the inertial navigation packages of modern aeroplanes and are outperforming their mechanical counterparts, i.e. the spinning wheel gyroscopes.

In this presentation, we will review the basic principles underlying the operation of optical gyroscopes and point out the advantages, as well as the disadvantages of such an approach. In particular, we will discuss the recent developments in fiberoptic gyroscopes that are being pursued by a number of organizations in the U.S. and abroad. The fiberoptic gyroscope promises to be smaller, cheaper, more reliable, and more efficient than the gas laser gyroscope. The success of the fiberoptic approach relies heavily on a number of critical areas, such as fiberoptic technology, integrated-optic technology, and solid-state lasers. In addition, since the fiberoptic gyro is a passive device, it is necessary to measure very small non-reciprocal phase shifts that are proportional to the applied rotation. However, in the ring laser approach, such a measurement is not required because any non-reciprocal phase shift will automatically influence the beat frequency between the counter-propagating ring lasers sharing the same cavity.

More recently, we have been investigating the feasibility of a solid state ring laser approach. Our method is based on the non-linear effect, stimulated Brillouin scattering (SBS), which is easily observable in single mode optical fibers. Because the fiber core diameter is on the order of a few microns, very large intensities, and hence, large stimulated Brillouin gain, can be generated within the core with a low power laser. In this way, we were able to achieve simultaneous Brillouin lasing along counter-propagating directions in a fiber resonator. Using such lasers, we demonstrated the first solid-state ring laser gyroscope. It should be noted that a conventional solid-state laser amplifier does not permit the simultaneous operation of two oppositely-directed lasers in the same cavity because of gain competition. The stimulated Brillouin amplifier is inherently directional and consequently there is no gain competition since each Brillouin laser is pumped separately.

Preliminary performance data of the Brillouin ring laser gyroscope will be presented, together with a discussion of the advantages of this device, as well as potential problem areas.

2:45
The Correlation Sonar as an Absolute Velocity Sensor for Autonomous Underwater Vehicle Navigation
Brian L. Grose, EDO Corporation

For an autonomous underwater vehicle to perform its intended mission it must know its position accurately. With the absence of positioning references and navigation systems available to a surface vessel, an autonomous underwater vehicle (AUV) must rely on other techniques. A measurement of an

AUV's absolute velocity, in a three- dimensional coordinate system, is one of the most important inputs to a navigational computer.

The Correlation Velocity Log (CVL) sonar system provides a measurement of absolute velocity relative to the ocean floor. Three-dimensional velocity determination is obtained from space/time correlation measurements. Using this technique it is possible to obtain bottom-referenced velocity measurements under a wide range of operating conditions, with modest acoustic power levels, and practical array dimensions. The technique also provides certain practical advantages over doppler-based velocity measuring systems.

Using correlation principles to determine platform velocity has been documented in the literature. Basically the technique relies on a pulse invariant principle---when a wave form is transmitted twice from the same source point and returned by the same set of reflectors, the two pulses will be identical (and thus have a high degree of correlation) when received at a specific receiving point. For the benefit of those who may be unfamiliar with the concept, a brief review of these principles will be provided.

Operation in an AUV environment places many unique operational requirements on a velocity measuring sensor. The CVL was designed to be capable of fully independent operation. This includes capabilities to find and track the bottom, find and track the velocity, and determine and generate appropriate wave forms for varying operating conditions. Additional requirements are small physical size, minimal power consumption, covertness, and minimal calibration and maintenance.

The implementation of theory into a practical sonar system presents additional complications. The technology has been applied in the development of several CVL models with different operational advantages. A brief review of these sonar systems and their specifications, with emphasis toward AUV applications will be presented.

A number of CVL sonar systems are in the field and have been extensively tested. A brief overview of measured CVL performance data will be discussed. This will include data acquired by independent sources.

3:30

Velocity-Aided Inertial Navigation System

Ms. Bonnie L. Hutchison, Lockheed Missiles and Space Company

Existing precision navigators---such as those used on submarines--are large, heavy and costly; require frequent maintenance and generally are not suitable for small autonomous vehicles. Other navigation systems are segmented solutions to specific problems, such as local area, relative navigation (transponder interrogators) or dead reckoning, low accuracy systems. A fully integrated, modular navigation system is required to provide worldwide, optimum performance during all phases and for all types of missions.

A modified Kalman filter has been developed to allow the implementation of a modular navigation system to a variety of vehicles and missions. The filter presently consists of 20 states that represent errors in a velocity-aided inertial navigation system. An IR&D project next year will expand it to 30 states incorporating relative navigation inputs to the system.

The Kalman filter is contained in Lockheed's modular navigation system, known as the Precision Underwater Navigation System (PUNS). The system is implemented in a single 68020 processor with a math co-processor. All code is resident in EEPROM. Hardware interfaces to equipment are provided through MIL-STD-1553, RS-232/422, A/D, and D/A interfaces.

The PUNS performance has been demonstrated to be less than 0.1% of distance traveled irrespective of the speed of the vehicle. A number of error reduction measures that are incorporated into the Kalman filter and in its observation routines enable this performance. These measures include a precise calibration of the Doppler sonar used as a velocity reference, careful averaging and filtering of velocity data to update the filter and detailed observation rejection routines that filter out erroneous data.

The PUNS has been extensively tested on Lockheed's test bed boat and demonstrated on the Naval Research Laboratory's Sea Lion vehicle. Hardware installations and recent test results will be shown. The PUNS is presently being utilized on the DARPA Mine Search System program. Interfaces to the present DARPA/CSDL vehicle will be illustrated.

JANUARY 16

8:40

Building Qualitative Elevation Maps from Side-Scan Sonar Data

Dr. Martial Hebert, Carnegie Mellon University

Deriving a terrain model from sensor data is an important task for the autonomous navigation of a mobile robot. This presentation describes an approach for autonomous underwater vehicles (AUVs) using a side-scan sonar system. First, some general aspects of the type of data and filtering techniques to improve the data are discussed. We then proceed to derive an estimated bottom contour, using a geometric reflection model and information about shadows and highlights. Several techniques of surface reconstruction and their limitations are presented. We also describe a method of feature extraction that is important for future data matching/fusion procedures.

Before attempting to reconstruct surfaces from sonar images, the raw images must be processed. Raw images from side-scan sonar tend to be very noisy because they do not measure only the TOF of the first echo received for computing the shortest distance to a certain point in space, but record all echoes. Hence, multiple echoes from a single scatterer are recorded at different instances in time and for each scan lead to false intensity peaks in space. Multiple echoes from several scatterers may add at the same point in space (and time) and thus make the situation even worse (speckle noise). Standard image operators (like gradient operators) tend to fail if applied to this type of data unless some prefiltering is done. Our approach to noise reduction is to apply a series of filtering operations, each of which addresses a particular type of noise. This approach gives us control over the amount of smoothing, noise reduction, and data enhancement that is achieved.

Points of interest or features are generally those that return a strong echo towards the transducer and appear as high intensity peaks in the image. These features may indicate distinct objects or obstacles that are potential candidates for feature-based image matching algorithms or may be important for obstacle avoidance or target detection. We introduce an image processing technique based on edge detection for the extraction of terrain features.

Shadows are an important source of information in a sonar image, indicating the presence of an object or change in bottom contour. Similar to optic shadows, no distinct echoes can be observed in an acoustic shadow zone, since it is shielded by the preceding contour. Ideally, the signal level within a shadow region is zero, however, due to previously discussed problems with noise, this is not the case. We present a technique based on occluding edges analysis for the recovery of shadow regions.

Recovering the bottom contour from side-scan sonar data poses a highly underconstraint problem that may not lead to a unique solution without making strong assumptions about the observed surface. Some of the difficulties encountered include: the orientation, x-y position and depth Z_F of the sonar fish for each scan line; the R to a surface patch; and the intensity (echo level) of the received echo for that particular surface patch. It should be noted that the known range R is the slant range to a particular surface patch, but that the angle of inclination φ to the horizontal is not known. Hence the reflecting surface patch can lie on any party of an annular section with range R as radius. The horizontal and vertical extension of the annular section is determined by the horizontal and vertical field of view of the sonar at range R, i.e. the aperture of the sonar.

Combining and matching different data sets, as mentioned before, provides a means to eliminate wrong data and gain more knowledge about the area of interest. However, since we only know the slant range R for each surface patch but not the direction of measurement, it is virtually impossible to find corresponding data points between two images accurately. In order to avoid this correspondence problem we would actually need a fixed x-y-z position in space for each data point. Hence we will use the return signal intensity at a certain range to compute the angle of inclination α of the surface normal for a particular reflecting surface patch, while measuring α with respect to the line of sight to the respective surface patch. Once α is known, we can attempt to find the actual bottom contour. The reflectance model and method of surface reconstruction is described in detail in this part of the presentation.

By using the described filtering methods we were able to obtain reasonably smooth data that still contain all the important information. Extracting features from the filtered data can then be used in the future to match different sets of data. Information about shadows, high intensity points and reflective properties, are used to develop algorithms to compute boundaries of objects and an approximate surface contour for the terrain scanned by the sonar. Side-scan sonar data will not allow us to build an accurate 3-D elevation map, but using the methods described in this paper, we are able to build what we call a 'Qualitative Elevation Map'. This map contains information about elevation constraints of the terrain surface, boundaries of distinct objects and regions with true and relative elevations. This map does not provide a detailed high resolution description of the environment, but it contains enough information to enable an AUV to navigate safely in unknown terrain. By matching data taken from different viewpoints, we are able to reduce the amount of unknown areas and eliminate false noise information.

Our future work will extend present algorithms to compute all the information needed for the qualitative elevation map and develop a robust matching algorithm. These techniques have been demonstrated on data from a conventional side-scan sonar, but our goal is to port them to a fast imaging sonar. The sonar mapping module will eventually be used in the navigation and mapping of a vehicle being developed at Florida Atlantic University.

9:25

A Localization Algorithm/Map-Matching Approach For Underwater Vehicle Navigation

Mr. Mark R. Abramson, C. S. Draper Laboratory

A localization algorithm at Draper Laboratory has been developed that can be used to navigate underwater vehicles through correlation of sensor measurements with a map of the operational environment. A previous survey of the field-test area provided water column heights that were used as a map for algorithm implementation. The sensor measurements to be correlated were obtained from an up/down sonar that provided both depth and bathymetric altitude information. The final component of our implementation strategy was to measure the relative distance traveled between sensor updates. The localization process compares the measured water column height against the values in the depth map. Map locations incompatible with incoming readings are eliminated and the remaining map locations are shifted by the relative distance traveled between updates. Eventually only one map location with the correct history of water column heights remains. Noise in the sonar and in relative-distance-traveled sensors can result in the true location being discarded inadvertently. Approaches for reducing this problem include adding a noise threshold to the depth map values, averaging sonar returns within a particular map cell and allowing a few "strikes" before a location is thrown out. Localization is complete when only one map cell remains as a possible location; the center of the lone cell can be used to reset the vehicle's navigator. Typically, the localization algorithm quickly trims the depth map to a few dozen clustered cells, then requires several more sensor cycles to obtain the unique location. Heuristics can be employed to accurately predict the correct position long before a unique map cell is identified.

A Mac II based simulation of the localization process has been developed to graphically display the depth map reduction and shifting steps. Field data is used as input to the the algorithm, with the depth map and kernel software identical to that in the embedded system. The ability exists to run Monte Carlo simulations to determine optimal algorithm parameters. Complex navigation error models and noisier sonar sensors can also be tested against the system. The simulation environment allows exploring new techniques *via* an expansion mode to add back possible map cell locations based on errors in measuring relative motion. Also various algorithm terminating heuristics can be examined.

The localization algorithm was field tested this past fall at Mendums Pond, NH, using the autonomous underwater vehicle (AUV), EAVE, developed at the University of New Hampshire Marine Systems Engineering Lab (MSEL). The AUV uses an acoustic transponder system for navigation and sports an up/down bathymetric sonar. MSEL has developed an environment for hosting real-time navigation and control algorithms. Field testing the localization algorithm consisted of flying EAVE along pre-planned trajectories and running the localization algorithm repeatedly during the length of the mission (approximately 30 minutes). For vehicle safety, "true position" was known to the low level vehicle systems that directed the mission trajectory. The embedded localization algorithm used only relative motion between sensor readings as one of its inputs. The algorithm began to reduce the initial 500 meter position uncertainty to within 10 meters in under 10 minutes. During the next 20 minutes the algorithm continued to track the position and slowly reduce the possible vehicle locations to one unique depth map location, resulting in a performance accuracy of under 6 meters. The field testing demonstrated that the algorithms could correctly localize (i.e. select the nearest depth map cell at 6 meter resolution) during the course of a 30 minute mission.

10:30

Processes of Dolphin Echolocation

Professor Herbert L. Roitblat, University of Hawaii at Manoa

The dolphin's evolutionary history has resulted in a biological sonar system specifically adapted for object detection and recognition in noisy reverberant marine environments. Other animals, most notably bats, have evolved systems that are specialized for aerial environments. Although current models of bat echolocation are consistent with many of the standard artificial sonar systems currently in use, the physical acoustics of the aquatic and aerial environments are very different. These differences, including the relative speed of sound and the impedance mismatch between medium and target, suggest that substantially different mechanisms and strategies are required for systems operating in the two media. Models derived from bat-echolocation performance may not be appropriate to dolphins or to effective use in a reverberant marine environment.

Bottlenosed dolphins (tursiops truncatus) can readily identify many characteristics of submerged objects through echolocation. Dolphin echolocation clicks emerge from the rounded forehead or melon as a highly directional sound beam with 3 dB (half power) beamwidths of approximately 10 degrees in both the vertical and horizontal planes. Echolocation clicks are very broad band, have peak energy at frequencies ranging from 40 to 130 kHz with source levels of 220 dB re: 1 μPa at 1 m. The average time between emitted clicks in a train is typically 15 - 22 msec longer than the round-trip travel time between the dolphin and the target. Bottlenosed dolphins have excellent directionally selective hearing up to at least 150 kHz. The specific processes by which the dolphin extracts acoustic information about the targets is unknown, and particularly interesting questions concern how the animal performs feature extraction from a set of returning echoes.

We have been studying the performance of a bottlenosed dolphin on an echolocation delayed, matching-to-sample (DMTS) task. In this task, a sample stimulus is presented underwater to a blindfolded dolphin. The dolphin is allowed to echolocate on this object ad lib. The object is then removed from the water, and after a short delay, three alternative objects are presented (the comparison stimuli). One of these objects is identical to (matches) the sample object, and the dolphin is required to indicate the matching stimulus by touching a response wand directly in front of it. The object that serves as sample and the location of the correct match vary randomly from trial to trial, so the dolphin must select the correct alternative by identifying the sample and locating the correct match. We have been modeling the dolphin's scanning strategies and object identification using sequential sampling theory and various kinds of artificial neural networks. Characteristics of dolphin echolocation and descriptions of our models will be presented.

Recent work investigating and modeling the dolphin's scanning strategies and object recognition processes will be described.

11:15
The Role of Object Recognition in Navigation
Professor W. Eric L. Grimson, MIT

Systems for intelligent navigation often are enhanced by techniques for object recognition, where the object to be recognized is the terrain surrounding the vehicle. Recognition of sites can be important for a number of variations on the navigation problem, including identification of goal locations, localization of the vehicle relative to a world map, and as a feedback mechanism to control for drift and measurement error in integrative navigation systems.

There has been considerable effort in recent years within the computer vision community to develop robust methods for recognizing instances of objects in cluttered, noisy sensory data. This talk will highlight some of the key successes in this area, and indicate some of the relationships between such methods and the problem of mobile platform navigation.

The key points to be covered include:

- Characterization of the general classes of approaches to object recognition;
- Characterization of the requirements of such methods, including specifications on the types of object models, information content of the sensory data, and amount of clutter allowed in the data; and
- Characterization of the performance of such methods, including their tolerance to noise in the data, their tolerance to occlusion and spurious data, and the likelihood of false positive and false negative identifications.

After outlining the basic components of such object recognition systems, and discussing their relationship to the navigation problem, we will briefly discuss extensions, including: sensing strategies for intelligently removing ambiguous interpretations of the data and learning methods for automatically building world models from sensory data.

1:15
Three-Dimensional Modeling of Seafloor Backscatter from Side-Scan Sonar for Autonomous Classification and Navigation
Dr. W. Kenneth Stewart, Woods Hole Oceanographic Institution

Sonars will continue to play an important role in world-modeling for autonomous underwater systems because of the greater range available to acoustic sensors than with other sensing modalities. However, attempts to automate the interpretation of side-scan sonar data are typically based on two-dimensional, image-processing and pattern-analysis techniques. Such side-scan "images" provide only indirect, qualitative, and view-dependent information, since the intensity of the returned signal is a function of both seafloor shape and scattering properties of the bottom materials.

This overview of work in progress at the Deep Submergence Laboratory describes several techniques for three-dimensional sonar processing in which seafloor shape information is used to reduce geometric and radiometric dependencies in the intensity signal. The approach is developed using Sea Beam bathymetry and Sea MARC I side-scan data. Preliminary results are also described for new split-beam (interferometric) sonars designed for high resolution seafloor characterization. Complex-domain processing of the quadrature-sampled signal gives amplitude and phase for three-dimensional modeling, and gives a measure of signal coherence and modeling certainty. The processed output is a quantitative model of three-dimensional shape and backscatter characteristics that will be applied to feature classification and terrain-relative navigation for intelligent underwater vehicles.

2:00

Neural Network Implementations for UUV Navigation

Mr. Mark Dzwonczyk, C. S. Draper Laboratory

Under its internal research and development program, Draper Laboratory is investigating implementation issues of deployable neural networks for automatic target recognition. Current research efforts are focused on the development of the Integrated Neurocomputing Architecture system, or INCA. The INCA employs a conventional processor for data management tasks and a large-scale analog neural network for real-time pattern recognition. The INCA is presently capable of implementing a fully parallel, 4 layer, 64 node per layer, feed-forward neural network #209#, a topology large enough for current pattern recognition problems of interest. The network consists of 16 Very Large Scale Integration (VLSI) analog devices hosted on a VMEbus-size prototype card with appropriate glue logic. As an integrated system, the INCA can be used as a testbed for algorithm development (with an optional Sun workstation for construction of neural models) or as a real-time pattern recognition platform.

The driving pattern recognition application is target detection from cluttered side-scan sonar data. Raw 8-bit sonar data is windowed into tokens of n x n pixels, where n #197# 10. Features are then extracted from each token and passed through the network for classification. In feed-forward operation, the INCA network can detect targets from incoming data in real-time.

This presentation will describe the key features of the INCA system and focus on preliminary results with the side-scan sonar target detection problem. Since the first generation of INCA devices are presently undergoing fabrication, results to date are limited to simulations. The INCA simulation, however, is representative of the actual network: conventional neural network simulations are married to analog device models to fully characterize the performance of the INCA system. For example, a model of competing current mirrors is used in place of the perfect sigmoidal threshold function incorporated into most neural models. Limitations on the weight granularity are also included in the INCA models. For the first generation of devices, learning will be off-line, but hardware-in-the-loop learning will be used to account for device peculiarities not addressed by the simulations.

The devices currently under construction use conservative VSLI design rules (2#181# CMOS) so that a proof-of-concept system can be rapidly constructed. Future efforts in custom microelectronic integration should realize a single INCA chip as a specialized pattern recognition device that can operate in real-time aboard a small UUV-class vehicle.

PUBLISHED PAPERS

Bellingham, J., Loch, J., Wallar, E., Beaton, R. and Triantafyllou, M., **Software Development for the Autonomous Submersible Program at MIT Sea Grant and Draper Laboratory,** 6th International Symposium on Unmanned Underwater Submarine Technology, June 1989, pp. 25-32.

A planning and control architecture is currently being developed for a low weight, low cost AUV that will enable the AUV (for its initial mission) to home in on and proceed to a pinger, while avoiding underwater obstacles. A sliding-mode controller has been developed to control the heading, speed and depth of the vehicle. A layered control system has been developed to plan the trajectory of the vehicle. Both algorithms have been ported to the AUV's onboard 68000 base computer. Preliminary test results for the sliding mode controller indicate in steady state that depth can be maintained to an accuracy of 0.5 ft. and the heading can be maintained to an accuracy of 5 deg. Testing of the layered control system is awaiting the successful performance of the forward looking obstacle avoidance sonar.

Bellingham, J., Consi, T., Beaton, R. and Hall, W., **Keeping Layered Control Simple,** Proceedings of the Symposium of Autonomous Underwater Vehicle Technology, June 1990, pp. 3-8.

Practical experience gained applying layered control to an autonomous underwater vehicle is presented. The paper focuses on six areas: handling vehicle dynamics, communication between layers, sensor processing, mission configuration, resolving conflict between layers, and avoiding states in which the vehicle becomes trapped. The complex nonlinear dynamics and large sensor processing requirements inherent in AUV applications have led us to make modifications to the traditional layered control approach. Of particular importance is the need to move closed-loop control and sensor processing outside the layered control architecture to reduce the memory and throughput requirements imposed on the main computer.

Bellingham, J., Beaton, R., Triantafyllou, M. and Shupe, L., **An Autonomous Submersible Designed for Software Development,** Proceedings of Oceans '89, Vol. 3, p. 799.

An autonomous submersible is being used at MIT Sea Grant as a platform for exploring approaches to mission planning. The vehicle is small, measuring less than three feet long and weighing 62 lbs. Layered control, which has been implemented for land vehicles at the MIT Artificial Intelligence Laboratory, will be used to give the vehicle the capability required to operate in unmapped environments and respond to unanticipated situations. Its repertoire of behaviors will include collisions, homing on pingers, and investigating interesting phenomena (e.g. sonar targets or magnetic anomalies). A potential mission for the submersible might be rapid response to industrial or natural disasters, for example measuring the characteristics of a chemical spill in a body of water.

Ezekiel, S. and Balsamo, S.R., **Passive Ring Resonator Laser Gyroscope,** Applied Physics Letters, 30, 478, 1977.

Ezekiel, S. and Balsamo, S.R., **New Approach to Laser Gyroscopes,** Proceedings of National Aerospace & Electronics Conference (NAECON), May 1977.

Ezekiel, S. and Ponikvar, D.R., **Stabilized Single Frequency Stimulated Buillouin Fiber Ring Laser,** Optics Letters, 6, 398, 1981.

Ezekiel, S., **Closed Loop, High Sensitivity Fiber Gyroscope,** Fiberoptic Rotation Sensors, S. Ezekiel and H.J. Arditty (eds.), Springer-Verlag, 1982.

Ezekiel, S., Prentiss, M. and Davis, J.L.,**A Brief History of Fiber Gyros and MIT's Contributions to Fiber Gyro Development,** SPIE Publication, 719, 9, 1986.

Ezekiel, S., Zarinetchi, F. and Smith, S.P., **New Developments in Fiber Optic Gyroscopes,** Proceedings of SPIE, Fiber Optic and Laser Sensors VII, Vol. 1169, September 1989, pp. 300-303.

Ezekiel, S., Zarinetchi, F. and Smith, S.P., **Fiberoptic Ring Laser Gyroscope,** Post deadline paper in Proceedings of OFS, Paris, September 1989.

Hebert, M. and Cuschieri, J., **Three-Dimensional Map Generation from Side-Scan Sonar Images,** Journal of Energy Resources Technology, Vol. 112, June 1990, pp. 96-102.

The generation of three-dimensional (3-D) images and map building are essential components in the development of an autonomous underwater system. Although the direct generation of 3-D images is more efficient than the recovery of 3-D data from 2-D information, at present, for underwater applications where sonar is the main form of remote sensing, the generation of 3-D images can only be achieved by either complex sonar systems or systems that have a rather low resolution. In this paper an overview is presented on the type of sonar systems that are available for underwater remote sensing, and a technique is presented which demonstrates how, through simple geometric reasoning procedures, 3-D information can be recovered from side scan-type (2-D) data. Also presented is the procedure to perform map building on the estimated 3-D data.

Hebert, M., **Terrain Modeling for Autonomous Underwater Navigation,** Proceedings of the 6th International Symposium on Unmanned Untethered Submersible Technology, June 1989, pp. 502-511.

The main task of perception for autonomous vehicles is to build a representation of the observed environment in order to carry out a mission. In particular, terrain modeling, that is modeling the geometry of the environment observed by the vehicle's sensors, is crucial for autonomous underwater exploration. The purpose of this work is to analyze the components of the terrain modeling task, to investigate the algorithms and representations for this task, and to evaluate them in the context of real applications. Terrain modeling is divided into three parts: structuring sensor data, extracting features, and merging and updating terrain models.

Hopkins, C. and Bass, A., **Temporal Coding of Species Recognition Signals in an Electric Fish,** Science, American Association for the Advancement of Science, Vol. 212, April 1981, pp. 85-87.

An electric fish in the African family *Mormyridae* recognizes members of its own species by "listening" to electric organ discharges, which are species-specific signatures. Reactions of fish in the field and of individual electroreceptors to both normal and modified computer-synthesized discharges emphasize the importance of the waveform (time-domain cues) in species recognition.

Hopkins, C., **Neuroethology of Electric Communication,** Annual Review of Neuroscience, 1988, 11; pp. 497-535.

Two groups of tropical freshwater fish, one South American and one African, send and receive weak electric signals in social communication. Like other, more familiar communication modalities, electric communication is a highly evolved system with many functions, including: sex-and species-recognition, courtship behavior, mate assessment, territoriality and other forms of spacing behavior, appeasement, alarm, and aggression. The signal repertoires of electric fish are quite rich and varied, and the functions served by these signals are diverse. This makes the system interesting from the ethological perspective. Also, electric communication signals appear to be relatively simple in structure, and therefore are comparatively easy to generate and imitate. And finally, electric fish have a highly specialized electrosensory system that contains, in some species, a subpopulation of receptors and neurons whose sole function is communication signal sensing. Because these sense organs appear dedicated to communication, the adaptive characteristics of the receptors and of the entire sensory submodality are best understood in the context of communication behavior.

Hopkins, C., and Davis, E., **Behavioural Analysis of Electric Signal Localization in the Electric Fsh, *Gymnotus carapo* (Gymnotiformes),** Animal Behavior, 1988, 36, pp. 1658-1671.

This study investigates how an electric fish is able to localize in space the electric signals from another fish. South American electric fish of the pulse-species, *Gymnotus carapo*, were housed in a large circular arena with a shelter in the center, and non-moving electrical models which mimicked the discharge of a conspecific were presented at the edge of the tank. The results suggest that *Gymnotus* cannot determine the direction or distance of an electrical source placed in their territory, but can approach the electric stimulus by aligning their body axis parallel to the electric field vector while swimming. By using this simple strategy they are able to find the source in a reliable, although indirect, way. They are well-oriented to the vector direction, even when the magnitude of the current is relatively homogeneous.

Hutchison, B. and Skov, B., **A System Approach to Navigating and Piloting Small UUV's,** Proceedings of the Symposium on Autonomous Underwater Vehicle Technology, June 1990, pp. 129-136.

This paper presents a description of trade studies and analysis conducted by Lockheed and RD Instruments to establish a general architecture for navigating and piloting systems for a small autonomous UUV. The system must be able to operate at shallow and deep depths, traverse long distances and perform precise near bottom operations on the same sortie. Precise navigation, utilizing markers as a reference, is required on some missions. Occasionally, the vehicle may be required to surface to communicate and can simultaneously utilize this opportunity to obtain a GPS fix. Lockheed and RD Instruments have developed a low power, modular, integrated solution to these requirements.

Roitblat, H., Moore, P., Nachtigall, P. and Penner, R., **Biomimetic Sonar Processing: From Dolphin Echolocation to Artificial Neural Networks,** Simulation of Adaptive Behavior, J.A. Meyer & S. Wilson (eds.), MIT Press, In press.

Analysis of animal performance can provide important clues about the design of automated artificial biomimetic systems. On the basis of behavioral observations, we have been developing models of dolphin echolocation ability that have applicability to the design of biomimetic sonar systems. A dolphin was trained to perform an echolocation delayed matching-to-sample task. The clicks the animal generated during task performance were recorded and digitized along with the echoes returned by the stimulus objects. The dolphin's performance was then modeled using artificial neural networks.

Roitblat, H., Penner, R. and Nachtigall, P., **Attention and Decision-Making in Echolocation Matching-To-Sample by a Bottlenose Dolphin (Tursiops Truncatus): The Microstructure of Decision-Making,** Sensory Abilities of Cetaceans, J. Thomas & R. Kastelein, (eds.), New York, Plenum Press, In press.

In delayed matching-to-sample (DMTS) the subject is presented with a sample and must later pick a matching comparison stimulus from a set of alternatives. The choice the subject makes in discriminating among the comparison stimuli is contingent on the identity of the sample that preceded the stimuli in the trial.

Despite a great deal of effort devoted to the investigation of the memory processes animals employ in DMTS, very little information is available concerning the decision strategies they use when selecting a correct match. This relative lack of information is partly due to the difficulty of collecting relevant data. The animal's decisions must depend on information it obtains from the sample and comparison stimuli, but measuring when and how much information an animal receives is extremely difficult. The echolocating dolphin provides an interesting exception to this generalization because each echo provides the animal a with discrete packet of information that can be measured relatively easily. As a result, we determine quite precisely when an animal is scanning a stimulus (for example, see Penner, 1989) and can examine the properties of the click and echo. In particular, we have been able to identify where the target is located and, on the basis of the echo, can identify the target that the animal is scanning.

Roitblat, H.L., Penner, R. and Nachtigall, P., **Delayed Matching-to-Sample by an Echolocating Bottlenose Dolphin,** Journal of Acoustical Society of America, 1988.

Roitblat, H.L., Moore, P., Nachtigall, P. and Penner, R., **Dolphin Echolocation: Identification of Returning Echoes.** International Joint Conference on Neural Networks 89, June 1989.

Roitblat, H.L., Gory, J. and Herman, L.M., **Sequential Effects in Dolphin Delayed Matching-to-Sample Performance,** Psychonomic Society, New Orleans, 1986.

Roitblat, H.L., Moore, Nachtigall, P., Penner, R. and Au, W., **Natural Echolocation with an Artificial Neural Network,** The International Journal of Neural Networks: Research and Application, Vol. 1, pp. 239-248.

Rolt, K.D., **Ocean, Platform, and Signal Processing Effects on Synthetic Aperture Sonar Performance,** S.M. Thesis, Dept. of Ocean Engineering, MIT, November 1990.

Rolt, K.D., Milgram, J. and Schmidt, H., **Ocean Broadband Undersampled Synthetic Aperture Arrays: Targets Stay Sharp, Aliases Smear,** Journal of Acoustical Society of America 88 (S1), S30(A), Fall 1990.

Rolt, K.D., Schmidt, H. and Milgram, J., **Ocean Medium and Platform Effects on Synthetic Aperture Sonar,** Journal of Acoustical Society of America, 87(S1), S155(A), Spring 1990.

Rolt, K.D. and Butler, J. L., **A Four-Sided Flextensional Transducer,** Journal of Acoustical Society of America, 83(S1), S19 (A), Spring 1988.

Schmidt, H., Baggeroer, A.B., Kuperman, W.A. and Scheer, E.K., **Robust Beamforming for Matched Field Processing Under Realistic Environmental Conditions,** Underwater Acoustic Data Processing, Y.T. Chan, Kluwer, Dordrecht NL, (eds.), 1989 and Proceedings of the 1988 NATO ASI on Signal Processing and its Applications to Underwater Acoustics, Plenum Press, New York, 1989.

Schmidt, H., Baggeroer, A.B., Kuperman, W.A. and Scheer, E.K., **Environmentally Tolerant Beamforming for High Resolution Matched Field Processing: Deterministic Mismatch,** Journal of Acoustical Society of America, March 1990.

Schmidt, H.and Kuperman, W.A., **Rough Surface Elastic Wave Scattering in a Horizontally Stratified Ocean,** Journal of Acoustical Society of America, 79, 1986, pp. 1767-1777.

Stewart, W., **A Model-Based Approach to 3-D Imaging and Mapping Underwater,** Proceedings of the Seventh International Conference on Offshore Mechanics and Arctic Engineering, February 1988, pp. 61-71.

An approach to multidimensional representation of underwater environments is presented with results of applications in three-dimensional sonar mapping. A non-deterministic model incorporates information from multiple knowledge sources and creates a framework for real-time processing. Probabilistic methods account for non-ideal sensors, while spatial decomposition and numerical techniques treat amorphous underwater features and allow an incremental approach to modeling the surroundings. An emphasis on representational and modeling issues is maintained with examples drawn from computer simulations and field data from profiling and imaging sonars.

Stewart, W., **Three-Dimensional Modeling of Seafloor Backscatter from Side-Scan Sonar for Autonomous Classification and Navigation,** Proceedings of 6th International Symposium on Unmanned Untethered Submersible Technology, June 1989, pp. 372-392.

This paper provides an overview of work in progress at the Deep Submergence Laboratory describing several techniques for three-dimensional sonar processing in which seafloor shape information is used to reduce geometric and radiometric dependencies in the intensity signal. The approach is developed using Sea Beam bathymetry and Sea MARC 1 side-scan data. Preliminary results are also described for new split-beam side-scan sonars designed for high-resolution seafloor characterization. Complex-domain processing of the quadrature-sampled signal gives amplitude and phase for three-dimensional modeling, and offers a measure of signal coherence and modeling certainty. The processed output is a quantitative model of three-dimensional shape and backscatter characteristics that will be applied to feature classification and terrain-relative navigation for intelligent underwater vehicles.

BIOGRAPHIES of PRESENTERS

Mr. Mark R. Abramson
Charles Stark Draper Laboratory, System Sciences Division

Mr. Abramson has been on the technical staff of the System Sciences Division since February 1988. As a principal investigator for the "Autonomous Underwater Terrain Navigation" IR&D program, he contributed to the development of a passive localization algorithm that was successfully field-tested on the University of New Hampshire's AUV. Since joining CSDL, Mr. Abramson has also been studying hierarchical mission planning systems with concentration on a geometry-based threat-avoidance planner and a heuristic-based optimal path searching algorithm (A*) for both underwater and airborne vehicles. Previous to CSDL, Mr. Abramson worked at GE's Automated Technology Department, developing pattern recognition algorithms for GE's REMBASS sensor system program as well as GE's smart mine, ATAP program.

Mr. Abramson received both his B.S. and M.S. in electrical engineering from Rensselaer Polytechnic Institute.

Professor Arthur B. Baggeroer
MIT, Department of Ocean Engineering

Professor Baggeroer's technical interests are the application of large, multichannel acoustical arrays for ocean acoustic and geophysical research, design of autonomous remote sensing buoys and development of high data rate underwater telemetry. Recent research has focused on acoustic propagation and ambient noise in the Arctic, which has led to determining the tectonic structure in several regions of the Arctic.

Professor Baggeroer received the B.S. from Purdue University in electrical engineering and received the S.M. and Sc.D. in electrical engineering from MIT. He presently is a member of IEEE, AGU and is a fellow of the Acoustical Society of America.

Dr. James G. Bellingham
MIT, Sea Grant College Program

Dr. Bellingham is the Project Manager for the Underwater Vehicle Lab at the MIT Sea Grant Program. Prior to joining Sea Grant, he was a Postdoctoral Associate at the MIT Specialty Materials Group, where he conducted research on the role of surface morphology to define thermodynamic and noise-generating properties of electrochemical interfaces.

Dr. Bellingham received his S.B., S.M., and Ph.D. in physics from MIT. He is presently a member of the American Physical Society, the Electrochemical Society and the American Vacuum Society.

Mr. Mark Dzwonczyk
Charles Stark Draper Laboratory, Fault-Tolerant Systems Division

Mr. Dzwonczyk is the Advanced Concepts Section Chief in the Fault-Tolerant Systems Division of Draper Laboratory. He has broad experience in the design and development of fault-tolerant computer architectures for ultra-reliable real-time systems. His work in fault-tolerant systems led to the study of the inherent fault-tolerance of neural networks. Presently he leads the development effort for the INCA system.

Mr. Dzwonczyk recently completed his Master's degree in the Department of Aeronautics and Astronautics at MIT, where his thesis involved the development of quantitative failure models of feed-forward neural networks for pattern recognition. He obtained a B.S. in electrical engineering from Tufts University summa cum laude in 1984. He is a member of the Sigma Xi and Tau Beta Pi honor societies and has professional affiliations with the IEEE, AIAA, and INNS.

Professor Shaoul Ezekiel
MIT, Department of Aeronautics and Astronautics

In 1968, Professor Ezekiel joined the MIT faculty as Assistant Professor in the Department of Aeronautics and Astronautics. Since 1978, he has held full Professorship in the Departments of Aeronautics and Astronautics, and Electrical Engineering and Computer Science, and in 1986 became director for the Center of Advance Engineering Study. Prior to MIT, Professor Ezekiel was a research and development engineer designing flight simulators for Canadian Aviation Electronics.

Professor Ezekiel received a B.S. in electrical engineering from the Imperial College of Science, London, England and his S.M. in Aeronautics and Sc.D. in instrumentation from MIT. He is a fellow of the Optical Society of America and the American Physical Society.

Professor W. Eric L. Grimson
MIT, Department of Electrical Engineering and Computer Science

Professor W. Eric L. Grimson has been on the faculty of the Department of Electrical Engineering and Computer Science at MIT since 1984. From 1987 to 1989, he held the Matsushita Chair of Electrical Engineering. From 1980 to 1984, he was a Research Scientist at MIT's Artificial Intelligence Laboratory. He is currently an Associate Professor in that department.

Professor Grimson has published research articles in machine vision, human vision, robotics, artificial intelligence, neural nets, and finite mathematics. He is the author of *From Images to Surfaces: A Computational Study of the Human Early Visual System*, published in 1981; the editor of *AI in the 1980's and Beyond: An MIT Survey*, published in 1986; and is the author of *Object Recognition by Computer: The Role of Geometric Constraints*, published in 1990, all by MIT Press.

Professor Grimson received the B.S. degree in mathematics and physics from the University of Regina in 1975, and a Ph.D. in mathematics from MIT in 1980.

Mr. Brian L. Grose
EDO Corporation, Sonar Systems, Division

Mr. Grose has recently joined EDO Corporation as a senior project engineer and is currently responsible for the technical development of EDO's Correlation Velocity Log sonar system. While at EDO, Mr. Grose has also applied his previous background in radio frequency (RF) engineering and in analog circuit design to the development of a linear class D switching power amplifier for sonar transducers. Previous to EDO, he was with BDM Corporation as an RF/radar systems engineer.

Mr. Grose obtained an A.S. in electronic technology from Snow College and a B.S. in electrical engineering from the University of Utah. Mr. Grose holds two patents in antenna design.

Dr. Martial Hebert
Carnegie Mellon University, The Robotics Institute

Dr. Hebert has been a research scientist with The Robotics Institute since 1986, performing research in the fields of object recognition, terrain modeling, and three-dimensional map building from range data. His current research focus is in terrain map building for the autonomous navigation of both land and underwater vehicles.

Dr. Hebert received an M.S. in mathematics and an advanced degree in computer science from the University of Paris-Sud. Dr. Hebert received his doctorate in computer science in 1983 with the thesis, "Recognition of Three-Dimensional Shapes."

Dr. Carl D. Hopkins
Cornell University, Section of Neurobiology and Behavior

Professor Hopkins' current research interests are: the neural basis of recognition of complex stimuli, adaptive significance of animal communication, biophysics of electroreceptors and information processing in an electrosensory system. Before joining the faculty at Cornell University, Professor Hopkins was a professor in the Department of Ecology and Evolutionary Biology at the University of Minnesota. Presently, he serves as associate editor for the Journal of Neuroscience and is *ad hoc* reviewer for the National Institute of Mental Health (basic behavioral sciences) and the National Science Foundation (International Grants Program).

Professor Hopkins received his B.A. in physics and mathematics from Bowdoin College and a Ph.D. from Rockefeller University in animal behavior, neurophysiology, and physical chemistry.

Ms. Bonnie L. Hutchison
Lockheed Missiles and Space Company

Ms. Hutchison has been an employee of Lockheed Missiles and Space Company for nine years and is presently program manager for remotely piloted and autonomous vehicles. Her activities with various programs include software development, system test, and system engineering. She was leader of the Precision Underwater Navigation IR&D effort for three years and is currently manager of Lockheed internal funding for future improvement of that system. She currently holds the position of group engineer responsible for the engineering and development of Navigation, Guidance and Control Systems and she is program manager of several contractual activities relating to Lockheed's Precision Underwater Navigation System (PUNS).

Ms. Hutchison has a B.S. degree in mathematics from Arizona State University.

Professor Herbert L. Roitblat
University of Hawaii, Department of Psychology

Professor Roitblat has recently been supported by both the Office of Naval Research, to study the processes of dolphin cognition, and the Naval Ocean Systems Center, to study the biomimetic sonar processing of dolphin echolocation. Since joining the University of Hawaii in 1985 as a professor in the Department of Psychology, he has also conducted research in serially-structured stimuli, sensory abilities of cetaceans, and cognitive dysfunction in post traumatic-stress disorder patients. Prior to his joining the University of Hawaii, Professor Roitblat was a professor in the Department of Psychology at Columbia University.

Professor Roitblat received a B.A. in psychology at Reed College and a Ph.D. in psychology from the University of California at Berkeley.

Mr. Kenneth D. Rolt
MIT, Department of Ocean Engineering

Mr. Rolt has been at MIT since 1988, and is presently a Ph.D. candidate concentrating studies and research in the fields of acoustics, radar/sonar imaging and signal processing. Major experiments accomplished include submarine ship-wake wave spectra experiments for SAR calibration and nonlinear ultrasonic hyperthermia. Prior to his joining MIT, he was an acoustic engineer for Raytheon Company performing analysis, design and construction of active and passive acoustic transducers and arrays.

Mr. Rolt received a B.A. in journalism and B.S. in mechanical engineering from the University of Massachusetts. He presently holds two patents and has several pending.

Professor Henrik Schmidt
MIT, Department of Ocean Engineering

Professor Schmidt joined the MIT faculty in 1987 and in 1989 became an Associate Research Director of the MIT Sea Grant College Program. In 1990, he was awarded the Doherty Professorship in Ocean Utilization. Professor Schmidt's present research interests include; arctic acoustics, numerical modeling of structural acoustics and development of hybrid analytical-numerical models for seismo-acoustic propagation in range dependent ocean environments. Before coming to MIT, he was senior scientist at NATO SACLANT ASW Center, Italy.

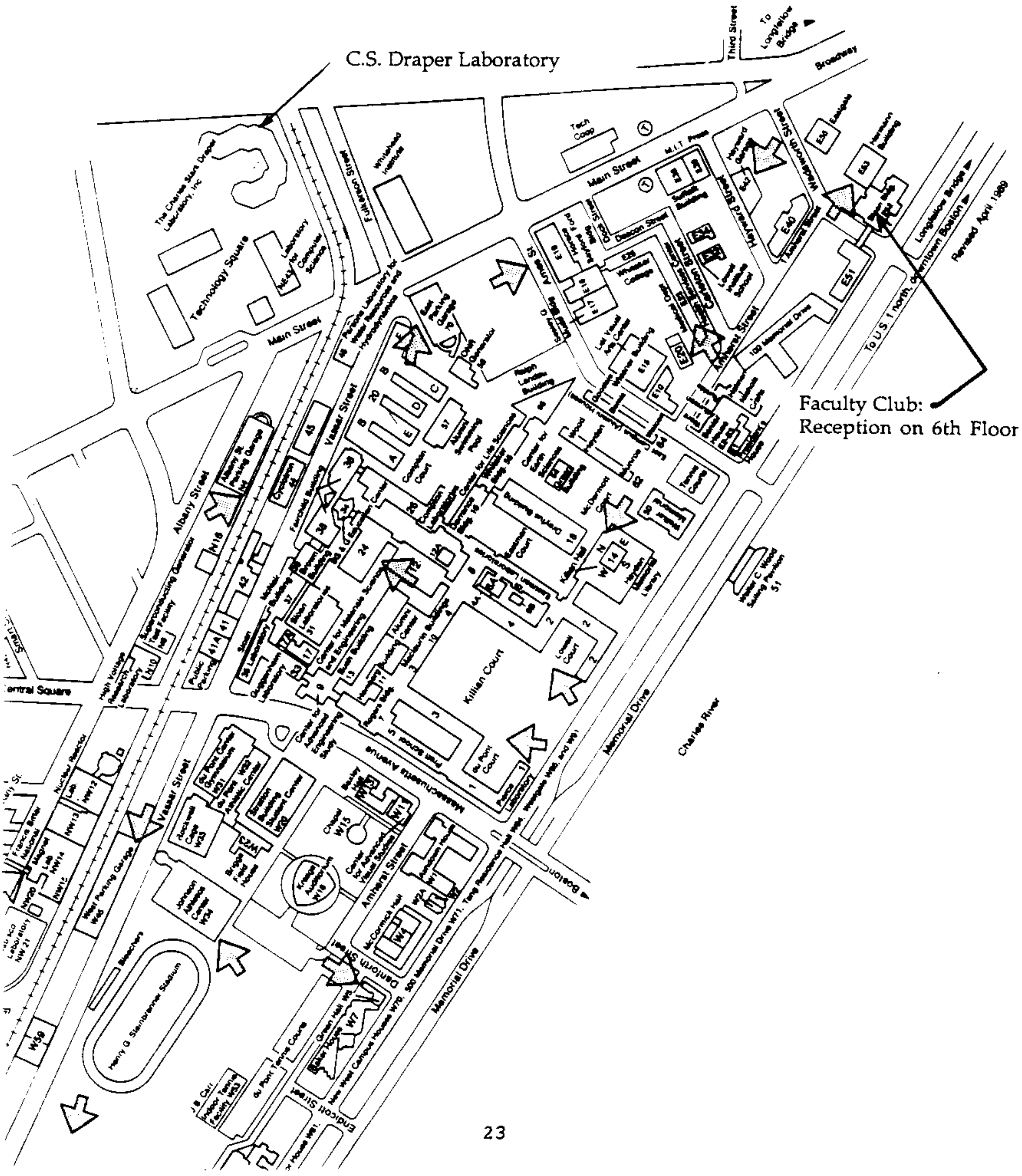
Professor Schmidt received his M.S. and Ph.D. in structural engineering (research in non-destructive evaluation of structures by acoustic emission) from the Technical University of Denmark. He is presently a fellow in the Acoustical Society of America and a member in the Society of Exploration Geophysicists.

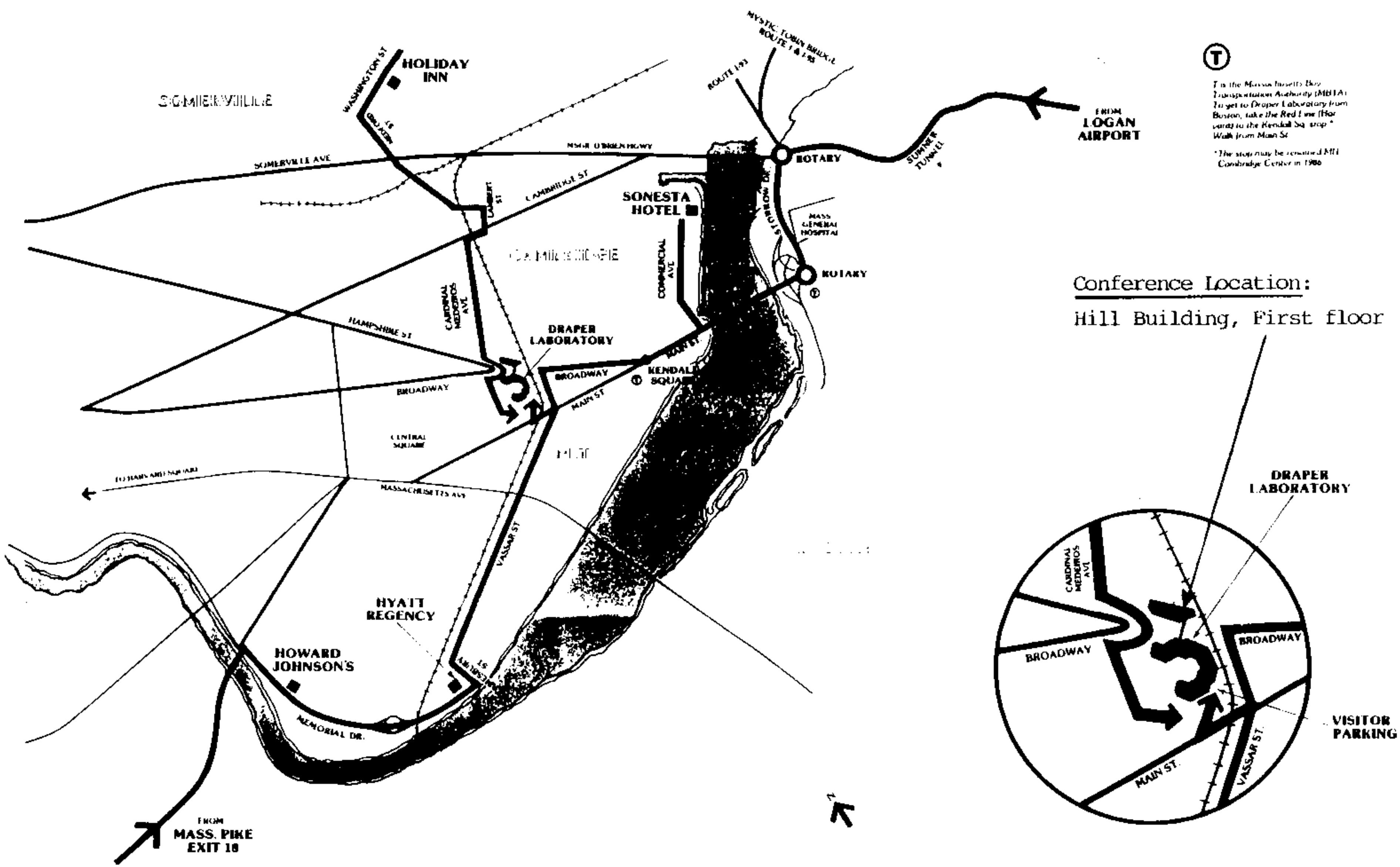
Dr. W. Kenneth Stewart Jr.
Woods Hole Oceanographic Institution

Dr. Stewart is an assistant scientist at Woods Hole Oceanographic Institution (WHOI) with research interests in underwater robotics, multisensor integration, real-time acoustic/optical modeling and imaging and precision underwater mapping and surveying. Prior to his joining WHOI, Dr. Stewart worked on a wide variety of projects, most with a marine and/or computer theme.

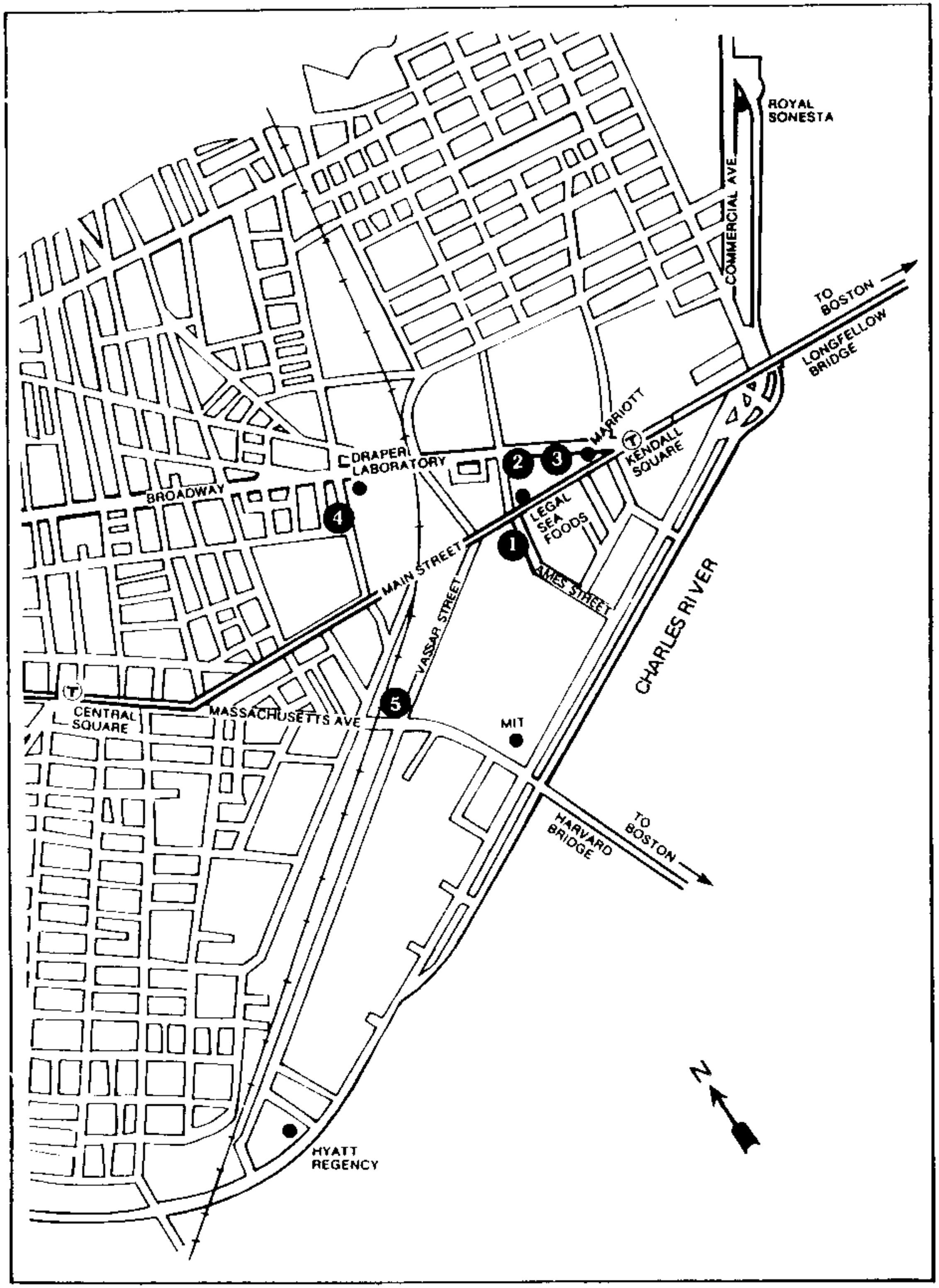
Dr. Stewart received an A.A.S. in marine technology from the Cape Fear Technical Institute, a B.S. in ocean engineering from Florida Atlantic University and a Ph.D. in oceanographic engineering through the joint WHOI/MIT program.

MAP of MIT CAMPUS





MAP TO C.S. DRAPER LABORATORY



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NOTES