The MIT/Marine Industry Collegium

Opportunity Brief

SMALL UNDERWATER VEHICLE DESIGN: MOTORS AND PROPULSORS

October 4 & 5, 1989
Cambridge, Massachusetts

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The MIT/Marine Industry Collegium
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INTRODUCTION

Every year since 1975, when the MIT Sea Grant Marine Industry Collegium had its first workshop on underwater vehicle technology, the Collegium has brought together leading researchers from academia, industry and government to present and discuss recent advances in underwater vehicle technology. These workshops have provided two important benefits to attendees: the opportunities to learn more about current research and to comment upon, and provide direction to, future academic research.

The MIT Sea Grant Program has been committed to advances in underwater vehicle research for a number of years. In 1975, the Program supported research that led to development of a simple, relatively inexpensive (less than $3,000) autonomous underwater vehicle (AUV), which had a primary objective of educating students.

At present, the MIT Sea Grant Program is supporting an Underwater Vehicle Laboratory devoted to advanced concepts in AUV development. The laboratory has designed and built an AUV which it will use as a test-bed for concepts in artificial intelligence based on layered control architecture. Dr. James Bellingham, the laboratory's project manager, will discuss some of his recent experience at this workshop.

This year's workshop will focus on motor and propulsor aspects of small underwater vehicles. This topic was chosen in response to comments of last year's attendees, who expressed interest in following up on 1988's successful workshop: "Power Systems for Small Underwater Vehicles."

The Collegium has brought together speakers from academia, industry and government to present their current research and explore potential application of those technologies. Of special interest will be two presentations on the potential use of oscillating foils for vehicle propulsion. Recent advances in lightweight composites has led to renewed interest in the use of foils. These presentations will offer a timely overview of this propulsion system.

This will be a two-day workshop, as it was last year. Of course, this does not provide enough time to present all of the most recent advances in the field. However, the workshop will bring researchers and design engineers together to present and discuss some of the more promising technologies in propulsion and motor systems. This will, in turn, help the Collegium continue to meet its strategic objective of providing a forum that encourages active transfer of technology among participants. We hope that this will ultimately lead to more efficient and progressive designs for future underwater vehicles.

I look forward to your active participation in this workshop.

John Moore Jr.
Manager
Marine Industry Collegium

WORKSHOP AGENDA

SMALL UNDERWATER VEHICLE DESIGN: MOTORS AND PROPULSORS

October 4

8:30 - 9:00	**REGISTRATION**
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11:50 - 1:00	**LUNCH**
1:00 - 1:45	**Oscillating Hydrofoils as Propellers** Neil Bose, Memorial University
1:45 - 2:30	**Development of a Small AUV** James G. Bellingham, MIT Sea Grant
2:30 - 2:45	**BREAK**
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SMALL UNDERWATER VEHICLE DESIGN: MOTORS AND PROPULSORS

October 5

8:00 - 8:30	**LATE REGISTRATION/REFRESHMENTS**
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10:20 - 11:05	**Advances in DC Brushless Motor Design** TBA, *Speaker Not Confirmed At Time of Publication*
11:05 - 11:50	**Use of Hydraulic Systems for Vehicle Propulsion** Robert Merritt, International Submarine Engineering
11:50 - 1:00	**LUNCH**
1:00 - 1:45	**Control of Propulsor Noise in Small Underwater Vehicles** Neal A. Brown, Atlantic Applied Research
1:45 - 2:30	**Incorporating Thruster Dynamics in the Control of an Underwater Vehicle** Dana R. Yoerger, Woods Hole Oceanographic Institution
2:30 - 3:15	**UUV Propulsion Design** Peter W. Sebelius, C.S. Draper Labs Robert I. Hickey, C.S. Draper Labs

SYNOPSES of PRESENTATIONS

OCTOBER 4

9:15

Fundamentals of Propeller Design and Analysis

Professor Justin E. Kerwin, MIT

Propulsors are required to be efficient converters of energy, yet they must maintain structural integrity, produce low levels of vibratory excitation of the hull, be free of damaging cavitation and, in many applications, be quiet. While some of the issues relevant to the propulsion of large ships, such as high power and large size, need not be considered in the present discussion, much of the technology is common to both ends of the size scale.

A gain in propulsor efficiency may save a container ship millions of dollars in fuel, yet the same technology might also expand the capabilities of a small, energy limited submersible. Many other propeller design issues share a common technology including: maneuvering characteristics, vibration, noise, vulnerability to damage and cost.

The technical problems are numerous. Propulsors suitable for small submersibles may vary from "simple" screw propellers, to complex combinations of rotors, stators and ducts. They can therefore be thought of as combinations of interacting lifting surfaces, generally with complex geometries, operating in a highly irregular flow field. The analysis of the flow may be further complicated by the presence of cavitations.

This presentation will first discuss recent developments in complex propulsor lifting line theory that includes methods of optimizing both major propulsor characteristics (such as diameter) and detailed characteristics (such as circulation and chord length distributions). A variety of examples will be given comparing predicted efficiencies for propellers with and without ducts, contrarotating propellers, propeller-stator combinations and propellers with vane wheels. An overview will then present the state-of-the-art of analytical design and analysis methods for both simple and complex propulsors.

Marine propeller hydrodynamics research to date has largely concentrated on the solution of both the steady and unsteady potential flow problem for arbitrary geometries. The non-cavitating propeller flow problem and the problem of the subsonic flow around complex aerodynamic configurations have much in common. Vortex lattice lifting surface methods and surface panel methods for solving this type of problem have advanced greatly in recent years. Examples will be given of several computational schemes.

The presentation will also address the difficult long-term problems that are associated with real fluid effects. Propulsors generate trailing vortex wakes (as do all lifting surfaces) that roll up and act in a difficult to predict manner. Wake tracking may become particularly important in analyzing off-design and maneuvering performance of small submersibles.

Finally, the flow into the propulsor is full of vorticity generated in the hull boundary layer. The interaction of the propeller with this inflow field must be accounted for, at least in an approximate way, for any valid analytical design procedure. Some brief comments on this aspect of the propulsor theory will be presented.

10:00

Design Considerations and Potential Applications for Contrarotating Propellers

Benjamin Y.-H. Chen, David Taylor Research Center
Arthur M. Reed, David Taylor Research Center

In this presentation a contrarotating (CR) propeller will be defined as having two coaxial open propellers, positioned a short axial distance apart and rotating in opposite directions.

Although CR propeller systems have been in existence since their first direct use in 1839, their use has been limited due to their complex shafting and gearing requirements. One exception is the extensive use of CR propellers for torpedo propulsion where torque balance is critical. Recent advances in the development of more efficient and lighter electrical propulsion systems has opened up the possibility for broader applications of CR propeller systems to other types of underwater vehicles. A CR propeller offers the following benefits over the traditional single screw propeller:

- Recovery of rotational energy that is normally lost in the slipstream.
- Higher efficiency for a given disk area (i.e. smaller optimum diameter and lower loading per blade).
- Increased cavitation inception speeds through reduced blade loading for blade surface cavitation and reduced circulation for tip vortex cavitation.
- Torque balance resulting in simpler machinery mounting systems.

The fundamental principals that need to be satisfied in the design of a CR propeller are momentum, mass and circulation conservation. Momentum conservation requires that the net force generated by the CR propeller be balanced by two kinds of drag: drag of the bare body and drag associated with the propeller-hull interaction. Mass conservation determines the circulation distribution of the aft propeller once the circulation distribution of the forward propeller is specified. Circulation conservation determines the magnitude of the aft propeller circulation to ensure proper thrust and torque ratios. In other words, once the magnitude of the forward propeller circulation is specified, the magnitude of the aft propeller circulation has to be calculated to conserve the total circulation.

In the first phase, the design requirements and the wake survey data need to be provided. The effects of hull configuration on the flow and the hull-propulsor interaction are traditionally represented by the nominal wake and two interaction coefficients: the thrust deduction factor and the wake fraction. In the intermediate design phase, cavitation and strength are the major concerns. Blade surface cavitation can cause blade erosion and thrust loss, which are detrimental to vehicle performance.

To improve the cavitation performances one can vary blade thickness, chord distribution and blade loading. One should remember that the strength and propulsive performance of the CR propeller will vary with these basic design parameters. The final design phase will determine the detailed blade geometry (pitch and camber distributions) through use of a lifting-surface theory that incorporates three dimensional flow field effects.

The presentation will address these design issues and others that an engineer must account for when considering a CR propeller. The presentation will also include a brief discussion on the research that is presently occurring at the David Taylor Research Center and its potential applications to the underwater vehicle industry.

11:05

AUV Propulsion Using an Oscillating Foil

Professor Michael Triantafyllou, MIT

Fish have been flapping their tails for millenia, creating a very powerful and versatile propulsive device. Recent theoretical results [1] show that fish are right: propulsive efficiencies of more than 80% are achievable, which are beyond the reach of any propeller, especially those used to propel small underwater vehicles. Also, transient conditions, and varying operating conditions are handled far more efficiently with an oscillating foil.

What we will address in this talk are the conditions for optimal heave and pitch motion of a foil (or system of foils) to achieve good thrust at reasonable efficiency, under conditions pertinent to a small AUV of typical dimension 3 to 10 feet in length. The classical theory is enhanced by recent findings as to the behavior of separated flows.

The optimal shape of a foil, if we can conclude from observing fish, is in a form resembling the lunate tail of carangiform fish propulsion. The relation between heave and pitch (amplitude and phase) is the crucial factor in achieving substantial thrust with reasonable efficiency. Although we can not hope yet for a full three dimensional solution, a two dimensional approximation could provide a lot of insight as to how to optimize the foil motion. A comprehensive, nonlinear theory could resolve this optimizing problem uniquely; this however, entails simulating the Navier Stokes equations for high Reynolds numbers, a formidable task for the fastest super computer. As a result, we will borrow from recent developments in separated flow dynamics to extend the linear theory developed by Wu (1961, 1971) and Lighthill (1969, 1970) so as to develop conditions for optimal tail motion. The extension will follow an idea first suggested by von Karmen and Burgers (1935).

An extension which we will discuss is the use of twin counter-oscillating foils, when foil-generated torque is small, causing no recoil (in the language of fish propulsion).

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1:00

Oscillating Hydrofoils as Propellers

Professor Neil Bose, Memorial University

Around the world, researchers have recognized that oscillating hydrofoils can act as propellers. Much inspiration for this work has come from observing the swimming of fish and cetacean mammals.

The tails of fast-swimming fish and cetaceans have all evolved into a lunate planform hydrofoil, which is used as the primary organ of propulsion. In cetaceans, the fluke planform is horizontal and oscillations are in heave and pitch with the flukes having flexibility in both the spanwise and chordwise directions. Morphological measurements, including offsets of fluke planforms and sections, have been collected for a variety of cetacean species. These measurements are being collated to show variation between species in planform area, size ratios, aspect ratio and sweep back. Information of this kind may be of use in the design of hydrofoils for flexible fin propellers.

Thrust generation and hydromechanical efficiency of an oscillating hydrofoil will be described. Descriptions will be given of two devices with which the speaker and co-workers have been involved: trochoidal propellers with high-aspect-ratio blade, and flexible fin propellers.

Trochoidal propellers are vertical-axis type propellers with a blade pitching motion that follows the slope of a trochoid: these propellers are also characterized by their blade tangential speed, which is slower than the speed of advance of the propeller. The trochoidal blade motion is effectively a combination of heave, pitch and surge motions (or sway, yaw and surge). Experimental work that has focused on the potential of these propellers for high speed use has been done at both the Marine Research

Institute, Netherlands and the David Taylor Naval Research Center. Our experimental work has focussed on propellers with high-aspect-ratio blades for general use.

Flexible fin propellers are comprised of a hydrofoil connected through a flexible arm to a pivot. By introducing a rotational oscillation to the arm at the pivot, the hydrofoil is made to heave, pitch and also surge to some extent. The actual motion and the phase differences between the components of the motion depend upon the flexibility of the arm and the amplitude of the oscillators. Experiments on a model propeller of this type were done by co-workers at the University of Glasgow.

1:45

Development of a Small AUV

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

The MIT Sea Grant Program has developed a small autonomous underwater vehicle (AUV), the "Sea Squirt." Designed to be easily handled, the vehicle measures in at 34 inches long, with an outside diameter of 8.7 inches and weighs 62 pounds. The small size of Sea Squirt allows it to perform "sea trials" with minimal labor and equipment. This unique feature provides researchers with an opportunity to gain valuable experience at a minimal cost. The vehicle is currently functional and is operated at least twice a week by Sea Grant researchers.

The presentation will first give a brief description of the vehicle, its components and its capabilities. Discussion will then focus upon the research program for this vehicle, that includes: developing robust software that will maintain vehicle integrity while accomplishing mission goals in an efficient manner.

2:45

Computational Methods for the Analysis and Design of Ducted Propellers

Dr. Spyros A. Kinnas, MIT

Since they were introduced around the third decade of this century, ducted propellers have always been considered as an alternative method of propulsion. In particular, they are very common in the propulsion of underwater vehicles, tug boats and fishing boats. The main reasons for using a ducted propeller, is to either increase the efficiency of propulsion (accelerating ducts) or reduce the propeller cavitation (decelerating ducts). Ducted propellers also are used when there is concern for propeller protection or human safety.

In the design of a ducted propeller, the accurate prediction of the duct and propeller forces is very important. An accurate representation of the flow around the duct as well as the propeller/duct interaction is thus essential. However, due to the complexity of the flow around a ducted propeller, the computational methods for the analysis and design of ducted propellers have been advancing slowly. Only recently has complete non-axisymmetric flow around a ducted propeller been addressed.

First, a brief history of the computational methods for the analysis of ducted propellers will be presented and then a current method of analysis will be described. The new method treats the propeller as a lifting surface model and the duct by a surface panel method. The complete non-axisymmetric interactions between duct and propeller are accounted for within this method.

A systematic method for the design of ducted propellers will also be outlined. For a given thrust and a desired thrust division between duct and propeller, the optimum propeller loading is determined such that it maximizes the efficiency of the propulsion unit. The geometry of the propeller and the duct is then determined such that their sections are working at ideal flow conditions, i.e. with minimal flow separation or cavitation.

Finally, the design procedure for a duct around a given propeller will be described and comparisons of the computational results with experimental results will be shown.

3:30

The Propulsive Efficiency of Underwater Vehicles

Dr. Bruce D. Cox, Hydrodynamics Research Associates, Inc.

This presentation deals with the hydrodynamic aspects of underwater vehicle propulsion efficiency with emphasis on the important role of propulsor-hull interaction. Introductory comments summarize the technical issues in a propulsor design including: selection of the type of propulsor (single, contrarotating, ducted, etc.), efficiency, cavitation, noise and performance during maneuvers. Examples of parametric computations and performance predictions are given to illustrate how trade-offs are made to meet stringent, and often competing, design requirements.

The central part of the presentation addresses the hydrodynamic analysis of powering performance. The classical naval architectural approach that considers the propulsion efficiency as the product of propeller efficiency, hull efficiency, and relative rotative efficiency will be discussed in some detail. Examples of the propeller-hull interaction coefficients (thrust deduction and wake fraction) are given for single, contrarotating and preswirl propulsors fitted to a vehicle stern. This is followed by a more fundamental theoretical description of powering efficiency that includes: the flow, forces, and energy involved in conventional ducted and integrated propulsors ingesting a portion of the vehicle boundary layer wake. Numerical results based on this theory illustrate how the powering efficiency depends on such factors as the boundary layer pressure and velocity profile, propulsor diameter and ingested mass flow.

The presentation concludes with a discussion of the special challenges associated with non-axisymmetric hulls. Topics include recovery of the boundary layer, stern and propulsor shaping (internal and external flow problems), and boundary layer suction. The status of analytical tools based on potential, Euler and viscous flow models is summarized.

OCTOBER 5

8:30

A Brushless D.C. Thruster Drive with Minimal Torque Pulsation

Dr. David M. Triezenberg, Franklin Motors

Franklin Electric has produced a variety of oil filled, pressure compensated induction motors for undersea applications. To reduce motor size and to meet the needs of small autonomous vehicles, a brushless dc drive is needed. This presentation covers the development of a 1.5 hp, 1200 rpm thruster drive for operation from a 120v dc source.

The drive motor that is under development has a wound stator with standard laminations and a permanent magnet rotor. The stator assembly is potted and canned. The remainder of the motor is oil filled. A number of brushless motor inverters are commercially available but these operate on the "six step" switching principle and produce torque pulsations at six times the electrical frequency. The subject drive employs a PWM inverter controlled to produce sinusoidal current in the motor windings, virtually eliminating torque pulsation. The inverter employs n-channel MOSFET transistors and recently available integrated circuit drivers. Operation of the drive requires a shaft position resolver. Commercially available units are not suitable for integration into an oil filled motor, so this component is custom designed to have its electrical windings canned along with the motor windings. For the prototype drive, all electronic controls are analog.

At the time of preparation of this abstract, construction of the prototype and its testing are incomplete. Thus, performance data are not available until the time of the presentation.

9:15

Superconducting Homopolar Motors for AUV's

Mr. James J. Gorman, Charles Stark Draper Laboratory, Inc.

A basic problem in AUV performance is the severe constraint imposed on mission range/speed/payload by contemporary energy storage and propulsion systems. Submersibles typically utilize brushless DC motors with battery terminal to shaft efficiencies (including controller) of between 75 and 80%. The energy source for these motors is often silver-zinc batteries storing approximately 50 to 70 Watt-Hours per pound. As a consequence of these basic parameters, tactical AUV operations are only feasible through economies of vehicle scale. The range/speed/payload envelope required for most attractive missions leads to larger vehicle diameters in the 40-60 inch range. Significant improvements in both developed energy storage density and propulsion energy conversion efficiency will be required to approach the desired 20 inch diameter of torpedo sized vehicles.

The broad objective of ongoing work at CSDL is to develop an integrated and highly efficient energy storage/propulsion system. The basic focus is to combine the excellent energy conversion efficiency of a superconducting (SC) homopolar motor (90-95%) with the energy density of a liquid hydrogen/liquid oxygen fuel cell (up to 600

Watt-Hours per pound demonstrated). These direct advantages are accompanied by several indirect, although potentially important benefits:

- Use of the cryogenic fuel to alleviate the cooling overhead associated with a SC field winding.
- Potential increase in power density of SC homopolar motors.
- Reduced motor noise.
- Very good low speed torque performance.
- Very large overload capacity (factor of 3-9 in DTRC motors).

In pursuing the above broad goal, a series of near and long-term objectives were formulated:

- Long term
    - Develop Scaling Laws for Advanced Energy Storage
    - Detailed Design of UUV-Size SC Homopolar Motor
    - Detailed Design of UUV-Scale Cryo-energy Storage
    - Thermal Management, SC Propulsion System
- DFY '89 (Completed)
    - Review SC Motor Types, Scaling Laws
    - Establish First-Order Energy Storage Trades
    - Evaluate "High" versus "Low" Temp. SCs
    - Detailed Analysis of SC Solenoid Field Coil

The DFY '89 objectives have been substantially achieved, and work is continuing on the long-term objectives.

KEY TRADEOFF ISSUES

Within the problem scope outlined above there are several key tradeoffs which must be resolved to optimize the energy/propulsion system for a given application. All of these trades are interlocked, requiring global consideration for effective design.

Motor Type Homopolar motors are configured in two broad types, disk and drum. Disk-type machines utilize the interaction between the axial component of the stator field and a radial current flow to produce torque. Drum-type machines conversely use the radial component of the stator field with a current traveling along the generator (parallel to axis) of a drum armature. The field winding of a homopolar machine is simply solenoidal, with unidirectional current flow. Another characteristic of homopolar machines is their typically very high voltage/current ratio (3-10 volts and hundreds to tens of thousands of amps). Various schemes have been developed to increase voltage/current ratios and avoid the substantial conductor/brush sizes normally required for reasonable power outputs. These schemes include: multiple series-connected disks or drums, circumferentially segmented disks or drums, and hybrid disk/drum combinations.

Torque/Speed and Voltage/Current Parametrics Each permutation of homopolar machine configuration may be described by a characteristic design chart correlating torque/speed and voltage/current ratios against field winding performance. Energy system and geometry constraints can be applied and preliminary motor configurations outlined via such charts. A series of such charts for the motor layouts under consideration forms the basis of global tradeoffs reconciling energy system load and geometric constraints.

Field Winding Material/Magnetic Performance The initial burst of enthusiasm for high temperature (>77 Kelvins) superconductors prompted consideration of same for liquid nitrogen (or colder) applications. Although these materials remain interesting, it appears that the allowable current densities for practical conductors (wire or ribbon) will be relatively low for some considerable time. Low temperature superconductors have previously been considered impractical by virtue of their reliance on the very low liquid helium temperatures. It has been learned, however, that several magnet systems have been constructed using niobium-tin (LTSC) at the triple point hydrogen environment. Such a system might operate directly with a triple-point hydrogen fuel cell, or perhaps more likely, using liquid nitrogen as the warm side of a heat exchanger. In either eventuality, it is important to gather or generate data on LTSC performance above the normal operating temperature. The overall efficiency of the propulsion/energy system will obviously depend upon the characteristics of the thermal management/cooling subsystem.

The other aspect of field winding performance is the configuration of the solenoid. Well developed methods exist for optimizing the shape for any of several parameters such as; centerline flux, integrated in-bore flux, minimum field near brushes, minimum superconductor utilization, or minimum dimensions for a given flux. The optimizing parameter will generally depend strongly on the type of constraints imposed. For example, overall diameter will likely be a critical constraint for a submersible motor. This will largely define motor layout in the presence of hard current density constraints in the field winding superconductor.

Current Collector/Brush Technology Employed The very high load current levels of SC homopolar motors built to date has led to almost universal employment of liquid metal brushes or current collectors. Such collectors typically use sodium-potassium, indium-gallium, or mercury captured in a channel and wetting a disc attached to the armature. Numerous design problems attend the choice of liquid metal brushes, including sometimes severe corrosion, magnetohydrodynamic losses (and stability limits), maintenance of brush wetting at low speed (usually centrifugal), and liquid metal supply/circulation control. While these problems have been successfully addressed in several motors of hundreds to thousands of horsepower, it remains to be seen if such designs are practical in ratings of 10-20 horsepower. Conventional metal-graphite brushes may yet find application in homopolar machines of small rating.

Energy Storage System Characteristics Although a cryogenic H_2O_2 fuel cell remains the most appealing energy source for a small SC homopolar motor; battery, thermal, and other chemical energy storage means must be evaluated to support global tradeoffs. The complexity and development time for a tailored fuel cell system may outweigh the performance advantages in minimizing the cooling overhead.

Thermal Management There are two basic aspects to the thermal management problem for superconducting motors: insulation design to minimize the heat input to the field winding, and provision of cooling power to deal with the inevitable leakage. It is the latter area that interacts most strongly with submersible design. Choices here include boiling off an expendable cryogen, mechanical refrigeration schemes, or some hybrid of the two. If the cryogen is being carried as fuel (i.e. liquid hydrogen) it will likely need warming for fuel cell operation, and thereby provide "free" winding cooling. If temperatures colder than triple-point hydrogen are required, an efficient Brayton Cycle refrigerator could be designed to operated with an liquid hydrogen warm side and 20 temperature difference of 10-15 Kelvins. The design issues surrounding these basic choices will be outlined.

PROGRESS AND FUTURE PROSPECTS AT CSDL

Progress was made in several of the above outlined technology areas. A wide variety of homopolar implementations was surveyed, including U.S. Navy, British, French, Czech, Russian and Finnish sources. The extensive homopolar motor program at DTRC (ca. 1975 to present) was also evaluated. Basic motor tradeoff methods were developed, most extensively for drum machines. Energy storage tradeoffs were reviewed, establishing likely specific energy levels and other constraints such as peak/nominal current draw capability. Superconductor vendors and researchers were surveyed in both the HTSC and LTSC arenas. It was concluded that HTSC field windings did not represent a near-term solution for UUV motor design. The intermediate temperature (10-20) Kelvins) regime appears most promising using Niobium-Tin conductors.

Future work will concentrate upon developing motor layouts that integrate the mechanical, electromagnetic, cooling, and energy storage requirements for UUV-scale applications. These layout studies will provide essential data on the sizing constraints and overhead (i.e. non electromechanical) requirements for a range of superconducting submersible propulsion systems. The ultimate analytical goal is a propulsion/energy storage module than can be embedded within a submersible preliminary design code.

10:20

Advances in DC Brushless Motor Design

TBA

Speaker not confirmed at time of publication.

11:05

Use of Hydraulic Systems for Vehicle Propulsion

Mr. Robert Merritt, International Submarine Engineering

The propulsion system is an integral part of a Remotely Operated Vehicle (ROV). Consideration must be given during the design spiral, to the impact on other subsystems (e.g. structure, ballast, electric power, control, navigation, manipulators and handling). The driving force behind the design, weight, speed, size and depth capability will ultimately determine the optimal vehicle configuration and, thereby the associated propulsion system.

Initial ISE vehicles were all electric thrustered with either variable speed universal motors or 3 phase constant r.p.m. motors with C.P. propellers. The requirement for more compact, reliable propulsion systems utilizing off-the-shelf components led to the electro-hydraulic systems now used. Current ISE vehicles ranging from 6HP to 250HP are 100% electro-hydraulic.

This paper reviews the rationale for the selection of an electro-hydraulic subsytem for ROV propulsion: when and why hydraulic propulsion systems make sense. A typical ROV hydraulic schematic will be described for both 10HP and 40HP vehicles. Standard ISE hydraulic thrusters will be presented and compared with a state of the art 10HP brushless D.C. thruster. The results of recent static thrust tests will be presented.

Consideration related to the selection of appropriate electro-hydraulic power packs, servo valves and hydraulic thrusters for optimal ROV performance will be discussed.

1:00

Control of Propulsor Noise in Small Underwater Vehicles

Dr. Neal A. Brown, Atlantic Applied Research Corp.

Propulsors for small underwater vehicles can be of several types including single screws, contrarotating co-axial, twin or multiple screws; any of which may be open or fitted with ducts, or even "buried" to form water jet propulsion. All however, are subject in varying degrees to hydrodynamic excitations which results in underwater radiated sound.

The controllable parameters of propulsors that can be manipulated to reduce noise, such as diameter and rotation rate, are intimately connected to system performance measures and design impacts such as propulsive efficiency and motor weight. These are influential in settling required battery capacity, trim and arrangement; effecting endurance, top speed and vehicle size.

As a practical matter we separate the propulsor noise problem into two parts: the hydrodynamic excitations and the structural/acoustic responses including radiation. The radiated noise spectrum is estimated by multiplication of the excitation force spectrum with the appropriate transfer gain spectrum.

Non-cavitating force sources can be inferred from sound measurements in a quiet acoustic wind tunnel; some can be measured in a water tunnel or self-propelled towing tank test; they may be scaled from other measured data or estimated computationally.

Transfer gains may be measured in static tests in an acoustic water tank, inferred from limited operating noise data, scaled from other vehicles, or computed (in principle).

We recognize several hydrodynamic noise excitation mechanisms for propulsors, originating in: cavitation, inflow harmonic content, inflow turbulence, blade boundary layers and blade row interactions.

Cavitation, when present, is the most powerful underwater noise source. Inflow harmonic content yields discrete frequency "blade rate" type propulsor forces and noise. Inflow turbulence, in contrast, yields the continuous spectrum or "broadband" equivalent denoted "turbulence ingestion noise." Blade boundary layers traversing trailing edges create continuous spectrum (sometimes discrete) forces and noise denoted "vortex shedding." Blade row interactions, both potential and viscous, yield mostly discrete frequency forces and noise.

Finally, propulsor parts may be excited by shaft or hull vibrations that results in radiation, coupling and damping by the propulsor.

Hydrodynamic excitations may be modified by changes in diameter and revolution rate, choice of blade numbers, clearances, inflow quality and by blade skew (sweep).

Transfer gains for force sources are usually governed by the involvement of structural resonances. A fundamental resonance of the hull is an important parameter in characterizing the transfer gain. This depends on hull size, material and depth capability. Modifications of transfer gains may be obtained through propulsor vibration isolation, damping, surface treatments or materials substitutions.

For force sources, the transfer gains are usually limited on the lower side by the direct dipole radiation of the force applied to the water without boundaries. The acoustics of bounded spaces (ducts, etc.) and boundary treatments can modify this lower bound.

1:45

Incorporating Thruster Dynamics in the Control of an Underwater Vehicle

Dr. Dana R. Yoerger, Woods Hole Oceanographic Institution

Motivated by the precise vehicle position control required for coordinated vehicle/manipulator operation, the incorporation of thruster dynamics in the control of an underwater vehicle is examined. An energy-based lumped parameter model of the nonlinear thruster dynamic response is developed and experimentally verified using static and dynamic thruster relationships. Three controllers, to compensate for the nonlinear dynamics, are designed including analog lead compensation, model-based computed torque and adaptive sliding control techniques.

To minimize the limitations inherent in the use of pure digital simulation to evaluate the proposed controller designs, a hybrid simulation was developed. The hybrid simulation utilized vehicle model and controller parameters and thruster hardware of the underwater vehicles, JASON and its prototype JASON, Jr. The arrangement included a one degree-of-freedom vehicle simulation using an actual thruster under digital control as the actuator. Each proposed controller was implemented and evaluated in this environment permitting controller evaluation and comparison based explicitly on observed vehicle tracking performance.

The incorporation of thruster dynamics is shown to significantly improve vehicle tracking performance. Superior, robust tracking performance with significant model uncertainty is further demonstrated in the application of the adaptive sliding control technique. The evaluated adaptive controller structure may permit on-line adaptation to complex hydrodynamic phenomena associated with complete vehicle/thruster configurations such as cross-flow and mutual interference.

2:30

UUV Propulsion Design

Mr. Peter W. Sebelius, Charles Stark Draper Laboratory, Inc.
Mr. Robert I. Hickey, Charles Stark Draper Laboratory, Inc.

This presentation will focus upon the impact of "Rapid Prototyping" to the design spiral for an unmanned underwater vehicle (UUV). Taking a systems integration approach, design engineers at Charles Stark Draper Laboratories (CSDL) utilized preliminary drag and power estimates, through model testing, to develop the UUV propulsion system. Specific topics that will be discussed include: initial design constraints, drag and power estimates, estimation of wake fraction and thrust deduction, propulsor selection, propeller blade number and geometry selection.

In conclusion, the scope of the testing, the test development and data evaluation will be addressed. The presentation will also include a brief discussion on the impact of a larger than expected wake fraction.

PUBLISHED PAPERS

Oscillating Foils

Bose, N. and Lien, J., **Propulsion of a Fin Whale (Balaenoptera physalus): Why the Fin Whale is a Fast Swimmer,** Proceedings of the Royal Society, London, England, in press.

Measurements of an immature fin whale (Balaenoptera physalus) which died as a result of entrapment in fishing gear near Frenchman's Cove, Newfoundland, were made to obtain estimates of volume and surface area of the animal. Detailed measurements of the flukes, both planform and sections, were also obtained.

A strip theory was developed to calculate the hydrodynamic performance of the whale's fluke as an oscillating propeller. This method is based on linear, two-dimensional, small-amplitude, unsteady hydrofoil theory with correction factors used to account for the effects of finite span and finite-amplitude motion. These correction factors were developed from theoretical results of large amplitude heaving motion and unsteady lifting-surface theory. A model that makes an estimate of the effects of viscous flow on propeller performance was superimposed on the potential-flow results. This model estimates the drag of the hydrofoil sections by assuming that the drag is similar to that of a hydrofoil section in steady flow.

The performance characteristics of the flukes of the fin whale were estimated by using this method. The effects of the different correction factors, and of the frictional drag of the fluke sections, are emphasized. Frictional effects in particular were found to reduce the hydrodynamic efficiency of the flukes significantly. The results are discussed and compared with the known characteristics of fin whale swimming.

Bose, N. and Lai, P.S.K., **Experimental Performance of a Trochoidal Propeller with High-Aspect-Ratio Blades,** Marine Technology, Society of Naval Architects and Marine Engineers, New York, New York, 1989.

Open water experiments were done on a model of a cycloidal type propeller with a trochoidal blade motion. This propeller had three blades with an aspect ratio of 10. These experiments included the measurement of thrust and torque of the propeller over a range of advance ratios. Tests were done for forward and reverse operation and at zero speed (the bollard pull condition).

Results from these tests are presented and compared with: a multiple-stream-tube theoretical prediction of the performance of the propeller and a prediction of the performance of a single blade of the propeller, oscillating in heave and pitch, by using unsteady, small-amplitude, hydrofoil theory with corrections for finite-amplitude motion, finite span and frictional drag. At present, neither of these theories gives a completely accurate prediction over the whole range of advance ratios, but a combination of these approaches, with an allowance for dynamic stall of the blades, should lead to a reliable simple theory for overall performance prediction.

Application of a propeller of this type to a small ship is discussed. The aim of the design is to produce a lightly loaded propeller with a high efficiency of propulsion.

Bose, N., **Rotary Foil Propellers,** Papers of the Ship Research Institute, Tokyo, Japan, Vol. 24, No. 5, 1987, pp. 45-67.

A multi-stream-tube theoretical model was developed for application to the rotary foil propeller. The outline of this method is described, together with the operation of a computer program that was written using this theoretical model. The basis of the method is for calculations on a two-dimensional rotary foil propeller. A three dimensional development of the method was carried out by assuming elliptical loading across the span of the propeller blades.

The results are presented here for a series of propellers with a range of parameter variations and for two types of blade motion: a purely sinusoidal variation of blade pitch angle relative to the undisturbed flow and a trochoidal motion as in the initial design of a rotary foil propeller model.

A design example is presented to show the approximate scale necessary for a full-sized rotary foil propeller.

Bose, N. and Lien, J., **Oscillating Foil Propulsion**, Shipstechnic Journal, Society of Naval Architecture Students, Cochin University of Science and Technology, India, 1989.

A study is in progress on the swimming of marine animals which derive their propulsion from oscillatory motions of a high aspect ratio lunate tail: this is known as carangiform swimming. Masses and geometrical data have been collected from seven species in this category. Theoretical fluid dynamics is being used to predict the energetic quantities of animals with lunate tails.

The work will result in a better understanding of the nature of oscillating foil propulsion and is relevant to new designs of oscillatory foil propulsion for ships.

Lai, P.S.K., McGregor, R.C. and Bose, N., **On the Flexible Fin Propeller**, 4th International Symposium of Practical Design of Ships and Mobile Units, Varna, Bulgaria, submitted for publication.

A theoretical model of the flexible fin propeller is presented. This theoretical model comprises a linearized unsteady lifting foil theory with finite span correction and a large deflection beam theory. These two theories are outlined. A model of a flexible fin propeller with an oscillating rectangular foil is investigated. The effect of different parameters on propulsive thrust and efficiency are investigate and discussed. Experimental results are compared with predictions.

Propulsive thrust increases as stiffness of the connecting beam increases, but propulsive efficiency drops. Higher propulsive thrust is obtained by increasing the angular oscillating amplitude of the beam. The effect of aspect ratio on propulsive thrust is not significant, but increasing aspect ratio improves efficiency significantly. Different taper ratios of the flexible beam have little effect on propulsive efficiency.

Lai, P.S.K., McGregor, R.C. and Bose, N., **Experimental Investigation of Oscillating Foil Propellers**, 22nd American Towing Tank Conference, St. John's, Newfoundland, August 1989, submitted for publication.

A flexible fin propeller model with a rectangular oscillating foil of aspect ratio has been tested in the Hydrodynamics Laboratory of the University of Glasgow. The performance of the model was tested in both forward speed and zero speed conditions. Experimental results are compared with theoretical results from a linearized mathematical model. High propulsive efficiencies around 0.7 were obtained with this model propeller.

In the zero speed condition, the propulsive thrust coefficient decreases as the oscillating frequency increases. Investigations were made into the speed of advance variation over the span of the foil and frictional losses in the driving mechanism. The test apparatus was checked to make sure that it functioned as intended in all respects.

The application of a flexible fin propeller to a small ship is found to be feasible from a hydrodynamic viewpoint.

Propulsors

Brown, N.A., **Torpedo Propulsor Noise and Design for Its Control (U)**, Naval Underwater Propulsion Conference, San Diego, CA, September 1972. (CONFIDENTIAL)

Brown, N.A., and Gray, L.M., **Prediction and Reduction of Torpedo Propeller Broadband Noise (U)**, 30th Navy Symposium on Underwater Acoustics, Bethesda, MD, October 1974.

Brown, N.A., **Cavitation Noise Problems and Solutions**, International Symposium on Shipboard Acoustics, Nordwijkerhout, The Netherlands, September 1976.

Brown, N.A., **The Use of Skewed Blades for Ship Propellers and Truck Fans**, Symposium on Noise and Fluids Engineering, American Society of Mechanical Engineers, Atlanta, GA, November - December 1977.

Brown, N.A., **State of the Art Techniques in Propulsion Noise Reduction (U)**, SEAHAC Conference, May 1979.

Brown, N.A., **Minimization of Unsteady Propeller Forces that Excite Vibration of the Propulsion System**, Propellers '81 Symposium, The Society of Naval Architects and Marine Engineers, Virginia Beach, VA, May 1981.

Brown, N.A., **Response to "Comments on the Low-Aspect-Ratio Unsteady Propeller Force Theory of N.A. Brown**, Journal of Ship Research, Vol. 29, No. 3, September 1985, pp. 159-161.

Chen, B.Y.-H. and Reed, A.M., **A Lifting Surface Program for Contrarotating Propellers**, Symposium on Hydrodynamic Performance Enhancement for Marine Applications, NUSC, Newport, RI, pp. 57-68.

A new lifting-surface computer program for a set of contrarotating propellers has been developed based on a modified version of the MIT lifting-surface design program with hub effects. This program automatically computes the velocities induced by one propeller on the other. In addition, the hub portion of the program is modified to account for the velocities induced by one propeller on the hub of the opposite propeller. Data from LDV measurements of induced velocities have been used to adjust the shape and distribution of the wakes shed from the two propellers. A comparison between the conventional and the new methods for the design of a set contrarotating propellers for a surface ship is also given.

Chen, B.Y.-H. and Reed, A.M., **A Design Method and an Application for Contrarotating Propellers**, American Towing Tank Conference, St. John's, Newfoundland, August 1989, submitted for publication.

A design methodology for contrarotating propellers has been developed based on rational hydromechanics. Three fundamental principles need to be satisfied: momentum, mass and circulation conservation. Momentum conservation requires the net force generated by the contrarotating propeller to be balanced by the drag of the bare body and the drag due to hull-propulsor interaction. Mass conservation determines the circulation distribution of the aft propeller once the forward propeller circulation distribution is specified. Circulation conservation determines the magnitude of the circulation distribution of the aft propeller to ensure the proper thrust and torque ratios. The effects of the hub boundaries have been taken into account in the design and analysis methods. A contrarotating propeller set was designed for uniform flow at the operating point of the propeller for a high-speed surface ship. Open water results show that the performance predictions agree well with the measurements.

Cox, B. and Reed, A.M., **Contrarotating Propellers-Design Theory and Application,** Propellers '88 Symposium, Virginia Beach, VA, September 1988.

This paper sets forth recent developments in the design theory for contrarotating propellers. The analysis includes: a more accurate solution for the optimum circulation distribution than has been previously formulated, prediction of slipstream contraction for the first time and faster and more accurate methods for computing the mutual interactions between the forward and aft propellers. In addition, the theory has been extended to allow for finite loading at the blade roots and takes into account the effect of the hub boundary. The paper provides numerical predictions of efficiency as a function of thrust loading, advance co-efficient, and comparisons between single and contrarotating propellers. Calculations and measurements are also presented for the forces and flow field velocities of a contrarotating propeller designed for uniform flow.

Cox, B.D. and Hansen, A., **A Method for Predicting Thrust Deduction Using Propeller Lifting Surface Theory,** DTRC Report 77-0087, November 1977.

Cox, B.D., **Recent Development in Propeller-Hull Interaction Theory,** SNAME Propellers '78 Symposium, Virginia Beach, VA, May 1978.

Cox, B.D., **Recent Theoretical and Experimental Development in the Prediction of Propeller-Induced Vibratory Forces on Nearby Boundaries,** Twelfth Symposium of Naval Hydrodynamics, Office of Naval Research, Washington, DC, June 1978.

Cox, B.D., **An Approximate Method for Calculating Propulsor Performance Based on Momentum Theory (U),** Hydrodynamics Research Associates, Inc., Report HRA-C-81-001, February 1981. (CONFIDENTIAL)

Cox, B.D., **A Propeller Design for a Low Drag Underwater Vehicle (U),** DTRC Report SPD-C-774-02, June 1981. (CONFIDENTIAL)

Cox, B.D., **A Review of Propeller Calculations,** Hydrodynamics Research Associates, Inc., Report HRA-83-001, February 1983.

Cox, B.D., **Theory and Computer Program for Calculating Induced Velocities of a Moderately Loaded Actuator Disc,** Hydrodynamics Research Associates, Inc., Report HRA-85-004, August 1985.

Cox, B.D., **A Note on Calculation of Periodic Propeller Forces Using Two-Dimensional, Unsteady Airfoil Theory,** Hydrodynamics Research Associates, Inc., Report HRA-85-006, October 1985.

Cox, B.D. and Bohn, J.C., **A Note on Podded Propulsion,** Hydrodynamics Research Associates, Inc., Report HRA-89-005, May 1989.

Cox, B.D. and S.K. Neely, **Propulsor Study for HUSD Underwater Vehicle,** Hydrodynamics Research Associates, Inc., Report HRA-89-007, June 1989.

Kerwin, J.E., Kinnas, S.A., Lee, J. and Shih, W., **A Surface Panel Method for the Hydrodynamic Analysis of Ducted Propellers,** Annual Meeting of Society of Naval Architects and Marine Engineers, November 1987.

The development of a panel method suitable for the analysis of ducted propellers is presented. The method is first applied to the problem of the two-dimensional hydrofoil, the propeller with hub and the axisymmetric duct in uniform flow. Some comparisons are made with exact solutions and with other panel codes. The difficulties associated with the modeling of ducted propeller flows are discussed. Convergence of the method for a typical ducted propeller is shown. The results include overall forces on the propeller and the duct, circulation distributions, and chordwise pressure distributions on the duct at different positions between blades.

Kerwin, J.E., Coney, W.B. and Hsin, C., **Hydrodynamic Aspects of Propeller/Stator Design,** Propellers '88 Symposium, Virginia Beach, VA, September 1988.

A theoretical method for determining optimum circulation distributions for propeller/stator combinations and for determining the circumferential variation in circulation for non-axisymmetric stators is presented. Comparisons of theoretical predictions and water tunnel measurements are given for a given propeller operating behind an axisymmetric and a non-axismmetric stator. Theoretical comparisons are made between a hypothetical propeller designed to operate without a stator, and an optimum propeller/stator design. This comparison includes predictions of efficiency, unsteady loading and cavitation.

Kerwin, J.E., Keenan, D.P. and Shih, W., **Correlation Between Theory and LDV Measurement of Propeller in Shear Flow,** International Towing Tank Conference, Kobe, Japan, October 1987.

In conjunction with ongoing efforts to develop improved numerical models for propeller analysis a number of experiments employing LDV techniques have recently been performed at MIT. In support of a free-wake propeller analysis code we made a unique set of measurements mapping the instantaneous tip vortex geometry of a propeller operating in unsteady flow. An effort to probe the structure of the tip vortex is also described. In our efforts to understand rotational inflows we have developed an axisymmetric Euler equation solver to predict the evolution of a rotational inflow under a propeller's influence. As part of this effort, measurements of axisymmetric shear flows were made in the MIT Variable Pressure Water Tunnel. Comparisons show that theoretical calculations of axial velocity are in good agreement with the LDV measurements.

Kerwin, J., Kinnas, S., Wilson, M.B. and McHugh, J., **Experimental and Analytical Techniques for the study of Unsteady Propeller Sheet Cavitation,** David Taylor Naval Ship R&D Center, Bethesda, MD.

Results of an experimental investigation carried out in the 24-inch water tunnel at DTNSRDC to determine cavitating propeller-induced surface pressures and reference-area surface forces are presented. New apparatus for the measurement of the reference area surface force on a disc is described. Reciprocity calibration measurements have been carried out and the resulting pressure-to-acceleration transfer function has been used to estimate the blade rate harmonics of the cavity volume velocity. Tests have been run with a seven bladed propeller operating behind a screen generated simulation of a steep axial wake velocity distribution for a single screw ship. A computational procedure for the prediction of three-dimensional unsteady propeller cavitation developed at MIT is briefly reviewed. An extension to this theory to include the non-linear effect of the leading edge radius on the cavity solution is developed. Results are given for the propeller and wake field used in the experimental program. The inclusion of the leading edge radius is seen to reduce the extent of cavitation, but its effect on the blade rate cavity volume velocity is found to depend on cavitation number, Comparison between measured and predicted activity extents and cavity volume velocity harmonics shows a consistent trend.

Kerwin, J.E., Van Houten, R.J. and Uhlman, J.S., **Numerical Solutions of Lifting Surface Sheet Cavitation, A Review of Research at MIT,** 20th American Towing Tank Conference, Hoboken, NJ, August 1983.

Kinnas, S.A., **A Numerical Method for the Analysis of Cavitating Propellers in Non-uniform Inflow: MIT-PUF-3 Program Documentation,** MIT Ocean Engineering Report 83-7, June 1983.

Kinnas, S.A., and Coney, W.B., **On the Optimum Ducted Propeller Loading,** Propellers '88 Symposium, Virginia Beach, VA, September 1988.

A numerical approach to determine the optimum circulation distribution of a propeller inside a given duct is presented. The propeller blades are modeled by lifting lines. The duct is represented in non-linear theory by using a potential based panel method.

The propeller lifting lines are approximated by a finite number of vortex horseshoes. The strengths of the horseshoes are determined by using a numerical non-linear optimization technique to maximize the propulsor efficiency. The non-axisymmetric duct/propeller interactions are included within the design procedure.

Results are presented for propellers designed to operate various thrust coefficients inside of two different ducts and at several advance ratios.

Kinnas, S.A., **Ducted Propeller Steady Flow, MIT-DPSF-2, User's Manual,** MIT Department of Ocean Engineering Report, May 1989.

Kinnas, S.A. and Coney, W.B., **A Systematic Method for the Design of Ducted Propellers,** May 1989, submitted for publication.

A systematic method for designing ducted propellers is presented. The objective is to design a combination of a duct and a propeller which develops a total required thrust with a given division between duct and propeller, and with the minimum absorbed power. The duct and the propeller sections are required to work at ideal angles of attack. The optimum spanwise circulation distribution on the propeller is determined via a non-linear optimization technique. At this stage, the propeller is modelled with lifting lines and the duct by ring vortices distributed along a finite length cylinder. The non-axisymmetric effect of the duct on the propeller is accounted for via images of the lifting lines with respect to the duct cylinder.

An approximate duct and propeller geometry is determined within the lifting line model. That geometry is then analyzed by using a method in which the propeller is treated by using a lifting surface model and the duct by using a surface panel model. The exact non-axisymmetric flow around the duct and the propeller is accounted for within that model. The resulting propeller and duct loadings from that model, are compared against the design requirements and the duct and propeller geometries are appropriately adjusted until those requirements are satisfied within acceptable accuracy.

Finally, two design examples, one for zero and another for a finite propeller/duct gap are presented.

UUV Design

Bellingham, J.G., Beaton, R., Triantafyllou, M. and Shupe, L., **Autonomous Submersible Designed for Software Development**, Ocean '89, Seattle WA, September 1989, submitted for publication.

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 avoiding 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.

Loch, J., Waller, E., Bellingham, J.G., Beaton, R. and Triantafyllou, M., **Software Development for Autonomous Submersible Program at MIT Sea Grant and Draper Laboratory**, 6th International Symposium on Unmanned, Untethered, Submersible Technology, Endicott City, MD, June 1989, submitted for publication.

A planning and control architecture is currently being developed for a 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 based computer. Preliminary test results for the sliding mode controller indicate, in steady state, that depth can be maintained to an accuracy of 5 degrees. Testing of the layered control system is awaiting the successful performance of the forward looking obstacle avoidance sonar.

Yoerger, D.R., Slotine, J.-J.E., Grosenbaugh, M.A. and DeLonga, D.M., **Dynamics and Control of Autonomous Vehicles**, 5th International Symposium on Unmanned, Untethered Submersible Technology, Durham, NH, June 1987.

Yoerger, D.R. and Slotine, J.-J.E., **Supervisory Control Architecture for Underwater Teleoperation**, IEEE Conference on Robotics and Automation, Raleigh NC, March 1987.

Yoerger, D.R. and Newman, J.B., **High Performance Supervisory Control of Vehicles and Manipulators**, Proceedings ROV '87, San Diego, CA, March 1987.

Yoerger, D.R. and Newman, J.B. and Slotine, J.-J.E., **Supervisory Control System for the JASON ROV**, IEEE Journal of Oceanic Engineering., OE-11, No. 3, July 1986.

Yoerger, D.R. and Newman, J.B., **JASON: An Integrated Approach to ROV and Control System Design**, Proceedings ROV '86, Aberdeen, Scotland, 1986.

Yoerger, D.R. and Slotine, J.-J.E., **Nonlinear Trajectory Control of Autonomous Underwater Vehicles Using the Sliding Methodology**, Proceedings Oceans '84, IEEE/MTS, September 1984.

BIOGRAPHIES of PRESENTERS

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.

Professor Neil Bose
Memorial University, Faculty of Engineering and Applied Science

Professor Bose is currently an Assistant Professor of Naval Architectural Engineering at the Memorial University of Newfoundland, Canada. Prior to joining the faculty of Memorial University, Dr. Bose was a Research Fellow with the Ship Propulsion Division of the Ministry of Transport, Tokyo Japan. He has also served as Lecturer for the Department of Naval Architecture and Ocean Engineering at the University of Glasgow.

Professor Bose received both his B.Sc. and Ph.D. in Naval Architecture from the University of Glasgow, Scotland.

Dr. Neal A. Brown
Atlantic Applied Research Corporation

In 1984, Dr. Brown founded Atlantic Applied Research Corporation (AARC). At AARC, Dr. Brown spends the majority of his time on funded hydroacoustic work for the Navy and prime contractor clients. Before AARC, he worked as a researcher/engineer for Bolt, Beranek and Newman, Inc.

Dr. Brown received an S.B. in Naval Architecture and Marine Engineering from Webb Institute. He received both his S.M. and Ph.D. in Naval Architecture and Marine Engineering from MIT. Dr. Brown was a Fulbright Scholar as well and attended the Technische Hogeschool in Delft, Netherlands.

Dr. Benjamin Y.-H. Chen
David Taylor Research Center, Propulsor Technology Branch

Since 1984, Dr. Chen has been a Research Naval Architect at the David Taylor Research Center. In this capacity he is a principal investigator for the development of advanced propulsor systems that include: contrarotating, vane wheel, asymmetric stator, postswirl and boundary layer control. Prior to DTRL, Dr. Chen was a Research Ocean

Engineer with Naval Ocean R&D Activity where he was group leader in investigating the effects of nonlinear, random seas and the dynamic response of ocean structures.

Dr. Chen received his B.S. in Civil Engineering from the National Taiwan University and received his M.S. and Ph.D. in Civil Engineering, within the Ocean and Coastal Engineering Program, at the University of Delaware. He is presently a member of ASME, ASCE and AGU.

Dr. Bruce D. Cox
Hydrodynamic Research Associates, Inc.

In 1979, Dr. Cox founded Hydrodynamics Research Associates (HRA), Inc. As President and Principal Scientist, Dr. Cox has overall responsibility for HRA's work in propeller design technology. Dr. Cox was previously with the Davidson Laboratory at Stevens Institute of Technology (SIT) as Research Scientist and Professor in the Ocean Engineering Department. While with SIT, he was responsible for research in propeller-hull interaction, propeller acoustics and ducted propeller theory and design. Dr. Cox has also worked for both the David Taylor Research Center and Westinghouse Electric Corporation.

Dr. Cox received a B.S. in Naval Architecture from Webb Institute and received both his S.M. and Ph.D. in Naval Architecture and Marine Engineering from MIT. Dr. Cox is a member of SNAME, and SNAME's H-8 Panel (Propeller Hydrodynamics), ASNE and Sigma Xi.

Mr. James J. Gorman
Charles Stark Draper Laboratory, Inc., Mechanical Analysts Division

Mr. Gorman is on the Technical Staff of CSDL within the division of Mechanical Analysis. He is currently directing an investigative research and development project for the design and analysis of advanced submersible structures. Mr. Gorman has also directed research efforts at CSDL to study the potential application of superconducting motors to small submersible vehicles. Prior to joining CSDL, Mr. Gorman was a Senior Engineer at Textron Defense Systems where he performed analysis and testing of composite materials.

Mr. Gorman received both his S.B. and S.M. from MIT in Aeronautics and Astronautics. He is currently a member of AIAA and Sigma Xi.

Mr. Robert I. Hickey
Charles Stark Draper Laboratory, Inc., Vehicle Design Section

Mr. Hickey is working with the CSDL as a Staff Engineer performing hydrodynamic testing of an unmanned underwater vehicle that is presently under development. Mr. Hickey has also written hydrodynamic simulations for advanced propulsor systems and has performed preliminary analysis for various energy systems for potential use in submersible vehicles.

Mr. Hickey is a part-time graduate student in the Department of Ocean Engineering at MIT. He received a B.S. in Applied Mathematics from the University of New Hampshire.

Professor Justin E. Kerwin
MIT, Department of Ocean Engineering

Professor Kerwin has been a Professor of Naval Architecture at MIT since 1960. His principal area of research is the study of ship hydrodynamics, in particular, the field of hydrofoils and propulsors. Professor Kerwin teaches courses in marine hydrodynamics and computer applications and is in charge of MIT's Variable Pressure Water Tunnel.

Professor Kerwin received his S.B., S.M. and Ph.D. in Naval Architecture at MIT. He is currently an associate member of the SNAME and is also a member of SNAME Panel H-8 (Propeller Hydrodynamics).

Dr. Spyros A. Kinnas
MIT, Department of Ocean Engineering

Since May 1987, Dr. Kinnas has been a Research Engineer within MIT's Department of Ocean Engineering. Dr. Kinnas's research activities include: computational and experimental hydrodynamics with special interests in cavitating and separated flows around hydrofoils, wings, or propellers and the analysis of the steady and unsteady hydrodynamic flows around combinations of lifting surfaces and bodies of revolution. Dr. Kinnas also teaches graduate courses at MIT that address the theory of hydrofoils, wings and marine propellers.

Dr. Kinnas attended the National Technical University of Athens where he obtained his Diploma in Naval Architecture. He received his Ph.D. from MIT in Naval Architecture.

Mr. Robert D. Merritt
International Submarine Engineering, Robotic Systems Development

Mr. Merritt is presently Manager of the Robotic Systems Development group at International Submarine Engineering (ISE). Having served as Program Manager for the development of ISE's HYSUB 40 and the Three Mile Island MANFRED (Manipulators for Reactor Defueling), Mr. Merritt has extensive experience in the assembly and performance testing of ROV handling and power distribution systems.

Mr. Merritt obtained his B.A.Sc. from the University of British Columbia and is an associate member of the ASME, SAE and IEEE.

Dr. Arthur M. Reed
David Taylor Research Center, Propulsor Technology Branch

Dr. Reed is a Senior Research Naval Architect and is Manager of the research and development program at David Taylor Research Center for advanced propulsors for surface ships. Dr. Reed has also been involved in the analysis of the hydrodynamic and propulsive characteristics for Small Water Plane Area Twin Hull (SWATH) ships.

Dr. Reed received his B.S., M.S. and Ph.D. from the University of Michigan. He is presently a member of SNAME, ASME, SIAM and Sigma Xi.

Mr. Peter W. Sebelius
Charles Stark Draper Laboratories, Inc., Vehicle Design Section

Mr. Sebelius, as Section Chief of the Vehicle Design Section at CSDL, has overall responsibility for the structural and mechanical design of submersible vehicles. Before joining CSDL in 1983, he was a Naval Architect with Potter and McArthur, Inc. Mr. Sebelius also served in the United States Navy as a commissioned officer and is now a Lieutenant Commander in the Naval Reserve.

Mr. Sebelius received both his S.B. and S.M. in Naval Architecture and Marine Engineering from MIT.

Professor Michael Triantafyllou
MIT, Department of Ocean Engineering

Professor Triantafyllou joined the MIT Ocean Engineering Department in 1978 as a Research Associate. In 1979, he was appointed to the position of Assistant Professor and in 1983 he became an Associate Professor. Between 1982-84, Professor Triantafyllou held the Doherty professorship at MIT in Ocean Utilization. His current research interests are in the areas of dynamics and control for ocean vehicles and systems. He has recently published papers on such diverse topics as: cable dynamics, dynamics of offshore structures, and dynamics and control of remotely operated vehicles.

Professor Triantafyllou received a Diploma in Naval Architecture and Marine Engineering from the National Technical University of Athens, an S.M. in both Mechanical and Ocean Engineering from MIT and his Sc.D. from MIT as well.

Dr. David M. Triezenberg
Franklin Electric, General Engineering

Dr. Triezenberg is presently Manager of General Engineering at Franklin Electric. Before joining Franklin Electric, Dr. Triezenberg was an Assistant Professor at Purdue. At one time he was employed with Westinghouse Electric Corporation as well as Electro-Mech, Incorporated.

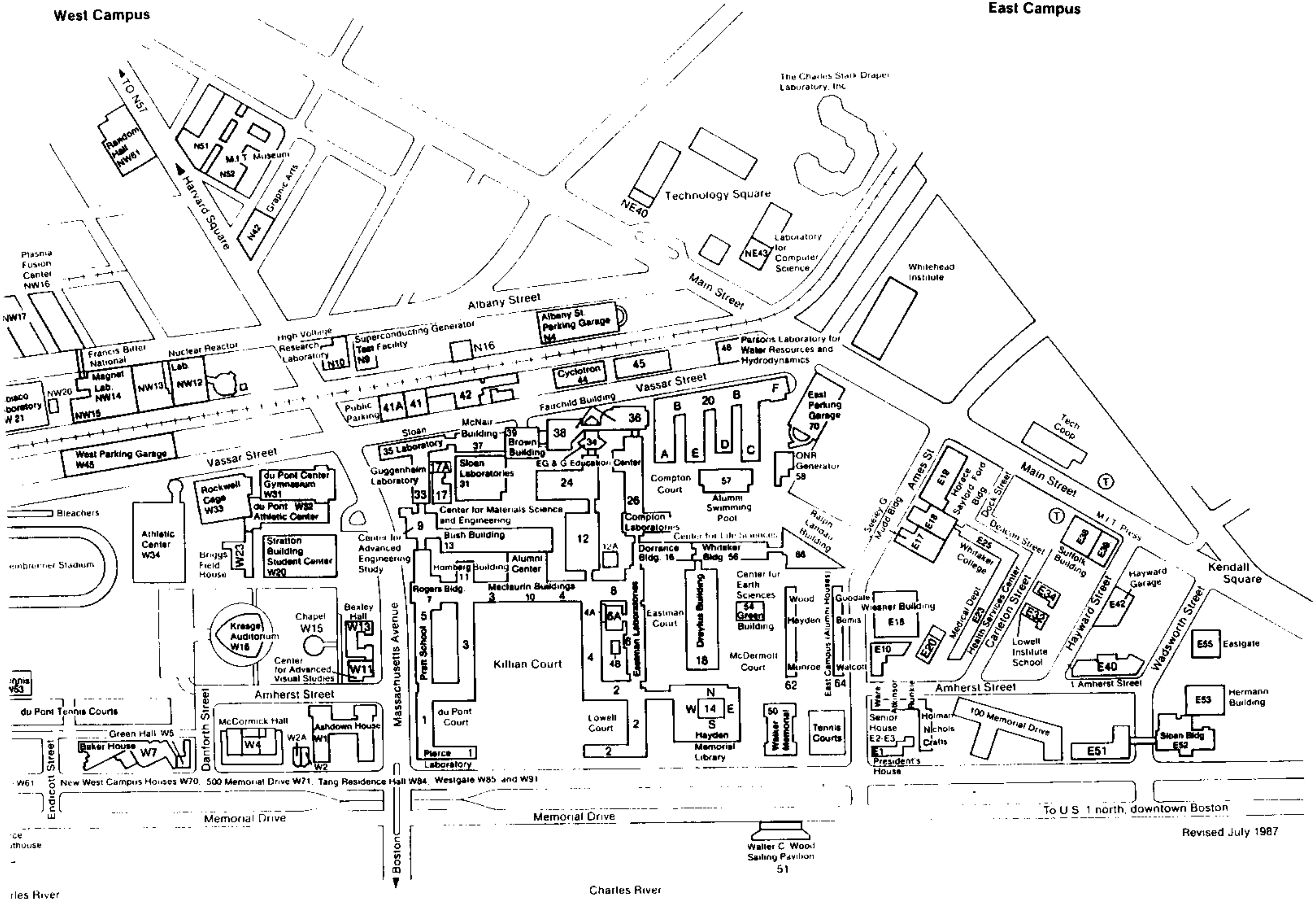
Dr. Triezenberg obtained his B.S., M.S. and Ph.D. degrees in Mechanical Engineering from Purdue University.

Dr. Dana R. Yoerger
Woods Hole Oceanographic Institution, Deep Submergence Laboratory

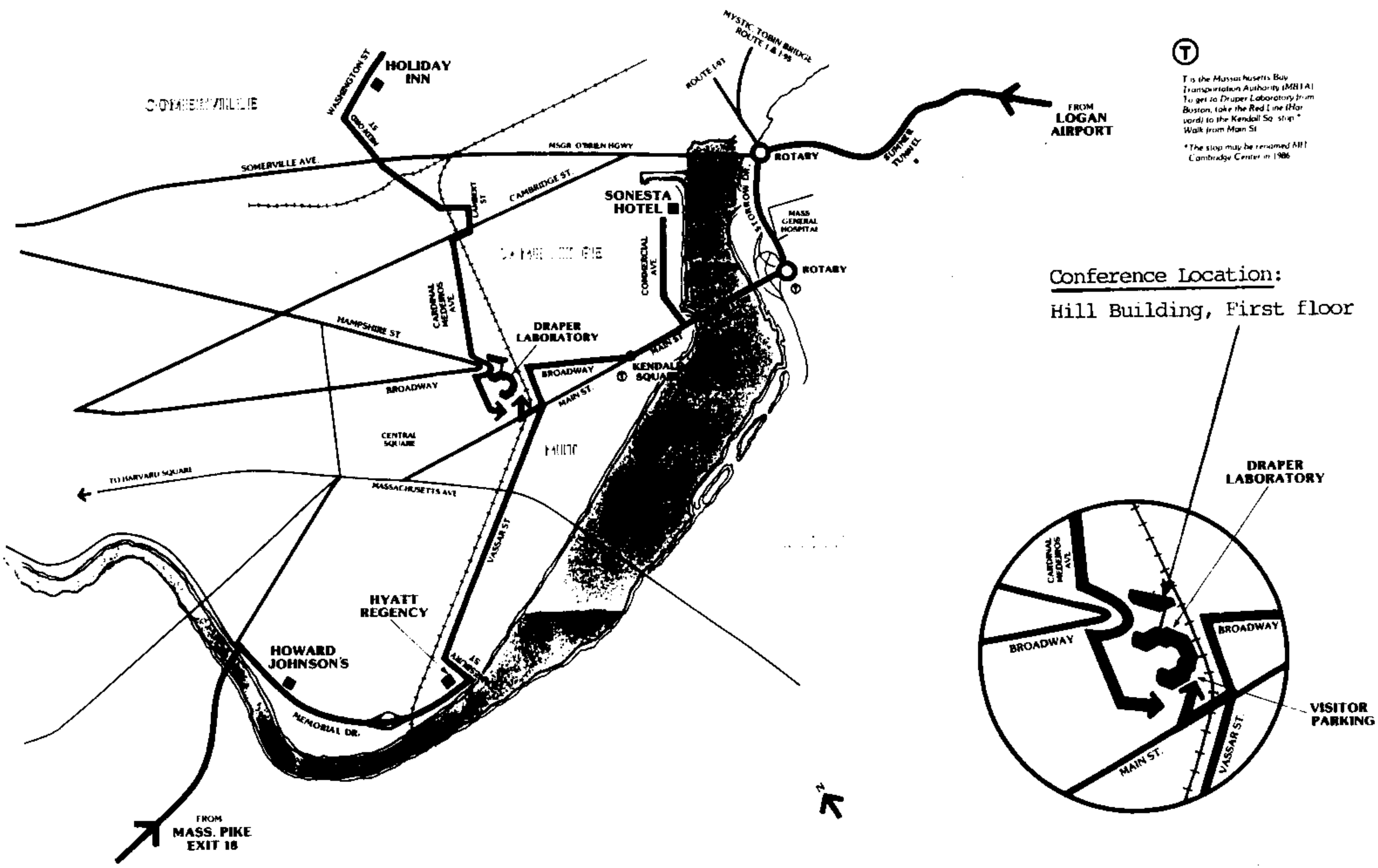
Dr. Yoerger has been an Associate Scientist with the Deep Submergence Laboratory, within the Department of Ocean Engineering at the Woods Hole Oceanographic Institute (WHOI), since 1984. At the Deep Submergence Lab, Dr. Yoerger's research activities have focused upon the areas of automatic control, vehicle dynamics and design. Dr. Yoerger was one of the principal players in the development of the JASON submersible that was used to discover and explore the Titanic. In addition to his research work at WHOI, Dr. Yoerger is also a lecturer in the Department of Mechanical Engineering at MIT.

Dr. Yoerger received his S.B., S.M. and Ph.D. from MIT in Mechanical Engineering. He is a member of the Administrative Committee for IEEE Oceanic Engineering Society and is currently Guest Editor for IEEE's Journal of Oceanic Engineering.

MAP OF MIT



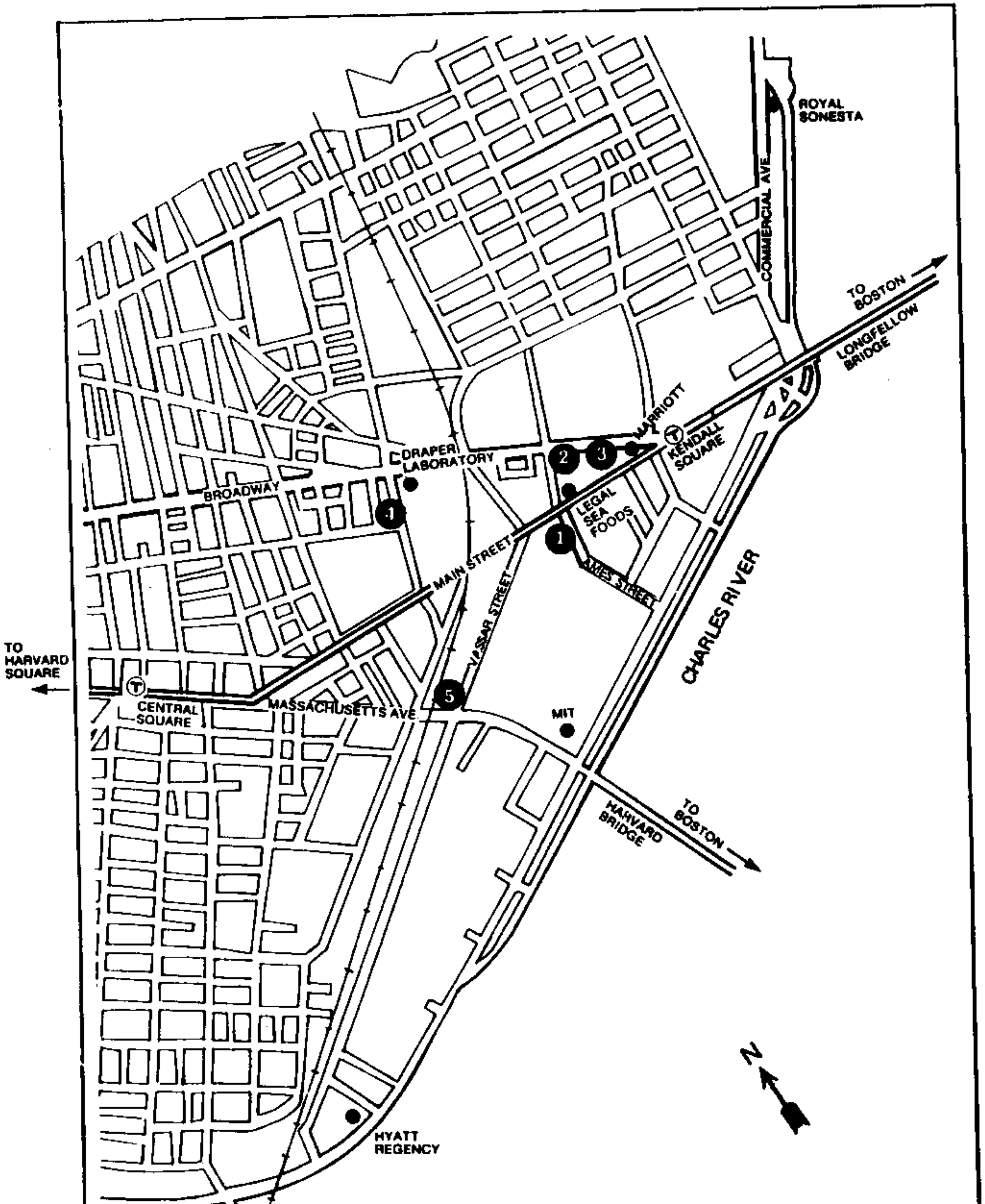
Revised July 1987



Conference Location:

Hill Building, First floor

MAP TO C.S. DRAPER LABORATORY



Kendall Square Vicinity Parking

❶ Ames Street Lot
Ames and Main Street
225-0847

❷ Cambridge Center Garage
5 Cambridge Center
Broadway and Ames Street
(off of Main St., next to Legal Sea Foods)
492-1956

❸ Cambridge Center Marriott Hotel
2 Cambridge Center (Valet parking)
494-6600

❹ Polaroid Parking Garage
Adjacent to Draper Employee Parking Garage
Technology Square

❺ Vassar Street Lot
Vassar St. and Massachusetts Ave.
(next to BayBank Automated Teller machine)

NOTE:
There is limited Draper Lab visitor parking available.
Many area hotels provide shuttle service to Draper Lab.

ACCOMMODATIONS*

Cambridge Marriott
2 Cambridge Center
Cambridge, MA
(617) 494-6600

Royal Sonesta Hotel
5 Cambridge Parkway
Cambridge, MA
(617) 491-3600

Hyatt Regency
Memorial Drive
Cambridge, MA
(617) 492-1234

Howard Johnson
777 Memorial Drive
Cambridge, MA
(617) 492-7777

*Listed in descending order to proximity of Workshop location.