Science and Technology Challenges and Potential Game Changing Opportunities

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FUTURE OF NAVAL ENGINEERING

- New enabling technologies rejuvenate mature disciplines
- The department of Mechanical Engineering at MIT is undergoing a radical transformation, which also affects the Ocean Science and Engineering
- New technologies in surface chemistry, robotics, sensors, engines and fuels, and ocean sensing offer both an opportunity and a challenge for radical changes in Naval Engineering
Department of Mechanical Engineering
Focus on Global Challenges

- Energy
- Environment
- Water
- Transportation
- Security

\{ \text{Sustainability} \}
\{ \text{Ocean Sciences and Engineering} \}

Addressing these challenges requires increasingly \textit{multidisciplinary} research and working in \textit{teams} with faculty from other departments.
Ocean Science & Engineering

- Ocean Environment
  - Hydrodynamics
  - Acoustics

- Sensing and Control
  - Sensors (Chemical, Optical, MEMs)
  - Signal Processing
  - Control

- Complex Marine Systems
  - Seismology
  - Navigation
  - Communication
  - Ocean Observation
  - GFD
  - Acoustics

- Vehicles and Platforms
  - Biomimetics
  - Hydro
  - Offshore Structures
  - Crashworthiness
  - Submersibles
  - Ships
  - Robotics
  - CAD
  - Sensors (Chemical, Optical, MEMs)
  - Signal Processing
  - Control

- Surface Chemistry
  - Vehicles and Platforms
  - Mechanics
  - Materials
  - Design
Center for Ocean Engineering
Department of Mechanical Engineering

- 24 Faculty: Ocean Engineering Area and other Areas of Mechanical Engineering
- 7 Faculty from Other Departments: 3 Chemical Engineering faculty, 1 Materials S&E faculty, 3 Electrical Engineering & Computer Science collaborate
- Several Woods Hole Oceanographic Scientists

31 FACULTY FROM 4 MIT DEPARTMENTS
NEW Center for Ocean Engineering
RESEARCH CHALLENGES

• Long-term funding by Chevron focusing on autonomous, remote oil & gas production in ultra-deep water

• Five-year ocean sensing program funded by the Singapore-MIT Advanced Research and Technology (SMART) Program

• All-Electric Ship Initiative by US Navy and the new Center for Naval Integrated Systems
ULTRA-DEEP WATER CHALLENGE

Present Technology

Near-term Technology

Long-term Technology
CONTINUOUS OCEAN MONITORING CHALLENGE:
Ship Traffic Surveillance & Inspection,
Autonomous Pollution Monitoring,
Smart Sensors for the Ocean,
Multi-resolution Sensing Using AUV

SINGAPORE-MIT ALLIANCE FOR RESEARCH AND TECHNOLOGY
ALL ELECTRIC SHIP INITIATIVE
Automation
New Hybrid Power
Continuous Monitoring
Reconfiguration

Center for Naval Integrated Systems:
New Educational Initiative
NEW ENABLING TECHNOLOGIES
NEW ENABLING TECHNOLOGIES

• **Nano-engineering Surface Chemistry:** Development of novel coatings to protect ship hulls and holds, and reduce deposits in pipelines;

• **New Structures:** New high strength steels that improve hull protection against impact and fatigue, including operation in very cold climates;

• **New Engines, PowerTrains and Fuels:** Hybrid powertrains, engines using alternative fuels, and fuel cells that use conventional fuels more efficiently;

• **Automation & Reduced Manning:** Electric ship initiative to design and operate ships with reduced manning and increased reliability;

• **Autonomous Vehicles for Operations, Reconnaissance, Inspection & Repair:** Routine launching and retrieval in rough seas, unmanned inspection, and remote underwater hull cleaning;

• **Autonomous Operation in Rough Seas:** Radar and satellite use for effective routing and operation of vessels in rough seas with unprecedented detail.

• **Smart-Hull Ships and Vehicles:** Sensor-dense arrays emulating the lateral line of fish can revolutionize hydrodynamic performance

• **Smart Hulls for Super-maneuverability and Efficient Propulsion:** Micro-sensors will allow flow control and hence efficient propulsion.
Nano-engineered Surfaces & Coatings

Fundamentally alter thermal-fluid-surface interactions for transformational efficiency gains
The Lotus Effect: “superhydrophobicity”

- Combination of Microtextured bumps and nanotextured wax crystallites
  - Revered as a symbol of sacred purity
  - Non-wetting and Self-cleaning

Hydrophilic: $\theta < 90^\circ$
Hydrophobic: $\theta > 90^\circ$
Superhydrophobic: $\theta > 150^\circ$
Superhydrophilic: $\theta < 5^\circ$

Lotus Leaf Ref: W. Barthlott (Univ. of Bonn, 1997)
Applications for “Omniphobic” Surfaces

• Now developing simple ‘dip coating’ process enabling delivery of omniphobic coating to existing textured substrates: control repellency even to low surface tension liquids such as oils, alcohols

Rapeseed oil ($\gamma_{lv} = 35.7 \text{ mN/m}$) on non-coated duck feather

Oil on duck feather dipcoated with fluorinated nanoparticles

Applications in Oil Separation:

• Design of subsea separators for separating water/oil mixtures in ‘produced oil’

Omniphobic Military (BDU) Fabric

$\gamma_{lv} = 22.7 \text{ mN/m}$

$\gamma_{lv} = 27.5 \text{ mN/m}$

$\gamma_{lv} = 50.8 \text{ mN/m}$

$\gamma_{lv} = 72 \text{ mN/m}$

Methanol

Hexadecane

Methylene Iodide

Water

EDAXS spectrum for Fluorine

After dip-coating: microtexture retained

Rapeseed oil

Water

Octane

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Ultra-High-Efficiency Heat Exchangers
Boilers, Evaporators & Condensers

Desalination (MSF Plant) (Abudhabi, UAE)

Power plant steam condensers

Marine Heat Exchangers

Hybrid Surface: Controlled Nucleation

Hydrophilic Hydrophobic

Novel nanoengineered surfaces would result in ~10-fold enhancement in heat transfer

Nanoengineered heat exchangers --> significant efficiency gains for power and water treatment (eg., 5-10% efficiency gains at the power plant level (50-100MW savings for 100MW plant))

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Durable Nano Coatings for Ships

Global shipping industry consumes 8.6% of world's oil and accounts for ~3% of global greenhouse gases (source: Reuters & Nature)

Novel Multifunctional nanoengineered coatings & surface treatments
- Antifouling & prevent/reduce biofilm adhesion
- Ultra-low drag surfaces (~ reduction by 40-70%)
- High-efficiency heat exchanger surface treatments
- Durable ceramic nano-coatings (erosion and corrosion resistant)

Examples of hard, durable ceramic nanotextures that can be applied to ship hulls
NanoEngineered Surfaces:

- Water – Oil (Liquid-Liquid) Separation
- Tailored Condensation
- Tailored Heat Transfer
- Anti Biofouling
  - Reduced Drag -- Reduce Energy
  - Reduced Maintenance – Reduced Down Time
NEW ENABLING TECHNOLOGIES

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- **Smart Hulls for Super-maneuverability and Efficient Propulsion:** Micro-sensors will allow flow control and hence efficient propulsion.
Trend of ductility with strength

Range of extreme-pressure steels

Elongation (%)

Yield Strength (MPa)

Low Strength Steels (<210MPa)  High Strength Steels  Ultra High Strength Steels (>550MPa)

Conventional HSS

AHSS

MART

Range of extreme-pressure steels
Designing Fracture Resistant Steels

Structure Level Experiment and Simulation:
Tearing of Steel Plates

Fundamental Material
Level Evaluation

Detailed FE model

Full scale

Lab test

Simulation

Butterfly specimen

Simulation Prediction
Shear and Normal test

SINGLE CRYSTAL

POLYCRYSTAL

TRIP Steels Stabilize Shear Localization Around Carbide Particles

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The Greening of Ships

• Reduction of $\text{CO}_2$ emissions through improving propulsion efficiency, utilization of biofuels and low carbon fuels, and on-board $\text{CO}_2$ capture for sequestration is timely.

• Solutions reduce fuel consumptions, diversify the fuel sources, and enhance security of resources.

• The Sloan Automotive Lab is advancing these technologies and applying them to a range of sea and ground propulsion systems.
Ship Power and Propulsion

Work on alternative fuels include the production and utilization of CO$_2$-neutral biofuels and petroleum-free synfuels.

Work on alternative powertrains include:
• Clean diesel with comprehensive after-treatment (Modern urea-based exhaust after-treatment to reduce NOx emissions) Sloan Automotive Lab;
• Clean pre-mixed gas turbine propulsion;
• High temperature fuel cells;
• Enabling technologies for hybrid-electric drivetrains.
• CO$_2$ capture in large scale mobile and stationary power plants.
ME Effort

Much in common with vehicle hybrid drivetrain

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Clean Gas Turbine Propulsion

Experimental design

Deign requirements

Modeling and validation

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Most efficient approaches to fuel production from biomass and heavy carbon feedstock use gasification and Fischer-Tropsch synthesis. Resulting biofuel is CO$_2$ neutral.

Advances in synthesis chemistry can lead to “designer fuels” compatible with alternative powertrains.
An Active Methodology for Clean Diesel

- Diesel technology is the more efficient propulsion technology for ships.
- Diesel, however, is the most polluting propulsion engine.
- Modern urea based exhaust after-treatment is able to reduce NOx emissions significantly.
- Active control minimizes urea consumption and reduces ammonia slip.
• With improved efficiency, burning low C and renewable fuels, and incorporating advancing power trains, the shipping industry can significantly reduce its carbon footprint.

• With CO₂ capture systems, it can eliminate its carbon emissions completely.

• Extend methods in developing CO₂ capture in stationary power systems to mobile propulsion systems.

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Shipboard Propulsion Systems

Integrated Propulsion Systems Enabled by:
- Efficient turbine/generator, high density batteries
- Solid State Power Electronics
- Multi-Megawatt Motor Drives
- Automated Control
View of All-Electric Ship Technology Ahead
New Levels of Automation and Energy Storage

Automation and reduced manning is a major objective

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Franz Hover: Design of the All-Electric Ship - Stochastic Simulation

Effect of random forces and modeling errors
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Autonomous Ship Hull Inspection with Acoustic Imagery

NEXT: UNDERWATER AUTONOMOUS INTERVENTION

2-D Imaging for Flat Sections

3-D Bathymetry for Complex Sections
Servoing on Acoustic Imagery under the *King Triton Vessel*

Precision control of the AUV using no external navigation source

40 drift-free circuits over one hour

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Plume-track, Retrieve Sensors & Equipment
(F. Hover, N. Patrikalakis, J. Leonard, M. Chitre, M. Adams, Sardha W.)

Autonomous Surface And Underwater Vehicles
GPS and Remote Sensing Satellites
Surface Traffic

Adaptive Sampling
Coordinated Behavior
Uncertain Communication
Self-navigating Network
Sensors
Sonars
AUV manipulators
Target
Launching and retrieval of AUVs and smart sensors in the open sea requires drastic design changes.

Operations will increasingly involve multiple AUVs and autonomous craft.

Ship and submarine design to store and launch AUVs, support their operation and communication requirements.
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Using Sensing, Phased-resolved Wave Forecasting, Ship Motions Predictions and Active Control for Optimal Ship Operations and Steering
High Speed Multi-hulls

Planing Boat in Waves

High Speed Trimaran

Stern Ramp

Boat Handling

Parametric Rolling
and Green Water

Ship-Ship Interaction
(UNREP)
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“SMART SNESOR HULLS” FOR EFFICIENT FLOW CONTROL

Super-maneuverability and efficient propulsion requires sensing of the flow around the hull.

Biomimetic flow control studies point the way. Fish employ their lateral line to sense external flow as well as their own flow patterns to optimize propulsion.
The blind cave fish and other nocturnal fish thrive in their environment.

How do they find prey? How do they avoid running into walls and obstacles, or each other?

Conclusively, they rely on their lateral line.
Lateral Line Organ: Distribution

- **Two types of lateral line structures:**
  - Surface Neuromasts
  - Canal Neuromasts

- **Superficial Neuromasts:**
  - Responsive to steady state and low frequency stimuli

- **Canal Neuromasts:**
  - Large size and more nerves
  - Sensitive up to hundreds of Hz
Fish Lateral Line Varieties

Long lateral line along the side is important for prey or threat localization, and for object detection

(Adapted from Gibbs, *Brain Behav Evol*, 2004)
Lateral Line Characteristics

- Neuromast Dimensions (see adjacent figure)
- Inter-pore Spacing: \( \sim 1 \text{ mm} \)
- Cupula Displacement: \( \sim 1 \text{ \mu m} \)
- Pressure Threshold: 0.1 - 1 mPa
- Canal System Filter Cutoff: 100 Hz

(Information and Figures adapted from Van Netten, *Biol. Cybern.*, 2006)
Design Overview

Three types of sensor arrays:
-- strain gauge design on silicon wafers, or flexible substrate
-- piezo-resistive and
-- piezo-electric designs, require silicon diaphragms, mounted on flexible liquid-crystal polymer substrates.

All three designs are sensitive to signals in the acoustic range.
A. Vortex Tracking

- Four sensors track a vortex
- Extended Kalman filter estimates strength and position
- Comparison against PIV data
Vehicle Energy Saving through Maneuvering Control

- MEMs pressure sensors can detect the helical vortices forming on the body of a maneuvering body, allowing flow control and hence significant drag reduction, and super-maneuverability.
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NAVAL SHIP OF THE FUTURE

• Highly automated, all-electric, using new engines and fuels, reconfigurable for robust operation,
• “Smart” hull brings super-maneuverability and high efficiency
• Coatings reduce need for servicing, reduces drag
• AUVs and smart sensors central to design and operation; autonomous operation in rough seas