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Engineering for the Marine Environment at an American Research University*

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Education and research are of equal importance in a leading research university in the USA, in terms of expenditures, use of laboratories, and human resources. Education requires supporting a comprehensive curriculum in BSE, MSE, M.Eng. and the advanced PE degrees of Marine Engineer and Naval Architect to prepare professionals for a lifelong career; and supporting a graduate curriculum in MSE./Ph.D. to educate researchers and future educators. Innovative research requires the ability to compete successfully for funded fundamental research across engineering boundaries, educates research professionals, and helps faculty to evolve. Demands from marine industry ranging from practical engineering to innovative research are broad and not necessarily compatible with our responsibility to educate engineers with knowledge of fundamentals and adequate flexibility to be successful professionals for the next 40–50 years. In our field, both research and education require daily use of experimental facilities that are large and expensive to upgrade and maintain. The discipline of Engineering for the Marine Environment is unique, broad in terms of applications, small in terms of human resources, and internationalized. Recent changes in politics, the economy, the nature of engineering, as well as advances in information technology complete the challenge. Definition of the challenge and this paper presents a solution suitable for the University of Michigan as a paradigm.

INTRODUCTION

IN THIS PAPER, the term 'Engineering for the Marine Environment' encompasses all specializations within our engineering discipline. The faculty of the Department of Naval Architecture and Marine Engineering at the University of Michigan introduced this term in 1994 [13] and used it in the SNAME promotional video 'The Call of the Sea' [29]. Naval architecture, marine engineering, offshore engineering, marine technology, ocean engineering, near shore or coastal engineering, marine systems, shipbuilding technology, and marine environmental engineering are some of the names used to represent activities within our engineering discipline. To an outsider, engineer or not, probably the term 'Marine Engineering' best describes our engineering discipline. To people in our profession, however, this term relates only to marine power systems.

This unresolved issue of finding the best name for our engineering discipline started in the decade of the seventies [4, 22], when commercial shipbuilding started to decline in the USA and our profession expanded into other engineering challenges in the marine environment. Several studies [4, 22, 24, 3 2] published on education aimed at better defining our engineering discipline and capturing its essence in a single name. Periodic revisits of this issue occur [23, 25–27] as our profession evolves. Most recently, the Royal Institute of Naval Architects (UK) [28], the Office of Naval Research (USA), and the NA&ME Department at the University of Michigan [14] independently reexamined the definition of our engineering discipline.

This is an appropriate time for a self-study as accelerated rates of change make continuous evolution necessary in the economy and engineering. High school graduates entering engineering seek the most glamorous high tech disciplines. Industry demands young engineers be ready to be productive upon graduation with a BSE [30], and research opportunities need professionals with stronger scientific background, while universities have a responsibility to provide engineers with a balanced education capable of supporting a 40–50 year career. At the same time, the nature of engineering is changing [18–21] a situation reflected even in the new assessment process [1, 2] introduced by the Accreditation Bureau for Engineering and Technology (ABET) in 1997. Fortunately, information technology provides tremendous new resources to support more efficient education within a 4 or 5 year program. Simulation Based Environment (SBE) [8], distance learning, education on demand [7], and electronic technology [31] are new means of providing education. Research universities face additional challenges in conducting original fundamental research unique to the marine environment, not just technology transfer or development. In a field with a broad spectrum of applications and few human

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resources, it is a challenge to focus and excel in research while supporting the full spectrum of curricula.

In this paper, Section 1 defines the uniqueness of engineering for the marine environment, Section 2 presents the challenge faced by a research university in the USA and Section 3 discusses the driving forces for evolution. Section 4 presents the solution we believe to be the best for the University of Michigan as a paradigm.

UNIQUENESS OF THE ENGINEERING DISCIPLINE

We choose to avoid the issue of what the most representative name is for our engineering discipline and collectively refer to all specializations in our profession by the term 'Engineering for the Marine Environment.' Instead, we place emphasis on determining the features of our engineering discipline that make it unique. The marine environment is unique; the structures and vessels operating in the marine environment are unique; the impact of engineering for the marine environment on national prosperity and the quality of human life is very strong.

The marine environment—oceans and lakes and rivers—covers 73% of the earth's surface. It is unique in the following ways [14]:

- Water is a high pressure medium.
- Salt or fresh water may be highly corrosive.
- Generation and propagation of waves can occur at the air—water interface.
- Wind generated waves are random and typically form multidirectional spectra.
- Water cavitates when high speeds result in low pressure leading to interfaces within the water medium.
- Marine hydrodynamics problems span a broad range of scales from the smallest dissipative turbulence scale and boundary layer, through wave and structure scales, to geophysical and mesoscales.
- Electro-magnetic penetration of water is shallow, requiring special communication and sensing for systems operating in and on water.

Marine structures, vehicles and systems are unique:

- Construction of each design on a small scale requires a high degree of specialization, and makes design for manufacturing more challenging and expensive.
- Marine structures are the largest human-made systems and their databases may be up to three orders of magnitude larger than those of aircraft.
- Marine structures are very complex and structural mechanics problems span a broad range of scales from micro scales for welding and fatigue to full structure scales.
- Marine vehicles and structures operate in and on the ocean thus having special design requirements relevant to seakeeping, capsizing, station-keeping, and random motions and loads in a hostile environment.

Finally, the impact of engineering for the marine environment on the quality of life is unique:

- The marine environment is a source of food, and clean and renewable energy.
- Ships carry 74% of world trade.
- Ships transport 95% of the USA's international trade.
- 85% of the population of the USA is expected to move within 50 miles of a coastline by the year 2010.
- Naval ships are essential to national defense.
- Ships are used to import 60% of the energy that is used by the USA

The economic importance of the marine environment makes it a place in which to explore, operate, and utilize its resources. Thus, it attracts engineering operations spanning across all engineering disciplines. The uniqueness of the environment and marine systems, however, require a special discipline within engineering education.

THE CHALLENGE

This section presents the challenge of education and research at an American research university in 'Engineering for the Marine Environment' in this section. Figure 1 schematically shows the various pieces of the puzzle. In an effort to present the various factors affecting the process in an organized fashion, they are divided into product, resources, and demands. Classification of the demands occurs at three levels: demands, constraints, and other requirements.

PRODUCT

Education and research are of equal importance at a research university in the USA. Service to the profession and outreach to the constituency are mandatory for successful delivery of the first two products. A discussion per product follows:

Education

Education covers the curricula and the intellectual environment, offering curricula at BSE, MSE, M.Eng., PE and Ph.D. levels. The first professional degree typically is a four year program with the first year in the College of Engineering and the last three in an engineering department, although the average graduation time is 4.7 years. As the engineering profession changes [19, 20, 21], however, it is becoming evident that the first professional degree for industry may soon become a five year program [3]. Several USA

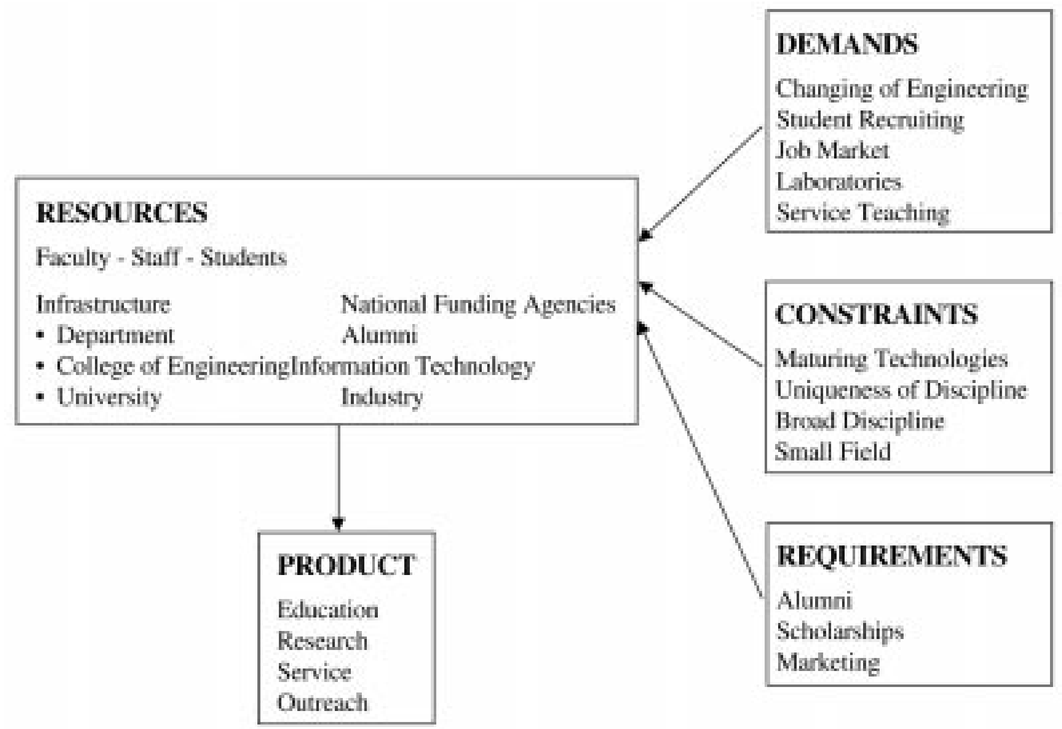

Fig. 1.

universities already offer such programs. The University of Michigan allows top students to take a five year combined BSE—MSE program. MSE and M.Eng. are one year graduate degrees. The former may lead to the Ph.D. program. M.Eng., has the additional admission requirement of two years of industry experience and requires completion of an industry project. The Naval Architect and Marine Engineer PE degrees are two year programs with course requirements equivalent to two master's degrees and the requirement of completion of a major development project with practical application. The Ph.D. curriculum is intimately related to research. It has a two year course requirement and extensive original research publishable in leading archival journals. Education of research assistants supporting a healthy research program requires a Ph.D. curriculum. A Ph.D. is granted to a research assistant when he or she develops an adequate amount of fundamentally new knowledge. This is conceptually different from the knowledge developed for a PE degree. The following questions arise:

Q1: Are departments in our engineering discipline large enough to support all curricula from BSE to Ph.D.?
Q2: What constitutes an acceptable balance between generic courses offered by other mechanics oriented departments (Mechanical, Civil, Aerospace) and courses studying the unique aspects of engineering for the marine environment?

National research agencies such as the Office of Naval Research (ONR), the National Science Foundation (NSF), NASA, the Sea Grant, the Department of Transportation (DOT) combine with private industry fund research. Areas of research mature faster than faculty retire and new are hired. For example, several traditional areas of research in marine mechanics such as seakeeping and ship structures, still require important development for design purposes, but have been declared mature for the purpose of fundamental research. New areas such as micromechanics, constitutive equations for new materials, etc., [9] are of fundamental nature and have no departmental barriers as we have in universities. In addition, multi-disciplinary research is currently more promising and attractive to funding agencies. The following questions arise:

Q3: Can we identify continually new fundamental research issues unique to engineering for the marine environment or is fundamental research generic across several engineering disciplines?
Q4: Can faculty remain flexible enough to develop and pursue new fundamental research in our engineering discipline or multidisciplinary research?
Q5: Do we have adequate human resources to do technology transfer from other engineering fields while also performing fundamental research?

Service has as many facets as the marine industry. Besides the traditional service to the profession, shared equally among all professionals in our field, the research community, under the leadership of research agencies or the National Research Council of the National Academy of Engineering periodically generates studies [9, 10, 22, 23] for research directions with a vision of 10–15 years. The following is only a rhetorical question since this is a mandatory service for faculty in a research university.

Q6: Can we provide leadership in defining the future of fundamental research in engineering for the marine environment?

There is probably a need for outreach to colleagues and researchers in our field internationally more than in any other engineering discipline. Our discipline is broad, unique, with limited human resources and large and expensive to maintain laboratories. We have been most effective as a community to achieve international synergy through ISSC and ITTC, exchange of visiting faculty, students, and even joint projects and use of laboratories.

Resources

Human resources, infrastructure, funding agencies, alumni, and information technology constitute our pool of resources.

Faculty have the responsibility of the credibility and quality of our products. Staff and students, however, provide valuable service in recruiting and mentoring younger students.

Infrastructure is most important in maintaining a high quality operation. In that respect, being part of a top quality university, with an administration that values the importance of small, high quality departments is helpful. A naval architecture and marine engineering department may quickly lose its identity and uniqueness and consequently be forced to oblivion if maintenance of large and expensive laboratories for education and research is not possible.

National funding agencies have an agenda to identify promising research areas, support fundamental research, and maintain areas of national need such as Engineering for the Marine Environment. It is in the mutual interest of funding agencies and departments in our engineering discipline to define and support fundamental research. The relevant question here, besides Q6, is:

Q7: Do we have the critical mass of faculty and high quality Ph.D. students to support a credible line of research that can actually have an impact in our field?

Industry has many facets and each requires a different kind of research support. In general, the shipbuilding industry asks for short-term development or technology transfer and is much less involved in university research than the automotive or aerospace industries. The offshore industry has a longer vision and more challenging problems and supports university research. The Office of Naval Research has the longest vision, greater focus for fundamental research, supports the Navy mission, and is instrumental in maintaining high quality research and state of the art facilities in research universities.

Q8: Do we have enough faculty to increase collaboration with industry without losing our focus on fundamental research?

Alumni are successful professionals and cumulatively a valuable resource. They provide advice, contact with industry, feedback on education, funding for fellowships and special infrastructure needs, endowments, job placement, summer jobs, ideas for future research, etc. They are an integral part of the university operation.

Information technology is a resource that is changing engineering education continuously [7, 8, 15] and is expected to have a major impact with the development of Simulation Based Environments [8, 15] and electronic means of distance education [7]. The relevant question is:

Q9: Simulation Based Environments soon will be the industry and government standard. How quickly can we develop SBE in research universities and implement it to make curricula more effective? This is further discussed in Section 3

The sources of pressure

These are constraints that define the feasibility domain in a design problem. Understanding them serves as sensitivity analysis. For the sake of presentation, listing is in ascending order of rigidity in demands, constraints, and requirements.

Demands

The changing nature of engineering, students with better informed about job opportunities, moving job markets, large and expensive laboratories, and teaching service courses place the strongest constraints on the puzzle.

The changing nature of engineering is obvious and discussion has been extensive in the literature [18–21]. We will only focus here on two issues important to our field. First, historically, naval architecture and marine engineering placed a strong emphasis on systems engineering with particular emphasis on performance in structures, hydrodynamics, propulsion, dynamics, vibrations, outfitting, etc. During early 1980's at the University of Michigan, we introduced the first program in ship production science in the USA. In 1994, we expanded the systems engineering concept and our entire undergraduate curriculum to include manufacturing and lifecycle cost estimates. Presently, however, systems engineering has stopped being the monopoly of naval architecture and marine engineering, and to some extent aerospace engineering. Most engineering disciplines with capstone design courses—from automotive to chemical engineering to VLSI design—have recognized the importance of this concept and have adopted it in industries and universities. Simulation Based Environments are being developed by the aerospace, automotive, shipbuilding and military industries, as well as the government. In SBE, virtual prototypes can be viewed, tested with physics-based applications, and redesigned. Such environments bring systems engineering within reach and understanding of most engineers with experience in design. Thus, the appeal that NA&ME had to students that they can learn to design a complete system has lost some of its uniqueness.

The second issue is that the complexity of advanced engineering requires large teams of engineers who can work concurrently, on line, using different computers, software and databases, while distributed widely geographically and culturally. This makes teamwork and communication skills important educational components in modern engineering curricula. Further, awareness of societal needs has made ethics and environmental implications important curricular threads. The new ABET accreditation requirements reflect these [12]. As a consequence of the above two characteristics of change in the nature of engineering the following question must be answered:

Q10: In SBE and online teamwork, the naval architect and marine engineer's understanding of systems engineering may no longer give him or her the competitive advantage. In SBE, what are the skills that uniquely qualify him/her?

Students in engineering seek education that will provide them with well paying jobs that are challenging and technologically advanced. They are also flooded with information and have much shorter attention span.

Q11: Have our professional societies changed, updated their image and marketing strategies to reflect the excitement and challenge of engineering for the marine environment to attract the best engineering students to our field?

The job market is very healthy. Graduates of the University of Michigan in NA&ME receive on average 4–5 job offers upon graduation; the historical average is three job offers. Our summer job program has twice as many openings as applicants. The job market in the marine industry is diverse and requires engineers with various skills from the traditional NA&ME education to the more modern engineer who understands the uniqueness of engineering for the marine environment and can operate in SBE. The obvious issue is:

Q12: American universities have de facto selected their niche of education to serve industry. Which is the new proper educational model for a research university in our engineering discipline?

Laboratories, and particularly towing tanks, maneuvering basins, wave tanks for offshore engineering research, cavitation tunnels, structures labs, and virtual caves, are large and expensive to maintain with state of the art equipment. Around the world, several such laboratories have been shut down with no prospect of reopening. The relevant question here is:

Q13: Can we generate enough revenue from research or applied industrial work to support such facilities that are difficulty to rebuild? Is international collaboration to maintain the most modern facilities feasible?

Certain universities require service teaching at the freshman level in order to share the teaching load across all departments. In small departments, this has a particularly heavy toll on faculty availability to teach our specialized courses.

Constraints

Research universities impose additional constraints that are discussed next.

Maturing technologies lose funding from the national fundamental research sponsors. Two problems arise from that. First, faculty must be flexible enough to pursue new, high risk, promising research areas. Second, when a faculty member in a mature research area retires, but there is still a need in that area for undergraduate education, some drastic solutions are needed. For example, marine engineering in the traditional sense has minimal research funding in America.

Q14: In a research university, how can we continue teaching marine engineering; by using service courses in mechanical engineering, eliminating marine power systems from the curriculum, hiring adjunct faculty at considerable cost, or evolving marine engineering into new viable research areas?

Section 2 defined the uniqueness of engineering for the marine environment. There is no doubt that since we have limited human resources it is necessary to use courses in other departments in some of the curricula offered: BSE, MSE, M.Eng., professional degrees, Ph.D.

Q15: At which level is it more important to educate engineers on the unique aspects of engineering for the marine environment; the first degree BSE, or the ultimate degree—Ph.D.?

Requirements

Additional workloads come from marketing, raising funds for student scholarships, and working with alumni. Probably, the latter is the most pleasant of our tasks given the dedication of most alumni to their alma mater.

DRIVING FORCES FOR EVOLUTION

The previous section discussed the demands on our resources. Demands are not stagnant; demands evolve in time and at an ever-increasing pace. To satisfy the demands successfully our product has to evolve preferably in anticipation or at least in response. Most importantly, the faculty and departmental resources have to evolve, preferably proactively anticipating future demands. Before developing a response to the challenge, we identify the driving forces for evolution of education and research. The static or dynamic nature of these forces determines whether the requirement is for a one-time adjustment of our product or a continuous evolution. Following is a list of some of the current driving forces for change:

D1 The changing nature of engineering brings up new multidisciplinary projects, requires dedicated solutions for designing and manufacturing new structures and systems in a much shorter time. The diversity of projects from biomedical engineering, new materials, to microelectromechanical systems requires more emphasis on fundamentals.

D2 Simulation Based Environments for virtual prototyping, testing by physics-based modules, design for manufacture, and acquisition make information technology a powerful tool of the future. Its nature is dynamic, and affects not only teaching of marine systems design, but also marine mechanics. Most important it makes synergy between the two have a visible immediate impact that can be most impressive to students.

D3 The uniqueness of education in our field has additional emphasis now. The uniqueness of the environment and the marine systems becomes as important as the skill to design systems in SBE. Accordingly, education in the unique aspects of engineering for the marine environment in early education (BSE) becomes even more important.

D4 In modern engineering, teamwork, communication skills, ethics, environmental awareness became an important aspect of education leaving less room for important courses in mechanics and materials. Thus, a five year education program may soon become the entry professional degree for industry.

D5 Research is probably the hardest pressed and there needs to be breakthroughs [23] in several areas, such as propulsion, viscous flows, stochastic mechanics, and design for manufacturing. Breakthroughs drive research, development and education as shown in Fig. 2 [10]. This requires multidisciplinary research with better synergy between the various specialties of marine mechanics and systems design.

THE UNIVERSITY OF MICHIGAN PARADIGM

Universities in the USA that offer degrees and/or have research programs in 'Engineering for the Marine Environment' have to find their own answers to at least the 15 questions provided in this paper. They will also need to decide how to

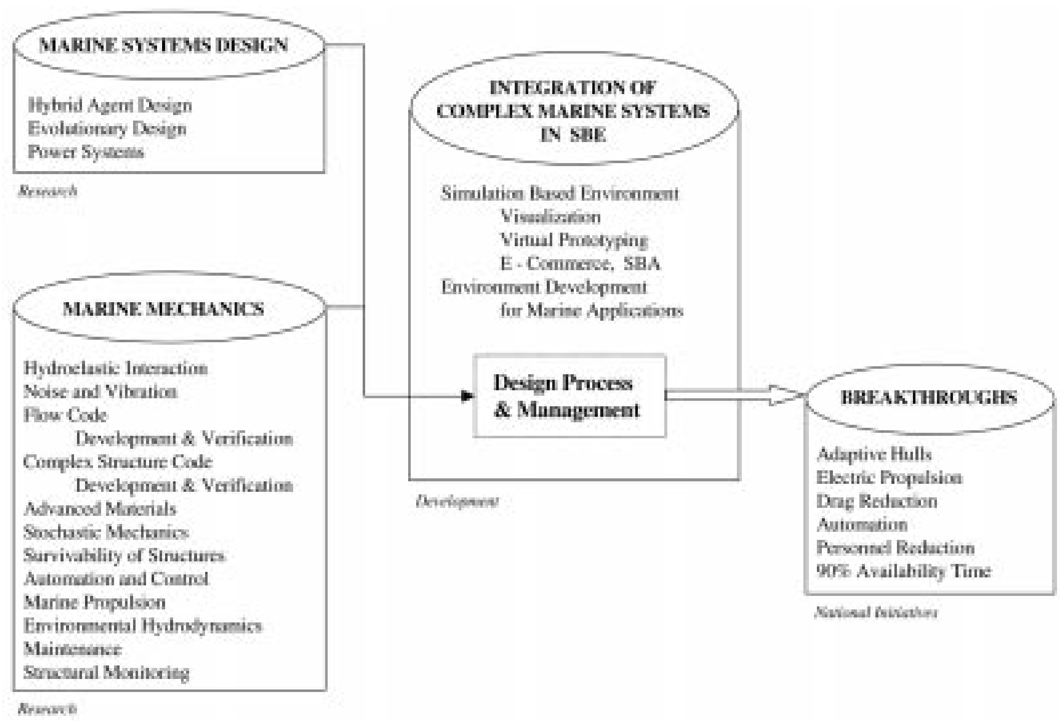

Fig. 2.

evolve in response to driving forces D1–D5. The solution for each department in our field is expected to be different, with the mission of the home university, its resources, its tradition, the support of alumni, etc., strongly influencing the solution. Thus, rather than attempting the impossible task of presenting an optimal solution, we present the University of Michigan paradigm.

Every research university with education and research programs in engineering for the marine environment in the USA is small and has limited resources and facilities. To survive and succeed, each university has to select its niche of excellence and focus its efforts. We have made such a choice at the University of Michigan and it is summarized below as a paradigm response to the challenges we face. Our approach has evolved over the past five years [13] and included the development of a plan for the evolution of the next five years [14]. The basic principles in our response are the following:

P1: *Engineering for the marine environment is a unique engineering discipline with colossal impact on national prosperity and the quality of life on earth. Accordingly, preparation for the practice of engineering for the marine requires a special discipline within engineering education.*

P2: *Our primary mission is to:*
- *provide the leading bachelor's program in naval architecture and marine engineering in the USA, with emphasis on the design, manufacture, and management of marine vehicles, structures, and systems.*
- *provide the leading graduate education and research program in engineering for the marine environment in the USA, one that spans a broad range of inquiry.*

P3: *An upgrade of the traditional systems engineering curriculum occurred in 1994 and resulted in the inclusion of courses on manufacturing and lifecycle cost estimation in addition to the introductory design class in the second year. Thus, students are introduced to these concepts prior to studying the core marine mechanics courses in the third year.*

P4: *As part of a College wide effort, the evolved marine systems design curriculum was overhauled (1997–2000) to implement increased emphasis on team work, communication skills, ethics, and environmental awareness. It satisfies the new ABET accreditation criteria.*

P5: *Marine mechanics and marine systems design are the two pillars of our education system at both the undergraduate and the graduate levels. The former provides the basic science and mechanics knowledge and the latter the ability to design systems operating in the unique marine environment. Such knowledge can support a successful 40–50 year career in engineering.*

P6: *Simulation Based Environments are developed for simulating and testing virtual prototypes and are being implemented in both the undergraduate and the graduate curricula. The anticipation is that teaching will become more effective, thus allowing more time for marine systems design, not only at the BSE level but also at the MSE/M.Eng., and even the research/Ph.D., levels. SBE also makes understanding of mechanics more important for development and evaluation of simulation modules and support of design decisions.*

P7: *The uniqueness of engineering for the marine environment is to be enhanced further by promoting focused study of the issues of fluid-structure interaction, the stochastic nature of excitation, and stochastic mechanics; and increased synergy between the five areas of marine mechanics (hydrodynamics, structures, dynamics, vibration and stochastic mechanics) in the junior and senior year analysis courses.*

P8: *A five year educational program is now open to the top undergraduate students. The anticipation is that industry may soon consider a five year engineering degree as the entry professional degree. The American Society of Civil Engineers (ASCE) has already made this policy decision [3].*

P9: *It is important to maintain and continuously upgrade facilities that are unique to engineering for the marine environment. At the University of Michigan we have a commitment to operate the following world class facilities [29]. All of these facilities are used in teaching at all levels from BSE to Ph.D., and for research and applied industrial testing.*

- *model basin*
- *undergraduate marine design lab*
- *virtual reality lab*
- *the University of Michigan virtual reality cave which is operated by department faculty*
- *low turbulence free-surface channel*
- *the remote operated submarine M-Rover*
- *a CAD laboratory operated by CAEN (Computer Aided Engineering Network)*
- *a CAD laboratory for the Simulation Technology Center*
- *two-dimensional gravity wave tank*
- *gravity-capillary water wave facility*
- *student propeller tunnel*

P10: *Research expenditures represent about 55% of our annual budget. A healthy research program is vital for generation of new knowledge, development of faculty, education of research professionals, and bringing new material into the curricula. In a research university such as Michigan, no area of specialty can survive without a clear vision of* *research and solid funding. There are numerous research issues unique to engineering for the marine environment. Many of the most exciting projects, however, with high potential for impact are interdisciplinary with application in our field. The Faculty work in teams to develop, and raise funds for the completion of such projects.*

P11: Engineering for the marine environment is broader than naval architecture and marine engineering. Accordingly, we have diversified our department; since 1987 we have replaced three retiring faculty with new young faculty with specialties in hydrodynamics that cover scales from meso to geophysical, tsunamis to wind waves, swell to capillary waves, and wave to turbulence scales. We have also hired a faculty member in noise/vibration/acoustics of marine structures.

P12: Marine power systems is an important part of the undergraduate and first year graduate curricula and teaching expertise will be maintained. We have redefined the research focus of marine power systems and plan to hire a new faculty member with a clear vision of research in this area. This will continue for the next twenty years, with the intent of contributing to a breakthrough in propulsion.

P13: Collaboration with research funding agencies to define actual new research areas is mandatory. The NA&ME Department at the University of Michigan is committed to remaining a leader in this important service to our profession.

P14: We have established active international collaborations with premier sister departments around the world that we value and intend to support. These are the University of Sao Paulo, Brazil; the Technical University of Berlin, Germany; the Norwegian University of Technology, Trondheim.

P15: The name of naval architecture and marine engineering still represents well the focus of our undergraduate education. Our graduate program, however, has diversified and evolved to engineering for the marine environment in the past 15 years. Marine mechanics provides the scientific basis of our education system with a critical synergy with marine systems design. Applications cover a broad range from large ships and submarines, to offshore towers and floating production systems, to ocean habitats and micro-electromechanical ocean systems. We maintain marine engineering in the department name as it represents an integral part of the curricula; to the general public it is a clear term with a broader interpretation.

CONCLUSIONS

This article has presented the challenge of providing high quality education and performing original fundamental research in engineering for the marine environment at a leading research university in the USA. Several demands for continuous evolution of curricula, research areas, and faculty arise from such an environment. The changing nature of engineering, adaptation of systems engineering by other engineering disciplines, the development of Simulation Based Environments, and the genesis of attractive disciplinary research topics provide additional incentives for evolution. In this environment of accelerating evolution, it is important to maintain the uniqueness of engineering for the marine environment while making essential contributions in fundamental research.

The approach we adopted in Michigan was presented as a paradigm for responding to this challenge. It calls for dedicated support of the uniqueness of the professional curricula (BSE, MSE, M.Eng., professional degrees) in naval architecture and marine engineering. At the research level, (MSE/Ph.D.), we have diversified to the broader aspects of engineering for the marine environment so that we can enhance our flexibility in pursuing new multidisciplinary thrust areas in research and provide advanced graduate education needed by the nation and world.

Acknowledgements—This paper summarizes the team effort of the faculty, staff, and students of the Department of Naval Architecture and Marine Engineering at the University of Michigan to evolve continuously and improve our educational and research programs. This continuing effort started in 1994 and has specific action plans through 2005. The author would like to thank Professor Michael G. Parsons of the University of Michigan and Professor Eugeniy Trushliakov of the Ukrainian State Maritime Technical University.

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while they are in tension along their entire length. Proven that Willer's theory (1941), on buckling of long columns was incorrect. Developed the correct asymptotic theory. (4) Hydrodynamic Forces on Slender Bodies. Derived complete expressions for inertia forces and moments acting on a small body in 6D motion in 3D unsteady flow in an unbounded ideal fluid. Far field approximation of the body motion by a series of multipoles provides formulas attractive for engineering applications.