Department of Mechanical Engineering and Applied Mechanics

ANNUAL REPORT 1992-93
Mechanical Engineering Faculty, 1868-1993—Joseph Akerman•Rayhaneh Akhavan•John Allen•Wyeth Allen•Herbert Alvord•Henry Anderson•Vedat Arpac•Ellen Arruda•Eugene Ash•Anthony Atkins•Arvind Atrey•James Barber•Myron Begemen•Kurt Binder•Jay Bolt•Claus Borgnakke•O. W. Boston•Frederick Boutwell•Thomas Boyle•Giles Brereton•James Brown•Joseph Bursley•Robert Caddell•James Cairns•Floyd Calhoun•Harry Campbell•Robert Carson•Steven Cecio•Milton Chace•Michael Chen•John Clark•Samuel Clark•Howard Colby•David Cole•Lester Colwell•Maria Comninou•Gerald Conger•Mortimer Cooley•James Daily•Joseph Datsko•J.B. Davis•Walter Debler•Charles Denison•Warren DeVries•Donald Douglas•David Dowling•Debashis Dutta•Glenn Edmonson•John Emswiler•Arnet Epple•Rune Evaldson•Lary Evans•John Faig•Shaya Fainman•Spilios Fassio•David Felbeck•Charles Fessenden•Robert Fijian•Francis Fisher•Walter Fishleigh•William Flaherty•Richard Flinn•Richard Folsom•Julian Frederick•Victor Gaulthier•William Gilbert•Steven Goldstein•Charles Good•Charles Gordy•William Graebel•William Graves•Mark Greg•Anton Greiner•John Grennan•George Grimes•Mehrdad Haghi•Keith Hall•Frederick Hammitt•Arthur Hansen•Ransom Hawley•William Hazelton•Naeim Henein•Alexander Henkin•Robert Heppinstall•Robert Hess•Dean Hobart•Robert Hoisington•Oliver Hollis•Harold Holmes•John Holmes•Stanley Jacobs•Clarence Jagodzinski•Gordon Jensen•Glen Johnson•Carroll Jones•Robert Juvinal•Elijah Kannaty-Asibu, Jr. • Bruce Karnopp•Massoud Kaviany•Hugh Keeler•Robert Keller•Clarence Kessler•Noboru Kikuchi•Henry Kohler•Yoram Koren•Sridhar Kota•Ralph Kraft, Jr. • Edward Lady•Jonathan Laitone•F.X. Lake•Poul Larsen•Walter Lay•Charles Lipson•Robert Little•Harold Lloyd•Donald Long•Roger Low•Kenneth Ludema•Axel Marin•Joseph Mazur•James McElhaney•Robert McKe•John Melvin•Herman Merte, Jr. • Frank Mickle•William Migget•Henry Miller•William Mirsky•Karl Moltrecht•George Morley•James Moyer•Clair Myron•Jun Ni•De Owen Nichols•John Nickelsen•Lorraine Olson•Martin Orbeck•Thomas Orr•Kenneth Packer•Edward Page•Jwo Pan•Panos Papalambros•Homer Parker•Donald Patterson•Felix Pawlowski•J. Raymond Pearson•John Penrose•Noel Perkins•Vernon Phelps•Walter Pierce•Christophe Pierre•R. Clay Porter•Philip Potts•David Pratt•Horace Purfield•Leland Quackenbush•Krishnan Radhakrishnan•Ravi Rao•Stillman Robinson•Don Rogers•Franklin Rote•John Rowen•Robert Ryan•Shyam Samanta•Albert Schultz•William Schultz•Frank Schwartz•Raymond Scott•Richard Scott•Leonard Segel•Steven Shaw•Allen Sherzer•Joseph Shigley•Scott Slezak•Frank Smith•Gene Smith•Hadley Smith•Homer Smith•Robert Smith•John Smoots•Louis Solomon•Richard Sonntag•Frank Sowa•William Spindler•Charles Spooner•George Springer•Wilbert Steffy•Jeffrey Stein•Robert Stevens•John Sullivan•Joseph Sweeney, Jr. • Douglas Tally•Clarence Taylor•John Taylor•William Telfer•Charles Thorpe•Stanton Tompkins•William Truckenmiller•Grétar Tryggvason•A. Galip Ulsoy•Gordon Van Wylen•William Verner•Frederick Vesper•Charles Vest•Edward Vincent•Quentin Vines•Phillip Visser•Frank Wagner•Leslie Wagner•Allen Ward•Henry Watson•Earl Webb•Philip Webb•Franklin Westervelt•Joseph Whitesell•Clyde Wilson•Alan Wineman•Ward Winer•Robert Winslow•Anthony Woo•DeVolson Wood•Shien-Ming Wu•Chin Tse Yang•Wei-Hsuan Yang•Wen-Jei Yang•Chia-Shun Yih•John Young•Paul Youngdahl•M.Y. Zarbrugh•Stanislaus Zowski

This list was compiled from a variety of sources and may not be a complete listing of all faculty.
CONTENTS

History 4
Laying the Foundation 6
Photo Gallery
The Engineering Shops 10
Building National Prominence 12
Photo Gallery
O.W. Boston 18
Automotive Research 20
Entering the Modern Era 24
Photo Gallery
The MICHIGAN Experience 28
Leadership in High Technology 30
Selected Research 1968-1993 35
Photo Gallery
Collecting Data 36
Dynamic Systems Simulation 38
Composite Materials 40
Holographic Interferometry 42
C.S. Yih's Fluid Mechanics 44
Ultrasonic Imaging 46
Photo Gallery
Looking into the Future 48
Fluid Mechanics 50
Heat Transfer 54
Manufacturing 57
Design 61
Robotics 65
Victors 68
Annual Report 1992-93 70
Student Honors 71
Enrollment and Degrees Granted 72
Professional Service 74
Publications 76
Funding and Expenditures 84
Awards and Honors 88
In 1910, Felix Pawlowski, a young scientist from Poland, arrived in America with a dream. Earlier at the University of Paris, he had taken the first course in aeronautical engineering ever given and was now determined to become America's first aeronautical engineer. When he sent letters to engineering colleges around the country requesting the chance to start an aeronautics program, he received mostly negative replies. The field was too new, and there was no assurance that it would ever amount to anything.

Finally, Pawlowski made contact with a leader as forward thinking as himself. That person was Mortimer Cooley, the first chairman of the Department of Mechanical Engineering at the University of Michigan. Cooley hired Pawlowski onto the faculty of Mechanical Engineering and encouraged him to create a course of study. Thus, Pawlowski became the first aeronautical engineering instructor in the country, and the program he developed, which granted its first degree in 1917, became the first program in aeronautics.

Pawlowski's story is important because it reminds us that both determination and risk-taking are important qualities in reaching for excellence—qualities just as important to our Department today as they were at the turn of the century.

Indeed, history has much to teach us and that is why we have devoted this book to looking at the achievements of our students and faculty over the last 125 years.

We hope you will take the time to look it over.

Panos Y. Papalambros
Chair,
Department of Mechanical Engineering
and Applied Mechanics
Over the last 125 years the Department has grown from a humble, two-room laboratory with one professor in 1868 to one of the top-ranked engineering programs in the country in 1993. The story of that evolution is presented in four sections dividing the years at logical breaking points. It is not a comprehensive history but one that tries to give a sampling of the activities of the Department in all four eras.

1868-1900—Laying the Foundation, Pages 6-11
1900-1940—Building National Prominence, Pages 12-23
1940-1970—Entering the Modern Era, Pages 24-29
University Catalogue, 1887

**Mechanical Engineering:**

"Prominence is given to the study of steam engineering, and in this branch, a large amount of practical work is done. The instruction is arranged to accommodate those who wish to devote their time principally to mechanical engineering proper, to steam engineering, or to marine engineering and naval architecture."

The story of the Department of Mechanical Engineering and Applied Mechanics at the University of Michigan begins 125 years ago when the engineering discipline at the University was still in its infancy. Engineering professors and students could be numbered in the dozens, and the only curriculum offered was in Civil Engineering. Seeing the need for a broader program, Professors DeVolson Wood and Stillman Robinson requested that the University offer a separate specialized course to focus on the newly developing fields of machine, power, and marine engineering. In 1868, the Regents voted to create the Mechanical Engineering program. Unfortunately, the University did not have the resources to maintain its new creation, and two years later the Mechanical Engineering program was reabsorbed into Civil Engineering, where it remained for eleven years.

During this time, students continued to receive strong and often innovative instruction in mechanical engineering. Professor DeVolson Wood described a challenging teaching technique he used in a course in 1872. "I assigned to them a problem, the character of which I was certain they were not familiar with, and asked them to solve it, make a drawing to
represent their idea, accompany it with a specification, and report it to me. (Example) After describing the construction and operation of the ordinary D valve (in a steam engine), and showing particularly that in order to open a port...the valve...is moving in the opposite direction from the piston, I asked the class to invent such an arrangement of parts as that the valve would open the port correctly if it moved the same way as the piston... In a class of thirty there would often be fifteen or twenty different solutions...” (An Encyclopedic Survey, p.1257.)

In 1881, the Department finally gained an independent identity thanks to an energetic young Naval officer, Mortimer E. Cooley, an 1878 graduate of the U.S. Naval Academy. He was one of a number of naval officers appointed by Congress to university faculties. His assignment at Michigan was to establish a Mechanical Engineering program, and over the next two decades, his dynamic leadership laid the foundation for a thriving department.

The Original ME Curriculum
Cooley quickly set to work developing the Department’s curriculum, which emphasized machines powered by steam and water. Students received a smattering of liberal arts courses and a solid base in math and basic science before taking the ME courses in their junior and senior years. There was no separate naval engineering department so these courses were also included. The original curriculum consisted of: Workshop Appliances and Processes, Pattern Making, Moulding and Founding; Mechanical Laboratory Work (Shop Practice in Forging); Machinery, Machine Construction, and Drawing; Mechanism and Machine Drawing; Machinery and Prime Movers (Water Wheels and Steam Engines); Machine Design; Thermodynamics, Original Design, Estimates, Specifications, and Contracts; and Naval Architecture.

The First Mechanical Laboratory
At the time of Cooley’s appointment, all engineering classes were held in the South Wing of the University Hall with no laboratory space available. To remedy that situation, Cooley used an appropriation of $2500 from the State legislature to construct and equip a two-story laboratory building.

Plans for the building were prepared by faculty member J.B. Davis. “It was a two-story structure of frame construction (24' x 36') with bricks placed edgewise between the stud- ding. The ground floor was divided into two rooms, the foundry on the east end and the forge shop, brass furnace, and engine room on the west. The foundry also included two flasks, other necessary foundry tools, and molding sand. The shop contained the first steam equipment in the Mechanical Engineering Laboratory, a forge, anvil, tools, a

Built for $2,500 in 1882, the first Mechanical Laboratory housed a foundry, forge room, brass furnace, engine room, machine room and pattern shop.
brass furnace, and a four-horsepower vertical fire-box boiler and steam engine. The second floor was also divided into two rooms, one of which was occupied by the pattern shop and the other by the machine shop. The equipment in these rooms consisted of a wood-turning lathe built by Cooley and members of his class, and an iron lathe, salvaged from the basement of University Hall and repaired by the students. The building was heated by an old-fashioned stove on the second floor. In cold weather, ice was melted in a pail of water on top of the stove in order to increase the humidity." (An Encyclopedic Survey, pp. 1259-60.)

In his first report to the Regents Cooley described the original course taught in the new laboratory, "Six students were permitted to take the first laboratory course held in the building. They were engaged for a large share of the time in overhauling and erecting machinery in the shop. The remainder of the time was devoted to grinding and putting in order the cutting tools, in performing some of the simpler operations at the workbench, in preparing work for the iron lathe, in wood-turning, forging, brazing, and soldering, and in running the engine." (An Encyclopedic Survey, p. 1259.)

Cooley reminisced about this first class in his autobiography, *The Scientific Blacksmith*, published in 1947 after his retirement as Dean of the College of Engineering. "How well I remember my first class in this little shop. Six engineers were taking the course. The first lesson was at the forge. I taught them how to build a fire. Then I wanted a piece of iron to heat. At the back door there was a wagon load of scrap of different kinds of metal, and I sent the members of the class to bring me back a piece of wrought iron. Much to my surprise not one of the six could identify wrought iron, cast iron, steel, or anything else in the pile. I asked the differences between the various kinds of metal, and every last one of them knew the chemical differences and the process of manufacture, but not one of them could identify one piece of metal from another. That incident thoroughly convinced me of the need for practical work to acquaint engineers with the characteristics of the materials they would be using after graduation" (p. 106).

Cooley did not remain long satisfied with the small four-room laboratory. In 1883 he convinced the University to donate to the Department the carpenter shop that had been used in the construction of the University library. It was dismantled and attached to the Mechanical Laboratory. In 1885, construction of a new laboratory building was authorized by the Regents, and the original lab, just four years old, was torn down to make room for it. Additional space was acquired
for the Department in 1891 when the former dental building was given to the engineering program for classroom space.

**Inspection Visits**

To supplement the learning experience of the laboratories, Cooley and other faculty arranged for students to undertake inspection visits to neighboring businesses. An entry in the University catalogue of 1890 describes this program. "As often as may be practicable, visits will be paid to the neighboring manufacturing establishments for the purpose of acquiring a knowledge of the methods employed in building, and in the construction of bridges, machinery, and ships. In the spring of 1886, members of the classes in civil and mechanical engineering spent a week, under the guidance of Professor M.E. Cooley, in visiting industrial works at Detroit, Cleveland, and Pittsburgh."

During the twenty-three years of the Cooley era, the Department had acquired a strong curriculum, had launched its first successful building program, and had formed a strong relationship with business and industry. In 1904, Cooley was rewarded for his achievements when he was named Dean of the College of Engineering, a post he held for the next twenty-four years.

**Sources:**


*Announcement*, College of Engineering, University of Michigan, 1895-1940.

"...every last one of them knew the chemical differences and the process of manufacture, but not one of them could identify one piece of metal from another. That incident thoroughly convinced me of the need for practical work to acquaint engineers with the characteristics of the materials they would be using after graduation."

Mortimer Cooley, *The Scientific Blacksmith*
In 1885, at the urging of Mortimer Cooley, the University built the Engineering Laboratory Building. Various shops in the building and yard were used for education and research until that building (first referred to as "The Shops" and later "The Annex") was razed to make way for the Undergraduate Library in 1956. The forge and foundry (right) were converted into the University's first automotive lab in 1913.
Over the years, the courtyard between the "The Shops" and the foundry was used for experiments as well. This 800 lb. Liberty aircraft engine was used in an engine cylinder pressure study (ca. 1923).

This machine shop, located in the second floor, was used for student work in blacksmithing and machine tool work. The building included its own power plant, and line shafts powered the belt-driven machines.

The facilities at the shops offered students exceptional opportunities in engineering training, always under the guidance of a highly respected professional staff.
1900-1940

Building National Prominence

University Catalogue, 1910

*Mechanical Engineering:

"...that branch of engineering which, broadly speaking, covers the fields of heat, power, design of machinery, industrial management, and manufacturing problems."

With a foundation well laid in the Cooley era, the Mechanical Engineering Department, as well as the entire engineering program at Michigan, was primed to step into a leading role in engineering education in the decades following the turn of the century. Drawing students from across the country and throughout the world, the engineering student body grew tenfold over the next forty years; graduate degrees were offered for the first time; laboratories were updated and equipped with modern instrumentation; and independent research projects became important academic endeavors along with the education of students. The university established stronger contacts with industry and
with other schools. Interdisciplinary programs leading to joint degrees with either law or business schools were created. The Department grew from a fledgling organization to one of the most prominent educational institutions in the country.

**Curriculum**

Perhaps the most important changes came in the curriculum. In the previous century, the ME program had emphasized steam power and manufacturing machinery almost exclusively, but the world of science and industry was changing and the Department changed as well. By 1940, the curriculum for the bachelor's degree had grown to include fifty-four courses with seventy-four semester hours of preparatory work, fifty hours of secondary and technical work and sixteen hours of electives. Semesters at this time were sixteen weeks long. Courses were grouped under these headings:

- Steam Power Engineering
- Internal Combustion
- Hydro-Mechanical
- Heating, Ventilation, and Refrigeration
- Industrial
- Automotive
These last two focus areas provide examples of how the Department adjusted its programs to the changing needs of industrial America.

**Facilities**

An advanced educational program requires advanced facilities, and the Department's growth in this area kept pace. The building that would be the symbol of Michigan engineering over the next seventy years was constructed in 1904—the West Engineering Building. Its laboratories were some of the most sophisticated in the country for that time, and five of those labs were part of the Mechanical Engineering program.

**General Mechanical Engineering Laboratory:** The equipment consisted of steam power machinery and apparatus; internal combustion engines; air compressors; refrigeration machinery; and heating and ventilating apparatus; as well as the auxiliary apparatus for use in testing the various machines.

**Hydraulic Laboratory:** This laboratory occupied a space of forty by sixty feet on two floors. A canal four feet wide and fourteen feet, six inches deep conveyed water from the naval tank to a well which furnished the suction supply for the pumps. A fifteen-inch centrifugal pump geared to a 150 hp variable speed motor returned the water through two weighing tanks, each holding 600 cubic feet to the naval towing tank. Nearby, the canal was provided with bulkheads, screens, weirs, and nozzles arranged with bulkheads dividing it into basins each 100 feet long, and by means of a sluice in the bottom connecting the canal with pumping systems.

**Automotive Laboratory:** Consisted of a large dynamometer room for engine testing, and a section for demonstration of automobiles, motor trucks, and their component parts. The lab was equipped with some twenty automobile, truck, tractor, and aeroplane engines of two, four, six, eight or twelve cylinders, complete operating and cutaway chassis, a chassis dynamometer, transmissions, rear axles, differentials, clutches, carburetors, ignition, starting and lighting systems, and other automobile equipment.
Physical Testing Laboratory: Materials were tested for strength in this laboratory.

Highway Lab: Tests were made on all materials used in road or pavement construction. (Announcement, 19-20)

Automotive Engineering
The automotive engineering program was an example of how the Department responded to an entirely new industrial direction. The Department's program in automotive studies began in concert with the beginnings of the auto industry in nearby Detroit. In 1913, the Department offered its first automotive course—Gasoline Automobiles. In 1916, Walter Lay joined the faculty with a mandate to create a laboratory and an entire automotive slate of courses. The first automotive laboratory course that he designed featured a full day's road test of a motor vehicle—either a single-cylinder Oldsmobile engine, a 1910 Kri, a 1907 air-cooled Franklin, or a 1911 Franklin engine. By 1914, at the beginning of World War I, the Mechanical Engineering Department had gained a strong reputation in automotive engineering and was called upon by the government to help in the war effort. Over the next few years, faculty trained 1081 Army personnel in automotive engine repair. Following the war, Professor Lay carried out pioneering research in cooperation with the nearby automotive manufacturers. The laboratory was one of the first to present comprehensive experimental data showing the advantages of streamlining. Another important project was a cooperative study with the State Highway Department to determine optimal highway grades, balancing cost of construction against operation cost of cars and trucks climbing the grades. Other studies were on engine heat balance, testing and improving of automotive parts, car safety, car noise, and riding comfort. By 1937, equipment in the Department's automotive laboratories consisted of motor vehicles, engines, transmissions, axles, superchargers, carburetors, mufflers, all the major units used on aircraft, motor vehicles, tractors and some marine applications of internal combustion engine power, electric dynamometers, water brakes, air meters, fuel meters, tachometers, and potentiometers.
Industrial and Production Engineering

During this same forty-year period, industrial practices and processes in all branches of manufacturing changed dramatically, and in response, the Department created a program on the leading edge of the discipline. The changes began in 1915 when a course inspired by the Gilbreths's "scientifc management" was introduced called Scientific Shop Management. It featured the study of the applications of scientific management in manufacturing plants. During World War I, this course was expanded to include two courses in the preliminary training of officers of the Ordnance Department of the Army—the first such courses offered by an American university. (The program was eventually expanded to 173 hours of study, and the first degree was awarded in 1926 to William Alden Capen who later became superintendent of the Keeler Brass Company in Grand Rapids.)

In 1921, Orlan W. Boston joined the faculty and was given the task by Dean Cooley of developing courses that would coordinate the disciplines of design, metallurgy, and production. Under Boston's leadership, the emphasis in the plan of instruction moved from that of manual training to the teaching of principles related to modern industrial practice.

In addition to curriculum development, Boston also initiated research projects including pioneering investigations on the fundamental principles involved in the machinability of metals. In 1934, Boston was made the chair of the Department of Metal Processing within ME and in 1936 was named Custodian of the Gaging and Measuring Laboratory of the Detroit Ordnance District. By 1935-1936 enrollment in Metal Processing courses was so large that crowded sections were taught every half-day during the week.

By the end of this era in 1940, the Department was well established as one of the leading mechanical engineering programs in the country.

Sources:
Stephen F. Timoshenko carried out research on the elastic method of stress analysis in the above laboratory as a professor in the Engineering Mechanics Department from 1927-1936. (Engineering Mechanics was later renamed Applied Mechanics and merged with Mechanical Engineering in 1979.) Timoshenko was a world recognized expert in the field of mechanics because of his original research, his teaching, and his textbooks.

The investigations he carried out while at the University of Michigan formed the foundation of the theory of the elastic behavior of solid matter. Among his other research contributions were: use of the energy method in problems of structural stability and buckling, and the formulation of the differential equation for lateral vibrations of beams, including the effects of shear and rotational inertia. He was also the first to formulate the basic differential equation for the problem of torsion of structural sections and was the first to obtain the shear center of a beam.

Timoshenko introduced scientific and mathematical approaches to the teaching of mechanics, and during his tenure at Michigan, the first bachelor's degree program in engineering mechanics in the country was established and the first doctorate degree in the field was awarded. During the course of his career, Timoshenko wrote eighteen textbooks that were translated into thirty-six languages.

Timoshenko was the recipient of numerous honorary degrees and medals in both the U.S. and Europe, and in 1948 the ASME named a medal after him to honor his contributions to the field.

Source:
Orlan W. Boston

During his 35 years in the Mechanical Engineering Department, Boston conducted research in many areas, including the machinability of metals. He developed an exceptional curriculum in concurrent engineering that united design, metallurgy and production engineering into the modern concept of industry. This photo of Boston as an undergraduate (at left, above) was taken in 1959 in the West Engineering Building.
This drilling dynamometer set-up (left) and lathe set-up for tool life tests (right) were designed and built by O.W. Boston (ca. 1923-30) in "The Shops."

Boston was given the task of redesigning the foundry of the Engineering Laboratory. These photos (taken the spring of 1924) show the foundry as laid out by Boston assisted by H.L. Campbell and John Grennan.
Automotive engineering has always played a central role in the research and teaching activities of the Department of Mechanical Engineering. The University's proximity to the heart of the nation's auto industry in Detroit has made Automotive Engineering a natural focus for the Department. Facilities grew from a wooden shed attached to the engineering laboratory in the early 1900s, to the spacious, modern automotive lab constructed on North Campus in 1956. Research interests have included most areas of automotive engineering, from early studies on streamlining and engine heat balance in the twenties and thirties to pivotal investigations on fuel efficiency and emissions in the seventies. The broad range of topics more recently has included computerized control, measurements of engine performance, and reduction in variation in vehicle assembly. In 1978 the Office for the Study of Automotive Transportation was established in the Department, the only one of its kind in the nation, now one of the most influential voices in setting government transportation policy.

The Department has provided a steady flow of highly trained automotive engineers to industry throughout its history. One current measure of the excellence of our students is their performance in the two national solar car races 1991 and 1993. Undergraduate engineering students many from the Department beat out competition from dozens of other engineering programs to win both solar car races (see pg. 68).
Mounted on a Chevrolet chassis, the “Blue Bird” served as one of the university’s first test vehicles. Its exotic design helped to determine air resistance to motion in land vehicles, and to explore the effect of changes in vehicle shape. In the days before strain gauges, Lay suspended the shell of the “Blue Bird” on an assembly of scales to measure wind resistance while driving.
An annex to the first Automotive Laboratory at the University was added in 1928, when no other space was available for the growing program. As Prof. Jay Bolt recounts, conditions in this annex were bad.

"...when it rained, water would drip through the roof for days afterward, and in the winter, snow melt would come through. Experiments often had to be covered to protect equipment and instruments."

In spite of its appearance the lab was a very useful facility. The equipment and instrumentation were well designed and state-of-the-art. The tar paper annex provided much needed laboratory space and kept unavoidable fumes and noise from the rest of the engineering building.

This large dynamometer was mounted on a turntable to provide access to several engines and projects. Dynamometers were rare and valuable research tools, always in high demand at this facility. Other "dynos" were set on rails and rolled from one test stand to another to ease the assembling of experiments and to allow for more test engines.
This early version of a chassis dynamometer permitted operation of a complete automobile at various loads and speeds. The experiment shown was an investigation of automobile noises produced during operation.

This mobile laboratory was donated to the automotive research laboratory in 1959 by the International Nickel Corporation.

Automotive research continued at the Engineering Annex until 1956 when it was moved to North Campus to make room for a new undergraduate library. The new facility, the Walter E. Lay Automotive Laboratory, was so named by Lay's former students and assistants to honor their mentor and friend.

The W.E. Lay Automotive Laboratory provides 20 engine test cells, a 5-bay vehicle laboratory, machine shops, instructional and computer labs, and offices. Student vehicle projects built here have taken high honors in competition.
Entering the Modern Era

The three decades following World War II brought some remarkable changes to the Department reflecting changes in the worlds of science and industry. During this era, the space race began, new technologies were developing in industry, and the Cold War demanded advanced military systems. Both government and business turned to universities for expertise in meeting these challenges. For the first time, funded research projects sponsored by the National Aeronautics and Space Association (NASA), the National Science Foundation (NSF), the Department of Defense, and industry became an important focus of Department activity. The graduate program expanded dramatically as a result and undergraduate education began to incorporate new technologies and methodologies. The Department took a lead within the College in responding to these changes, creating a modern curriculum and building a research-oriented faculty.

Restructuring
Although the Department had split and merged with various engineering programs over the years, in 1956 it experienced one of its most important changes. Industrial engineering was becoming too large and prominent an area to remain as a subset within Mechanical Engineering. The first solution was to elevate it to department status within Mechanical, and the Department was renamed Industrial and Mechanical Engineering. Two years later, however, the industrial engineering component split off to become a separate entity. The faculty within that group was split, some going to the new department, called Industrial and Operations Engineering, and some staying in Mechanical as the Production Engineering group.
Investigations of the dynamic stresses that aircraft landing gear are subjected to were conducted for the growing aircraft industry in 1952. A significant increase in sponsored research characterized this period of the Department’s history.

Another change during this time was the establishment of the U-M Dearborn Campus in the late fifties. ME faculty, including Raymond Pearson, Axel Marin, Howard Colby and Gordon Van Wylen, were instrumental in the creation of the ME program at the new school.

Another program that came to life with the help of ME faculty was the Bioengineering Program in the College of Engineering. ME Professor Glenn Edmonson was its founding father, establishing the group and arranging for the original funding. The Bioengineering Program continues today as one of the strongest multidisciplinary programs in the College.

Research

The new emphasis on research during this era was felt in both traditional areas of mechanical engineering such as automotive and production engineering and newly emerging technologies such as space, nuclear, and automation engineering. Along traditional lines, one of the first ME faculty to be heavily involved with basic research was Professor Edward Vincent who investigated heat transfer in gas turbine rotor disks and wrote *Gas Turbines*—a first-of-its-kind book that brought Vincent international distinction. The production engineering group carried out major world-recognized research on surface roughness measurement and the machinability of exotic materials as requested by the War Production Board during World War II. In this group were Orlan W. Boston, Robert Caddell, Lester Colwell, Joseph Datsko, William Gilbert, and Kenneth Ludema.

Other important research included the Orthotics Research Project in the School of Medicine to develop assistive devices for the upper limbs of disabled persons. ME researchers on this project included Raymond Pearson, Robert Juvinnall, Rune Evaldson, and Robert Hess. The project was sponsored by the Department of Vocational Rehabilitation and NSF at $100,000 per year. One of the first environmental impact studies having to do with control of exhaust emissions of power plants was carried out by Professor Clay Porter in cooperation with civil engineering faculty.

Research exploring newly emerging technologies started receiving strong support in the Department during Gordon Van Wylen’s tenure as chair. He was the first to pursue money for basic research from government when he went to the Army Ballistic Missile Center (a precursor to NASA) in Huntsville, Alabama, and obtained funding for the project “Discharge of Cryogenic Liquids from Tanks.” Throughout the sixties, faculty members Wen-Jei Yang, Herman Merte, Vedat Arpaci, and John A. Clark worked on it and other space projects that had impact on the design of the Saturn launch vehicle in the U.S. space program. Nuclear power related research was carried out in the sixties on projects funded by the government. Two examples were Frederick G. Hammit’s work on cavitation in liquid metal used in breeder reactors and Edward Lady’s doctoral research on boiling at low heat flux. In another newly emerging technology,
Professor Lester Colwell did pioneering work on numerical control of machines. The total contract research conducted in ME labs throughout the sixties was estimated at $1,100,000. The publications of the faculty from their research and teaching in these laboratories numbered about eighty, including three textbooks.

Curriculum
As research activities expanded, so did the graduate program. In the first seven decades of the Department's existence, it had conferred only twenty-one Ph.D. degrees. From 1940-1970 that number soared to 151. In line with these changes, the Department began to actively recruit faculty members with doctorate degrees.

In 1958, graduates and undergraduates in the Department received a first taste of a technology that would one day revolutionize engineering education and research. Several faculty members were released from teaching duties to participate in the Ford Foundation sponsored “Project on the Use of Computers in Engineering Education.” They learned about the University's mainframe computer and how it could be used in teaching and research. Faculty began to assign key punch computer problems in classes.

In 1961 to keep pace with all of these changes, the undergraduate program was completely revamped. Chairman Gordon Van Wylen described the reorganized curriculum in the 1961 departmental annual report. “A complete reorganization of the undergraduate laboratories has been effected. Each of the undergraduate laboratories will be made an integral part of one of the classroom courses and both will be handled by the same faculty member. It is anticipated that this will make the lab work a more significant educational experience for the student and that the theoretical and experimental aspects of engineering will be more effectively related to each other. (The six courses with labs are fluid mechanics, dynamics, engineering materials, manufacturing processes, thermodynamics, and heat transfer).” This new educational approach was copied in the following years by many universities across the country.

Facilities
By the early fifties it was apparent that the old engineering buildings were no longer adequate for the level of research activity and the growth in the educational programs. ME chairmen complained that their classrooms and laboratory space in the East and West Engineering Buildings were woefully inadequate.
Some relief was provided by a partial move to new buildings on the North Campus. In 1956 the automotive laboratory was completed and occupied. The State had provided the construction costs of $1,850,000, and Michigan industries added $500,000 for equipment (including facilities for testing fifteen engines at a time). Steelcase had donated the furniture, and International Nickel Company donated a mobile laboratory. In 1958-1959, researchers in thermodynamics, heat transfer, and fluid mechanics moved to new laboratory facilities in the G.G. Brown Building on North Campus.

Researchers and students in ME also began to have access to extensive on-campus computing facilities. In 1953, the Michigan Digital Automatic Computer (MIDAC) was designed and built at the Willow Run Research Center. It was one of only twenty high-speed electronic digital computers in the country—the second in the Midwest. It was said to be "some 20,000 times faster than a professional mathematician using a desk calculator,"* and in 1959, the Board of Regents authorized establishment of the U-M Computing Center on North Campus with powerful mainframe computers and a terminal system known as the MTS or Michigan Terminal System.

**Centennial Year**

In October of 1968 the Department hosted a two-day Centennial celebration. A report on the activities was published in 1973 in both soft and hard covered versions edited by Assistant Professor Charles M. Vest. The report documented the Department's position as a leader in modern engineering education and research.

*(TechniUM + No. 18, June 1980)*

The Mechanical Engineering Department provided significant support for the nation's defense efforts during the Cold War. From biomechanical studies for cockpit design to detonation combustion, researchers worked on a variety of military contracts at the Ann Arbor and Willow Run laboratories. This M47 tank was used to study tracked vehicle drive assemblies and suspension systems. Work was also done on servomechanisms and exotic propulsion systems.
The MICHIGAN Experience

Michigan was the first university west of the Alleghenies to offer a degree in engineering, and from the very beginning, Michigan engineers developed a reputation for a hard-nosed, no-nonsense approach to their work. Many students came long distances to study here, bringing little more than exceptional talent and the fierce determination to succeed. Then, as now, students expected the best education they could get, and MICHIGAN has always lived up to their expectations.
When the Mechanical Engineering Department first began 125 years ago, an engineer needed to prepare for a career in railroading, surveying, shipbuilding, or manufacturing. In every era since then, the role of the mechanical engineer has evolved and expanded to include new industries and fields including automotive engineering, hydraulics, cryogenics, space technology, and nuclear power. The last twenty-five years have been no exception as the field has expanded into new areas of high technology including lasers, solar energy, automated control, acoustic emission, composite materials, and flexible manufacturing. In addition, many of the activities of the mechanical engineer have been transformed by easy access to one of the most influential developments of any era—the computer, which over the last ten years has come to permeate the everyday world of business and industry. Computers have also made it possible to explore many problems in traditional research areas that were previously inaccessible.

In response to these developments, the Department has also undergone significant change: sponsored research and graduate programs have grown rapidly; researchers have expanded beyond the university to create high-tech businesses arising from their studies; the long-awaited move to North Campus has been completed; the entire College of Engineering has been computerized; and the Department has gained strength through its merger in 1979 with the Applied Mechanics Department, acquiring the new name Mechanical Engineering and Applied Mechanics (MEAM).
Professor John Clark's investigation of solar energy is an example of an ongoing commitment to new fields of scientific inquiry that characterizes research in the Department of Mechanical Engineering and Applied Mechanics. Pictured here is one of two large solar arrays used in Clark's research that were mounted on the roof of the G.G. Brown Building. These panels absorbed heat directly and used a circulating liquid as a transport medium.

Research

The research focus that began in the previous thirty years came into its own in this era as total research expenditures climbed from about $500,000 a year in the early 1970s to nearly $7 million a year in 1993. This emphasis not only increased engineering knowledge but also enriched the educational experience of MEAM students. Researchers pursued interests in many areas of high-technology as well as in traditional areas.

Professor John A. Clark's work in the area of solar energy, which included two senior/graduate level courses, is an example of research in a new technological field. The energy crisis of the mid-seventies sparked a search for alternative energy sources, and solar energy was considered one of the most promising. Professor Clark established the Department's Solar Energy Laboratory in 1973. It was the chief source of technical advice and research for all the solar companies in Michigan from 1973-1985. The lab carried out research on solar collection and storage devices including concentrating collectors, wind-energy systems, photo-voltaic conversion devices, thermal recovery devices on furnaces tied into solar devices (heat grabber), and the boiling collector with refrigerant instead of water or air—the most efficient type of solar collector. Clark carried his activities into the private sector as the technical director of Star Pak Energy Systems Company, which developed and marketed the devices conceptualized in the UM solar lab. Star Pak devices were in turn described and analyzed by students in the lab using sophisticated computer modeling. This close relationship continued until the early 1980s when interest in solar energy declined and with it the solar industry in Michigan. Clark continued his interest in the field with projects in the areas of modeling the terrestrial solar flux on arbitrarily oriented surfaces, the technical and economic modeling of complete solar thermal, and energy conservation systems.
Automotive research is an example of a traditional area. In the decade of the seventies, important research was carried out by the group consisting of Professors Donald Patterson, William Mirsky, Jay Bolt, and David Cole. One example is a project supported by a three-year grant from a consortium of industrial firms. The purpose was to see if thermal reactors could control emissions as well as catalytic converters. Industry was interested because thermal reactors would have allowed the continued use of leaded fuel. Their research revealed the limitations of thermal reactors, paving the way for the universal use of catalytic converters. Another important development was the establishment in 1978 of the Office for the Study of Automotive Transportation (OSAT) by Professor David Cole. OSAT is the only on-going university-based group in the country that has focused on a study of the automotive industry. The fifteen-member staff has examined the auto industry from every angle, researching a range of topics from industry competitiveness and labor relations to forecasts of technical and market trends.

Automotive faculty were some of the first to carry their technology beyond the university in establishing private companies. Professors Cole, Mirsky, Patterson, and Weber (Civil) founded MI Automotive Research company for testing automotive engines and products. This firm spawned another small company, Engine Test Instrumentation, Inc., and later the group founded QED Environmental Systems to manufacture a pump design they invented for obtaining water samples around dump sites. These three firms combine to employ 150 people in the Ann Arbor area.

Other important research of the last 25 years includes work by professors James Barber (thermoelastic effects in contact mechanics and tribology), Samuel Clark (adhesion and reliability of flexible composites), Maria Comninou (crack closure and contact at interfaces), Elijah Kannatey-Asibu, Jr. (acoustic emissions), Kenneth Ludema (rheology and tribology), Christophe Pierre (the phenomena of vibration and wave localization in spatially repetitive structures with imperfections), Albert Schultz and James Ashton-Miller (biomechanics of mobility impairments in the elderly), Richard Scott (optimization of layered composite media, vibration and wave propagation in rotating elastic structures), George Springer (structure of rarefied rocket plasma), Alan Wineman (mechanical response of rubber and polymers under conditions of large deformations), S.M. Wu (dimensional measurement in manufacturing), and Wen-Jei Yang (thermal fluid phenomena in biological, anatomical and physical systems).
Detailed reports on other significant Departmental research from the last 25 years can be found on pages 50-67.

Facilities
In 1984, the ME department left the East and West Engineering Buildings on Main Campus, its home of eighty years, to take up residence in new laboratories, offices, and classrooms on the North Campus, completing the move begun in the fifties. For the first time in thirty years the Department was consolidated at one location.

Laboratory facilities within the North Campus buildings were upgraded to an unprecedented degree during this era thanks to increased research funding. The Department now supports advanced laboratories with state-of-the-art computing and experimental equipment for research in the areas of automotive/combustion; biomechanics; computational mechanics; computational design; design prototyping; dynamics; computational fluid mechanics; cavitation and multiphase flow; transport, reaction and phase change in porous media; variable gravity heat transfer; optical and mechanical coordinate measuring machines in manufacturing; precision machining; tribology; welding; machine tool sensing and control; mobile robotics; and ceramic composites.

Time-sharing was the principal method of computing employed by both faculty and students until the eighties with the advent of the personal computer (PC) revolution. That revolution was brought to the College of Engineering in 1983 with the establishment of the Computer-Aided Engineering Network (CAEN). Today, CAEN operates one of the largest integrated, multi-vendor workstation networks in the academic world. Over 2000 workstations and microcomputers are distributed in faculty and graduate offices and in research and teaching laboratories throughout the College. Several distributed file systems provide over 150 gigabytes of centrally administered file storage that can be reached by any computer on the network. The system is recognized as a model distributed computer architecture for engineering and computer science instruction and research.

Curriculum
An undergraduate curriculum review committee was appointed in the spring of 1992 by the new Department Chair, Panos Papalambros. The committee was charged with making a thorough review of the current curriculum and proposing necessary changes.
The review committee gathered informal input from the faculty and students, examined the curriculum at other engineering schools, and conducted two formal surveys of the alumni from the classes of '87, '82, and '72. Both surveys showed that generally the Department does well in preparing students in the engineering sciences, but less well in the nontechnical aspects of engineering. The alumni, in particular, stressed the need for a stronger communication component.

In the spring of 1993, the Committee presented to the faculty a preliminary proposal for curriculum revisions, which was given general approval. It maintained the curriculum's strong core in engineering science but also put much more emphasis on hands-on experience, creative problem solving, and communications and teamwork. Although a number of details still had to be worked out, two major changes were in progress by the fall of that year.

The first was a major reorganization of the required laboratories. Instead of single credit laboratory modules attached to a number of introductory courses, these laboratories were consolidated into two courses—a thermal/fluid laboratory already developed and a mechanical sciences laboratory course under development. In these labs, students will learn how to design, conduct, and interpret experiments. Eventually these courses will be merged into junior and senior laboratory classes, which will include a strong technical communications requirement focusing on presentations and technical report writing.

The second change was the establishment of a sophomore level class in design and manufacturing to include computer-aided design and actual hands-on experience in a machine shop. This early introduction to actually making things will allow the subsequent junior and senior design courses to put more emphasis on the completion of working prototypes. The junior and senior courses will also include life-cycle issues, such as environmental impact and disposal after useful life.

To support the work in these courses, plans have been made for a major renovation of the student machine shop. Floor space and staffing will be at least doubled, hours of operation will be expanded to evenings and weekends, and the inventory of machines will be increased by eighty percent.
Research has come to play an ever increasing role in the Department's activities over the last twenty-five years. A selection of some of the most influential studies from that era is featured in this section.

Photo Gallery

**Collecting Data**

- Dynamic Systems Simulation 36
- Composite Materials 38
- Holographic Interferometry 40
- C.S. Yih's Fluid Mechanics 42
- Ultrasonic Imaging 44

**Looking to the Future**

- Fluid Mechanics 46
- Heat Transfer 50
- Manufacturing 54
- Design 57
- Robotics 61
The Nuts and Bolts of Collecting Data

One of the most interesting changes that has taken place in the Department over the years is in the apparatus used for collecting data. For a long time, researchers had to rely on their ability to directly observe phenomena, measure them with simple meters and scales, and quickly log their findings in journals. The dedication of scientists working under these conditions is legendary.

As technology advanced the opportunity for creating more sophisticated data-gathering equipment presented itself. With that opportunity came a myriad of challenges including overcoming the weight and bulkiness of equipment and increasing the sensitivity of apparatus. Over the years, scientists at the University of Michigan and the Department of Mechanical Engineering have come up with some creative approaches to data gathering and analysis.

The Sanborn Recorder was a significant improvement in acquiring research data in the late 1940s. Its analogue trace, on heat sensitive paper, permitted continuous monitoring of relatively high-frequency strain gauge outputs in this machine research project.

Video technology was difficult to apply to vibrational dynamics research in 1959, but offered great promise.

Strange looking university research vehicles, like this mobile microwave laboratory of 1960, have been a common sight on the roads around Ann Arbor for over 60 years. From Walter Lay’s “Blue Bird” (p. 21) to “Maze-n-Blue” (p. 68), Mechanical Engineering has always pursued innovative approaches to education and scientific inquiry.
Before miniaturization, electronic data-gathering components could be a logistical challenge in themselves, as suggested by this cart assembled by electrical engineers in 1958.

Stroboscopic photography revolutionized the study of motion and process. In this 1951 study, a researcher is using a stroboscope to analyze the machining characteristics of woodcutting.

From slide rules to supercomputers, devices for scientific calculation have gone through amazing changes in the last 125 years. This researcher is using a Monroe Calculator in his examination of heat exchanger coils.

This optical pyrometer (ca. 1954) enabled a production engineering researcher to measure temperature in this induction furnace. The device utilized the human eye to compare a heating element to visible, radiating color. Before the advances in electronic imaging technology of the 1960s, many devices tried to assist natural vision in making measurable observations.
As a graduate student and then a professor in the Mechanical Engineering Department in the sixties, seventies, and early eighties Milton Chace carried out pioneering research in the area of computer-aided engineering and the technology of mechanical dynamic system analysis (MSA technology). In 1977 Chace and his colleagues Mike Korybalski and John Angell formed a company in Ann Arbor called Mechanical Dynamics, Incorporated (MDI) to provide MSA software to Fortune 500 companies designing new mechanical products. Chace left the University in 1983 to pursue his business interests full time. MDI has been a highly successful example of technology transfer. The company has grown steadily, has several thousand clients worldwide, and has won awards for product excellence and export success.

Mechanical dynamic system analysis permits a wide range of mechanical simulations to be performed using a computerized model. This enables engineers to explore many types of mechanisms without expensive prototypes.
The ideas that led to MDI were first formulated by Chace as a graduate student in the 1960s. Chace saw that problems in mechanism design could be reduced to a clearer level of simplicity, using classical vector calculus. He found that the prediction, and simulation, of motion of planar mechanisms could be based on the solution of simple vector loop equations. He found also that there was a wonderful extension to three-dimensional mechanisms, most of which could be represented by a limited set of four-sided spatial vector loops, which he termed "vector tetrahedrons." Chace's categorization of these equations was amenable to being structured for solution by digital computer.

After receiving his Ph.D., Chace worked for IBM for two years and then returned to the Mechanical Engineering Department as a faculty member in 1967 to continue his research. Chace's work at IBM had shown him that comparatively few applications were ideally kinematic; most were multistatic-dynamic involving practical effects such as impact, motor torque-speed characteristics, elasticity, etc. Different solution procedures than those used for kinematics would therefore be required.

Problems in multistatic, large displacement, rigid-body dynamics are, in general, represented mathematically by simultaneous, nonlinear, ordinary differential equations. Applied mathematicians had long before shown that these could be solved by a stepwise process termed numerical integration. Also, by a technique of Lagrange multipliers, the constraint vector loops characteristic of kinematics could be included in the same formulation required for the dynamics conditions.

Using these methods, Chace's initial research team, which included Don Smith, Mike Korybalski, Allan Rubens, and John Angell, first developed a two-dimensional program named DRAM (Dynamic Response of Articulated Machinery), completed in 1969. It included a computer lan-

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High-Toughness / High-Performance Composite Materials

In the late 1960s and early 1970s Anthony G. Atkins, then a visiting Associate Professor and David K. Felbeck, Professor, conducted a research and development program that led to graphite-epoxy composite materials of improved properties. Prior to that time, very high strength had been achieved in these materials, but at the price of very low toughness. Such brittle materials therefore had somewhat restricted applications as engineering materials. Under NASA sponsorship, Felbeck and Atkins applied basic knowledge regarding the origins of toughness in materials to this class of potentially very useful composites. With very high strength and stiffness (elastic modulus), such materials would be highly desirable for applications to space vehicles if their toughness could be improved.

Early research by Atkins and Felbeck, on boron-epoxy composites, demonstrated that by applying a coating of low-strength resin to a fraction of the surface of boron fibers, the resultant composite would have increased toughness. When applied to pre-preg layers of commercial graphite-epoxy, the procedure consists of adding very thin layers of Mylar between the layers of pre-preg. The Mylar layers contain a matrix of fine punched holes, so that when cured, adjacent pre-preg layers of composite would bond over a fraction of the total interfacial area. Using these procedures, Felbeck and Atkins demonstrated that high-performance composites could be produced with about six times the fracture toughness of ordinary composites, while experiencing reductions of strength and elasticity of less than about 10%.

Working with Atkins and Felbeck during this period were Ph.D. students Roger Heimbuch (who later received the first Departmental Distinguished Alumnus Award), Theodore U. Marston, and Li-Chung Jea.

When NASA first proposed in the early 1980s a one-year recoverable orbiting satellite for scientific experiments, Felbeck submitted a proposal, subsequently funded, to fly
selected samples of toughened graphite-epoxy composite materials in order to learn whether detrimental changes would occur as a consequence of space exposure in near-earth orbit.

Felbeck's experiment consisted of one set of tensile specimens of toughened graphite-epoxy composite material with a range of cross-ply angles and a fraction of interlaminar contact, as well as a set of toughness specimens with the same set of variables. To isolate the effect of time after manufacture of the specimens, two identical ground control sets of specimens were produced in addition to the flight specimens, one set to be tested at the approximate time of launch and one set to be tested following recovery. The experimental frame was designed and fabricated by William H. Durrant; specimens were manufactured by Stephen B. Culp; and both men participated in the specimen test program.

The samples were prepared to be contained aboard the Long Duration Exposure Facility (LDEF), an eleven-ton cylindrical frame 10 m long, containing on its outer surface fifty-seven experiments prepared by researchers in government, private industry, universities, and eight foreign countries.

LDEF was launched in April 1984 on board the space shuttle Challenger. The initial deployment was at an altitude of 481 km in an orbital plane approximately five degrees from the ecliptic. All experiments were intended for subsequent recovery so no data were transmitted during the orbiting period.

Recovery was originally planned for a year later but was first delayed by scheduling and launching problems. Then, before recovery could take place, the Challenger shuttle blew up during launch, halting all shuttle launches for several years. Recovery of LDEF was for some time considered a low priority by NASA until unanticipated large solar activity during 1989, which caused expansion of the atmosphere with consequent rapidly increasing loss of altitude by LDEF. With a fiery re-entry estimated to occur in February or March 1990, LDEF was recovered by the space shuttle Columbia in January 1990 at an altitude of 33 km.

Although only a limited number of specimens was feasible, the results of this 5.8 year orbiting experiment show that the toughened graphite-epoxy composite, if properly coated for protection from atomic-oxygen erosion, is sufficiently durable for use during near-earth space missions of the order of at least five years.
Holographic Interferometry and Computed Tomography
by David Watt

In the 1970s, Professor Charles Vest was carrying out research in the area of experimental and theoretical convection heat transfer, and although he continued to direct research in this area, his best known work concerned the use of holographic interferometry and computed tomography. This work followed closely on the development of the laser and the discovery of laser holography.

Holographic interferometry is based on the interference between two holographic images of an object. When the object has been altered, for instance by the presence of a crack, the resulting image is overlain with a striking pattern of bright and dark fringes. These fringes can be interpreted to identify qualitatively the nature of the modification of the object, or they may be used to obtain quantitative measurements. The advantages of holographic techniques over conventional methods are that they do not require contact with the object and that measurements at a large number of points on the object can be obtained from a single image.

Vest's group did a great deal of work on both the development of this technique (especially on the interpretation of interferograms and the application of digital and electronic augmentation techniques) and the practical applications of it, studying fields as varied as microcrack formation, flow in stratified media, natural convection heat transfer, nondestructive testing, and the formation of spots on animal coats. In 1979, Vest published a well-known book on the field of holographic interferometry and its applications.

The work on holographic measurement of temperature fields in natural convection heat transfer led directly to Professor Vest's work on computed tomography. In heat convection studies, an expanded beam of laser light is passed through a transparent fluid, and an interference fringe pattern is generated that contains information concerning the fluid's density. In the early 1970s, Vest and his students began to consider the experimental information available...
from multiple beams traversing the fluid in a variety of directions. They quickly realized that given an adequate number of viewing directions, three-dimensional measurements of the density could be obtained mathematically from interferometric measurements. The mathematical procedure for obtaining these measurements is called tomographic inversion and is similar to the procedure used to obtain medical images from CAT and MRI scanners.

The implications of this work were to provide a powerful imaging method that could be used to validate important predictions in combustion, aerodynamics, and heat transfer. Between 1970 and 1987, Vest and his students worked on the computational and experimental aspects of this problem. Experimental studies in convection heat transfer, transonic aerodynamics, and turbulent shear flows and a number of algorithmic studies were also carried out. The work of Vest, his students, and some of his contemporaries laid the groundwork for a number of studies currently being carried out using tomographic methods in combustion and hypersonic flow.

Using the setup above, an interferogram (far left) is first obtained on a holographic plate. The gradient boundaries are too indistinct for direct measurement so the image is digitally processed into a more sharply defined image (preceding page). Processed images from several viewpoints give a measurable three-dimensional map of the transparent jet. A realistic visualization of the transparent turbulent jet (near left) can be achieved by further processing the gradient into an absolute phase image.
Chia-Shun Yih's Fluid Mechanics

Professor Chia-Shun Yih was the Stephen P. Timoshenko Distinguished University Professor in the Mechanical Engineering and Applied Mechanics Department from 1968 until his retirement in 1988. He is one of the most honored professors in the Department's history, a member of the U.S. National Academy of Engineering and of the Academica Sinica in China. His contributions form a significant segment of the literature on the mechanics of fluid flows. The following summary of his contributions was taken from the introduction to Yih's most recent book Selected Papers. The introduction was written by Yih's longtime friend and colleague C.C. Lin.

Chia-Shun Yih's contributions to the literature of fluid mechanics have been important and extensive. With his bountiful love for nature, it is not surprising that some of his most significant contributions deal with fluid flows that are ubiquitous in our environment. The field of stratified flows itself is rich in physical phenomena. This richness owes its origin to the interplay of the heterogeneity of the fluid medium and the gravitational field. This fact was noted by Yih in the preface to his book Stratified Flows, 1980, which first appeared in 1965 under the title Dynamics of Nonhomogeneous Fluids. This book, which is primarily based on Yih's original contributions to the field, has since become a classic reference for all serious students and researchers.

While much of Yih's success owes to his physical insight, it is perhaps equally true that he is always able to use precisely the right mathematical tool. For example, in the paper "Gravity waves in a stratified fluid," Yih made use of Sturm's second comparison theorem to obtain the result that the phase speed decreases as the wave number increases, in small-amplitude wave motion of a heterogeneous liquid with a free surface. He has also been very successful in introducing ingenious mathematical transformation of variables to
enable certain general classes of difficult problems of wavy motions with finite amplitudes to be solved with relative simplicity.

For example, in his paper "A class of solutions for steady stratified flows," the use of a more general form of transformation of variables led Yih to an elegant theorem in three-dimensional shallow-water theory. The theorem states that "so long as the shallow water theory is valid, a class of steady stratified flow with a free surface originated from rest can be found corresponding to each irrotational steady free-surface flow of a homogeneous fluid originated from rest."

The subject of internal hydraulic jumps of great importance to environmental and hydraulic problems was first treated by Yih and Guha in 1955. That paper has been referred to in nearly every paper written on that subject since.

In the field of hydrodynamic stability, his investigations include results that are applicable generally and examinations of how specific fluid properties may affect the instability of the flows. His solutions to many stability problems involved the utilization of new techniques or adapting those in other contexts.

Yih has also worked on surface waves in fluids of homogeneous density. His papers on patterns of ship waves give two formulae in closed form from which the patterns can be determined simply, be they of gravity waves, gravity-capillary waves, or internal waves. From Yih's formulae, all the known results of Kelvin, Havelock, and others for all sorts of waves can be obtained readily, without the rather obscure reasoning initiated by Lord Kelvin. These formulae have brought the theory of ship waves within the reach of fourth-year undergraduates.

Yih's work on jets, plumes, and diffusion stems from his early work on convective plumes caused by a point source of heat. The similarity solutions for straight turbulent jets were well-known in the nineteen thirties. Guided by a dimensional analysis, Yih worked with Hunter Rouse in 1947-48 on the experimental determination of the velocity and temperature distributions in a round turbulent plume caused by a point source of heat. But it was not until 1977 that Yih was able to give the eddy viscosity an expression on dimensional arguments and thus to give analytical solutions for both round and plane turbulent plumes for certain turbulent Prandtl numbers. The eddy viscosity was assumed constant in any plane normal to the plume axis. Yih was able to apply that same sort of analysis to jets and plumes in a transverse wind. One interesting analytical result is the double-helix structure of jets and plumes in a transverse wind, which one can observe in a chimney plume on a windy day.

These two photos show the effect of acceleration on an unstable free-surface. The instability at top shows the free-surface at near g' and then a few milliseconds later. This study with S.P. Lin first appeared in 1964.
As a student of physics and later as a Professor of Mechanical Engineering at the University of Michigan, Julian Frederick was instrumental in the development of two of the most important technologies of our age: ultrasonic imaging and acoustic emission. He wrote a widely used text on these subject entitled *Ultrasonic Engineering* and he was a founding member of the American Acoustic Society.

Frederick began his work in ultrasonics as a research associate in the Physics Department under the tutelage of Professor F. Firestone. Firestone's research team discovered the phenomenon of magnetostriction, which was the foundation for ultrasonic detection technology. During his tenure in Firestone's lab, Frederick helped to develop materials for magnetostriction and worked on high frequency electronic circuits for creating electromagnetic fields. He was also part of the team that developed the use of sound waves to detect cracks in metal, a technology that has expanded from those early beginnings to have widespread application in industry.

In 1957, Frederick left Firestone's laboratory to join the faculty of Mechanical Engineering. Over the next twenty-five years, he carried out research to develop and refine fundamental knowledge and applications in the field of ultrasonics. Some of his early studies were in the areas of manufacturing and medicine. For example, Frederick worked in collaboration with researchers in the University of Michigan Medical School to detect hard regions in heart muscle using ultrasonics. This was one of the first studies on ultrasonic detection in medical applications, a technology that has now become widespread.

In the early 1960s, Frederick began to investigate the fundamental causes of noise emission, turning his research toward the passive detection of sounds generated in solids. This activity has become known as acoustic emission.
Frederick, together with Professor D.K. Felbeck, was able to demonstrate that noise emitted from lightly stressed aluminum alloys was caused by the creation and sudden growth of dislocation systems from Frank-Read sources. Working with graduate students A.B.L. Agarwal, N.G. Sankar, and R.C. Bill, Frederick and Felbeck developed very sensitive displacement sensors that could detect displacement of approximately 2 nm, which is 105 times smaller than the diameter of the aluminum atom. They constructed their apparatus inside a very heavy, very thick, insulated suspended cubical chamber, about 4 mm on a side, which was installed in the basement of the East Engineering Building on the main campus. Their best work was done late at night, when the outside truck and automobile traffic was at a minimum. Using these sensors, they were able to detect sudden bursts of dislocation motion over areas as small as 10 mm in diameter. This was the first known independent proof that dislocation generation by bursts actually occurred. Nowadays, any noise produced by a metal, even the very loud emissions from growth of a crack, are referred to as acoustic emission, but the early use of this term implied extreme sensitivity. Professors Frederick and Felbeck and their students published four papers on several aspects of this important discovery.

In the 1960s and 1970s, Frederick turned his attention to work on crack detection in metals with principal applications in the detection of cracks in the steel enclosures and pipes in nuclear reactors. One requirement of this application was to find a way for nuclear-power plant technicians with relatively little training to obtain good data about possible cracks. The most difficult part of the operation was to hold the ultrasonic transducer tightly and flat against the metal surface that was being examined. It was useful to place a "spot" of petroleum jelly in the contact region, but even this had limitations. Frederick developed ways to use water as the bridge between the transducer and the metal surface, which turned out to relax the requirements for flat and tight contact.

Once the transducer could be easily moved, the idea arose to obtain data from several transducer locations and, thereby, get images of a crack from different angles of view. Further, several transducers could be aimed at the same location on the metal from some distance. This technique is known as the Synthetic Aperture Method. This led to a project sponsored by the U.S. Nuclear Regulatory Commission, Division of Reactor Safety Research to develop new and improved methods for visualizing cracks and other discontinuities in structures and materials. Images of the cracks created by ultrasonic waves were displayed by using computer graphic techniques in pseudo three-dimensional types of displays. A key objective of the research was to develop techniques for obtaining greater accuracy in characterizing the cracks being evaluated. The work was carried out with the use of an Interdata 7/32 computer having 256k bytes of core memory and 20 megabytes of storage. Data were acquired and processed by the computer and the results displayed on a vector graphic display. As better computers were developed, the images improved. In 1978, Frederick reported gray-scale indicating the strength of signals from the crack. The strength in turn indicated the separation of the crack walls. Further work continued on color representation in image reconstruction up to the time of Frederick's retirement in 1982. As an emeritus, Frederick remained active and was working on a second book, this one on Acoustic Emission in Non-Destructive Testing, when he died in 1983.
Looking to the Future

Mechanical Engineering at the University of Michigan continues to chart new territories in engineering science. This section highlights a few of the scientific and technological challenges MEAM researchers are currently exploring.

This prototype of a multi-arm milling machine, designed by Profs. Allen Ward and Jeffrey Stein, is the first of a new generation of "novel" machining centers. It allows greater mobility for machining complex geometries quickly and accurately.

Prof. Herman Merte's experiment in pool boiling in microgravity was one of a group of NASA "get-away specials" (G.A.S.) flown on shuttle flight STS-47 in April, 1993. This "G.A.S. Can" package permitted nine tests to be conducted in a prototype pool boiling vessel.
Investigators in the MEAM biomechanics lab examine many characteristics of human posture, muscular control, and structural stability. Areas of study include geriatric mobility impairments, obstacle avoidance strategies, and human scoliosis.

Prof. Noboru Kikuchi has hypothesized that his homogenization method of design may lead to advanced materials composed of microstructures similar to human trabecular bone and other natural materials. For example, the microstructures of a car’s skin could be designed to carry fluids just as veins circulate blood, providing a more uniform heat to the interior and providing a means for self-repair of rust spots or damage due to accidents.

Prof. Noel Perkins has developed techniques for studying the dynamic behavior of slack cables in active use. This apparatus developed with the help of graduate assistant Chris Lee will be used for examining cables underwater.
Fluid Mechanics

Over the last two decades, powerful new computers and algorithms have made it possible for researchers to increase their knowledge of the fundamental physics of fluids. The MEAM fluid mechanics group is at the forefront of this important area of research, making significant contributions to the understanding of fundamental structures and processes of fluid flows using direct numerical simulations and experimental studies. Professors Rayhaneh Akhavan, William Schultz, and Grétar Tryggvason have developed theoretical models that provide a better understanding of fluid behavior in applications as diverse as flows around cars, ships and fish; combusting flows in turbomachinery; and dispersion of atmospheric pollutants. Professor Steven Ceccio carries out highly innovative experimental studies of basic fluid processes (particularly cavitation) with applications in hydromachinery, such as hydroelectric turbines, high-speed pumps, and ship propulsion systems. The group carries out sponsored projects totalling approximately $850,000 for agencies including the Office of Naval Research, the Gas Research Institute, Kimberly-Clark, National Aeronautics and Space Administration, the National Science Foundation, the Naval Research Laboratories, and the Air Force Office of Scientific Research. The selected projects described below are illustrative of the group's work.

A Numerical Study of Fish Swimming

Associate Professor William Schultz

Until this study, understanding of fish locomotion has been driven by hydromechanical models based on thrust and resistance. This theory, however, is inappropriate for a wide range of swimming modes and for questions of stability. This study introduces a more general numerical model for fish swimming in an unbounded fluid. The swimming of neutrally-buoyant fish is simulated assuming it is surrounded by an infinite two-dimensional inviscid flow with the wake represented by discrete point vortices. For a fish shape that is a prescribed function of time, we predict the motion of the center of mass and the orientation angle from conservation of linear and angular momentum. Our fully-computational, two-dimensional inviscid model requires no slender-body assumptions nor “adjustable” parameters required in slender-body theory. The numerical model compares well to an observed fast-start (acceleration from rest) of a rainbow trout.
and to a turning maneuver of a rudd (Weihs 1972). We study the effects of body shape and deformation on swimming speed and power for carangiform motions. Steady swimming results show that the predicted maximum speed occurs when the swimming wavelength is equal to the fish length—the velocities are appropriate for observed stride lengths. The simulated swimming power with a simple viscous force model compares favorably to expectations based on measured metabolic rates. Simulations with varying viscous forces suggest that the inviscid wake-induced drag may be more important than viscous drag since power predictions are reasonable. The trends of swimming power with tail-beat amplitude show excellent agreement with trends from the slender-body theory of Lighthill (1975) in the range where the slender-body theory is valid. The effects of the body thickness agree qualitatively with the conclusions of Newman & Wu (1973) and Newman (1973 a,b).

**Modeling of Bubbles and Drops**  
*Associate Professor Grétar Tryggvason*

The dynamics of flows containing two fluids separated by a sharp interface, such as a bubble or drop, are of the utmost importance for both natural and technological processes, such as boiling heat transfer, air entrainment in casting (porosity), spray combustion, spray painting, and rain. Professor Tryggvason is carrying out research to simulate multiphase flows fully and thereby lead to a better understanding of phenomena that take place at the smallest scales within these flows. To examine the small scale processes in multiphase flows is extremely difficult. The small time and spatial scale makes measurement difficult, and the change in phase usually eliminates visual access to the interior of the flow. Full numerical simulations of the flow can in principle give all the necessary information, since the governing equations are (for the most part) well known. In practice, however, this is one of the difficult areas of computational fluid dynamics. Progress has been slow, and almost all current studies make a number of simplifications, such as inviscidness, Stokes flow, two-dimensionality or axisymmetry. Tryggvason has developed a numerical technique that allows accurate and efficient simulation of flows that take into account physical phenomena in the fluids, including viscosity, inertia, and surface tension. In Tryggvason’s immersed boundary technique, fluid is resolved on a stationary mesh, and the interface is represented by a moving mesh of lower dimension. It allows for the prediction of the
performance of the process in much greater detail than was possible before. The method has several advantages over previous methods: it handles the colliding interfaces easily; it is relatively simple; and it is easy to code and to vectorize. The method, therefore, allows for relatively easy simulation of fully three-dimensional phenomena.

**Turbulence Control in Wall-Bounded Flows**

*Assistant Professor Rayhaneh Akhavan*

Overcoming the large drag coefficients associated with turbulent flows has remained a main goal of turbulence research for several decades. In fact, turbulent-drag reduction is currently considered a major “barrier problem” to further optimization of most aerodynamic and hydrodynamic bodies. Turbulent drag accounts for nearly 50% of the drag of most underwater bodies. Over the years, a variety of turbulence-control and drag-reduction measures for wall-bounded flows have been devised. For most of these techniques; however, drag reduction is quite modest, on the order of 5-10%. Professor Akhavan and her students Wen-Je Jung, Norberto Mangiavacchi, and Amid Ansari have devised a method that may reduce drag by a much higher percentage. Research on the structure of turbulent boundary layers over the past two decades has revealed that production of turbulence in wall-bounded flows occurs in well-organized (coherent) structures in a quasi-periodic manner. Through the use of direct numerical simulations, Akhavan’s team has found that the internal dynamics of these coherent structures can be utilized to obtain turbulence control and drag reduction in wall-bounded flows. In numerical experiments performed on the San Diego Supercomputer Center 64-node Intel iPSC/860 hypercube, Akhavan and her team have discovered that by exposing a turbulent boundary layer to spanwise oscillations at selected frequencies, turbulent drag can be reduced by more than 40%. The oscillations can be introduced either by the spanwise motion of the wall or by superimposing a spanwise oscillatory pressure gradient on the flow. These results indicate a simple and effective means of control of turbulence in wall-bounded flows. Further optimizations for practical applications are currently under study.
Experimental Studies of Cavitation in Fluid Flows

Assistant Professor Steven Ceccio

When the absolute pressure of a liquid is reduced below the vapor pressure gas and vapor cavities may form in a process known as cavitation. The presence of cavitation can seriously affect the performance of hydromachinery, such as hydroelectric turbines, high-speed pumps, and ship propulsion systems. Cavitation can reduce performance, create noise and vibration, and cause fatigue and erosion. By understanding the physical processes that lead to cavitation, we can delay its onset and help to mitigate its effects. Professor Ceccio's research group is studying the fluid mechanics of cavitation inception. Cavitation first occurs when small microbubbles within the fluid are swept into low pressure zones and explosively grow. In turn, their growth can alter the nearby flow, further inducing cavitation. The inception process can be intermittent, making it difficult to study systematically. In order to carry out studies of cavitation Ceccio has developed electrical probes, which can be used to detect and quantify the dynamic process of cavitation inception. Once detected, a variety of techniques can be used to record the cavitation process, including high-speed photography and acoustic probes.

Cavitation inception usually occurs in complex, three-dimensional flow fields. To study such flows, Ceccio has been working with Professor Luis Bernal of the Aerospace Engineering Department to implement a holographic particle imaging velocimetry system (HPIV). With HPIV, flow velocities are determined after the motions of many small tracer particles are detected and recorded. Holograms are used to simultaneously record the motions of many particles within a sampled flow volume, and these images are digitally analyzed to produce a set of velocity vectors within the flow field.

The fluid mechanics of cavitation is investigated in Prof. Steven Ceccio's laboratory. Cavitation is an important phenomenon because it adversely affects the functioning of hydromachinery. This blow-down apparatus induces cavitation by generating intense short duration surges through a three-inch diameter test section.
Heat Transfer

MEAM heat transfer faculty carry out research on a diversity of topics including Efficient Drying versus Pulse Combusters (Professor Vedat Arpaci), Flame Spread Over Charring Materials (Associate Professor Arvind Atreyia), Thermocapillary Flows in Welding and Crystal Growth (Professor Michael Chen), Forced Convection Boiling in Microgravity (Professor Herman Merte, Jr.), and Visualization of Flows in Torque Converters (Professor W.-J. Yang). Research funding for the group totals approximately $800,000 from sponsors including GE Aircraft, Ford Motor Company, the Gas Research Institute, the National Aeronautics and Space Administration, Whirlpool Corporation, the Department of Energy, and the National Science Foundation. Below is a sampling of projects being carried out by heat transfer faculty.

Microscales, Irreversibility, Radiation, Acoustics, Chaos

Professor Vedat Arpaci

Microscales of complex (hydromagnetic, radiating, reacting, pulsating) turbulent flows are an emerging research area with significant practical applications. On fundamental grounds, the turbulent dissipation of all forms of energy (mechanical, chemical, nuclear, electromagnetic, radiative) into thermal energy is a measure of irreversibility characterized by these scales. On technological grounds, the foundations of the so-called "empirical" heat and mass transfer correlations for turbulent flows can be interpreted in terms of these scales.

In a joint research program between the University of Michigan and the Sandia National Laboratories, the Sandia experimental data demonstrating the increased efficiency of heat and mass transfer via pulse combustion is theoretically interpreted by the Michigan models based on the microscales.

In a joint research program between the University of Michigan and NASA-Lewis Research Laboratories, the Lewis data on the surface-tension driven turbulent motion in evaporating droplets is also theoretically interpreted by the Michigan models based on these scales. A computational program based on a Godunov projection method that evaluates the nonlinear (inertial, convective) terms with high precision complements the modeling effort.

A research program supported by the Ford Motor Company involves Michigan doctoral students gathering turbulent data on Ford engines and supporting the data by models based on the appropriate microscales.
The present research interests of Professor Arpací include also the radiative and acoustical properties of interacting particles in sooty, seeded, polluted, smudgy media, which have important technological as well as environmental applications. These interests also include chaotic thermocapillary driven flows, which find important space applications.

**Formation and Oxidation of Soot and NOx in Diffusion Flames**

*Associate Professor Arvind Atreya*

Soot and NOx formation processes are of considerable interest to practical combustion designers because they control the combustion efficiency, pollutant formation, and thermal radiation in combustion systems. While all these aspects are important in large industrial furnaces and combustors, flame radiation plays a particularly important role because thermal radiation is the primary mode of energy transfer in these systems. Higher flame radiation increases the efficiency of energy transfer, while lower flame radiation results in higher flame temperature which increases the production of NOx and also requires equipment capable of handling high temperature exhaust gases. Thus, the technical problem is to reduce the flame temperature and hence the NOx production rate by promoting flame radiation. This can only be accomplished by increasing the soot production rate in such a way that it is completely oxidized before leaving the flame zone. NOx and soot formation processes therefore are intimately linked.

This research focuses on determining the soot formation and oxidation rates in countercflow diffusion flames and developing a model for a radiating flamelet for use in turbulent diffusion flames. The effect of variables used in controlling furnace flames, namely, the preheat temperature, the chemical composition of the reactants, the strain rate and dilution by products of combustion on soot formation, is also being investigated. In addition, NOx measurements and modeling are included in the study.

**Transport, Reaction and Phase Change in Porous Media Laboratory**

*Professor Massoud Kaviany*

Porous media, such as powders, foams, fabrics, soils, coals, fiberglass insulations, and concretes all undergo nonisothermal processes in their fabrication and usage. The fluid filling in the pores of these media can be gaseous or liquid or
both, and the fluid can be multicomponent. The heat transfer aspects of porous media become important when there is an exothermic chemical reaction (combustion), a phase change among any phase pairs of gas, liquid and solid, or a simple change in the sensible heat. Applications in mechanical engineering are vast including the areas of climate control, energy conservation, energy harvesting, environmental cleanup, heat exchangers, manufacturing, materials, and processing.

The scientific-engineering treatment of transport, reaction, and phase change in porous media addresses the fundamentals of conduction, convection, radiation, and chemical reactions at the pore level. Since porous media of finite size are of interest, these processes must also be studied at the interface of the porous media with bounding media (a fluid or solid). The presence of a bounding surface drastically changes the distribution of the phases in two-phase flows and the velocity distribution in single-phase flows.

Professor Kaviany has addressed these problems by the direct simulation of the processes (conduction, convection, radiation, phase change, and reaction) at the pore level. These direct simulations have been deterministic and statistical (Monte Carlo simulation in the case of radiation using geometric optics). The anisotropy of the effective medium properties adjacent to the interfaces has been formulated, and the transfer coefficients have been developed.

The goal of his research and instruction in this area has been to identify critical technologies and obtain sponsorship from the firms or institutions in need of these technologies. He then formulates and performs fundamental research that can address (and in some cases directly solve) these problems. He also organizes the findings in a manner useable by the students and other researchers.
Manufacturing

During the last decade, MEAM has developed one of the strongest manufacturing automation groups in the world—specializing in research in automated monitoring, sensing, and control as applied to machinery. Twelve manufacturing faculty members carry out educational and research activities in ten laboratories. A broad range of technology developed by the group has been transferred for use in industry. The research program supports approximately seventy graduate students and has funding totalling approximately $3 million. Sponsors include the U.S. Air Force, Chrysler Corporation, the U.S. Department of Energy, Ford Motor Company, General Electric, General Motors, Kodak, the Michigan Strategic Fund, the National Science Foundation, and the Office of Naval Research. Below is a sampling of research projects currently underway in the manufacturing laboratories.

Tool-Wear Estimation in Machining
Professor Galip Ulsoy

The purpose of this research is to develop on-line tool-wear estimation methods for machining processes. The real-time estimation of tool wear in machining operations is important for scheduling tool changing times and for adaptive process control and optimization. However, tool wear cannot be measured directly during cutting. Professor Ulsoy has developed an approach that permits estimation of tool wear under varying cuttings (e.g., changes in depth-of-cut, feed and speed), as would be required in many production situations. The method uses force measurement during cutting together with a process model. The model is the basis for an adaptive state estimator, which simultaneously estimates model parameters and the model states (i.e., state of wear of the tool). This force-based estimation is intermittently calibrated by the use of a computer vision system for direct optical wear measurement between parts. For production situations where a single tool-edged produces many parts, the vision system can be used by itself. On the other hand, if a single part is produced by one or more tool edges, then the force-based system only can be used. The two are used in conjunction for production situations where a tool produces several (e.g., 10) but not many (e.g., 100) parts. Laboratory tests for a turning operation with varying cutting conditions show excellent results. The maximum error in the flank wear estimate is less than 30μm.
Variable-Gain, Cross-Coupling Control for Multiple Axes
Professor Yoram Koren

Unlike traditional CNC controllers, where each axis of a machine tool is controlled independently, the U-M CNC controller uses the cross-coupling control method, which makes all the axes utilize each other’s actual position information simultaneously, so that the tool can produce considerably more accurate curves. In our lab demonstrations, the cross-coupling control method reduces contour errors of 2-D and 3-D curves by up to an order of magnitude (i.e., 10:1) compared to traditional CNC controllers. The concept of the cross-coupling control method for 5-axis machine tools has already been developed and will be implemented and evaluated on a 5-axis milling machine in the near future.

Strategies for Automating the Modeling Process
Associate Professor Jeffrey L. Stein (with Yih-Tun Tseng and Bruce Wilson)

Many solutions for manufacturing design and control problems require the development of a dynamic model of the machine or machine process. Unfortunately, no software tools (or in any other tools, for that matter) exist to help manufacturing engineers to develop these models. The purpose of this research is to develop software tools to assist in automating the modeling process. Professor Stein’s group has identified the basic structure of the general modeling process that is used by engineers to create valid, proper, quantitative models of physical systems, where proper is defined as a model of necessary yet sufficient complexity. They have proposed several strategies that could serve as the basis for an artificial intelligence (AI)-based computer environment for automating the modeling process. These are: (1) decomposing: the process of transforming real systems into a collection of objects or components and assigning them motion attributes, which can be accomplished with a user-interactive dialogue with the computer; (2) mapping: the process of associating physical objects (components) with ideal phenomena (basic physics), which is a totally automated strategy based on associating energy phenomena with each identified motion of the components; (3) structured modeling: a systematic and, thus, totally automated process of lumping the energy phenomena, defining state variables, and assembling the model based on motion constraints; (4) modifying: a heuristic-based strategy for altering decomposing and structured modeling processes that have failed to meet modeling specifications. This strategy is imbedded in a program called COMMA
(COMputer Modeling Assistant), which demonstrates the feasibility of designing an automated modeling program. They have also developed a less general, but more powerful program MBA (Model Building Assistant), which is focused on automating the synthesis of lumped-parameter models of machine tool drive systems and is a useful tool for designing such systems.

**Precision Engineering in Machining**

*Associate Professor Jun Ni*

The objective of this research is to achieve greatly improved machining accuracy through the use of sensing, modeling, and control methods. Ni’s group has three on-going projects: (1) On-line control of hole quality in boring operations. A real-time sensing system is built into the boring bar structure to sense the machined cylindrical surface during machining. The processed signatures are used to actuate the boring cutter via a piezoelectrical translator so that the compensation can be achieved on line. (2) Feasibility study of chatter prevention and suppression. Rather than detecting the machining chatter after the fact, this project focuses on the feasibility of preventing the chatter during its onset. The key is the early identification of the chatter before it fully develops. (3) Real-time generation of NC tool path. An innovative method of generating the NC cutter path is being developed. CAD models in the IGES format can be used directly on line to generate the NC tool path instead of the conventional off-line approach.
The 2mm Program

Assistant Research Scientist S. Jack Hu

An automobile body provides the basis for the complete assembly of a vehicle. Improper dimensions of a car body will introduce problems in final assembly, as well as problems in the complete vehicle, such as fit and finish, wind noise, water leakage, closing effort, and so forth. In this research, Dr. Hu's group is working with a number of automobile manufacturers to advance their automobile body manufacturing techniques and process control methodologies to achieve world-class quality. The aim is to reduce variations on critical dimensions to within 2mm. A second objective of the program is to improve the scientific understanding of the sheet metal assembly processes and to establish a technical infrastructure for future sheet metal process control and assembly systems. To achieve these objectives, researchers are assigned to different stamping and assembly plants, variation reduction teams are formed in each plant, and problems in stamping and assembly are identified and solved one by one.

In the 2mm program, MEAM researchers work with industry to reduce variation in vehicle body assembly.
Design

The seven full-time professors who comprise the Department's design group are nationally recognized for their contributions in a broad range of leading-edge research. Their efforts emphasize close interaction with industry and include topics such as geometric modeling; techniques for optimizing conceptual designs; computational methods of designing complex mechanical devices; automated process planning; machine design; artificial intelligence applications to design; design education; design management; and computer graphics. The budget for design research exceeds $500,000 annually and comes from both industrial and governmental sources including the National Science Foundation, the Office of Naval Research, Ford Motor Company, the Army, General Motors, Nissan, Suzuki, General Electric, Chrysler Corporation, Horiba, Applicon-Schlumberger, and the Air Force Office of Scientific Research. The reports below feature three of the many important research projects being carried out by this group.

Project MAXWELL

Professor Noboru Kikuchi, Professor Panos Papalambros, and Assistant Professor Debasis Dutta

Project MAXWELL aims at bringing together two innovative research efforts underway at the University of Michigan and at Carnegie Mellon University. MEAM researchers are synthesizing a new, mathematically rigorous method for the concurrent design of form and material composition called the homogenization method. Carnegie Mellon researchers are developing a novel method for the rapid fabrication of such designs by thermal spray shape deposition called MD* (recursive Mask and Deposit). By merging these two efforts together in an integrated methodology will allow for the manufacture of superior products not possible before. Such parts will possess superior structural and mechanical properties (e.g., lower weight to stiffness ratio) and will satisfy packaging and other manufacturing requirements (e.g., ease of assembly). The current application domain is in automobile design and manufacture and includes sheet metal/composite panels, brackets, suspension components, and special structures for side impact energy absorption.

The homogenization method is based on the observation that topological design is necessary in addition to size and shape design. If topological changes are not allowed, size and shape optimization procedures can improve a design by
approximately 5-15%. Topological modifications, however, can often yield 30-50% improvement. In the homogenization method, the topology and shape problem is formulated as a new optimization problem involving material distribution. Given a solid with a prescribed volume, microscale voids are generated within the design domain where a solid structure is not required for supporting loads. Therefore, instead of designing the shape and physical dimensions of the cross section of a structure, infinitely many microscale voids are generated within the configuration wherever the stress is small. If a portion in the domain is highly stressed, the homogenization method prevents the creation of microscale holes and that portion remains solid. Furthermore, the orientation of noncircular voids has a significant effect on the overall material response. Therefore, in the new optimization problem, the design variables are the density of microscale voids and their orientation over a specified domain. By removing material completely from portions of the domain densely packed with voids, the optimum shape of the structure is identified, while its topology is determined by accounting for the number of “global” holes.

The design images produced by the homogenization method are transformed into realistic manufacturable designs using advanced geometric modeling and image processing techniques. The designs are then implemented using Carnegie Mellon University’s MD* layered manufacturing process.

**Design of Compliant Mechanisms for Microelectromechanical Systems (MEMS)**

*Associate Professor Sridhar Kota*

*Graduate Research Assistant G. K. Ananthasuresh*

The study of microelectromechanical systems (MEMS) is a fast growing area of research that has an immense potential for applications on the micro level. This research addresses the design aspects of such systems. Through MEMS it is possible to integrate movable mechanical elements with electronic circuits and sensors and then fabricate the entire assembly using the same process. Developments in the past decade have been truly revolutionary. Microfabrication technologies have been developed that can build electrostatic motors, linear actuators and resonators, springs, grippers, and gears, all of which are in the size range of a few tens of microns to a few hundreds of microns. These technologies are limited, however, by exigencies in fabrication and design at the micro level that are nonexistent at the macro level. One such difficulty is the virtual loss of the third
dimension, since most of the microstructures are fabricated using integrated-circuit-chip-based micromachining techniques that are predominantly two dimensional. Also, to justify the cost, MEMS should be batch-produced with minimal or no assembly. These difficulties can either be surmounted with further breakthroughs in microfabrication technologies or circumvented with novel designs. This research is aimed at the latter. We are introducing a novel class of mechanical designs that require no assembly, called compliant mechanisms for MEMS applications.

Compliant mechanisms are single-piece flexible structures that deliver the desired mechanical motion by undergoing elastic deformation as opposed to the rigid body motions of conventional mechanisms. Since the motion is dependent on geometry and applied forces, these mechanisms are treated in the light of kinematics and continuum mechanics. Compliant mechanisms have many attractive features including ease of manufacture, non-mechanical actuation, elimination of the need for accessories, less friction, less wear, less noise, etc. Potential applications include simple parts of machinery, hand-held instruments, robotic grippers, measuring instruments, and transducers at both the micro and macro levels.

As yet there is no systematic method for synthesizing compliant mechanisms. The objective of this research is to evolve such a method by extending Professor Noboru Kikuchi's newly developed design technique called homogenization. The application of homogenization to the synthesis of micro-compliant mechanisms enables the synthesis problem to be solved up to the fabrication detail starting from functional specifications only.
The Set-Based Concurrent Engineering Project

Assistant Professor Alien Ward

Design is usually considered an iterative process, in which a solution is posed, analyzed, and then modified. The set-based concurrent approach is an alternative that can be demonstrated with a simple problem such as arranging a meeting among a group of people. The iterative approach is to identify a time, then call everyone to see if they can make the time. If someone can’t, the time must be modified. The set-based approach is to pick the week in which the meeting must take place and ask people to identify the times during the week that are already committed. Picking a time is then easy. Similarly, the Toyota Motor Company requires its suppliers to develop a set of possible subsystem designs for each product, exploring the trade-offs before establishing the specifications.

Good engineering designers have always applied this sort of approach, but it has received little theoretical attention. Fully effective application requires ways to represent sets of possible solutions and allows high levels of design automation, as well as the efficient exploration of truly novel design concepts. Current activities include: (1) the development of a national electro-mechanical catalog selection system, operating over “electronic highways”, which will accept a schematic from a design and return a nearly optimal selection of bids for subsystems; (2) development of new, fundamental mathematics for design synthesis (rather than analysis); (3) studies of US and Japanese design practices, and the development of training material based on “best practice”; (4) development of new classes of computer-controlled machine, which may reduce life cycle costs for milling machines by up to 40%; (5) development of CAD software allowing automotive stylists and body and stamping engineers to quickly find the “intersection” of marketable, rigid, and manufacturable designs.
Robotics

Robotics has been identified as one of seven key technologies that will drive global economic competitiveness over the next few decades. MEAM has taken a leadership role in this critical area through work carried out by Professor Yoram Koren and Dr. Johann Borenstein in the Mobile Robotics Laboratory and in the Humechtronics Laboratory. Their work includes basic theoretical advances in areas such as navigation, obstacle avoidance, mapping, and environmental exploration as well as applications for business and government. The group's research funding totals approximately $425,000 from sponsors including NSF, Golder International, and Cybernet Systems. Below is a sampling of projects from the robotics laboratories.

Error Eliminating Rapid Ultrasonic Firing

Associate Research Scientist Johann Borenstein

Ultrasonic sensors are subject to noise and sporadic false readings, just like any other sensor system. In most operating environments, environmental ultrasonic noise is fairly rare. However, robots with multiple ultrasonic sensors may introduce their own noise, a phenomenon known as crosstalk. When operating a mobile robot under such real-world conditions, it is impractical to base the decision for an obstacle maneuver on a single (possibly erroneous) sensor reading that seems to indicate the presence of an object. A more practical approach combines multiple range samples. When traveling at a high speed, it is crucial to quickly and repeatedly gather multiple samples in time to avoid a collision. Fast sampling of multiple sensors, however, introduces even more ultrasonic noise and increases the occurrence rate of crosstalk. To overcome this problem, we have developed a method that will allow rapid sampling of all sensors while reducing erroneous readings by a factor of 1-2 orders of magnitude. Moreover, our method will completely eliminate crosstalk. This method, called error eliminating rapid ultrasonic firing (EERUF), can be implemented in software and will work with a modified off-the-shelf ultrasonic sensor interface board.
Analysis of Potential Field Methods for Mobile Robot Obstacle Avoidance

Professor Yoram Koren and Associate Research Scientist Johann Borenstein

Potential field methods are rapidly gaining popularity in obstacle avoidance applications for mobile robots and manipulators. While these methods are particularly attractive because of their elegance and simplicity, substantial shortcomings inherent to these techniques have been identified. Koren and Borenstein have devised a mathematically based method for systematically examining these problems in qualitative and theoretical terms. The heart of their analysis is a differential equation that combines the robot and the environment into a unified system. The equation permits the analytical formulation of a stability condition that states that for every environment/robot configuration there is a speed at which motion becomes unstable (when potential fields are utilized).

Multi-Degree-of-Freedom Vehicle for Constraint Environments

Associate Research Scientist Johann Borenstein

Multi-degree-of-freedom (MDOF) vehicles have many potential advantages over conventional (i.e. 2-DOF) vehicles but are difficult to control because of their over-constrained nature. These difficulties translate into severe wheel slippage or jerky motion under certain driving conditions. To overcome this problem, the Mobile Robotics Laboratory is developing a new concept (patent pending) in the kinematic design and the method of control for MDOF vehicles and mobile robots. Experimental results show smooth and accurate motion. Dead-reckoning accuracy is substantially better than that reported in the literature for other MDOF vehicles. It was found equal to or even better than that of comparable 2-DOF vehicles.

NavBelt for the Blind

Associate Research Scientist Johann Borenstein and Dr. Shraga Shoval

The NavBelt is a robotic device that alerts a blind user to obstacles in the environment. The device consists of a belt with eight electronic sensors worn around the waist, a computer to process the information from the sensors worn as a backpack, and headphones to receive the signals from the computer. The sensors send out signals in a 120 degree arc at a five meter range that bounce off obstacles.
The computer picks up the signal, interprets it and sends a stereophonic beeping sound to the headphones alerting the user. The beeps can tell where an object is, how far away, its size, whether it is moving, and how it relates to other obstacles.

**Mechanical Snake Robot**
*Professor Yoram Koren and Assistant Research Scientist Yansong Shan*

The mechanical snake robot is designed with two special features that allow it to operate in natural outdoor environments or in cluttered indoor environments where robots usually cannot function. Its first unique feature is the method of locomotion. Most snake robots move on wheels, which inhibits flexibility. The UM snake mimics the motion of a live snake using a design with seven links using caster balls and DC motors for the forward motion and solenoids that contact the floor for static points. The second feature is a method of control called obstacle accommodation that allows the snake to touch obstacles in the environment safely instead of having to avoid them completely.

**The HoverBot**
*Associate Research Scientist Johann Borenstein*

The HoverBot is an electrically powered flying robot similar to a model helicopter. It is designed with four rotors instead of one to provide greater stability. Without expensive autopilots, any conventional helicopter will tip over and crash unless constantly and actively stabilized by the pilot. Model helicopters will tip over even faster than large ones because their time constant is shorter. On-board controllers are impractical because they add too much weight. Preliminary tests on the four-rotor design indicate that it provides stability without additional weight.

The mechanical snake robot is designed to operate in settings that are too hazardous or too constricted for humans to enter.
Amazing Maize & Blue

In 1990 and 1993 Michigan engineering students competing against the best undergraduate engineers in the country won back-to-back national championships in solar car competition.

Michigan's dominance in this event began in 1988, when GM issued a challenge to college students across the country to design and build solar cars to race from Florida to Michigan in Sunrayce '90.

Over the next two years a team of about one hundred student Wolverines toiled almost around the clock to create their car, and in June of 1990, they arrived at the starting line with Sunrunner, ready to take on the competition from 32 other student built cars from around the country. As the race progressed over the next seven days, Sunrunner pulled into the lead and stayed there, crossing the finish line with a 90-minute lead over the second place car.

Five months later in November of 1990, Sunrunner competed in the World Solar Challenge in Australia finishing third in the world. The following summer, Sunrunner was retired from competition and put on exhibit in the Henry Ford Museum in Dearborn Michigan.

Soon thereafter, the call went out from GM for Sunrayce '93 and a new team of Michigan students went to work. Starting from scratch, the team began to build Michigan's second solar car, Maize & Blue. One change in the rules for the '93 race was that cars were not allowed to use space-grade solar cells as Sunrunner had; only the less efficient standard cells were allowed. Therefore, when Maize & Blue lined up at the start in Texas for the 1000 mile race to Minneapolis, she had one less advantage than Sunrunner had. Using a daring strategy and synchronized teamwork, the Michigan students pulled into the lead on the fifth day of the race and finished in first place, 90 minutes ahead of the second place car.

Maize & Blue will be seeking more honors in the World Solar Challenge in Australia in the fall of 1993.
CARMEL wins the 1992 Artificial Intelligence Robotics Competition

The CARMEL robot developed in the MEAM Mobile Robotics Laboratory took first place in the Artificial Intelligence Robotics Competition held July, 1992 in San Jose, California. Three MEAM Ph.D. candidates, Ulrich Raschke, Shraga Shoval and Liqiang Feng, were on the U-M team and Dr. Johann Borenstein, the head of the Mobile Robotics Laboratory, acted as team consultant. In the competition, CARMEL impressively outperformed eleven competing mobile robots from other universities and from industry. Among the entrants were robots from IBM, Carnegie Mellon University, and MIT.

In one stage of the competition the robots were required to find a number of objects as quickly as possible. CARMEL was the only entrant to find all of the objects and finished in only 9-1/2 minutes, way ahead of the next closest robot from Carnegie Mellon, which took 28 minutes.

According to Borenstein, CARMEL's exceptional performance can be attributed to two of the robot's features: (1) CARMEL has an on-board computer, which allows fast processing of sensor data and motor commands, and (2) CARMEL has a VFH obstacle avoidance method which allows obstacle avoidance at high speeds. VFH was developed by Borenstein and Professor Yoram Koren.

The student leader of the project was David Kortenkamp (EECS) and the academic and administrative supervisor was Dr. Terry Weymouth (EECS).

As a result of the victory, CARMEL was selected to receive a Best of What's New award for 1992 from Popular Science magazine. The awards recognize the year's 100 top products, technologies, and scientific achievements as determined by the editors of the magazine. The winners were featured in a 24-page cover story in the December, 1992 issue of Popular Science.
MEAM has many accomplishments to its credit in 1993. These include the completion of a renovation of facilities, a major revision of the undergraduate curriculum, and the attainment of a top-five ranking among all ME programs in the country.

One noteworthy initiative is in the area of automotive research. In June, the Department was awarded funding for a major research project: *The Center for Automotive Structural Durability Simulation*. The initial grant is for $1.2 million for two years from the Ford Motor Company.

The Center is an exciting development for the Department because it is a cross-disciplinary team project that aims at both fundamental research and specific deliverables for the automotive industry. Professor Panos Papalambros will serve as the Center’s director and Professor Jwo Pan as its associate director. This Center is the type of effort that will be critical over the coming decade as the nation shifts research priorities from a defense focus to a civilian one that can contribute to global economic competitiveness.

Another MEAM achievement arising from these same priorities is involvement in the COE’s newly created Program in Manufacturing (PIM), a nondepartmental, degree-granting program focusing on students returning from industry for advanced degrees. MEAM Professor Galip Ulsoy is the chair of the new program, and many of its activities will be carried out in MEAM laboratories. The first degree offered will be the Masters in Manufacturing Engineering, a joint effort with the business school designed to provide a broad education within engineering and business disciplines.

Please take the time to review all of the achievements of our faculty and students contained on the following pages.
# MEAM Student Leaders, Honors, Fellowships

## Student Societies
- **Michael Lefebvre**—President, *Society of Automotive Engineers*
- **Angela Martens**—President, *Pi Tau Sigma*
- **William Rockwell**—President, *Michigan Student Society of Professional Engineers*
- **Karen McClure**—President, *American Society of Mechanical Engineers*
- **Bernadette Lois**—President, *Epieans*

## Student Awards

<table>
<thead>
<tr>
<th>Award</th>
<th>Recipients</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>J.A. Bursley Award</strong></td>
<td>Karen Kenreich, Michael Rutz</td>
</tr>
<tr>
<td><strong>Distinguished Achievement Award</strong></td>
<td></td>
</tr>
<tr>
<td>Undergraduate</td>
<td>Kathryn Laberteaux, Andrew Filip, Keith Cook</td>
</tr>
<tr>
<td><strong>Graduate</strong></td>
<td>Eric Mockensturm, Marlin Kruse</td>
</tr>
<tr>
<td><strong>Outstanding Student Leader Award</strong></td>
<td>Christina DeGnore, Galen Gornowicz, Bernadette Lois, Yolanda McKay</td>
</tr>
<tr>
<td><strong>The Ivor K. McIvor Award</strong></td>
<td>Taein Yeo</td>
</tr>
<tr>
<td><strong>Honorable Mention</strong></td>
<td>Whie Chang, Ernst Mayer</td>
</tr>
<tr>
<td><strong>Charles Barth Prize</strong></td>
<td>Cory Culbertson</td>
</tr>
<tr>
<td><strong>Arlen R. Hellwarth Prize</strong></td>
<td>Christina DeGnore</td>
</tr>
<tr>
<td><strong>A.D. Moore Award</strong></td>
<td>Sharon Smolinski</td>
</tr>
<tr>
<td><strong>Vulcan Award</strong></td>
<td>Lori J. Park</td>
</tr>
</tbody>
</table>

## 1992-1993 Student Fellowships

<table>
<thead>
<tr>
<th>Program</th>
<th>Recipients</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amoco</strong></td>
<td>Byron Newberry</td>
</tr>
<tr>
<td><strong>Benton</strong></td>
<td>Robert Landers</td>
</tr>
<tr>
<td><strong>Department of Defense</strong></td>
<td>Diana Rincon</td>
</tr>
<tr>
<td><strong>Devlieg</strong></td>
<td>Kenneth Lipka</td>
</tr>
<tr>
<td><strong>Fulbright</strong></td>
<td>Guy Babbit</td>
</tr>
<tr>
<td><strong>National Science Foundation</strong></td>
<td>Kathleen Derwin, Matthew Castaniere, Amy Lerner, Eric Mockensturm, Ann Tassin</td>
</tr>
<tr>
<td><strong>Rackham Merit Fellowships</strong></td>
<td>Marcus Darden, Todd Easler, Evaristo Gonzalez, Matthew Grogan, Kim LeBrane, David Ortiz, Jose Ruiz, Charisse Russell</td>
</tr>
<tr>
<td><strong>Rackham Predoctoral</strong></td>
<td>G.K. Ananthasuresh</td>
</tr>
<tr>
<td><strong>Regents</strong></td>
<td>Rustom Bhiladvala</td>
</tr>
<tr>
<td><strong>USX Marathon</strong></td>
<td>Douglass Hargett</td>
</tr>
<tr>
<td><strong>Whirlpool</strong></td>
<td>Joe Borneo</td>
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## Enrollment and Degrees Granted

<table>
<thead>
<tr>
<th>Enrollment (Fall 1992)</th>
<th>Degrees Awarded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doctor of Philosophy</td>
<td>Doctor of Philosophy</td>
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<tr>
<td>Master of Science in Engineering</td>
<td>170</td>
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<tr>
<td>Bachelor of Science</td>
<td>173</td>
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<tr>
<td>Non-Candidate for Degree</td>
<td>801</td>
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<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1145</td>
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</tbody>
</table>

## Doctoral Degrees Conferred

### Fall (December) 1992

- **Huseyin Akçay**  
  Chair: P. Khargonekar (EECS)  
  Robust Linear System Identification

- **Randall Beikman**  
  Co-Chairs: N. Perkins and A. Ulsoy  
  Static and Dynamic Behavior of Serpentine Belt Drive Systems

- **Suhyun Choi**  
  Co-Chairs: C. Pierre and A. Ulsoy  
  Vibration Localization in Rotating Shafts

- **Liqiang Feng**  
  Chair: Y. Koren  
  Adaptive Mobile Robot Motion Control

- **Mian-Ju Gu**  
  Chair: A. Schultz  
  Biomechanical Analysis of Postural Balance in Young and Elderly During Perturbed Stance

- **Craig Hoff**  
  Chair: W.-J. Yang  
  The Effect of Distributed Flow Leakage on Pulse Propagation in Viscelastic Arteries

- **Jiann-Lin Hwang**  
  Chair: G. Brereton  
  An Experimental Study of the Fluid Mechanics of Turbulent Pipe Flow When Subjected to Forced Oscillation at High Frequencies

- **Hyun-Yong Jeong**  
  Chair: J.-P. Pan  
  A Macroscopic Constitutive Law for Porous Solids with Pressure-Sensitive Matrices and its Implications for Plastic Flow Localization and Crack-Tip Behavior

- **Myoungseob Kim**  
  Chair: J.-P. Pan  
  A Study of Crack-Tip Fields and Fracture in Elastic-Plastic Materials

- **Kevin Kirk**  
  Chair: F. Merte  
  A Study of the Relative Effects of Bumgency and Liquid Momentum in Forced Convection Nuclear Boiling

- **Christopher Lee**  
  Chair: N. Perkins  
  Modal Interactions in the Nonlinear Oscillations of Elastic Cables

- **Jinkoo Lee**  
  Chair: G. Johnson  
  Tolerance Optimization Using Genetic Algorithm and Approximated Simulation

- **Bor-Tsen Lin**  
  Chair: A. Ward  
  Inductively Defined Formalisms for Design Inferences on Sets of Intervals

- **Hai-Ping Lin**  
  Chair: N. Perkins  
  Theoretical and Experimental Investigations of Slack Cable/Mass System Dynamics

- **Donald Malen**  
  Co-Chairs: W. Hancock and R. Scott  
  Engineering for the Customer Decision Methodology for Preliminary Design

- **Gary Snavely**  
  Chair: P. Papalambros  
  An Abstraction-Based Methodology for Mechanical Configuration Design

- **William Waldron**  
  Chair: A. Wineman  
  Influence of Normal Stress Effects on Finite Shear Deformations of Compressible Nonlinear Isotropic Solids

### Winter (May) 1993

- **Abdulghaffar Aljawi**  
  Co-Chairs: C. Pierre and A. Ulsoy  
  Vibration Localization in Dual-Span Axially Moving Elastic Systems

- **Engin Atik**  
  Co-Chairs: J. Stein and B. Figan  
  Disturbance Rejection in the Heel Contact Phase of Gait

- **Zine El Abidine Ben Aoun**  
  Chair: J. Pan  
  Influences of Pressure-Sensitive Yielding and Non-Singular Stress on Plane-Stress Elastic-Plastic Crack-Tip Fields

- **Hsieh-Ching Chen**  
  Co-Chairs: A. Schultz and J. Ashton-Miller  
  Tripping Over Obstacles: Biomechanical Analysis of How Young and Old Try to Avoid It

- **Sung-Hoon Choah**  
  Chair: K. Ludema  
  Characterization of the Boundary Films Formed in Sliding on Steel Surfaces at High Temperatures
Woosuk Choi  
Chair - G. Johnson  
**Vibration of Roller Chain Drives with and without a Tensioner**

Shin Fann  
Chair - W.J. Yang  
**Numerical and Experimental Studies on Transport Phenomena in Rotating Channels with Throughflow**

Umesh Gandhi  
**Co-Chairs: J. Ni and S.M. Wu**  
Application of System Identification in Improving Crashworthiness Analysis

Mohammad Hassani  
**Co-Chairs: D. Talley and C. Borsnakke**  
An Imaging Method for Analyzing Spherical and Non-Spherical Particles

Peein Huang  
**Co-Chairs: S.M. Wu and J. Ni**  
Laser Optical Measurement Systems and Their Application to the On-line Error Compensation of Coordinate Measuring Machines

Inskil Jung  
Chair - G. Hulbert  
**Automatic Time-Step Control Algorithms for Structural Dynamics**

Steven Donald Jones  
Chair - A.G. Ushoy  
**Quantification and Reduction of Dynamically Induced Errors in Coordinate Measuring Machines**

Wen-Je Jung  
Chair - R. Akhavan  
**Response of Wall Turbulence to High Frequency Streamwise and Spanwise Oscillations**

Youngil Kim  
**Co-Chairs: R. Sonntag and C. Borsnakke**  
Generalized Equation of State for Refrigerants with Applications

Ali Koral  
Chair - G. Brereton  
**A New Orthogonal Decomposition Method for Turbulent Flows**

Shyh-Shyan Lin  
Chair - D. Patterson  
**Piston/Ring Assembly Friction Measurement and Modeling**

Chong Jin Ong  
**Co-Chairs: D. Dutta and E. Gilbert**  
**Penetration Distances and Their Applications to Path Planning**

Ki Ook Park  
**Co-Chairs: W. Schultz and K. Ludema**  
**An Asymptotic Analysis for Compressible Gas Lubrication of Rough Surfaces**

Kyoungkoo Park  
**Co-Chairs: R. Sonntag and C. Borsnakke**  
**Generalized Thermodynamic Properties of Refrigerants**

Leonard Pomrehn  
Chair - P. Papalambros  
**A Recursive Optimization Algorithm for Discrete Optimal Design**

Chih-Yao Roan  
**Co-Chairs: S.M. Wu and J. Hu**  
**Identification, Monitoring, and Diagnosis for Dimension Control of Automotive Body Assembly**

Sukhendu Samajdar  
**Co-Chairs: J. Barber and S. Samanta**  
**Bulk Processing, Microstructure and Property of a Superconductive Ceramic-Metal Microcomposite System: YBa2Cu3O7-S-Ag**

Yansong Shan  
Chair - Y. Koren  
**Robot Obstacle Accommodation: Mechanics, Control, and Applications**

Terrence Wagner  
Chair - P. Papalambros  
**A General Decomposition Methodology for Optimal System Design**

Taein Yeo  
Chair - J. Barber  
**Thermelastic Contact Stability: Analytical and Numerical Methods**

Faruk Yigit  
Chair - J. Barber  
**Stability Analysis of Thermelastic Contact with Solidification of Casting**

Byung Ok Yoon  
Chair - B. Kamopp  
**Dynamic Analysis and Optimal Design of Overhead Cam Systems**
Faculty News and Professional Service

Professional Service

Arvind Atreya
- Program Subcommittee, International Symposium on Combustion
- Subcommittee for Fire and Combustion, ASME
- U.S./Japan Panel on Fire Research (Associate Member)

James Atkinson-Miller
- Board of Editors, Journal of Orthopaedic Research
- Executive Committee, Bioengineering Division, ASME
- Terminology Subcommittee on 3D Description of Scoliosis, Scoliosis Research Society

James Barber
- Elasticity Committee, ASCE
- Editorial Board, Journal of Thermal Stresses

Giles Breneron
- Organizer, 1993 International Symposium on Particles on Surfaces, Fine Particle Society
- Faculty Adviser, ASME Student Section

Michael Chen
- Director, Thermal Transport and Thermal Processing Program, NSF
- Associate Editor, Applied Mechanics Reviews
- Session Chair, Thermal Fluid Issues in Manufacturing, National Heat Transfer Conference

David Cole
- Energy Engineering Board, National Research Council
- U.S./Canada Free Trade Act Select Panel
- International Coordinating Committee, SAE

- Membership Service Board, SAE
- Advanced Powerplant Committee, SAE
- Organizer, U-M Automotive Management Briefing
- Organizer, Symposium on North American Free Trade Strategies for Auto Suppliers.

Maria Comninou
- Executive Board, Technology and Society Division, ASME

Debasish Dutta
- Co-organizer, Symposium on Concurrent Engineering, 1992 ASME WAM
- Organizer, Invited Session on Automated Assembly, Workshop on Intelligent Manufacturing Systems, IFAC

Steven Goldstein
- Special Study Section, NIH
- Program Committee, Orthopaedic Research Society
- Committee on Biomedical Engineering, AAOS
- Editorial Consultant, Journal of Biomechanics
- Associate Editor, Journal of Orthopaedic Research
- Associate Editor, Journal of Biomechanical Engineering
- Junior Awards Committee, Applied Mechanics Division, ASME

Glen Johnson
- Vice-chair and Executive Committee Member, Design Division, ASME WAM
- Program Representative, Design Division, ASME
- Chair, Design Automation Committee, Design Division, ASME
- Computer Aided Design Committee, Computer Division, ASME
- Editor for Computer Aided Design and Optimization, Mechanism and Machine Theory

Elijah Kamatey-Asibu, Jr.
- Executive Committee, Production Engineering Division, ASME
- Associate Technical Editor, ASME Journal of Engineering for Industry

Bruce Kamopp
- Advisor, U-M Student Solar Car Team

Massoud Kaviany
- Vice Chairman, Theory and Fundamental Research Committee, Heat Transfer Division, ASME

Noboru Kikuchi
- Computational Methods in Applied Mechanics Committee, ASME

Yoram Koren
- Keynote Speaker, CIRP Annual Assembly, France
- Associate Editor, CIRP Proceedings on Manufacturing Systems
- Associate Editor, SME Journal on Manufacturing Systems

Herman Merte
- Advisory Committee on Educational Credentials, Board of Professional Engineers, State of Michigan
- Space Station Science and Applications Advisory Subcommittee, NASA

Panos Papalambros
- Editorial Boards:
  - Journal of Artificial Intelligence in Design and Manufacturing
  - International Journal of Engineering Design
  - Journal of Global Optimization
  - Journal of Engineering Optimization
  - Journal of Japan Society of Mechanical Engineers

Noel Perkins
- Technical Committee on Vibration and Sound, ASME
- Co-organizer, Symposium on Structural Dynamics of Large-Scale and Complex Systems, 14th ASME Conference on Mechanical Vibration and Noise

Christophe Priece
- Associate Editor, ASME Journal of Vibration and Acoustics
- Structures and Dynamics Committee, ASME Intl. Gas Turbine Institute
- Vibration and Sound Committee, ASME
- Co-organizer, Symposium on Structural Dynamics of Large-Scale and Complex Systems, 14th ASME Vibration and Noise Conference
- Visiting Researcher, Institute for Computational Mechanics in Propulsion NASA Lewis Research Center
Albert Schultz
- Honors Committee, Bioengineering Division, ASME

William Schultz
- Fluids Committee, Applied Mechanics Division, ASME

Steven Shaw
- Contributing Editor, *Nonlinear Dynamics*
- Editorial Board, International Journal of Bifurcation and Chaos
- Dynamics of Structures and Systems Committee, Applied Mechanics Division, ASME

Louis Sosolowsky
- Officer, International Shoulder Group
- Joint Biomechanics Committee, Bioengineering Division, ASME
- Solid Biomechanics Committee, Bioengineering Division, ASME

Jeffrey Stein
- Associate Editor, *Journal of Dynamic Systems Measurement and Control*
- Chairman, Symposium on Automated Modeling, ASME, WAM
- Chairman, Technical Panel on Modeling and Identification, Dynamic Systems and Control Division, ASME
- Organizer, Panel Discussion on Fundamental Research in Manufacturing for National Competitiveness, ASME, WAM

Galip Ulsoy
- Honors Committee, Dynamic Systems and Control Division, ASME
- Organizer, Symposium on Control of Manufacturing Systems, 1992 American Control Conference
- Associate Editor, *ASME Journal of Dynamic Systems Measurement and Control*
- Editorial Board, *Mechanical Systems and Signal Processing*
- Proposal Review Panels, NSF

Anthony Woo
- Manufacturing Board, ASME
- Fellowship Committee, NIST/NSF/ASA
- Organizer, Symposium on Concurrent Design 1992 WAM, ASME
- Associate Editor,
  - *ASME Transactions Journal for Engineering for Industry*
  - *Journal of Design and Manufacturing*
  - *International Journal of Computation Geometry and Applications*
  - *International Journal of Computer Applications in Technology*
  - *Visual Computer*
  - *Journal of Manufacturing Systems*

Promotions

Johann Borenstein
Assistant Research Scientist to Associate Research Scientist

John Holmes
Assistant Professor to Associate Professor

Sridhar Kota
Assistant Professor to Associate Professor

Jun Ni
Assistant Research Scientist to Associate Professor

Noel Perkins
Assistant Professor to Associate Professor

Steven Goldstein
Adjunct Associate Professor to Professor

New Faculty

Arvind Atreya
Associate Professor
Atreya is a graduate of Harvard University and was on the faculty of Michigan State University for nine years. His research interests include combustion, fire, heat transfer, and mass transfer.

Yansong Shan
Assistant Research Scientist
Shan received his Doctorate degree in 1992 from the University of Michigan. His dissertation was entitled "Robot Obstacle Accommodation: Mechanics, Control and Applications."

In Memoriam

Professor Emeritus William Mirsky died January 22, 1995, following an illness of several months. He received his doctorate from the University of Michigan in 1956 and was on the faculty for 35 years before retiring in 1988. Among his interests as a faculty member were the creative revision of courses, research on combustion and air pollution, and the application of computers in engineering education.

Professor Sam Wu died October 28, 1992, due to complications during open heart surgery. Professor Wu joined the MEAM faculty in 1987 after a 25-year career at the University of Wisconsin. During his tenure here, he founded and acted as director of the NSF-U/UCR Center for Mechanical and Optical Coordinate Measuring Machines and was the director of the Manufacturing Research Laboratory. Professor Wu was a world-recognized scholar in the areas of statistics and manufacturing, and during his 30-year career, he mentored 125 Ph.D. students, a world record for a university professor.
Faculty Publications 1992

Journal Articles

**Assistant Professor Raybanch Akhavan**

**Professor Vedat Arpaci**


**Associate Research Scientist**


**Associate Professor Arvind Atreya**


**Professor James Barber**


**Assistant Professor Giles Breteron**


**Assistant Professor Steven Cuccio**

**Professor Maria Comminou**

**Professor Walter Deabler**

**Assistant Professor David Dowling**

**Assistant Professor Mehrdad Haghi**

**Assistant Professor Scott Hollister**
Hollister S, Kituchi N, Goldstein S, “Do Bone Ingrowth Processes Produce a


**Associate Professor John Holmes**


**Assistant Professor Gregory Hubbert**


**Associate Professor Glen Johnson**


**Associate Professor Elijah Kannatey-Asibu, Jr.**


**Associate Professor Bruce Kannopp**

**Professor Massoud Kaviany**


**Associate Professor Robert Keller**

**Professor Noboru Kikuchi**


**Professor Yoram Koren**


**Associate Professor Sridhar Kota**


**Professor Kenneth Ludema**

**Professor Herman Merte**
Ervin JS, Merte Jr, H, Keller RB, and Kirk K, "Transient Pool Boiling in

**Associate Professor Jun Ni**


**Professor Panos Papalambros**

**Associate Professor Noel Perkins**


**Associate Professor Christophe Pierre**


**Professor Albert Schultz**


**Associate Professor William Schultz**

**Professor Richard Scott**


**Assistant Professor Louis Soslowsky**


**Professor John Taylor**

**Associate Professor Grétar Tryggvason**


**Professor Galip Ulsoy**

Professor Alan Wineman


Professor Wei-Hsin Yang

Professor Wen-Li Yang


Professor Vedat Arpacı


Assistant Professor Ellen Arruda


Associate Research Scientist
James Ashton-Miller


Professor James Barber
Barber JR, "Instability of Unidirectional Solidification due to Pressure-Dependent Thermal Contact Resistance at the Mould/Casting Interface," Contact Mechanics Int. Symp., Lausanne, Swiz.

Li NY, Hector Jr LG, and Barber JR, "Theories of Growth Instability during Solidification of Metals: Part II, Stress Function Approach," Int. Conf. Transport Phenomena in Processing HI.


Assistant Research Scientist
Johann Borenstein

Assistant Professor Giles Berenon


Assistant Professor Debasish Dutta


Srivastava YL and Dutta D, "Blending and Joining with Cyclides," ASME Design Automation Conf, Phoenix, AZ.


Research Scientist Robert Ervin


Assistant Professor Steven Goldstein


Assistant Research Scientist
Shixin (Jack) Hu
Hu S and Wu SM, "Identifying Sources of Variation in Automobile Body Assembly Using Principal Component Analysis," Transactions of NAMRI, pp. 311-316.

Assistant Professor Gregory Hubert


Associate Professor Glen Johnson


Associate Professor
Elijah Kannatey-Asibu, Jr.

Associate Professor Bruce Karnopp

Professor Massoud Kaviany

Professor Noboru Kikuchi

Professor Yoram Koren

Associate Professor Sridhar Kota


Professor Herman Merte


Associate Professor Jun Ni


Professor Panos Y. Papalambros


Associate Professor Noel Perkins


Associate Professor Christophe Pierre


Shaw SW and Pierre C, "On Nonlinear Normal Modes. (invited paper)"


Associate Professor William Schultz


Professor Richard Scott
Haering WJ, Ryan R and Scott RA, "A New Flexible Dynamic Formulation for Beam Structures Undergoing Large Overall Motion," 33rd Structures, Structural Dynamics and Materials Conf, AIAA 92-1102, Dallas, TX.

Assistant Research Scientist
Ahmet Selamet
Selamer A, "Mean Coefficients of Radiation in Sooty Media in Light of the Lorenz-Mie and Lorentz-Drude Theories," SAE Congress, Detroit, MI.

Associate Professor Steven Shaw

Assistant Professor
Louis Soslofsky


Professor John Taylor


Associate Professor Greta Tryggvason

Hydrodynamics, National Academy Press, Wash. D.C.


Professor Gaip Ulsoy


Professor Alan Wineman
Associate Research Scientist
James Ashton-Miller

Professor James Barber

Assistant Professor Giles Breton

Associate Professor John Holmes

Assistant Professor Gregory Hubert

Smolinski P, Liu WK, Hubert GM, and Tamma K (eds), New Methods in Transient Analysis, ASME, New York, AMD 143.

Professor Noboru Kikuchi


Associate Professor Sridhar Kota


Professor Wen-Jei Yang


### Research Expenditures
#### July 1, 1992 - June 30, 1993

<table>
<thead>
<tr>
<th>Sponsor</th>
<th>Researchers (Dir. listed first)</th>
<th>Project Title</th>
<th>$ Funded</th>
<th>$ Expended</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Force</td>
<td>Akhavan</td>
<td>Intermittent Fine Scale Structure of Vorticity and Dissipation Fields in Turbulent Shear Flows</td>
<td>82,010</td>
<td>59,849</td>
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<tr>
<td>USAF-OSR</td>
<td>Dutta</td>
<td>Next Generation Solid Models for Electronic Prototyping</td>
<td>74,705</td>
<td>2,445</td>
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<tr>
<td></td>
<td>Dutta, Woo</td>
<td>Next Generation Solid Models for Electronic Prototyping</td>
<td>0</td>
<td>0</td>
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<td></td>
<td>Dutta</td>
<td>N.G. Machining of Cyclide Surfaces</td>
<td>139,143</td>
<td>8,688</td>
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<tr>
<td>USA Research Office</td>
<td>Pierre, Shaw</td>
<td>Modal Analysis Techniques for Nonlinear Large-Scale Structural Systems</td>
<td>89,558</td>
<td>6,868</td>
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<tr>
<td>Battelle Labs</td>
<td>Yin</td>
<td>Effects of Pipe Geometries on Crack Opening Angles Surface Cracks with Residual Stress</td>
<td>5,000</td>
<td>7,895</td>
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<tr>
<td>Battelle Labs</td>
<td>Ward</td>
<td>Electronic Evaluation Guide Development</td>
<td>139,100</td>
<td>84,820</td>
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<tr>
<td>EPA</td>
<td>Brecon, Borgnakke, Paterson</td>
<td>Small Engine Test Facility</td>
<td>67,680</td>
<td>105,363</td>
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<tr>
<td>Lawrence Livermore</td>
<td>Kaviani</td>
<td>Hydrodynamic Interactions Among Fibers in High Efficiency Filters</td>
<td>16,000</td>
<td>40,499</td>
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<tr>
<td>NASA</td>
<td>Kaviani</td>
<td>Hydrodynamic Interactions Among Fibers in High Efficiency Filters</td>
<td>49,995</td>
<td>12,815</td>
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<tr>
<td>NASA</td>
<td>Merte</td>
<td>Grad. Student Res. Prog. - Bouancy Effects on the Forced Convection Critical Heat Flux</td>
<td>22,000</td>
<td>16,896</td>
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<td>NASA</td>
<td>Tryggvason</td>
<td>Computational Studies of Drop Collision and Coalescence</td>
<td>67,680</td>
<td>105,363</td>
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<tr>
<td>NASA-Langley</td>
<td>Felbeck</td>
<td>High-Toughness Graphite/Epoxy Composite Material Experiment</td>
<td>65,000</td>
<td>10,574</td>
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<tr>
<td>NASA-Lewis</td>
<td>Arpace</td>
<td>Droplet Evaporation under Microgravity</td>
<td>49,000</td>
<td>44,047</td>
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<td></td>
<td>Atreyra</td>
<td>An Experimental and Theoretical Study of Radiative Extinction of Diffusion Flames</td>
<td>115,498</td>
<td>101,734</td>
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<td></td>
<td>Holmes, Mansfield</td>
<td>Elevated Temperature Creep/Fatigue of Fiber-Reinforced Ceramics</td>
<td>149,999</td>
<td>137,475</td>
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<td></td>
<td>Merte, Keller</td>
<td>Pool Boiling Experiment</td>
<td>35,782</td>
<td>42,877</td>
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<td></td>
<td>Merte, Keller, Platt</td>
<td>A Study of Forced Convection Nucleate Boiling in Microgravity — additional funding</td>
<td>169,001</td>
<td>59,314</td>
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<td></td>
<td>Pierre</td>
<td>Effects of Mistuning on the Forced Response of Turbomachinery Rotors</td>
<td>190,000</td>
<td>2,383</td>
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<tr>
<td>NCMS</td>
<td>Ni</td>
<td>Post Process for the Gen. of Probing Cycles &amp; Anal. for Preventive Maint. on a Cambell Grinder</td>
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<td>Kimberly-Clark</td>
<td>Schultz, W., Perkins</td>
<td>Fluid Mechanics of Paper Forming</td>
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<td>Rhl. &amp; Frac.</td>
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<td>Mechanical Engineering, Rheology and Fracture Laboratory</td>
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<td>Saginaw Machine</td>
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<td>Advanced Compensation Techniques for Enhancing Machine Tool Accuracy</td>
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<td>SONY</td>
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<td>Development of a Meshless Analysis Capability for Mechanical Design Optimization</td>
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<td>Tecumseh Prod.</td>
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<td>Toyota</td>
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<td>Tarus Research - SM Wu</td>
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<td>TRC</td>
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<td>Innovative Kinematic Design for a Four-Degree-of-Freedom Vehicle</td>
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<td>Experimental Determination of Air Flow in Refrigeration Devices</td>
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<td>Cooperative Research in Applied Engineering (Fellowship)</td>
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<td>Computational Mechanics for Time Dependant Processes</td>
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<td>Machine Anatomy Laboratory Development</td>
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<td>Synthesis, Simulation and Rapid Prototyping Using Motion Building Blocks</td>
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Honors and Awards to Faculty and Staff - 1992-1993

National Honors

Albert B. Schultz, Vennema Professor of Mechanical Engineering and Applied Mechanics, was elected to membership in the National Academy of Engineering, one of the highest professional distinctions accorded an engineer. He is one of only seventy-three members elected from across the country in 1993 bringing total membership in the Academy to 1,684. Professor Schultz was cited for his contributions to the biomechanics of the spine, treatment of lower back pain, and understanding of falls in the elderly.

Panos Papalambros and A. Galip Ulsoy were named Fellows of the American Society of Mechanical Engineering.

University of Michigan
Faculty Awards

Distinguished Faculty Achievement Award
The late S.M. (Sam) Wu

Faculty Recognition Award
Noel Perkins

AMOCO Teaching Award
Bruce Karnopp

College of Engineering
Awards and Honors

Paul G. Goebel Endowed Professorship 1993-1998
Yoram Koren

Excellence in Service
Bruce Karnopp

Excellence in Teaching
Walter Debler

MEAM Faculty Awards

Excellence in Research
Noboru Kikuchi
Christophe Pierre

Excellence in Service
Joseph Datsko
Galip Ulsoy

Excellence in Teaching
Glen Johnson
Alan Wineman

Other Awards and Honors

Pi Tau Sigma, Professor of the Term, ASME Travel Award
Giles Brearston

UMEI Special Recognition Award for Service
Walter Debler

Society of Manufacturing Engineers, Outstanding Young Manufacturing Engineer
Member of the North American Manufacturing Research Institute (NAMRI) of SME
Jack Hu

Technion University, Lady Davis Professor (while on sabbatical in Israel in 1992)
Yoram Koren

ASME/Kodak Best Paper in Design Automation (Co-author)
Panos Papalambros

Pi Tau Sigma, Professor of the Term
Noel Perkins

ASM/ESD Advanced Composites Conference, Best Industrial Paper Award, (Co-recipient)
Alan Wineman

Japan Society of Mechanical Engineering, Thermal Engineering Memorial Award
Visualization Society of Japan, Best Paper Award
Wen-Jie Yang

Papers Selected for Publication in the 50th Anniversary Issue of Journal of Dynamic Systems Measurement and Control
Yoram Koren
Jeffrey Stein
Galip Ulsoy

Staff and Alumni

MEAM Staff Excellence Awards
Ruth Howard
Cynthia Quann-White
Beverly Pyle

MEAM Alumni Society Merit Award
Roger Heimbuch
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MEAM Publications

Maggie Hostetler:
Writer and Editor.

Rodney Hill:
Designer, Photo Editor, Illustrator.

The Regents of The University of Michigan:
Deane Baker, Ann Arbor; Paul W. Brown, Mackinac Island; Laurence B. Deitch, Bloomfield Hills; Shirley M. McFee, Battle Creek; Rebecca McGowan, Ann Arbor; Philip H. Power, Ann Arbor; Nellie M. Varner, Detroit; James L. Water, Muskegon; James J. Duderstadt, ex officio.

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Mechanical Engineering and Applied Mechanics
1992-93 Annual Report

Departmental Offices
2250 G.G. Brown Laboratory
The University of Michigan
Ann Arbor, MI 48109-2125
(313) 764-2694

321 Walter E. Lay Automotive Laboratory
The University of Michigan
Ann Arbor, MI 48109-2121
(313) 764-4254