1. Introduction

In the late 1940s, the need for automating flight control began to be more fully appreciated. Demands on pilots of high performance aircraft were increasing, and guided missiles were by their nature pilotless. At the same time, theory and design of feedback control systems were receiving increased attention. These trends did not go unnoticed in the Department of Aeronautical Engineering at the University of Michigan. With Emerson W. Conlon as chair, the Department initiated a series of systems-related academic and research activities that led to the establishment of flight dynamics and control as a major thrust area. These activities evolved over the years and led to recognition of the University of Michigan as a leader in flight dynamics and control education and scholarship within the higher education community.

The following is an informal account of the development of the flight dynamics and control systems field and of the University of Michigan faculty members who guided that evolution. This account emphasizes the first 40 years of the seven decades running from the late 1940s to the present. During those years, the Department was distinctive for the unusual strength and breadth of its systems-theoretic research and educational activities. The current perspective of flight dynamics and control systems, as developed in the Department during more recent decades, is very broad. In addition to its continued strength in the systems area, the Department’s activities in flight dynamics and control systems take into account widely varied fields including computer science, measurement technology, communication systems, autonomous vehicles, materials, and applied mathematics.
2. The Early Years, 1946-1952

The beginnings of systems activities in the Department of Aeronautical Engineering can be gleaned from the 1954 Department history authored by its then chair, Emerson Conlon. Among many other things, the history describes two important events that occurred in 1946: the offering of a two-year program of graduate studies in Pilotless Aircraft for Air Force officers and the hiring of Myron H. Nichols.

Little is now known about the details of the program in Pilotless Aircraft, except that it most likely became active in the 1946-1947 academic year and that by the next academic year it had over 50 participating officers. Some later time, probably the fall of 1949, the program was renamed the Guided Missiles Program. This Program lasted until the mid-1960s and was a major Departmental activity. It substantially increased graduate enrollment and led to the introduction of many new graduate courses. By 1953 the courses covered, among other things, material on: the processing of measurement data, telemetry, feedback control, control and guidance of pilotless aircraft, remote control of aircraft, flight dynamics, analog computer simulation, and the theory of nonlinear systems. The courses were available to all graduate students, not just the Air Force officers.

In 1946 the Department of Aeronautical Engineering had little experience in aeronautical systems issues such as processing of aircraft data, flight dynamics, feedback control systems, and related academic areas. The appointment of Myron Nichols, who had a strong and highly varied background in aeronautical systems, was the first to address this deficiency. He received the PhD degree in physics from the Massachusetts Institute of Technology 1939 and then went to Princeton University as a Research Fellow. During 1941 and 1942 he worked on issues connected to the later development of the atomic bomb. He continued at Princeton, from 1943 to 1946, to lead a research and development group on multichannel telemetry systems for remote transmission of rapidly varying data, e.g., data generated during flight tests of aircraft and missiles. Over subsequent years the originality and importance of the group’s work was widely recognized. Nichols’s group also contributed to flight tests of the Lark guided missile.

When Nichols arrived at the University Michigan in 1946, his primary objective was to conduct experiments on properties of the upper atmosphere. He brought with him a talented group of engineers and physicists from Princeton’s Palmer Physical Laboratory. They became members
of the Department’s High Altitude Research Laboratory, headed by Nichols and initially located in the University of Michigan’s Aeronautical Research Center at Willow Run Airport. The High Altitude Research Laboratory obtained support from the federal government for a large research project. Among other things, this project used captured German V2 rockets to make measurements of atmospheric properties at altitudes up to 40 miles. In the fall of 1947 the High Altitude Research Laboratory moved to the main campus in Ann Arbor.

While still located at Willow Run Airport, Nichols created an informal research group, known as “Research Techniques.” This group included a variety of interested persons both from the Aeronautical Research Center and from other University of Michigan departments. One of the group’s most interesting projects concerned early analog computers and how they might be used to solve scientific and engineering problems. This investigation was the beginning of the Department’s subsequent leadership in analog computer development and real-time simulation of aircraft and missile dynamics.

In addition to his activities in the High Altitude Research Laboratory, Nichols was committed to the development of academic programs in the Department and, in particular, those associated with the Pilotless Aircraft Program and the subsequent Guided Missile Program. His experience at Princeton gave him an excellent view of what was then going on in the design of contemporary aircraft and missile systems. He had the foresight to recognize the coming importance of measurement and control-related techniques in aeronautical systems. In the 1946-1947 academic year he introduced and taught two special courses: one on measurements and aeronautical instrumentation and the other on guided missiles. It was just the beginning of Nichols’s active participation in the development of the extensive Guided Missiles curriculum.

By 1948 it was clear that additional faculty were needed in the systems area. The teaching load associated with the Guided Missile Program was large, new courses remained to be created, and a demand existed for research in the systems area. By 1950, two faculty members were added.

Lawrence L. Rauch completed his PhD in mathematics at Princeton University in 1949, and he arrived at the University of Michigan in the summer of 1949. His dissertation, under the direction of Solomon Lefschetz, treated nonlinear dynamical systems, but Rauch had broader interests in control systems, information theory, radio telemetry and nuclear energy. He had been in Nichols’s group at Princeton and he had worked closely with him on telemetry systems.
Their collaboration continued over the years and resulted in various publications, including the widely cited book, *Radio Telemetry*, published in 1954.

Robert M. Howe joined the Department in the summer of 1950 after completing his PhD degree in physics at the Massachusetts Institute of Technology. In 1947 and 1948, while enrolled as a graduate student in physics at the University of Michigan, he had participated in the analog computer investigations of Nichols’s Research Activities group. He continued that interest at the University of Michigan as a faculty member, advancing the design and application of analog computers. These applications ranged from computer use by students to major contributions in real-time computer simulation of aircraft and missile dynamics. In 1960 he authored the book *Design Fundamentals of Analog Computer Components*.

The trio of Nichols, Rauch and Howe played a key role in the Department, establishing high standards in research and education. The first courses in the Guided Missiles Program were introduced, thereby forming the basis for expansion of the flight dynamics and control curriculum in subsequent years.

3. Instrumentation Engineering and Information and Control Engineering, 1952-1968

Nichols and Rauch had forward-looking views of systems theory and related engineering applications. They felt that instrumentation engineering (the term used by Charles Stark Draper at the Massachusetts Institute of Technology to describe engineering systems involving both measurement and control) had wide ranging applications beyond aeronautical engineering and should be an independent area of graduate study. Joined by professors from other departments, they convinced the Rackham School of Graduate Studies to introduce, in 1952, MSE and PhD degrees in Instrumentation Engineering. At the end of two years of graduate study, Air Force officers in the Guided Missile Program typically received two degrees, an MSE in Aeronautical Engineering and an MSE in Instrumentation Engineering.

In 1954 Nichols left the University of Michigan to join the Ramo-Wooldridge Corporation, the future TRW. Apparently it was for good reason. As Howe described it, “Within three weeks he was in charge of the entire Atlas Program, our first intercontinental ballistic missile.”
By late 1957 many new flight dynamics and control systems courses had been added to the graduate degree programs of the Aeronautical Engineering Department and to the Instrumentation Engineering Program. Rauch was the first chair of the Program, and he did much to encourage the development of these additions. Several of the courses involved novel laboratory activities using Departmental analog computer facilities for real-time simulation. The whole array of courses was attractive to an increasing number of students seeking graduate degrees in Aeronautical Engineering and/or Instrumentation Engineering.

In response, four assistant professors were added to the Department. Donald T. Greenwood received his PhD from the California Institute of Technology in 1951; he worked at Lockheed until 1956 when he arrived at the University of Michigan. Edward O. Gilbert and Elmer G. Gilbert held Instructor positions beginning in 1954; after completing their PhD degrees in Instrumentation Engineering, they joined the Department as faculty members in 1957. Their interests included flight dynamics, flight simulation, and control systems. Frederick J. Beutler received his PhD degree from the California Institute of Technology; he joined the University of Michigan faculty in 1957, providing a strong background in random processes.

As a side note, the Department’s expertise in analog computers and real-time simulation led to the founding in 1957 of Applied Dynamics International. Three faculty members were involved: Howe and the Gilbert brothers. The company was well known for developing and marketing analog computers, emphasizing their use in education and real-time simulation. In 1963, Edward Gilbert left the University of Michigan to become Chief Engineer at Applied Dynamics. Applied Dynamics International continues to the present with an emphasis on real-time simulation exploiting digital hardware and software.

The dynamics and control faculty and students interacted with other groups in the Department. A notable example of such an interaction is an early research program on space research, that was conducted by the High Altitude Research Laboratory. After development of the Nike-Cajun two-stage, solid propellant sounding rocket in the mid-1950s at the University of Michigan, a series of multi-stage rockets were developed and launched by the University of Michigan. This culminated in the successful launch of a five-stage “Strongarm” rocket that reached a peak altitude of over 1,200 miles, breaking the existing altitude record at the NASA Wallops Island flight facility.
In 1960, the program name “Instrumentation Engineering” was changed to “Information and Control Engineering”. The program itself was not changed; the term “instrumentation” had dropped out of common use. Howe served as chair of the Information and Control Engineering Program from 1963 to 1968.

In 1961, William L. Root left the Massachusetts Institute of Technology Lincoln Laboratory to join the University of Michigan as Professor of Aerospace Engineering. He was a well-known pioneer in statistical communication and information theory; his textbook *An Introduction to the Theory of Random Signals and Noise*, published in 1958, became a classic in the field. His distinction and the rising distinction of other Information and Control Engineering faculty members contributed to the high reputation of the Department.

In 1967, N. Harris McClamroch and Tyrone Duncan joined the University of Michigan faculty after completing PhD degrees at the University of Texas and Stanford University, respectively. William T. Powers joined the University of Michigan faculty in 1968 after completing his PhD degree at the University of Texas.


Faculty and student interest in the theory and utilization of information processing systems had grown throughout several departments in the College of Engineering to the extent that an interdepartmental graduate program, the Computer, Information and Control Engineering Program, was created in 1968 to cover this emerging collection of systems, computing, and communications fields. The Program, known as CICE, did not have responsibility for faculty appointments, but it did have responsibility for consolidating graduate level course work and research projects within the subject areas of it purview. Graduate degrees in CICE were granted by the Rackham School of Graduate Studies.

The Computer, Information and Control Engineering Program involved faculty from several departments: primarily Aerospace Engineering, Electrical Engineering, Industrial Engineering, and Mechanical Engineering. Many of the faculty from the Department of Aerospace Engineering played key leadership roles in the establishment and operation of the new CICE program. Specifically, during the winter of 1968, Elmer Gilbert, Robert Howe, Lawrence Rauch, and William Root were instrumental in working with other departments to establish the
organizational and academic framework for CICE. Aerospace faculty members Root, Rauch, and Beutler served successively as chairs of the CICE program. The following Aerospace Department faculty members had varying degrees of involvement in the CICE Program through teaching courses and mentoring of graduate students in the program: Fred Beutler, Laurence Fogarty, Elmer Gilbert, Don Greenwood, Robert Howe, Harris McClamroch, Richard Phillips, William Powers, Lawrence Rauch, and William Root. Each of these faculty members maintained their primary academic appointment in the Aerospace Department, but all or parts of their research and teaching were carried out as part of the CICE Program.

The CICE Program grew and flourished. By 1982, it had grown to more than 120 students, with 43 affiliated faculty members from five different departments, and with a graduate student curriculum that included almost seventy courses covering digital computer hardware and software, analog and hybrid computing, stochastic processes, signal processing, statistical communications, digital and analog systems, and control and optimization. The Program was a great success in nourishing these emerging disciplines at the University of Michigan. CICE developed a strong national reputation and it produced many successful and influential alumni. It was one of the earliest academic programs in the United States to offer a degree program that spanned computing, information processing, control, and communications. CICE students were provided with an integrated systems perspective that is now widely viewed as a key to the development of many 21st century information technologies, including those that are essential to the modern aerospace enterprise.

The impact of the Computer, Information and Control Engineering Program on the operations of the Aerospace Engineering Department during the period 1968 to 1985 was significant. In the short term, it reduced the full time faculty engaged directly in the Aerospace Department, and it reduced the population of graduate students who might otherwise have studied in the Aerospace Department. The impact of the Computer, Information and Control Engineering Program on the College of Engineering was strongly positive as an interdepartmental experiment that strengthened the College of Engineering’s educational and research portfolios as well as positioning the Department of Aerospace Engineering for future expansion. In addition, it helped to establish the Department of Aerospace Engineering as a leader, within the aerospace academic community, in information processing and control systems. The modern view of flight dynamics and control systems within the broader framework of computer and information processing systems is due, in part, to this heritage.

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The Computer, Information and Control Engineering Program was dissolved in 1985, as a consequence of the reorganization of the Department of Electrical Engineering and Computer Science. At that time, Aerospace Department faculty members Robert Howe, Elmer Gilbert, Harris McClamroch, and William Root, who had previously been involved in the CICE Program, moved their full-time teaching and research back into the Aerospace Department; Fred Beutler transitioned to a full time appointment in the Department of Electrical Engineering and Computer Science.

The transition to the new organizational structure occurred gradually over the period 1983-1986. New graduate level courses in information and control systems were created in the Department of Aerospace Engineering; some of these courses were cross-listed with other departments and some courses were listed solely as Aerospace Engineering Department courses. The number of graduate students studying flight dynamics and control systems in the Aerospace Department quickly increased. Research activities carried out by those faculty who had participated in the CICE program and research activities by those faculty who had centered their research in aerospace applications were easily integrated into the Department’s objectives. The new organization of flight dynamics and control in the Aerospace Engineering Department reflected the continuing evolution of theoretical aspects of engineering during this period as well as challenges in engineering technology, especially relating to information processing, automation, and the emerging use of computers. During this period, there was significant growth in the importance of funded research programs. The main government funding resources came from the National Science Foundation, NASA, and the defense agencies. Funding from non-governmental sources was minimal.

The following is a brief summary of activities carried out, during the period 1968 to 1985, by Aerospace faculty members who were involved in either the CICE Program or in flight dynamics scholarship and research.

Professors Rauch, Root, and Beutler constituted a strong group of researchers who focused on telecommunications and stochastic processes. Lawrence Rauch, in addition to his administrative duties in CICE, continued his long-term research program on radio telemetry, telecommunications and space communications. He received several awards for his outstanding contributions to the field of telemetry. He left the University of Michigan in 1977 to become the
Chief Technologist at the Jet Propulsion Laboratory. In addition to administrative duties in CICE, William Root did important research in detection theory, characterization of communication channels, information theory and complex stochastic systems. Root was a leader on the University of Michigan campus, and he received many awards for his outstanding research, including the Shannon Lectureship Award bestowed by the IEEE Information Theory Society. He retired in 1986. Fred Beutler made important contributions to sampling theory, statistical communications, functional analysis and systems theory, and stochastic control; his interests later in this period included analysis and optimization of queueing networks. Although he was a member of the faculty only during the period 1967-1970, Tyrone Duncan introduced new theoretical notions for the calculus of stochastic processes. Subsequently he has had a distinguished career in the Department of Mathematics at the University of Kansas, where he is well known for his work on stochastic control.

Robert Howe was Chair of the Department of Aerospace Engineering from 1968 to 1982. He continued his research program on guidance and navigation, control and simulation, and the use of analog and hybrid computers for aerospace applications. Howe served on the Air Force Scientific Advisory Board, and he was recognized with the AIAA deFlorez Award for Flight Simulation in 1988. Also, in 1960 Laurence Fogarty joined the department from the flight simulation company Link Aviation, where he was chief of engineering. He taught courses in flight dynamics and control, in addition to managing hybrid computing facilities for education and research. Donald Greenwood was active in teaching and research focused on classical dynamics. His book Principles of Dynamics, first published in 1965, and his subsequent book Classical Dynamics, published in 1977, have been widely accepted textbooks.

Aerospace Engineering faculty continued active research programs on theoretical and applied aspects of control engineering. Beginning with seminal papers on control theory for linear systems in the early 1960s, Elmer Gilbert maintained an active research program, making important contributions in the following areas: numerical aspects of optimal control, multivariable decoupling of linear and nonlinear control systems, periodic optimal control, and input-output models for nonlinear systems. During this period, Harris McClamroch’s research was on nonlinear multivariable stability, optimal control, statistical estimation, and control of flexible spacecraft. He was also involved in research programs on control of buildings and bridges, working with collaborators in the Civil Engineering Department. During the 1980s,
both Gilbert and McClamroch were active participants in the College-wide robotics research laboratory sponsored by the Air Force.

After a distinguished career in the Vietnamese Air Force, Nyugen X. Vinh joined the University of Michigan faculty in 1968. He established an active research program on various aspects of aerospace dynamics and control; these included astrodynamics, flight mechanics, optimization of flight trajectories, and optimal control; he co-authored three important books on these topics. He received several AIAA awards, including the Dirk Brouwer Award and the Mechanics and Control of Flight Award. He retired in 1997. William Powers was an active educator and researcher in the Department of Aerospace Engineering in the period 1968 to 1980. His research contributions included singular optimal control theory and optimal low thrust control of space trajectories; he made important contributions to several NASA space missions and to applications of automotive control. His subsequent career at Ford Motor Company led to several important leadership positions at the vice-presidential level; he played an important role in bringing advanced control concepts into Ford products.

For many years, Harm Buning taught an introductory aerospace engineering course and the senior level space systems design courses; he was widely recognized by alumni and faculty colleagues for his outstanding contributions to undergraduate education. As a consequence of his reputation as an outstanding teacher and of his NASA contacts, he taught astrodynamics and orbital dynamics to several Apollo astronaut classes at Johnson Space Center.

Finally, Richard Phillips developed an education and research program related to computer graphics, distributed processing, and computer-aided design; his work had a substantial impact on the growing use of new computational tools in aerospace engineering.

5. Flight Dynamics and Control Systems, 1985-present

The broad perspective that recognizes the importance of flight dynamics and control systems, viewed within a broader information and computing context, continued in the Aerospace Department after 1985. Howe, Gilbert, and McClamroch were instrumental in re-establishing the flight dynamics and control group in the Aerospace Engineering Department beginning in 1985. They modified and expanded the flight dynamics and control curriculum, and they formulated and implemented a plan to hire new faculty members in the area.
Elmer Gilbert continued research on optimization, linear and nonlinear systems, and control synthesis. He did work on robot path planning in the presence of obstacles, control systems with hard constraints, and reference governors. He retired in 1994. His contributions to the field were recognized by major awards: the IEEE Control Field Award in 1994, the Richard E. Bellman Control Heritage Award in 1996, and by election to the National Academy of Engineering in 1994. Harris McClamroch made research contributions on nonlinear control of nonholonomic and under-actuated control systems and on geometric methods for multi-body dynamics and control problems; these were motivated by control problems in robotics and spacecraft systems. He served as Chair of the Department of Aerospace Engineering from 1992 to 1996. He was active in the IEEE Control Systems Society, serving in numerous administrative positions, including as editor of the IEEE Transactions on Automatic Control, 1989-1992, and as President of the IEEE Control Systems Society in 1998. He retired in 2010.

Pierre Kabamba joined the University of Michigan faculty in 1983, bringing his expertise in dynamics and control, especially in robust control. He had broad research interests, including optimal control and guidance and navigation. He was an excellent collaborator and communicator, maintaining active research programs with faculty and students in several departments. He was the author of two books, and he received several teaching awards. He died in 2014. Dennis Bernstein moved from the Harris Corporation to the University of Michigan faculty in 1991. He arrived with an outstanding and extensive research background; his contributions at the University of Michigan continued and expanded his earlier research interests in robust control. He developed successful research programs in several different theoretical and experimental directions associated with identification, estimation and adaptive control for aerospace applications. He served as editor of the IEEE Control Systems Magazine, 2003-2011. His book *Matrix Mathematics: Theory, Facts and Formulas*, published in 2009, is a monumental and widely cited reference source.

Vincent Coppola was a researcher in nonlinear dynamics; he collaborated on several control problems during his period at the University of Michigan. After a career in industry, David Hyland served as Department chair from 1996 to 2003; he established a research programs in spacecraft systems, including adaptive imaging using spacecraft formations. Daniel Scheeres became a faculty member of the Department in 1999. Previously, he had been a technical staff member at the Jet Propulsion Laboratory, 1992-1997, and a faculty member at Iowa State.
University, 1997-1999. He was a recognized researcher on orbital mechanics, making important contributions to dynamics and control of space vehicles near asteroids and other spacecraft control problems. He maintained many research connections with NASA and with the Japanese Space Agency. He left the University of Michigan in 2007 to join the University of Colorado, where he is currently a distinguished chaired professor.

Another wave of faculty hiring occurred after 2006. Ella Atkins and Anouck Girard joined the University of Michigan in 2006. Ella Atkins built on her background and interests in computer science to establish new research and educational programs on mission planning, trajectory optimization, and embedded sensing for manned and unmanned aircraft. Her research incorporated many advanced computing technologies into flight vehicles. Anouck Girard established a research program on unmanned vehicle systems, hybrid, distributed, and embedded systems, maneuver coordination and control of ground, air and ocean vehicles and robots.

James Cutler arrived at the University of Michigan in 2008 to develop applied research and educational programs on space systems, taking a multidisciplinary approach to enabling future space capability with particular emphasis on novel, nano-satellite missions. He has guided students teams to develop, launch into orbit, and carry out data analysis for the Radio Aurora Explorer, the first National Science Foundation space mission. In 2010, Ilya Kolmanovsky moved from Ford Motor Company Research and Advanced Engineering to continue his research on a variety of theoretical and applied control problems. His research spanned a wide range of topics, including applications of control, estimation and diagnostics to aerospace and automotive systems. He studied spacecraft control, propulsion systems and optimal energy management. He received the Donald Eckman Award as the outstanding young control researcher in 2002.

James Forbes was a faculty member from 2013 to 2015; his research was in control of aerospace and robotic systems. Dimitra Panagou joined the University of Michigan faculty in 2014; her research program has emphasized exploration, development and implementation of provably correct control solutions to constrained multi-vehicle systems.

All of these faculty members maintained active funded research programs that involved undergraduate and graduate students. Their expertise helped to expand the flight dynamics and control curriculum to include advanced methods for aircraft and spacecraft control, as well as avionics and information processing technologies important in modern aerospace vehicles.
6. Conclusions

This brief history of flight dynamics and control systems in the Department of Aeronautical Engineering/Department of Aerospace Engineering confirms several important themes that characterize the evolution of flight dynamics and control that has occurred at the University of Michigan since its beginning in 1946. The themes include:

- a strong, critical mass of University of Michigan faculty members, with expertise in flight dynamics and control and related subject areas, who are recognized scholars in their fields.
- great student interest in the practical application of flight dynamics and control to aerospace vehicles and their flight in the atmosphere and in space.
- emphasis on viewing flight dynamics and control as an interdisciplinary subject that is tightly coupled with advanced measurement, computing, information, and systems engineering.
- commitment to leadership in advancing and transmitting the knowledge base in flight dynamics and control through University of Michigan research contributions and educational innovations.

7. Appendices

The following Appendices provide additional details and documentation that support the prior description of the field of flight dynamics and control systems and its evolution in the Department since 1946.

7a. The Guided Missiles Program

In 1949, the newly created US Air Force realized that their officers had received little or no academic training in the emerging technology of guided missiles. In response, they established two-year graduate programs in the aeronautical engineering departments at both MIT and the University of Michigan. The Guided Missiles Program (GMP) at the University of Michigan was in the Department of Aeronautical Engineering and consisted of two full years of graduate study taken from specified courses in the standard Engineering College Bulletin. Normally,
officers participating in the GMP received two MSE degrees, one in Aeronautical Engineering and the other in Instrumentation Engineering (later named Information and Control Engineering).

Upwards of 50 US Air Force officers were enrolled annually in the program, which also attracted substantial numbers of officers from the US Army, the US Navy, and the Canadian Air Force. The initial effect of the GMP on the Department was dramatic, both in the large number of additional graduate students and in the development of a broadly based new curriculum. Professor Myron Nichols was the initial director of the GMP.

Over the years the GMP was highly successful for both the Department and the participating officers. In response to the evolving needs of the Air Force, the curriculum and the main directions of the program changed. For example, in the late 1950’s the GMP became the Astronautics Program. That program was phased out in the middle 1960’s. Overall the two programs had highly positive effects on the Department. Its curriculum in flight dynamics and control systems was expanded, modernized, and held to high standards. The faculty increased in numbers beyond what otherwise would have been possible.

Officer graduates also did well. Some remained at UM to carry out graduate level research and obtain doctorate degrees in the Department. Others rose to high ranks in the military, government, or industry. Some participated directly in US space program. This included Astronauts: Ed White, Jim McDivitt, Jim Erwin, Al Worden, and Ted Freeman. Astronaut Jack Lousma did not participate in the GMP but did receive a BS degree from the Department.

7b. Development of Multiple-stage Rockets

The High Altitude Research Laboratory in the Department of Aeronautical Engineering was among the very first research groups in the world to conduct atmospheric measurements at the edge of space. Its activities began in 1946 and continued until the early 1960s.

The research initially involved the analysis of upper atmosphere samples at altitudes between 100,000 and 300,000 feet collected in rocket transported bottles returned to earth. Starting in 1947, captured German V-2 rockets launched at White Sands, New Mexico, were used to collect and retrieve the sample bottles. The V-2 rockets had poor reliability and high launch expense. In the middle 1950s they were replaced by solid fuel rocket systems, such as the Nike-Cajun
two-stage sounding rocket developed at the University of Michigan. Both of its stages utilized already existing solid fuel rockets, with a booster of the Nike-Ajax surface-to-air missile as the first stage and a Cajun weather sounding rocket as the second stage. Fins were used to stabilize both stages. The rocket was capable of sending a 50 pound payload to an altitude of 100 miles. In the 1957 International Geophysical Year, more Nike-Cajun sounding rockets were fired than any other rocket type to gather upper atmosphere data, including the large number launched by the University of Michigan High Altitude Research Laboratory.

The High Altitude Research Laboratory was also responsible for the subsequent development of the Exos and Strongarm rockets. Exos had three stages: the US Army Honest John artillery rocket, followed by the Nike-Ajax booster, followed by the Yardbird. Exos was capable of carrying a 120 pound payload to 300 miles altitude. Strongarm was developed to take a 20 pound payload to 1100 miles altitude. Its five stages were: Honest John, Nike-Ajax, Nike-Ajax, Yardbird and Baby Sargeant, where Baby Sargeant was a Jet Propulsion Laboratory rocket used for the last two stages of the first US satellite.

In all multiple-stage sounding rockets there is usually a coast period between stage firings to delay excessive velocity buildup at low altitudes. In the case of the Strongarm, even with final stage ignition at over 100,000 feet, there was sufficient atmosphere to cause excessive aerodynamic heating of the solid state rocket fuel. For this reason the final stage was coated with teflon, which obliterated at a low enough temperature to protect the propellent. In its first test firing in 1960, carrying an electron-density experiment developed by the University of Michigan Electrical Engineering Department, the Strongarm sounding rocket achieved a burnout velocity of 17,000 ft./sec. and an altitude of 200 miles, after which it coasted to over 1,200 miles, breaking by far the existing altitude record at the NASA Wallops Island launch facility. As a point of interest, Robert Howe was involved in the optimization of staging parameters for the Strongarm rocket.

7c. Course Listings and Evolution of the Curriculum

Advances in in flight systems, dynamics and control since 1946 have been extraordinary. These advances have been enabled by major advances in materials, instrumentation, electronics, communications and computing that have been quickly adopted into flight systems and aerospace flight vehicles. Major advances have occurred in the theoretical depth of
understanding, in the applications of new technologies, and in integration of complex systems. All of these features are reflected in the research carried out by faculty and students during this time period and in the evolution of the curriculum, most obviously in the regularly scheduled academic courses, taught in the Department.

Course titles and descriptions for all relevant courses in the regular curriculum are available in the College of Engineering Bulletins which have been published annually. Specifically, course descriptions related to flight dynamics and control systems can be found under the Bulletin listings: Department of Aeronautical Engineering, the Department of Aerospace Engineering, the Instrumentation Program, the Information and Control Program, and the Program in Computer, Information and Control Engineering. In the 1950s and 1960s, not-for-credit summer short courses in dynamics and control were offered to practicing engineers.

An examination of the available course materials, since 1946, leads to the following summary of course topics:

- Instrumentation: signals, measurement systems, noise, telemetry, flight electronics, avionics
- Control theory: automatic control, feedback, control systems theory, linear and nonlinear control, optimal control, optimization
- Control of aerospace vehicles: flight control for rockets, missiles, aircraft and spacecraft; pilot-aided control and pilotless or autonomous flight control; attitude control; motion and path planning for aerospace vehicles
- Guidance and navigation: guidance for missiles and rockets, proportional navigation, optimal guidance, target miss error analysis, celestial navigation, satellite and aided navigation
- Identification, estimation and adaptation: incorporating and accounting for model uncertainties, noise and disturbances in aerospace control
- Computer systems: analog computing, hybrid computing, digital computing, flight simulation, flight software and flight computer systems, real time and embedded systems
- Mathematical models: dynamics of aerospace flight vehicles, orbital mechanics, models that account for randomness and noise, models for communications, computing and control in aerospace systems
Faculty members who have had academic appointments in the Department of Aeronautical Engineering or the Department of Aerospace Engineering since 1946 have typically identified with one of the several sub-disciplines of aerospace engineering. Here we list those faculty who have had some identification with flight systems, dynamics and control. The dates of their University of Michigan appointments are indicated.

Myron H. Nichols (PhD in physics from the Massachusetts Institute of Technology), 1946-1954.

Lawrence L. Rauch (PhD in mathematics from Princeton University), 1949-1977.

Robert M. Howe (PhD in physics from the Massachusetts Institute of Technology), 1950-1991.

Donald Greenwood (PhD in electrical engineering from the California Institute of Technology), 1956-1994.

Harm Buning (MSE in aeronautical engineering from the University of Michigan), 1956-1992.

Edward O. Gilbert (PhD in instrumentation engineering from the University of Michigan), 1957-1963.

Elmer G. Gilbert (PhD in instrumentation engineering from the University of Michigan), 1957-1994.

Frederick J. Beutler (Ph.D. in mathematics from the California Institute of Technology), 1957-1989.

Laurence E. Fogarty (PhD in aerospace engineering from Cornell University), 1960-1971.

Alfred C. Robinson (PhD in aerospace engineering from the University of Michigan), 1962-1983.
William L. Root (PhD in mathematics from the Massachusetts Institute of Technology), 1962-1986.

Richard L. Phillips (PhD in aeronautical engineering from the University of Michigan), 1961-1987.

N. Harris McClamroch (PhD in engineering mechanics from the University of Texas), 1967-2010.

Tyrone E. Duncan (PhD in electrical engineering from Stanford University), 1967-1970.

William F. Powers (PhD in engineering mechanics from the University of Texas), 1968-1981.

Nguyen X. Vinh (PhD in aerospace engineering sciences from the University of Colorado), 1968-1997.

Pierre T. Kabamba (PhD in mechanical engineering from Columbia University), 1983-2014.


Dennis S. Bernstein (PhD in CICE from the University of Michigan), 1991-present.

David C. Hyland (PhD in aerospace engineering from the Massachusetts Institute of Technology), 1996-2003.

Daniel Scheeres (PhD in aerospace engineering from the University of Michigan), 1999-2007.

Ella M. Atkins (PhD in computer science and engineering from the University of Michigan), 2006-present.

Anouck Girard (PhD in mechanical engineering from the University of California, Berkeley), 2006-present.
James W. Cutler (PhD in electrical engineering from Stanford University), 2008-present.

Ilya V. Kolmanovsky (PhD in aerospace engineering from the University of Michigan), 2010-present.

James R. Forbes (PhD in aerospace science and engineering from the University of Toronto), 2013-2015.

Dimitra Panagou (PhD in engineering from National Technical University of Athens, Greece), 2014-present.