Fifty Years in Dynamics and Control Research and Education

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This issue of "Historical Perspectives" is the fourth in a series of remembrances from past presidents of the IEEE Control Systems Society.

I retired in the fall of 2010 from the Department of Aerospace Engineering at the University of Michigan (UM), where I spent my entire professional and academic life after I completed my graduate studies at the University of Texas in 1967. Throughout my career, I have always identified myself as a part of the control engineering community.

It has been my good fortune to participate in the growth of the control field over the past 50 years. The changes in the field, both in terms of theoretical advances and important applications, have been spectacular. My perspective is that of a control researcher with broad theoretical and applied interests and of a university faculty member who taught control courses, collaborated on many different control research projects, and was the research adviser to numerous students. This breadth of opportunity has been of great satisfaction to me, and I am lucky to have been a part of this exciting field.

MY CAREER EVOLUTION

Initially, my research interests concentrated only on the topic of my graduate study, but I expanded my research interests as I taught a variety of control courses and as I was exposed to a broader set of control ideas as a young faculty member. Over the arc of my career, the continuing themes of my research have always been developing mathematical models that are accurate reflections of physical and engineering reality, the design of control systems, and the analysis of system (nonlinear) dynamics using mathematical tools. This background provides the basis for my use of the terminology "dynamics and control" to describe my personal interests.

Mark Aizerman's visit to the University of Michigan in 1985, with N. Narasimamurthi, Semyon Meerkov, Harris McClamroch, Demos Teneketzis, and Elmer Gilbert.

Graduate studies in engineering mechanics at the University of Texas emphasized course work in nonlinear dynamics and vibrations, solid mechanics, and fluid mechanics. My master's thesis dealt with the oscillatory and secular dynamics of bubbles in a vibrating fluid; this work involved both experimental tests and the construction of mathematical models of bubble dynamics to explain the observed results. This first research experience was tremendously exciting, and it provided me with the motivation to seek a research career. As I began my doctoral studies, I took several control courses that were taught in the Department of Electrical Engineering.

As one of the initial recipients of a NASA graduate fellowship, in those post-Sputnik days, I had the freedom to develop my doctoral research in any area of interest. Based on my study of published Russian literature, I chose to study the effects of parameter variations on system dynamics, called sensitivity analysis in those days and called robustness in today's language. To avoid the common approach in the published literature that made use of sensitivity derivatives, I decided to study the effects of large parameter variations. I obtained bounds on performance variations that result from parameter variations. This work made close contact with Hamilton-Jacobi theory and Lyapunov stability theory; I obtained bounds for a quadratic performance measure in the case of linear dynamics with linear perturbations.

I published my first technical paper on this topic in *IEEE Transactions on Automatic Control* (*TAC*) as a graduate student in 1967, and I have viewed the IEEE Control Systems Society (CSS) as my main professional home since that time. These initial research successes

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were critical in giving me the confidence to view control research as a viable career option. I am especially grateful to two advisers at the University of Texas, Prof. Lyle Clark and Prof. Jake Aggarwal, for their guidance and advice in this formative period of my life.

Throughout my academic life at UM, from 1967 to 2010, my research covered many topics, including in roughly chronological order: dynamics and control of time delay and functional differential equations, optimal control of time-delay systems, stability and robustness of multiloop feedback systems, stochastic control of Markov and semi-Markov processes, optimal control of distributed discrete-parameter systems, estimation and filtering, Lagrangian and Hamiltonian control systems, control of nonholonomic systems, nonlinear control of underactuated systems, attitude control, and dynamics and control of multibody systems. These theoretical interests supported applied research in automated manufacturing, robotic systems, control of civil structures, and control of aircraft and spacecraft. A listing of my publications on these research topics can be obtained from the curriculum vitae on my Web site (http://www.engin.umich.edu/aero/people/faculty/harris-mcclamroch).

At UM, my initial academic responsibilities from 1968 to 1983 were in the computer, information, and control engineering (CICE) graduate program. This interdepartmental graduate-level academic program, established in 1968, was a leader at that time in demonstrating the common framework of computing, communications, and control and the value of breadth of knowledge in these subject areas. I was fortunate to be a part of this group, which was led by Prof. Larry Rauch, Prof. William Root, Prof. Robert Howe, Prof. Elmer Gilbert, and others, all of whom I viewed as the best possible role models. My research was also influenced by Prof. Lamberto Cesari, a distinguished professor in mathematics at UM. After 1983, when the CICE academic program was phased out, I resumed my academic responsibilities in the Department of Aerospace Engineering.

Abraham Haddad, Mike Masten, and Harris McClamroch.

My research interests shifted toward nonlinear dynamics and control problems that arise in aircraft flight and spacecraft orbital and attitude maneuvers. This shift in interests was gradual, even as I continued to collaborate with UM faculty in several different departments. I was lucky to have a succession of truly outstanding doctoral students in the 1990s and 2000s. This was a very busy period in my academic life as I balanced department administration, service to the CSS, and my active research and teaching commitments. At the same time, this was one of the most satisfying periods of my entire career.

PLEASURES OF A RESEARCH CAREER IN DYNAMICS AND CONTROL

Of course, I enjoyed teaching, working with undergraduate and graduate students, and developing and carrying out research programs. I loved much about the routines of academic life: the seasonal academic cycles, the ever-changing student body, the challenges of organizing and presenting material in courses, the meetings with students, and the development and guidance of an evolving research agenda. It would be easy to reflect further on those routines. However, it is perhaps better to reflect, in brief, on selected personal highlights of my career.

My comments are divided into two categories: my enjoyment in being a faculty member in a large public research university, namely UM, and the importance of being an active member of the CSS.

UM provided me with many opportunities for learning and intellectual growth in all phases of my academic life. It nourished me as a young faculty member, and it gave me many opportunities to develop administrative and leadership skills as a senior faculty member. I am grateful that I had the chance to teach and to work with many outstanding students. In retrospect, I value my interactions with students at all levels of academic ability. I did my best to inspire students with my own passion for dynamics and control, and I had both successes and failures. My 27 doctoral students provided major stimuli for my own intellectual growth and allowed me to establish close friendships with these outstanding, and now successful, individuals from many different backgrounds and countries.

Finally, I am grateful that UM provided first-class resources and an

intellectual environment that encouraged the highest levels of scholarship and leadership. I was greatly influenced by numerous stimulating research interactions with UM graduate students and colleagues, especially Prof. Elmer Gilbert, Prof. Dennis Bernstein, Prof. Jessy Grizzle, and Prof. Ilya Kolmanovsky. I am an avid seminar goer, and I have benefited from attending outstanding seminars and lecture programs over the years, including the UM interdepartmental control engineering seminars and seminar programs that have been run in many departments.

I have long identified the IEEE CSS as my primary professional home, in spite of the fact that my doctoral degree was in engineering mechanics and my main appointment at UM was in the Department of Aerospace Engineering. The wide scope of subject areas within the purview of the CSS more than covered my many research interests.

The CSS has outstanding publications with strong scholarly traditions, and it runs outstanding conferences with extensive participation from the international control community. These publications and conferences have been the primary, if not only, means whereby I have kept up with the cutting-edge research in dynamics and control, both theory and applications. I appreciate that the CSS is a volunteer organization, with many committed volunteers. I have been one of those volunteers, and I am proud of the many hours I spent on CSS business, in publications as editor of *TAC* from 1989 to 1992 and as president of CSS in 1998.

EXPERIENCES WITH *IEEE TRANSACTIONS ON AUTOMATIC CONTROL*

Although I had authored several papers in *TAC* before 1985, I was surprised when Ray DeCarlo asked me to take over the responsibilities as associate editor for technical notes and correspondence from him. I had little prior experience with editorial duties, but I was excited to accept the appointment, and I began in February 1985. At that time, this position was solely responsible for publication decisions of technical notes (12 pages or fewer in length) and correspondence regarding prior *TAC* publications. I could call on the regular associate editors to serve as reviewers or to obtain reviews, or I could select reviewers on my own. During this period, I handled and made publication decisions on approximately 400 submissions a year. This was a demanding responsibility, but I learned to make difficult publication decisions based on my experience and the best advice from reviewers that I could obtain. This was a great learning experience for me, and my research knowledge and insights were greatly expanded. I worked under *TAC* Editor Abraham Haddad for four years, and he was a great help with my transition to *TAC* editor in January of 1989.

My responsibilities as editor were completely different. I operated a publication office that received and handled submitted regular papers, and I managed all aspects of *TAC* publication policies. I worked closely with the Editorial Board, the IEEE Publications office, as well as with individual authors. This was a visible position, especially to authors of submitted papers. I was often called on to mediate difficult publication decisions and to deal with unhappy authors of rejected papers. This was a period of rapid growth in *TAC*, and the number of journal pages published increased substantially. More than 500 papers were submitted to *TAC* each year. The office operations were challenging due to the fact that computers were primarily used to write letters and for e-mail communications; we spent much time in building and converting paper records to a computer database. I hired several full-time secretaries who had some database skills. At this time, more than 900 submissions for the IEEE Conference on Decision and Control and the American Control Conference were submitted to our editorial office and processed by the *TAC* editorial board.

Anthony Michel and Harris McClamroch.

The editorial office operations ran smoothly, except during several difficult secretarial transition periods and during periods when we processed conference submissions. We were able to handle all of this paper flow for a while, but it became clear that new procedures would be necessary. This led the CSS Board of Governors to eventually establish the Conference Editorial Board. I became chair of UM's Department of Aerospace Engineering in January 1994, and so I was happy to pass the *TAC's* editor's torch to John Baillieul later that year.

Some of my observations on research and scholarship in dynamics and control are as follows:

Harris McClamroch and John Baillieul.

I am proud of the many hours I spent on CSS business, in publications as editor of *TAC* from 1989 to 1992 and as president of CSS in 1998.

- Research contributions are based on concentrated hard work; a natural ability for abstract thinking and creativity are useful attributes, but without a serious commitment to building on these talents, they usually are not decisive in research accomplishments.
- The best research is the outcome of a team effort. In my case, much of my published research was carried out jointly with graduate students, but I have also found that all of my research collaborations have provided broader and deeper perspectives than what I could have produced alone. Although my curriculum vitae lists many single-author publications, I am most proud of my multiauthor publications.
- The state of the art in dynamics and control evolves slowly and incrementally, based on contributions of many researchers; there are occasional intellectual breakthroughs that introduce fundamentally new research directions, but these are the exception.
- Important research contributions arise from surprising sources; no region, nation, or cultural background has a monopoly on good ideas: dynamics and control research is a global enterprise.
- Research contributions come in many forms: breakthrough ideas and methods, synthesis of concepts, exposition and dissemination, application, experimentation, and technology transfer. It is important to recognize that the research supply chain depends on myriad contributions in all stages of the supply chain.
- A deep (not superficial) understanding of engineering and physics is required to develop useful mathematical and computational models; the importance of models and their limitations is often given insufficient attention by control researchers. My view is that the utility of a black box approach to dynamics and control analysis and design is severely limited. In terms of their interactions, dynamics and control necessarily form a "closed loop."
- There is an amazing richness of mathematical tools that can be used to solve engineering problems. Mathematical concepts and tools are regularly introduced to provide new insights into the fundamental concepts of dynamics and control, and I see this as one of the main drivers in its rapid growth during the last 50 years.
- The availability of computational tools for control engineering problems has increased enormously in recent years. The computational tools are of immense value, but they should be used with caution, respecting their limitations.
- All dynamics and control systems are nonlinear to some extent. Classical and differential geometry are essential in the study of nonlinear dynamics and nonlinear control.
- It has been satisfying to watch the continuing emergence of dynamics and control theories for digital, continuous, and hybrid systems over the past several decades. This trend will definitely continue.
- The driving force in the development of new dynamics and control concepts and ideas today is primarily motivated by the need to solve new problems in control applications and technologies. This contrasts with the developments in the 1960s and 1970s when abstract theoretical issues seemed to be the dominant driving force. It is likely that this reflects the natural evolution of dynamics and control as it has matured. I anticipate that concept-driven dynamics and control research will continue to flourish even as applications-driven research expands.

CONTINUING ON

I became professor emeritus at UM in 2010. I maintain limited research activity by continuing a long-term research collaboration with Melvin Leok and Taeyoung Lee. This provides me with a part-time opportunity to remain intellectually active by working on research on the dynamics and control of Lagrangian and Hamiltonian systems using geometric methods. I am grateful that my current situation permits this, and I intend to continue this research collaboration as long as I am able. I remain interested in published literature, although I no longer attempt to keep up with new publications and developments. I attend control conferences only irregularly. This particular balance with other aspects of my life suits me at present.

I am thankful that I have had a professional career in the field of dynamics and control. It has provided me with the opportunity to study a broad set of subject areas and to have numerous intellectual challenges and opportunities for intellectual growth. I have identified by name only a few of the many individuals, former faculty colleagues, former students, research colleagues, and fellow CSS volunteers who have been close friends and inspirations, but I give thanks for all of those in the control community who have enriched my professional life over the last 50 years.