What follows is my personal perspective on early events that played a significant role in the formation of the field now known as Smart Structures. It is by no means meant to be all inclusive or definitive in any way, but merely an account of personal experiences that ultimately lead to the development of the material contained and presented herein.

On March 23, 1983 then President Ronald Reagan announced his intentions to develop a new system to reduce the threat of nuclear attack and end the strategy of mutual deterrence in an address to the nation entitled, Address to the Nation on Defense and National Security. The system he proposed became known as “Star Wars,” after the popular movie, because it was meant to provide a protective shield over the nation from space. His speech mobilized the entire nation on a research and development path toward this end.

Investigations were conducted into new areas such as space based radar, large aperture antennae and large flexible mirror concepts. These proposed systems represented an entirely new class of structures that proved to provide new challenges in materials, structures, control systems and modeling. For example antennae needed to monitor large areas of real estate in the continental United States required apertures on the order of 100 m. This coupled with the hefty cost of launch to space, on the order of $10,000 per pound, resulted in the design of light weight, highly flexible, lightly damped structures. Analysis of such structures revealed some never before seen characteristics such as very high modal densities, large numbers of paired modes due to the symmetries associated with the designs, lightly damped modes and concomitant large order models. It became clear that the research community and the academic community in particular needed to develop new tools and techniques to cope with the issues associated with these Large Space Structures (LSS).

During this period Dr. Tony Amos, then a Program Manager with the Air Force Office of Scientific Research (AFOSR) began holding a series of invitation only workshops to discuss these systems, associated problems and potential solutions. The list of invitee’s included members of government, academia and the private sector who were all active in this area of research. Senior, mid-career and junior researchers from diverse fields that encompassed structural vibrations, active control, fluid dynamics, applied mathematics and more were in attendance. The group
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included a number of well-known, distinguished scholars such as Professor Leonard Meirovitch in the field of vibrations, Professor Holt Ashley the field of aeroelastic structures and unsteady aerodynamics, and Professor Michael Athans in the field of control theory. This was during a period in which multidisciplinary collaborations were rare and it quickly became apparent to the group that we lacked a common nomenclature for discussion. A simple example involved terminology to describe structural damping. Some spoke of loss factor, some of damping ratio and others of “Q” factor. This of course led to numerous philosophical debates and vociferous discussions on the fundamentals required for characterization and performance assessment for LSS. This group met regularly for several years and culminated with the formation of an annual meeting at Virginia Polytechnic and State University hosted by Professor Meirovitch entitled *VPI & SU/AIAA Symposium on Dynamics and Control of Large Structures* in Blacksburgh, Virginia. It became clear over time that LSS were lightly damped structures that could have demanding performance tolerances such as the shape or profiles required for antennae in space based radar applications. It also became clear that these systems could benefit from advanced active control techniques for damping augmentation and performance enhancement.

In the ensuing years a number of test platforms were constructed to allow researchers to gain first hand experimental knowledge of this new class of structures. Prominent among these was the NASA Hoop Column Antenna; a Langley Research Center conceived design for increased sensitivity to ground or space-based signals.

The antenna consisted of a deployable central column and a 15-m hoop, stiffened by cable into a structure with a high tolerance surface and offset feed location. The surface was been configured to have four offset parabolic apertures, each about 6 m in diameter, and made of gold plated molybdenum wire mesh. Vibration analysis of this structure yielded modal densities that had not routinely been encountered before revealing 70 significant modes over a bandwidth of just 4.1–6.2 Hz. Conventional control synthesis techniques often lead to large order state space models and controllers, ill-conditioned matrices that required inversion and sometimes needed to account for spatially distributed nonlinearities. Traditionally engineers modeled and designed such systems using linear, time invariant, lumped parameter methods and techniques for control. This yielded a system of low order ordinary differential equations (typically with constant coefficients) that could be readily analyzed using modern computational and linear algebra tools. When applied to large order systems new issues of model reduction, stability, physical realizability etc. began to surface. This suggested to me at the time that these structures represented true continuums that displayed both temporal and spatial dynamics and should be modeled and controlled using techniques appropriate for Distributed Parameter Systems (DPS).

Distributed Parameter Systems may involve parameters that are time varying and distributed over certain spatial domains. The dynamic behavior of these systems is governed by partial differential equations, integral, or integro-differential, and occasionally by more general functional equations. Because of the fundamental nature of such systems (all physical systems have spatial extent), and the importance of applications areas, the study of DPS has had the attention of mathematicians and control theorist for many years. The dichotomy was that while much had been developed in
this area by way of mathematics, very little if any control systems were built because the resulting designs could not be physically realized.

It was at this time that I became aware of the important work that was being done by R.L. Forward and C.J. Swigert in so-called “electronic damping” during the late seventies and early eighties. These were two Air Force researchers that had been experimenting with using lead zirconium titanate (PZT) to damp optical structures with good results. Their approach of using such exotic materials as actuators for active vibration control was quite unconventional and novel. These materials were lightweight and used very little power and hence appeared to be ideal for application to large space structures. Unlike conventional actuation devices which applied control authority at a single point in space; it appeared that these materials represented actuators that applied control forces which were distributed over space and time and hence were characteristic of DPS. The merging of this class of actuators with DPS “plants” for control seemed a natural undertaking. A single actuator could cover an entire structure and provide a relatively low order controller that was physically realizable. In 1985 Thomas Bailey, a Masters Thesis student of mine at MIT, built and tested such a system. The structure consisted of a steel cantilevered beam with tip mass, covered by a thin sheet of polyvinylidene fluoride (PVDF) as an active damper for vibration control. Both the structure and the actuator were modeled as DPS and energy based control techniques (Lyapunov’s 2nd method) were used to synthesize an “electronic damper”. The result was a demonstration of a truly adaptive structure which could significantly increase its damping when subjected to an outside disturbance.

The experiment received much interest from the DPS community and Professor H.T. Banks of Brown University who was well versed in the issues of DPS control subsequently contacted me to discuss the implications of my experiment. This began an odyssey of lectures and seminars around the country, encouraged by Professor Banks, to initiate collaborations in this area. These included a visit to the Institute for Computer Applications in Science and Engineering (ICASE), the Air Force Rocket Propulsion Laboratory (RPL) and presentations to the International Federation of Automatic control (IFAC). These lectures and seminars help shaped my ideas and the material presented in this textbook. I am particularly grateful to Professors John Brown, Gary Rosen and Steve Gibson for the insights that they provided into the nature of continuum systems.

As time progressed several notable experimental test platforms became available. Dr. Alok Das for example established the RPL Experiment, which was a flexible satellite test bed located in my laboratory at the Charles Stark Draper Laboratory.

Dr. Jer-nan Juang established a cantilevered beam testbed at the NASA Langley Research Center and his work and contributions there were highly regarded. These platforms and others help move the development of hardware implementation rapidly along. Dr. Francis Moon and his then student C.K. Lee pioneered the application of PVDF sensors to both 1-D and 2-D structures. Dr. Edward Crawley and his students produced seminal papers on the use of piezo crystals for the control of LSS. Professor Andrew Von Flowtow developed a novel means of resistor shunting of piezoelectric crystals to produce an elegant solution to the active damping of flexible
beams. Professor Amr Baz pioneered the use of active materials to develop active constrained layer (ACLAD) damping solutions and Professor Alison Flatau broadened the application of electrostrictive materials to this class of problems. Professor Chris Fuller extended the application of active materials to control sound radiation from vibrating structures. Dr. Dan Inman developed techniques for sensing and actuation using a single transducer. There were many strong contributions by others to the state of application; too many to due justice here, but those listed had a personal and significant impact on my thinking and work presented here. In 2001 Drs. Alok Das and Ben K. Wada chronicled these contributions in an SPIE Milestone Series of Selected Papers on Smart Structures for Spacecraft. These papers form the basis for what has now become simply the field of Smart Structures.

This was also a time of much activity in the development of Modern Robust Control Theory and major developments were taking place in the design, synthesis and realization of temporal filters for the control of LSS. Little work was being done however toward a structured design of the associated spatial filters needed for the control of such plants. Issues such as sensor and actuator placement were being addressed on an ad hoc basis, treated separately from overall control system synthesis. In actual practice a significant amount of information is needed to describe large scale systems. Traditional State Space approaches lead to the need for large numbers of sensors and actuators to identify and control such structures.

The spatially distributed/continuum nature of vibratory structures makes it difficult to apply modern lumped parameter control philosophy and techniques. While there exists a substantial amount of technical literature on the control of DPS, there are still relatively few applications or practical implementations of the theory. Modal representations are commonly employed to succinctly approximate a structures behavior. This representation is of course complete when all terms of the expansion are included. Dr. Mark Balas in a series of seminal papers demonstrated the practical limitations of the then current techniques and the unique challenge that such structures posed to the controls engineer. Often for practical implementation when one must truncate the modal expansion, it is then difficult to determine the number of modes required to accurately model the structure, and to reconcile the location of sensors and actuators and to address overall system stability issues. Computational limitations can also necessitate the need for truncation and model order reduction. Reduced-order models have been shown to suffer from control and observation spillover effects. Control and observation spillover can cause closed loop instability for even a simple flexible beam problem that is otherwise open loop stable.

The work presented in this textbook addresses the issue of the design and implementation of distributed parameter control schemes which exploit both spatially distributed sensing and actuation through the use of modern smart material technology. The merging of DPS with distributed parameter transducers leads to simple, realizable control system designs. It is hoped that this text will provide a significant reference for practicing professionals, students and researchers in the area of transducer design using smart materials for smart structures.
Finally I would be remiss if I didn’t acknowledge the contributions of my many students over the years that have contributed to the development of the techniques presented in this book. Thomas Bailey developed the basic tenants for using spatially distributed actuation and energy based strategies for structural control. John Plump applied these techniques successfully to the RPL structure and later defined the concept of active constrained layer damping. Shawn Burke developed a unified approach to structural control using all of my previous students’ works and his extensive background in the field of acoustics and control. Jeannie Sullivan extended our knowledge of the use of spatially distributed active materials for control with applications to two dimensional structures. There are of course many more to numerous to list here including my most recent students in the University of Maryland’s Morpheus Laboratory who helped with the editing and problems sets given in this text. Much of the clerical, administrative and editorial work done here is due in large part to the dedication of Laurie Postlewait, Mollie Buechel and Carolyn Sager. Finally I dedicate this book in its entirety to my lifelong role models Lillie Echols and James Edward Hubbard Sr. My sincere appreciation also goes out to my mentors and technical advisors over the years from M.I.T., Drs. Stephen H. Crandall, Donald C. Fraser, Wesley L. Harris, Hank Paynter and Herbert H. Richardson.

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