Laboratory Facility for Flexible Structure Control Experiments
Ümit Özgüner, Stephen Yurkovich, Joseph W. Martin, and Paul T. Kotnik

ABSTRACT: A laboratory facility to study various control problems related to flexible mechanical structures has been developed in the Control Research Laboratory of the Department of Electrical Engineering at The Ohio State University. Various experimental configurations that address generic problems in large flexible space structures and flexible robotic manipulators continue to be developed. While problems in vibration damping and slewing are considered from the viewpoint of modeling, identification, and control, a major part of the effort is also directed toward true actuation, sensing, and feedback implementation issues. In this paper, we give a brief overview of the facilities, present experimental configurations, and describe current experiments.

Introduction
It is well known that the control area is particularly amenable to interdisciplinary, collaborative research efforts. At The Ohio State University (OSU), such collaboration has been continuing for a number of years among faculty from the Departments of Electrical Engineering, Aeronautical and Astronautical Engineering, and Mathematics. In 1984, this collaboration was formalized with the establishment of an umbrella organization and the decision to jointly pursue a unified research area of common interest to focus the research efforts of the individuals. The selected area was control of flexible structures, and a proposal written to the university for the establishment of a laboratory facility in this area was selected for funding. The Flexible Structures Facility was thus initiated within the Department of Electrical Engineering in 1985, supported jointly by a university research grant and by the Department of Electrical Engineering. Facilities in the laboratory were further enhanced through a grant from the National Science Foundation (NSF) and Digital Equipment Corporation (DEC) for a MicroVAX II-based computer facility for conducting real-time data acquisition and control experiments.

During the planning stages of this facility, we looked at a number of related experiments and setups that have been reported in the literature, for example, [1]-[5]. We were struck by the observation that very few facilities are available for either educational or research use in general and very few, if any, are set up for analysis of simple, generic problems. Some excellent setups have been developed by private industry for their own use but are not generally available for the education of graduate students. Some fairly complex structures for experimentation also have been developed for specific research goals or as models of specific space structures; it was not clear, however, if these would be kept operational once project support ceased. Finally, some (mostly university-based) experiment setups showed a remarkable naivete in one or more aspects of the design (actuation, sensing, data acquisition, choice of computer, and so on), possibly due to funding level. A major thrust of our laboratory has been not only in experimentation, but also availability and permanence.

To support our philosophy, a set of three experimental configurations were initially selected. Primary objectives of these experiments were that they (1) be fairly simple to implement and instrument; (2) tie in directly to our present research in decentralized control, modeling, and identification; and (3) be usable as building blocks to provide expertise for more complex experimental configurations. The three initial experimental configurations constructed and instrumented were: (1) a fixed-fixed beam; (2) a free-free suspended beam; and (3) a slewing beam. The first two beams are 1.8 m long and are instrumented with sets of strain gauges and accelerometers, all accompanied by electronics designed in-house. The actuation is accomplished through the use of proof-mass actuators developed locally [6]. The third experiment consists of a 1-m aluminum beam, with counterbalancing, which is mounted for direct-drive slewing on a high-precision, high-torque servomotor. End-point sensing is accomplished through accelerometer measurements, as well as from position feedback through a high-speed linear array camera. Position and rate sensing are also available at the hub. Experiments on identification and active vibration damping have been conducted using the interface developed for the Control Research Laboratory Computer Facility. Experiments on self-tuning controllers are under way, and experiments on sensor-actuator location and failure accommodation are also projected with this setup.

Control objectives for these experiments range from active vibration suppression to slewing and pointing motion in minimum time, and combinations thereof. Furthermore, system and parameter identification for control is the other primary objective in the development and utilization of these experiments.

Computer, Interfacing, and Software Issues
The Control Research Laboratory, under which the Flexible Structures Facility operates, is served mainly by a DEC MicroVAX II, which has been purchased through grants from NSF, DEC, and matching support from The Ohio State University. The system has 9 Mbytes of random-access memory, 210 Mbytes of disk storage, and communicates with the Electrical Engineering Department’s VAX system through both Ethernet and a separate communication network, providing access to other university computers and users. Data acquisition and control is accomplished through 32 channels of analog-to-digital (A/D) and four channels of digital-to-analog (D/A) on two boards: a parallel interface board and a timer/counter board. Plotting capabilities are available both on various graphics terminals and as hardcopy output. Each A/D/D/A board (AXV-IIC) provides 12 bits of accuracy with a maximum conversion speed of 20 kHz per channel. The timer board (KWV-11a) is capable of timing events to microseconds.
The effective use of the A/D and D/A boards initially proved to be somewhat of a problem, since software provided by DEC for real-time operations (that is, the VAX ELN environment) would be too slow for the applications we envisioned. Thus, device drivers had to be written for these boards, a nontrivial task due to the complicated addressing scheme used on the MicroVAX. Once these were developed, however, the MicroVAX was quite easy to use in our feedback control environment. (In fact, we believe that the resources provided by a more sophisticated machine, especially in editing and debugging, outweigh whatever advantage there may be in utilizing a "simpler" microcomputer.) The processor utilized in the MicroVAX is quite good, with a single-precision floating-point multiplication instruction that takes 3.5 usec. In general, the instruction set is powerful, although no specific real-time facilities are provided.

One of the crucial, and possibly most expensive, parts of the interfacing circuitry in a laboratory such as this is the sensing and driving amplifiers. Three basic boards were developed in-house to be used for a variety of experiments. These were: (1) an instrumentation amplifier that can be used for bridge networks, (2) a power amplifier, and (3) a voltage regulator. The instrumentation amplifier is designed around the Analog Devices 2B31L. This is a three-stage amplifier circuit: the first is a differential amplifier, the second is a buffer amplifier, and the third stage is a three-pole low-pass Bessel filter. The filter has a cutoff frequency set at 100 Hz. Also on the module is a power supply for the instrument bridge. The common-mode rejection provided is 140 dB. Upon leaving the 2B31L, the signal is buffered and then passes through an RC high-pass stage to eliminate the drift when the accelerometers are used. The low-frequency cutoff is at 0.15 Hz. Otherwise, in the overall instrumentation, the upper and lower cutoff frequencies are set to be well outside the band of interest. For the power amplifier board, a design utilized at NASA Langley Research Center (LaRC) was adapted for our use. The circuit is configured around a Burr-Brown OPA-501 power op-amp (260 W) and will accept a −10 to +10 V input to provide an output of −2 to +2 A. Each power amplifier is provided with its dedicated regulator, which is more advantageous than a single regulator for all amplifiers. Power is supplied to all instruments, including the actuators to be described in the next section, by two 1000-W, 0-40-V, 25-A dc supply systems, providing more than twice the current needed in the experiments.

### Free-Free Beam Task Selection Menu

1. Select sensors/actuators
2. Set data acquisition time
3. Set sampling period
4. Set A/D converter gain
5. Get amplifier/ADC bias
6. Obtain natural response
7. Obtain forced response
8. Perform control
9. Plot results
10. Save data
11. Load data
12. Return to VMS

**Enter your selection**

**Selected I/O stations**

- Sampling period = 0.00E+00 sec Accel. #1 S.G. #1 Act. #1
- Acquisition time = 0.00E+00 sec Accel. #2 S.G. #2 Act. #2
- A/D converter gain = 1 Accel. #3 S.G. #3 Act. #3

**Sensor/Actuator selection**

1. Accelerometer 1
2. Accelerometer 2
3. Accelerometer 3
4. Strain gauge 1
5. Strain gauge 2
6. Strain gauge 3
7. Actuator 1
8. Actuator 2
9. Actuator 3
10. Done

**Enter your selection**

**Selected options**

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The software developed on the MicroVAX was designed to be user-friendly. Although it was written for a specific experiment, it can be utilized for other experiments with minor modifications. Two of the many menus that appear on the screen during the running of an experiment are given in Fig. 1. It is assumed that, in such an experiment, the "Perform Control" option in the Task Selection Menu refers to a previously defined (compiled) control algorithm.

### Proof-Mass Actuator

Nonground-referenced linear actuators are not yet widely available on the market, and this fact led to an in-house development. Figure 2 offers a schematic view of the device itself, while Fig. 3 is a photograph of a set of the devices mounted on a beam. The device is built around a linear motor manufactured by the Kimco Division of BEI Motion Systems with a total mass of 25 g, and can deliver a peak force of 2.2 N. The coil (solenoid) is rigidly mounted to a beam clamp that fixes the actuator to the beam. Also connected to the clamp are rigid arms that support the springs. The proof mass is coupled to the framework through the springs, which provide a restoring force for the proof mass and transfer force to the beam. It is possible, in fact, quite simple, to change

![Free-Free Beam Task Selection Menu](image1)

![Free-Free Beam Task Selection Menu](image2)

![Proof-Mass Actuator](image3)
the location of the actuator on the structure. Thus, it is possible, for example, to experimentally determine control effectiveness as the point of force application is varied incrementally on the flexible beam.

The major problem in including actuator dynamics in the mathematical model of large space structures is due to the very nature of actuation for such structures. One difficulty with these devices is that their dynamics are inherently coupled to the dynamics of the structure, and the coupling must be accounted for if an accurate model is required for optimum control.

The model of the particular momentum exchange device developed in the laboratory was described in [6]. We note that our actuator is similar in philosophy to those being developed by industry and NASA for various programs. We have had to face problems similar to those encountered in the preceding developments, compounded due to constraints imposed by scale. Specifically, due to size and weight restrictions, we have not attempted either acceleration measurements or relative position measurements on the proof mass. This has restricted our options in developing inner-loop controllers, which would have simplified the effect of the actuator on the structure. In spite of that, we have been able to control the structure satisfactorily.

Free-Free Suspended Beam Experiment

One of the experimental configurations that is fully operational at this time is a free-free suspended beam, as shown in Fig. 4. The beam is 1.8 m long and is instrumented with sets of strain gauges and accelerometers, all accompanied by electronics designed in-house. The actuation is accomplished through the use of the proof-mass actuators developed locally. The accelerometers are Entran Model EGA-125-250 with 2-kHz bandwidth and 1-mV/g sensitivity. They are small and add very little mass (0.5 g) to the beam itself. Internally, the accelerometers are constructed using piezoresistive elements in a Wheatstone bridge configuration (as are the strain gauges). The location of the actuators and sensors are shown in Fig. 5. The actual beam parameters are given in Table 1. Several approaches have been considered to obtain a model for the experimental configuration: a purely analytic approach starting from the partial differential equations, a finite-element approach, a hybrid-experimental approach utilizing both of the preceding with modifications based on experimentally obtained data, and system identification approaches.

Various experiments have so far been performed on the preceding. These include natural response measurements to estimate damping, fast Fourier transforms on impulse response to verify natural frequencies, forced response observations to check experimental frequency response against analytically generated ones, on-line and off-line system identification studies [7], and so on.

Controllers have been designed to produce significant vibration damping on this structure. Thus far, most extensive tests have been performed using a set of lead compensators calculated from the root-locus plots. These have been implemented with velocity feedback, with the velocity estimates generated from the integration of accelerometer data [8], [9].

Slewing Beam Experiment

Control design for lightweight flexible slewing structures has gained the attention of control theorists only recently, and several approaches have emerged. Most prominent are approaches that either linearize and truncate for controller design or solve a nonlinear...
Table 1

<table>
<thead>
<tr>
<th>Beam Parameters</th>
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<tbody>
<tr>
<td>Material</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Length, m</td>
<td>1.8</td>
</tr>
<tr>
<td>Cross Section, m²</td>
<td>1.5875 x 10⁻⁶</td>
</tr>
<tr>
<td>Height, m</td>
<td>0.1</td>
</tr>
<tr>
<td>Young's Modulus, N/m²</td>
<td>6.8944 x 10⁷</td>
</tr>
<tr>
<td>Mass Density, kg/m³</td>
<td>2750</td>
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</table>

(robots) problem for rigid link motion control and treat the flexible dynamics separately. For example, the problem of observation spillover and truncation error effects is treated in [10], where, in simulation studies, a linear feedback scheme around a reduced-order model is introduced for a single-link flexible arm. Several other analyses have appeared along these basic lines, using various approaches. From an applications viewpoint, however, only a few studies have been documented for parameter estimation, system identification, and control. Most prominent among these are the works of Book et al. [11]-[14] for time-optimal slew experiments, related studies at Jet Propulsion Laboratory in flexible beam control [15], Canon and Schmitz [16] using noncolocated and tip position sensing in the control algorithm, and several studies conducted at NASA LaRC [17], [18].

In this section, we describe a generic experiment set up to facilitate modeling and control studies for slewing flexible structures. The beam, shown in Fig. 6, is slewed by a direct-drive dc motor and has a rigid counterbalance appendage. Current experimentation is from two viewpoints: (1) rigid-body slewing and vibration control via actuation with the hub motor, and (2) vibration suppression through the use of structure-mounted proof-mass actuation (using the device described in the previous sections) at the tip. Real-time parameter estimation techniques, within the closed loop for self-tuning adaptive control, are also being implemented on this apparatus. For use in all of these studies, general system identification approaches are also being investigated.

The apparatus consists of a 0.0625-in.-thick aluminum beam counterbalanced with a rigid aluminum appendage with mass equal to that of the arm. Hub actuation is accomplished by a 3.4-ft-lb direct-drive dc motor that has an optical encoder with a quadrature digital output to sense motor-shaft position and a tachometer to measure motor-shaft speed, allowing for both hub position and velocity feedback for control. The dimensions of the beam are shown in Fig. 7 and the physical characteristics of the beam are given in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Physical Characteristics of OSU Slewing Beam</th>
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<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Modulus of Elasticity, N/m²</td>
</tr>
<tr>
<td>Modulus of Rigidity, N/m²</td>
</tr>
<tr>
<td>Density, kg/m³</td>
</tr>
<tr>
<td>Cross-Sectional-Area Moment of Inertia</td>
</tr>
<tr>
<td>Flexible Arm, m⁴</td>
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<tr>
<td>Rigid Appendage, m⁴</td>
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</table>

The motor used in this experimental setup was manufactured by the Inertial Motor Corporation of Pennsylvania. This is a six-pole, permanent-magnet dc motor. It has a rated stall torque of 4.802 N-m (680 oz.-in.). A linear analog power amplifier closes a velocity loop with the motor resulting in near-linear characteristics. The amplifier has potentiometer adjustments for current limit, input signal gain, tachometer signal gain, and amplifier compensation (bandwidth adjustment). Using these adjustments, the motor/amplifier pair can be set up so as to be critically damped. The tachometer signal gain and the amplifier bandwidth potentiometer are adjusted so that the tachometer output reaches its final value as fast as possible without any overshoot. This is typically done in a no-load situation.

Control of the slewing beam is accomplished through the MicroVAX II. Until recently, an IBM Personal Computer AT was used as the controlling computer for the apparatus; details of the three interface cards developed may be found in [19]. A special-purpose card was developed to interface with a linear array camera. The linear array camera is used in this setup for tip position monitoring, as well as for position sensing for feedback control; again, the reader is referred to Fig. 6. This camera consists of a linear vector of photosensitive diodes (512 elements), which are scanned at a rate of 200 Hz (variable between 50 Hz and 500 Hz) for typical experiments. The data are sent from the camera to the interface using the RS-422 data communications standard. This is a 0-5-V differential communication method capable of data rates of up to 10 Mbits/sec.

Fig. 6. OSU slewing beam experiment.
Sensors are utilized at two places on this beam. The first set of sensors, located at the motor shaft, detects motor-shaft position (angular displacement) and motor-shaft velocity. The second sensor is located at the tip (free end) of the beam. This sensor consists of an accelerometer and is next to an 18-V incandescent lamp, utilized as a light source since typical light-emitting diodes do not generate light of high enough intensity to be sensed accurately by the camera.

An 1800-line quadrature shaft encoder is used to detect the angular displacement of the motor shaft. The encoder itself is optically excited and generates three channels of output, which are at TTL voltage levels. In typical experiments, only two channels of the encoder output are used; the third (which is the index output) is not needed. The remaining two channels of output (channel A and channel B) are used by the software to determine both the shaft direction and position. To be able to detect direction, the current and post states of the encoder are needed. The necessary calculations for direction determination are very quick and easy to do in software and require a minimum of storage space, and the shaft position can be determined to within 0.1 deg. It is important to note that the shaft position determined in this manner is relative, and not absolute, for controller designs successful to date, however, this was sufficient. To generate an absolute position, an external reference would have to be used at the start of each experimental run.

Also located on the motor shaft is a tachometer, whose output is used as the feedback control signal for the velocity loop between the motor and amplifier. This output signal is digitized and fed back to the computer for use in control algorithms. The tachometer output voltage was determined experimentally.

A linear accelerometer is mounted at the tip of the beam, a piezoelectric-type accelerometer manufactured by Entran Devices, Inc. Some of the relevant characteristics are listed in Table 3. The accelerometer output is a low-voltage analog signal (in the range of 1-10 mV) requiring a high-gain amplifier to be useful for control applications. Thus, electrical noise becomes much more of a concern than with the other sensors.

To date, several successful controller designs have been proven on this setup [20], [21]. These range from tip position (camera data) feedback to observer-based, state-variable feedback using measured tip positions, to a design that employs acceleration feedback from the tip, with no camera data. A mathematical model, which matches experimental data, has been developed [22]. Several other methods for slewing control and vibration damping are under current investigation. These include frequency-weighting approaches in output feedback schemes, and self-tuning adaptive control approaches [23], [24]. Moreover, active vibration damping schemes using structure-mounted proof-mass actuators are being investigated.

Two of the menus that appear on the terminal during typical slewing beam experiments are shown in Fig. 8.

### Ongoing Developments

Three additional experimental setups, all at various stages of development, are under way for continued activity in the Flexible Structures Facility of the Control Research Laboratory at OSU. The first, which is constructed and undergoing instrumentation, is a vertical beam, approximately 2 m long, cantilevered from the top by a wooden support structure anchored to a wall of the laboratory. The primary intent of this experiment is to supply a test bed for various system identification studies involving both on-line and off-line schemes. Both strain and acceleration measurements will be available, interfaced through the MicroVAX II system, with camera sensing for position monitoring.

With the use of the OSU proof-mass actuator, two major objectives will be accomplished. First, experiment design and optimal input synthesis algorithms currently under investigation may be implemented easily; second, vibration control (for example, including the first pendulum mode) may be carried out for models as identified.

A second experiment under construction in the laboratory is a two-link, lightweight, flexible manipulator arm. The structure is situated in the vertical plane and consists of a direct-drive motor for the first link with a geared dc motor for the second link. The first design uses fiberglass rods for the links, providing ample strength with a fairly significant degree of flexibility. A separate computing system has been designed for this experiment; the heart of the controller is a Motorola 68020 processor.

A recent effort has been oriented toward the utilization of piezoelectrics for actuation and sensing purposes. To this end, a very small (12 in.) clamped-free beam has been used.

**Table 3**

<table>
<thead>
<tr>
<th>Accelerometer Device Characteristics</th>
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<tbody>
<tr>
<td>Range, g</td>
</tr>
<tr>
<td>Sensitivity, mV/g</td>
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<tr>
<td>Resonant Frequency, Hz</td>
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<tr>
<td>Excitation, Vdc</td>
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<td>Nonlinearity, percent</td>
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Fig. 8. Two of the menus for the slewing beam experiment.
developed and instrumented with two layers of PVFy material. Experiments on this structure are presently continuing.

Finally, in late 1988, a multibay truss structure will be constructed, the dimensions and materials for which are still in the planning stages. In addition to the proof-mass actuation employed in the other experiments described earlier, it is planned that this experiment will utilize inertial wheel devices and materials for which are still in the planning stages. Strain gauges, accelerometers, and rate gyros will be used for sensing.

Acknowledgments

A number of organizations and individuals have contributed to this effort in various ways. We must first acknowledge The Ohio State University Research Grant that was given specifically to develop the facility. National Science Foundation Grant DMC-8506143 and a joint grant from Digital Equipment Corporation to the first author, together with cost sharing from OSU and the Department of Electrical Engineering, provided the computer facilities. Professor H. C. Ko, Chairman of the Department of Electrical Engineering, has supported us extensively in many ways during the development of the laboratory. We would like to thank Dr. Ray Montgomery and NASA Langley Research Center for providing us with the expertise that we utilized in the experiments, and Whirlpool Company for providing support. A number of students contributed, and we wish to specifically thank Mr. R. Ulman, Ms. A. Cagle, and Mr. F. Pacheco. We would finally like to thank Mr. R. Wilson, who, as Department Computer Facility Manager, contributed, with his organization, to the establishment of our realtime computer resources.

References

AACC Awards

Nominations are due by December 1, 1988, for three awards presented by the American Automatic Control Council (AACC). For information about the most recent recipients of these awards, see the biographies and photographs listed under the heading American Automatic Control Council Awards in this issue of the Magazine. The award nomination should be sent to the AACC Secretariat, c/o Bill Miller, 1051 Camino Velasquez, Green Valley, AZ 85614. For further information and help on the nominations, contact the IEEE Control Systems Society Chairman of Award and Fellow Nominations, Prof. M. Vidyasagar, Department of Electrical Engineering, University of Waterloo, Ontario N2L 3G1, Canada, phone: (519) 885-1211, or contact the Society Vice President for Member Activities, H. Austin Spang, General Electric Research & Development Center, 37-2011, Schenectady, NY 12301, phone: (518) 387-6490.

- Richard E. Bellman Control Heritage Award. For distinguished career contributions to the theory or applications of automatic control. The nominee is to have spent a significant part of his/her career in the United States. Posthumous nominations not allowed. Nominations by December 1.
- Donald P. Eckman Award. For outstanding performance by a young engineer in the field of automatic control. Nominees must be younger than 35 years at the time of the award. Based on contributions made while the nominee was a resident of the United States. Nominations by December 1.

- Education Award. For outstanding contributions to automatic control education in any form. Nominations by December 1.

Henry D’Angelo Memorial

Henry D’Angelo died of leukemia at his home in Brookline, Massachusetts, on April 3, 1988. He was 55. At the time of his death, D’Angelo held joint appointments at Boston University as Professor of Manufacturing Engineering and Professor of Electrical, Computer, and Systems Engineering.

Professor D’Angelo was perhaps best known to members of the Control Systems Society for his numerous contributions to the analysis and design of control systems, computer modeling of societal systems, microcomputer interfacing, and advanced manufacturing systems. He was a frequent participant in the annual Conference on Decision and Control and author of the well-known book Linear Time-Varying Systems: Analysis and Synthesis (Allyn and Bacon, 1970). He also authored Microcomputer Structures, which is an introduction to digital electronics, logic design, and computer architectures (McGraw-Hill/Byte, 1981). Professor D’Angelo’s most recent research was focused on estimation and simulation problems for complex manufacturing networks. He conceived and developed hardware capable of emulating the behavior of a large factory system on a time scale orders of magnitude faster than what is feasible with the fastest general-purpose computers available today.

As a Systems Engineer for the Sperry Gyroscope Company, D’Angelo worked on automatic navigation problems. He taught at Memphis State University (mathematical sciences), was a Distinguished Visiting Professor at Morehouse College (mathematics), a Professor and Head of Electrical Engineering at Michigan Technological University, and an Associate Dean of the College of Engineering at Boston University. He served as a consultant for the Denver Research Institute, the University of Tennessee Medical School, and the Mitre Corporation.

In 1974, he was the winner of the American Society for Engineering Education Award for excellence in engineering education.

Henry D’Angelo is survived by his wife Gail and four sons, Agostino, James, Peter, and Paul. We will miss him as a colleague and as a friend.

Intelligent Control Symposium

The Third IEEE International Symposium on Intelligent Control will be held August 24-26, 1988, at the Key Bridge Marriott, Arlington, Virginia. The symposium is sponsored by the IEEE Control Systems Society, in cooperation with the IEEE Council on Robotics and Automation and the IEEE Systems, Man, and Cybernetics Society. The symposium will be hosted by George Mason University. Topics of interest include all aspects of intelligent control and machine intelligence, including architecture, tools, and applications.

For further information, contact: Prof. Harry E. Stephanou, Dept. of Electrical and Computer Engineering, George Mason University, Fairfax, VA 22030, phone: (703) 323-3451.