**VIBRATIONS—Charudatta Mehendale, Ph.D. student in the Dept. of Mechanical Engineering (*l*.), consults with Dr. Karolos M. Grigoriadis, associate professor (*r*.), on the development of the Active Rack Isolation System (ARIS), designed to enable experimentation without interference from vibrations or exterior acoustics at the International Space Station.**

# Active Control of Vibration Isolation for Microgravity Experiments

Karolos M. Grigoriadis, Associate Professor, Department of Mechanical Engineering
Ian J. Fialho, Ph.D., The Boeing Company
Ramu Chandra, M.S. student, UH Department of Mechanical Engineering
Charudatta Mehendale, Ph.D. student, UH Department of Mechanical Engineering

***Abstract—*** This work considers the use of linear parameter-varying methods to control a vibration isolation system with stiffness hysteresis. From a linear parameter-varying (LPV) design, perspective hysteresis is modeled as a stiffness parameter that takes values in a compact convex set with vertices determined from displacement constraints that exist in the system. The resulting controller consists of two vertex controllers along with interpolation based on the current measured stiffness. The proposed method is applied to the control of the Active Rack Isolation System (ARIS), which is the primary vibration suppression system for providing a microgravity environment aboard the International Space Station (ISS). Simulations show that the parameter-varying design is stable and that robust isolation performance is achieved over the range of displacements considered. The LPV controller accounts for hysteretic umbilical stiffness variations and is scheduled based on the real-time stiffness measurements. This methodology performs better than a single linear time-invariant robust H-Infinity controller.

A CRITICAL FUNCTION OF THE INTERNATIONAL SPACE STATION (ISS) is to serve as a premier on-orbit microgravity laboratory for conducting acceleration-sensitive scientific research in diverse disciplines, such as material science, combustion, fundamental physics, chemical processing, fluid mechanics, and biotechnology.[1,2] However, due to a variety of vibroacoustic excitations on the ISS (steady-state sources, such as pumps, compressors, exercise equipment and fans, and transient sources, such as astronaut motion, impacts. and attitude control forces and torques) the acceleration environment is expected to significantly exceed the micro-*g* specifications of many acceleration sensitive experiments.[3] In order to isolate experiment payloads from station disturbances the Active Rack Isolation System (ARIS) is currently under development by Boeing and NASA.[4,5] A diagram of a typical ARIS payload rack is shown in Fig. 1. The ARIS function is to sense rack acceleration via three triaxial accelerometer heads (labeled 3) and to uses eight pushrods, driven by rotary-type voice coil actuators (labeled 5) to actively generate the forces needed to perform active vibration attenuation. Position sensors housed in the actuator assembly are used to sense the relative position between the rack and the station. The rack must operate within a ±0.5 inch rattlespace, which is enforced by hardstop bumpers (labeled 6 in Fig. 1).

Modeling and control of ARIS are complicated because of several challenging factors. A considerable challenge is the presence of umbilicals that route electrical power, data, cooling water and other essential resources as required by the science payload from a utility interface panel at the front bottom section of the rack (Fig. 2). These umbilicals are the main contributor to the overall variable stiffness and hysteresis of the system and are the primary

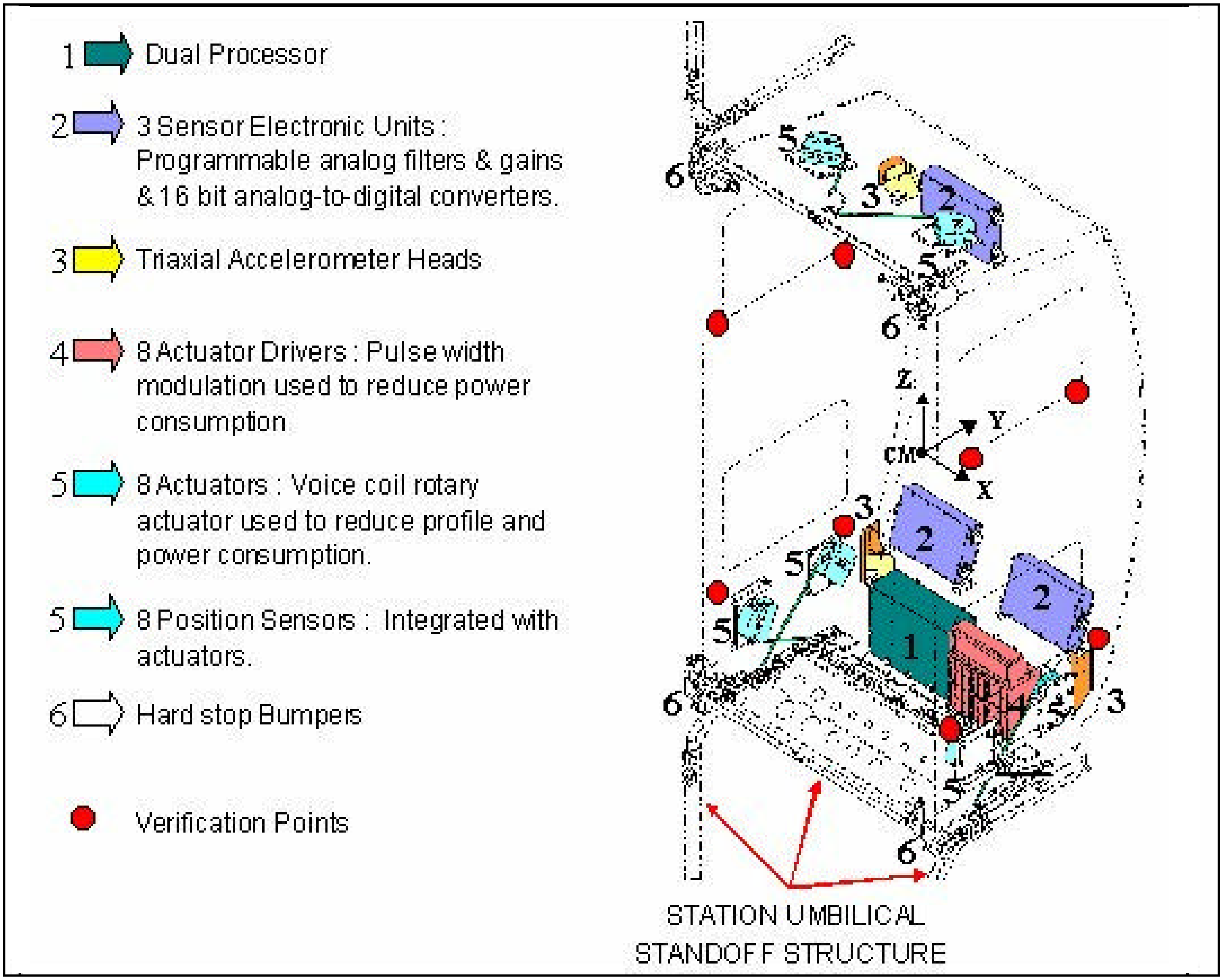

**Figure 1. ARIS payload rack**

load path for station disturbances across the station-rack interface.

The objective of the ARIS feedback control system is to provide the appropriate actuation forces for scientific experiment acceleration cancellation. The active controller acts on the nine accelerometer measurements and the eight position measurements to generate the eight actuator forces. The primary control design objective is to attenuate station accelerations across the station-rack interface. In addition, at low frequency, the controller must keep the rack centered in its sway space, i.e., achieve low frequency position tracking. Low frequency station disturbances, such as venting, accelerate the station, and as a consequence the control system must accelerate the rack in order to prevent it from bumping into its hardstop bumpers. The extremely stringent micro-*g* vibration isolation requirements make this an extremely challenging vibration control problem. Current control schemes fail to meet the desired acceleration attenuation characteristics, and recent ARIS flight data show attenuation levels that are 6 db higher than the performance requirements.[3] The variable umbilical stiffness nonlinearity and hysteresis along with inertia coupling of the vibrating system, unmodeled system dynamics and hardware implementation constraints on the controller make this an extremely challenging modeling and control design problem from both a theoretical and a practical perspective.

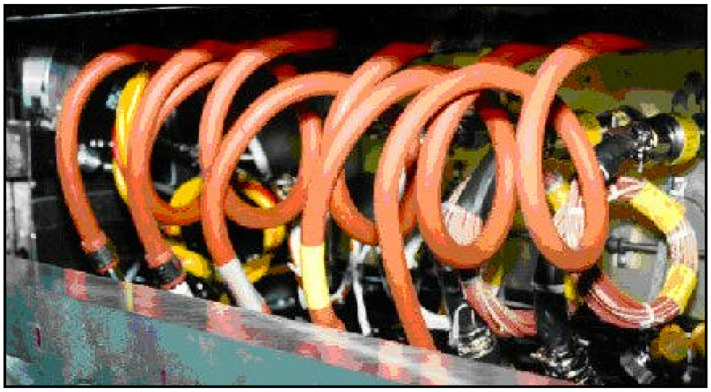

**Figure 2. ARIS umbilicals**

### Technical Plan and Equipment

The objective of this research is to investigate and develop advanced novel modeling and control methods for vibration attenuation in the presence of variable nonlinearities and decentralization constraints, with focus on the application to the control of ARIS. A particular emphasis of the project is the control of hysteretic systems, a subject that has not been addressed effectively in the control engineering literature. In the ARIS system, the umbilical set (Fig, 2) exhibits a hysteretic force versus displacement curve, and, as a consequence, the stiffness matrix K varies as a function of the relative position of the rack in its sway space. A typical umbilical hysteresis curve is shown in Fig. 3. As can be seen, the umbilicals tend to soften with displacement. The net stiffness changes by over a factor of two, over the range of rack motion and hence must be accounted for in controller development.

Conventional control designs cannot accommodate such variable nonlinearities resulting in unacceptable performance. In addition to the above hysteretic behavior, the ARIS system model has significant structural uncertainty due to high frequency unmodelled flexible modes that come into play above 26Hz and limit the control bandwidth. Additional challenging objectives include the ability to provide vibration attenuation subject to control implementation and decentralization constraints and the ability for rapid control software redesign. ARIS control decentralization constraints are enforced by the presence of separate high and low frequency control loops and the fixed architecture control structure of currently deployed hardware. Rapid redesign is essential for on-orbit deployment of ARIS racks to address fast changing rack/payload/station configurations.

A novel robust parameter dependent control design methodology is proposed to address the above challenging control problem. The main idea for compensating the hysteretic nonlinearity of the system is to schedule the controller in real time to the current operating point of the hysteresis loop in Fig. 3. Hence, the control gains are variable and are adapted on-line to the current operating point in the hysteresis loop. This concept extends prior work of the PI on the control or nonlinear parameter varying systems,[6,7] and, recently, these methods have been applied by the PI and his students to engine control systems.[8] In particular, this concept has been used successfully to control systems with saturation nonlinearities by adapting the controller to the current saturation level of each individual input channel.[9]

However, the treatment of hysteresis nonlinearities provides a challenging problem due to the multivalued nature of such nonlinearities. System model uncertainty is to be addressed in a robust control framework by providing guaranteed closed-loop performance for the vibrating system for all perturbed models that result from the unmodelled dynamics. The computational control synthesis problem for such parameter dependent systems results in a convex optimization problem with Linear Matrix Inequality (LMI) constraints that can be solved efficiently allowing rapid redesign.[10]

## Results

In this work, we consider a simplified model of a vibration isolation system with rigid body dynamics. The control problem considered is the use of output feedback, i.e., inertial acceleration and relative position, to robustly stabilize the closed-loop system and achieve a level of disturbance rejection from the external disturbance, i.e., offboard acceleration, to the measured output. The novelty of the present work is that the stiffness parameter is assumed to vary nonlinearly with relative displacement. In particular, the stiffness force versus displacement curve is assumed to exhibit hysteretic behavior. One possible approach to the problem is to linearize the hysteresis curve over a range of displacements, resulting in a set of stiffness values over which robust stability and performance must be achieved. Obviously the achievable robustness will depend on the range of stiffness variation that results.

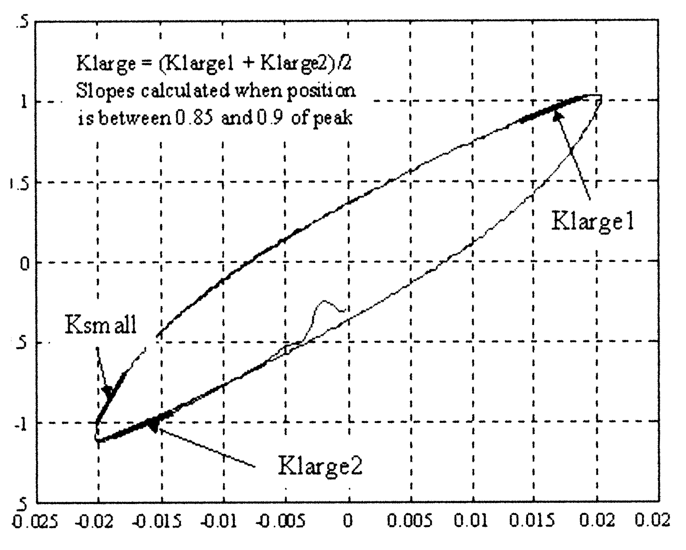

**Figure 3. Umbilical hysteresis**

A significantly less conservative approach would be to design a single nonlinear controller that explicitly accounts for the stiffness nonlinearity. In this work, we consider the application of linear parameter-varying (LPV) methods to the latter approach. The nonlinear plant is linearized over a range of displacements, and the resulting family of linearizations is modeled as a linear parameter-varying system. LPV methods are then used to design a gain-scheduled controller that adjusts its dynamics based on the current stiffness estimate.

The umbilicals do not have a constant stiffness within the whole range of rack motion, but, rather, an hysteretic characteristic. As can be seen in Fig. 3, as displacement increases umbilical stiffness gradually decreases from $K_{small}$ to $K_{large}$. On hysteresis turnaround, the stiffness increases back to the larger value. From an LPV perspective this hysteretic variation in stiffness can be modeled as a parameter variation between the maximum and minimum values of stiffness K. Theoretically at least, the stiffness can be estimated in real-time, using either on-line stiffness identification or an accurate model of umbilical hysteresis. This stiffness estimate can then be used to schedule the LPV controller. The ARIS model above is a rigid body model of the rack and is therefore valid only for low frequencies. In reality, rack flexible modes come into play above 26 Hz, and the acceleration loop must therefore be rolled off to gain-stabilize against these modes. This places a constraint on allowable control bandwidth. In the present work, the acceleration open loop transfer function (measured by breaking loops at the acceleration inputs to the controller) is required to lie below the piecewise linear gain-stabilizing constraint curve formed by joining the points (27 Hz, -15 dB), (43 Hz, -45 dB), and (78 Hz, -54 dB).

Accelerometers tend to be noisy at low frequency due to a variety of effects such as measurement biases, drift, and electronic noise. The controller senses this false acceleration and attempts to cancel it, thereby causing the rack to move around in its rattlespace. This can be mitigated by ensuring that the transfer function from accelerometer noise to onboard acceleration is small at low frequency. The position sensors, on the other hand, tend to be noisy at high frequency. In order to reject this noise, the position control loop must be adequately rolled off at high frequency. Transient propulsive station disturbances such as venting and thruster firings cause relative motion between the station and the rack. In order to validate any designed controller, a worst-case transient velocity profile of the station is chosen and applied to the model in order to determine whether the relative displacement remains within 0.5 in. This is necessary to ensure that the rack does not bump into its hardstops during normal operation.

The resulting control design interconnection has 17 states. The LPV controller, designed using the LMI control toolbox in MATLAB, consists of two vertex controllers with 17 states each. Once the LPV controller is designed, there is a simple necessary condition which can be checked before any simulations are carried out, i.e., check that the closed-loop LTI systems corresponding to the frozen values of the parameters are stable. The designed controller was then verified through frequency and time domain simulations. For the time-domain simulations, the hysteresis model of the spring was used to validate the performance of the controller. Figure 4 shows the isolation performance achieved by the two vertex LTI controllers, as well as that of several controllers in the interior of the parameter set. Clearly, the required isolation goal is robustly attained.

Finally, a “worst case” velocity profile is applied as an offboard velocity in the model to determine whether the rack motion is restricted to 0.5 inches. This corresponds to a velocity profile induced on the station by a propulsive venting disturbance. The results of the simulation (see Fig. 5) show that the required displacement constraint is met. The maximum displacement of the rack is less than 0.084 inches, which is well below the 0.5-inch limit. The isolation performance is excellent at low frequency in spite of the maximum displacement of the rack being very small. This is due to the fact that LPV control permits us to use a real-time estimate of umbilical stiffness for control. These results compare very favorably with those in Fialho[5] where the stiffness variations were modeled as an uncertainty in the model and were not available to the controller in real time.

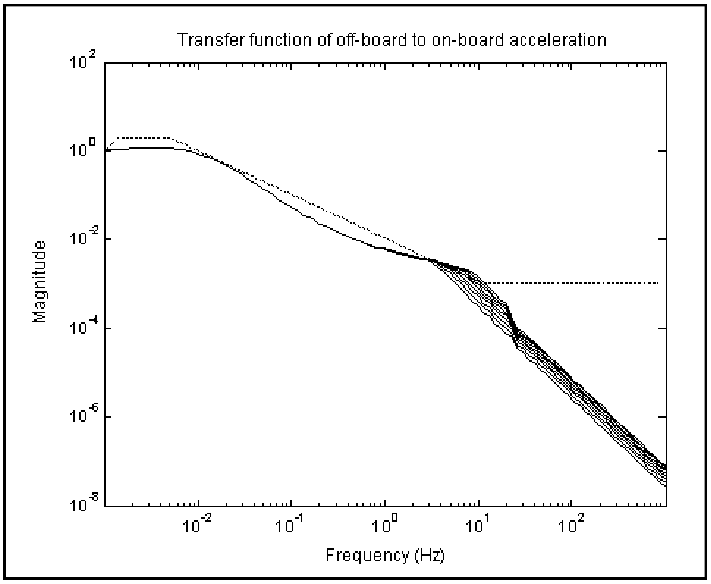

**Figure 4. Isolation performance**

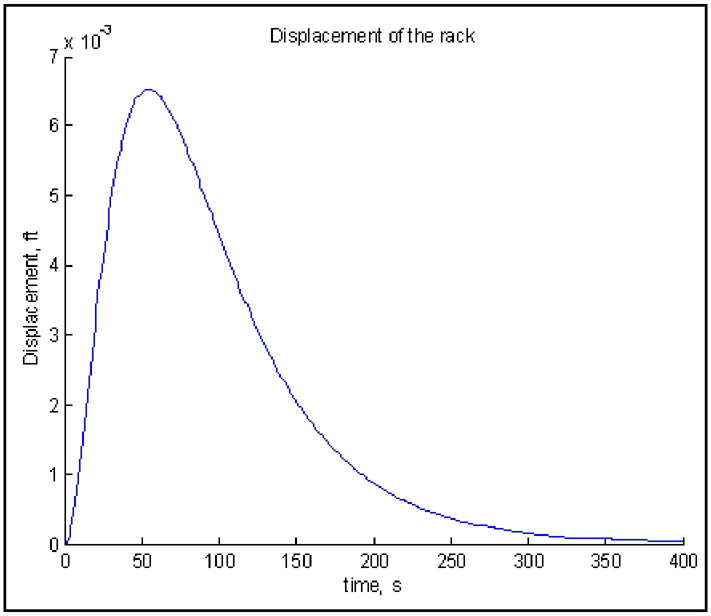

**Figure 5. Rack displacement with worst case velocity profile**

## References

[1] National Research Council. *An Initial Review of Microgravity Research in Support of Human Exploration and Development of Space*. Washington, D.C.: National Academy Press, 1997.

[2] National Research Council. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space*. Washington, D.C.: National Academy Press, 2000.

[3] C. M. Grodsinsky and M. S. Whorton. “Survey of Active Vibration Isolation Systems fro Microgravity Applications,” AIAA *J. Spacecraft and Rockets* 37 (2000): 586-96.

[4] I. Fialho and S. Thampi. “The Interplay Between Hardware and Control System Design in the Development of the Active Rack Isolation System,” *Proc.*, 41st AIAA Structures, Structural Dynamics and Materials Conference, Atlanta, GA, 2000.

[5] I. Fialho, “$H_\infty$ Control Design for the Active Rack Isolation System,” *Proc.*, American Control Conf., Chicago, IL, 2000.

[6] K. Tan, and K. M. Grigoriadis. “State-Feedback Control of LPV Sampled-Data Systems,’’ *Mathematical Problems in Engineering* 6 (2000): 145-70.

[7] F. Wu, and K. M. Grigoriadis. “LPV Systems with Parameter-Varying Time Delays: Analysis and Control,’’ *Automatica* 37 (2001): 221-29.

[8] K. Tan. “Linear Matrix Inequality Optimization Methods for Control of Parameter Varying Mechanical Systems,” Ph.D. Dissertation, University of Houston, Department of Mechanical Engineering, May 2000.

[9] F. Wu, K. M. Grigoriadis, and A. Packard. “Anti-windup Controller Design Using Linear Parameter-Varying Control Methods,’’ *Int'l. J. of Control* 73 (2000): 1104-14.

[10] R. E. Skelton, T. Iwasaki, and K. M. Grigoriadis. *A Unified Algebraic Approach to Linear Control Design*. Taylor & Francis, 1998.

[11] K. Tan and K. M. Grigoriadis.

"Robust Decentralized Control Using an Alternating Projection Approach," *Proc.*, 2000 American Control Conf., Chicago, IL, 2000.

**Publications**

Chandra, R., I. Fialho, and K. M. Grigoriadis. "Linear Parameter-Varying Control of Hysteresis for Active Microgravity Isolation," *Proc.*, 2002 American Control Conf., Anchorage, AK, 2002.

Tan, K. and K. M. Grigoriadis. "Output Feedback Control of LPV Sampled-Data Systems,'' *Int'l. J. of Control* 75.4 (2002): 252-64.

Grigoriadis, K. M. and F. Wu. *Actuator Saturation Control via Linear Parameter Varying Control Methods*. New York: Marcel Dekker, 2002. 273-98.

Wu, F. and K. M. Grigoriadis. "LPV Systems with Parameter-Varying Time Delays: Analysis and Control,'' *Automatica* 37.2 (2001): 221-29.

**Thesis**

Chandra, R. "Parameter-Varying Control of Engineering Systems," M.S. Thesis, Department of Mechanical Engineering, University of Houston, Aug. 2001.

**Presentations**

Chandra, R., I. Fialho, and K. M. Grigoriadis. "Linear Parameter-Varying Control of Hysteresis for Active Microgravity Isolation," *2002 American Control Conf.*, Anchorage, AK, 2002.

Tan, K. and K. M. Grigoriadis. "Stabilization and Control of Continuous-Time Symmetric Systems," *40th IEEE Conf. on Decision and Control*, Orlando, FL, 2001.

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