Miniature Vibration Isolation System (MVIS)

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Abstract--In recent years, there has been a significant interest in, and move towards using highly sensitive, precision payloads on space vehicles. In order to perform tasks such as communicating at extremely high data rates between satellites using laser cross-links, or searching for new planets in distant solar systems using sparse aperture optical elements, a satellite bus and its payload must remain relatively motionless. The ability to hold a precision payload steady is complicated by disturbances from reaction wheels, control moment gyroscopes, solar array drives, stepper motors, and other devices. Because every satellite is essentially unique in its construction, isolating or damping unwanted vibrations usually requires a robust system over a wide bandwidth. The disadvantage of these systems is that they typically are not retrofittable and not tunable to changes in payload size or inertias.

Previous work, funded by the Air Force Research Laboratory, Defense Advanced Research Product Agency, Ballistic Missile Defense Organization and others, developed technology building blocks that provide new methods to control vibrations of spacecraft. The technology of smart materials enables an unprecedented level of integration of sensors, actuators, and structures; this integration provides the opportunity for new structural designs that can adaptively influence their surrounding environment. To date, several demonstrations have been conducted to mature these technologies. Making use of recent advances in smart materials, microelectronics, Micro-Electro Mechanical Systems (MEMS) sensors, and Multi-Functional Structures (MFS), the Air Force Research Laboratory along with its partner DARPA, have initiated a program to develop a Miniature Vibration Isolation System (MVIS) (patent pending) for space applications. The MVIS program is a systems-level demonstration of the application of advanced smart materials and structures technology that will enable programmable and retrofittable vibration control of spacecraft precision payloads. The current effort has been awarded to Honeywell Satellite Systems Operation. AFRL is providing in-house research and testing in support of the program as well. The MVIS program will culminate in a flight demonstration that shows the benefits of applying smart materials for vibration isolation in space and precision payload control.

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1. INTRODUCTION

Honeywell has proposed a modular approach for the MVIS, consisting of a series of cube-like structures, fittingly called H-Cubes (patent pending) that are mounted similar to the mountings of legs on a table (refer to Figure 1). This modular cube approach allows the isolator to be mounted directly in the loadpath with very little change to the payload or bus structure. The cubes' hybrid system architecture consists of both active and passive stages of integrated electronics and mechanical hardware, contained within approximately an 8 cubic inch volume (1 in^3 flight goal) weighing only 6 oz. The modules for the MVIS will be designed to provide greater than 20dB reduction of vibration transmission from bus to payload, over a dynamic range of 5 to 200 Hz. In addition, the MVIS will assist in reducing any harmonics that emanate from the payload to the bus by 40 dB/decade above the break frequency of the passive stage.

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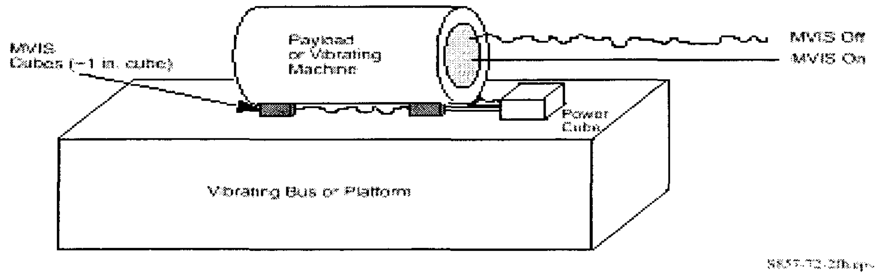

Figure 1 Modular Mounting Approach

2. BACKGROUND

There have been several programs which have matured certain technologies far enough to make the MVIS concept a reality. The Synthesis and Processing of Intelligent Cost-Effective Structures (SPICES) program was one of the DARPA consortium programs that developed tools to manufacture multifunctional structures for vibration control. The Advanced Controls Technology Experiment (ACTEX-I) is a BMDO funded experiment that has demonstrated on-orbit vibration suppression using these advanced composite structures with embedded piezoelectric sensors and actuators. The development of the three-parameter passive D-Strut™ [1][2] by Honeywell has led to a mature technology that can attenuate high-frequency vibrations at 40 dB/decade within a very small volume. The system is tunable through changes in the fluid media, bellows shape, and orifice design. The BMDO funded Vibration Isolation, Suppression, and Steering (VISS) [3] hexapod experiment uses this D-Strut technology combined with an active voice coil system to provide a robust hybrid active/passive isolation system. Under the VISS program, a Mid-Wavelength Infrared (MWIR) telescope will be actively controlled to suppress vibrations from on-board cryocoolers and from bus disturbances. AFRL's Satellite Ultra-Quiet Isolation Technology Experiment (SUITE) uses damped flexures in conjunction with piezoelectric stack actuators to perform a similar function. Lastly, MEMS experience has shown that an acceptable accelerometer can be made the size of a nickel. With these basic technologies in place, the development of a modular, tunable, and programmable vibration isolation system is feasible.

10. MINIATURE VIBRATION ISOLATION SYSTEM

Vibration isolation can be accomplished by either passive, active, or hybrid methods. The static, dynamic, and thermal loads on a payload determine the complexity of isolation architecture to be implemented. Passive methods offer an advantage in high-frequency isolation because there is no sensor or control loop required for their use. Obtaining 40 Db/decade roll-off past the design break frequency for a three-parameter passive isolator is achievable today. Break frequencies for these isolators are typically around 20 Hz; however, optical payloads are also very sensitive to lower-frequency disturbances, which can cause blurring in optical images. These disturbances can come from reaction wheels, solar arrays, or other flexible bodies; therefore, an active layer in the design is useful for attenuating lower-frequency disturbances. Sometimes the active layer is even used for steering of the payload, as in the case of the VISS program, where the voice coil gave significant stroke capability. Using a serially configured hybrid isolator, in a local tripod, or bipod cube has many of the advantages of using an active or parallel configured hybrid isolator hexapod system, except it sacrifices the stroke capability for miniaturization potential. This sacrifice is acceptable because most precision payloads have a significantly smaller stroke requirement. A reduced stroke requirement allows the MVIS modules to use Lead Zirconate Titanate (PZT) actuators for low-frequency control in a manner similar to the voice coils on VISS, and still use passive D-Strut layers for high-frequency isolation. Honeywell's hybrid system architecture solution relies on a passive stage to attenuate frequencies above 20 Hz and an active stage to reduce the dynamic amplification at resonance, and also to reduce lower-order modes. The system is based on tripod, or bipod isolation at each attachment point of a payload, as opposed to a complete isolation platform. The advantages to such a system are readily apparent when varied sizes of payloads are considered and retrofitting is desirable. In order to allow for a precision payload to be retrofitted with a miniaturized vibration isolator, the module must be small and able to survive launch loads so as to not affect the design-cycle of the spacecraft in any way. The H-Cube module is the key to modular and efficient integration into optical payload attachment.

The MVIS baseline system is comprised of at least three isolation cubes and one central power distribution cube. The isolation cubes are based upon a two-stage design as represented in Figure 2.

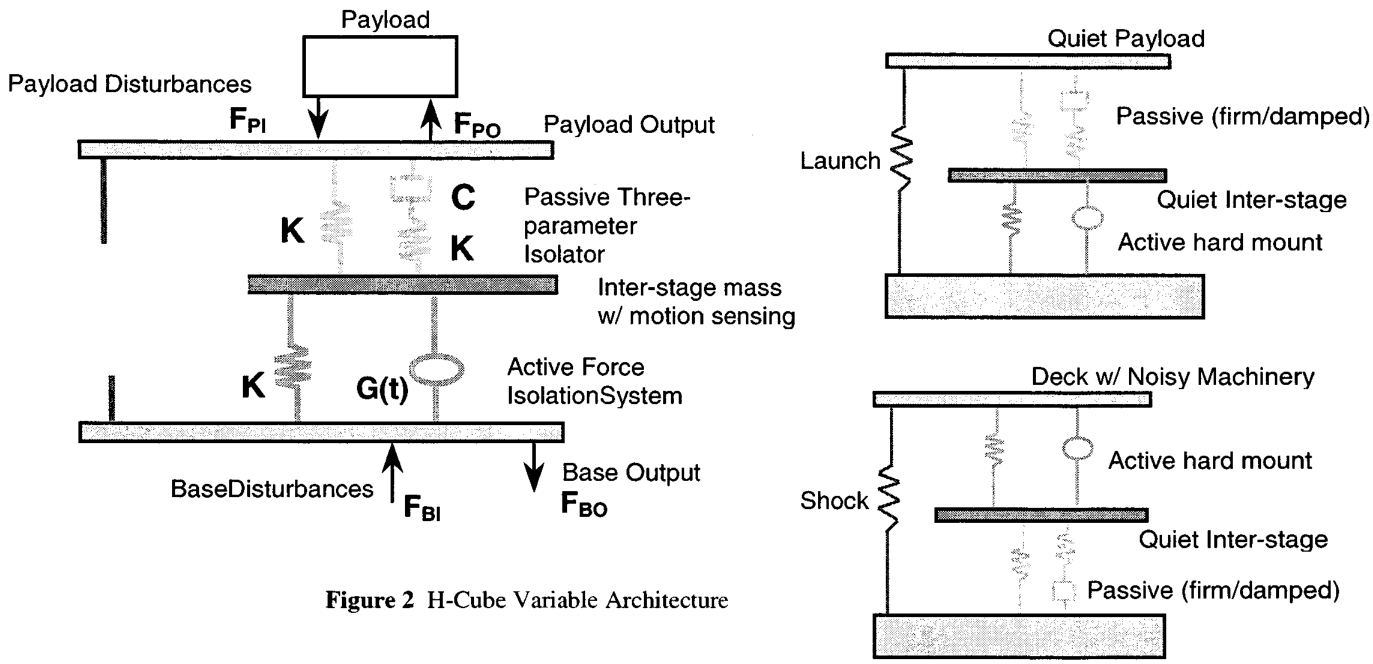

Figure 2 H-Cube Variable Architecture

The H-Cube architecture can be used in two configurations. The first configuration is for a satellite application where the primary disturbances are coming through a vibrating spacecraft bus and into the payload. The second method assumes that the disturbances are coming from noisy machinery on the payload side and progressing through the isolator to the base, as in the case of submarine decking. Both applications have similar noise and vibration attenuation goals; however, the actuation mechanisms will vary due to the large difference in disturbance loads and payload weight.

As depicted in Figure 2, base disturbances from the bus propagate through the active stage, which is represented by a spring and a time-dependent force. The active stage uses the output of the sensor on the inner stage to close the loop and suppress low-frequency disturbances of less than approximately 50 Hz. Essentially, the active stage's only mission is to keep the inner stage from moving and is not concerned with the actual motion at the payload innerface stage. Higher-frequency vibrations are propagated through the inner stage into the upper three-parameter passive stage where they are attenuated at 40 Db/decade past approximately 20 Hz. The three-parameter isolator is represented by its primary stiffness, primary damping, and secondary stiffness. These parameters can all be tuned, depending on the payload specifications and attenuation requirements. The resulting outuput force to the payload is minimized to achieve the desired performance metric. The MVIS has the ability to be used inversely as a payload or disturbance isolator, as well. Because precision payloads and gimbal motors typically have vibrating sources of their own, there can be some disturbance coming from the payload that moves into the passive stage first for attenuation prior to getting into the bus. The elegance of this design is that if all disturbances are high-frequency coming from the payload side disturbance, active stage requirements are minimal. In addition, if the active stage should ever malfunction, the passive stage will still do a good job of attenuating the higher-frequency disturbances. Any residual, low-frequency disturbances from the payload are mitigated by the active stage and the remaining disturbance (if any) is seen as an output to the base. This feature is extremely useful if the MVIS is used as a disturbance isolator where minimal vibration input to the bus is required.

During launch, the H-cube module must be locked-out in order to avoid over-stressing the passive and active components within the unit; this is accomplished via a parallel device. This device can be a simple, rigid element that is removed from the load path on orbit, or a non-linear metallic flexure, such as a Shape Memory Alloy (SMA), which can absorb the energy through its deformation. For simplicity, the MVIS program assumes a rigid launch-bumper design that will not affect the performance of the H-Cube on-orbit; however, Honeywell internal research is examining the potential of an integral device, constructed of SMA, to minimize size and weight.

Based on architecture previously described, the initial design of the H-Cube is depicted in Figure 3. The H-Cube is based on a rotated regular cube with eight quadrants, and two opposite corner faces. Actual assembly methods may differ after Phase One to ensure robustness during launch and on-orbit. The H-Cube module has four main subcomponents. The first component is the cut-off inner-face cube to the payload and/or bus. The first component will be constructed of a machined alloy for dimensional tolerance and ease of attachment. The second main subcomponent is the passive isolation stage, which is comprised of electroformed, fluid-filled bellows. This stage is assembled with the next major subcomponent, which is the integrated, active PZT stack, and the MEMS inner-stage sensor. The last primary subcomponent is the multifunctional structure housing, which must accommodate the connections for the PZT actuator, MEMS sensor, and control electronics cards.

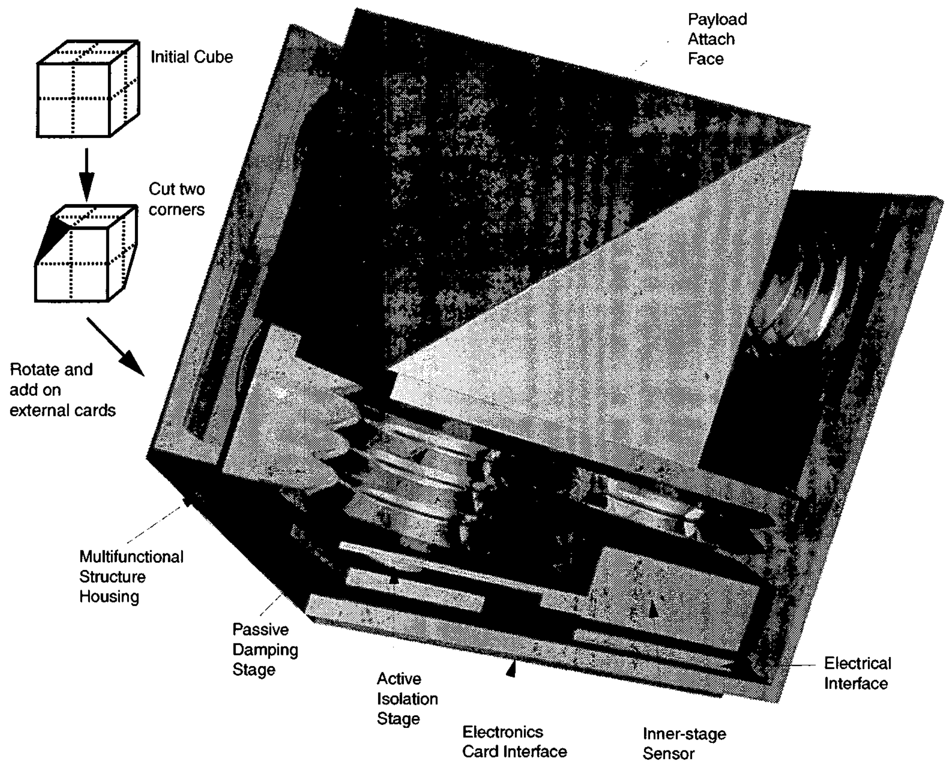

Figure 3 H-Cube Module

10. CONTROL ARCHITECTURE

The MVIS program will be based on the isolation of an optical payload similar to the Mid-Wavelength Infrared (MWIR) telescope used on the VISS program. These performance requirements will be fed into the design of the inner-stage sensor, passive stage, and active stage subsystems. The electronics design is currently baselined to make use of the AFRL-developed AIC/DS2 8-bit controller card. The power distribution cube and signal conditioner cards will be developed to work in conjunction with this controller card, if the card can handle the sensor and actuator processing requirements. If the current controller card is not capable of handling three simultaneous sensor and actuator commands over the specified control bandwidth, then additional cards can be still utilized on the cube face to increase authority. The control-law design and software development is baselined to be a local feedback scheme at the module level only; however, to allow for future growth, the control software and associated electronics will be capable for future accommodation of a global control signal coming from the central distribution cube (refer to Figure 4 a&b).

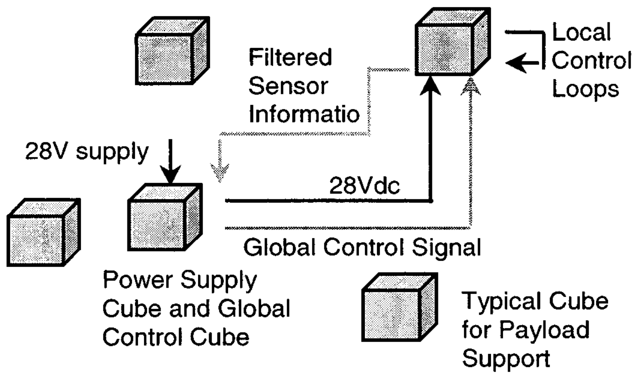

Figure 4a Basic Control Architecture for MVIS

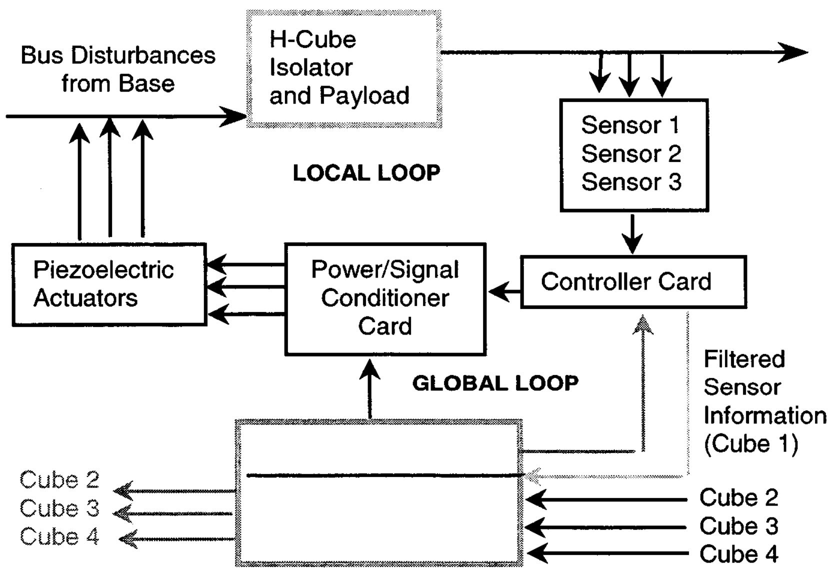

Figure 4b Basic Control Architecture for MVIS

10. Payload Specifications and Requirements

The MVIS is designed to isolate payloads in a class similar to that used on the VISS program. During that program, a 35-lb MWIR telescope was baselined as the payload. The payload shape and size is also indicative of the laser cross-link communication terminals being developed for Low Earth Orbit (LEO) commercial communication systems today; therefore, targeting this type of payload fits market trends in laser communications.

Because MVIS is designed using PZT actuators, maximum stroke of the active portion of the hybrid system is limited to displacements in the micro-inch range. Steering of the payload is not possible, as it was on VISS; conversely, large struts and voice coils are now not required. The only other size-limiting element of the VISS design was the QA-3000 class sensors, which were utilized due to their low-noise floor. For the MVIS program a size versus cost versus performance trade will be conducted to determine if the program will utilize a custom MEMS-based sensor less than 1 cm^3 as an equivalent to the QA-3000, or a less expensive more commercially available mini sensor. With these two changes, it is now possible to shrink the entire isolation system down to a cube measuring approximately 2 in. on each side (1 in flight goal). Another desirable feature of the MVIS is its ability to retrofit an existing payload that is hard-mounted to a bus by simply putting the H-Cube modules in the attachment load-path. In addition, H-Cube modules will have an expandable architecture; cubes can be added to support heavier payloads, or accommodate unique mounting schemes.

During the test and validation program phases, the MVIS will be designed and tested to reduce wideband vibrations from a spacecraft precision payload by >20 Db, for frequencies greater than 5 Hz. Most importantly, MVIS will be designed to fit within an approximate 8 in^3 volume (1 in^3 flight goal), while also being retrofittable, programmable, and tuneable in its architecture, to satisfy a certain range of payload classes. This design presents tremendous advantages for present and future precision payload isolation, especially with the advent of such systems as Teledesic and Skybridge.

10. Passive Stage Design and Test

The MVIS hybrid isolator is a combination of active PZT and passive (viscous D-strut) stages. These stages are designed to complement each other to provide both low-frequency and high-frequency vibration isolation at minimal cost. The passive isolation stage is based on the patented D-Strut design, which consists of primary bellows, secondary bellows, damping fluid, and end caps (refer to Figure 5 and 6).

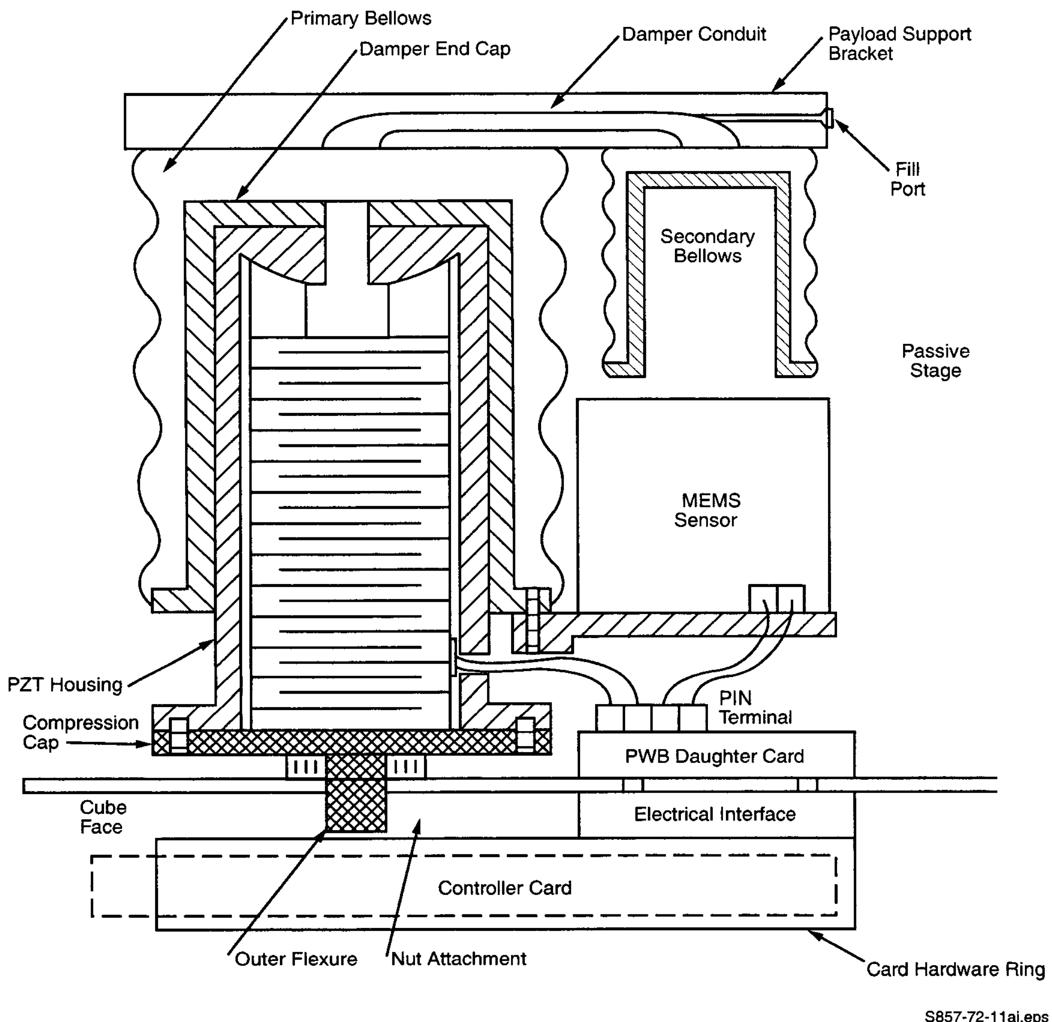

Figure 5 MVIS Passive and Active Stage Assembly

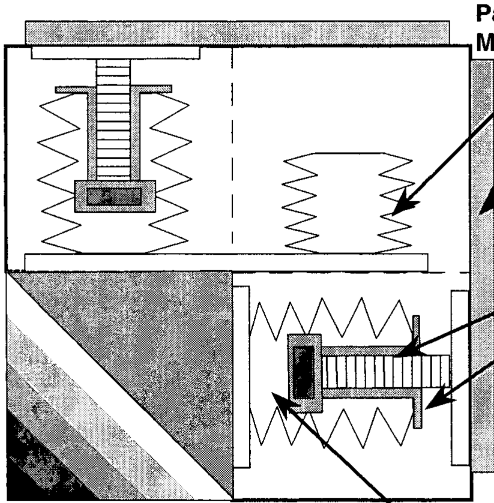

Figure 6 MVIS Quadrants

Primary bellows provide the static stiffness (KA). Dynamic stiffness is provided by the primary bellows volumetric stiffness (KB)(bellows ballooning). Primary bellows, and secondary bellows, in conjunction with end caps, also serve as the hermetically sealed fluid chambers of the damping element. It has been shown that the best performing passive isolation system is one where KA and KB are comparable in magnitude. For a softer actuator like MVIS, a considerably larger KB is needed to provide larger amounts of damping and to make the active system more robustly stable, simplifying the control design. Damping (CA) is provided by viscous fluid flow through the damping annulus from the primary bellows chamber to the secondary chamber as the actuator strokes. The secondary bellows also provides fluid thermal expansion and contraction compensation for the D-Strut. The hermetically sealed system is filled such that the fluid is under positive pressure. This preload pressure prevents fluid cavitation when the D-Strut strokes. This simple device can be designed to provide almost any combination of stiffness and damping (KA, KB, CA), thereby tuning the D-Strut to provide desired system performance.

Using the ideas developed for a three-parameter passive isolator, Honeywell has developed and utilitzed a plan of attack for passive design of the actuator. For active or passive vibration isolation systems, it can generally be stated, "the softer the better." This means the lower the system break frequency can be made, the better the isolation system performance will be. Ideally, an engineer could design the system with the break frequency around 1 Hz and isolate almost any disturbance; however, stroke and size constraints of the physical system will rarely permit this design to be implemented. Hence, the active portion of the isolator will be utilized to enhance performance at the lower frequencies, while the passive was designed to isolate above a 20 Hz break frequency.

10. Active Stage Design and Test

The actuator component of the active stage is based on a PZT stack with inner-digitated electrodes. These stacks are commercially available, with either epoxied or co-fired layers. The advantage of a PZT stack is that very small levels of power (<0.5 W) are required to produce several pounds of force. PZT actuators are used in many applications today, including fast-steering mirrors on laser cross-link terminals. The PZT actuator is packaged within a metallic frame that pre-compresses the stack in order to avoid damaging tension loads during launch, or on-orbit. During assembly of the active stage, the MEMS sensor is incorporated onto a platform that is tied directly to the external PZT housing. The motion of this platform and the PZT is the basis for the quiet inner stage illustrated in Figure 2. Both sensor and actuator are connected to a pin terminal on a Printed Wiring Board (PWB), which is affixed to the internal cube housing. This small PWB will also be wired through the housing via surface connectors to the AIC/DS2 controller card and signal conditioning cards. The bottom of the PZT stack is attached to the cube housing via a pre-load diaphragm that is free to flex when the PZT is actuated.

During operation, motion that is sensed at the inner stage is fed into the controller card, which, in turn, supplies a drive signal to the PZT actuator. The actuator pushes on the inner cap of the passive stage and flexes the primary bellows (refer to Figure 5 and 6); this, in turn, causes a low-frequency motion on the payload and any high-frequency noise in the drive signal is automatically attenuated via the passive stage. The system can be easily disassembled and is designed for ease of insertion into the passive stage. The MEMS sensor can be removed from the inner stage for replacement, or the PZT stack can be removed for repair.

10. Fabrication and Assembly

As a goal, the whole MVIS module assembly is mounted within, approximately, a 1 in. cube. The payload support bracket of the passive section is epoxied to the cube that attaches to the payload. The base support bracket is mounted to the bottom walls by way of the cap flexure, which is, in turn, mounted through holes with a nut attachment. Bottom walls serve as a stiff structural shell that also houses electronics cards. The multifunctional structure housing serves the following three purposes: 1) it provides a rigid lightweight structural tie between the tripod actuator assembly and the spacecraft; 2) it serves as a tie for the isolator electronics and the spacecraft; and #) it serves as a housing for the controller and daughter electronics cards. The cube is then bolted to the spacecraft at the bottom face, to the payload on the top face, and locked in place for launch.

A launch protection mechanism will be implemented with the oblique top face at the payload attach point. Existing designs that employ damped, passive-launch bumpers will be used to minimize the stroke of the system during launch, and to protect the internal components of MVIS modules. During on-orbit operation, the strokes will be small enough to not interfere with the launch-protection mechanism. This same design has been used for passive isolators being implemented for optical inner-satellite links on Teledesic. If a rigid launch look is required, the AIC/DS2 controller card could be utilized to pull a pin or such restraining device on orbit.

10. Approach Benefits and Applications

The space industry will see the first major applications of the MVIS technology for numerous disturbance sources upon a spacecraft bus. Some of these many disturbance sources and potential mitigation methods for spacecraft are listed in Table 1.

Table 1 Potential Mitigation Techniques

Disturbance Source on Spacecraft	Current Mitigation Technique	Potential Mitigation Technique
CMG/RWA-induced vibration	Minimized within component	MVIS connection to bus
Solar array drive motor	None	MVIS module built into motor attach points
Thermal snap	CYE mismatch minimized	Passive damping
Lightly damped structure	Passive damping	Passive damping
Gimbal-motor-induced vibration	None	MVIS module built into motor attach points
Cryocoolers	None	Local MVIS module built around cryocooler
Appendage flexibility	ACS software compensation	Add damping to antennas and equipment
Slew disturbances	ACS compensation	Quick settling of precision equipment using MVIS system

Honeywell's work on this contract concentrates on design, development, and testing of the satellite application with the goal of spinning-off the technology into other communities. A list of potential commercial and military applications is shown in Table 2, along with the various sizes of the H-Cube modules that would be required to meet the anticipated performance needs. A small-size H-Cube would be indicative of the MVIS-type system that used PZT active stages. A medium-size H-Cube module could use either larger PZT actuators or voice coils, and would be approximately three times bigger than MVIS. A large H-Cube module would be targeted for heavier loads and would use voice coils or magnetostrictive active stages; this would be used in applications where weight is not a critical design parameter. In all cases, the same hybrid passive/active and inner-stage architecture is utilized.

Table 2 Potential Commercial and Military Applications

Commercial		Military	
Application	**H-Cube Size**	**Application**	**H-Cube Size**
E-beam lithography	Small-medium	Avionics racks	Small
Electron microscopy	Small	High-speed machinery	Small-medium
Holography	Small	Optical payloads	Small
Laser-assisted deposition	Small-medium	Machinery floor isolation	Large
Laser spectroscopy	Small	RWA/CMG isolation	Small
Mask Aligners	Small	Compressor isolation	Large
Micro-lithography	Small		
Micro-machining	Small		
SEMs	Small		
Ultra-short pulse lasers	Small-medium		
Wafer-probing	Small		
Wafer-stepping	Small		
Wire-bonding	Small		
Assembly line systems	Medium		
Industrial control hardware	Medium		
Industrial packaging equipment	Medium		

10. CONCLUSIONS

Significant accomplishments in the area of PZT actuators, MEMS sensors, multi-functional structure fabrication, miniaturized programmable control electronics, and advanced control software have made the concept of a miniaturized vibration isolation system possible. The small packaging of MVIS through advanced smart materials and structures technology saves weight over conventional methods, and its ability to be retrofitted and programmed for various payload classes can dramatically reduce payload integration cost. The MVIS program will culminate in a flight demonstration in approximately 2 years. The MVIS concept will provide an entirely unique and unparalleled method for vibration isolation with numerous potential military and commercial applications.

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Keith Denoyer *is the Technical Advisor to the Spacecraft Technologies Branch at the Air Force Research Laboratory Space Vehicles Directorate, located at Kirtland AFB in Albuquerque, NM. He is responsible for directing technical activities in the areas of precision control, advanced structures, launch environment mitigation, and advanced power systems. He received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1996, an M.S. in Mechanical Engineering from Stanford University in 1992, and a B.S. in Mechanical Engineering from the University of Michigan in 1990.*