Steady As She Goes

Earthbound telescopes are bolted to mountaintops, but the orbiting ones slated for the next century will have to ride lightweight, flexible trusses.

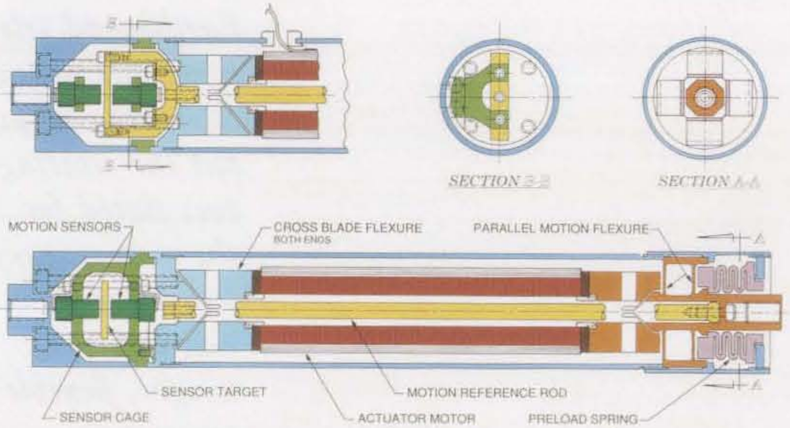
Fanson and the Lab's latest active structure. The 11-inch by 16-inch trusswork weighs 50 pounds. The test mass at the arm's end weighs 52 pounds. The whole structure is built on a 3500-pound base to eliminate outside vibrations.

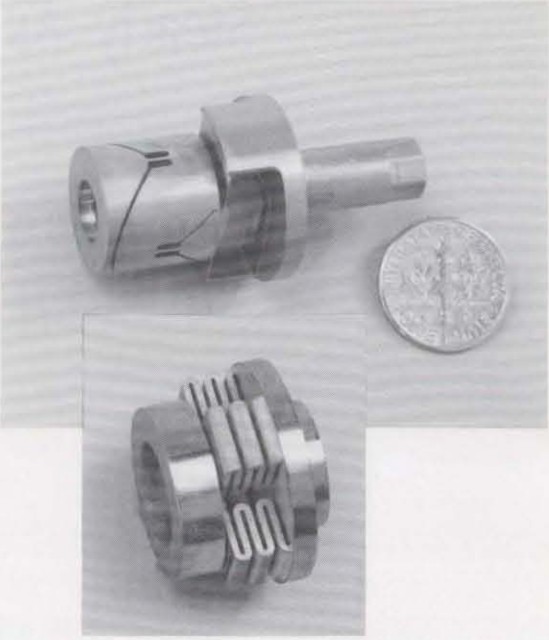
A telescope's optics must maintain position to within a small fraction of a wavelength of the light being focused, in order to produce a sharp image. Interferometers, telescopes that combine light gathered by two mirrors a fixed distance apart and measure the resulting interference patterns, are particularly sensitive to changes in the baseline distance between the two mirrors. Earthbound instruments are bolted to mountaintops, but the orbiting ones slated for the next century will have to ride lightweight, flexible trusses. Whenever on-board equipment with moving parts kicks in or cuts off, the vibration shakes the truss, setting the instruments dancing like the dangling butterflies on a baby's cribside mobile. With no air resistance to dampen the motion, it persists much longer than it would on the ground. Some items—such as the "reaction wheel," a free-spinning flywheel from which torque can be drawn to pivot the spacecraft—run constantly, giving the structure a persistent throb. How can something so inherently shaky be made rigid?

Thomas Caughey (PhD '54), professor of applied mechanics and mechanical engineering, got interested in this question in the late 1970s, as did other people. The received wisdom was that vibrations should be sensed as velocity changes and damped by attitude-control thrusters—the small jets that keep the spacecraft oriented. Unfortunately, thrusters are a prime source of bad vibes. So Caughey and then-grad student Chuen Goh (PhD '83) studied ways to use displacement information to generate damping forces within the structural members instead. Caughey and Goh showed that displacement control could dampen low-frequency flexing without starting higher-frequency vibrations that could make the structure unstable.

But how to generate the internal forces? Piezoelectric substances expand and contract very predictably when a voltage is applied to them. Robert Forward, an engineer at Hughes Research Laboratory and a noted science-fiction writer, first proposed using them in structures. (Piezoelectric quartz crystals' precise vibrations, like electronic tuning forks, are highly accurate frequency controllers essential to radios and timepieces. Other materials are almost as ubiquitous.) Piezoelectrics have no moving parts that might set up additional vibrations, and they could run off a spacecraft's solar panels.

When the time came for James Fanson (MS '82, PhD '87) to pick a thesis topic, Caughey sent him up to JPL to talk to Jay-Chung Chen (MS '64, ENG '67, PhD '72) about various control issues. Chen had heard Forward speak, and was keen to try piezoelectrics. Fanson and Caughey concurred, and so JPL's first "active structure" to use internal forces was built with money from the director's discretionary fund. The idea was apparently one whose time had come—a handful of researchers elsewhere were taking the plunge, too. Soon afterward, NASA organized a Control-Structure Interaction (CSI) program to deal with the vibration problem and other issues of spacecraft control. This program, which encompasses several NASA centers, became the eventual home for the half-dozen or so JPLers now working on active structures.





The piston's innards (above). Like a chainsaw-cut tree that's ready to topple, the "cross blade flexure" (upper right) is almost sliced through, tapering down to two thin, flexible regions—the "blades"—at right angles to each other. The blades absorb any sideways load on the piston. The "preload spring" (lower right) is really four springs in one. The machining was done in the Lab's own high-tech machine shop.

The group is on its fourth structure, a nine-foot-tall trusswork tower topped by two four-foot arms at right angles. Built of stock aluminum tubes attached to 1½-inch-diameter ball joints, it looks like it came straight from Tinkertoy heaven. This elaborate web includes eight piezoelectric pistons the size of spring-loaded toilet-paper rollers.

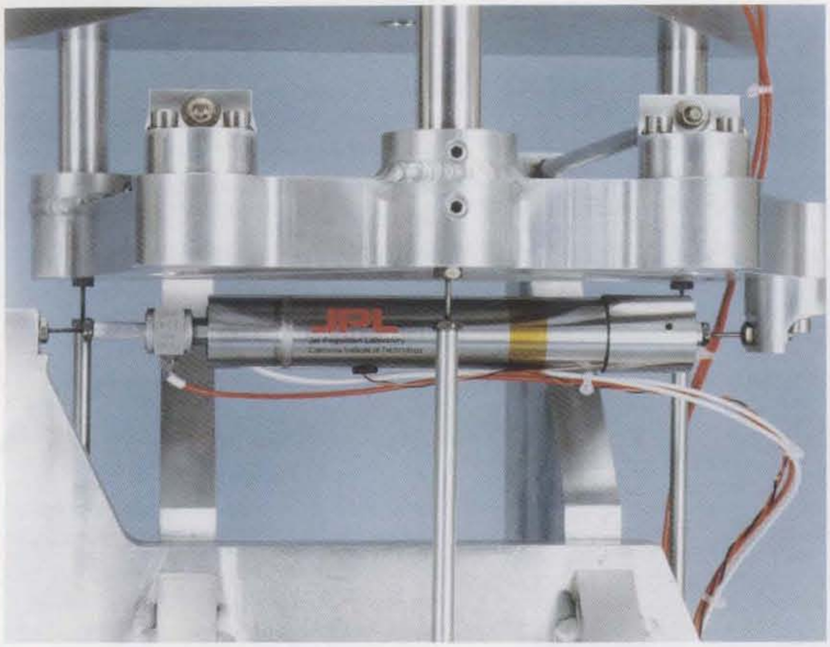
"We're trying to improve structural performance using humans as a model. Our floppy, fleshy bodies can do very precise things because of continuous feedback from our eyes, middle ears, and other sensors. We're essentially trying to put nerves and muscles onto steel skeletons," says Fanson.

The piston's muscle is a stack of lead zirconate titanate (PZT) rings, each about half the size of a Lifesaver and a millimeter thick. PZT is a standard high-performance piezoelectric ceramic—it's the buzzer in smoke detectors and digital watches, among other things. The piston has a total stroke, or expansion range, of 0.003 inches (0.076 millimeters), and its overall length can be controlled to an accuracy of a few nanometers (billionths of a meter)—about ten atomic widths. A rod from one end of the piston runs through the hole in the stack of Lifesavers and connects to a sensor that measures the motion between one end of the piston and the other, and a force sensor on the piston's fixed end tells how much load the ceramic is taking.

The piston itself is a fancy bit of machining. The parts must move freely without touching each other, because on this atomic scale of motion, the slightest bit of friction, the tiniest dead spot, the least tendency of contacts to stick and then suddenly break free—"stiction"—would be ruinous; lubrication is out of the question in the hard vacuum of space. Furthermore, ceramics are brittle, cracking when flexed, so the piston can't take forces in any direction except along its length. So each piston end has an ingenious fitting, sculpted from a titanium block, that absorbs any sideways load and yet allows axial motion. Inside the piston, soft aluminum "crush wafers" nestle the ceramic, distributing the remaining force evenly around the ring, and a four-spring unit, machined from a single block of steel, puts enough pressure on the assembly to keep everything together.

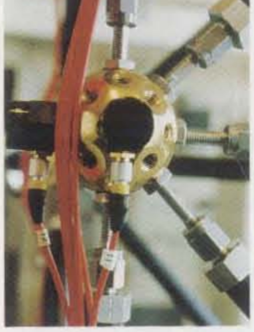
While the muscles are piezoelectric pistons, the nerves are wires connecting a central controller to sensors scattered throughout the structure. Just knowing what's going on at the piston isn't sufficient—you have to know what the whole structure is doing, just as your brain has to know what your legs are up to as well as your arms when you catch a ball. The piston might be near a boom's base for efficiency's sake, because a small motion there translates to a larger movement at the free end, but it's the free end that you want to keep stable.

Associate Professor of Electrical Engineering John Doyle's group has been working with the CSI group to design the algorithms that will constitute the controller. The basic issue is: how do you close the feedback loop between a piston and a sensor some distance away when there's a lot of flex in the framework between them? If the feedback starts going the wrong way, even



"We're essentially trying to put nerves and muscles onto steel skeletons."

Above: The isolation plate and its active member.
Below: Even the ball joints get wired with position sensors.



by just a little bit, it can rapidly amplify the vibrations, and the truss can shake itself apart. But any controller is based on some mathematical representation, or model, of the system—masses, lengths, stiffnesses, and so forth—that will necessarily be incomplete. You need to develop a "robust" controller, unfazed by small behavioral differences between the model and the real thing. The trick, according to Doyle, is to put these uncertainties into the model as explicitly bounded differences. For example, if the model pictures a long, thin boom as a one-dimensional line, then some part of the system has to know that the boom *does* have a thickness, and under what circumstances—high-frequency vibrations, in this case—that thickness matters. "Engineers have developed intuition about the uncertainties in their models," Doyle says. "But as something becomes more complex, the effect of a particular action becomes less obvious, as do the consequences of modeling uncertainty. We're trying to develop a set of mathematical tools that will help engineers expand their intuition. The tools apply to any feedback-based control system, from flying an airplane to chemical processing."

The controller must be able to handle a wide frequency range. Every structure has a set of frequencies at which it vibrates naturally. Overtones of the basic resonances proliferate at higher frequencies. And as structures get larger, they begin to resonate at lower and lower frequencies. When the resonant frequencies creep down into the region where the attitude-control thrusters operate, the problem becomes very serious indeed. Mariner 10, launched to Venus and Mercury in 1973, was nearly lost when its solar panels and low-gain-antenna boom began to flex in resonance with the thrusters, according to William Layman, JPL's CSI task manager. The controller interpreted the motion as an attitude change and kept firing the thrusters to compensate, putting the spacecraft into a stable oscillation. Half of the attitude-control propellant was blown before Mission Control could find and fix the problem.

The CSI program is using the proposed Orbiting Stellar Interferometer (OSI) as a test case to identify the problems that need to be solved, and then to develop and apply the relevant technology. The tower is part of that study, incorporating a laser interferometer and three layers of active control. The first is the active members in the truss, of course. The second is a mounting to which a vibrationally noisy component is bolted, and which is attached to the truss with an active isolation system. And the third is an "optical delay line"—an active mounting for the interferometer optics that nudges them a fraction of a wavelength to keep the interferometers precisely separated—based on a design that OSI's principal investigator, JPL's Michael Shao, developed for ground-based use. (Keeping the pieces of a segmented mirror, such as the Keck telescope's, in position falls into the same category. The Keck has mechanical pistons for the job.) The group will start experiments with the active components soon. Right now they're shaking the truss over a wide range of frequencies to find its natural resonances.□—*DS*