USING SPACE WISELY

BY KIMM FESENMAIER

When you first enter the Space Structures Laboratory in the Guggenheim building, you can't help but be struck by the diversity of models—some suspended from the ceiling, some displayed like museum artifacts behind glass, some just laid out on tables. There are those that look like intricately folded origami creations, those that resemble oversized, metallic Chinese finger traps, and others—like the 4-meter-diameter model of NASA's superpressure balloon—that look as if they came straight out of some fantastical toy store.

Welcome to Sergio Pellegrino's lab, the place where the structural engineer and his postdocs and graduate students build and test all sorts of lightweight, shape-transforming structures, and where they study the relationship between structural form, stability, and ability to package and deploy into a required configuration. As different as they may look, however, these structures share at least one key trait: all of the models represent studies of how objects *fill* space, and most are designed for applications *in* space.

"The goal for much of my work," says Pellegrino, "is to make simpler and cheaper spacecraft. I want to use clever structural engineering to make access to space more affordable."

In that vein, one of Pellegrino's most ambitious projects focuses on an idea he and his colleagues first started contemplating several years ago: how to more easily build large or very large space telescopes at a lower cost than has been possible.

To understand the idea, you need to first recognize that the heart of any space telescope is its primary mirror—and that the larger the mirror is, the more photons it can collect and focus, and the farther into the cosmos it can help astronomers see. That's why astronomers would like to launch telescopes into space with enormous mirrors—mirrors larger even than the record-breaking 6.5-meter-diameter one on the James Webb Space Telescope (JWST), which is currently being built for launch in 2018.

It's quite challenging to build and integrate flawless mirrors on such a scale, however. Plus, a given launch vehicle can carry only so much cargo, in terms of both volume and mass. Take the JWST. In order to fit the spacecraft within the Ariane 5 rocket scheduled to lift it into orbit, the telescope's mirror is constructed in a segmented fashion out of lightweight beryllium, with sides that fold down and lock in place for launch and extend once in space. But even with such a design, its full 6.5-meter span is at the upper limit of what is possible with today's technologies and launch vehicles.

That's why, Pellegrino says, a new approach is needed—an approach that moves most of the telescope-assembling from Earth to the scope's ultimate destination. "We are trying to demonstrate the paradigm of assembling telescopes in space," he says.

"We" is a team of engineers and scientists that includes program area manager John Baker of the Jet Propulsion Laboratory (JPL), who joined this new effort in 2010. The team has become convinced that a different approach is needed to build the giant space telescope of the future. They envision launching a number of identical spacecraft, each bearing its own mirror segment and each having the ability to maneuver independently. Once in space, those smaller vehicles could use thrusters to reconfigure and position themselves so that they dock and become mechanically interconnected to form a giant mosaic mirror.

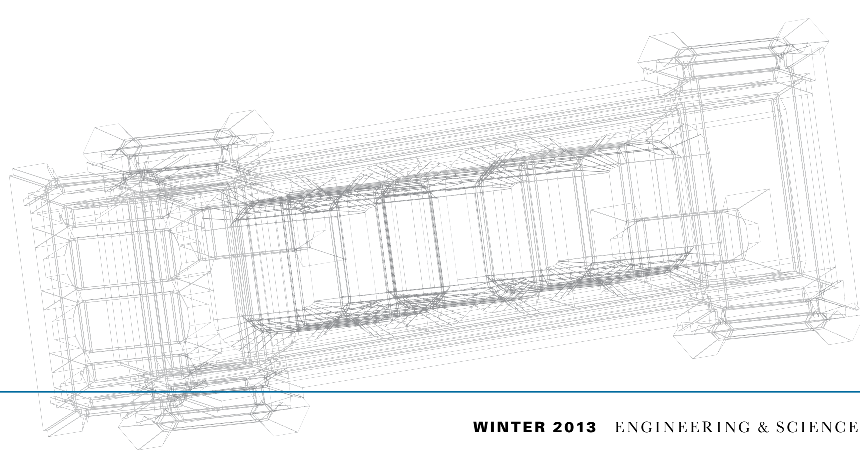
Aside from making it possible to get ever-larger mirrors into space, team members say, this strategy would also allow a damaged mirror segment or part simply to be plucked out of the configuration and swapped for a new one. Plus, the diameter of the mirror could be expanded as funding and additional launches became available.

"There's a whole history that says if you're going to build a large telescope in space, the cost will be a function of the weight of the mirror," says Baker. "But with this alternative approach, we would have the ability to actually fly very lightweight, low-cost mirrors. We could, in theory, end up building really large telescopes for a lot less money."

Before anyone is going to fund or undertake a full-blown mission using this new approach, however, someone needs to prove that the technological pieces of the concept are feasible on a smaller scale. Pellegrino, along with his colleagues and students, intends to be that someone.

"We want to show a path so that others can get inspired and go from there," Pellegrino says. "That's my goal. We will say, 'Here is a concept

Left to right: Sergio Pellegrino, Manan Arya, Keith Patterson, and John Steeves discuss the design of various test hardware, like the docking test robot and the deformable mirrors, and models for AAReST in Pellegrino's lab.



A rendering of AAReST shows the black backdrop behind the CubeSats, which will open into a sunshade, while the black boom, folded around the spacecraft for launch, will deploy out straight, as shown, holding the telescope sensors and camera (shown in gold to represent multilayer insulation).

that you might want to start from. By all means, go and make it better.'"

AN AARESTING IDEA

Pellegrino and his team have been working on just such a technology-demonstration mission, a project called AAReST—Autonomous Assembly of a Reconfigurable Space Telescope. It's not a NASA mission. Think much smaller. To date, it's an effort that has been funded largely by Caltech's Keck Institute for Space Studies (KISS), Division of Engineering and Applied Science, and Innovation in Education Fund.

Despite the mission's modest budget, it has some rather ambitious goals. The plan is to launch several individual spacecraft all bundled together and command them to separate from one another in orbit before independently repositioning themselves. Then those smaller vehicles will have to dock back together in a wholly new configuration—one that creates a wider mirror. And, finally, since the individual mirrors will be made identical to one another, they will need to be adjusted while in orbit to create one focused, coherent image. Therefore, the mission also needs to demonstrate a feasible technology for actively deforming and controlling the shape of these lightweight mirrors.

As currently envisioned, AAReST will begin its journey as a compact cluster of three nanosatellites—two 3U CubeSats attached to a 9U CubeSat. CubeSats are small, standardized spacecraft that have been used over the past decade for various educational missions. A 1U CubeSat is a standard box 10 by 10 by 10 centimeters in size. The whole cluster can be stowed in a launch vehicle in a configuration that would take up no more space than a minifridge. This should allow the mission to limit costs by piggybacking as a launch vehicle's secondary payload.

Ten-centimeter deformable mirrors will sit one atop each of the two 3U CubeSats; additional rigid glass mirrors will sit on the 9U CubeSat. Once in space, the 9U CubeSat will extend a hinged, carbon-fiber boom carrying the telescope's instrumentation package—including a camera, corrective optics, and a mirror shape sensor—away from and above the rest of the CubeSats. These instruments will then help correct the shape and focus of the deformable mirrors.

From its new position on high, the camera will snap photographs of the stars and other objects that the mosaicked mirror brings into view, showing that the four mirrors, getting feedback from the sensor package, are capable of correcting their own shape and improving the quality of captured images.

In a grand finale of sorts, the two 3U CubeSats will detach from the rest of the spacecraft and usegas propulsion systems to reposition themselves atthe sides of the 9U CubeSat. Once complete, that partial do-si-do will have created one extended mirror; the telescope then will recalibrate itself to adjust to the new configuration, making any needed adjustments to the mirrors before taking new images.

Sound like a lot to demonstrate with one small mission? Baker thought so too. “The thing that was most intriguing to me about AAReST was that it didn’t look possible at first,” he says. “Creating an adaptive optics element at pretty low cost and then actually using it on a very small spacecraft to test it out? Both of those things seemed pretty impossible.”

NEVER UNDERESTIMATE CALTECH STUDENTS

What might also have seemed impossible to Baker was that much of the work on this most difficult and innovative of projects would end up being done by a talented and dedicated group of students. That’s right … students.

Around 2010, following two KISS studies that looked into the idea of self-assembling space telescopes, including those with large primary mirrors, Pellegrino recognized that there was a real opportunity to incorporate an educational component into the mission that he was beginning to envision.

The result is that, in addition to its technological goals, AAReST has an important educational objective: to help train new aerospace engineers by giving them hands-on experience working out the details of an actual space mission. As a result, today’s AAReST team is made up almost entirely of Caltech students and postdocs joined and guided by Pellegrino, Baker, and Caltech instructors. Professors Craig Underwood and Vaios Lappas from the University of Surrey in England complete the team.

Pellegrino has even incorporated the mission into the curriculum of Ae 105—Aerospace Engineering—a graduate-level course. Over each of the past three years, students in the class have spent the second half of their academic year working on various aspects of the AAReST mission—improving the design of the telescope and its components, producing and testing prototypes, and otherwise refining the mission. Last year’s class conducted a detailed thermal analysis of the telescope’s components, determined how to arrange the mirrors after launch to ensure that the telescope would be able to image its target star (which will most likely be Sirius), evaluated the detailed design of the lenses in the optical system, and used physical and computer models to measure the small disturbances that would be created by a reaction wheel—which would control the direction of the spacecraft without the use of fuel-consuming rockets—provided by the University of Surrey for stabilizing the telescope’s orientation.

“Unlike a typical space mission, it has been our main objective to involve students, to teach classes, and to have students build the spacecraft and to do it openly so that *every* student can participate,” Pellegrino says.

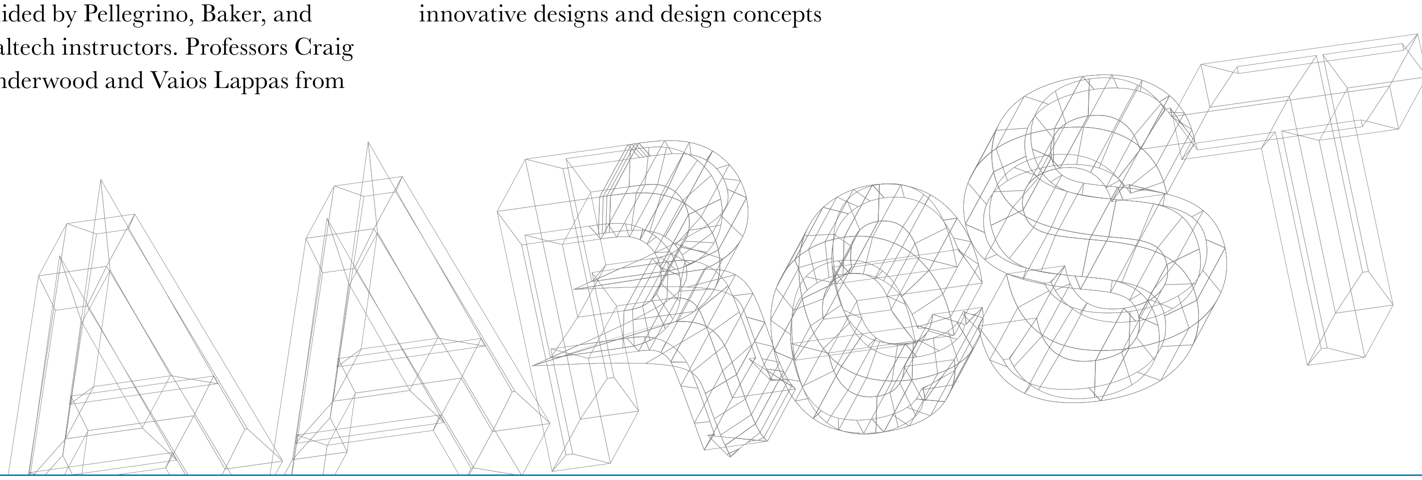
The team is currently on target for a 2015 launch of AAReST, although they’re not sure exactly which rocket will take the telescope up into space. Logistics aside, Baker says, the design is looking better all the time. “We have innovative designs and design concepts for the camera, the mirror elements, and the boom,” he says. “And the students have done all of the design, all of the thermal analysis, all of the shading and baffling, the covers, and the electronics. It’s quite impressive.”

This early prototype of a deformable mirror was used by researchers to test the concept of AAReST.

MIRROR

MIRROR, MIRROR

Among those impressive students is Keith Patterson, a graduate student who has been working on AAReST since its earliest days. Despite having been fascinated by space since childhood, Patterson says he “knew nothing about mirrors, adaptive optics, or any of this stuff” when Pellegrino first mentioned needing help on a project that would involve developing thin, lightweight mirrors for a potential space mission. Still, Patterson jumped in without hesitation. “I’m pretty much open to working on anything as long as it has to do with space,” he laughs.



Today, Patterson knows plenty about mirrors—he's one of the leads in the development of the novel technology behind AAReST's small deformable mirrors—as well as about the ins and outs of the mission. He's been a teaching assistant for Ae 105 several times and spends about half his time in JPL's Microdevices Lab clean-room facilities, designing and fabricating and then refining mirror concepts with the help of his mentor, Risaku Toda of JPL.

The first ultrathin mirrors Patterson and his colleagues developed were made of silicon wafers coated with a reflective material. More recently, however, they've switched away from silicon and are developing a technique for using glass wafers instead, since glass is softer and can therefore take on a curved shape more easily. All the mirrors, being less than 0.3 millimeters thick, are quite lightweight.

Behind the wafer—be it silicon or glass—the engineers deposit alternating layers of metal electrodes and piezoelectric polymers, which are materials that will deform when an external electric field is applied. These electrodes allow the researchers to apply different voltages to specific points on the mirror, altering its curvature in just the right spots. By patterning the electrodes in different ways—forming a series of concentric circles, a triangular lattice, or, most recently, a floral pattern called "the Notre Dame"—the researchers can create mirrors that have the ability to be adjusted precisely as needed to produce the best images possible.

"When I first started working with Sergio, basically all I knew was that there was going to be a project on thin mirrors," Patterson said. "To start from something so vague and then try a bunch of things and find that sweet spot where something actually works … and *then* to have the potential for these things to actually fly and be demonstrated in space … that is pretty exciting."

APPLICATIONS BACK ON EARTH

As the AAReST mission has progressed, aspects of the work have overlapped with and inspired separate but related projects in Pellegrino's lab. The small mirrors that will top the CubeSats, for example, motivated other students to consider using similar techniques to make much larger lightweight mirrors.

"The mirrors in a telescope are the most difficult mirrors to make because they have to be so precise," Pellegrino says. "We thought, Why don't we try to develop some bigger mirrors for an application that isn't as demanding but actually needs big solar-collecting surfaces? So we started looking at solar concentrators—lenses that focus sunlight to collect heat."

With funding from the Resnick Institute and the Dow Bridge Innovation Fund, the Pellegrino group's pursuit of this line of research has led to the production of large, more-durable carbon mirrors for solar concentrators.

"We are doing work on some rather fundamental research while we work on the AAReST mission," says Pellegrino. "In fact, we often get inspiration from AAReST's problems to try out new things in the lab. It's interesting and exciting that our technology-demonstration mission can also inspire our research." e&s

John Baker is program area manager of the Human and Robotic Mission Systems Architecture Office and also the Planetary SmallSat lead at JPL.

Sergio Pellegrino is the Joyce and Kent Kresa Professor of Aeronautics and professor of civil engineering at Caltech. He is also a senior research scientist at JPL.

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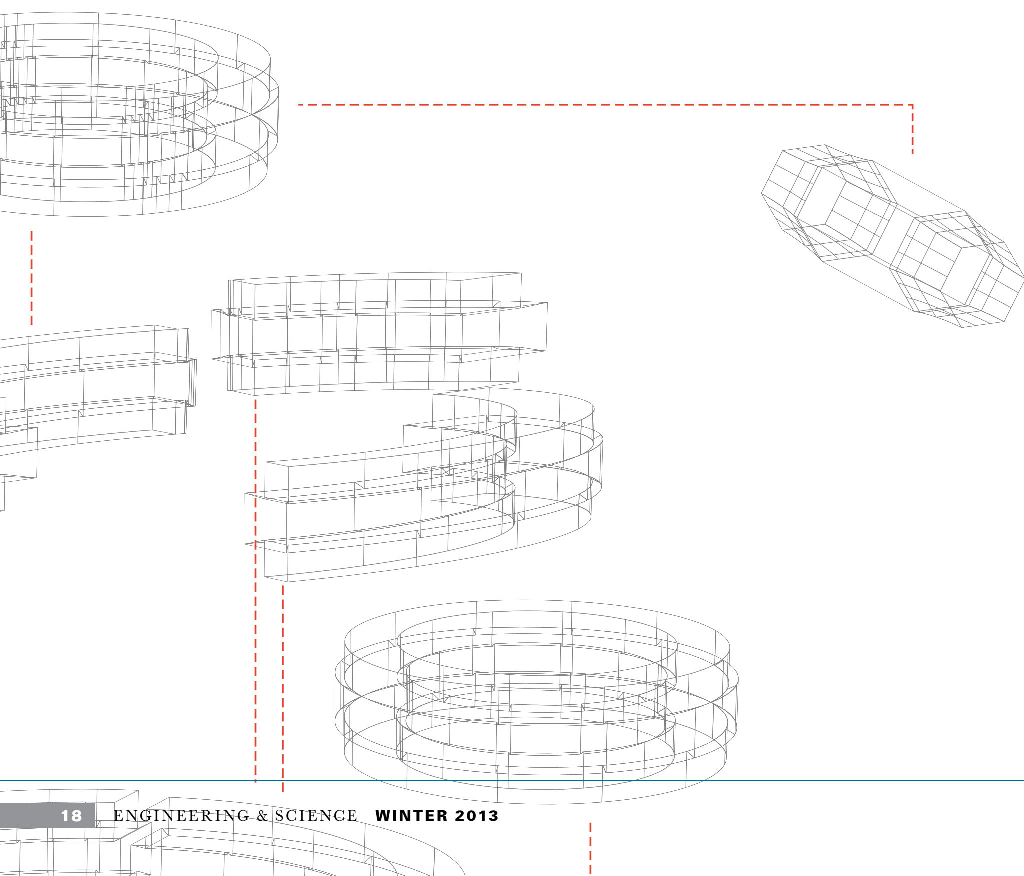

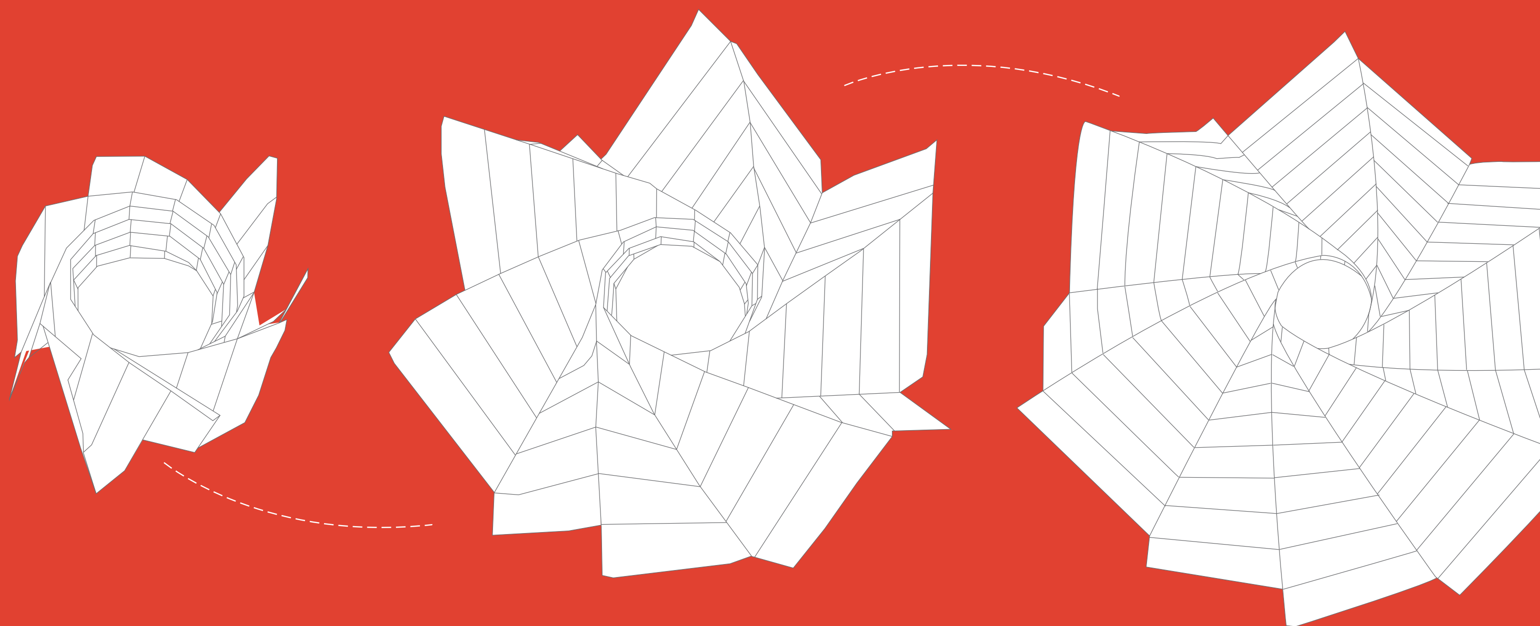

You can hear small crackling sounds echo—pop, pop, pop—in the Pellegrino lab as graduate student Manan Arya pulls two corners of a shiny silver sheet of Mylar in opposite directions. Ideally, the intricately folded sheet in his hands would unfurl without a sound. But there's still work to be done before those pesky little pops will be silenced. Arya is tinkering with the design for a new solar sail—an extremely lightweight reflective sheet that would be propelled through space by the force of photons hitting it as they stream away from the sun. Solar sails are nothing new, and the idea behind them is simple: if you can extend a large enough sail in such a way that it is always getting pushed even just slightly by the sun's light, it—and anything attached to it—will eventually pick up momentum and ultimately travel at exceedingly high speeds.

"I believe it's the only viable way we have right now for properly exploring the solar system and places outside the solar system," Arya says.

His inspiration comes from a Japanese experimental spacecraft called IKAROS, which successfully deployed the first functioning solar sail in space in 2010. Rather than attempting, as others have, to deploy booms that could guide the unfurling of segmented sails, the IKAROS team used centrifugal force, simply spinning the spacecraft to unwrap one large sail.

"They went a completely different route and surprised everybody," Arya says. "Without supporting structures, the spacecraft as a whole becomes much lighter, which means it can accelerate faster and get to destinations faster."

Currently, Arya is thinking along those same lines while trying to devise an even better way to package a sail so that it can be even larger while still deploying seamlessly; such a sail, he says, might carry a more capable spacecraft into the farthest reaches of the solar system.

"I like the fact that there is exactly one problem here and that it's something I can contribute to," Arya says. "The problem is: how do you package something that's very large into a small space? That's it. Once it's large enough and light enough, it will fly."

For now, Arya is experimenting with miniature sails to see how they behave when they are folded in different patterns and when they have different sizes and thicknesses. Over the summer, Caltech alumnus Robert Lang (BS '82, PhD '86), one of the world's leading origami experts, stopped by the Space Structures Laboratory to chat with Arya about his work and what he might try next.

Still, there are some difficulties to overcome before the sail can set sail. "Different folding patterns behave very differently," Arya says. "The problem with my current models is that there is definitely strain—a real problem for the sail's ability to function properly—while they are being deployed. You know about the strain because of the popping sounds. You could do complicated measurements and look at the forces jumping around. But you can also just hear it by the pops."