Satellite Hardware: Stow-and-Go for Space Travel

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Man-made satellites have to fit a lot into a compact package. Protected inside a rocket while blasted through the atmosphere, a satellite is launched into Earth orbit, or beyond, to continue its unmanned mission alone. It uses gyroscopes, altitude thrusters, and magnets to regulate sun exposure and stay pointed in the right direction. Once stable, the satellite depends on solar panels to recharge its internal batteries, mirrors, and lenses for data capture, and antennas for communication back to Earth. Whether it is a *bread-loaf*-sized nano, or the schoolbus-sized Hubble Telescope, every satellite is susceptible to static electricity buildup from solar wind, the very cold temperatures the Earth's shadow (or deep space), and tiny asteroids along the route.

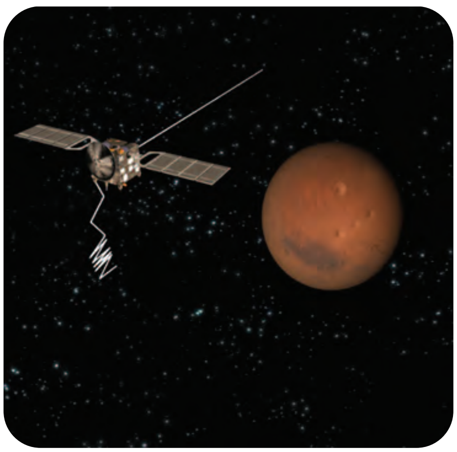


Fig. 1 — *MARSIS satellite nearing Mars, showing one composite antenna boom already deployed and a second boom in the process of unfolding. Courtesy of European Space Agency.*

In such a hazardous environment, the functional longevity of the average satellite is limited. While more than 2000 satellites are estimated to be in Earth orbit at any one time, the countries and private enterprises that own them must keep sending up replacements at a high cost. As a result, aerospace engineers continually strive to develop smaller, lighter satellites that are less expensive to make, and less expensive as rocket payloads, and still capable of meeting their application requirements.

Fig. 2 — *Deployable inflatable boom test carried out in mid-air over the Atlantic Ocean in an Airbus A300 ZERO-G aircraft by a team from Institute of Composite Structures and Adaptive Systems at the German Aerospace Center (DLR), Stüttgart.*

Unfolding satellite hardware

The size of critical hardware like solar sails, solar concentrators, and reflector antennas is limited to some degree by the weight and stowage capacity of each satellite. But to function properly, much of this hardware needs to expand outside the confines of the spacecraft that carries it. The engineering solution is to design deployable structures that unfold once the satellite is in position. This allows compacting a big piece of hardware into a small configuration for transportation, then expanded to operational size in space.

Many satellites accomplish this important task using motors and gears for mechanical deployment of their hardware, but other designs rely on self-deployment instead, using energy stored within the hardware itself during compaction. To illustrate, imagine folding a plastic drinking straw repeatedly into a small, zigzagged cluster, then letting go so it springs back into a straight line. This kind of release action happens without the additional mass and power source that are required for mechanically deployed booms.

Self-deployable booms, made of flexible composites, were used for the antennas on MARSIS, the European Space Agency's Mars Express Spacecraft (Fig. 1), and are currently being designed into a number of future satellite missions. The booms are lightweight, easily folded, less expensive, and fairly insensitive to friction compared to traditional motorized designs.

Modeling complex behavior in zero gravity

Structures of this type have been proposed for decades, but their behavior (highly nonlinear geometric deformation, buckling, dynamic snapping, etc.) was difficult to quantify and predict. As a result, earlier boom components were usually refined through repeated, costly physical experiments (including ones conducted during the 22 seconds of weightlessness generated in a plunging test aircraft (Fig. 2).

"But now we can accurately portray these features using realistic simulation," says Chinthaka Mallikarachchi, a postdoctoral scholar working with Prof. Sergio Pellegrino at

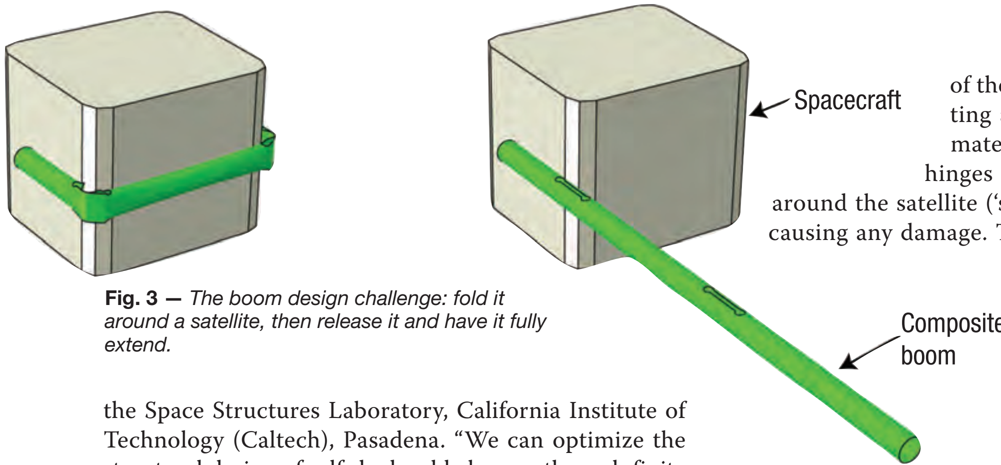


Fig. 3 — *The boom design challenge: fold it around a satellite, then release it and have it fully extend.*

the Space Structures Laboratory, California Institute of Technology (Caltech), Pasadena. "We can optimize the structural design of self-deployable booms through finite element simulations and conduct physical tests only on our final designs. Since ground testing on Earth of structures that are going to be deployed in the zero-gravity vacuum of space is either difficult or very expensive, such virtual testing is the answer to a lot of the challenges we face."

Mallikarachchi's work over the past several years—on the simulation of a carbon-fiber-reinforced boom that can be folded around a spacecraft—was carried out almost exclusively using Abaqus Unified FEA from SIMULIA, Dassault Systèmes brand for realistic simulation (Vélizy-Villacoublay, France; www.3ds.com). "SIMULIA's academic package has been quite helpful to us in conducting this kind of research," he says. "We used the meshing and visualization features in Abaqus/CAE. The Abaqus/Explicit solver is the most important feature for us since it accurately captures all the complexities of our boom designs. And the general contact, shell general section, equation constraint, and restart features were very user-friendly, as were the availability of python scripting and keywords for input files."

The modeled boom was a 1-m long, thin-walled (0.22 mm) tube (38 mm diameter) made of two plies of plain-weave carbon fiber in an epoxy matrix. Certain regions of the tube were weakened by cutting away some of the composite material to form tape-spring hinges so the tube could be folded around the satellite ('spacecraft' in Fig. 3) without causing any damage. Three possible hinge designs with different slot parameters were considered. The FE mesh was made finer over the hinge regions to capture the details of the complex deformation occurring in these regions.

Abaqus supports years of research challenges

Early research used micromechanical modeling to capture the behavior of the boom's thin laminate material through homogenization of a periodic unit cell (with Abaqus/Standard). From this, the material stiffness was computed in the form of a matrix and used to define the shell elements in the Abaqus/Explicit simulations of the quasi-static folding and dynamic deployment. The numerical simulations were then integrated with a material failure criterion. The combination of these tools (Fig. 4) allowed an analysis of the detailed effects of hinge design changes on three different boom models, which led to identifying the design that could be most safely folded and deployed.

Modeling the boom deployment involved first pinching the hinges to fold the boom around the spacecraft, then releasing all constraints so the boom dynamically deployed and self-latched. "This behavior needed to be fully understood and optimized, since overshooting at the end of deployment could damage the boom, the spacecraft, and other equipment attached to it," says Mallikarachchi. "Alternatively, a too-slow, highly damped deployment might never achieve the fully expanded configuration that's needed."

Project test launch: simulation versus reality

During FEA simulations, the first boom design overshot the fully deployed configuration and was rejected. When the failure analysis and hinge angle were optimized against the time response (full deployment occurred in about 0.3 seconds), Design III performed better than Design II. Using the simulation data, the team built and tested a boom according to Design III specs, filming the results from two different camera angles. Side-by-side motion comparisons of Abaqus FEA and boom deployment (Fig. 5) confirmed that the real boom also deployed in 0.3 seconds, became fully latched, and then

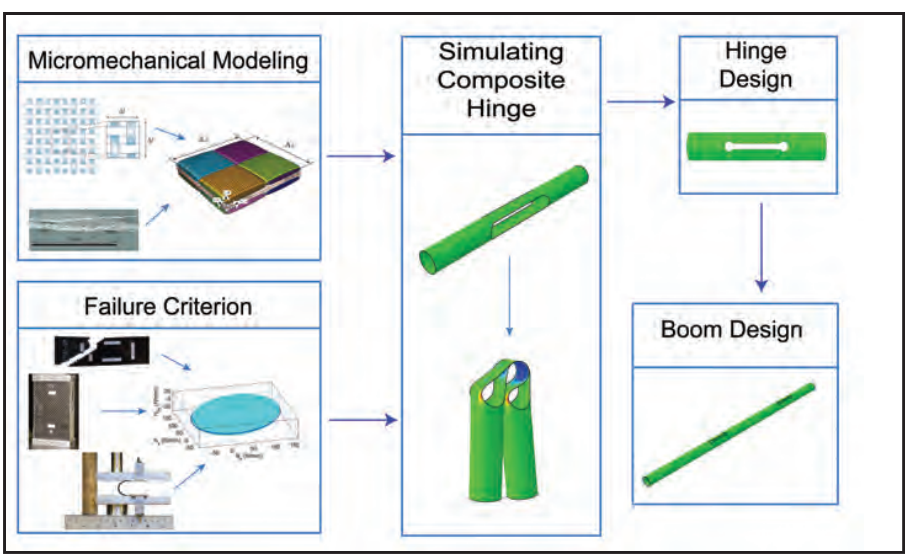
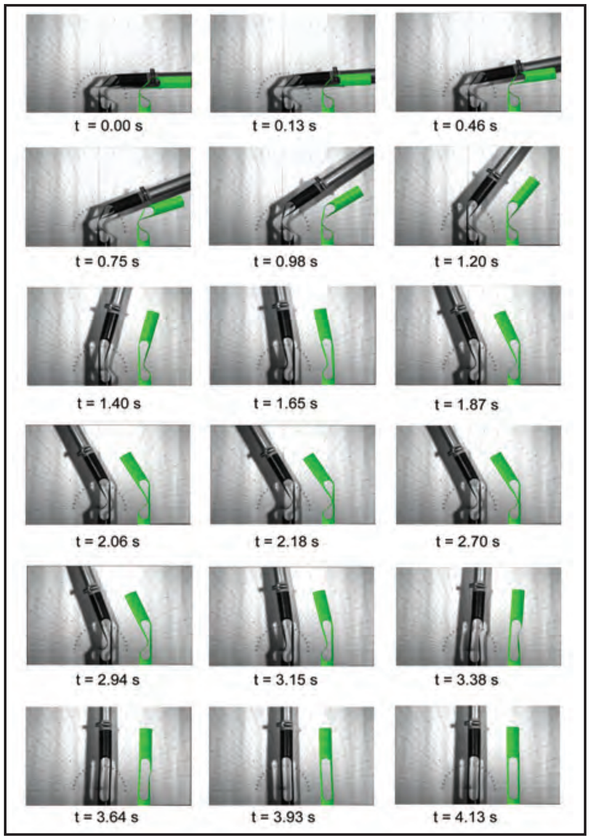


Fig. 4 — *Summary of several years of Caltech research, using Abaqus FEA, to develop a deployable composite boom for satellite hardware deployment.*

Fig. 5 — *Side-by-side images of boom test and Abaqus FEA model demonstrate the accuracy of the simulation (video available at www.asminternational.org/portal/site/www/news/videos/).*



oscillated around the deployed configuration in excellent agreement with the simulation.

"Our studies showed that the most critical points are the fully folded configuration and, during deployment, the point at which the second hinge latches, affecting the load on the root hinge," says Mallikarachchi. "The hinge transition region between the straight and curved part of the slot experiences the most stress/strain, so special care should be given to this area during fabrication of this kind of boom."

The team's validation of the boom design paves the way for further exploration of satellite hardware deployment. "Our simulation techniques can be used to design deployable booms with multiple hinges and optimized boom geometry to meet any specific mission requirements," says Mallikarachchi. "Future work could consider alternate laminates and thermal and viscoelastic effects in different materials," he concludes. ❍

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