



## Transformers: Shape-Changing Space Systems Built With Robotic Textiles

**These easy-to-fabricate textiles can be used in robotics and smart habitats/shelters.**

*NASA's Jet Propulsion Laboratory, Pasadena, California*

Prior approaches to transformer-like robots had only very limited success. They suffer from lack of reliability, ability to integrate large surfaces, and very modest change in overall shape. Robots can now be built from two-dimensional (2D) layers of robotic fabric. This expands on ideas of electronic fabrics for electronic textiles, and incorporates sensors, actuators, power, and communications. The 2D solution is easier/cheaper to fabricate, packs more compactly, and ensures a wider range of shape change than 3D modules.

These transformers, a new kind of robotic space system, are dramatically different from current systems in at least two ways. First, the entire transformer is built from a single, thin sheet; a flexible layer of a robotic fabric (ro-fabric); or robotic textile (ro-textile). The ro-textile would be produced as a gossamer-thin ( $\approx 100 \mu\text{m}$ ) and light flexible layer, survivable to extreme environments. Along its large surface, the ro-fabric would be partitioned into modular cells. Each cell would include, distributed within this skin-like thin layer, all the structures for spacecraft/robotic subsystems, including propulsion and power (solar), avionics and controls, sensing, actuation (e.g., shape-memory alloys), and communication (circuits and antennas).

Second, the ro-textile layer is foldable to small volume and self-unfolding to adapt shape and function to mission phases. Tightly folded at launch, it would self-unfold to take the shape/function needed by the mission target, and then again transform its shape as needed. For dramatic changes, one can speculate it could morph between a large solar sail for interplanetary interstellar travel, its component patches could separate in swarms of winged flyers in atmosphere, or it could take shape as a limbed robot capable of surface mobility and sample manipulation.

Some 3D payloads may still be needed, e.g., some special instruments that cannot be integrated as 2D structures; these would be carried as payloads in kernels around which the 2D layer would fold. Proper partitioning of the ro-fabric sheet would allow shaping of practically any 3D shape, as insured by various mathematical proofs. Flexible layers would provide further freedom for modification of shape at sub-cell resolution.

The surface of ro-fabrics is composed of connected (zipped) multi-cell patches that can separate to operate in formations; these may be all the same or specialized (e.g., one with more sensing circuitry). Each cell would normally embed

the circuits of all subsystems (electronics/computing, propulsion, and power photo-elements/imaging cells, actuators, conductors for antennas, etc.).

A cell-based architecture fits well with modular, reconfigurable electronics, based on field programmable (FP) arrays, or in general on distributed computing/electronics. From computational perspective, each (cm-size) cell of the ro-textile could be a basic computational element — a single FPGA (field programmable gate array)/FPAA (FP gate/analog array) mixed cell, a cluster of cells, or a large-density array of FP cells (the low density may be suitable for non-silicon materials that may be preferable for reasons other than high integration). The ro-textile would be built with materials that survive to extreme environments without insulation or thermal control.

In summary, this concept may be a solution to faster, cheaper, and lighter space systems, reducing the launch cost and the redesign cost for new missions; thus, one can launch more of them and at shorter intervals, and send them to more places after launch.

*This work was done by Adrian Stoica of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-48349*

## Fibrillar Adhesive for Climbing Robots

**This material can be used to hang items on walls without the need for drilling holes, as surgical sutures, or to attach and maneuver components during assembly.**

*NASA's Jet Propulsion Laboratory, Pasadena, California*

A climbing robot needs to use its adhesive patches over and over again as it scales a slope. Replacing the adhesive at each step is generally impractical. If the adhesive or attachment mechanism cannot be used repeatedly, then the robot must carry an extra load of this adhesive to apply a fresh layer with each move.

Common failure modes include tearing, contamination by dirt, plastic deformation of fibers, and damage from loading/unloading. A gecko-like fibrillar adhesive has been developed that has been shown useful for climbing robots, and may later prove useful for grasping, anchoring, and medical applications.

The material consists of a hierarchical fibrillar structure that currently contains two levels, but may be extended to three or four levels in continuing work. The contacting level has tens of thousands of microscopic fibers made from a rubber-like material that bend over and create intimate contact with a surface to

achieve maximum van der Waals forces. By maximizing the real area of contact that these fibers make and minimizing the bending energy necessary to achieve that contact, the net amount of adhesion has been improved dramatically.

The suspension structure consists of millimeter-scale fibers that are bonded to the contacting level through a wet assembly step. These millimeter-sized fibers serve as a discretized way of both conforming to roughness on the surface and distributing the overall climbing loads down to the individual contacts. These structures have been tested on an experimental testbed meant to determine the contact forces very exactly, and have also been demonstrated by hanging weights off of a patch adhering to a variety of walls (glass, metal, wood, plastic, drywall, etc).

This material is fabricated via a molding process. A new process has been de-

veloped at JPL to make this process simpler, more reliable, and to allow new geometries not previously possible. These new geometries will make the adhesive and the reliability significantly better, and will drive down cost and development time.

The process involves using optical lithography to make a master pattern, and from this master pattern, making a reusable master mold that is used to cast the adhesive strips. To create the master photoresist pattern that will be used to make the master mold, a self-aligned double exposure technique was used. Two different angled UV exposures are performed using a single opaque pattern on a transparent wafer. This simplifies fabrication considerably.

A second advantage of this technique is the ability to achieve right-angle wedge-shaped structures with both sides

of the wedge leaning to the same side, i.e., an actual overhang of the fibers, which is more like the arrangement of a gecko foot's fibers. A third critical difference is the use of a standard positive Novalac photoresist, which has a wide process latitude.

The new microfabrication process has allowed the shape of the wedge-like fibers to be controlled. Prior to these process improvements, only right-angle wedges had been fabricated. Now, the process not only allows for increased control over the angle of these fibers, but is also much more reliable, manufacturable, and cost-effective.

*This work was done by Aaron Parness and Victor E. White of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-48156*

---

## Using Pre-Melted Phase Change Material to Keep Payloads in Space Warm for Hours Without Power

*Goddard Space Flight Center, Greenbelt, Maryland*

Adding phase change material (PCM) to a mission payload can maintain its temperature above the cold survival limit, without power, for several hours in space. For the International Space Station, PCM is melted by heaters just prior to the payload translation to the worksite when power is available. When power is cut off during the six-hour translation, the PCM releases its latent heat to make up the heat loss

from the radiator(s) to space. For the interplanetary Probe, PCM is melted by heaters just prior to separation from the orbiter when power is available from the orbiter power system. After the Probe separates from the orbiter, the PCM releases its latent heat to make up the heat loss from the Probe exterior to space.

Paraffin wax is a good PCM candidate. It has a high solid-to-liquid enthalpy,

which is about 225 kJ/kg, and a range of melting points. For example, C<sub>18</sub>H<sub>38</sub> has a melting point of 28 °C, which is well within the payload temperature limits. At the time of this reporting, paraffin wax PCM had a TRL (technology readiness level) of 7.

*This work was done by Michael Choi of Goddard Space Flight Center. Further information is contained in a TSP (see page 1). GSC-16539-1*