FloraMorph: A Non-Planar Origami-Folded Solar Array

Principal Investigator: Manan Arya (355)
Jonathan Grandidier (346)
Jet Propulsion Laboratory, California Institute of Technology
Program: Innovative Spontaneous Concepts

Project Objective:

- Develop an architecture for lightweight deployable solar arrays that can package compactly and self-stiffen upon deployment using a non-planar corrugated unfolded form
- Tune the non-planarity of the deployed structure to balance deployed stiffness and power collection
- Predict the effects of non-planarity on power collection over a range of solar incidence angles
- Compare the performance against the state of the art
- Construct a foldable prototype of this system to demonstrate feasibility and raise this concept to TRL3

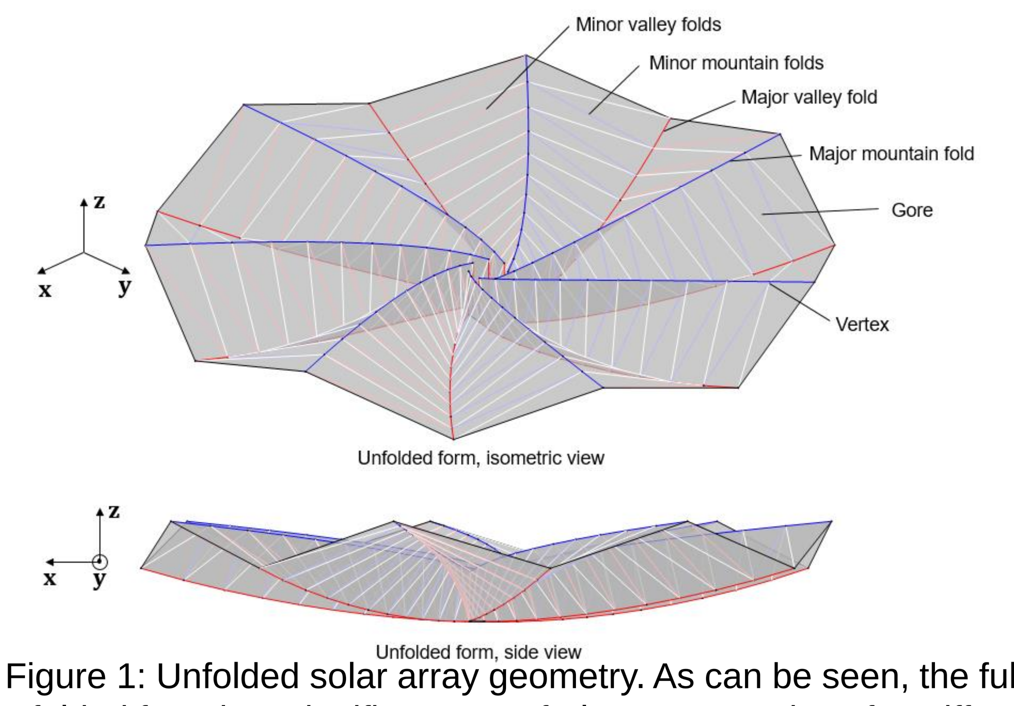

Figure 1: Unfolded solar array geometry. As can be seen, the fully unfolded form has significant out-of-plane corrugations for stiffness.

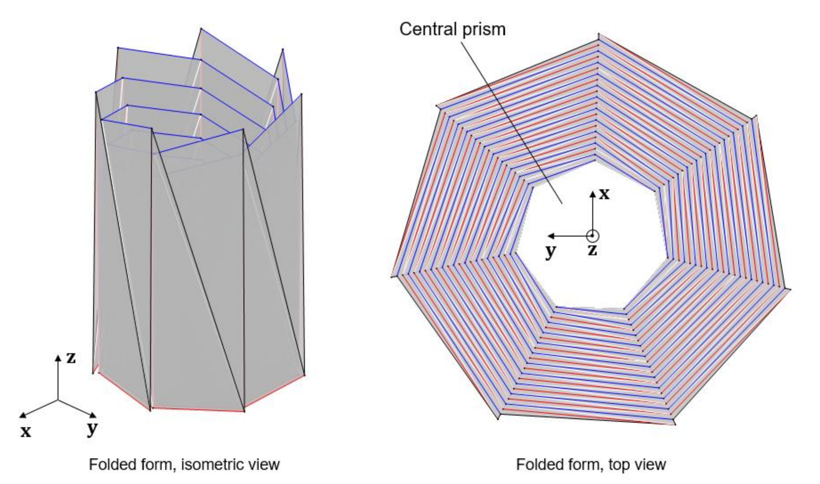

Figure 2: Folded solar array geometry. The folded form has a helical nature to account for the material thickness. The generative algorithm guarantees isometry between the folded and unfolded forms, i.e. that the structure is unstrained when stowed and when deployed.

Results:

- This solar array architecture leverages origami design principles to achieve high compaction when stowed, but a non-planar corrugated surface when deployed. This deployed non-planarity adds out-of-plane bending stiffness, which means that no additional supporting structure is required, leading to savings in mass and complexity.
- A generative design algorithm was developed to produce a family of foldable non-planar geometries. The origami design approach guarantees that the structure is unstrained when stowed and deployed, that folding is localized at the hinge lines, and that the photovoltaic (PV) cells are not strained. Using this algorithm, a 1.53 m-diameter prototype was designed and fabricated.
- A numerical code was written to predict the power output of these non-planar solar arrays, accounting for cosine losses, angle-of-incidence losses, and self-shadowing losses at each triangular facet of the structure. Figure 3 shows the predicted power output of the prototype geometry, assuming 1 sun irradiance (1353 W/m2), with 33% efficient cells populating almost all of the facets. The predicted power output at normal solar incidence is 792 W. Compare this to an annular flat-plate solar array, with the same inner and outer diameter as the prototype, which would produce 875 W. The 83 W difference between the corrugated and flat geometries is due to local reflective angle-of-incidence losses at each facet; both these solar arrays intercept the same amount of solar flux since they have the same projected area. This 83 W difference is compensated by the structural efficiency of the corrugated architecture, as shown by the physical prototype.
- A foldable prototype structure was constructed with 1 mm-thick carbon-fiber-reinforced plastic plates
- The power output prediction code was used to compute array performance at off-normal solar angles, as well. Note that the code accounts for self-shadowing effects of the non-planar geometry. The power output of a flat-plate structure is also plotted. As can be seen, the performance of the two geometries is indistinguishable up to a 50° solar incidence angle, beyond which the non-planar geometry actually outperforms the flat plate. This is because both geometries have similar projected areas when tilted up to about 50°; beyond that, the projected area of the flat plate goes to zero, while the projected area of the non-planar geometry does not.
- A non-dimensional stiffness study was conducted of the prototype geometry using a non-linear reduced-order structural finite-element model (FEM). This study showed that the structure does indeed have stiffness in the deployed configuration without any external members, and that these structures are, in principle, amenable to finite-element analysis.

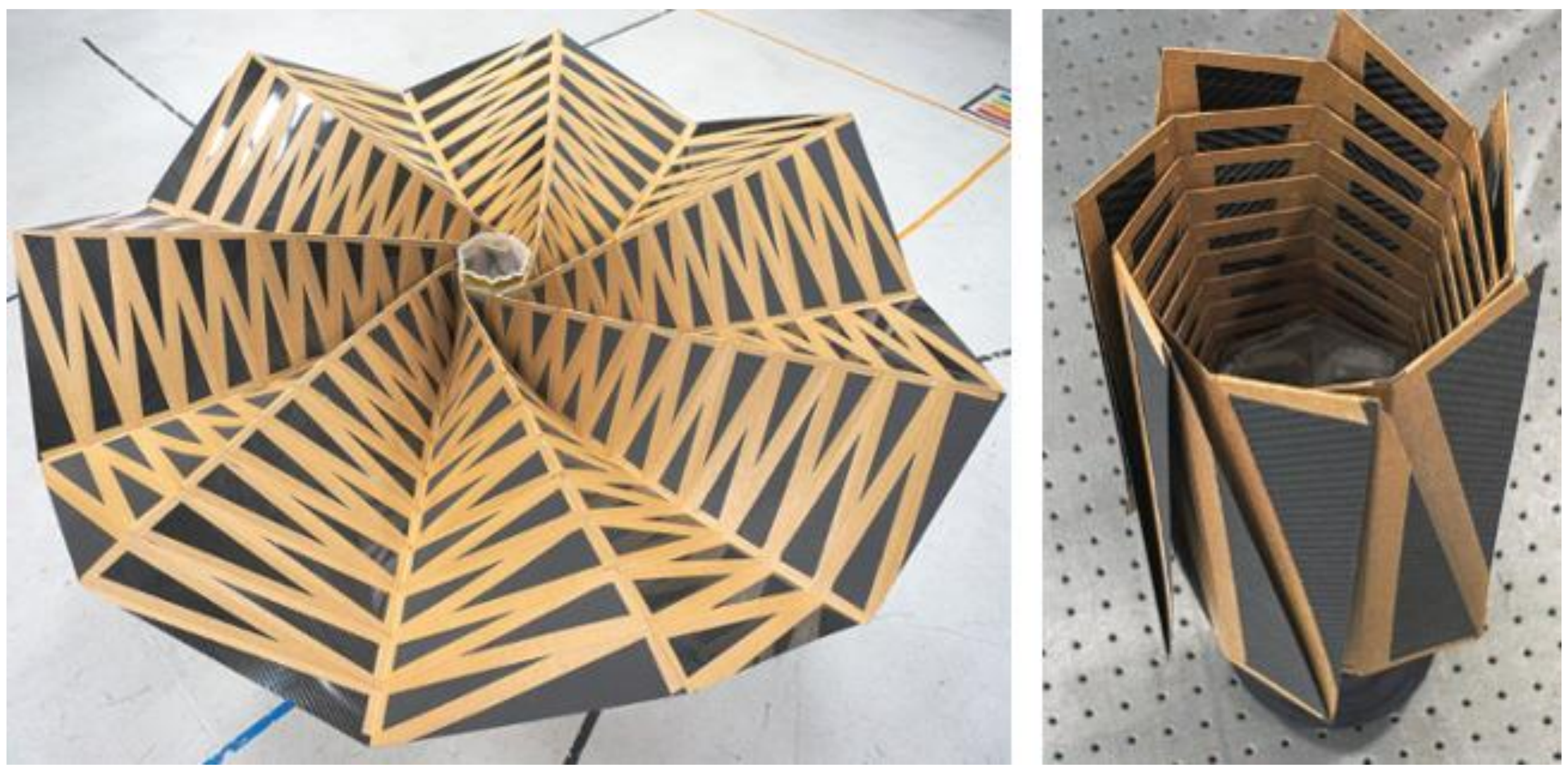

Figure 7: On the left, the 1.53 m-diameter physical prototype fully deployed. On the right, the same prototype folded, with a diameter of 0.175 m. The structural prototype was constructed using carbon-fiber-reinforced-plastic (CFRP) plates hinged together with tape. The prototype did not include any PV cells.

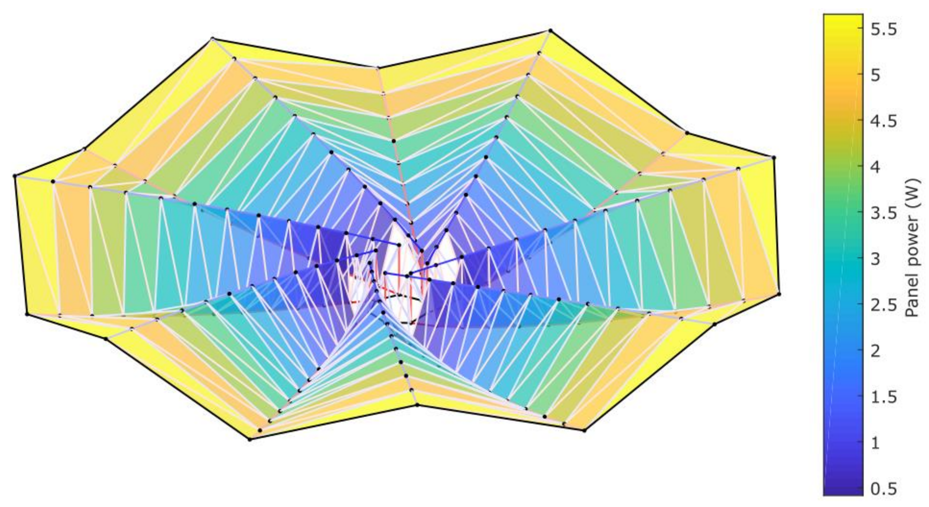

Figure 3: Predicted power output for each triangular facet at 1 sun for a global normal solar incidence angle for the manufactured prototype geometry. The total predicted power for this geometry is 792 W.

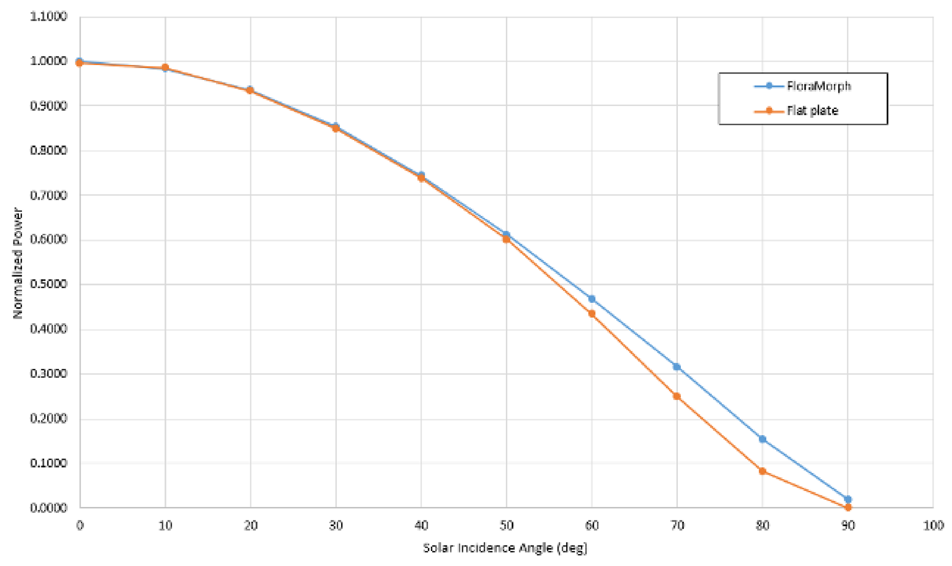

Figure 5: Normalized output power over a range of solar incidence angles for the prototype geometry. This accounts for cosine losses, local angle-of-incidence effects, and self-shadowing effects.

Design deployed diameter (m)	1.58
Design stowed diameter (m)	0.17
Design structural mass (kg)	1.94
Design PV mass (kg)	2.15
Total design mass (kg)	4.09
Assumed PV efficiency	33%
Design power (W)	792
Design specific power (W/kg)	194
Measured deployed diameter (m)	1.53
Measured stowed diameter (m)	0.17
Measured structural mass (kg)	2.07
Specific power (W/kg) (using measured structural mass, design PV mass, design power)	188

Figure 4: Prototype parameters.

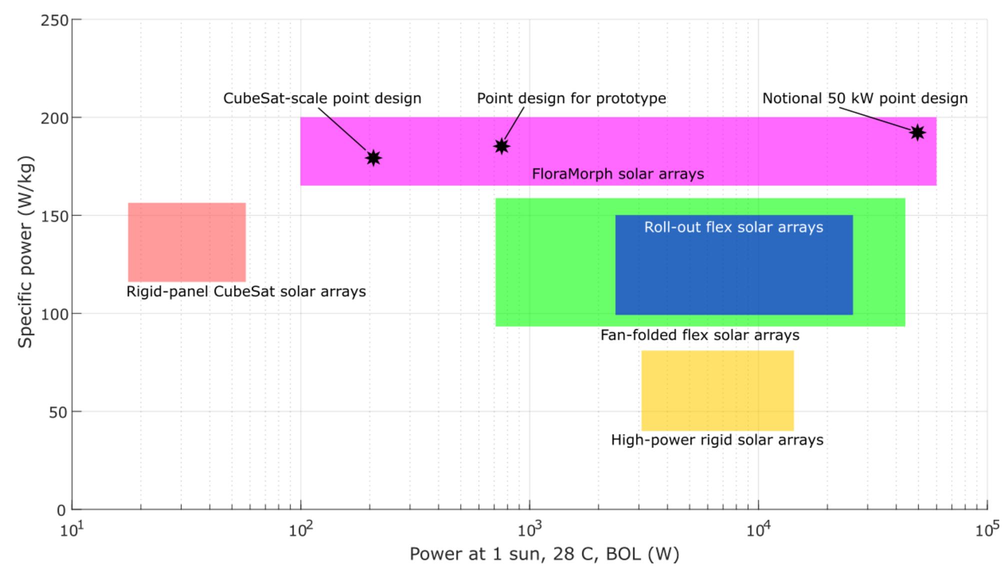

Figure 6: FloraMorph compared to state-of-the-art deployable space solar array systems.

Benefits to NASA and JPL:

- We have demonstrated that this solar array structural architecture promises significant gains over the state of the art in terms of specific power. We have also demonstrated that the non-planar deployed geometry does not much degrade output power as compared to planar solar arrays. We constructed a 1.53 m-diameter deployable prototype that demonstrated compact stowage, low mass, and deployed stiffness sufficient to sustain its shape in Earth gravity.
- Deployable solar arrays are a key enabler for low-cost, long-lived spacecraft. As we push out into the outer solar system – the moons of Jupiter, Saturn, and the ice giants – large-area, reliable, deployable solar arrays will be critical for enabling small orbiters and landers to explore these destinations.
- Existing deployable solar arrays that have robust and simple mechanical architectures (e.g. z-folded rigid arrays) do not scale well to large deployed area. State-of-the-art high-power solar arrays (e.g. MegaFlex, DSS ROSA), on the other hand, need external support structures and deployment mechanisms add risk, complexity, and mass. The FloraMorph architecture scales well to large power systems, since it requires no external structure. And, unlike existing state-of-the-art solar arrays, this architecture also scales well to small sizes, especially to CubeSat and smallsat scales, where the lack of additional stowed structure is suitable for the tight volume constraints associated with this class of spacecraft.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Publications:

Manan Arya, “Origami Wrapping Patterns That Are Non-Planar When Unfolded”, Engineering Mechanics Institute 2019 Conference, June 2019

PI/Task Mgr. Contact Information:

manan.arya@jpl.nasa.gov; 818-354-1975