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The Abracadabra of Engineering: Strong Structures from Flimsy Materials

Rockets are great for blasting spacecraft into orbit or on their way to another planet. But the trouble with rockets is that they gulp fuel faster than a Hummer pulling a camper trailer. In only a few minutes their tanks are empty. Then what? The spacecraft is left to coast the rest of the way.

Of course, there's no air in space causing drag or friction to slow the spacecraft down, and it may be going 60,000 kilometers per hour (40,000 miles) or so to begin with. But if its destination is a billion or more miles away, wouldn't it be much better to keep the "pedal to the metal" for the whole trip?

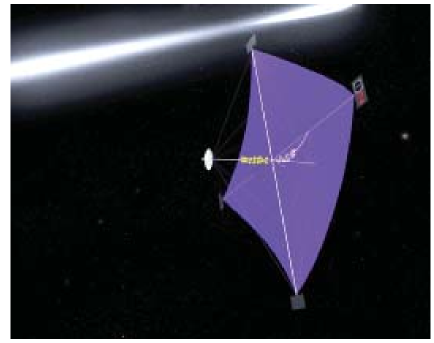
Definitely! So, NASA is working on some new modes of space transportation.

One way to keep the spacecraft accelerating is to harness the sunlight. Sunlight exerts a very gentle pressure on objects it hits. That means that a spacecraft could have a solar sail that would work like a sail on a boat, harnessing the energy of the sunlight instead of the wind. If the sail were a mirror and reflected all the sunlight, the spacecraft would get the maximum push. The sunlight, pushing constantly on the sail, would get the spacecraft going faster and faster. Over a few weeks or months, that constant acceleration would really begin to add up!

To take the best advantage of this source of energy, the area of the solar sail needs to be quite large—say at least as large as a football field and maybe as big as a kilometer (over half a mile) on a side. The bigger the sail, the more the Sun's energy would be harnessed to accelerate the spacecraft.

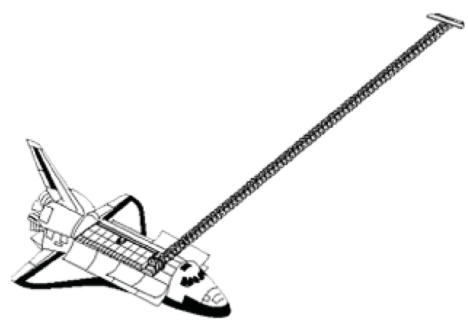
Outer space has lots of room for huge sails. But huge sails present other problems. How do you fold up and stow such a huge sail for launch? Then, once in space, how do you have it open automatically, not get stuck or ripped, then stay flat and smooth like a mirror? And, perhaps most obvious, how do you make such a huge sail and its support structure lightweight enough that it won't take a Saturn V rocket[1] to boost it into space in the first place? Such a "gas hog" of a rocket would defeat the purpose of having the sail.

Solar sail designers have come up with a number of designs. One promising design is a square sail in four triangle-shaped quadrants, with the quadrants supported by rigid masts, very much the way a sailboat's mast tensions its triangular sails. The sail is an extremely thin film of a synthetic material with aluminum coating to make it reflective like a mirror. The masts are made of high-tech, extremely lightweight, thin, and strong materials that hold up well in space.



But just using advanced materials is not enough. Space engineers have to come up with the best and simplest way to design the mast so it can squeeze into the smallest possible space, deploy without problems, be as rigid as possible once deployed, and not cause any "unpleasant side-effects" for the spacecraft.

Here's a design that was previously used for a different kind of mast on a Space Shuttle mission. The mast was 60 meters (200 feet) long, and supported a radar mapping instrument in the end.

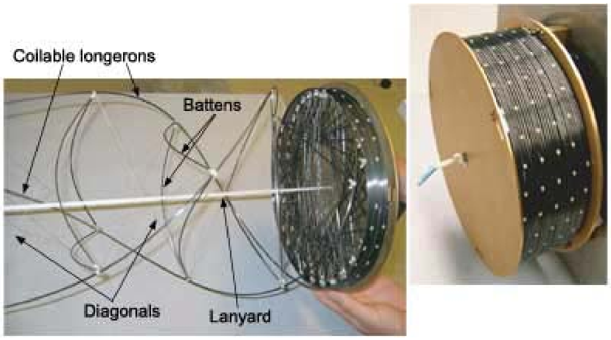


For use to support solar sails, this mast is about 15 times too heavy to be useful, so NASA engineers adapted a different type of mast and used "gossamer" (super-lightweight) materials that, working alone, are not very impressive, but when assembled into a truss, become an effective solar sail mast. The engineers made a 40-m- (131-ft-) long test mast that (although rigid when opened out in space), coils up like a Slinky® toy to about 40 cm (16 inches) long inside the spacecraft for launch.

This design is called SAILMAST. It is to be tested for the first time in space as part of NASA's Space Technology 8 mission.

You can try for yourself some of the simple ideas the SAILMAST engineers used in their design.

1 The Saturn V was the huge rocket used in the Apollo Program to send people to the Moon.

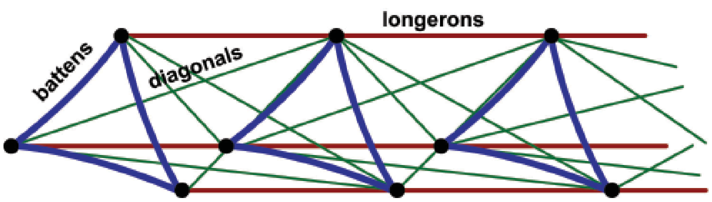


The SAILMAST coils up to only 40 cm (16 in) thick when stowed inside the spacecraft for launch (as on the right), but extends to 40 m (131 ft) when deployed in space.

Make a Model Structure for a Solar Sail Mast

Using simple, flimsy materials, you will build a rigid structure similar to the basic design of a real solar sail mast created by space engineers.

Tools needed:



Scissors	1
Ball pen – 1/4" diameter Or *round* pencil (long)	1
Ruler w/straight edge	1
Hole punch (single or multiple hole)	1
Clothespins (optional)	6
Plastic drinking straw	1
Small paper clip	1

Materials needed for each model:

Paper – letter size	3 sheets
File card – 3" x 5" **or**	1 card **or**
Photocopy machine compatible card stock	1 sheet
String (kite string or other lightweight string)	10 feet
Transparent tape – 1/2" wide	6 inches
White glue, small bottle	few drops

Time needed: Two class periods

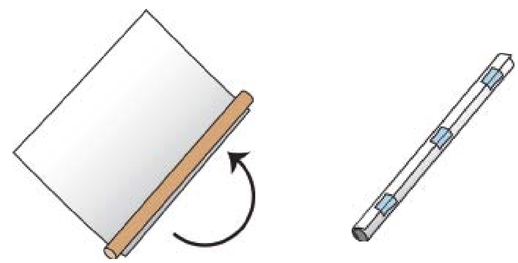
We suggest the following division of labor to move the project along at optimum speed.

Divide up into teams of four:

1. One to make the *longerons*
2. One to copy and produce *corner fittings*
3. One to make the *battens*.
4. One "assembler," to cut the string, helping to tape the *longerons* and *battens*, copy *corner fittings* or whatever. The assembler, with assistance from the others, glues and clamps *corner fittings* to the *longerons*, strings the *battens*, and strings the *diagonals*.

A. Make *Longerons* and *Battens*:

1. Fold the 3 sheets of letter size paper exactly in half length-wise, then again in half width-wise.
2. Unfold the paper and, with scissors, cut 12 identical 4-1/4" x 5-1/2" panels (only 9 will be needed).
3. Lay the pencil or ballpoint pen along the 5-1/2" edge of one panel and roll the paper tightly around the pencil, forming a *longeron* tube. Be sure to evenly align the layers of paper at the edges of the tube.
4. With small pieces of transparent tape, tape the paper edge to the *longeron* at its center and about an inch away from each end.

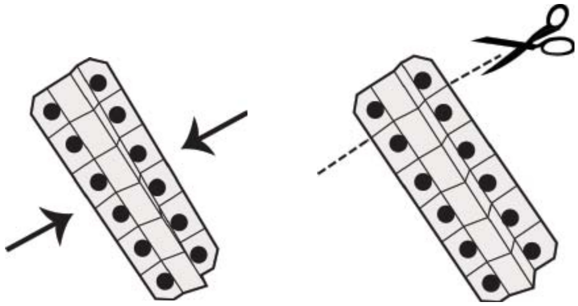


5. Remove the pencil from the *longeron*.
6. Make two more *longerons* in the same way.
7. Make six *battens* in the same way, except roll up the shorter (4-1/4") sides of the paper.

B. Make *Corner Fittings*:

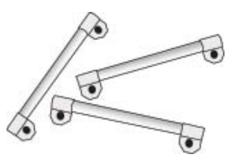
1. At the end of this article is a pattern for the corner fittings. Photocopy it onto either regular copy paper or heavier card stock. If on regular paper, evenly glue the pattern onto a 3" x 5" (or larger) file card.
2. Apply two pieces of transparent tape to the card, where indicated, to reinforce the fittings.
3. Cut out the panel of connectors along the dark perimeter line. Then use the hole punch to punch each hole.
4. With ballpoint pen and straightedge, trace over the three dashed fold lines, pressing to score them.
5. Fold the panel upward at the two outer fold lines.
6. Fold the card downward along the center fold line.

7. Cut along solid lines with scissors to separate the six *corner fittings*.



8. Put a few drop of glue on a fitting, at the inside of the center fold line and around the holes on the tabs.

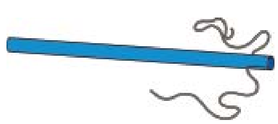
9. Place the edge of the *corner fitting* at the very end of a *longeron*, **with the center fold line exactly aligned with the *longeron's* paper edge.** Wrap the *corner fitting* around the *longeron* so the tabs meet and the holes are aligned. Hold the tabs together until the glue has set. Clothespins are excellent for this purpose.
10. In the same way, attach *corner fittings* to both ends of each *longeron*.



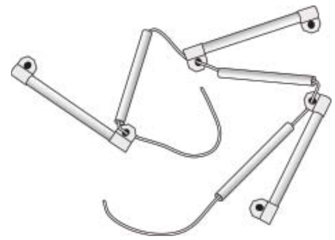
C. String Together *Longerons* and *Battens*:

1. Cut about 30" of string.

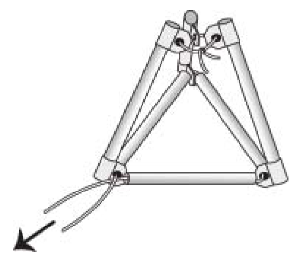
Handy hint: To assist in threading the string through the *batten* tubes, use the plastic drinking straw as a "needle." With scissors, cut two small slits in one end of the straw (as if you were starting to cut the straw in half lengthwise). Then, slide one end of the string into the slits to "thread the needle."



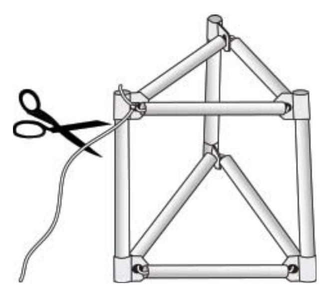
2. Thread the string through the hole of a *longeron corner fitting*, then through a *batten* tube. In the same way, thread the string through two more *longerons corner fittings* and two more *batten* tubes.



3. When all three *longerons* and three *batten* tubes are strung together, thread the string back through the first *longeron* corner fitting to loosely pull the whole thing into a triangle. Thread the string through everything a second time.
4. Thread a piece of string through the connectors at the opposite end of the *longerons*. Tie a temporary, loose knot to stand the longerons as a tripod.



5. Pull the first string tight so that the whole assembly comes together and the *corner fittings* are snug against the ends of the *battens*. Tie the two ends of the string together two or three times and cut short.
6. Untie the temporary string holding the corner fittings together at the opposite ends of the *longerons*.
7. Cut another 30" piece of string and in the same way, connect the *longerons* to the other three *batten* tubes on the opposite side.

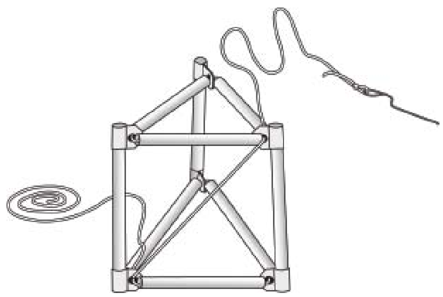


D. Brace with Diagonals:

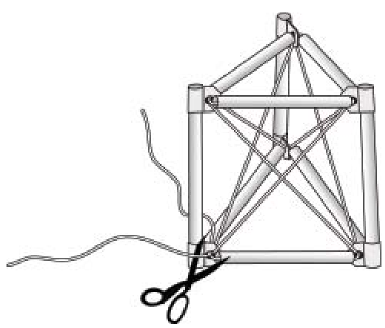
Hint: Threading the string through the corner fittings is easier if you make a "needle" out of a small paperclip. First, tie a loop in the end of the string. Straighten out the larger curve of the paperclip. Hook the loop in the string over the smaller curve and bend it closed to make the "eye of the needle."

Another hint: It helps to have one person support the still-flimsy structure with longerons vertical while another person strings the diagonals.

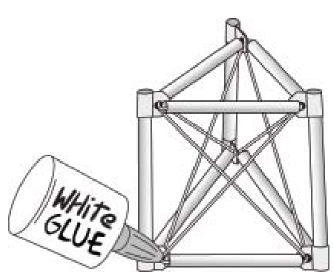
1. Cut a piece of string about 5 feet long. Thread one end through a corner fitting hole.
2. Thread the other end through the diagonally opposite connector.



3. Continue to thread the string through connectors at diagonally opposite corners until returning to the first one, and thread through it.
4. Pull the string taut, to tighten it through all connectors, while moving the structure around and adjusting the diagonal strings until the longerons are vertical and the top is level. Tie the two ends of the string together and cut the ends short.



5. Apply a generous drop of glue to the corner fittings just where the string passes through so the string will not slip in the fittings. Try not to disturb the structure until the glue is dry.



But then . . .

Model truss structure of flimsy paper and kite string is strong enough to support all these heavy books!

How Does It Work?

You will find that your model, made only of paper and string, is actually quite sturdy, especially considering how light it is. This is the trick with space structures, and you've just shown how it can be done: with a truss!

But just how is it that flimsy, flexible materials can be made into a rigid structure?

The model structure represents the use of *tension* (pulling forces) and *compression* (pushing, pressing or squeezing forces) to get the parts to work together as a team in the form of a "truss." Those forces work to rigidly hold each **corner** of the truss to an exact position in relation to the other corners of the structure. Triangles are crucial to a truss, because they resist changing shape much better than squares, as long as their 3 sides aren't stretchy.

At first, paper may not have sounded like a great material to resist compression in our truss. When it's a flat sheet, paper has very little **bending** strength. It can be easily bent in any direction. Once a sheet of paper is bent or curled, however, it is able to resist bending. At right angles to the bend it shows maximum strength. A rolled piece of paper becomes a strong pillar, or column.

String is a poor tool for pressing or pushing things. It's great for pulling them, though. Together, paper and string make an excellent team to keep the corners of our truss in an exact position in relation to the other corners of the structure.

The structural design engineer's job is to figure out the best way to use tension and compression to hold each corner of a structure in a fixed relation to all the other corners of the structure.

One way to separate the corners of our structure is with three columns; two batten columns and the longeron column. If the corners tried to move closer, they'd cause pressure, or **compression** in these columns which would stop them. Compression is fine, but it won't keep the corners from drifting apart.

A string would do it; connected to diagonally opposite corners, it could pull them together with **tension**. We call those strings **diagonals**. Pulling a diagonal (**tension**) causes the longerons and the battens to be squeezed (**compression**), trapping the corners so they cannot move. The structure within the corners is rigid. If the string became slightly loose, the corners could move a bit, making the structure wobbly.

When diagonal strings are pulled tight, the total **tension** force of the strings at each corner is exactly equal to the total **compression** force of each corner's columns.

When this kind of structure is used in space, it must collapse into a small volume, and open again as a rigid structure. Our paper longerons and battens would be crushed when rolled up for travel, and would have no strength when unrolled in space.

SAILMAST engineers solved these problems by using advanced, highly flexible graphite fibers for both the longerons and the battens. This material has shape memory similar to that used in a retractable metal tape measure.

The longerons and battens in the SAILMAST keep their shape and strength when the structure is rolled and unrolled in a space mission. But there's another requirement the space engineers had to consider. SAILMAST's parts will change size as they are alternately chilled by the extreme cold of space and heated by the sun. Even small changes in diagonal, batten and longeron dimensions would cause change in tension and pressure at the corners. The SAILMAST structure would become wobbly or oddly twisted.

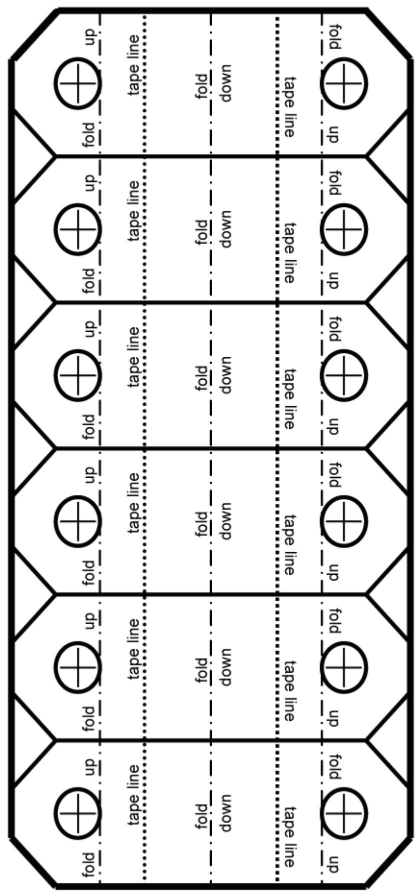
So the tension exerted by the diagonals is so tight that the battens are slightly bowed inward, putting some extra outward force on the longerons. Regardless of changes in size due to extremes of temperature, the spring tension of the bent battens continuously exerts exactly enough pressure to keep the corners apart, the diagonals in tension, and the SAILMAST structure rigid.

About ST8 SAILMAST

As part of NASA's New Millennium Program Space Technology 8 mission, the SAILMAST will pave the way for new missions of discovery in space. If SAILMAST performs as expected, it will be ready for use in new spacecraft designs that use solar sails for long, but speedy (relatively!) journeys to deep space destinations.

Learn more about SAILMAST at spaceplace.nasa.gov/en/kids/st8/sailmast, where you can see a movie of a real SAILMAST uncoiling in the laboratory. Also, go to nmp.nasa.gov/st8 and see a movie of a solar sail stretching out on the mast, just like it would do on a real spacecraft.

NASA's New Millennium Program has the job of helping to develop new technologies for space missions and testing them in the actual harsh environment of space. This way, new science missions can benefit from the latest advances without having to take chances on untried or risky technologies.



Template for corner fittings.

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