ELASTIC, ELECTROSTATIC AND SPIN DEPLOYMENT OF ULTRALIGHT SAILS

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Gossamer structures are so diaphanous and fragile that 'hands-off' handling is a very practical requirement. We address deployment of ultralightweight structures, using elastic, charge and spin forces that do not rely on mechanical contact with the large fragile structure. These mechanisms we compare in terms of practical features such as support equipment required.

Keywords: Solar sails, ultralight structures

1. DEPLOYMENT ISSUES

This work explores several "exotic" methods of ultralightweight spacecraft deployment. They are of interest in order to reduce to a minimum the mechanical contact during deployment and to provide for control of the structure after deployment. The lightness and elasticity of new ultralight materials such as carbon fiber mats can tolerate virtually no external mechanical contract so that everything is entirely "hands off".

Deployment is a complicated electromechanical problem, exacerbated by the difficulty and expense of realistic lab or space experiments. Practical requirements are, for example,

- to deploy and control very light but very large structures with a minimum of mechanical contact,
- to deploy from a minimum stowed volume (maximum packing fraction),
- to provide for control after deployment

This work treats analytically both elastic and electrostatic deployment. Spin deployment experiments are reported in another paper [1].

1.1 Spin Deployment

Spinning a large ultralightweight foil, which we will refer to as a 'sail' for concreteness, generally stabilizes a sail structure to both pitch and yaw. Solar sail concepts fall into three-axis-stabilized square sails and spin-stabilized sails. Spinning produces the centrifugal force, which provides the required tension to hold the sail flat and prevent the deformation and fluttering. But stable controllable deployment must be assured.

Recent demonstrations of spin deployment at JPL by Salama and co-workers have deployed an ultra-thin 2.5-micron mylar film at a diameter of 80 cm [2]. In 1993, Russia deployed the 20-meter Znamya reflector system in orbit using spin. Specific mechanisms for deploying using spin have been described [3]. Figure 1 shows a spacecraft spinning up with cold gas thrusters (note that they give only one spin direction) and deploying the gores via centrifugal force, from unfurling to full deployment. A more advanced method would be to eliminate tethers and other hardware and deploy entirely by spin alone.

It is attractive to remotely induce spin, entirely hands-off. The other virtues hands-off methods have are *reversibility* (should spin grow too fast, for example) and *real-time control*.

As we treat in detail in [1], a large, folded structure can be opened with a purely electromagnetic torque exerted by a microwave beam. The directing microwave beam will carry angular momentum, if it is circularly polarized. The force from a beam spinning up a sail can be comparable to the longitudinal electromagnetic (pressure) force on the receiving area.

Reference [1] describes experiments on a new way to spin objects using electromagnetism. The method is called '*geometric absorption'* and relies on a new understanding of angular momentum in classical electromagnetism. We demonstrated geometric absorption in experiments 2000 at JPL and UCI [4]. To optimize this efficient method of spinning an object, the primary method is to shape the object. The currents induced on the conducting surface of the sail have a geometry that maximizes coupling of angular momentum. This is done by controlling the aspect ratio (squares vs. strips) and by making cuts in the surface to change current flow paths. We find that the efficiency of converting angular momentum to the object from the wave can be increased an order of magnitude by such techniques.

We measured the coupling of spin to be higher than the direct absorption of electromagnetism from simple photon capture absorption coefficients, which are ~1 to 0.1 for absorbers and ~ 0 for conductors. The geometric (spin) absorption coefficient can be as high as 5.

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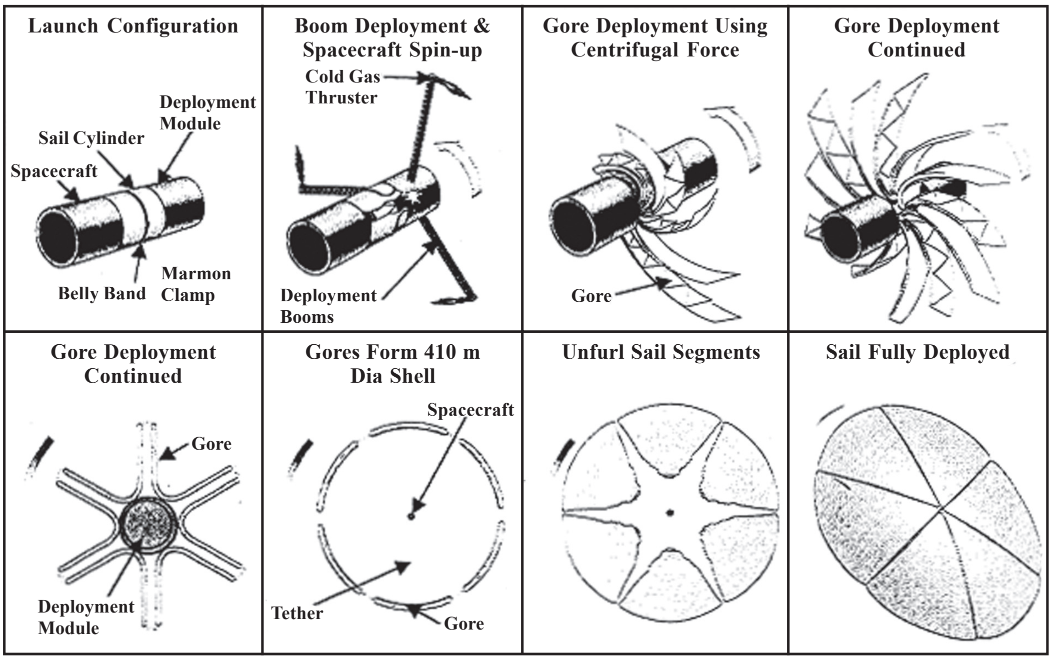

Fig. 1 Sail deployment by spin. This sequence shows a concept for a large sail, spin driven by cold gas thrusters. In reference 1 we show how to spin-deploy remotely using a microwave beam, allowing reversing of the spin direction. (From Reference 2).

A closely related method is Thermo-molecular (also termed 'Radiometric') Deployment. In the 19th Century, the effect was seen in the Crookes Radiometer [5]. The physical explanation of the effect [6] is that a net thrust is generated on surfaces of the sail heated by irradiation from one side. Air molecules heaving the hot side are, of course, slightly hotter. The sail then suffers a differential impulse as these molecules leave. This method uses the difference of temperatures on opposite sides of a structure to drive rotation in a properly shaped structure. The very low-density gas (~ 100 mTorr) can be supplied by placing the structure in the upper atmosphere (~100 km) or by providing a transient gas background. The attractiveness of thermal-molecular driven spin is similar to the virtues of beam-driven spin. However, it requires a healing system, which can be microwave or laser or some other way of projecting energy such as an intense luminescent source. It also requires the use of a local gas background at close quarters. The required gas is so tenuous that only about a gram per second would be needed in a vacuum to provide enough gas for the thermal molecular effect to occur. A small gas bottle releasing gas slowly into the deployment region could provide that. Therefore, this method could be entirely practical.

2. ELASTIC DEPLOYMENT SCALING

Elastic deployment expands the sail to its final shape by using energy stored in the material when it was stowed. The geometry of storage (rolled-up sections, umbrella unfolding method, etc.) probably will influence the practicality of deployment. The high elasticity of C-C microtruss recommends it for this deployment method. Figure 2 shows that a C-C strip of high elasticity unrolls a page-sized sheet (16.87 in x 3 in, 42.8 cm x 7.7 cm, see description in Section 3.3). The unrolling takes place in ~1 sec. However, the material 'remembers' the rollup and subsequent repeats of the exercise aren't reproducible. Therefore, present-day C-C sheets would be reliable for only a single deployment.

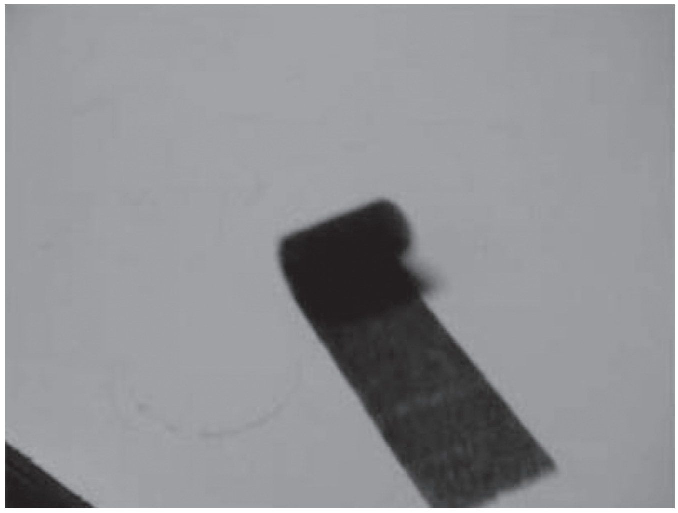

Fig. 2 Frame from a rollout of a C-C sail, deploying by internal elasticity.

To calculate the timescale for deployment, a series of 2-D ODE calculations, solved by Mathematica software, for rolling out meters-size sails of various sizes of Kapton and the carbon microtruss material was run. The results are shown in fig. 3. The Kapton sail deploys faster, in about one minute, and carbon deploys in about two minutes. Note that the time from the simulations is faster than linear with length but not greatly non-linear. We can compare directly to the video of an unrolling C-C (Fig. 2), which took ~1 sec to unroll to 43 cm. The calculation for 0.3m is 0.5 sec, for 1 m is 1.7 sec, so agreement is good. These calculations were also done for sails in furled umbrella geometry as shown in fig. 4. For this geometry, the times are about the same, but now Kapton is slower.

So, from the calculations and simulations, we can expect unloaded elastic materials to deploy quickly to dimensions

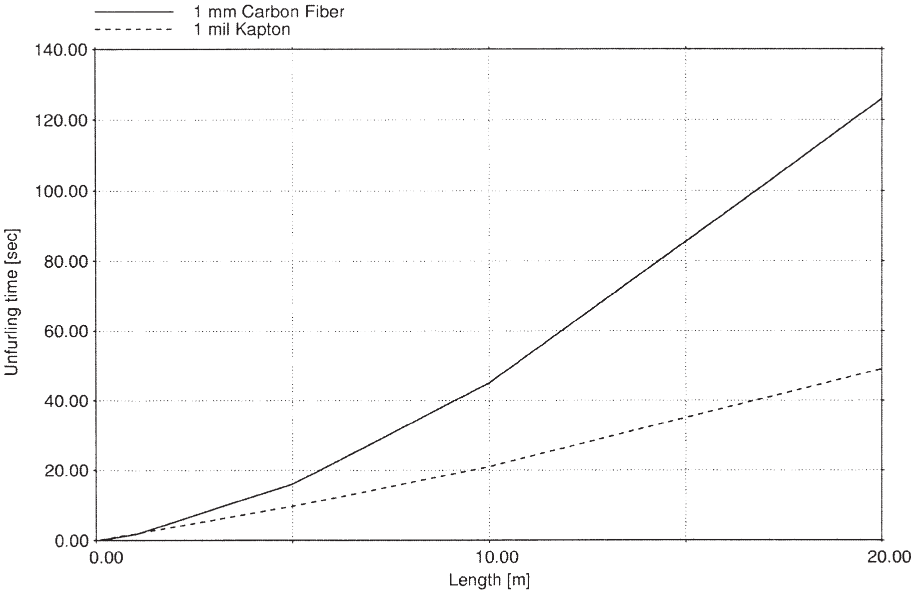

Fig. 3 Elastic deployment time of rolled carbon-carbon microtruss and Kapton sails from ODE runs. Note the timescale is about that of umbrella' configured deployment, shown in fig. 4.

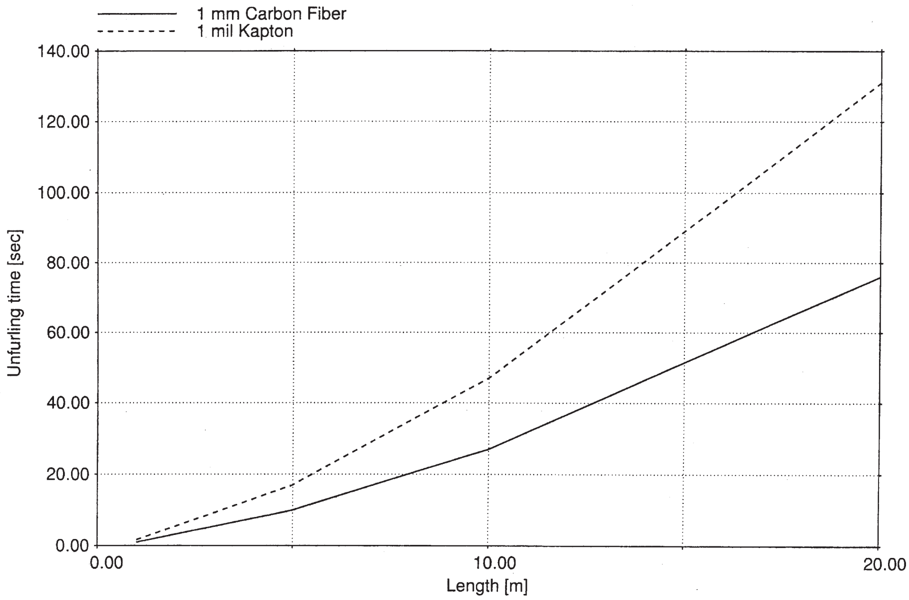

Fig. 4 Elastic deployment time of an 'umbrella' configured sail from ODE runs. Note the timescale is about that of rollout deployment, shown in fig. 3.

of tens of meters, which is quite fast. When loads are attached, the mass and location of them may greatly change this conclusion.

3. ELECTROSTATIC CHARGE DEPLOYMENT

The concept of charge deployment is to expand the sail to its final shape by using the electrostatic repulsion of a charge, which has been applied to the sail. It is the most 'hands-on' of the techniques described here because it does require an electric connection that supplies charge to the initial sail configuration. This method was proposed by Chauncey Uphoff [7]. Calculations show that this deployment can be rapid. Our standard case (expansion from 0.6 m to 20 m) can be done within minutes to hours depending upon what electric field that can be sustained on the sail surface in space.

In low Earth orbit the presence of ions and gas molecules limits deployment to timescales of hours; in hard vacuum it can be only minutes. The drawback is that a power supply is needed and that electrical (not mechanical) contact must be made with sail before it is deployed. This is not a major limitation. Charge transfer can be driven through a plasma discharge, for example. Another factor is that the spacecraft must be able to operate onboard electronics with a deposited charge. This is a typical requirement for spacecraft, where charges can be deposited due to a number of mechanisms—solar storms, etc. The method of application probably will be a probe extended from a power supply which will transfer charge and then detach from the sail. Care must be taken to discharge the positive charge on the power supply after charging the sail.

In practice, the expansion of the sail will be modified by mechanical energy from storing—for example, in wrinkles. To estimate the timescale for deployment, as a first approximation we assume that this energy is small compared to the electrostatic energy we apply to the sail. The equation of motion is

$$F = md^2r/dt^2 = -Q^2/2\varepsilon_0{}^2R^2 \tag{1}$$

The solution by double integration for the deployment time t_D from an initial radius R_i to a final radius R_f for charge Q is

$$t_D = \sqrt{\varepsilon_0 m}\left[R_f^{3/2} - R_i^{3/2}\right]/Q \qquad (2)$$

The deployment time varies inversely with the applied charge but only as the square root of the mass. For an example, we use the case discussed in other sections of this report: A sail stored in a 0.6 m size volume is to expand to a final diameter of 40 m. We take the mass density to be 10 g/m^2, so the total sail mass is 13 kg.

In principle, very short deployment time can be obtained by simply increasing the charge. However in real space situations, we can't operate with the electric field at the surface of the stored sail large enough to cause a breakdown in the background tenuous atmosphere. From the SPEAR II experiments [8], we know that a safe field for use in low earth orbit (LEO) is 3 kV/cm. This limit occurs only in LEO, where some residual atmosphere exists. At MEO or GEO breakdown is much less constraining.

Electric fields limit the deployment time because they limit the charge that can be applied. For our example, we choose 3 kV/cm at the surface of the stored sail and 3-nanocoulomb charge. Substituting in the above the equation, the deployment time is 2.7 hours. This is such a small charge that it can be applied in a short time with a very small power supply.

This ideal example could fail if the stored electrostatic energy were insufficient to overcome mechanical energy stored in wrinkles, or of charge leaks off through ambient plasma. These would force the design to higher charges, which could eventually exceed the electrostatic breakdown limit. A more refined approach would require estimation of the energy stored in wrinkles which oppose expansion.

4. COMPARISON OF METHODS

In Table 1, we use a standard configuration to calculate deployment specifics. The point of comparison is taken from the work of H. Price on sail designs [9] in which a sail deploys from a 0.6-m containment to 20-m extent. Table 1 shows that the various methods would be quite different in practice. Elastic requires the least equipment, but allows no control after release. Spin requires the most sophisticated equipment, and gives subtle control, including reversibility. Electrostatic would leave the charge on the spacecraft. The choice among these methods would be more realistic after conducting the activities shown in the right hand column of Table 1.

5. ACKNOWLEDGEMENTS

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TABLE 1: *Comparison of Deployment Techniques.*

Deployment Technique	Features	Support Equipment	Example*	Future Activities
Beam-Driven Spin	Can provide both longitudinal motion and spin, Remotely driven, controllable in real time, reversible	Microwave transmitter system	Start at 12 rad/sec, 40 degrees, results in.7.25 rad/sec at 70 degrees in 100 sec with microwave power 0.88 MW	Further increases in spin transfer efficiency, spinning larger objects
Thermo-molecular-Driven Spin	Can provide both longitudinal motion and spin, Remotely driven, controllable in real time, very efficient	System for heating sail (microwave, laser, etc.), transient small gas source	Same timescale as above	Experiments to quantify the effect for larger spacecraft
Elastic	No support equipment, not remotely controllable, can fail to unroll if material has been 'worked' previously	None	For Kapton or C-C microtruss, ~ 1 minute	Demonstration of unfurling of C-C on 1 meter scale
Electrostatic	Not truly 'hands-off'	Power supply to apply charge	For Q=3 nC, t_D=2.7 hours, surface E=3 kV/cm	Laboratory demonstration

* Case based on example of H. Price, sail deployed from an initial radius 0.3 m to final radius 20 m.

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