IAC-09.C3.4.4

Making the first steps towards solar power from space – microgravity experiments testing the deployment of large antennas

Leopold Summerer, Oisin Purcell
ESA - Advanced Concepts Team
Keplerlaan 1, NL-2201AZ Noordwijk,
The Netherlands, Leopold.Summerer@esa.int

Massimiliano Vasile
Space Advanced Research Team, Department of Aerospace Engineering, University of Glasgow
James Watt South Building, G12 8QQ, Glasgow, UK, m.vasile@eng.gla.ac.uk

Gunnar Tibert
KTH, Royal Institute of Technology
Department of Mechanics,
SE-10044 Stockholm, Sweden, tibert@kth.se

Nobuyuki Kaya
Kobe University, Dept. of Computer and Systems Engineering
1-1 Rokkodai, Nada, 657-8501 Kobe, Japan, kaya@kobe-u.ac.jp

Concepts for solar power from space have received renewed attention over the past year. High costs for fossil fuel during most of 2007 and 2008 have contributed to increasing the interest not only in traditional renewable energy sources but also in options usually considered as rather "exotic". Solar power from space is one of these. Given the potential size of such an endeavour, it is particularly important to demonstrate its feasibility and convince energy sector representatives and critics via concrete demonstrator projects targeting key technologies.

The construction of a light-weight, very large structure as needed for transmitting antennas and the demonstration of wireless power transmission over very large distances are two of these key technologies. The present paper presents two experiments *Furoshiki-2* and *Suaineadh* addressing these key technologies.

1. INTRODUCTION

In order to advance the maturity of solar power from space (SPS) concepts, the development and demonstration of key subsystem and enabling technology is of central importance. Following the detailed technical analysis made during the "Fresh Look Study" and subsequent system studies in Europe and Japan, one of these important enabling technologies is related to the possibility to deploy and maintain very large structures. While SPS concepts still show considerable variations in design, shape and operating methods, the need for very large structures is common to all of these [1][2][3][4].

This paper provides first a quick overview of different, large structures in space together with their deployment and construction methodologies and then presents two small experiments: *Furoshiki* and *Suaineadh*. Each of these intends to demonstrate one technology how to deploy very large structures.

The ability to deploy and control large lightweight structures in space as required for SPS would be beneficial to a wide range of space applications, such as telecommunication platforms, GEO based high-resolution Earth observations spacecraft and space-based astronomy. The two experiments described in the present paper intend to make steps in this direction and lead the way to further research in the field of very large space structures.

2. DEPLOYMENT AND CONSTRUCTION METHOD OF LARGE SPACE STRUCTURES

All structures larger than the internal dimension of launcher fairings need to follow some sort of deployment or assembly process in space. This can range from the most common and probably best studied process of deploying solar panels, to formation flying and docking and human/robotic assisted assembly of separately launched modules.

For very large, in-homogeneous and very complex structures such as the space stations MIR and ISS, astronauts have proven to still be unrivalled due to human flexibility and ingenuity. Human presence however requires much higher safety standards and mission complexity. Due to the limited and costly access of humans to space, the construction of space stations lasts usually many years. The construction of space station MIR lasted over ten years: The construction of the International Space Station has started in 1998, is currently about 80% completed but will be fully assembled only in 2011 according to current plans. It will then have a mass in excess of 400 metric tons, compared to the 125 tons of space station MIR.

Even if augmented by the use of robotic assistants, this approach is tedious, expensive and lengthy and represents a serious barrier to space applications that require or would benefit from very large structures.

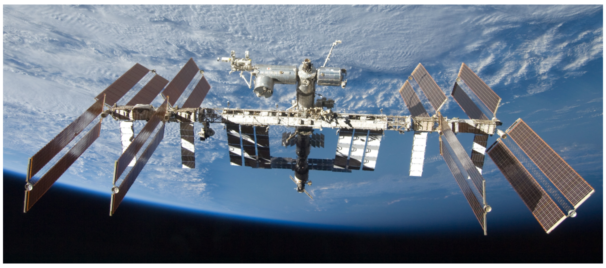

FIG. 1: ISS configuration as taken from the Space Shuttle on 8 September 2009, Source: NASA

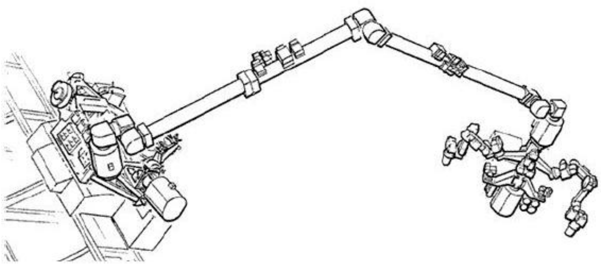

FIG. 2: ISS Space Station Remote Manipulator System (SSRMS), Source:NASA [5]

Single satellites containing elements larger than the launcher fairings are usually deployed robotically in a semi-autonomous manner. While the unfolding of solar panels is the most common example and has been continuously improved in terms of reliability and total deployed size - especially to fulfil the power requirements of geostationary telecom satellites - there are several other methods described and partially used to deploy larger structures without modular docking and assembly: these include inflatable structures, tethers, booms etc.

Very large structures that are simpler than the modular space station type structures and more homogeneous, such as solar sails, solar power satellite components and eventually very large geostationary high-resolution microwave antennas fall in between these two domains. Several different competing technologies are being considered, developed and tested as alternatives unfolding and to robotic or human assembly; most notably inflatable structures, formation flying and formation flying combined with consequent docking.

Due to the limited space available in current and foreseeable launch systems, such large structures require to be stored inside launcher fairings in a non-deployed, usually folded way, implying a controlled mechanism of deployment in space, normally after orbit insertion.

In this paper we are defining as very large space structures those having a surface area greater than roughly 1000 m^2 and an assembly or deployment that takes place while in orbit. Listed are current, past and proposed very large space structures. All of these are relying on angular momentum for the deployment and the stabilisation of the structures.

Znamya

The Russian federal space agency has twice deployed large, sail-like mirrors in space. A 20 m diameter version, was successfully deployed in space in 1993 using a *Progress* vehicle following immediately to its undocking from the MIR space station. The test demonstrated that a spin deployment of such a gossamer structure can be controlled by simple means. It was observed from the MIR space station [6]. Their intended final use was to contribute to the illumination of northern Russian cities during dark winter months to aid economic development [7]. In 1999 a 25 m version failed during the deployment, when it tangled on an antenna on the *Progress* spacecraft that was deploying it, caused by a mission operations software malfunction [8].

The large mirrors (foil material) of the Znamya experiment were spun on motor-driven axles to keep their shape through centrifugal force. The simple deployment process was driven solely by spinning up the stowed reflector using an on-board electric motor. The way in which the foil is folded is of great importance and was heavily researched and tested before the mission design was finalised [6][9].

Heliogyro

Proposed first in 1967 a solar sail concept called *heliogyro* has been studied since but has never flown [10]. While the initial design consisted of two long, thin centrifugally rigidized 5.7 km long, 1.5 m wide and 6 μm thick blades connected to a central core, further variations included structures up to 60 km

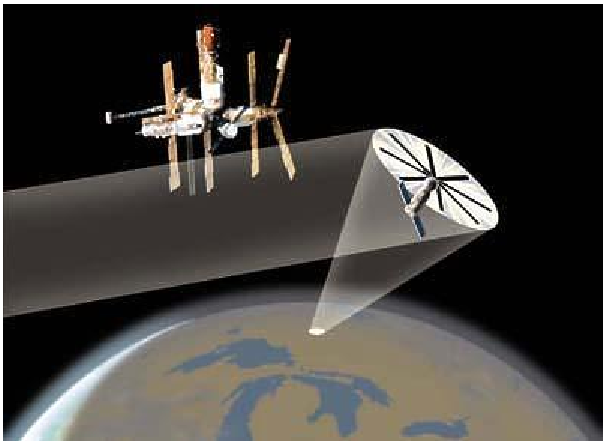

FIG. 3: Znamya-2, Source: [6]

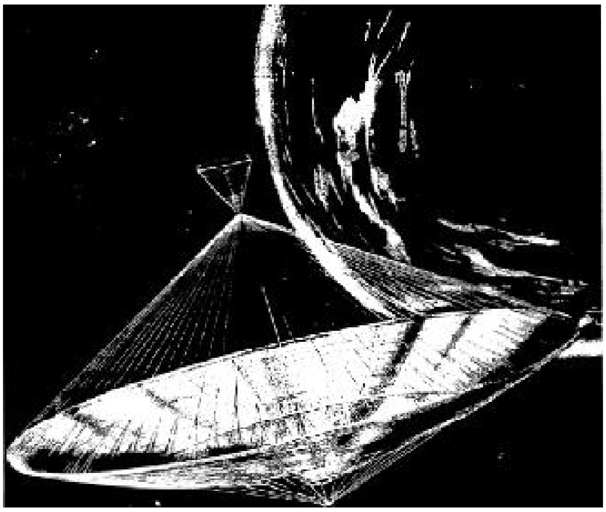

FIG. 4: LOFT fully deployed, Source: [13]

in diameter and a mass of estimated 45 tons.

The blades would be stowed in rolls, obviating the need for complex folding and packaging, and deployed and rigidized via the maintained rotation of the base craft [8]. The main advantage of the Heliogyro is its low stowage volume and ease of deployment, these advantages are in part due to the lack of boom structure required by the blades [11].

LOFT

LOFT is a concept for a large-aperture paraboloidal reflector for a low-frequency telescope. A feasibility study of the system was carried out in 1968 [12][13]. Its central component is a parabolic reflector which would be deployed and contour-stabilised by a slow spinning motion around its axis of symmetry, orbiting at an altitude of 6000 km. With a reflector diameter of 1500 m and a total height of 1020 m, the proposed reflector would have be the largest structure ever put in space. It was proposed to be constructed out of a conductive aluminium web with 0.40 m mesh width. The central deployable mast would have a diameter 3.04 m and a length of 760 m. The estimated total mass of the system was 2640 kg. The size of the packaged LOFT was estimated to be 5.5 m in diameter and 5.9 m in height. The technical analysis concluded that the burden of technology development would become primarily one of structural design [13].

At the time of conception there were a lack of practical and credible methods in order to fabricate, package, deploy in space, and maintain adequate dimensional tolerances in the structure. The selected angular velocity was a compromise: fast enough to generate sufficient tensile stresses in the net and to avoid dynamic coupling with the slower orbital frequency, but slow enough to keep the demand for orientation control torques at tolerable levels [13].

During deployment, the spin propulsion system transfers angular momentum through the front stays to the reflector. The system is programmed to provide the total angular momentum to the structure at a time when about 60% of the reflector is deployed. When the initial deployment is completed, the radial deployment continues. Coriolis forces slow the rotational speed down as the network is deployed into an approximately flat disk. Calculations performed by Schuerch and Hedgepeth show that complete deployment could be accomplished in less than two days [13]. This time would be needed due to the physical size of the disc and also the need to reduce perturbations of the disc surface during deployment that may cause failure.

3. *FUROSHIKI* AND *SUAINEADH* CONCEPTS

The idea of using space webs to build large structures in space originates from Japan under the name of *Furoshiki* net experiment - referring to a traditional Japanese cloth used to wrap belongings [14–17]. It is composed of a large membrane or net held in tension by controlled corner satellites or by spinning the whole assembly. The large aperture of the Furoshiki-structure could be used as a phased antenna or as element for solar power satellites. Kaya et al. added to the general idea of centrifugal deployment of a net, the concept of crawling robots acting or placing antenna elements onto specified locations on the net similar to spiders [14].

***Furoshiki*-1 - test of a linear deployment method**

The first *Furoshiki* experiment was performed in January 2006 with a dedicated launch of an S-310 sounding rocket from the Uchinoura launch site in Kagoshima, in the south of Japan. JAXA, the universities of Tokyo and Kobe as well as the Vienna University of Technology assisted by ESA's Advanced Concepts Team performed an in-space deployment experiment of a large triangular space web [15].

The sounding rocket was completely de-spun, three daughter sections were released radially by a spring at an initial velocity of 1.2 m/s each of these corner satellites reached their maximum distance from the the central satellite (10 m) about 8 seconds after deployment initiation sequence, deploying in a multi-body controlled manner the 130 m^2 web.

Two of the three daughter satellites had N_2 cold gas thrusters consisting of small gas canisters, an electro-magnetic valve and a small nozzle. These thrusters were used for suppressing *bound-back* effects of the daughter sections after the net is deployed to its maximum length as well as for keeping the tension of the net when the robots started to crawl on the net. They thrusted in the direction of the central mother section. The upper part of the daughter sections held a momentum wheel to keep the attitude of the daughter satellites against disturbances coming from the net or atmospheric drags, etc [15].

At the same time, the antenna elements on the mother as well as daughter sections received a weak pilot signal from the ground and automatically adapted their respective phase to send their signal in direction of the source of the pilot signal, demonstrating that the beam direction of wireless power transmission antennas could be fully and safely controlled from the ground via a pilot signal. Upon full deployment of the net, two small robots have been released from the central hub onto the net, on which they moved in a controlled and automated section. One of these robots was captured by the one-board camera from the mother section [15].

While this first *Furoshiki* experiment was very successful and achieved all the mission goals, it also underlined the complexity of the deployment of the net relying only and fully on the relative orbits of the daughter sections, which thus have to incorporate active thrusters (to avoid re-bouncing) and an attitude control system. Based on the analysis of the experiment, two studies were conducted in the Ariadna frame in order to further the theoretical understanding of the impact of the net geometry, the mesh geometry and moving robots on the net on the centrifugal deployment strategies and control laws [18][19][9].

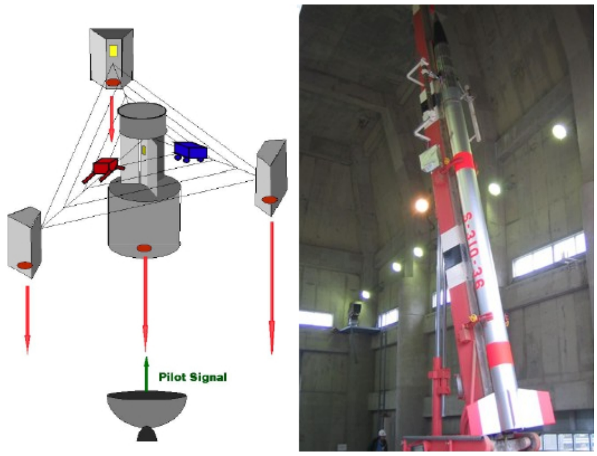

FIG. 5: Schematic view of *Furoshiki* experiment (left) and picture of S-310 sounding rocket (right).

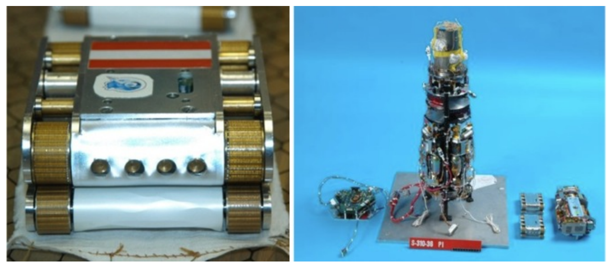

FIG. 6: Robotic web-robot *RobySpace* (left) and all *Furoshiki* components (right)

Experiments with centrifugal deployment methods

A variety of control techniques can be implemented for centrifugal deployment, having reviewed these techniques a design that implements a reaction wheel is considered to be optimum in most scenarios. Melnikov and Koshelev detail the advantages of using a reaction wheel for controlling the spin rate [6]:

- A high deployment velocity and a short deployment time is possible.
- The deployment would be smooth without coiling off-coiling on dynamic phenomena.
- A low angular velocity at the end of the deployment produces acceptable centrifugal forces.

They propose that the electric motor to power the reaction wheel should have a drooping characteristic to produce a stable, self-controlled system [6]. The reaction wheel works as a momentum exchange element i.e. if the system was slowed down, its momentum is increased to increase the angular velocity and vice versa. Melnikov and Koshelev state that by using an electric motor with a drooping characteristic, a high initial angular velocity can be obtained, a low angular velocity in the end, short deployment time and a stable and smooth deployment without entanglements and reeling up of the reflector (web). More exactly, they propose that the momentum should vary according to the MK law:

$$M = \widehat{M}(1 - \omega/\omega_0) \tag{1}$$

where $\widehat{M}$ is the initial momentum applied to the centre hub and ω_0 is the initial angular velocity of the centre hub. Melnikov and Koshelev concluded that a higher value of $K = M_0/\omega_0$ produces a more stable deployment [6]. The main advantage with the MK law in (1) is that it is directly applicable, with appropriate parameters, to centrifugal deployment using folding patterns and deployment sequences that are difficult to model accurately, e.g. the one-step deployment of space webs used in [20], Fig. 7. Two disadvantages are that torque is applied as long as the spin rate is lower than the initial spin rate ω_0 and that it is not optimized in terms of energy consumption. Therefore, two modified control laws were developed from the results of optimal control simulations [21]. To resemble the optimal control torque more, Fig. 8, while keeping the simplicity, a power of the ω-dependent factor in the MK law was introduced to derive the MK power law:

$$M = \widehat{M}\,(1 - \omega/\omega_0)^\gamma \tag{2}$$

The parameter γ should be sufficiently large to give a small ω_f, yet sufficiently small to restrain the decrease of ω in the initial deployment phase. The main drawback of the MK power law is that it does not include the final angular velocity, which is important to keep the stresses in the web small enough for the material strength, but large enough to get sufficient out-of-plane stiffness of the web. One option is to replace ω_0 with ω_f and ensure that M is non-negative [21]:

$$M = \max\left[0, \widehat{M}\,(1 - \omega/\omega_f)\right] \tag{3}$$

Eq. (3) is denoted the modified MK law. Finite element simulations using the software LS-DYNA show that the modified MK law require less energy and is effective to control the final spin rate.

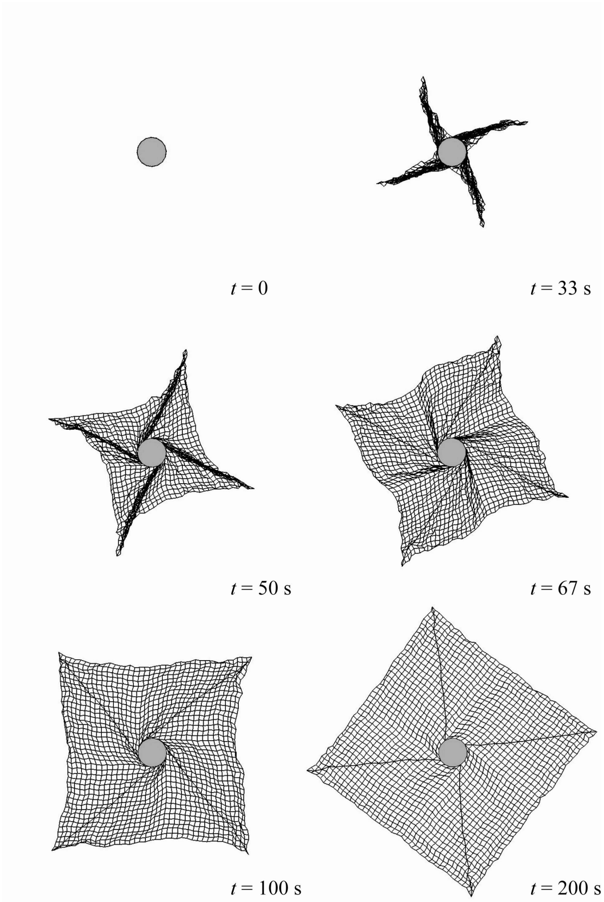

FIG. 7: Controlled one-stage in-plane centrifugal deployment of the space web, Source: [20]

Suaineadh

Suaineadh is an experiment that has been selected to be launched under the REXUS sounding rocket programme. While *Furoshiki-2* will test the deployment of an unprecedentedly large structure, Suaineadh is going to investigate and test the full net deployment dynamics on a homogeneous, small meshed web. The experiment aims to deploy a scaled square net (4 m^2) in milli gravity and stabilise it by exploiting centrifugal forces and a reaction wheel. A simple mock up of the experiment will be constructed during 2009 and ground based testing is expected to confirm the theoretical and numerical results obtained in 2007 and 2008. The currently foreseen launch date is February 2010.

Figure 9 shows an exploded view of the main components of the *Suaineadh* experiment, which will be ejected from the nose-cone section of the Rexus sounding rocket.

The experiment consists of a mother section with four daughter sections attached to it, one for each corner of the square web. The mother and daughter sections will be spun away from the mother section exploiting the residual rocket rotational speed as a launch mechanism. The rotational velocity, and the associated forces acting on the daughters and the

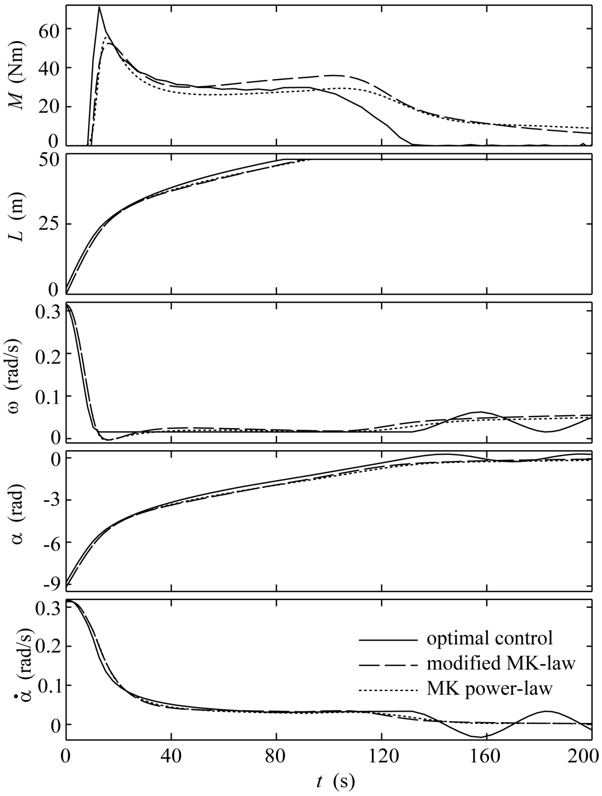

FIG. 8: Comparison of control laws for space web deployment, Source: [21].

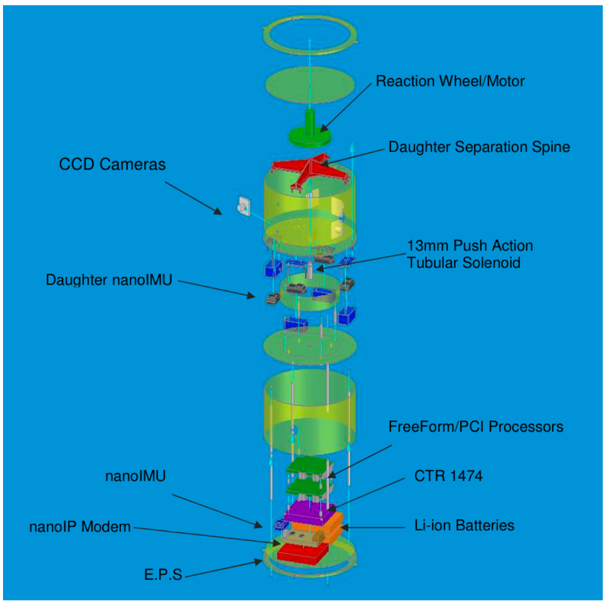

FIG. 9: Exploded view of the *Suaineadh* experiment components

net, will be controlled with a spinning wheel placed in the mother section and commanded by a dedicated CPU. Five IMU's placed on the four daughters and on the mother sections will measure the acceleration and the relative attitude of the central hub and the tips of the web. Four cameras will capture some images of the deployment process from the corners of the web.

The combination of the data coming from the cameras and from the IMU's is expected to give a complete information on the deployment and on the stabilisation of the web in mg. The Rexus experiments are launched on a unguided, spin-stabilised rocket. It is capable of taking 40 kg of student experiment modules to an altitude of approximately 100 km.*

The *Suaineadh* experiment is a joint effort of KTH, the Aerospace Engineering Department of the University of Glasgow and a group in the Mechanical Engineering Department of the University of Glasgow (led by Prof. M. Cartmell), supported and assisted by the Advanced Concepts Team of ESA.

Furoshiki-2

The *Furoshiki-2* experiment is a proposed follow-on experiment from the successful *Furoshiki-1* experiment carried out in 2006, which deployed a 140 m^2 net using an active multi-body controlled deployment mechanism. This new experiment's main goal is to deploy a much larger net in micro gravity (500-1000 m^2), using the angular momentum to deploy the web. Benefiting from the experience obtained during the first Furoshiki experiment, the secondary goals of the experiment are the demonstration of wireless energy transmission from space to Earth via retrodirective antennas on the net, possibly enough to lit a small light emitting diode and to demonstrate the ability of autonomous robots to operate in the μg environment on such a spinning net.

The experiment consists of a mother section with four daughter sections attached and a net interconnecting each of the elements. The complete package can be deployed using a simple control technique that utilizes the spin rate of the rocket and a reaction wheel similar to the *Suaineadh* experiment.

---
* Rexus programme description at the DLR website: `http://www.dlr.de/rd/en/desktopdefault.aspx/tabid-2282/3421_read-10516/`

4. FUTURE PROSPECTS

Several modifications and advancements to future space-webs are currently considered. One of these would be the use of photovoltaic fibres for the mesh to provide additional power independent from the orientation of the net to the sun. Recently published results promise 4% efficient fibres and textiles based on dye-sensitized titan, a technology developed at the Swiss EPFL [22][23]. The dye, which is anchored to the titania nanoparticles, absorbs light and injects an electron into the titania; the electron percolates through the titan until it reaches the primary electrode. Electrons re-enter the cell at the counter electrode where they reduce the tri-iodide anion to iodide; the latter diffuses to the oxidized dye and reduces it back to its neutral state thus completing the circuit [24].

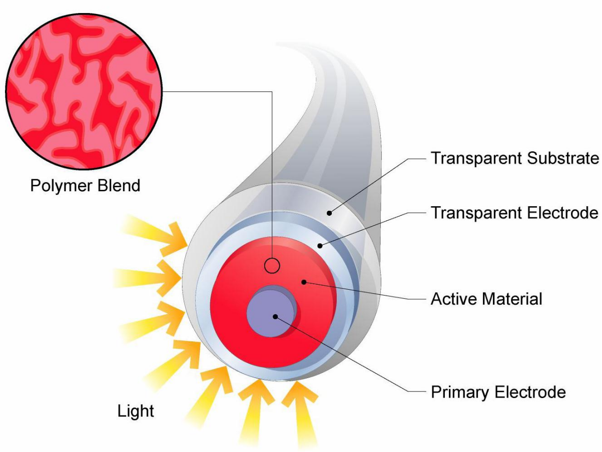

FIG. 10: Illustration of a PV fiber, Source: [25]

In recent testing the mechanical and electrical characteristics of the fibers were analysed. This testing concluded that local damage of the fiber is shown to have far less influence on the PV efficiency than damage induced by tensile deformation. This indicates the feasibility of producing textiles from such fibers, provided the fiber tension is well controlled. Electrically the fibers showed that power loss was primarily linked to the loss of adhesion of the dye coating, rather than tensile failure of the dye coating. The critical strain for the onset of significant functional degradation was 1%, but the fiber continued to show a significant power output up to about 2.5% strain [26], which seems to make it suitable for space net applications.

5. CONCLUSION

The largest structure launched and built in space so far is the International Space Station (ISS), launched in modules and assembled in low Earth orbit in a complex, lengthy and expensive manner by astronauts and robotic arms. Deployable mechanisms for increasingly larger solar panels (e.g. to cover the power need of large telecommunication satellites) constitute a key technology for modern space applications. Very thin, light-weight structures such as solar sails, thin film solar panels for very large solar panels and very large antennas for microwave frequencies from geostationary orbit require a new approach for their deployment and construction. Using angular momentum has been suggested since many decades and tested on few prototype space missions.

In this paper, recent studies and two sounding rocket experiments to advance the understanding of such centrifugally deployed meshed structures have been described.

[1] J. Mankins, "Approaches to strategic research and technology (R&T) analysis and road mapping," *Acta Astronautica*, vol. 51, no. 1-9, pp. 3–21, 2002.

[2] J. Mankins, H. Feingold, M. Strancati, A. Friedlander, M. Jacobs, D. Cornstock, C. Christensen, G. Maryniak, and S. Rix, "Space solar power - a fresh look at the feasibility of generating solar power in space for use on Earth," Tech. Rep. SIAC-97/1005, NASA, SAIC, Futron Corp., April 1997.

[3] F. Tatsuhito, H. Suzuki, and M. Mori, "Demonstration missions of space solar power systems," in *ISTS'08*, no. 2008-r-1-07, 2008.

[4] ESA, L. Summerer, ed., *Proceedings - Solar Power from Space - SPS'04*, (Granada, Spain), ESA, ESA, June 2004.

[5] NASA, "International space station assembly - a construction site in orbit," Tech. Rep. IS-1999-06-ISS013JSC, NASA, 1999.

[6] V. M. Melnikov and V. A. Koshelev, *Large space structures formed by centrifugal forces.* ESI Book Series, Earth Space Institute, 1998.

[7] C. McInnes, *Solar sailing: technology, dynamics and mission applications.* Astronomy and Planetary Sciences, Springer-Verlag Telos, 1999.

[8] J. Grossman, "Solar sailing: The next space craze?," *Engineering & Science*, vol. 4, 2000.

[9] M. Gärdsback, *Deployment Control of Spinning Space Webs and Membranes.* PhD thesis, Royal Institute of Technology, Stockholm, November 2008.

[10] R. H. MacNeal, "The heliogyro - an interplanetary flying machine," Tech. Rep. ARC-R-249, Astro Research Corporation, March 1967.

[11] L. Friedmann, *Starsailing: Solar Sails and Interstellar Travel.* John Wiley & Sons, 1988.

[12] H. Schürch and J. M. Hedgepeth, “Large low-frequency orbiting radio telescope,” Tech. Rep. No. ARC-R-282, Astro Research Corporation, October 1968.

[13] J. M. Hedgepeth, “Dynamics of a large spin-stiffened deployable paraboloidal antenna,” *Journal of Spacecraft and Rockets*, vol. 7, no. 9, pp. 1043–1048, 1970.

[14] N. Kaya, M. Iwashita, S. Nakasuka, L. Summerer, and J. Mankins, “Crawling robots on large web in rocket experiment on Furoshiki deployment,” *Journal of the British Interplanetary Society*, vol. 58, pp. 402–406, November/December 2005.

[15] N. Kaya, M. Iwashita, K. Tanaka, S. Nakasuka, and L. Summerer, “Rocket experiment on microwave power transmission with Furoshiki deployment,” *Acta Astronautica*, vol. 65, no. 1-2, pp. 202–205, 2009.

[16] N. Kaya, S. Nakasuka, L. Summerer, and J. Mankins, “International rocket experiment on a huge phased array antenna constructed by Furoshiki satellite with robots,” in *ISTS'04*, (Miyazaki, Japan), 2004.

[17] S. Nakasuka, T. Aoki, I. Ikeda, Y. Tsuda, and Y. Kawakatsu, “Furoshiki satellite - a large membrane structure,” *Acta Astronautica*, vol. 48, no. 5-12, pp. 461–468, 2001.

[18] G. Tibert and M. Gärdsback, “Space webs,” Ariadna Final Report 05-4109a, ESA Advanced Concepts Team, 2005.

[19] D. McKenzie, M. Cartmell, G. Radice, and M. Vasile, “Space webs,” Ariadna Final Report 05-4109b, ESA Advanced Concepts Team, 2006.

[20] M. Gärdsback and G. Tibert, “Deployment control of spinning space webs,” *Journal of Guidance, Control and Dynamics*, vol. 32, no. 1, pp. 40–50, 2009.

[21] M. Gärdsback and G. Tibert, “Optimal deployment control of spinning space webs and membranes,” *Journal of Guidance, Control and Dynamics*, vol. 32, no. 5, pp. 1519–1530, 2009.

[22] P. Patel, “Toward cheaper, robust solar cells,” *Technology Review*, March 2008.

[23] D. Kuang, S. Uchida, R. Humphry-Baker, S. M. Zakeeruddin, and M. Graetzel, “Organic dye-sensitized ionic liquid based solar cells: Remarkable enhancement in performance through molecular design of indoline sensitizers,” *Angewandte Chemie International Edition*, vol. 47, no. 10, pp. 1923–1927, 2008.

[24] R. Gaudiana, R. Eckert, J. Cardone, J. Ryan, and A. Montello, “Photovoltaic fibers,” *Organic Photovoltaics VII - Proceedings of the SPIE*, vol. 6334, p. 633401, 2006.

[25] Konarka Technologies Inc., “Konarka to develop photovoltaic fabric with leading swiss university,” tech. rep., Konarka Technologies Inc., 116 John St., Lowell, Massachusetts 01852, February 2005.

[26] J. Ramier, C. G. Plummer, Y. Leterrier, J. .-A. E. Månson, B. Eckert, and R. Gaudiana, “Mechanical integrity of dye-sensitized photovoltaic fibres,” *Renewable Energy*, vol. 33, no. 2, pp. 314–319, 2008.