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Post-launch analysis of the deployment dynamics of a space web sounding rocket experiment

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ABSTRACT

Lightweight deployable space webs have been proposed as platforms or frames for a construction of structures in space where centrifugal forces enable deployment and stabilization. The Suaineadh project was aimed to deploy a 2×2 m^2 space web by centrifugal forces in milli-gravity conditions and act as a test bed for the space web technology. Data from former sounding rocket experiments, ground tests and simulations were used to design the structure, the folding pattern and control parameters. A developed control law and a reaction wheel were used to control the deployment. After ejection from the rocket, the web was deployed but entanglements occurred since the web did not start to deploy at the specified angular velocity. The deployment dynamics was reconstructed from the information recorded in inertial measurement units and cameras. The nonlinear torque of the motor used to drive the reaction wheel was calculated from the results. Simulations show that if the Suaineadh started to deploy at the specified angular velocity, the web would most likely have been deployed and stabilized in space by the motor, reaction wheel and controller used in the experiment.

1. Introduction

Structurally flexible deployable space structures are studied due to their light weights and high packaging ratios. A space web is a flexible structure tensioned by thrusters or by centrifugal forces in a spinning assembly. These webs can act as lightweight platforms for construction of large structures in space [1–3]. The idea of using space webs originates from the Japanese “Furoshiki Satellite” [4–8], a large membrane structure. In a previous sounding rocket experiment, three corner satellites were released radially by separation springs from the center satellite. Thrust control was applied to prevent recoiling. However, the web entangled due to out-of-plane motions or end of deployment shocks. A more reliable deployment control is desirable [9–12].

Centrifugal deployment is a feasible technique to construct large structures in space. The attitude and the shape are controlled by corner satellites using centrifugal forces by rotating the central satellite. Centrifugal deployment has been widely studied since the 1960s [13]. For example, simple control methods are used to obtain a stable deployment [9], geometrical stiffness can be induced by centrifugal forces for lightweight, flexible material without requiring stiff members to maintain their shapes [14], possible lower cost thanks to no rigid frame, and ideally reliable automatic deployment in orbit with low power consumption [15]. Spin stabilization is one of several strategies for space webs. The rotational inertia dominating in the plane of the spinning satellite keeps the out-of-plane motions of the web small.

In the past years there have been attempts at launching lightweight solar-sails. IKAROS [16], the world's first successful solar sail, was deployed by centrifugal forces. The main hardware components were the electrically controlled panels, central mechanism deployment module and sails. Normally, the centrifugal force deployment of a space web could be split into two steps [3,16,17,18]: in the first step, booms or panels are extended slowly and quasi-statically controlled by guide rollers or other mechanisms; in the second step, the web is extended to a final flat shape by the centrifugal force. However, rollers or other extending mechanisms may take up too much space for small deployable structures. A one-step deployment method was thus identified as a possible choice for future web deployment without complicate extending mechanisms [11,12,19]. This method can also be used as a backup when sails or webs fail to deploy by roller mechanisms or stored strain energy. Therefore, it is important for future spinning webs to establish a feasible technique for a one-step deployment.

The difficulties in deployment control in space are web recoiling and entanglement. To reduce the risk of entanglement, an adequate choice of folding pattern and a proper control of

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deployment speed of the web are required [10]. A star-like folding patterns is a promising candidate for centrifugal force deployment. Experiments are required to verify the viability of the proposed folding and deployment. However, the zero-g condition in space is difficult to simulate on ground tests for large scale web deployment [3,20]. Computational simulations, e.g., the finite element method [11,21], multi-particle models [19,22] and analytical methods [9,11,12,23] have been used to analyze the dynamics of centrifugal force deployment. Ground scaled model experiments [20,22] are also used to compare with simulations. However, near zero-g experiments are still required to validate the one-step deployment by centrifugal forces.

A team from the University of Strathclyde (Glasgow, UK), the University of Glasgow (Glasgow, UK) and KTH Royal Institute of Technology (Stockholm, Sweden) was formed in 2010 to deploy a space web, the Suaineadh experiment, in milli-gravity conditions as a test bed of the one-step deployment concept. It was supported by the Advanced Concepts Team of the European Space Agency (ACT/ESA), the Swedish National Space Board (SNSB), the German Aerospace Center (DLR) and the Swedish Space Corporation (SSC) through the Rocket Experiments for University Students (REXUS) programme. The aims of the experiment were to deploy and stabilize a space web by means of the centrifugal forces acting on the spinning assembly. The design of the mechanical, communication and electrical systems and some lessons learned from the project is described in [24–26].

Suaineadh was ejected from the nosecone of the REXUS-12 sounding rocket and was able to use 140 seconds of weightlessness by flying in a parabolic trajectory. Four small daughter sections were attached to four corners of a square web, Fig. 1, and released from the initial folding state from the central hub. An active control method was used by a reaction wheel with the feedback from an inertial measurement unit (IMU) in the center hub. Four other IMUs were installed in daughter sections in order to provide information of the motion. Operational data were accumulated visually via cameras and on-board sensors. Suaineadh was deployed at an altitude of approximate 80 km in March 2012. Unfortunately, it could not be located after the impact, but was luckily found by chance almost 18 months later in September 2013, close to the predicted position in the impact zone. All data could be recovered from the on-board memory.

The objective of this paper is to analyze the result from the Suaineadh experiment and evaluate if the simple control law was effective. Various effects, like the web coiling direction and angular velocities, are discussed. A numerical model, previously used in the design, was also used for results analysis. It is emphasized that the reconstruction of the deployment dynamics is done with the limited information provided by the IMUs and the onboard cameras. Results are extracted from video footage as the IMU fixed to the central hub did not work during launch and the moment of inertia of the hub was not measured due to budget and time constraints. We hope that our lessons reported here could provide useful information for future similar projects.

The remainder of this paper is outlined as follows. In Section 2, an overview of the Suaineadh experiment design is presented. Section 3 describes the analytical model for the web satellite. In Section 4, experiment and simulation results are presented and discussed. In Section 5, conclusions of the experiment are presented.

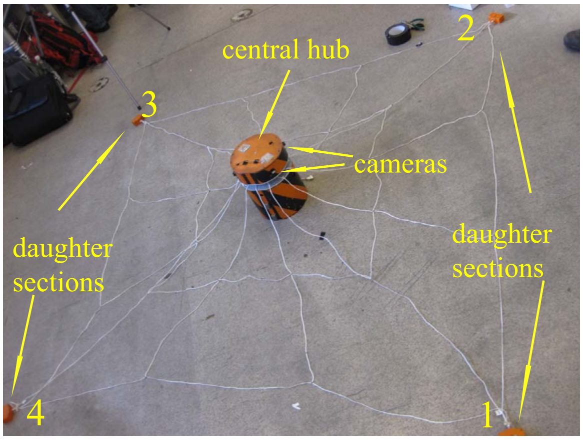

Fig. 1. Central hub and daughters (CHAD) with attached web at the launch campaign.

2. Experiment design

The Suaineadh experiment could be divided into two distinct parts: (i) the central hub and (ii) the web with four corner daughter sections, Fig. 1. The central hub was responsible for controlling the deployment, stabilizing the web deployment and recording measurements. Four cameras on the central hub were used to record the web deployment and stabilization phases. The space web was folded around the central hub in a star folding pattern [12] and deployed by centrifugal forces acting on the attached daughters.

2.1. Space web

In the beginning of the project, the web was supposed to be a non-permeable membrane. But the residual atmospheric drag at the ejection altitude would cause the membrane to fold out-of-plane according to finite element simulations. A membrane or even dense web would impair and decreased the significance of the acquired scientific data. Reasons for this were mainly because of the high speed, 500–600 m/s, of the central hub and daughters (CHAD) during deployment and the still significant air density around the apogee of the rocket trajectory. The REXUS-14 experiment Space Sailors [27] successfully deployed a solar sail on the top of the sounding rocket REXUS-14 at an altitude of 81 km in May 2013, but the sail collapsed under the aerodynamic pressure at the beginning of the descent as expected. In the end, a coarse web of braided Spectra cord was chosen, Fig. 1. This skeleton type web could overcome the problem of air pressure and still produce useful scientific data for post flight analysis.

2.2. Spin direction of the hub and coiling direction of the web

Fig. 2(a) shows the REXUS-12 rocket spinning in a positive roll. The de-spinning mechanism of the rocket was intrinsically important to the control method used for the web deployment. If the experiment was mounted on a rocket which did not de-spin, assuming the angular velocity initially was 3–4 Hz, the time span for full deployment would be too short to guarantee post-deployment stability, and a larger torque was required to transfer angular momentum from the reaction wheel to the hub. It could also be concluded from analysis that the hub started to recoil very early in the deployment process because the hub was rotating too fast.

After the rocket de-spun, the spinning frequency was almost 0 Hz. Of course, if the web deployment would initiate at this speed, no web deployment would occur due to the lack of centrifugal forces acting on the daughter sections. Therefore the reaction wheel was used to spin up the CHAD before web deployment started.

Before launch, the reaction wheel polymer bearings were preloaded with a very small force to eliminate play in the axial