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Inflatable shape changing colonies assembling versatile smart space structures ☆

Thomas Sinn [a,*], Daniel Hilbich [b,1], Massimiliano Vasile [a,2]

[a] Advanced Space Concepts Laboratory, Department of Mechanical & Aerospace Engineering, University of Strathclyde, Level 8, James Weir Building, 75 Montrose Street, G1 1XJ Glasgow, United Kingdom

[b] Microinstrumentation Laboratory, Reconfigurable Computing Laboratory, School of Engineering Science, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia, Canada V5A 1S6

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ABSTRACT

Various plants have the ability to follow the sun with their flowers or leaves during the course of a day via a mechanism known as heliotropism. This mechanism is characterised by the introduction of pressure gradients between neighbouring motor cells in the plant's stem, enabling the stem to bend. By adapting this bio-inspired mechanism to mechanical systems, a new class of smart structures can be created. The developed overall structure is made up of a number of cellular colonies, each consisting of a central pressure source surrounded by multiple cells. After launch, the cellular arrays are deployed in space and are either preassembled or alternatively are attached together during their release or afterwards. A central pressure source is provided by a high-pressure storage unit with an integrated valve, which provides ingress gas flow to the system; the gas is then routed through the system via a sequence of valve operations and cellular actuations, allowing for any desired shape to be achieved within the constraints of the deployed array geometry. This smart structure consists of a three dimensional adaptable cellular array with fluid controlling Micro Electromechanical Systems (MEMS) components enabling the structure to change its global shape. The proposed MEMS components include microvalves, pressure sensors, mechanical interconnect structures, and electrical routing. This paper will also give an overview of the system architecture and shows the feasibility and shape changing capabilities of the proposed design with multibody dynamic simulations. Example applications of this lightweight shape changing structure include concentrators, mirrors, and communications antennas that are able to dynamically change their focal point, as well as substructures for solar sails that are capable of steering through solar winds by altering the sails' subjected area.

1. Introduction

One of the most expensive features of a modern space mission is the rocket launch [1]. Launch costs can be decreased by reducing the mass and the volume of the spacecraft, which can be achieved either by launching another satellite in the same payload fairing or by delivering the payload using a less powerful, and therefore less expensive, rocket. A viable option to decrease the volume and mass of a space craft is the use of deployables for large structures such as solar arrays, reflectors, concentrators, or even space habitats [2]. A widely used deployable structure today is the umbrella deployable, which is effective but relatively unreliable due to a large number of moving parts [3]. More exotic systems use electrostatic forces to

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* Corresponding author. Tel.: +44 7411 246 531.
E-mail addresses: thomas.sinn@strath.ac.uk (T. Sinn), dhilbich@sfu.ca (D. Hilbich), massimiliano.vasile@strath.ac.uk (M. Vasile).
[1] Tel.: +1 778 782 4923.
[2] Tel.: +44 141 548 2326, fax: +44 141 552 5105.

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deploy a structure [4] or a spinning assembly to deploy a membrane or web using centrifugal forces [5–6]. A very promising field is the use of inflatable structures due to their simple and reliable deployment mechanism and low storage volume. Inflatable space structures have been around since the 1950s, for example with the ECHO II satellite [7] which deployed an inflatable satellite over 40 m in diameter. Since that time, interest in inflatable structures has steadily increased due to their potential to be used in large-volume space habitats, which could play an important role in the manned exploration of our solar system. Aside from using inflatable structures, additional mass and volume can be decreased by enabling a space structure that is able to serve multiple purposes during its mission life. An example of this is a solar energy collector that could serve as a communication antenna by adjusting its shape, and thereby its focal point.

In order to achieve multipurpose structures, extensive research has been undertaken in the field of structures that can change their properties by an external excitement [8]. For example, structural deformation could be induced through an applied electric field, or a change in stiffness could be achieved through an applied temperature change. Unfortunately, most of the adaptive materials available today require a constantly applied actuation force to obtain the desired shape, which results in high power consumption. Other devices are bi-stable, using a short actuation impulse to switch between two different stable states. It is especially important that a space structure can stay in the deformed shape without the necessity of constantly driven actuation due to onboard power constraints. Over the last half century, continuous research and development work has been undertaken in the field of pneumatic devices that mimic biological muscles for actuating mechanical systems, for example in high lift surfaces on planes [9]. Pneumatic muscles were created that shorten when inflated and thereby become capable of lifting substantial loads [10]. Especially interesting for the proposed application are the methods employed by R. Vos [11],[12] and his work on a morphing airfoil that utilises gas filled elastic pouches that vary their diameter depending on the pressure of the environment. Such an airfoil is able to independently adapt its shape depending on the altitude without the need for further control.

Previous work by the authors on the development of a deployable smart structure [13] borrows from nature's concept of heliotropism [14], which is demonstrated by the head of a flower following the path of the sun during the day. This comparably rapid shape change in the plant is executed by motor cells in a flexible segment of the plants stem. These motor cells pump potassium ions into the tissue of neighbouring cells, increasing the cell's torpor pressure. This pressure change alters the geometry of the cell and enables the plant to bend its flower head. This principle can be adapted to a mechanical structure capable of changing its shape by employing an array of cells, each with the capability of inflating and deflating independently similar to the above-mentioned morphing airfoil. The resulting volume change in individual cells results in intercellular pressure gradients and a global shape change of the structure [15]. Since these structures are designed to be used in space under the influence of only small gravitational forces, it is possible to design an extremely light, flexible structure with the capability of changing its shape with very low internal differential pressures in the order of a few hundred Pascal. Fig. 1 shows the DARPA/SRI International energy chart of exciting actuators with their maximum strain and blocked stress. Smart inflatable space structures are found in the bottom right corner of the chart due to their high deformation capability of up to 200% (employing hyper-elastic materials like silicon rubber) and very low blocked stress capability when used in a micro gravity environment with only minor, slow perturbations.

The bio inspired concept of a lightweight structure consisting of up to thousands of modular colonies capable of changing their shape is presented in the following sections. The paper outlines the design of the inflatable hyper-elastic cells and their shape changing mechanism, and also includes detailed subsystem descriptions.

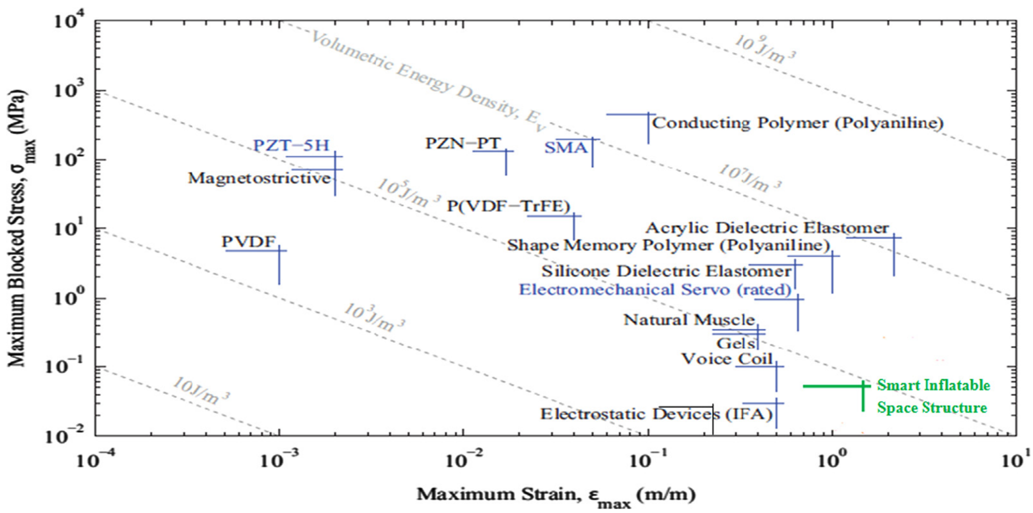

Fig. 1. SRI International/DARPA specific energy chart of existing actuators and the developed smart inflatable space structure (original from Ref. [11]).