

SELF-FOLDING SMART STRUCTURE INSPIRED BY NATURE'S HELIOTROPISM

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ABSTRACT

Various plants are capable of comparably fast movements due to so called motor cells able of changing their internal pressure causing the flower head to rotate towards the sun. This principle, known as heliotropism, can be adapted by assembling an array of inflatable cells with highly flexible walls interconnected by micro pumps and valves to facilitate a pressure change between cells. Due to this internal pressure change, the volume of specific cells will vary causing the structure to deform and bend. By producing an array of a few cells thick but hundreds of cells long and wide, a plate that is able to change its shape can be created. The idea presented in this paper is to combine the folding capability of the developed smart plate with the origami principle of creating complex shapes from a single sheet of material without the need of irreversible cutting.

1. INTRODUCTION

There are mainly two factors which drive the costs of space craft's nowadays [1]. The first one is the launch costs which are mainly governed by the size and the mass of the object being launched into space. The second factor is the complexity of the spacecraft and the amount of systems that are needed to fulfil given mission tasks. A means to overcome these constraints is the use of deployable smart structures. These kinds of structures are capable of being stored in a volume a fraction of their flight dimensions. Additionally, they are able to change their properties to adapt to the environment or different tasks. An example of such a structure could be a solar concentrator dish which is stored during launch in the rocket fairing with a fraction of its in orbit dimensions. Once the structure is deployed, it has the capability to alter its curvature to adjust the focal point depending of the position of the sun. Research at the University of Strathclyde has been undertaken in this field since 2010 which lead to the development of a variety of inflatable structures capable of changing their shape. Already three experiments have been launched on sounding rockets and balloons to investigate the deployment behaviour of these smart inflatables and the functionality of an all inflatable

shape changing satellite with the electronics of a cube satellite disaggregated over its surface [2]. As a follow up on this research, this paper will discuss the capability of the developed structure to obtain more complex shapes.

2. BIOINSPIRED STRUCTURE

Over millions of years nature optimised it's organisms to survive the harsh conditions on Earth. This evolution did not necessarily mean the survival of the strongest or biggest but more the survival of the best adapted. To take advantage of the millions of years of development, more and more systems in our daily life are inspired by nature. A popular example are lotus effect paints enabling water and dirt repelling surfaces. A biological principle which is the inspiration for the developed concept is called heliotropism.

2.1. Heliotropism

Certain flowers have the capability to follow the path of the sun over the sky during a day with their flower head [3]. By changing the turgor pressure between adjacent cells in the plant's stem, called motor cells, the stem of the plant flexes [4]. With this mechanism, the flower has the ability for comparably fast movement of its head without the need of growing additional cells. Due to the simplicity of the principle, the movement due to pressure change seems perfect for the application on deployable space structures.

2.2. Mechanical Analogue

The cells of plants can be taken as a blueprint to develop a mechanical structure that is capable of changing its shape. For the mechanical analogue, a structure was created consisting of hundreds to thousands of cells. Each cell can be inflated separately and expand its volume to over 300-900% of its initial stored volume. The proper selection of material is important to obtain a structure capable of large deformations. A material class that offers such a high elastic range are hyperelastic materials like silicon rubbers.

The volume change of the cells corresponds directly to the amount of air particles or fluid within each cell. By

adding micro pumps or valves fabricated with piezo-electrics or MEMS (Microelectromechanical systems) technology, neighbouring cells become capable of exchanging molecules between each other [5]. By creating an array hundreds of cells wide and long and a few elements thick, a thin smart sheet can be formed. The shape change within this sheet is undertaken by transferring air or fluid from certain cells in the bottom layer to the top layer or vice versa. This shifting of molecules will lead to a volume decrease of the bottom cell and a volume increase of the top cell resulting in a buckling of the sheet. Coordinated actuation can be used to control this buckling to form the desired deformation or fold line.

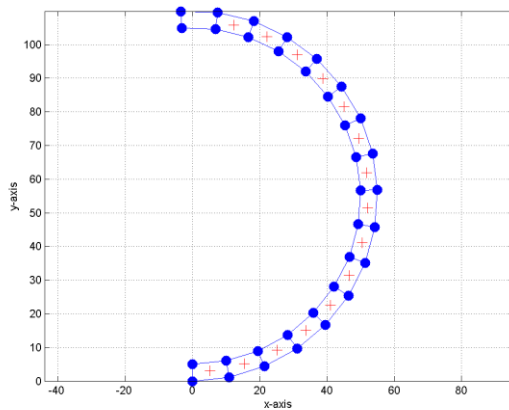


Figure 1. Static 2D plot of actuated cell array forming a 180 degree fold

To achieve a simple 180 degrees folding line over the entire sheet, cells in parallel lines need to be actuated. Fig. 1 shows the 2D static plot of the deformed two cell thick array creating a 180 degree fold. Each cell is represented by a blue dot in Fig. 1. It can be seen that the actuation occurs from the inside line to the outside line of cells with increase of volume of the outer cells. With a given actuation capability of 20% of its original length, a full 180 degree fold will require 16 cells.

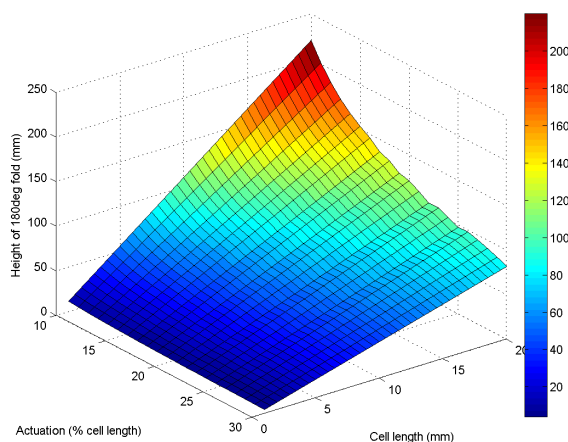


Figure 2. Height of 180 degree folds depending on actuation and initial cell length

Fig. 2 shows the relation of achievable fold thickness of a 180 degree fold in relation to the initial cell diameter and the actuation capability of the used cell. This graph highly depends on the used material and size of the system. The graph in Fig. 2 was created for a Mylar cell deformable structure with 15cm cell diameter. The scalable nature of the developed structure enables the creation of a system that is applicable from nano scale up to large space structures. The limiting factor today is only the fabrication technology for miniaturised systems.

3. ORIGAMI MATHS

Origami is a traditional Japanese art of paper folding originating in the 17th century AD. Origami is the art to create more or less complex sculptures or shapes via folding from one single sheet of paper without the use of adhesive or irreversible cutting. Especially this aspect makes it very interesting for using within the smart structure approach undertaken here. The free flying smart sheet of paper would have the capability to transform itself into any desired shape. There are only four main laws behind origami math which were outlined by Robert Lang [6]:

1. Areas joint by a fold line can be colour coded in two colours and fields with the same colour will never be adjacent.
2. At any interior vertex, the number of mountain to valley folds must always differ by two.
3. Alternate angles around a vertex sum up to a straight line.
4. However sheets are stacked during folding, a sheet can never penetrate a fold.

With these simple rules, Mr Lang developed a mathematical code which is capable of creating folding pattern for any complex shape. The left side of Fig. 3 shows the crease lines created to fold the beetle sculpture in Fig. 3 right side.

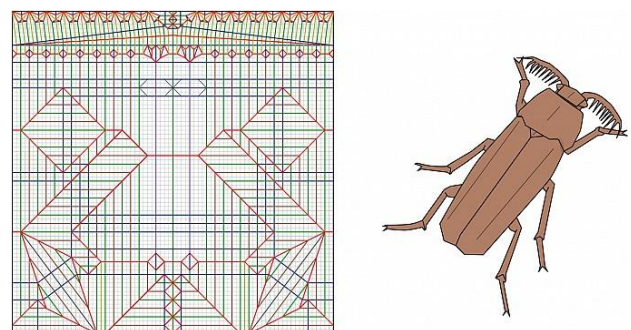


Figure 3. Crease pattern (left) and corresponding sculpture (right) (source: R. Lang [7])

This can be used to create crease patterns which can act as the blueprint to instruct the developed adaptive sheet to deform its flat shape into more complex application dependent shapes.

4. BENCHTEST MODEL

To prove the functionality of the concept and to validate the simulations, a bench test model was created. Previous research at the University of Strathclyde was focused on the inflation characteristic of smart structures consisting of Mylar and Kapton cells [8]. But due to high deformation characteristic requirements for this application, a hyperelastic material bench test model needed to be created to enable the required large deformations of the cells. The silicone rubber used for the bench test model is capable of elongating up to 900% of its original length before breaking and is useful at a temperature range of -53°C to 232°C , making it suitable for the manufacture of inflatable structures for space applications [9]. Nevertheless, further research has to be carried out into the materials property alteration due to UV radiation or atomic oxygen degradation occurring in the space environment.

4.1. Fabrication

The tools used for the casting of the inflatable cells were designed specifically for this purpose and manufactured using a 3D printer. It was found that the best way of manufacturing was in two parts; a top structure involving the cavity for the air to travel through and a base layer of thin silicone rubber that could then be adhered to make an enclosed assembly.

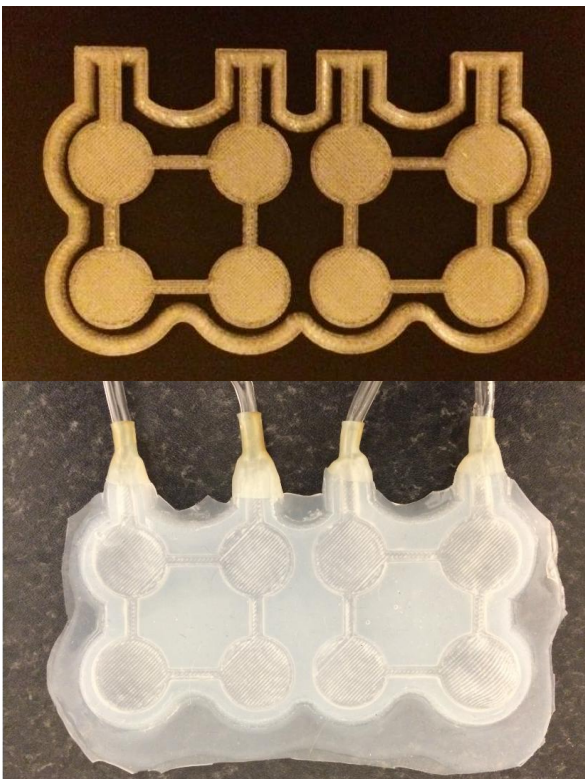


Figure 4. 3D printed mold (top) used to cast 4x2x1 cell structures (bottom)

The two layers were adhered using another layer of liquid silicone rubber mixture and allowing it to cure in order to seal the layers together. Several types of tools

were tested in order to manufacture working prototypes of the inflatable cells however it was found that moulds such as the one shown in Fig. 4 top delivered consistent results (see Fig. 4 bottom) and was the most straightforward to use. It would be desirable to decrease the thickness of the cell walls in order to reduce the quantity of silicone used by adapting the mould however this causes difficulties in the fabrication process, often resulting in the silicone rubber being ripped on removal from the mould. If this problem was to be tackled however it would improve the inflation of the cells and make the structure more lightweight and compact.

4.2. Inflation

The inflation of the cells was undertaken with syringes to control the amount of air within each cell. The inflation of two adjacent cells can be seen in Fig. 5.



Figure 5. Two fully inflated hyperelastic cells

The quality of the inflated shape highly depends on the fabrication method. Issues might arise due to air leaks between the air inlet and silicone cells and the limited volume of air that could be input at any one time, the cells may not reach their full level of inflation. However, also in these cases a diameter increase in the range of 200-300% can be observed. One of the manufacturing limitations is the even spreading of silicon rubber in the moulds causing variation in the thickness of the cell walls and resulting in uneven inflation of cells (as can be seen in Fig. 6).



Figure 6. Inflated 4x2x1 cell array

4.3. Shape Changing Structure

For the shape change experiments two 4x2x1 layers (Fig. 6) were joined by using a thin layer of silicon rubber to form a 4x2x2 array. To enable the shape change of the bench test model, the channels in between the cells can be closed or opened with a clip to allow or constrain airflow between the cells similar to the use of MEMS valves. To counteract the effects of gravity, the bench test model was hung by strings attached to two points. The attachment of the gravity off-load system can be seen in Fig. 7 between the first and the second and the third and the fourth cell.

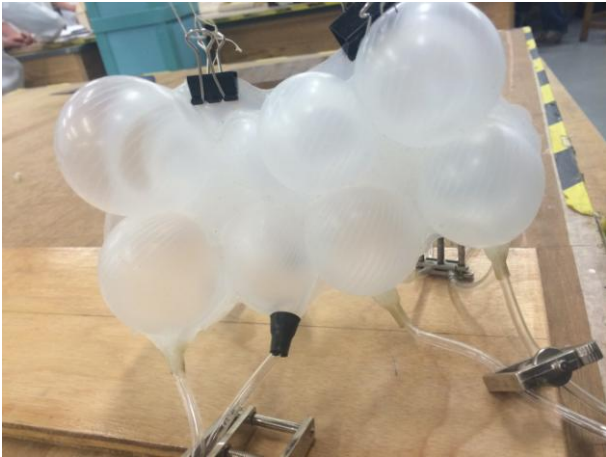


Figure 7. Shape alteration due to different cell volumes

Inflating the cells causes different cell volumes resulting in structure deformation. This can be clearly seen in Fig. 7 where just the front 4x2x1 array is inflated and the top middle cell to the left is less inflated than the surrounding cells. This actuation causes the array to form a positive curvature of the centre line.

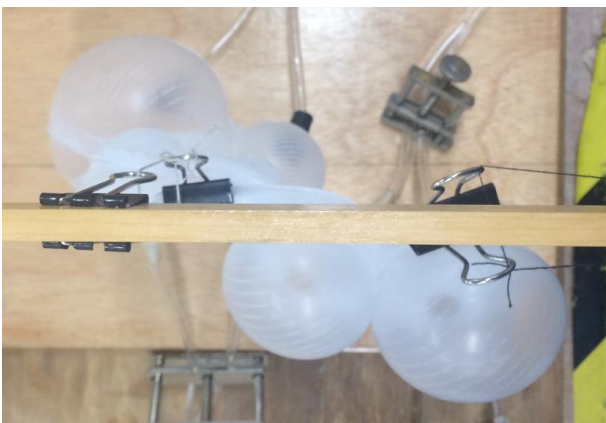


Figure 8. Opposite actuation of cells

By inflating the two opposing four cells of the array, an S-shaped structure can be obtained. This deformation can be seen in Fig. 8. Bench test models with higher actuation and deformation capabilities and thereby more cells are possible but they require a proper gravity off-loading rig and a lighter smaller air distribution system between the cells.

5. SIMULATION

The biggest limitation of the bench test models are currently the fabrication and actuation techniques. For this reason a simulation tool needed to be developed to simulate structures of hundreds to thousands of cells. Another restriction especially for ground based bench tests of lightweight space structures is the perturbation caused by gravity. Simulating the structure in gravity free space is a means to overcome this constrain.

A multi body dynamic code has been developed [10] where the cells are discretised as a mass spring damper system. Each cell is discretised as a cube consisting of 12 torsion-bending beam elements with the cell's mass distributed to the corners of the cubes. The volume change and therefore the actuation of the cells are facilitated by applying an internal force on the walls of the cells. The equation of motion is solved continuously with changing cell properties and external perturbations like gravity or other disturbances. With this code is possible to simulate the inflation and actuation behaviour of these large structures in orbit.

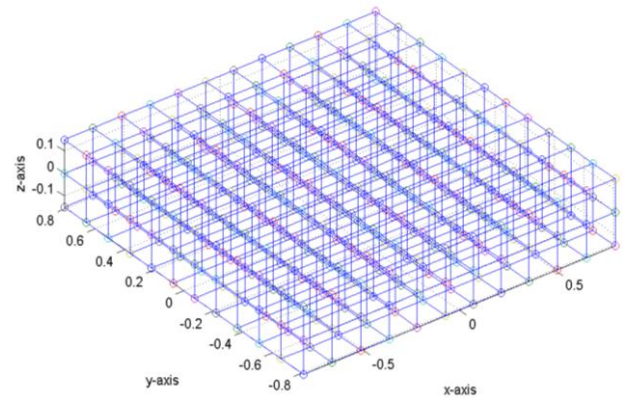


Figure 9. Simulation of inflated 11x11x2 cell array

At the beginning of the simulation all cells are uninflated and stored at a fraction of their deployed size. Fig. 9 shows the result of an 11x11x2 cell array after inflation with all cells inflated with the same rate. From this initial configuration, the cells can be commanded according to the folding blueprint to form any desired shape.

To show the functionality of the concept, a simplified array of 20x2x2 cells was created. This array was free flying in space and actuated to create a fold line in the middle of the array.

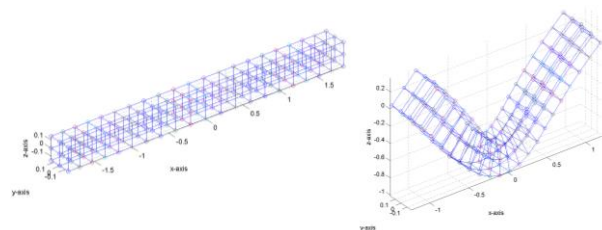


Figure 10. Folding of a 20x2x2 array

The left of Fig. 10 shows the free flying array after inflation. After the residual movements of the inflating structures were damped, the six middle cells of the array were actuated by transferring one half unit of air mass from the top to the bottom cells over a time of four seconds. The right side of Fig. 10 shows the resulting deformation of the array after 20 seconds of simulation time. As mentioned before, the code is capable of simulating the full dynamics of the system. As a result of this, the deformation of the structure introduces a momentum to the system which could be used for attitude control of the attached space craft.

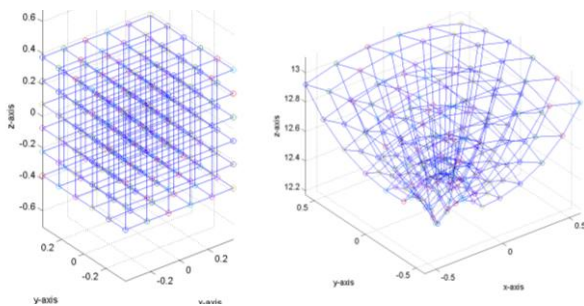


Figure 11. Deformation of a smart 5x5x5 cube

Fig. 11 shows the simulation of a 5x5x5 cube that forms two double curved surface once actuated. The actuation of this cube was done by transferring fluid from the bottom two to the top two layers to create a pressure gradient over the two directions. The result obtained by this simulation is very useful to understand the interactions of cells in the vertexes of the origami crease pattern where valley and mountain folds meet.

6. CONCLUSIONS

A concept of a morphing deployable structure was presented in this paper. The design of the smart matter is inspired by nature's heliotropism and its interconnected shape alternating cells enabling a flower head to turn. A mechanical analogue was created with hyperelastic cells connected by micro pumps. The pressure change between the cells and their arrangement in a flat sheet like array enables the structure to fold itself. With the help of origami math, very complex shapes can be created without the need of cutting or use of adhesive. A multibody dynamics simulation code was created to simulate folding of arrays consisting of hundreds of cells. Bench test models consisting of hyperelastic silicon rubber cells were used to validate the principle and to provide input parameters for the simulation. The idea outlined in this paper has great potential due to the fact that a smart matter can be created that can transform itself into almost every possible shape. With advancing fabrication techniques, especially towards nano-engineering, every cell could be made at a millimetre scale or smaller. Application of a structure like this range from medical devices like stents up to large smart space structures like shape changing solar sails or antennas.

7. REFERENCES

1. Wertz, J.R., Everett, D.F., and Puschell, J.J. (2011). *Space Mission Engineering: The New SMAD. Microcosm Press.* Hawthorn, CA, USA
2. Sinn, T., de França Queiroz, F., Brownlie, F., Leite, L., Allan, A., Rowan, A., Gillespie, J. (2013), iSEDE demonstrator on high altitude BEXUS: Inflatable satellite encompassing disaggregated electronics, IAC-13-E2.3. *64th International Astronautical Congress*, Beijing, China, 23-27 September 2013.
3. Wilson, E. B. (1891). The Heliotropism Of Hydro. *The American Naturalist.* vol. 25, no. 293, pp. 413-433
4. Galen, C. (1999). Sun Stalkers: How Flowers Follow The Sun. *American Museum of Natural History.* ETATS-UNIS, New York, US, vol. 108, no. 5, pp. 49-51
5. Sinn, T., Hilbich, D., Vasile, M. (2013) Inflatable shape changing colonies assembling versatile smart space structures, IAC-13-C2.5.2. *64th International Astronautical Congress*, Beijing, China, 23-27 September 2013.
6. Lang, R. J. (1994). Mathematical algorithms for origami design. *Symmetry: Culture and Science*, 5(2), 115-152.
7. Lang, R.J.. Robert J. Lang Origami, Homepage: <http://www.langorigami.com/> (accessed March 2014)
8. Clark, R., Sinn, T., Lücking, C., Donaldson N., Brown, R., Parry, T., Dolan, I., Lowe, C., Bewick, R.. (2012) StrathSat-R: Deploying inflatable CubeSat structures in micro gravity, IAC-12-E2.3.7. *63rd International Astronautical Congress*, Naples, Italy, 1-5 October 2012
9. According to the manufacturer's data sheet: Ecoflex, http://www.smooth-on.com/tb/files/ECOFLEX_SERIES_TB.pdf (accessed March 2014).
10. Sinn, T., Vasile, M. (2014). Multibody Dynamics for Biologically Inspired Smart Space Structure. AIAA-2014-1364, *AIAA Science and Technology Forum and Exposition (SciTech2014)*. National Harbour, Maryland, 13-17 January 2014.