Morphing lattice boom for space applications

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ABSTRACT

Structures used in space applications demand the highest levels of stiffness for their mass whilst also performing in a hostile environment. To partly address these requirements and so as to also pack efficiently for stowage during launch we propose a new type of compact telescopic morphing lattice space boom. This boom stows within a 1U CubeSat volume and is lightweight being only 0.4 kg. The boom has a total length of 2 m in its deployed state which is 20 times its stowed height. The device comprises two multi-stable cylindrical composite lattices that are joined telescopically. These lattices nest inside one another in the stowed configuration, with the objective of improving packaging efficiency. Notably, prestress and lamina orientation are used to smoothly change shape from being compact when stowed to being extended when deployed. The lattices in the boom have been designed to maximise deployment force and to be self-deploying by tuning manufacturing parameters. As a result, only a small, lightweight mechanism is required to regulate deployment speed of the lattice boom. By reversing its direction, this mechanism can be used to retract the lattice boom to its stowed configuration, thereby enabling two-way reconfigurability.

1. Introduction

Deployable space structures have many conflicting requirements due to the hostile environment of operation and the constraints of spacecraft launch capacity. Even with recent reductions in space launch costs, the price to launch a single kilogram of payload into space is still in the thousands of dollars [1], therefore all spacecraft systems need to be as lightweight and space efficient as possible. This includes essential systems such as solar generators and communication antennae that both require large surface areas for operation. To satisfy these requirements, deployable space booms, that can simultaneously stow in a compact package and reliably deploy and produce a large surface area, are used. There are many different types and configurations of deployable booms, such as Collapsible Tube Masts [2,3], storable tubular extendible members (STEM) [4-6] and tensegrity booms [7,8]. The Roll-Out Solar Array (ROSA) [4] is a deployable solar generator that uses two STEM composite slit-tube booms on either side to deploy, Fig. 1 (a). The ROSA uses a 5.4 × 1.7 m, mesh of III-V photovoltaic cells to generate 15 kW of electricity. In the stowed configuration, the STEM booms are flattened and rolled onto a cylindrical mandrel. Using stored strain energy, the booms deploy into the extended state, utilising eddy current dampers to control the deployment rate. The ROSA was successfully tested in orbit, however; a telescoping misalignment prevented the structure from latching in the stowed state and it had to be jettisoned. Although the ROSA had some experimental complications, compared to a rigid panel system with the same electricity output, the ROSA was 33% lighter and four times smaller in the stowed state.

A different approach to the design of deployable booms is the utilisation of tensegrity structures. Tensegrity structures consist of tension elements (cables), and compression elements (struts). The tension elements form a continuous network that is supported and prestressed by the discontinuous, compression elements. A tensegrity boom, developed by Ring et al. [8] proposes a deployable structure that claims to have a 100:1 packing efficiency. This boom is a deployable, periodic trussed structure, which deploys from a nanosat form factor, such as a CubeSat. The boom itself is made of an array of battens and diagonal members that deploy via the tape spring longerons that are rolled up in the base of the structure. Inside the base, three electric motors reside that retain the tape spring longerons that are rolled up in the base of the structure. These are the mass of the boom, the packaging efficiency, the bending stiffness once deployed and the deployment mechanism [10].

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The mass of the boom is crucial due to the thrust requirement in launch. The packaging efficiency is a ratio between the lengths of the boom when stowed and deployed. High packaging ratios are therefore beneficial as such values maximise potential deployed lengths. A significant bending stiffness is necessary in space booms to resist vibrations that occur by manoeuvring the spacecraft. Finally, a deployment mechanism that is reliable and controlled is required to prevent damage to the boom and any attached components while ensuring complete deployment in-orbit.

The AstroTube developed by Oxford Space Systems [9,11] is a recent example of a deployable boom that utilises a morphing structure, a composite tape spring, in its design. This structure can change from a compact, rolled state to a long deployed state, by manipulating its internal strain energy. Using this structure, AstroTube can stow to the volume of a 1U CubeSat and deploy to a length of 1.5 m, while only weighing 0.61 kg. This boom was successfully tested in orbit, making it “the longest retractable boom (AstroTube) that has ever been deployed and retracted from a 3U CubeSat”. Fig. 1(b) shows the boom in a ground test, fully deployed to 1.5 m in length. Using a morphing tape spring allowed the boom to be lightweight, self-deploying, packaging efficient while also possessing a high bending stiffness.

The focus of current work is on the multi-stable composite lattice, a morphing structure that is suitable for application in deployable space booms. The lattice comprises narrow, thin strips of composite material on both clockwise (CW) and counter-clockwise (CCW) helical paths, bound together with metal fasteners. This structure is inspired by the tail of T4 bacteriophage that can change shape from being short and wide to being long and thin. Replicating this behaviour, the lattice can also morph from a compact stowed state to an extended deployed state, Fig. 2. It achieves this shape changing ability through the interplay between prestress, stiffness properties and structural geometry [12]. By adjusting these manufacturing parameters, it is possible to tune the morphing lattice to develop a stable shape at any position of deployment. A structural model of the lattice was recently developed [13,14], which accurately predicts the location of these stable shapes extending prior work by Pirrera et al. [12] to include thermal strains, transverse curvatures and the stretching (membrane) effects of double curvature. Using this model, the morphing lattice can be tailored to feature different characteristics, to suit different space applications.

The objective of this work is to design and manufacture a new type of deployable space boom, which utilises the morphing composite lattice. Preliminary results of this work were first presented in Ref. [15]. Current work advances this design by reducing the number of lattices used in the boom, while maintaining the same deployed length, and by using composite pins as fasteners, to reduce weight. The morphing lattice is lightweight, packaging efficient and can be designed to self-deploy, making it ideal for use in a deployable space boom. The lattice boom developed in this work is designed for small satellites and therefore stows to the volume of a 1U CubeSat or 1000cm³. This boom uses, two morphing lattices that have been tuned to be self-deploying, resulting in only a small, lightweight mechanism being required to control the speed of boom deployment. These two lattices are designed to store within each other, which increases the packaging efficiency of the boom, as the 1U stowed volume is maintained but the deployed length is greatly increased. Composite pins are used to assemble the lattices to minimise the mass of the structure. Once the structure is deployed, the deployment speed regulating mechanism may be used to retract the boom back to the stowed state. An FE model was created of the boom to analyse the telescopic deployment of the lattices. Additionally, deployment force and bending experiments were completed on the lattices of the boom. In the fully deployed state, the boom is 2 m in length, 20 times its initial height and 0.5 m longer than the deployed length of the AstroTube which is of similar weight and stowed volume.

This paper is structured as follows. Section 2 covers the manufacturing details and mechanics of the morphing lattice. Then in Section 3, the design concepts of the lattice boom are developed and then realised with a prototype discussed in Section 4. Using the prototype as a reference, the final morphing lattice boom is conceived in Section 5. Section 6 details a FE analysis on the structure to validate the proposed design aspects. This design is then discussed paying attention to its manufacture and resulting experimentation in Section 7. Finally, Section 8 discusses future improvements and testing on the lattice boom.

2. Morphing lattice

The morphing composite lattice is comprised of prestressed helical carbon fibre reinforced plastic (CFRP) strips. To give the strips a pre-curvature, they are cured in an autoclave at an elevated temperature on a curved mould with a relatively large radius. The strips are then prestressed by constraining them to the smaller radius of the lattice. Constraining the strips to each other creates different states of multi-stability as it allows for energy transfer between the membrane, bending and coupling modes to occur. The stable shapes of the lattices are determined using a structural model that calculates the total strain.
energy derived from bending, membrane and coupled deformations. Using this structural model, the lattice can be tuned to exhibit different characteristics, such as multi-stability, self-deployability and resistance to pulling forces.

3. Design concepts

As stated in Section 1, the multi-stable composite lattice has all of the characteristics that make up an efficient deployable space boom. The lattice is highly packaging efficient as it is able to change from compact when stowed, to long when deployed, by only making use of its internal strain energy. The lattice is super lightweight, as the narrow strips are made from thin panels of CFRP. The composite material also gives the structure the necessary bending stiffness required for a slender space boom. Space structures also require high reliability and simplicity to ensure that they deploy accordingly. The morphing lattice has a low potential for error as all the strips move together, fastened with simple pin joints. All of our previous lattices featured eight strips, however by decreasing the number of strips to six, a lattice can stow to a smaller volume, while still deploying to the same length, thereby increasing its packaging efficiency. Using fewer than six strips would increase packaging efficiency further but it creates stability problems. A lattice with only four strips would only have two mounting points at the base, with a significantly decreased bending stiffness. Another technique to increase packaging efficiency is to minimise the width of the lattice strips. The minimum allowable strip width is determined by the diameter of the fasteners used, therefore a 1.5 mm composite pin allows for a minimum strip width of 6 mm, with 2.25 mm on either side of the hole.

Another technique to increase the packaging efficiency of a deployable boom is to nest the lattices within one another. A lattice in its stowed state, it has a large unused interior volume. This approach utilises this empty volume by stowing a second lattice, with a smaller radius, inside of it. By attaching the top of the outer lattice to the bottom of the inner lattice, telescopic deployment is achieved. In deployment, both lattices change shape with the outer lattice pushing the inner lattice upwards, and by doing so, greatly increasing the deployed length. The nesting of lattices can be repeated with a third and fourth lattice, depending on the outermost lattice stowed radius. When nesting lattices, it is noted that the lattices must be tailored to be self-deploying. However, self-deploying lattices have the potential problem of rapid deployment. This effect can be ameliorated by stiffness tailoring of the strips, noting that the bending stiffness of the structure would also change. Therefore, a mechanism that controls the deployment speed of the lattices is required. One possible solution uses a stepper motor mounted in the internal volume of the innermost lattice. On the motor, a spool of cable would be located that is connected to the top fasteners of the innermost lattice. As the motor turns, the cable would release, allowing the lattices to deploy at a slow, controlled pace. Once fully deployed, the lattices could be retracted to the stowed shape by reversing the rotation of the motor. A stepper motor is a good choice as it can exert high torque in a small volume. Although a motor significantly increases the mass of the boom, this effect is offset by the potential ability to retract the structure into the stowed state.

4. Prototype

To verify the concepts proposed in Section 3, a prototype of the lattice boom was manufactured. This prototype tests the nesting capabilities and telescopic deployment of lattices, as well as the use of a small motor to regulate the speed of lattice deployment. The prototype features two, four strip lattices both with a lay-up of [0/90/0] in the strips, cured on a mould of 400 mm in radius. This lattice configuration was used, as previous work [13] showed that it is stable in the deployed state, a requirement for the deployable lattice boom. The inner lattice has a stowed radius that is 8 mm smaller than the outer one, thereby increasing its level of prestress. The different radii prevent the fasteners on both of the lattices from interfering with each other in deployment. To achieve telescopic deployment, the top of the outer lattice was connected to the bottom of the inner lattice with narrow steel plates. As a morphing lattice changes from the stowed state to the deployed state, its radius reduces. Therefore, a mount that accommodates this change in radius was manufactured. This mount features rods and sliders, which can hold the lattice in position, while also allowing it to change its radius. As mentioned in Section 3, a minimum of six strips is required for a self-standing lattice, the prototype boom uses lattices with four strips and therefore requires some manual guidance to ensure straight line deployment. An uni-polar stepper motor was used to control the deployment speed of the boom. On this motor was a spool of cable with one end attached to the top two fasteners of the inner lattice. The motor was then mounted on top of the sliders, in the centre of the two lattices, utilising the empty volume inside, Fig. 3 (a).

To deploy the prototype boom, the motor was activated and the spool of cable was slowly released, allowing the lattices to deploy. The lattices were observed to deploy in stages, where the inner lattice, with its increased level of prestress, deploys first. This lattice seamlessly deployed up to the connection point between the lattices, where deployment transitions to the outer lattice. At this point, the deployment of the boom stopped and required a manual push to continue to full deployment. The reason deployment paused at this point was due to two issues, friction in the sliders and a low deployment force in the lattices. The deployment force of both lattices in the prototype is approximately 1 N, and therefore even small frictional forces and the weight of one lattice on top of another hinders deployment. To roughly approximate a zero gravity environment, the prototype was deployed horizontally which resulted in a much smoother deployment where both lattices deployed in series with no sticking taking place, Fig. 3 (b).

By reversing the rotation of the stepper motor and winding in the cable, a retraction test was completed on the boom. The outer lattice retracted first, due to having an overall lower strain energy, to the stowed configuration, however an issue arose when retraction transitioned to the inner lattice. As it retracted, the inner lattice became snagged on the spool on the motor, and on further retraction it became caught on the nuts of the outer lattice. Despite these shortcomings, the prototype was deemed to be success, as it showed that the proposed concepts are viable. Retraction of telescopic lattices is also possible, but some design modifications are required. The results of this prototype strongly influenced the overall design of the lattice boom.
5. Design methodology

The primary application of the lattice boom is in nanosatellites, such as CubeSats. Therefore, a 1U CubeSat stowed volume was used as a major design constraint. From this constraint, the lattice boom was designed and optimised to maximise deployment length and bending stiffness and also to minimise mass. This design constraint also makes the lattice boom comparable to the AstroTube deployable boom, which also stows to a 1U CubeSat volume.

5.1. Nesting of lattices

As shown by the prototype, two lattices can successfully deploy telescopically and store within one another. The lattice boom also uses two lattices in its design, leaving the empty central volume for the deployment speed regulating motor. A boom configuration with a third internally stored lattice was trialled; however, during deployment, this lattice closed in on the motor inside of it and deployment stalled. The outer lattice of the boom has a stowed diameter of 98 mm, reaching ample space for the internal motor. The spacing between the lattices is important as it reduces the likelihood of the fasteners of the lattices interfering with one another in boom deployment. When the lattices are in their stable deployed state, the outer lattice is designed so that it radially compresses on the lattice in-side of it. This effect creates a strong connection to facilitate effective transfer of forces throughout the lattice boom.

5.2. Lattice design

The most critical aspect of the lattice boom is the design of the two morphing lattices. Both lattices need to have a high bending stiffness, stow in a compact volume and be able to self-deploy into the extended state. As stated in Section 3, a minimum of six strips, with three mounting points at 120° to each other, is required for a self-standing lattice. To maximise the deployment length of the boom while meeting the stowed volume constraint, a CAD model was used to optimise the lattices in both the stowed and deployed states. Table 1 shows the dimensions of the strips, the pre-curvature used, the composite lay-ups and the deployed lengths of the selected lattices. One problem with the boom prototype was the low bending stiffness and deployment force of the structure. To overcome this problem, the 2D mathematical model developed in previous work [13] was used to tailor the lattices in this boom. This model calculates the internal strain energy of the lattice which is a function of the structural geometry, the pre-curvature and the stiffness properties of the strips. Using this model, the two lattices in this boom were tailored to have a high deployment force and to be self-deploying. A [0/0/90/0/0] layup is used in the outer lattice as it has similar stability characteristics to the prototype lattices, stable in the deployed state, while generating a higher deployment force and having higher bending stiffness. Fig. 4 show the stability landscape of the two lattice configurations used in the lattice boom. In this figure, a stability point is represented by where the force curve crosses the x-axis; therefore, both of these lattices are stable in the deployed configuration. As the stowed radii of the lattices becomes smaller, to meet the volume constraints, the level of prestress in the strips increases. Therefore, half of strips of the inner lattice has five layers and the other has three to make both lattices have a similar deployment force. This avoids having the lattices interfering with each other during deployment as the inner lattice deploys first, followed by the outer lattice.

To minimise the weight of the of the lattice boom, composite pins and plastic caps are used as fasteners in the assembly of the lattices. Usually, steel bolts and locknuts are used to secure the strips in place, however as the boom is designed for CubeSat applications, the structure needs to be as lightweight as possible. For example, the inner lattice using metal fasteners has a mass of 83 g, 53% of which is attributed to the fasteners. Using the same strips but with the composite/plastic fasteners, the lattice has a mass of 48 g, a decrease of 42%. Using composite fasteners in both of the lattices results in a weight saving of 75 g, reducing the mass of the entire boom by 15%, when compared to the same structure with metal fasteners.

5.3. Deployment speed regulator

In the prototype, a relatively heavy uni-polar stepper motor was used to control the deployment speed of the boom. The lattice boom uses a similar configuration with a smaller, lighter motor. This motor is a bi-polar stepper motor that is able to fit inside of the inner lattice and

![Fig. 3. Lattice boom prototype stowed (a), fully deployed (b).](image-url)
provides sufficient torque to restrain the lattice boom during deployment. This motor weighs only 140 g, is 44.1cm³ in volume and can provide 0.18Nm of torque. The required torque of the motor was calculated using the maximum deployment force of the two lattices combined and the radius of the spool of cable used to restrain the lattices. A spool of cable is fitted on the shaft of the motor, with one end of the cable attached to the top of the inner lattice. A guide is attached to the top of the motor to ensure that the motor pulls the lattices through the centre.

5.4. Mount

As the lattices of the boom deploy, they become longer and their radii decrease. Therefore, a mounting system that can adapt to this radius change is required. In the prototype, it was noticed that sliders have the tendency to stick which restricts the deployment of the outer lattice. This sticking response is caused by a twisting effect at the end of the lattice strips, which increases the friction on the sliders by a significant amount. The lattice boom uses linear bearings and rails to provide smooth motion while transitioning between the stowed and deployed configurations, avoiding the friction issue. Since each lattice has six strips, three bearings and rails are located at 120° to each other. A base plate is used to fix the linear rails in place. To attach the lattice strips to the bearings, small 3D printed connectors are used. Additionally, a triangular spacer is mounted to the centre of the base plate that moves the motor out of the path of the bearings. Fig. 5 shows the internal and external design of the lattice boom in both the stowed and deployed configurations.

6. Finite element analysis of telescopic deployment

6.1. Prestressing lattice strips

To verify the suitability of the two lattice configurations chosen for telescopic deployment, see Table 1, a FE analysis of the lattice boom was performed using Abaqus/CAE 2017 [16]. The material used is IM7 8552 prepreg thermoset CFRP, the details of which can be found in Table 2. In previous work [13], the full lattice was modelled as a single strip to reduce computational cost. However, due to the complexity of telescopic deployment of lattices, it is necessary to model all twelve strips of both

![Fig. 4. Force/Displacement plots of the inner and outer lattices.](image)

![Fig. 5. Lattice boom motor and mount (a). full boom stowed (b), deployed (c).](image)
lattices. These strips were created as shell extrusions, in the manufactured radii of both 200 mm and 150 mm. Fig. 6 (a). A mesh sensitivity study on a single strip lattice, using S4R shell elements, showed that an element size of 3mm2 is sufficient to accurately simulate the strips of the lattice while also being computationally efficient. Additionally, the length of all strips was halved, using symmetry principles, to reduce model complexity. This scales the strain energy to half of the actual structure while producing a stability landscape that is representative of the full boom. Non-linear geometric effects were included in the analysis to model the highly deformable nature of the lattice. The analysis on the deployable boom was split into two models, prestressing and deployment, and a Newton-Raphson analysis was used to aid both solutions.

In the first model, the strips of the lattices were created in the manufactured shape and prestressed by coiling them into the radii of the two lattices. Initially, the strips are co-located, as shown in Fig. 6 (a) and then each strip was translated and twisted into its respective position on the lattice. To start the analysis, an initial boundary condition was applied to a centre line of each strip, preventing them from translating in the z-axis and from rotating about the x- and y-axes. Next, a displacement applied to the centre of each strip, moving them into their respective positions in the lattices. A z-rotation was then applied to the strips that are at 120° to their initial position. The new position of all strips is shown in Fig. 6 (b). Coiling of the strips was achieved by applying a z-rotation to each end of the strip, forcing them into the smaller radii of the lattices. This process creates different levels of prestress in the strips, related to their initial curvature, lay-up and the radius of the lattice.

Next, all strips were moved into the stowed configuration of the lattices. First, one end of each of the strips was constrained to have at zero displacement in the z-axis. Next, boundary conditions to prevent the ends of the strips from rotating about the z-axis were used to stop the strips from uncoiling, while allowing them to deform and deploy in the z-axis. To move the strips, displacement boundary conditions were applied to their free ends, moving them 36 mm in the z-axis. An additional boundary condition of 18 mm in the z-axis was applied to the midpoint of the strips to guide their deformation. Fig. 7 (a) shows the prestressed strips of the two lattices in the stowed state, with the smaller lattice stored within the larger one. In this figure, the different levels of prestress in the strips can be observed. The five layer strips in the inner lattices are the most stressed, in red, the three layer strips in the inner lattice are the least stressed, in green, and the five layer strips of the outer lattice are moderately stressed, in orange.

### 6.2. Deployment of lattice boom

The deformed strips were subsequently imported into a second model for deployment analysis. The reason for using a second model is that the coating of the strips and the fastener constraints cannot be performed in the same analysis. The imported strips have the geometry and mesh of the previous model at the last step of the previous analysis, but they do not have any of the prestress. This stress was added to the model through an initial state predefined field. This takes the prestress of the previously completed job and applies it to the strips of the same name. Next, the fasteners that hold the strips together were simulated using coupling constraints. These lock individual nodes together in x-, y- and z-displacements, but all rotations are left free. In this model there were 81 coupling constraints simulating the many fasteners of the two lattices. Additionally, there were three more coupling constraints that connect the top of the outer lattice to the bottom of the inner lattice. These were used to achieve the telescopic deployment desired.

The first boundary condition applied to this model was a displacement lock in the z-axis on the bottom of the strips of the outer lattice, simulating the boom mount. Next, a boundary condition on the ends of each strip was applied, preventing rotation about the z-axis. This effect reduces high stress concentrations occurring due to edge effects. Additionally, the outer lattice was locked in its position to allow the inner lattice to deploy. A displacement boundary condition was applied to the top of the inner lattice of 380 mm and another is applied at the midpoint of the strips of 190 mm. These boundary conditions were used to guide the lattice in the first stage of telescopic deployment, as shown in Fig. 7 (b). In the second step of this model, the locking and displacement boundary conditions of the previous step were deactivated. New displacement boundary conditions were applied to the top and midpoint of the outer lattice, of 547 mm and 273.5 mm respectively. Again, these boundary conditions serve to guide the lattices through the second stage of deployment, shown in Fig. 8. The completed model extends from a height of 42 mm in the stowed state to a deployed length of 1.02 m. This model verifies the suitability of the selected lattice configurations for

| Material | $E_{11}$ (GPa) | $E_{22}$ (GPa) | $G_{12}$ (GPa) | $v_{12}$ | $v_{23}$ | Ply thickness (mm) |
|----------|----------------|----------------|----------------|----------|----------|------------------|
| IM78552  | 163.7          | 11.5           | 5              | 0.3      | 0.021    | 0.11             |

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Fig. 6. Strips in manufactured state (a), strips in lattice positions (b).
telescopic deployment in a space boom.

6.3. Bend test of lattice

To obtain the bending stiffness of the lattices of the boom, a simulation of the simply supported bend test was also completed on both lattices. The lattices were examined individually, rather than together as a boom, to match the experiments completed in Section 8.3. The analysis starts with the lattice in the deployed configuration, and the position of the boundary conditions and the point load are shown in Fig. 9. At each end of the lattice the displacement in the $y$-axis is prevented, yet the ends are allowed to rotate and translate in the $x$- and $z$-axes, simulating simply supported testing conditions. At the centre of the lattice, a 30 N point load is applied in the $y$-direction to the top of the lattice. The deflection generated by the force is recorded and used to calculate the bending stiffness of the lattice for comparison with experimental testing.

7. Manufacturing

7.1. Mount

The base structure of the boom was machined from a plate of stainless steel and six holes threaded for M2 bolts. Steel was selected, as the tapped holes would not hold securely in softer, lighter materials, such as aluminium. These holes attach the linear rails to the plate, which were manufactured from hardened steel to prevent wear. The 3D printer connectors were bolted to the linear bearings for attaching to the bottom of the outer lattice. The central, triangular spacer, used to mount the motor, was also machined from steel to accommodate the threaded holes. Fig. 10 (a) displays the assembled lattice mount.
7.2. Deployment speed regulator

The stepper motor used to regulate the deployment speed of the lattice boom was attached to the centre of the lattice mount using a small L-bracket connected to the triangular spacer, Fig. 10 (b). To reduce weight, both the cable spool and guide were manufactured with PLA plastic using a 3D printer. A stepper drive board was used to control the speed and direction of the stepper motor. Rotation speed is controlled by the frequency of a square wave of voltage between 5 V and 0 V. In the lattice boom, this frequency is controlled via a potentiometer. The rotation direction is controlled by a ground-mounted switch. When the switch is closed the voltage (5 V) turns the shaft CW and when the switch is open the voltage is zero and the shaft turns CCW.

7.3. Lattice manufacture

Two moulds of 150 mm and 200 mm in radii were used in the manufacture of the lattice strips to attain the necessary level of prestress for the desired lattices. These moulds were made from thin plates of stainless steel, rolled into cylindrical shapes. The composite laminates were then laid upon these moulds and cured in an autoclave at 180 °C, at 7-bar pressure. The composite laminates post-cure curvatures are shown in Fig. 11 (a). A water-jet cutter was used to accurately cut these panels into 6 mm strips. Due to the pre-curvature in the panels, sufficient distributed weight was used to flatten the laminates for cutting purposes.

To accurately place the holes in the strips, a steel template was manufactured with the desired hole size and spacing for both lattices. Then the strips were clamped between the steel template and a block of wood and then drilled. This process produced clean centred holes in the strips with little breakthrough. Once all the strips were cut and drilled, they were assembled into lattices using the composite pins. These pins were manufactured using a 1.5 mm diameter, extruded CFRP rod, cut into sections of 8 mm in length. 3D printing was then used create the small end caps for either side of the pins. First, the pin was inserted into the lattice and then using epoxy resin, the two end caps were glued into place, securing the strips of the lattice, Fig. 11 (b). Metal fasteners were used in key areas of the lattice, such as the ends of the structure, where additional support is required.

7.4. Full assembly

One of the key aspects of the lattice boom is the nesting of the two lattices together to increase packing efficiency. The nesting of lattices relies on the connection between the top of the outer lattice to the bottom of the inner lattice to achieve telescopic deployment. Therefore, the manufacture of connection is the first step of the boom assembly. Narrow steel plates were used to join the top of the outer lattice to the bottom of the inner lattice. The outer lattice was tailored to squeeze onto the inner lattice in the deployed state to strengthen the joint between the two lattices.

Next, both lattices were compressed into the stowed configuration and a line of cable was connected between the top three fasteners of the inner lattice. Then another line of cable was linked to the centre of this connection and then pulled through both of the lattices. This cable was then wound around the spool on the stepper motor attached to the boom mount. Next, the outer lattice was bolted to the 3D printed connectors on the linear bearings, completing boom assembly, Fig. 12.
passively restrains the boom from deploying while powered off. This is achieved by tuning the stiffness of the strips to produce minimal deployment force when the lattice boom is stowed. To deploy this boom the motor is powered on, the spool of cable begins to rotate and release, allowing the inner lattice to deploy slowly. This first lattice deploys steadily and smoothly, however, as deployment transitions to the outer lattice, a unique phenomenon develops. As the outer lattice deploys, the boom begins to bend to the side and appears to start falling over, Fig. 13.

Then, as the structure continues to deploy, the boom starts to straighten of its own accord, reaching the fully deployed state, as shown in Fig. 14. This self-correcting, bending phenomenon is caused by the large non-linear deployment force of the lattices. While the lattice is changing shape, its deployment force temporarily increases and its bending stiffness decreases. The deployment force is restricted in the axial direction by the motor and spool of cable, so the resulting compression force causes the lattice to buckle to the side instead. As the boom deploys further, the deployment force (compression) of the two lattices decreases, as shown in Fig. 14, and the buckling effect disappears, causing the boom to self-straightens into the deployed state of 2 m in length. To retract the structure into the stowed state, the motor is reversed and the cable is rewound onto the spool, pulling the lattices down. Unfortunately, the lattices begin to buckle again and is not able to retract without manual assistance.

This temporary buckling effect is undesirable, as in space operation, deploying to the side may cause the boom to collide with other equipment. Therefore, a modified deployment speed regulating system was designed, which utilised three cables, rather than just one. These cables run along the inside wall of the lattices at 120° to each other and are linked to the lattice fasteners in their vertical path to the top three fasteners of the inner lattice. These tension elements prevent the structure from buckling during deployment, as each of the cables restricts deployment of the boom equally, preventing the structure from bending in any particular direction. This arrangement results in a straight line deployment, similar to the deployment observed in the FE model. However, as a consequence of using three cables instead of one, the internal stepper motor no longer had sufficient torque to restrict the deployment speed of the boom. Therefore, this new deployment method was tested by releasing the cable slowly by hand, until a suitable motor could be procured. A manually controlled retraction test was also performed on the boom with the new cable system. After these adjustments, the structure could retract fully, without bending to the side, into the stowed state.

8. Experimentation and discussion

8.1. Full boom deployment testing

The new lattice boom, in the stowed configuration, has a volume of a 1U CubeSat and weighs 400 g. In this configuration, the stepper motor passively restrains the boom from deploying while powered off. This is achieved by tuning the stiffness of the strips to produce minimal deployment force when the lattice boom is stowed. To deploy this boom the motor is powered on, the spool of cable begins to rotate and release, allowing the inner lattice to deploy slowly. This first lattice deploys steadily and smoothly, however, as deployment transitions to the outer lattice, a unique phenomenon develops. As the outer lattice deploys, the boom begins to bend to the side and appears to start falling over, Fig. 13.

Fig. 12. Lattice boom in stowed state.

Fig. 13. Lattice boom bending in mid deployment.

To examine the deployment force of the lattice boom, it was separated into its inner and outer lattices, as the boom is too long to be tested in any of the testing instruments available. The experimental methods detailed in previous work [13] were used to load both lattices in a Tinius Olsen Tensile tester. A 100 N load cell was used in all experiments. Each lattice was tested five times to ensure consistency in the results and the unloading response was recorded to exclude any influence from experimental slacks.

Fig. 15 (a) shows the force/deployment response of the inner lattice from the analytical, FE and experimental models. Correlation between the analysis methods varies as the lattice morphs from the stowed state to the deployed state. Between an extension of 0 mm–500 mm, the experimental force is much greater than that predicted by the other two models. This increase in force is caused by the experimental model deploying in steps, rather than all at once as assumed by the other models. Due to the high prestress in the lattice strips, high levels of friction are present in the lattice while in the stowed state. As the tester moves upwards, allowing the lattice to deploy, only the top of the lattice starts to change shape, while the rest stays in the stowed state. As the tester moves upwards, allowing the lattice to deploy, only the top of the lattice starts to change shape, while the rest stays in the stowed state. Fig. 15 (b) shows the inner lattice, mid-deployment, presenting the stepped deployment of the lattice. The top portion of the lattice that deploys first generates a larger force than that predicted by the other models at that stage of deployment as the analytical and numerical models assume that the lattice deploys uniformly. However, beyond an extension of 500 mm, good correlation is shown between the three models, as they all exhibit a similar peak force and stable position. This portion of the graph has greater concordance between experiment and models since the experimental lattice now morphs more uniformly.

Fig. 16 shows the force/deployment responses of the outer lattice
from the analytical, FE and experimental models. The experimental model of this lattice also has the issue of stepped deployment, resulting in an increase in force for the initial response. This lattice has a smaller prestress than the inner lattice, so the effect of stepped deployed is not so severe. Similarly, during later deployment, the graph shows better correlation, with the two models exhibiting a similar peak load to the experiment at the same position of deployment. Unfortunately, the experimental curve trends towards a similar stable position as the other two models. Although the analytical and numerical models do not capture the full force/deployment response of the physical lattices, they do predict important design aspects of a deployable boom, such as the peak force and the stable position.

8.3. Lattice bending stiffness testing

To examine the bending stiffness of the lattice boom, it was separated into its inner and outer lattices as once again, the full boom is too long to fit into the available testing machine. A simply supported bend test with a central point load was performed on both lattices to obtain their bending stiffness. Fig. 17 shows the experimental rig for testing the lattices, mounted on to the Tinius Olsen testing machine. Wood is not often used in test rigs as it is a soft material, but it is suitable for current purposes as the lattices are relatively flexible. In the experiment, the head of the tester moves down at a constant rate of 5 mm/min and applies a point load to the lattice creating a deflection. The force applied and the deflection of the lattice is recorded by the Tinius Olsen testing machine. The bending experiment was repeated five times to show consistency in the results. The bending stiffness of the lattice is calculated from simple beam theory for the deflection of a simply supported beam with a point load [18].

Fig. 18 shows the bending stiffness of the inner lattice as it deflects under the applied load for both the FE and experimental model. Initially, the lattice has a higher stiffness that decreases as the deflection of the lattice increases. The decrease in bending stiffness arises due to the applied load squeezing the lattice locally, causing it to reduce in radius. This reduces the lattice’s second moment of area, causing its bending stiffness to decrease accordingly. It is noted that the first experimental test exhibits a higher stiffness than the subsequent tests, this is likely due to the fasteners of the lattice loosening after the first test. However, as the deflection of the lattice increases, good correlation is shown between the FE and all experimental tests and the bending stiffness becomes stable and consistent. This consistent value is the effective bending stiffness of the lattice, which both the FE and experimental models show to be 830,000 Nmm2.

Fig. 19 shows the bending stiffness of the outer lattice as it deflects under the applied load for both the FE and experimental model. Thieill’s lattice also has an initially higher stiffness that decreases as the deflection increases. Good correlation is observed between the FE and experimental model for the outer lattice. As the deflection of the lattice increases, the bending stiffness, once again, becomes stable and consistent. In this lattice, the effective bending stiffness differs between the two models as the FE predicts the bending stiffness to be 2,200,000 Nmm2 while the experiment shows the stiffness is 1,800,000 Nmm2.

9. Conclusion

A deployable space boom that utilises two morphing composite lattices has been presented for the first time. The boom stows to the volume of a 1U CubeSat, or 1000cm3 while weighing only 0.4 kg. In the deployed configuration, the morphing lattice space boom can reach 2 m in length, 33% longer than the comparable AstroTube. It can deploy at a steady rate from the stowed to the deployed state using an internally stored stepper motor. Using the current motor, the boom temporarily buckles during deployment before reaching the extended state. A new
deployment method was developed that allowed for straight-line deployment and full retraction. The deployment force and bending stiffness of the individual lattices were measured experimentally and shown to compare well with FE and analytical models. In future work, a test rig will be designed to experimentally test the lattice boom as a whole. Future modifications of the boom will involve procuring a more powerful motor of a similar volume and weight, or alternatively, creating a gearbox system that would increase the torque of the current motor. Other possible modifications include: doubling the number of the strips in the lattices to enhance the bending stiffness of the boom and the inclusion of a third lattice to increase the deployed length. These advances would make the lattice space boom stiffer, more reliable and deploy further.

**Author statement**

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**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence...
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