DEPLOYABLE OPTICS FOR CUBESATS

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ABSTRACT

Since the beginning of the space age, many structures with different levels of complexity have been proposed for the deployment of equipment such as solar arrays, antennae, and scientific instruments. By increasing the packaging efficiency, stowing during launch and then deploying in orbit provides an opportunity for the improvement of the capabilities of small satellites payloads while maintaining a contained launch volume. The latter is particularly important when considering the launch of future constellations and, in particular, CubeSats where the volume is significantly constrained by the size of the pod.

The focus of this work is the development of a camera/telescope barrel ideally suited for a Cassegrain configured space instrument, hosting the primary mirror at one (satellite side) end and the secondary mirror supported by a cruciform element at the other end (aperture). The barrel is stowed and deployed using a telescopic approach with three coaxial large diameter hollow cylinders making up the segments of the barrel.

For an optical telescope, one of the most important challenges is in maintaining a highly accurate distance between the optical elements (in this case, primary and secondary mirrors which are positioned with an accuracy of a few micron). Thermo-mechanical distortions due to on orbit temperature variations and any micro-vibration excitation from sources on the spacecraft can cause significant degradation of the optical performance.

To maintain the required shape stability, the main structural parts are made in a thermally invariable material and incorporate features to provide alignment and locking out.

The large diameter of the structure, and low coefficient of thermal expansion, give the assembly excellent resilience to thermal and micro-vibration disturbances whilst keeping mass to a minimum. This “tube” arrangement also naturally fulfils the light baffling requirements of the telescope.

Another significant challenge is the apparatus to drive the sequential deployment of the cylinders. Systems that use lead screws and gears have been proposed, however they present significant complexities and their mass has a substantial impact on the mass budget of the overall assembly. Here, a novel robust and simple wire-driven system is proposed to operate the deployment. The main advantages being the simplicity, light weight, and robustness with respect to severe vibration environments. This article will describe the development of the device and the testing of the proof of concept /qualification model.

INTRODUCTION

Instruments designed for cubesats or small satellites have significant size constraints. In the first case, the cubesat unit size limits the dimensions to smaller than 10 cm, or 20 cm for typical multiple-unit cubesats (up to 12U); in the second, the desire to limit the size of the satellite platform hosting the instrument is the significant driver, as a smaller satellite is going to be easier and cheaper to launch.

While many satellite components can be miniaturised to a high degree, imaging optics are constrained by the laws of physics, and achieving high resolution and sensitivity obliges one to demand the largest possible optical system. For optical payloads like cameras or telescopes, the size of the optics (e.g. mirror, lenses, focal length) is directly related to the instrument performance, and for a given orbit, in order to achieve a specific resolution, a particular size of instrument is required.

Many imaging applications require, in addition to large mirrors, a system of baffles and shades to reduce scattered light from outside the field of view.

Typically, a Cassegrain configuration is used (see Figure 1~~Figure 1~~), as this enables a more compact design, where a barrel hosts the primary mirror at one end (satellite side) and the secondary mirror supported by spokes is connected to the edge of the barrel at the other end (aperture). The size of the barrel dominates the size of the whole instrument which essentially determines the size of the spacecraft. On the other hand, the diameter and length of the barrel are driven by the diameter of the primary mirror and focal length, which are linked to the instrument required performance.

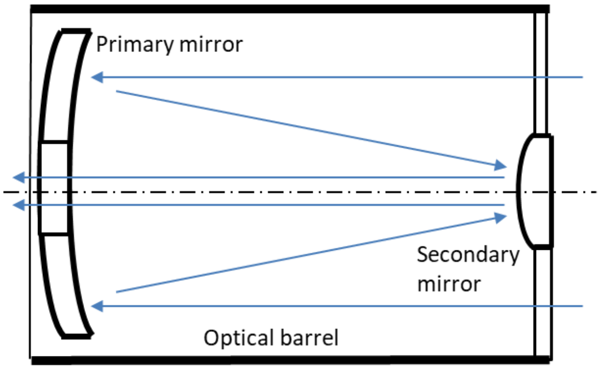

Figure 1: Schematic cross section of a typical telescope Cassegrain configuration

The issues above can be partially overcome using deployable structures to stow the instruments in a smaller volume during launch and deploying the optical elements to their required size once in orbit.

Deployable space structures have been used for decades for a variety of purposes. One of the most common examples is that of deployable solar arrays, which are routinely used for all satellite sizes. From the large GEO telecom satellite that need significant surface to capture the power necessary to their functioning, but still need to fit in the faring of the launch vehicle, to CubeSats, which need more power than can be provided by body mounted panels and still need to fit in the cubesat dispenser.

Also, in the areas of the optical payloads / telescopes, the example can go from very large and expensive to very small, and cheap deployable structures. For instance the JWST [1], represents the current cutting edge design for large telescopes, based on the deployment of precisely machined and polished mirrors whose positions and shape can be adjusted by a series of actuators. This technology comes at an overall staggering cost. At the other end of the spectrum there are micro- and mini-satellites that implement low cost solutions. A good example is the camera developed by SSTL and Surrey Space Centre [2]. Here the objective was the development of a camera/telescope barrel ideally suited for a Cassegrain configured space instrument [4]. The barrel was stowed and deployed using a telescopic approach with three coaxial large diameter carbon fibre hollow cylinders making up the segments of the barrel [5]. The large diameter of the structure and low coefficient of thermal expansion (CTE) of the carbon, gave the assembly excellent resilience to thermal and micro vibration disturbances whilst keeping mass to a minimum. This “tube” arrangement also naturally fulfils the light baffling requirements of the telescope. In this design three lead screws equally pitched on the base flange drive up the intermediate barrel on lead screw nuts located on the intermediate barrel flange, which in turn drives a second set of screws which drive out the end barrel simultaneously. The base lead screws are driven by a large diameter ring gear mounted on the base flange which is driven by a dual stepper motor.

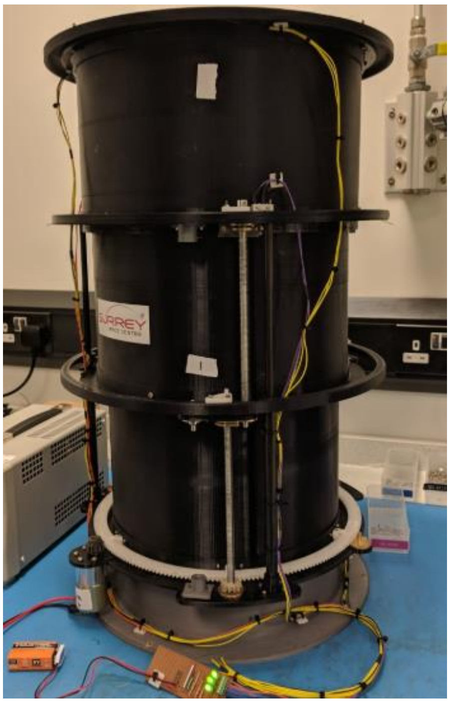

Figure 2: SSTL-SSC deployable barrel model [4] in its deployed configuration

Indeed, the total mass of this telescopic system is higher than the mass of a monolithic barrel, equivalent to the deployed telescopic system; however, the stowed size of the telescopic system is less than half of the size of a monolithic configuration.

Cubesats deployable structures

Specifically, for cubesats, their very reduced size naturally points towards deployable structures as a way to overcome the size limitations imposed by the need to fit in the standard pods.

Various groups have worked on different types of deployable solar arrays, antennas, sails [5, 6 , 7, 8], and specifically for optical structures, [9, 10]. In this last area a variety of solutions have been proposed to improve the performance of their optical payloads.

These range from a deployable membrane [11] that works as a photon sieve diffractive optic that transmits the light though the photon sieve to a focal plane array within the CubeSat, to rigid deployable mirrors which are deployed like petals [12].

Importance of deployable telescopes in small imaging satellites

Many satellites now in orbit provide moderate spatial resolution and wide fields of view to support whole Earth mapping. This has left behind a gap in very high resolution, frequent flyover coverage, which is driving small satellite projects to move toward very high-resolution instruments that would be deployed in constellations.

A very high resolution imager requires a long focal length telescope which results is very inefficient use of the space in the satellite; often over half the payload volume can be occupied by the empty space between the primary and secondary mirrors as seen in Figure 1.

One solution to this problem is to make the secondary mirror deployable. In this way, the primary mirror resides within the volume of the spacecraft, but the secondary is deployed out from the spacecraft, moving most of this empty volume outside the spacecraft. This comes at the cost only of the deployment mechanism, and then only in the additional weight it requires above that of a rigid, traditional telescope housing.

Another approach to making the telescope more compact is to segment the primary mirror and deploy the mirror segments in a flower petal-like arrangement 12. While this has some attractive features and may be advantageous in some situations, we highlight two critical weaknesses of this approach. First, the mechanical alignment of the mirror segments poses severe challenges, since they must be positioned, and maintained in position, with sub-micron accuracy along three degrees of freedom, so that for a four-segment primary one must adjust 9 degrees of freedom. The calculation of the necessary adjustments is a nontrivial exercise for Earth Observation since one lacks the point-like objects (stars) that provide clear references that can be used to infer the various focal errors present. In general one is forced to either align the instrument while imaging a star and then rely on the rigidity of the structure to maintain alignment for an imaging pass, or to rely on very computation-heavy focusing procedure using ground features which is subject to disturbance by atmospheric effects. In no case can such a system attain the same image quality that could be achieved with a monolithic primary, which to some extent degrades the value of the large aperture in the first place.

Second, the deployable primary mirror cannot provide any significant volume savings for the payload optical system. The segments occupy the same volume as the deployed system, but only change their relative orientation – and the deployment mechanism itself occupies space and weight that would not be required for a monolithic primary.

The primary concern with replacing a rigid structure with the deployable secondary support will be that the secondary mirror may be misaligned upon deployment. However, our preliminary work on the structure shows that deployment can reliably place the secondary mirror in the expected position to within microns. Typically a focus adjustment within such a telescope provides upwards of 1mm of adjustment, so we expect that any variation in the secondary mirror position may be compensated for by a focuser, although this remains to be rigorously confirmed by optical modelling, and naturally depends on the form of the telescope mirrors and the resolution that must be achieved. While the focuser would only compensate for one of the three degrees of freedom, we expect to require correction, optical design choices can make the telescope performance relatively insensitive to a transverse displacement.

Proposed wire-driven system deployment system

This project proposes to develop a novel, robust, and simple wire-driven system operate the deployment of the optics.

REQUIREMENTS

The Australian CSIRO, together with the Auckland Space Institute are considering the development a cubesat-scale Cassegrain configuration telescope. This design formed the basis and motivation of the deployable structure. The design drivers listed in Table 1 were established at the beginning of the project.

Table 1: Deployable telescope design drivers

Description
Deployment repeatability <0.1 mm in any axis.
Thermoelastic distortion uniform and gradient across of the structure -5 °C to 0 °C <20 µm decentration, <0.01° tilt and <5 µm separation.
Geometric footprint within 100 mm x 100mm
Stowed first model frequency >100 Hz
Deploy a secondary mirror 250 mm from the primary mirror
Accommodate a 90 mm diameter primary mirror
Deployment mechanism shall not interfere thermally with barrel location

DESIGN

The basic dimensional requirements of the optical system drove the structural design, though there exist a variety of options which are driven by practicality.

Barrel Structure

The concentric telescopic barrels could be configured with either the outer barrel being held stationary at the base or vice versa. While holding the inner barrel stationary at the base, as in other designs (see for example Figure 2~~Figure 2~~), caters for a potentially wider field of view, it proves slightly more complex in the stowed configuration. These issues are easily overcome, though the initial design opted for the outer barrel being held static as the base structure, depicted in a deployed state in Figure 3 and stowed in Figure 4.

Figure 3: Initial design in deployed state

The amount of barrel segments is a trade-off between minimum diameter, set by the primary mirror diameter, manufacturing resolution and tolerance, space available for the stowed assembly, material strength, frictional forces during deployment, etc. The initial prototype design takes into account a manufacturing accuracy of <0.2 mm and keeps the stowed volume to approximately 1U. These parameters can obviously be tailored to the requirements of a particular application.

Deployment Mechanism

In order to deploy the structure, a cable needs to be routed parallel to the primary telescope axis to move each barrel segment. A smooth channel through which the tethers can freely move without snagging on anything along their path must be provided. The cable material could be routed outside or within the barrel structure.

Figure 4: Initial design in stowed state

An initial approach was to use thin tubes which would be attached to each segment by some means, possibly clamped mounting points or chemical bonding, to each segment, bent in gentle curves to reduce friction as the cables are tensioned. Initial investigations at building such structures were relatively successful, although here additive manufacturing (AM), also known as 3D-printing, presented an alternative which avoided these additional parts completely, assuming the possibility of creating channels small enough to fit within the walls of the barrel and which are sufficiently smooth so as not to add significant friction which hinders deployment.

The torque required to reel in the cables and deploy the barrels is provided by a spring motor, since this device maintains a passive tension and minimises issues such as magnetic interference. The torque a single spring motor can provide is sufficient to retract all three cables though tension balancing will most likely be necessary. Current commercial-off-the-shelf (COTS) products which are suited to the task are readily available. The mounting of the spring motor behind the primary mirror is depicted in Figure 5. It is offset to one side to allow for the requisite additional optical components to be added behind the aperture in the primary mirror. The cables are routed from the barrels to the spring motor through the primary mirror mounting.

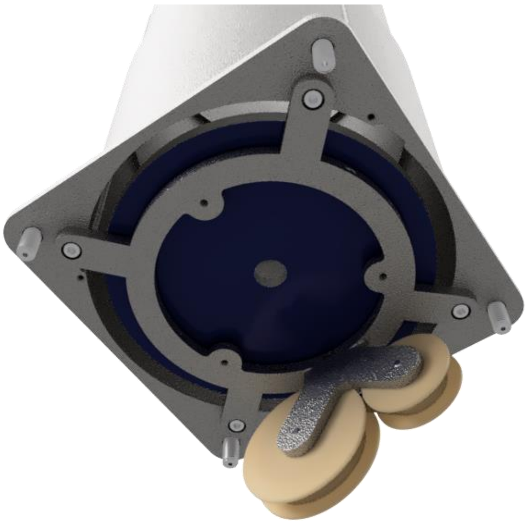

Figure 5: Spring motor mounted below primary mirror.

Barrel Location

Once fully tensioned, the system should have a repeatable precision in the final deployed position to ensure that the telescope can maintain a tolerable degree of calibration. Design options posited to achieve this included using a cone and cap configuration, for example, however it was decided to use a triangular groove mating with a spherical ball structure. The use of this contacting configuration produces an isostatic mounting which allows for some relative deformation, for example due to thermal expansion and other effects. A section view of two parts located in this way is shown in Figure 6. By using three of these features, equally distributed around the perimeter of the barrels, the relative position of the barrels is triangulated, potentially minimising any distortions or build-up of internal strains.

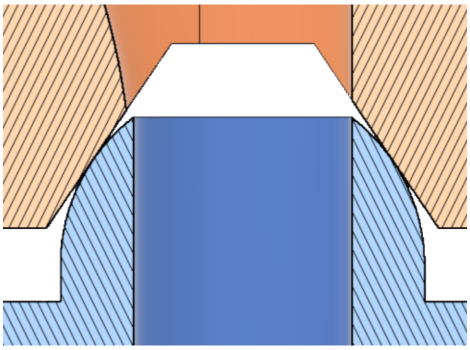

Figure 6: Section view of ball and groove location

MATERIAL CHOICE

A variety of material alternatives were considered to address the design drivers. The highest priority was to establish which commercially available materials could be used to meet the requirement for low thermal expansion and then to find appropriate manufacturing methods.

Materials must be thermally stable to allow for a repeatable deployment under any conditions and to maintain a stable platform under large thermal gradients which can affect the relative positioning of the mirrors.

The obvious choice for this type of structure was a carbon-fibre-reinforced polymer (CFRP), as this type of composite material has high strength, high stiffness, low density and, potentially, close to zero CTE. There are a variety of resins and manufacturers which are used in constructing CFRP parts, which presents some difficulty in establishing the precise CTE for any given COTS material without rigorous testing.

Despite this, typical values for CTEs of CFRP manufactured from sheets of carbon-fibre can prove suitably low enough to be viable options for supporting structures. Standard sizes, however, prove to be a limiting factor in the compactness and increase the complexity of the design by the sheer number of additional parts needed to assemble the complete telescope.

To reduce this complexity, the possibility of using AM was considered. Using CFRP as an AM material is commercially viable yet due to the chopping of the fibres, the material loses much of its thermal stability because the polymer's properties become the dominant factor. This increased CTE does not completely rule CFRP out as an excellent lightweight option for deployable optical structures, such as baffles, yet alternative materials have potential benefits over CFRP where precision is required. Outgassing of commercial polymers would also need to be carefully considered, especially for an optical application.

A material that is typically used for parts that demand stability over a certain range of temperatures is InVar. This is a nickel-iron alloy with an extremely low CTE, named particularly for its thermal invariability. An added benefit of InVar is that it can be additively manufactured, vastly reducing the amount of parts required to create complex structures. A major drawback of InVar in comparison to CFRP is the much higher density. Nevertheless, InVar was selected as a target material to create the deployable optical structure.

Consideration also has to be given to the cable material for the deployment system. A variety of possible materials would suffice under 1 g conditions though, again, outgassing in an optical application is of major concern. Kevlar was chosen as a primary candidate for this purpose due to its high strength, general durability under harsh conditions and low outgassing in vacuum.

PROTOTYPE

Manufacture

The initial prototype, to test and perfect the mechanical principles of the system, was printed in Nylon 12 on a selective laser sintering (SLS) system. This prototype was made at the intended scale and is shown in Figure 7 and Figure 8, and has shown that the major concerns of the initial design have been addressed.

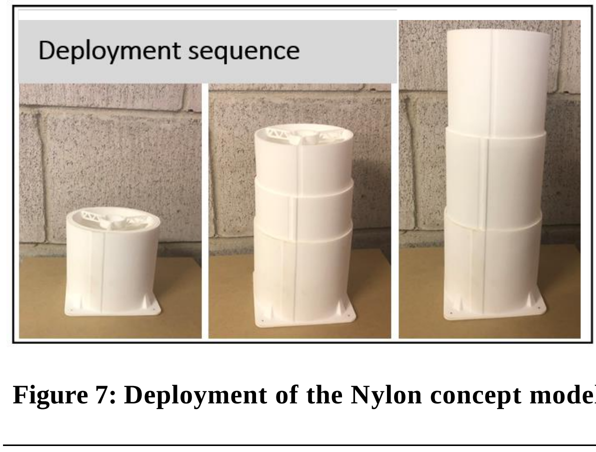

Figure 7: Deployment of the Nylon concept model

Figure 8: Nylon prototype in deployed configuration

A minor problem with this manufacturing method is the surfaces finish, which is coarse to the touch, which adds to the friction of all interfaces. What remains to be fully tested in this prototype is the capability of the spring motor to adequately deploy the structure in 1 g, the intent being to demonstrate that the spring motor can overcome both excessive friction and gravity to build confidence in a more refined model.

FUTURE WORK

Light-weighting

Since AM techniques are being used to fabricate the system, it can also take advantage of lightweight thin walls made rigid through complex ribbing systems that could only be produced with AM. The net result will allow for considerable weight reduction of the payload.

Material Investigation

Further prototypes need to be additively manufactured using InVar, to confirm both the accuracy of the manufacturing process, which differs from the processes used for initial prototypes, and the potential gains to be made in deployment accuracy and thermal stability by using a material with such a low CTE.

Verification

Testing of the system, initially focused on the material properties and the accuracy and repeatability of deployment, is to be carried out. High accuracy optical testing will also need to be done to ascertain the degree of accuracy achievable. More deliberate requirements based on an actual mission are to be established such that the system can be used to demonstrate its practical usefulness, particularly when considering on-orbit environmental conditions.

CONCLUSION

This paper reports the initial design and prototyping of a deployable Cassegrain telescope for cubesats. Thermal stability can be achieved by a careful choice of material, though certain trade-offs must be made depending on the application. AM techniques can benefit the design though this does pose limitations on which materials can be used. Because of the geometric complexity that AM allows in comparison to conventional manufacturing techniques, it has allowed many parts to be consolidated into just a few. Using CFRP in AM is a feasible solution provided a low deployment accuracy can be tolerated. The low CTE nickel-iron alloy, InVar, promises to be both thermally stable and viable as an AM material.

The initial prototype has been manufactured in Nylon and proves the viability of the design even at a relatively low print resolution. Large questions remain unanswered however, particularly regarding thermal stability and deployment repeatability, where high accuracy measurements will need to be made.

Environmental analysis and testing will also need to be carried out with the specific focus of monitoring distortions caused by thermal gradients within the assembly. Vibration testing of a light-weighted structure will also be of particular interest since this process could compromise overall strength, negating the advantages it provides.

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