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Autonomous Assembly of a Reconfiguarble Space Telescope (AAReST) – A CubeSat/Microsatellite Based Technology Demonstrator

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ABSTRACT

Future space telescopes with diameter over 20 m will require in-space assembly. High-precision formation flying has very high cost and may not be able to maintain stable alignment over long periods of time. We believe autonomous assembly is a key enabler for a lower cost approach to large space telescopes. To gain experience, and to provide risk reduction, we propose a demonstration mission to demonstrate all key aspects of autonomous assembly and reconfiguration of a space telescope based on multiple mirror elements. The mission will involve two 3U CubeSat-like nanosatellites ("MirrorSats") each carrying an electrically actuated adaptive mirror, and each capable of autonomous un-docking and re-docking with a small central "9U" class nanosatellite core, which houses two fixed mirrors and a boom-deployed focal plane assembly. All three spacecraft will be launched as a single ~40kg microsatellite package.

INTRODUCTION

In recent years, there has been a desire to develop space-based optical telescopes with large primary apertures (over 20 m in diameter). Currently the largest primary aperture under development is that of the James Webb Space Telescope with a diameter of 6.6m[1]. It represents a major shift in telescope design due to the use of a deployable primary mirror. However, its size is still limited by the diameter of the launch vehicle; a limitation for all current space-borne telescopes. One method to overcome this obstacle is to autonomously assemble small independent spacecraft, each with their own mirror, while in orbit. In doing so, a telescope with a large, segmented primary mirror can be constructed. Furthermore, if each of these mirrors is manufactured to have an identical initial shape (and then adjusted upon assembly), a substantial reduction in manufacturing costs can be realized. We believe autonomous assembly of such elements is a key enabler for a lower cost approach to large telescopes. In order to prove the feasibility of such a concept, a collaborative effort between the California Institute of Technology (CalTech) and the University of Surrey – Surrey Space Centre (SSC) has been formed.

Our overall goal is to create and demonstrate the technology fundamental to the eventual hardware development of a both segmented and sparse, coherent, 100m diameter class aperture telescope utilizing a mosaic primary mirror where each hexagonally shaped mirror segment is attached to a low-cost small satellite (MirrorSat) that is able to execute autonomous rendezvous and docking manoeuvres.

To gain experience, and to provide risk reduction, we have proposed a demonstration mission to demonstrate all key aspects of autonomous assembly and reconfiguration of a space telescope based on multiple mirror elements. The mission will involve two "nanosatellite" class vehicles: 3U CubeSat-type "MirrorSats", and a central "9U" microsatellite, which houses the central primary mirror and focal plane assembly. The MirrorSats are capable of autonomous un-docking/re-docking with the central craft to form different optical configurations. All three spacecraft will be launched as a single <40kg microsatellite package. This represents further refinement of the previously reported design for the AAReST mission[2].

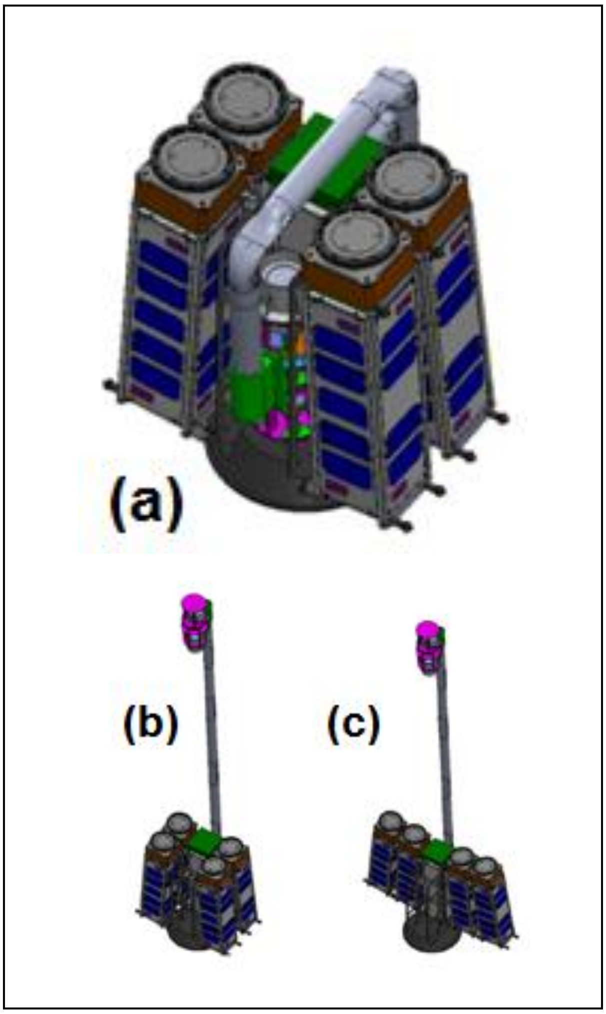

Figure 1: AAReST Satellite concept in stowed (a) and deployed compact (b) and wide (c) configurations

The spacecraft busses are based on Surrey's SNAP-1 heritage[3] and the STRaND nanosat/CubeSat technology currently in development at the Surrey Space Centre (SSC) by the University of Surrey and Surrey Satellite Technology Ltd. (SSTL)[4], whilst the optics, imaging sensors and shape adjusting adaptive mirrors (with their associated hexapod adjustment mechanisms) are provided by CalTech. The spacecraft bus provides precise orbit and attitude control, with inter-satellite links and optical navigation to mediate the docking process[5]. The docking system itself is based on the electromagnetic flat docking system developed at SSC[6].

The key focus of the AAReST mission is to demonstrate the hardware and techniques needed to autonomously assemble a reconfigurable space telescope in orbit – but to do this at low cost. We expect that the successful execution of the mission will boost confidence in the autonomous assembly approach for the construction of much larger space telescopes, which will have revolutionary astronomical capabilities.

Teams at CalTech and SSC are currently working on the mission planning and development of space hardware. The STRaND-1 precursor mission has been launched, with developmental work underway on the follow up STRaND-2 demonstrating visual inspection, proximity operations and nanosatellite docking[7].

MISSION CONCEPT

The key focus of the AAReST mission is to demonstrate the hardware and techniques needed to autonomously assemble a reconfigurable space telescope in orbit – but to do this at low cost. Hence, we have based the mission on the technology and heritage previously developed for SNAP-1, together with the latest developments in CubeSat technology, to form a "microsatellite-class" mission. We expect that the successful execution of the mission will boost confidence in the autonomous assembly approach for the construction of much larger space telescopes, which will have revolutionary astronomical capabilities.

The overall mission planning is the responsibility of CalTech, and has five key objectives:

- Demonstrate all key aspects of autonomous assembly and reconfiguration of a space telescope based on multiple mirror elements.
- Demonstrate the capability of providing high-quality images.
- Provide opportunities for education in space engineering at CalTech and University of Surrey and to foster links between the two.
- To offer a training opportunity for JPL new hires.
- To use this demonstration to provide outreach activities worldwide, to encourage participation of young people in science, technology and engineering.

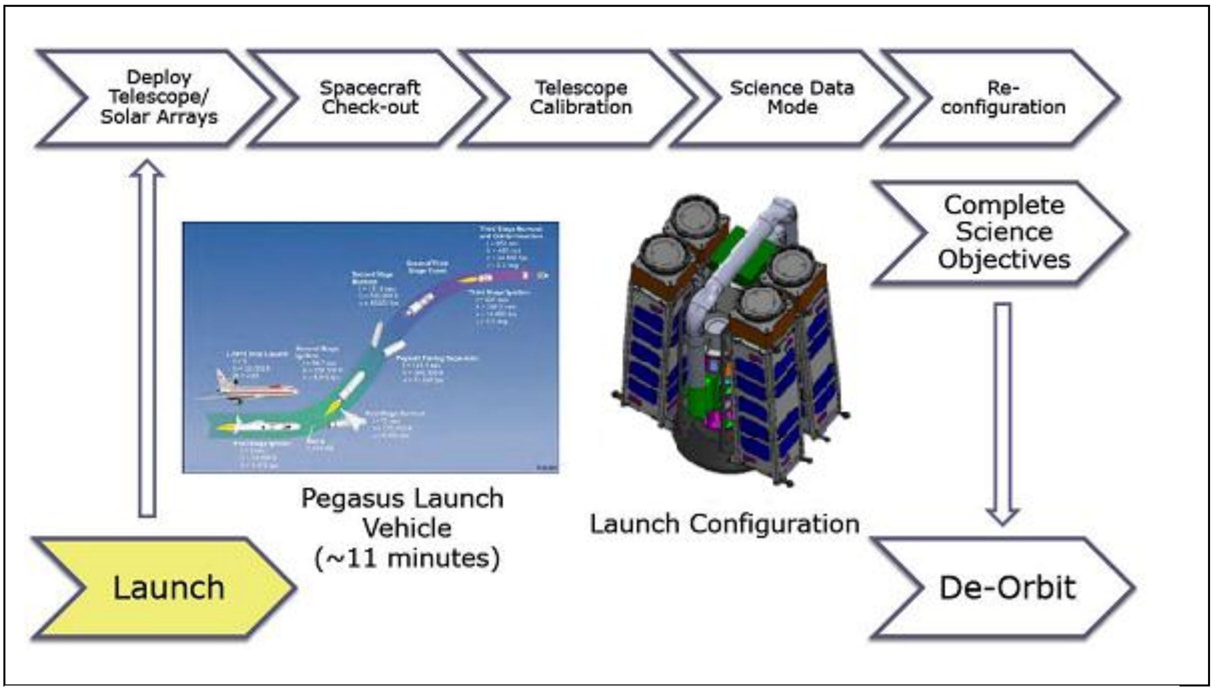

Figure 2: AAReST Mission Concept

On orbit, the mission profile (Fig.2) will firstly establish the imaging capability of the compact compound spacecraft (Fig. 1(b)) before undocking, and then autonomously re-docking a single MirrorSat. This will test the docking system, autonomous navigation and system identification technology. If successful, the next stage will see the other spacecraft undock and re-dock in a linear formation (Fig. 1(c)) to represent a larger (but sparse) aperture for high resolution imaging. Both celestial and terrestrial targets will be imaged.

The AAResT Mission concept science operations are broken down into five phases with key objectives:

- Minimum Mission Objective
  - Image stars, Moon and Earth with fixed mirrors (c. 1º FoV)
  - Demonstrate “precision” (c. 0.5º) 3-axis control
  - Demonstrate acceptable jitter/drift (< 0.02º /s)
  - Calibrate image sensitivity, noise, etc.
- Key Science Objective 1
  - Image with combined deformable and fixed mirrors in “compact mode”
  - Demonstrate deformable mirror technology
- Key Science Objective 2
  - Autonomously deploy and re-acquire “MirrorSat” (manoeuvres are within c. 20cm-30cm distance)
  - Demonstrate electromagnetic docking technology
  - Demonstrate ability to re-focus and image in compact mode
- Key Science Objective 3
  - Autonomously deploy MirrorSat and re-configure to “wide mode” (manoeuvres are within c. 3-4m distance)
  - Demonstrate Lidar/camera RDV sensors and butane propulsion
  - Demonstrate ability to re-focus and image in wide mode
- Extended Mission Objective
  - Deploy and recover MirrorSat from beyond 10m (up to 1 km distance)
  - Demonstrate ISL/differential GPS

We also propose an outreach activity so that young people worldwide can select targets and gain access to the images produced.

TECHNOLOGY DEVELOPMENT

Spacecraft Bus

The work at Surrey has focused on the development of the bus, guidance and propulsion systems for the “MirrorSat”, which will be based on a 3U CubeSat structure. Many of these systems have been flown on the STRaND-1 satellite (Fig.3). STRaND-1 was launched on 25th February 2013 into a 785km Sun-Synchronous orbit with first signal from the spacecraft acquired hours later. STRaND-1 is a low-cost 3U CubeSat demonstrating the Surrey AOCS hardware and software consisting of a full 3-axis attitude control system, based on a 3-axis magnetometer, CMOS-Array-based Sun and Earth sensors, 3-axis magnetorquer and 3 reaction-wheel assembly. STRaND-1 also utilises a

75s specific impulse ~25-100mN thrust water-alcohol resistojet propulsion system (WARP) based on SNAP-1 heritage and a miniature 8-way 1-10μN pulse-plasma thruster (PPT) for fine attitude and orbit control.

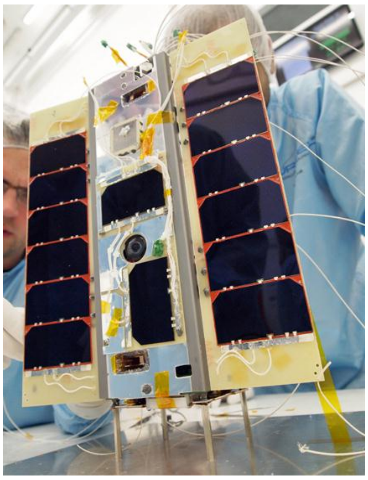

Figure 3: AAReST precursor missions: STRaND-1 CubeSat during AIT

The AAReST MirrorSat will also carry an S-band inter-satellite link (ISL) with a range >1km, a GPS receiver (based on the SGR05 as flown on SNAP-1), which will give a time reference and +/-15m position knowledge, an newly developed magnetic docking system and a machine vision system based on the microsoft Kinect® sensor for optical navigation during the rendezvous phase. These technologies did not fly on STRaND-1, but instead are being developed via a ground-based demonstrator and are planned for the STRaND-2 follow up mission, demonstrating on-orbit rendezvous and docking of two 3U CubeSats (fig. 4).

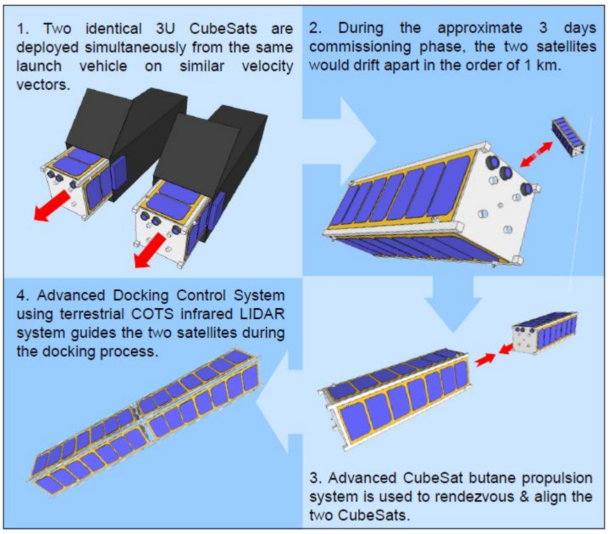

Figure 4: STRaND-2 mission concept

The central microsatellite is considered as three separate 3U CubeSats: two fixed MirrorSats common with the free-flying satellites, one "support sat" and additionally there is an optical payload contained within a 3U envelope and deployed on a boom. This approach is taken to maximise commonality with the MirrorSats to reduce complexity and costs. The power available will be approximately 20W, and an up-rated attitude control system will provide at least 0.1^{o} control in 3 axes – with finer control expected by using the primary telescope and/or separate star camera as part of the attitude sensing system. This craft will contain the VHF uplink and UHF downlink derived from STRaND-1. It will also carry the S-band ISL system to communicate to each of the mirror craft, and when docked, the MirrorSat power will be linked through to the central satellite's power system. The central satellite will carry the butane propulsion system, to carry out larger orbital manoeuvres.

Docking and Machine Vision Systems

CalTech and Surrey are developing an electromagnetic (EM) docking system based on four powerful electromagnets, set running through the free-flying MirrorSats which fit into a matching set on the central mirror satellite on the fixed MirrorSats. The last few metres of the docking procedure will be autonomously controlled electromagnetically. The docking system utilizes a rigid probe and cone configuration, allowing successful docking at extreme angles up to 45º (half angle). The MirrorSats will have a latching docking adapter on each docking facet, so that the magnets do not remain powered after docking. Both mechanical and electro-permanent magnet solutions are being investigated for the latching mechanism.

The machine vision system, to determine relative attitude of the MirrorSats and core microsatellite will be base on the Kinect® sensor system. The stripped down sensor will be mounted on both the MirrorSats and central satellite to ensure that at least one sensor will not be sun blinded during docking. Additional, LED and passive fiducial glyphs are planned as an additional means of relative attitude and range determination.

Ground testing of the docking and machine vision systems for use on STRaND-2 and AAReST is under way through the use of air bearing table and spacecraft simulators. Experiments have been conducted at both CalTech and Surrey to determine the capabilities of the magnetic docking system by the manoeuvring of a 3U CubeSat simulator by way of ducted fans simulating manoeuvring thrusters on the MirrorSat. Surrey has built a 100x150cm air-bearing table, allowing X-Y translation and rotation around the Z axis[8] for this purpose. The design of the table makes use of porous carbon technology. This material allows an even release of air through the surface, without the disturbances that can be create by the macroscopic “Air Hockey” type surface, as used in analogous experiments at CalTech. The spacecraft simulator is supported by a Perspex puck providing a fly height of ~50µm (see Fig. 5).

Figure 5: AAReST RDV-docking test-bed

The spacecraft simulator consists of a power system, wireless communications, an Arduino based controller, propulsion system and docking system. The propulsive system used on the satellite simulator makes use of 6 ducted fans. Each fan is capable of delivering a controllable thrust of 10 - 350mN.

Control of the spacecraft simulator is achieved through use of a Kinect® sensor mounted externally to the craft. This sensor allows for full translation and rotation tracking of objects within its field of view, by means of glyph recognition on both the spacecraft simulator and docking target. The Microsoft Kinect® SDK provides 30fps RGB image stream at 640 x 480 pixels resolution to the glyph identification algorithm.

Initial experiments with the simulator test bed have demonstrated consistent docking under the force generated by the magnetic docking system from a distance of 30cm and manoeuvres were demonstrated up to 40cm from the target. Conventional machine vision algorithms were used to perform manoeuvres with this system (see Fig. 6). Implementing Kinect® sensor technology and the magnetic docking system in these experiments demonstrates the viability of these systems for use in the AAReST mission for assembly of a large scale space telescope.

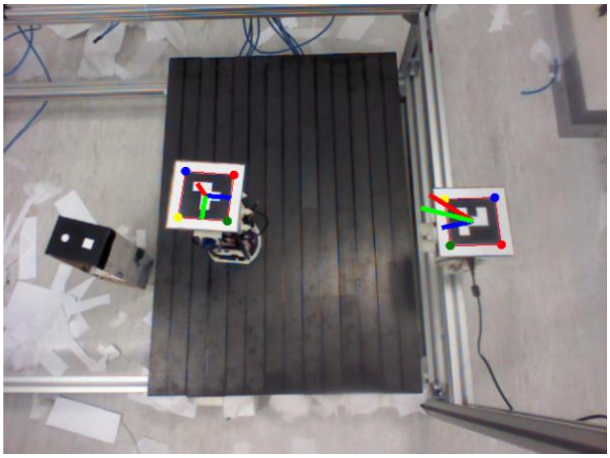

Figure 6: Docking experiment in progress – coloured dots and lines are computer generated locations and vectors derived from the machine vision system

OPTICAL IMAGING SYSTEM

The primary mirror segments are attached to both the fixed and free-flying MirrorSats, After separation from the launch vehicle, the telescope will deploy its sensor package to the focus of the mirror array using a boom. The sensor package contents include a detector at the image plane, corrective lenses to compensate for the prime focus design, as well a Shack-Hartmann wavefront sensor. Using the wavefront sensor within the camera package for mirror shape information, the mirrors would be adjusted and calibrated in order to minimize the size of the mirrors' individual point spread functions (PSF). The mirrors would not be co-phased down to sub-wavelength levels (as would be required for a proper science mission), as this would require an additional metrology system that is prohibitively expensive for a small mission like this. Instead, images would be taken to demonstrate the ability of the mirrors to self-correct their shape, as well as the ability to re-point and correct the individual PSF's[9].

In compact mode the telescope will have a (sparse) aperture size of ⌀0.34m (f/3) in compact mode and ⌀0.58m (f/2) in wide mode. A 1280 x 1024px CCD imaging sensor is planned.

Adaptive mirrors

The deformable mirrors of the telescope are designed to be thin and light-weight. The actuation of the mirrors will be accomplished by in-plane, or surface parallel, actuation through the use of piezoelectric materials rather than using externally applied loads to deform the mirror, which would require a backing structure. In order to stabilize the nearly flat, low stiffness thin mirror, a semi-rigid ring will encircle the mirror, to which the mirror will be attached. In order to retain complete actuation authority over the mirror surface, this rim will also be active through the use of piezoelectric actuators. At small scale, the mass of the rim is larger than the mirror element itself, however, if these mirrors are scaled to larger sizes, the mass of the rim scales only linearly, while the impact of the quadratic scaling of the mirror element mass is alleviated by its small thickness.

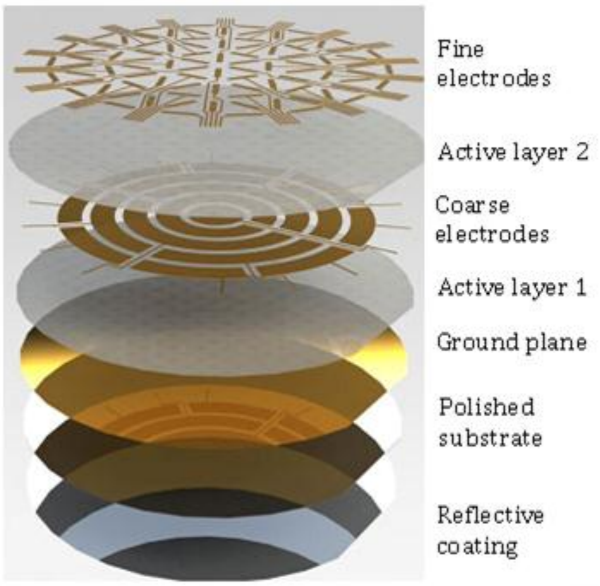

Figure 7: exploded view of a 10cm diameter deformable thin, laminated mirror design

The design (Fig. 7) has the mirror reflecting surface as the bottom (passive) layer and incorporates a continuous active layer with its electrodes divided into four annuli. The patterned active layer above this comprises a lattice of 90 interconnected strip actuators, individually addressed by electrodes. The top three layers comprise the routing traces. The passive layer and the two active layers are each approximately 100μm thick. The mirror would be built up on a mold and the reflective layer deposited upon separation.

A wavefront sensing system provides closed-loop control feedback to maintain the correct mirror position and focus to achieve a coherent aperture (Fig. 8). In addition, the whole mirror structure would be mounted on a piezo-actuated 3-point dynamic mount allowing piston, tip and tilt mirror adjustments. An optical test-bed is currently under construction to test these technologies.

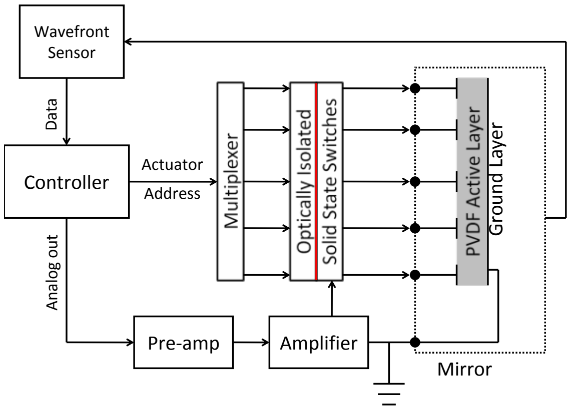

Figure 8: Mirror Control System

CONCLUSIONS

Small satellites have a demonstrated capability of providing cost-effective, rapid-access to space and are ideal for technology demonstration. AAReST demonstrates how nano-satellite technology can be used to provide confidence building demonstrations of advanced space concepts. This joint effort has brought together students and researchers from CalTech and the University of Surrey to pool their expertise and is a good model for international collaboration in space. The spacecraft bus and docking systems will be based on flight proven systems through Surrey's SNAP-1 and STRaND programs, whilst the optical payload is undergoing extensive design and ground testing. The mission will demonstrate autonomous rendezvous and docking, reconfiguration and the ability to operate a multi-mirror telescope in space. Launch is planned for 2015.

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