Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) for Astronomy and Earth Observation

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Abstract: This paper presents a concept for a multi-aperture space telescope built up of autonomous reconfigurable spacecraft elements which, when docked together, can synthesise a large aperture through the use of adaptive optics. The eventual aim is to develop telescopes with apertures exceeding 20m, and thus to move on a generation from the James Webb Space Telescope (JWST) planned for launch in 2014. To gain confidence, a pre-cursor mission (AAReST) is proposed, comprising seven nano-satellites – a central hexagonal primary mirror satellite, carrying the focal plane assembly, together with six additional "mirrorcraft" capable of un-docking and autonomously re-docking to form a reconfigurable multi-aperture telescope. The telescope will be used for both astronomical and terrestrial observations, and there will be an outreach programme for educational access. The University of Surrey is primarily responsible for the spacecraft bus technology, including guidance and propulsion, whilst CalTech is primarily responsible for the mission planning and adaptive optics. Both are working on the autonomous manoeuvring/docking system. The project has oversight and support from NASA-JPL, and the aim is to fly AAReST in 2013-2014. The main bus elements of the "mirrorcraft" will fly as part of Surrey's STRaND CubeSat mission due for launch in 2011.

Keywords: Space Assembly; Space Telescope; Adaptive Optics; Nano-Satellites

1. Introduction

Future space telescopes with an aperture diameter over 20m will require in-space assembly. High-precision formation flying of telescope mirror segments has been proposed, but this will have a very high cost and may not be able to maintain a stable alignment over long periods of time. An alternative is to construct the telescope, in space, by docking the mirror elements together. We believe autonomous assembly of such elements is a key enabler for a lower cost approach to large telescopes.

Demonstration of a low-cost approach for carrying out such autonomous assembly will be a key step in risk reduction, and has much broader application as a breakthrough technology for the utilization of space. 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.

The largest telescope aperture currently feasible, the James Webb Space Telescope [1], has a 6.6 m aperture diameter and hence the successful completion of this project will lead to an order of magnitude increase in aperture size. Our approach and methods are scalable and hence very general.

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 seven "nanosatellite" class vehicles – a central hexagonal prism shaped nanosatellite, which houses the central primary mirror and focal plane assembly, together with six 3U CubeSat-type "MirrorSats", capable of autonomous un-docking/re-docking with the central craft to form different optical configurations. All seven spacecraft will be launched as a single <50kg microsatellite package.

The spacecraft busses are based on Surrey's SNAP-1 heritage [2] 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), whilst the optics, imaging sensors and shape adjusting adaptive mirrors (with their associated hexapod adjustment mechanisms) are provided by CalTech/JPL. The spacecraft bus provides precise orbit and attitude control, with intersatellite links and optical navigation to mediate the docking process [3]. The docking system itself is based on the electromagnetic flat docking system being developed at SSC [4].

Teams at CalTech and SSC are currently working on the mission planning and development of space hardware. It is aimed to launch a precursor to the MirrorSat in 2011.

2. 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.

On orbit, the mission profile (Fig.1) will firstly establish the imaging capability of the compound spacecraft (Fig. 2(a)) 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 four spacecraft undock and re-dock in a linear formation (Fig. 2(b)) to represent a large (but sparse) aperture for high resolution imaging. Both celestial and terrestrial targets will be imaged. We also propose an outreach activity so that young people worldwide can select targets and gain access to the images produced.

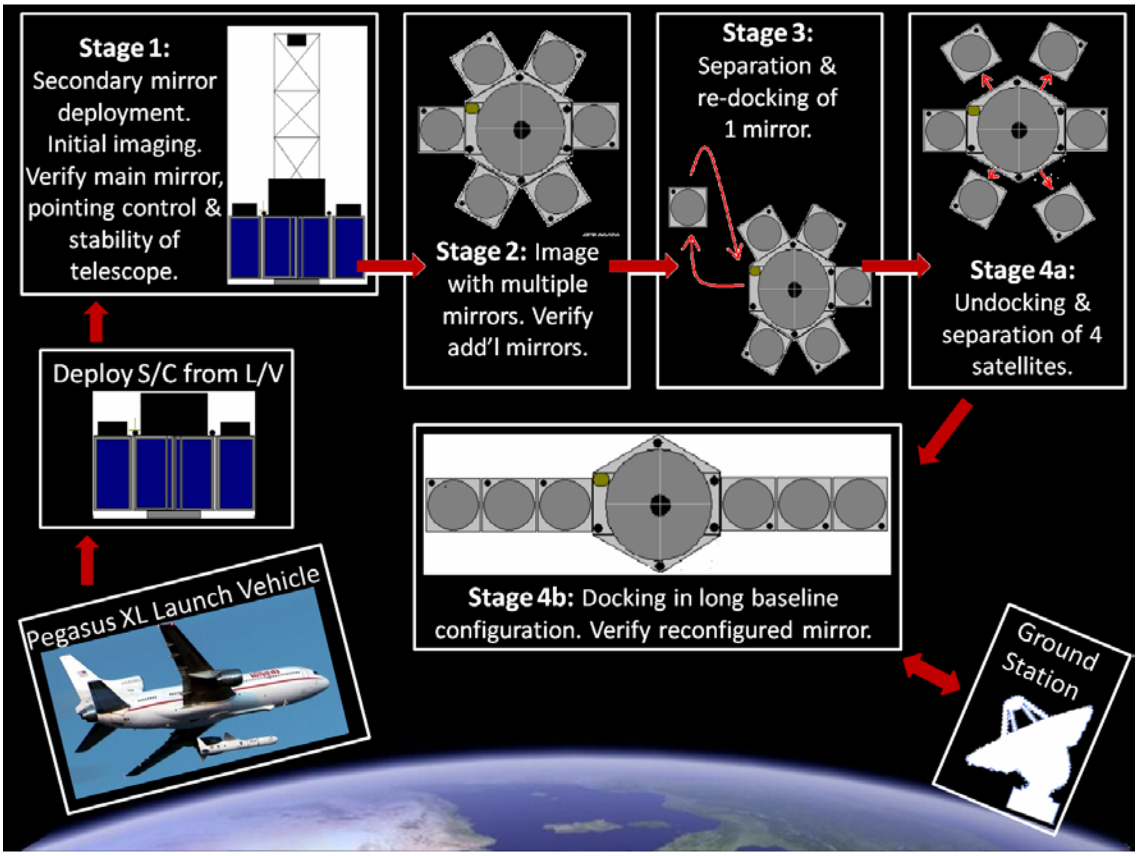

Figure.1. AAReST Mission Profile

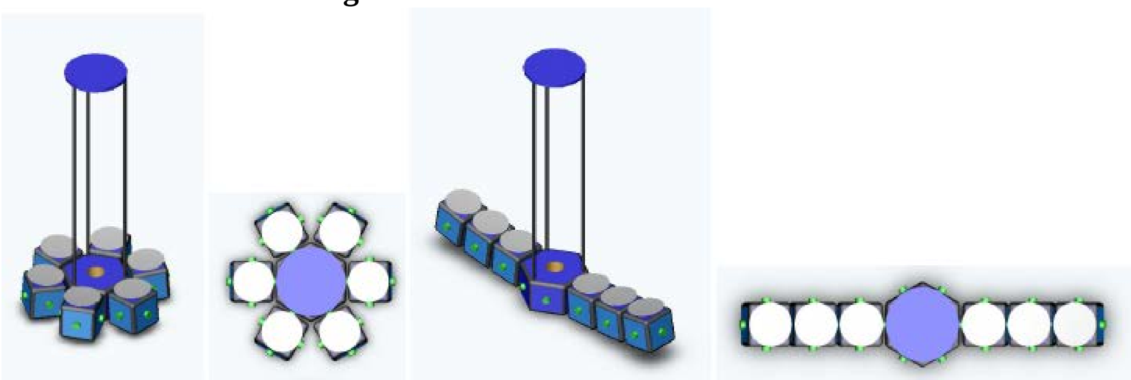

Figure 2. (a) Compact Telescope Imaging Mode; (b) High Resolution Sparse Aperture Imaging Mode

3. Technology Developments

3.1 Preliminary Bus Design

Currently, the work at Surrey has focused on the development of the bus, guidance and propulsion systems for the "mirrorcraft", which will be based on a 3U CubeSat structure. Together with partners at SSTL and Stellenbosch University, we have developed 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 (Fig. 3.) The aim is for ~1^{o} control in all axes, with 0.5^{o}/s slew rate. The mirrorcraft each carry a GPS receiver (based on the SGR05 as flown on SNAP-1), which gives a time reference and +/-15m position knowledge. A MEMS gyro unit may also be incorporated.

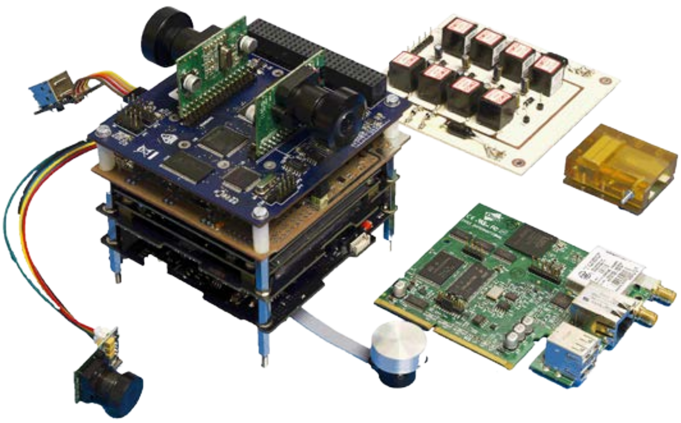

Figure 3. STRaND-1/AAReST Mirrorcraft Core Avionics showing the Cube-Sense Board with Sun and Earth Sensors, Reaction Wheel, Micro-Pulse-Plasma Thruster and High Voltage Drive Unit, ClydeSpace Power System and Battery and the High Performance Computer.

Together with SSTL, SSC is developing a 75s specific impulse ~25-100mN thrust butane resistojet propulsion system based on SNAP-1 heritage, and have also developed a miniature 8-way 1-10N thruster pulse-plasma thruster (PPT) for fine attitude and orbit control. All these technologies will fly on Surrey's STRaND-1 CubeSat (Fig. 4) due to launch in 2011. The AAReST mirrorcraft will also carry an S-band inter-satellite link (ISL) with a range >1km, a magnetic docking system and a machine vision system for optical navigation during the rendezvous phase. These technologies will not fly on STRaND-1, but instead are being developed via a ground-based demonstrator.

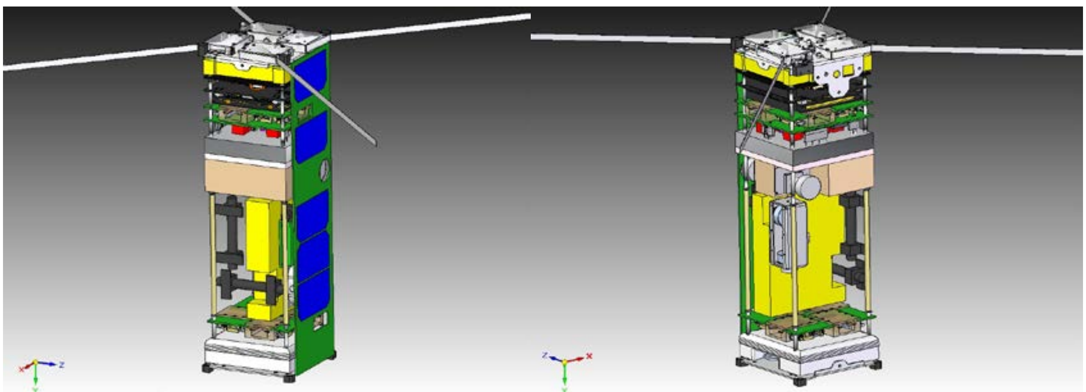

Figure 3. STRaND – A Joint University of Surrey – SSTL Technology Demonstration Mission

The central mirror satellite (Fig.4) will have an external shape set as a hexagonal prism, with a central core avionics system comprising two 3U cubesat structures. 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 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 six mirror craft, and when docked, the mirrorcraft 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.

3.2 Docking System

CalTech and Surrey are developing an electromagnetic (EM) docking system based on four powerful elecrtromagnets, set at the ends of the mirrorcraft, which fit into a matching set on each side facet of the hexagonal-prism shaped central mirror satellite (Fig. 4). The last few metres of the docking procedure will be autonomously controlled electromagnetically. Each magnet has a latching docking adapter at each end, so that the mirrorcraft can stack side-by-side (Fig. 5). This system will be ground tested in 2011 on an Air-Bearing Table.

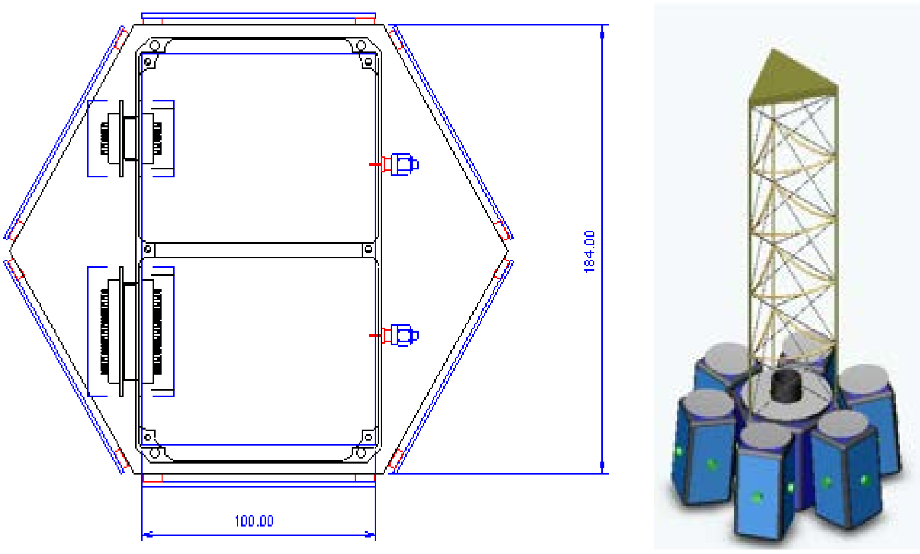

Figure 4. AAReST Central Mirror Satellite

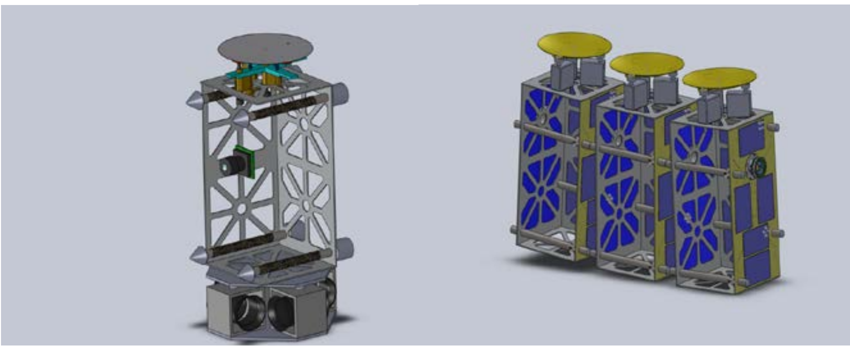

Figure 5. Electro-Magnetic Docking System
(Single Mirrorcraft Structure Shown Mounted on an Air-Bearing Thruster for Ground Test)

3.3 Adaptive Mirror Development

CalTech, with support from JPL and the Keck Institute of Space Studies (KISS), are also developing the optical payload – including the adaptive deformable mirrors. Current efforts are focused on the design and fabrication of 10cm diameter thin shell mirrors with shape correction capability, implemented with low coefficient of thermal expansion (CTE) materials. Active shape control is achieved via PVDF piezoelectric actuators embedded in flexible polymer active layers.

The design (Fig. 6) 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.

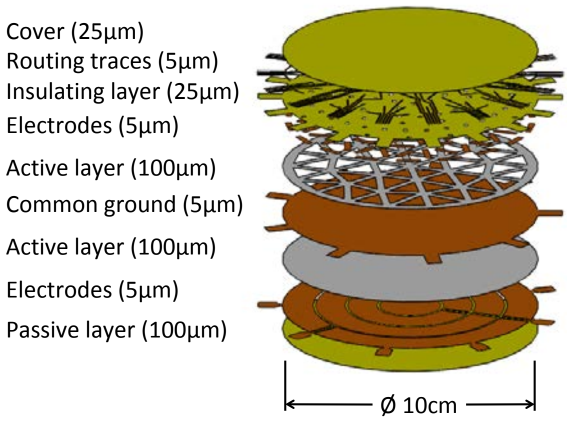

Figure 6. Exploded View of the Proposed 10cm Prototype Mirror.

A wavefront sensing system provides closed-loop control feedback to maintain the correct mirror position and focus to achieve a coherent aperture (Fig. 7). 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.

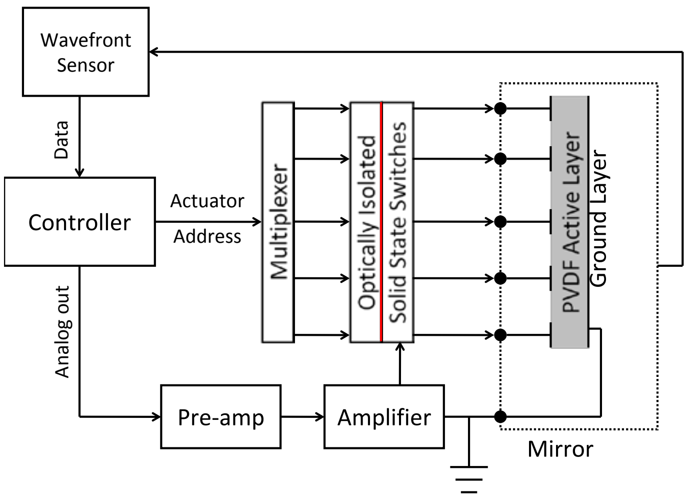

Figure 7.Mirror Control System

4. 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, NASA-JPL and the University of Surrey to pool their expertise and is a good model for international collaboration in space. The mission will demonstrate autonomous rendezvous and docking, reconfiguration and the ability to operate a multi-mirror telescope in space.

5. Acknowledgements

We wish to acknowledge the teams at Surrey, CalTech and JPL contributing to this work. In particular, Keith Paterson at Caltech for the work on the mirrors; Chris Bridges, Pete Shaw, Theo Theodorou, Lourens Visage, Vaios Lappas at the Surrey Space Centre and Shaun Kenyon at SSTL for their work on STRaND-1, and Herman Steyn at the University of Stellenbosch for his work on the attitude determination and control system.

6. References

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