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

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The James Webb Space Telescope (JWST) has the largest aperture feasible with today’s launch technology at 6.6m.

Future larger aperture telescopes of ~20m diameter will require in orbit assembly.

Proposing a small scale CubeSat based demonstration mission.
Mission Overview

• **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 use this demonstration to provide outreach activities worldwide, to encourage participation of young people in science, technology and engineering.
Mission Overview

- **Spacecraft and Mission Concept**
  - Launched as a single “microsat” into LEO
  - Comprises a “Fixed Core NanoSat” + 2 separable “MirrorSats”
  - Total Mass (incl. attach fitting) < 40kg
  - Envelope c. 40cm x 40cm x 60cm
- **Spacecraft and Mission Concept**
  - **Science Mission Phase 1**: (Minimum Mission Objective)
    - Image stars, Moon and Earth with fixed mirrors (c. 1° FoV)
    - Demonstrate “precision” (c. 0.5°) 3-axis control
    - Demonstrate acceptable jitter/drift (< 0.02 °/s)
    - Calibrate image sensitivity, noise, etc.
  - **Science Mission Phase 2**: (Key Science Objective 1)
    - Image with combined deformable and fixed mirrors in “compact mode”
    - Demonstrate deformable mirror technology
• **Spacecraft and Mission Concept**
  
  – **Science Mission Phase 3:** (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
  
  – **Science Mission Phase 4:** (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

**Wide Mode (Ø0.58m, f/2)**
Mission Overview

• **Spacecraft and Mission Concept**
  – **Science Mission Phase 5** (Extended Mission Objective)
    • Deploy and recover MirrorSat from beyond 10m (up to 1 km distance)
    • Demonstrate ISL/differential GPS
  – **Overall Mission Plan:**
    - Deploy Telescope/Solar Arrays
    - Spacecraft Check-out
    - Telescope Calibration
    - Science Data Mode
    - Re-configuration
    - Complete Science Objectives
    - Launch
    - Launch Vehicle (~11 minutes)
    - De-Orbit
Spacecraft Bus

• **Spacecraft Bus – Design Approach**
  - **Low-cost** approach based on CubeSat technology
  - **Heritage** from Surrey’s SNAP-1 NanoSat Programme (2000) (particularly butane propulsion and pitch MW/magnetic ADCS)
  - **Incremental** hardware, software and rendezvous/docking concepts developed through Surrey’s STRaND-1, STRaND-2, and QB50/CubeSail missions currently under development.

Spacecraft Bus

- **Spacecraft Bus – Design Approach**
  - Maximise use of COTS technology.
  - Modular approach, where each module is essentially a CubeSat.
  - Spacecraft bus is treated as a **9U** and two **3U CubeSats** fitted to a framework/attach fitting structure.
    - Two fixed MirrorSats + Central Box = **9U Fixed Core Spacecraft**
    - Two Free-Flyer **3U MirrorSats** with Deformable Mirrors
  - Raw power is shared by MirrorSats through docking ports.
**MirrorSat Requirements**

- Based on Surrey’s STRaND-1 and STRaND-2 developments
- Supports Deformable Mirror Payload (DMP)
- Must be able to operate independently of other units (at least over 3-4m separation – ideally out to 1km)
- Must be able to communicate with the core spacecraft (ISL)
- Must be able to undock, rendezvous and re-dock multiple times
Fixed Core Spacecraft Requirements

- Supports Space Telescope Payload (STP) and Science Imaging
- Must be able to point accurately (< 0.5° error all axes)
- Must be stable in attitude ( < 0.02°/s for 600s)
- Must be able to supply 2W dc continuous to 2 Deformable Mirror Payloads when in docked configuration during imaging
- Must be able to communicate with the MirrorSat spacecraft and the ground at a minimum data rate of 9.6 kbps.
- Must be able to operate with Sun >20° off optical (Z) axis.

Design Approach

- Mixture of COTS and bespoke technology
Example of Expected Imagery
– Optical Model Simulation of Telescope in “Compact” and “Wide” Modes

0.5° angular diameter
1280 x 1024 pixels

Perfect image

Aberrated image
MirrorSat EM Docking System

- Investigations at CalTech by Prof. Underwood using Surrey’s electro-magnets showed:
  - Capture distance was between 20-30cm for two pairs
  - Automatic self-alignment worked, but...
  - Choice of polarities was important to avoid miss-alignment/false-capture.
  - Attractive force was highly non-linear!
  - Biases due to the air-bearing table were problematic
- Modelling by CalTech confirmed results.
• **Developed New RDV/Docking Test-Bed**
  
  – CalTech (air jet) air bearing table was easy to work with, but residual biases made it hard to establish the effect of (tiny) magnetic forces at distances beyond 30cm.

  – Established at SSC a new instrumented 2D Air Bearing Table based on micro-porous carbon technology. (100x150cm)

  – First results look promising – no sign of bias – but very hard to align all units level to the micron accuracy needed!
Developed Test-Bed CubeSat and RDV Target

- Used a combination of COTS CubeSat parts (e.g. ISIS structure) and 3D printed rapid-prototyping to develop a host CubeSat and RDV target.

- Used Zigbee and Arduino technology to establish ISL, and autonomous command and control from a PC.

- Used 6 compact high-performance ducted-fans to represent thrusters

- Re-fabricated EM docking system using 3D printing RP technology.
Investigated Microsoft Kinect®
- We calibrated the Kinect® and assessed its accuracy at providing pose and range estimates.
- Accuracy was good (<3mm lateral error, <2cm depth error) from within the EM docking system’s acquisition distance (30cm) out to 8-10m.

Kinect® Depth View from a 3U CubeSat Model with Solar Panels in the SSC Space System Development Laboratory
Developed Initial Autonomous RDV Controller

- Used machine vision techniques in combination with “gyphs” to establish unique ID, pose and distances between targets
- Developed and demonstrated a initial Steering Controller and a Continuous Feedback Controller to control RDV and docking.
• **Performed Autonomous Docking/Un-Docking**
  
  - Multiple autonomous rendezvous docking/un-docking manoeuvres were carried out using EM docking system and ducted-fan propulsion under wireless computer control.
CalTech Mirror Development

- **Design and Fabrication of 10cm Diameter Thin Shell Mirrors**
  - Shape correction capability
  - Low CTE materials
  - PVDF piezoelectric, flexible polymer active layers
  - Actuator addressing and multiplexing electronics
  - Supporting mount and spacecraft interfaces

- **Optical Testbed for Mirror Behavior /Capability Validation**
  - Wavefront sensing for mirror shape determination
  - Electronics and software for closed-loop active mirror shape control
  - Later on: Setup to be expanded for telescope mirror array
CalTech Mirror Development

10cm $\phi$ Adaptive Mirror

Fine electrodes
Active layer 2
Coarse electrodes
Active layer 1
Ground plane
Polished substrate
Reflective coating

Courtesy of Keith Patterson
Conclusions

• 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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