Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) Rendezvous and Docking on a 2D Test-bed

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**Project Scope:**

- 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
Mission Overview

• **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

Compact Mode (⌀0.34m, f/3)
Mission Overview

- **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 (⌀0.58m, 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

- **Launch**
  - Pegasus Launch Vehicle (~11 minutes)
  - Launch Configuration
- **De-Orbit**
  - Complete Science Objectives
**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.

SNAP-1 (2000)  
STRaND-1 (2013)  
STRaND-2 (2014?)
**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
RDV/Docking System

- **MirrorSat EM Docking System**
  - Air bearing table investigations by CalTech using permanent magnets showed:
    - Probe/drogue works with an acceptance angle of $\pm30^\circ$.
    - Use of 4 magnets is good, but 4 docking ports is over-constraining.
    - Mechanical latches rejected as being too uncertain/complex to implement reliably.
MirrorSat EM Docking System

- CalTech Experiments:
  - Capture and Align Spacecraft on Final Approach
    - Within 30 cm offset*, 45 degree cone**
      - Tolerate +/- 30 degree roll/pitch/yaw
      - Reasonable Relative Velocity
    - Within 15 cm offset, 45 degree cone
      - Tolerate +/- 20 degree roll/pitch/yaw
      - Reasonable Relative Velocity
    - Within 5 cm offset, 45 degree cone
      - Tolerate +/- 10 degree roll/pitch/yaw
      - Reasonable Relative Velocity

*Radius from centre of one face to centre of ‘docking plane’

**Half angle
• **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 mis-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®

- Broken down to explore key electronics & systems

- Remained functional after a vacuum test with a chamber pressure of $2.6 \times 10^{-6}$ bar for 28 hours.

- Further powered tests required in thermal vacuum (imager) & needs to be tested for radiation susceptibility.
Investigated Microsoft Kinect®

- The Kinect® projects a NIR speckle pattern via a laser diode which is picked up by a NIR sensitive camera for depth processing using PrimeSense SoC technology (60 fps).
- The Kinect® also has a full colour (VGA) camera for machine vision.
- Combined with SSC pose estimation software and unique visual “glyph” identifiers (placed on the MirrorSats) – we can identify and find the pose of the MirrorSat to the order of a few degrees, and its range typically to better than 1% of the distance to the target.
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 “glyphs” 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.
Conclusions

- Through the Surrey “STRaND” programmes, the expertise of the staff and students in SSC and with a small amount of support from the UK Space Agency (UKSA) and EPSRC, the ARReST spacecraft bus and EM docking system has been taken forward.

- The EM docking system has been demonstrated to capture after maneuvering to a separation of ~30cm and shows the expected auto-alignment property – at least in 2D. A 3D (5/6DoF) test is needed.

- COTS sensors (such as the Microsoft Kinect®) look to provide a cost-effective solution for the RDV sensor over the last 10m, though sensitivity to Sunlight must be investigated.

- The ARReST S/C concept is iterating towards a solution which can meet the mission objectives in an efficient manner.
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