Application for RSO Automated Proximity Analysis and IMAGING (ARAPAIMA): Development of a Nanosat-based Space Situational Awareness Mission

K. Harris, M. McGarvey, H. Chang, M. Ryle, T. Ruscitti, B. Udrea, and M. Nayak
Overview

- Introduction
- Mission success criteria
- Concept of operations
- 6U Cubesat design
- Subsystems
- Conclusions
University NanoSat Program

Hardware demonstration

Hands-on experience

Funding

Mission military relevance

Aerospace Industry

Department of Defense

Advancing capabilities in U.S. space superiority
Team

- Embry-Riddle Aeronautical University
  - “Prime Contractor”
  - Overall design procurement and integration
  - PI: Bogdan Udrea

- University of Arkansas
  - Nanosat propulsion system
  - Co-I: Adam Huang

- Red Sky Research LLC
  - Science
  - Co-I: Mikey Nayak
Military Relevance

Addresses 3 of 15 prioritized USAF space capabilities:
4. Space situational awareness
8. Satellite operations
10. Offensive space control

Advances Rendezvous & Proximity Ops (RPO) technology

XSS-11 autonomous proximity operations.
(Image from spacetoday.org)
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Mission Overview

ARAPAIMA is a 6U cubesat which autonomously maneuvers in close proximity to a Resident Space Object (RSO) for visible, IR, and 3D imaging.

Mission objectives:

- Determine the 3-D shape of the RSO without previous knowledge
- Autonomously navigate and safely maneuver in close proximity to the RSO, in low earth orbit
- Estimate the attitude state of the RSO by remote observation
Science Problem Statement

- Perform relevant space-based SSA with a nanosat
- Without a priori knowledge of RSO shape or attitude:
  - Assess the capability of the visual and visual-aided navigation algorithms to:
    1. Extract 3D shape knowledge of the RSO
    2. Estimate the attitude state of the RSO
  - Perform infrared radiometry science
- Execute near-optimal trajectories to maximize space-based surveillance of the RSO in low earth orbit
- Validate on-board autonomous relative trajectory
  - Planning
  - Control
  - Execution
Mission Success Criteria

- **Minimum success**
  Take an unresolved image of the RSO and downlink it to the ground station.

- **Full success**
  Maneuver into the proximity of the RSO, with preloaded commands, and take an image in which the RSO occupies at least 15% of the pixels of the visible and IR spectrum cameras.

- **Extended mission success**
  On-board planning and execution of maneuvers to acquire a relative orbit with respect to the RSO and use the LRF to generate a 3D point cloud.
Imageg Results - Simulation

Unknown RSO: Upper stage with attachment of interest

Results of Autonomous Proximity Imaging
With robust RSO attitude solution, LRF-only sensor can recover shape knowledge of unknown RSO.

LRF-only point clouds: 89,000 / 11,000 / 3,500 strikes

Shape reconstruction after: 32 / 12 / 4 hours of surveillance
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Overall Concept of Operations

1. Launch
   Orbit: LEO
   LV: TBD

2. Ejection from CSD

3. Partial solar panel deployment

4. Detumble and sun acquisition

5. Complete solar panel deployment and uncovering of payload

6. Early orbit and systems checkout
   Minimum mission success

7. RSO approach
   ADCS and propulsion systems have been verified
   RSO: TBD

8. Science operations and downlink
   See science CONOPS for more detail

9. Deorbit
Relative Orbit Acquisition (1/2)

Propellant optimal trajectories for acquisition of a circular relative orbit. (Each color represents a different initial in-track distance.)
ARAPAIMA prior to maneuver to 250m relative orbit
Science Concept of Operations

ARAPAIMA CONOPS
Application for RSO Automated Proximity Analysis and IMAging

LV release
- Systems checkout
- Guidance checkout (Imaginary RSO)
- NMC, SK
- Waypoint
- Trim burn

EOL
- Prove rendezvous, dock with asteroids, non-cooperative RSOs

Refine matching maneuvers
- Seed error model
- “Hover” over RSO feature

IDVD guidance: Fast circumnavigation
- SSA material recognition
- LRF-only point cloud survey

10x10x10x100 km NMC insertion (ground-based SSA)

10x10x10x25 NMC insertion (ground-based SSA)
- Transition to Angles Only Nav
- Drifting spiral NMC 10x10x10±10

Waypoint guidance 1, 2 km teardrops
- Verify AON solution

3D RSO shape reconstruction
- Establish 250 m relative orbit
- Mono stereovision (structure from motion)
- Pose estimation (Bounded Hough x’form)

Secondary mission objectives
- Decision Point
- Guidance
- Navigation
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ARAPAIMA Cubesat

- Deployable 6U solar panel
- Computer stack
- Propulsion tank
- S3S startracker
- Reaction wheel
- Body-fixed 2U solar panel
- Deployable 3U solar panel
- Payload

Dimensions:
- 36cm
- 24cm
- 12cm
Structures: Model
Overview

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Propulsion System

- HFC-236fa, $I_{sp} = 47\text{s}$
- 100mN OMT
- 8 x 10mN RCS thrusters in 4 clusters
On-Board Computer

- Two independent Versalogic C/104 Tiger boards
- Manages all subsystems including payload.
- Payload independence ensures payload has enough data resources to be mission effective without conflicting with other subsystems
Communications

- **Basic Information**
  - Set elevation mask: 10 degrees
  - Propagation range: 2880 km

- **Modulations:**
  - Uplink: GFSK (2 bits per symbol)
  - Downlink: O-QPSK

- **Data Rates**
  - Uplink: 9600 bps
  - Downlink: 1.3 Mbps

- **Frequencies**
  - Uplink: 450 MHz (UHF)
  - Downlink: 2.25 GHz (S-band)

- **Uplink Budget:**
  - Carrier to Noise Ratio: 54.85 dB-Hz
  - Data Link Margin achieved: 9.03 dB

- **Downlink Budget:**
  - Carrier to Noise Ratio: 71.19 dB-Hz
  - Data Link Margin achieved: 6.35 dB
Ground Operations

- TRACKING
- ORBIT DATA
- ATTITUDE DETERMINATION
- SCIENCE DATA
- ATTITUDE ENGINEERING DATA
- MISSION PLANNING
- SPACE WEATHER
- GROUND COMM
- UHF
- S-BAND

- PROCESSED ATTITUDE DATA
- ATTITUDE PREDICTION AND CONTROL
- ATTITUDE COMMANDS AND DATA
Static Analysis Performed:
- Single and 6 node analysis
- Rectangular shape w/o solar panel configuration
- More simple and understandable
- Examined using extreme IR and albedo values

Results:
- Hot Case ~85° ±1° C
- Cold Case ~ 11° ±1° C

Results are shown with an 11 °C margin
Electrical Power System

- Solar panels provide power for both system and charging of battery
- All power is routed through switch controlled by on board computer
- Three supply voltages of 12V (Direct from battery), 5V, and 3.3V
- Silicon Solar panels and Lithium Ion batteries are best choices so far
Payload Testing

- Testing:
  - Aluminum plate, solar panel, Mylar, fine steel mesh
  - Incidence angles: 0° - 45°
  - Distance: 5m - 30m
  - Varying light conditions
Payload Emulator Test Results

- Analyzed using Gaussian and Weibull distribution
- Bloom imaging
- Error characterization for LRF modeling:
  - Pulse dilation
  - Influence of the material reflectance
Further Testing

- The next step is to use the payload emulator to simulate point clouds and images of moving models.
- Models include, Envisat, X37-b, Delta IV upper stage, among others.
- This testing allows for not only testing of the individual components but also the payload as a whole.
Feature Detection

Roll, Pitch, & Yaw Approximations
Attitude Dynamics Modeling

- **External disturbance torques:**
  - Aerodynamic
  - Gravity gradient
  - Residual magnetic moment
  - Solar radiation pressure

- **Internal disturbance torques:**
  - Reaction wheel imbalance
  - Propellant slosh
  - Solar panel vibration
  - Orbital maneuver thruster misalignment
Aerodynamic Disturbance Torques

- Direct simulation Monte Carlo (DS3V)
- Parameters: 
  O ~ 94%, N ~ 6%, 
  T=1491K, 
  $n=3.8 \times 10^{14} \#/m^3$, 
  v=7.6km/s, 
  mfp=27.33km
## Conclusions/Project Timeline

<table>
<thead>
<tr>
<th>Review</th>
<th>Months from Kickoff</th>
<th>Date</th>
<th>Expectations (Mechanical, Electrical, Software)</th>
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</thead>
<tbody>
<tr>
<td>System Concept</td>
<td>2</td>
<td>12 Mar 13</td>
<td>Mission concept</td>
</tr>
<tr>
<td>System Requirements</td>
<td>4</td>
<td>30 Apr 13</td>
<td>CAD model, electrical board concept, software/hardware identified</td>
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<tr>
<td>Preliminary Design</td>
<td>8</td>
<td>16 Aug 13</td>
<td>Physical model, breadboards, high-level block diagram</td>
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<tr>
<td>Critical Design</td>
<td>14-16</td>
<td>Feb-Apr 14</td>
<td>Refined CAD, elegant breadboard, software 1.0</td>
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<tr>
<td>Engineering Design</td>
<td>20</td>
<td>Aug 14</td>
<td>Engineering unit, flight-ready configuration board, software 2.0</td>
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<tr>
<td>Flight Competition</td>
<td>25</td>
<td>Jan 15</td>
<td>Flight CAD, flight-ready configuration board tested, software 3.0</td>
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Thermal Modelling Suite

Active Silicon
COMPUTER IMAGING PRODUCTS

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY
Questions?