An Integrated Vision-Based System for Spacecraft Attitude and Topology Determination for Formation Flight Missions

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**Vision-Based Attitude and Formation Determination System**

**Problem Description**

**Mission and Technology Specifications**

**Attitude and Formation Member Determination**
- Star tracker
- Visual Beacon

**Formation Determination**
- Estimation methods

**Least-Squares Adjustment**

**Architecture and System Design**

**Case Studies and Performance Results**

**Summary and Future Work**
**Problem Description**

- **Merit and utility of distributed and multi-spacecraft missions is well defined**
  - Reliability and reconfigurability
  - Performance vs. monolithic systems

- **NASA has outlined a technology roadmap that is predicated upon use of formation systems**
  - Constellation-X, MMS, TPF, PI

- **Challenge is to maintain accurate relative positioning to perform mission objectives**

- **Availability of external data sources may limit formation navigation capability:**
  - GPS, TDRSS, CelNav, or groundstation information availability is practically constrained to certain access times, orbits, or geometries

- **Coordinated operation requires precise navigation equipment**
  - Existing relative positioning equipment are not optimized for small spacecraft.

- **Traditional ranging systems do not provide “formation attitude” or inertial positions of member spacecraft**

- **Existing systems require formation determination equipment to be included onboard all member spacecraft**
  - Implementations don’t leverage over-determined solution to improve estimates
# NASA Benchmark Formation Flight Missions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Apogee alt (km)</td>
<td>400*</td>
<td>108 426*</td>
<td>[transverse amplitude about L2 = 300 000]</td>
</tr>
<tr>
<td>Perigee alt (km)</td>
<td>400*</td>
<td>1 276*</td>
<td>[normal amplitude about L2 ≤ transverse amp.]</td>
</tr>
<tr>
<td>Inclination (deg)</td>
<td>97.03</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Number of SC</td>
<td>6</td>
<td>4</td>
<td>20+</td>
</tr>
<tr>
<td>SC control</td>
<td>3-axis</td>
<td>spin</td>
<td>3-axis</td>
</tr>
<tr>
<td>Relative position control requirement (m)</td>
<td>5 (with respect to desired relative trajectory)</td>
<td>10% of SC separation at apogee</td>
<td>0.01 (science mode)</td>
</tr>
<tr>
<td>Formation Topology</td>
<td>projected circular</td>
<td>tetrahedral</td>
<td>aspherical</td>
</tr>
<tr>
<td>Pointing requirement (arcsec)</td>
<td>360</td>
<td>3600</td>
<td>1 (science mode)</td>
</tr>
<tr>
<td>Mission duration (yr)</td>
<td>2</td>
<td>2</td>
<td>12</td>
</tr>
</tbody>
</table>

*Reference orbit; no spacecraft exists in this orbit.

VBAFDS Step-1: Attitude and Formation Member Determination

- Star tracker images star field
- Spacecraft identifies star pattern and other spacecraft in the formation (“nodes”)
- Spacecraft determines its own inertial attitude and relative bearing angles to other nodes
- Applies VBAFDS processing algorithms in conjunction with range and other available data sources

Spacecraft determines inertial attitude

Spacecraft determines relative angles to nodes
**Star Tracker Pattern Recognition Approach**

- **Most modern star tracker algorithms are fairly robust; ignore “false stars” caused by proton hits or debris.**
  - Sources identified through standard centroiding techniques
  - Can usually be ruled out by correlating multiple sequential images and persistency checks.
  - The Pyramid Algorithm, developed by Junkins and Mortari, can work in the presence of up to 24 false stars.
  - The Rosetta Comet Mission star tracker is expected to work in the presence of several thousand false stars, caused by light reflecting off comet dust particles.

- **Once a positive star match is made, the star tracker can match the remaining objects in the image against the star catalog, to determine which objects are not stars.**

- **Once initial acquisition has been performed, the star tracker will know approximately where to expect other satellites (and stars) to appear, which will greatly speed up image processing and tracking.**
Related Technologies: MST (Miniature Star Tracker)

**U.S. Government-Funded SBIR/STTR Program To Produce A Small, Low-Power Star Tracker**
- Collaboration with MIT Space Systems Laboratory

**Expected Phase II Contract, Fall 2004**

**Top Level Design Objectives:**
- Field of View: 30 degrees Conical
- Accuracy: <100 arc-seconds
- CMOS Imager: 1000 x 1000 Pixel Array
- Roll Max: 0.3 deg/sec
- Update Rate: 1Hz
- Mass: 300 grams
- Power: <1 Watt @ 5.5VDC
- Dimensions: 5.1 cm x 7.6 cm x 7.6 cm
- Volume: 300 cu cm
- Output: x,y,z Earth-Centered Inertial Frame
- Limiting Star Magnitude: 4th
- Star Pairs Tracked Simultaneously: 4 Max.
- Interface: RS-422
- Radiation Tolerant Up To 20 Krad
**Visual Identification of Member Spacecraft**

- Member spacecraft of formation must be able to uniquely identify themselves
- Single focal-plane solution preferred for simplicity
- Required beacon irradiance calculated based upon detector specifications, dispersion with separation distance, and off-center viewing angles
- Optical considerations included through definition of an effective pixel capture area
  - Function of detector FOV and focal length, normalized by the number of pixels in the array
- Detector noise considered: photon noise and the dark current (thermal noise)
- Required that effective SNR \( \geq 1 \) to drive beacon sizing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LED</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Wavelength, ( \lambda )</td>
<td>592 nm</td>
<td>650 nm</td>
</tr>
<tr>
<td>Luminous Intensity, ( I_v )</td>
<td>13800 mcd</td>
<td>3.5-4.0 mW</td>
</tr>
<tr>
<td>Forward Voltage</td>
<td>2.15 V</td>
<td>2.8-4.0 V</td>
</tr>
<tr>
<td>Forward Current</td>
<td>20 ( \mu )A</td>
<td>50-65 mAmp</td>
</tr>
<tr>
<td>Diameter</td>
<td>5 mm</td>
<td>10.5 mm</td>
</tr>
<tr>
<td>Beam Angle, ( \theta )</td>
<td>0.262 rad</td>
<td>1.3 mRad</td>
</tr>
</tbody>
</table>

**Agilent Technologies**

**Midwest Laser**
Visual Beacon Design

- Laser beacon suite provides power-efficient solution; low “observable” angular separation
  - 8-Laser suite required for 10 km separation
- Alternate beacon sources to be considered: LumiLEDs, Laser Diodes, Laser LEDs

![LED Beacon](chart_1)

![Laser Beacon](chart_2)
VBAFDS Step-2: Formation Determination

- All spacecraft communicate relative bearing angle information of observed nodes to one another, which results in determination of formation geometry.
- One element of range data (inter-node distance) is required to uniquely determine formation size.
- Ranging equipment can be eliminated on nearly all formation spacecraft
  - OR redundant measurements can be used to improve state estimates!
    - Preference for same sensor suite on each member platform for standardization

![Visual acquisition of neighboring nodes](chart10/visual_acquisition.png) + ![Determination of relative angular bearings to neighboring nodes](chart10/relative_bearings.png) → ![Determination of formation geometry](chart10/formation_geometry.png)
### Carrier Processed RF Ranging

<table>
<thead>
<tr>
<th>Timing Std. Performance</th>
<th>2e-12</th>
<th>2e-11</th>
<th>2e-10</th>
<th>3e-7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Allan Deviation/sec</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>10 km Performance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>S-Band</strong></td>
<td>25cm-1M</td>
<td>2.5-10m</td>
<td>25m-100m</td>
<td>&gt;100m</td>
</tr>
<tr>
<td><strong>X-Band</strong></td>
<td>7-10cm</td>
<td>70cm-1M</td>
<td>7m-10m</td>
<td>~100m</td>
</tr>
<tr>
<td><strong>Ku-Band</strong></td>
<td>3-5cm</td>
<td>30-50cm</td>
<td>3-5m</td>
<td>~50m</td>
</tr>
<tr>
<td><strong>L-Band</strong></td>
<td>Not Needed</td>
<td>Not Needed</td>
<td>Not Needed</td>
<td>2-5m</td>
</tr>
<tr>
<td><strong>10km Performance/ CDGPS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(Requires ISL to xfer differentials)</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Precise Antenna Location Required ?</strong></td>
<td>Yes</td>
<td>Yes (at &lt; 1m)</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### Current Ranging Systems Operational or Under Development

<table>
<thead>
<tr>
<th>ISL-ISR Systems</th>
<th>Frequency</th>
<th>Range</th>
<th>Range Accuracy</th>
<th>Mass</th>
<th>Size</th>
<th>Power</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFF/JPL</td>
<td>30 GHz</td>
<td>1300km</td>
<td>1μm</td>
<td>2 kg</td>
<td>N/A</td>
<td>1W avg. 5W peak</td>
<td>Carrier/Phase, post processed 100M CPS not dynamic accuracy</td>
</tr>
<tr>
<td>AFFCI/JPL</td>
<td>UHF L-Band</td>
<td>1000km</td>
<td>100m</td>
<td>1 kg</td>
<td>N/A</td>
<td>2W</td>
<td>UHF comms ISL-GPS Augmented-DRACO</td>
</tr>
<tr>
<td>StarRanger</td>
<td>Ku-Band 10/12 GHz</td>
<td>50km</td>
<td>3cm</td>
<td>2 kg</td>
<td>5x10x15 cm</td>
<td>12W</td>
<td>Carrier/phase processed. Accuracy dynamic, 128kbs ISL</td>
</tr>
<tr>
<td>Stanford</td>
<td>UHF L-Band</td>
<td>50km</td>
<td>2-5m relative</td>
<td>~2 kg</td>
<td>N/A</td>
<td>6W</td>
<td>Attitude to 0.5°, time xfer 1μs, ISL 38.4 kHz</td>
</tr>
</tbody>
</table>
Position Estimation

**Measurement Types**
- Range: scalar quantity + uncertainty
- Bearing: Azimuth and Elevation + uncertainty

**Estimation Methods**
- Traverse: when range and bearing are known
- Triangulate: when two angles and one range of a triangle are known
  - Unknown ranges values can be solved for using the law of sines or the law of cosines
  - Stereo vision case
  - Two satellites separated by a known baseline and bearing can calculate the distance to other satellites using only bearing measurements (no ranging required).
- Trilateration: when distances to four established satellite positions are measured, then relative position can be calculated without any bearing information
  - Like GPS

The VBAFDS algorithm suite combines traverse, trilateration, and triangulation techniques iteratively until all points have been solved for, or all combinations have been exhausted

The initial positions estimates use the minimum number of measurements possible to solve for relative positions
VBAFDS Step-3: Least Squares Adjustment

\[ JX = K + V \]

\[
\begin{bmatrix}
\frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} & \ldots & \frac{\partial F_1}{\partial x_n} \\
\frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} & \ldots & \frac{\partial F_2}{\partial x_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial F_m}{\partial x_1} & \frac{\partial F_m}{\partial x_2} & \ldots & \frac{\partial F_m}{\partial x_n}
\end{bmatrix}
\begin{bmatrix}
\Delta x_1 \\
\Delta x_2 \\
\vdots \\
\Delta x_n
\end{bmatrix}
=
\begin{bmatrix}
l_1 - F_1(x_{10}, x_{20}, \ldots, x_{n0}) \\
l_2 - F_2(x_{10}, x_{20}, \ldots, x_{n0}) \\
\vdots \\
l_m - F_m(x_{10}, x_{20}, \ldots, x_{n0})
\end{bmatrix}
+
\begin{bmatrix}
v_1 \\
v_2 \\
\vdots \\
v_m
\end{bmatrix}
\]

\* Once an initial estimate of formation geometry is found, a system of equations is setup to adjust the estimate:

- J = The Jacobian matrix
- X = The vector of adjustments to the estimate \((x_1, x_2, \ldots, x_n)\).
  - This is what will be solved for.
- K = Measurements \(L = (l_1, l_2, \ldots, l_n)\) minus Measurement Equations \((F_1, F_2, \ldots, F_n)\)
  - \(F_n\) calculates what \(l_n\) should be given the current estimate \((x_1, x_2, \ldots, x_n)\)
- V = The residuals.
  - This is what we are trying to minimize.
**VBAFDS Processing Architecture**

### Processor Sizing:
- **BlackFin MPU with 256kB resident ROM, 8kB RAM**
  - ~1k lines of operating code
  - 256K memory required, 136kB operating
  - 100kB Star Catalog
- **5 Image holding capability, 6MB additional RAM**

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**External Data Sources:**
- GPS
- TDRSS
- Ground U/L

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**RF/Optical Ranging**

**Timing**

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**VBAFDS Processor**

**Propagator**

**Position Filter**

**Attitude Filter**

**Initial DCM**

**Star Catalog**

**Pattern Recognition Software**

**Image**

**MST Star Tracker**

**IMU**

**30 Field of View**

**Active Pixel CMOS Imager**

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**RS-422**

**10MHz**

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**Chart 14**
**Simulation Environment and Results**

**Simulation features:**
- 6DOF simulation with a J4 orbit propagator and rigid body attitude dynamics.
- Flexible scripting interface (Lua).
- 3D Visualization.
- Simple sensor models.
- Integrated VBAFDS algorithm suite

**Baseline Scenario: “MMS-like” Constellation**
- Four satellites in a tetrahedron.
- Three satellites take visual bearing measurements to a fourth satellite that would carry a beacon.
  - Inertially fixed attitudes, so that at orbit apogee the three satellites all point to the fourth satellite.
- All satellites take range measurements to the other satellites.
- The extra range measurements at the base of the tetrahedron provide redundancy and allow the covariance of the results to be minimized.
Simulation Environment – NASA HEO Mission
Simulation Results – NASA HEO Mission

*Plots of bearing angle versus time for an orbit*

3-Axis Stabilized

Spin-Stabilized (3 RPM)
**HEO Mission 3-Axis Case**

**Measurements**
- Bearing
  - 72 arcsec
- Range
  - 1 m
- 3 sigma

**Results**
- 10000 sets of random measurements
- Blue line
  - Error distribution before adjustment.
- Green line
  - Error distribution after adjustment.
- Graphs show how the adjustment reduces the variance of the estimates significantly.
**Least Squares Adjustment Results: Improved Measurements**

- **HEO 3-Axis Case**
  - Bearing
    - 10 arcsec
  - Range
    - 1 cm
- Increased sensor capabilities increase results!
  - So does access to additional, selectively available measurement data
    - GPS
    - TDRSS
    - CelNav
    - Ground U/L
**Scenarios - Trilateration**

*Like GPS or TDRSS*

- Demonstrates Trilateration
- Four satellites are used as reference points.
  - These could be GPS or TDRSS satellites, or specialized satellites in the formation.
- Other satellites take only range measurements to the four reference satellites.
- Redundant range measurements can be included to reduce the effects of random errors.
Scenarios – A-Train

**In-Track Constellation of satellites**

- Each satellite takes a bearing measurement to one or possible two satellites in front of it.
- Each satellite can take range measurements to multiple other satellites in the constellation.
- Large separation distances could mean reduced accuracy in bearing measurements.
- However a lot of redundant measurements could be made in a case like this.
Scenarios – Triangulation or “Stereo-Vision”

**Stereo Vision**
- Two satellites separated by a known baseline separation distance and bearing.
- Visual bearing measurements of other satellites.

**Minimal hardware**
- The other satellites would not require ranging or visual sighting hardware, but could carry it to provide redundancy.
- Might be a good technique to monitor a large distributed swarm of satellites.
Summary of VBAFDS Approach

- **Provides determination of formation Shape and Attitude**
  - Ranging alone gives you the dimensions of your topology, but not how the formation as a whole is oriented.
- **Can work for lots of different types of formations.**
  - The generic algorithm approach is able to handle any arbitrary formation geometry, given that the minimum number of measurements are available.
- **Can work where external position data (e.g. GPS, TDRSS, Ground U/L) is not available**
  - Could facilitate relative formation navigation around the moon, libration point.
- **Can fuse multiple sources of measurements to improve accuracy.**
  - The generic least-squares-adjustment software can simultaneously incorporate any number of heterogeneous measurement sources.
    - Can integrate “selectively-available” data to improve overall accuracy
      - Range measurements could be augmented by taking additional accurate bearing measurements.
  - Could be modified in the future to incorporate knowledge of satellite dynamics.
    - Kalman Filtering would provide a means of integrating the dynamics and measurement models.
    - Could it be feasible that tracking the relative acceleration between satellites in a constellation would facilitate coarse orbit determination
- **Next step is development of Laboratory- and Field- Visual Identification Testbeds for technology development and maturation**
  - Goal of NASA TRL 5