Development of *CubeStar*
A Robust, Low-Cost, CubeSat Star Tracker

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ESL history (SUNSAT)

- Africa’s first fully indigenous satellite
- Satellite was designed and developed without any technology transfer help
- Developed by graduate students and staff in period 1992-1998
- First microsatellite (64kg) with SPOT-5 type 3-band multispectral resolution camera
- Launched in 1999 on Delta II USAF rocket into a 640 x 850 km orbit
- 2 Year useful orbital life
Current ESL Satellite Research

- Cube Components
- ZA-AeroSat (QB50)
- ZA-Cube2
- Tethers
- Solar Sails
## Typical CubeSat ADCS

Sensors consist of:
- Magnetometer
- Coarse / fine sun sensor
- Horizon sensor
- MEMS rate sensor

<table>
<thead>
<tr>
<th></th>
<th>EO - sunlit</th>
<th>EO - eclipse</th>
<th>Interplanetary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available sensors</td>
<td>Coarse &amp; Fine Sun Horizon Sensor Magnetometer MEMS Rate</td>
<td>Magnetometer MEMS Rate</td>
<td>Sun</td>
</tr>
<tr>
<td>Attitude knowledge</td>
<td>0.2 degrees</td>
<td>5 degrees</td>
<td>unavailable</td>
</tr>
</tbody>
</table>
CubeStar Aims

• Develop CubeSat compatible Star Tracker within 2 years by reusing existing subsystems

• Enhance capabilities of current CubeSat ADCS
  - attitude knowledge in eclipse
  - better attitude knowledge throughout orbit
  - make interplanetary travel possible
Hardware Heritage

CubeSense

- CMOS cameras
- FPGA + external SRAM
- PIC Microcontroller

CubeComputer

- 32bit ARM Cortex M3 clocked at 48MHz
- External EDAC protected SRAM
Choosing an Image Sensor

The most crucial component of a star tracker.

<table>
<thead>
<tr>
<th></th>
<th>Desired Specs</th>
<th>Chosen Sensor’s Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>CMOS APS</td>
<td>CMOS APS</td>
</tr>
<tr>
<td>Resolution</td>
<td>At least 512x512</td>
<td>1024x512</td>
</tr>
<tr>
<td>Size</td>
<td>1/3” (for S-mount lens)</td>
<td>~1/3” (6.45mm)</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;&lt;500mW</td>
<td>220mW</td>
</tr>
<tr>
<td>Pixel size</td>
<td>As large as possible</td>
<td>5.6x5.6 μm</td>
</tr>
</tbody>
</table>

Special features:

• Designed specifically for low light applications
• Automotive Qualified
• Automatic dead pixel correction
• Average frame brightness output
Deciding on FOV

<table>
<thead>
<tr>
<th></th>
<th>Typical</th>
<th>CubeStar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular FOV</td>
<td>20</td>
<td>42</td>
</tr>
<tr>
<td>Limiting Mag</td>
<td>5</td>
<td>3.8</td>
</tr>
</tbody>
</table>

CubeStar Lens

- f: 6mm
- F stop: 1.2
- Format: 1/3 inch
- Mount: S Mount
1. Image sensor captures image which gets stored in the FPGA’s external SRAM
2. Image gets transferred from FPGA’s external SRAM to processor’s external SRAM
3. Processor performs image processing and outputs attitude to satellite (while step 1 repeats in parallel)
Algorithms – 3 steps

**Centroiding**
- Purposefully defocus image
- Region Growing
- Find brightest pixel in each region
- Centre of gravity equation

**Star Matching**
- Geometric Voting Algorithm
- Makes use of up to 20 stars
- Robust against false stars

**Attitude Determination**
- QUEST algorithm
- All matched stars and confidences used
- Saves attitude to assist in next frame
Lost In Space vs Tracking

TRACKING
Previous attitude estimate used to predict location of stars – compared to detected centroid locations. Wide FOV means no attitude propagation estimate required.

ASSISTED MATCH
Rough attitude estimate used to create smaller sub-catalogue. More robust

LOST IN SPACE
Full star catalogue used for matching
Simulation Results

- Monte Carlo simulations done in MATLAB

- Hundreds of ideal sky images simulated and input into star tracker algorithms

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Sky Coverage</th>
<th>Robustness</th>
</tr>
</thead>
<tbody>
<tr>
<td>X/Y</td>
<td>Lost In Space</td>
<td>5 false stars</td>
</tr>
<tr>
<td>Z</td>
<td>Assisted</td>
<td>10 false stars</td>
</tr>
<tr>
<td>0.006 degrees</td>
<td>93%</td>
<td>96%</td>
</tr>
<tr>
<td>0.012 degrees</td>
<td>&gt;99%</td>
<td>93%</td>
</tr>
</tbody>
</table>
Hardware Implementation

3 stacked boards
45x30mm each
Calibration

• No fancy equipment required

• Determine focal length
  -used images of a known constellation near centre of image

• Determine distortion coefficients
  -used well known MATLAB camera calibration toolbox
  -output of toolbox suggests 0.2 pixel accuracy (unlikely)
  -room for improvement
Real Sky Results 1

Right Ascension over time with the star tracker fixed relative to the Earth

Declination over time with the star tracker fixed relative to the Earth
Real Sky Results 2

Bore sight pointing accuracy:

1σ  0.0140 degrees
3σ  0.0419 degrees

Rotation accuracy:

1σ  0.0292 degrees
3σ  0.0877 degrees
Summary

• Successfully developed a CubeSat compatible star tracker in under 2 years by reusing subsystems

• Fullfills performance requirements of current and near future CubeSat missions

• Low Power, Volume, Weight: 350mW orbit average, < 1/4U, <100g

• Flexible. Could be reprogrammed to track the moon or Earth’s horizon

• Scheduled to fly in 2015 on ZA-Aerosat (QB50)
Questions?

Thank you for your attention