Autonomous Navigation Using Celestial Object Measurements for a CubeSat Lunar Mission

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Outline

- Background and Motivation
- Optical Sensors for Lunar Mission
- Autonomous Navigation Flowchart
- Measurement Options and Models used in the Navigation Software
- Simulation Studies
- Image Processing and Image Testing
- Student Participation
- Summary
Background and Motivation

- Funding through the Vermont Space Grant Consortium (VSGC), a NASA sponsored program to promote research infrastructure within the state, encourage Vermont students to engage more in mathematics and science, and promote consideration of careers in aerospace-related areas.

- Norwich University is working in collaboration with Vermont Technical College and the University of Vermont on a CubeSat project that focuses on autonomous navigation in space for missions beyond earth orbit.

- Vermont Technical College is leading an effort to build a single CubeSat scheduled in Fall 2013 to launch into low earth orbit to do some initial testing of the navigation system using a camera to capture images of the moon and stars.

- Long term goal is to design a navigation system for a three axis stabilized, 3U CubeSat on a Lunar Mission. NASA’s GEONS (GPS Enhanced Onboard Navigation System) software is being used in the navigation system. Norwich University is working on the attitude and orbit determination using optical sensors and celestial navigation capability in GEONS.
Autonomous Navigation Using Celestial Object Measurements

GEONS navigation software is capable of processing GPS signals near earth and celestial object measurements when the spacecraft is outside of GPS range.

- Use of optical sensors for attitude and orbit determination.
- Line-of-sight (LOS) unit vector to sun from sun sensors
- LOS unit vector to Moon or Earth from camera images
- Attitude obtained from Star Tracker
3U CubeSat with One Possible Configuration of Optical Sensors for a Lunar Mission

- Sun sensors (1 and 2) provide Sun LOS vectors.
- Camera (3/4) provides a picture of the Moon or Earth from which the Moon or Earth LOS vector can be determined.
- Star tracker (3/4) for attitude measurements.
- This module occupies about 1/3 of one CubeSat.
Star Tracker
Moon/Earth Imaging Camera

This can be used for both the imaging camera and star tracker.

<table>
<thead>
<tr>
<th>Manuf.</th>
<th>Berlin Space Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model #</td>
<td>ST-200 / IM-100</td>
</tr>
<tr>
<td>Size</td>
<td>32x32x53 mm³</td>
</tr>
<tr>
<td>FOV</td>
<td>20° x 18°</td>
</tr>
<tr>
<td>Accuracy</td>
<td>30 arc sec.</td>
</tr>
<tr>
<td>Image Size</td>
<td>4 MP</td>
</tr>
<tr>
<td>Resolution</td>
<td>2.2µm</td>
</tr>
</tbody>
</table>
# Sun Sensors Options

## Sinclair Interplanetary

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model #</th>
<th>Size</th>
<th>FOV</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinclair</td>
<td>SS-411</td>
<td>34x32x21 mm³</td>
<td>140°</td>
<td>±0.1°</td>
</tr>
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</table>

## SSBV

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model #</th>
<th>Size</th>
<th>FOV</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSBV</td>
<td>CubeSat</td>
<td>33x11x6 mm³</td>
<td>120°</td>
<td>&lt; 0.5°</td>
</tr>
</tbody>
</table>
**Autonomous Navigation Flowchart**

- Star Tracker Camera
- Earth/Moon Camera
- Sun Sensors

Sensor Measurement Processing Software

- Attitude Quaternion
- Line of Sight (LOS) Vectors to celestial bodies as they are available (Moon, Earth, Sun)

**GEONS (GPS Enhanced Onboard Navigation System)**

- Celestial Object Measurement Model
- High Fidelity State Dynamics Model
  - Earth - Joint Gravity Model-2 (JGM-2) - up to degree 30 and order 30
  - Lunar – LP100K non-spherical gravity model
- Estimator (Extended Kalman filter - process noise models and factored covariance matrix)

Spacecraft Attitude

Spacecraft Position and Velocity
GEONS includes two different kinds of satellite models for Celestial Object Measurements:

- 3 axis stabilized satellite
- Spin stabilized satellite

Sensor Measurements for 3 axis stabilized satellite include Line-of-sight (LOS) measurements to the center of celestial objects such as sun, Moon, Earth, etc.

- Appropriate for the type of sensor typically flown on a three-axis stabilized satellite when the satellite is at a large distance from the celestial object.
- This model assumes that the celestial object is a point source.
- Requires the attitude of the spacecraft to be input into GEONS from an onboard attitude estimator separate from GEONS or from a star tracker that directly outputs the attitude quaternion.
Sensor Measurements for **spin stabilized satellite:**

- Sun angle measurements from sun sensor
  - Measures the angle between the sensor-to-Sun LOS unit and the satellite spin axis when the sun is in the measurement plane, i.e. the plane containing the spin axis and a vector normal to the sensor.

- Horizon scanning measurement from horizon sensor
  - Measures elapsed time for sensor to cross over earth from horizon to horizon

Ref. Folta
Pseudoangle Measurements

- Adapted from methods developed by Battin for computing a celestial position fix based on the measurement of the angular distance between a planet and a star or two planets.
- Uses the angle between simultaneously measured LOS unit vectors to the planet and star or two planets.
- The advantage of this method is that the resultant pseudoangle measurements eliminate the need for direct input of the attitude matrix.
- Disadvantages of this method are that it requires simultaneous measurements and that it requires individual star identification and measurement.

Ref. Battin
Choice of Celestial Object Measurement Model for CubeSat Lunar Mission

Best choice is the 3 axis stabilized measurement model using Line-of-sight vectors

- CubeSat on Lunar Mission will be 3 axis stabilized.
- Availability of a COTS CubeSat-sized star tracker for direct input of attitude quaternion.
- Proximity of Moon lends itself to using a camera for determining LOS vector to Moon.
- LOS to sun from sun sensor
- At a sufficient distance away from Earth, the same camera for Moon sensing can be used for LOS vector to Earth
Summary of GEONS Required Input for Implementing Celestial Object Measurements using the 3 Axis stabilized satellite model

- **Line-of-Sight Unit Vectors**
  - Components of Line-of-Site unit vectors from satellite to celestial object given in the Earth Centered Inertial (ECI) coordinate frame.

- **Attitude**
  - The attitude (from the star tracker) is input in the quaternion format
Relevant Coordinate Frames

Spacecraft Center of Mass

Body Frame, B

Sensor Frame, S

Earth Centered Inertial Frame, ECI

\((R_{SC})_I\) = spacecraft position vector with respect to the inertial frame, I
The Extended Kalman Filter algorithm consists of two major processes:

1. Time Update. This process consists of propagating the estimated state (position and velocity) and state error covariance factors (uncertainties) from the time of the previous measurement to the time of the current measurement.

2. Measurement Update. This process consists of correcting the current state and state error covariance factors to include the effects of the current measurement.
   - Predict the Measurement using a Measurement Model Equation, \( \hat{Y} \)
   - Take the actual measurements, \( Y \)
   - Compute the measurement residual = \( Y - \hat{Y} \)
   - Compute the Kalman Gain, \( K \), which a weighted average between the prediction and the measurements taking into account the uncertainties of the measurements.
   - Corrected state = Estimated state + \( K(Y - \hat{Y}) \)

The following two slides will show how we get the measurements, \( Y \), and the predicted measurement from the model, \( \hat{Y} \).
Camera takes picture of the Moon and image processing software determines a line-of-sight unit vector, $P_s$

$P_s = \text{LOS unit vector from spacecraft to Moon in camera sensor frame}$

$P_B = M_{BS} P_S \quad \text{Measurement in body frame}$

where $M_{BS} = \text{transformation between body frame and sensor frame}$

$P_I = (M_{BI})^T M_{BS} P_S \quad \text{Measurement in inertial frame (GEONS input)}$

where $M_{BI} = \text{transformation between body frame and inertial frame}$
Use the measurement model to predict the measurement using the estimated state, \((R_{sc})_{I}\), and \((R_{M})_{I}\) from Moon ephemeris functions.

Predicted LOS unit vector measurement in the inertial frame:

\[
\left( \hat{P}_M \right)_I = \frac{(R_M)_I - (R_{SC})_I}{(R_M)_I - (R_{SC})_I}
\]

Predicted measurement in the body frame:

\[
\left( \hat{P}_M \right)_B = M_{BI} \left( \hat{P}_M \right)_I
\]

where \(M_{BI} = \) attitude matrix
Simulation Studies Using GEONS

Folta et al. perform simulation studies using GEONS to assess the navigation accuracy achievable for eccentric high-Earth orbits (HEO) (using nano-satellite sensor technology)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HEO satellite from study by Folta (3 X 60 earth radii orbit)</th>
<th>Possible values for CubeSat Lunar Mission proposed in current work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar directional measurement</td>
<td>15 arc min</td>
<td>6 arc minute accuracy</td>
</tr>
<tr>
<td></td>
<td>(noise standard dev)</td>
<td></td>
</tr>
<tr>
<td>Earth directional measurement</td>
<td>15 arc min</td>
<td>Accuracy unknown at this time for Moon/Earth imaging</td>
</tr>
<tr>
<td></td>
<td>(noise standard dev)</td>
<td></td>
</tr>
<tr>
<td>Attitude determination</td>
<td>Approx. 15 arc min</td>
<td>0.5 arc min accuracy (ST-200 Star Tracker from Berlin Space Technologies)</td>
</tr>
<tr>
<td>Realistic Position Error after 42 days</td>
<td>16 km (earth, sun, doppler) 43 km (earth only)</td>
<td>Future work required to assess the position error for the current work</td>
</tr>
</tbody>
</table>
Moon Imaging Analysis Using STK

The imaging analysis involved modeling the orbit in STK software and generating simulated images of the Earth and Moon from various orbit positions.

Orbit was based upon the European Space Agency’s SMART-1 mission.

Images were created using the field of view and image size from the selected imager from Berlin Space Technologies.
The goal of testing is to:
- Take pictures of the Moon using a digital camera
- From the image, determine the LOS unit vectors to the Moon
- Compare measured LOS vector to LOS vector predicted from STK software and ephemeris function.
Moon Image Testing Process

- Mount camera on tripod and orient the camera so that the Moon is in the field of view.
- Measure the camera orientation ("attitude") by measuring the azimuth and elevation with respect to local, topocentric coordinate frame.
- Take picture of the Moon. The image is then sent through a bitmap reader to determine the location of Moon center and edge of Moon.
- These points are then used in a MATLAB program that, along with the image size, field of view, and Moon actual size, determines a LOS vector to the Moon in the camera’s frame.
- The Moon LOS vector is then transformed from the camera’s reference frame to ECI frame.
- Compare this measurement with the LOS vector predicted using STK and the Moon ephemeris equations.
Topocentric coordinate frame used for Moon image testing

- Zenith
- Vector to Moon
- North
- East
- Moon LOS vector
- Az
- El
- Angle from North – digital compass
- Angle from zenith – digital inclinometer
- Camera
- Body frame orientation measurements
Image Processing

Bitmap Reader determines pixel coordinates of the center of the Moon, c, and the edge point, e, for the size of the Moon in the image.

(LOS vector from camera to Moon)
Status of Work on Image Testing

• Code has been written to analyze images of full Moon to determine the center and edge location of the Moon

• Code has been written to determine a Line-of-Sight vector to the center of the body.

• Code has been written to transform the Line-of-Sight vector in the sensor frame to the Topocentric frame and to the Inertial frame.

• The process and functions for predicting LOS vector from STK and from ephemeris functions have been determined.

• Moon images have been recorded and the results are currently being processed.
Norwich Student Participation

- Work on CubeSat project started in January 2010
- 16 Norwich engineering students (8 Electrical/Computer and 10 Mechanical)
- 2 faculty mentors (Electrical/Computer and Mechanical Engineering)
- Three senior design projects
- 8 summer research students
- Research and Education Focus:
  - Autonomous navigation
  - Celestial Navigation
  - Sensors (cameras, star trackers, sun sensors)
  - Image processing

- Results presented at
  - ASME International Mechanical Engineering Congress and Exposition (Nov 2010)
An initial concept of autonomous navigation using celestial object measurements has been demonstrated for a CubeSat Lunar Mission.

Optical sensors have been selected that provide the necessary measurement inputs into GEONS for orbit determination.

Initial image testing has begun to verify the image processing required for determining Line-of-Sight vectors to celestial bodies.

The celestial navigation concept developed in this work is applicable to interplanetary CubeSat missions for at least the segments of the mission for which near bodies such as planets, moons, and/or asteroids can be identified in images.
Future Work

Image Processing:
- Consider different phases of the Moon in addition to full Moon
- Influence of image size and number of pixels
- Image processing software (edge detection, centroid finding)

Error Analysis that considers the following:
- Distance from S/C to celestial body (Moon, Earth, Sun)
- Image processing errors
- Ephemeris functions used for Moon, Earth, Sun (low, med, high precision options)
- Choice of central body for gravity model (Earth or Moon?)
- Orbit Estimation and filter algorithms used

Teaching Materials:
- Incorporation into existing courses and laboratories
- Considering offering technical elective on this topic
Acknowledgements

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References


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