Development of Quaternion-Based Satellite Detumbling and Sun Acquisition Algorithms

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INTRODUCTION

Satellites are crucial in modern society! They impact countless aspects of daily life:

- Internet, Communication, Media
- Weather, GPS, Navigation
- Military, Science, Innovation

The future possibilities are endless!

- Global internet access (Starlink, Kuiper)
- High resolution imaging for military, astronomy, etc.
- Interplanetary missions, resource & terrain mapping

All satellite functions rely on precise attitude (orientation) determination. Satellites have multiple **Modes of Operation** for different functionalities. This project focuses on modeling two fundamental modes: **Detumbling and Sun Acquisition.**

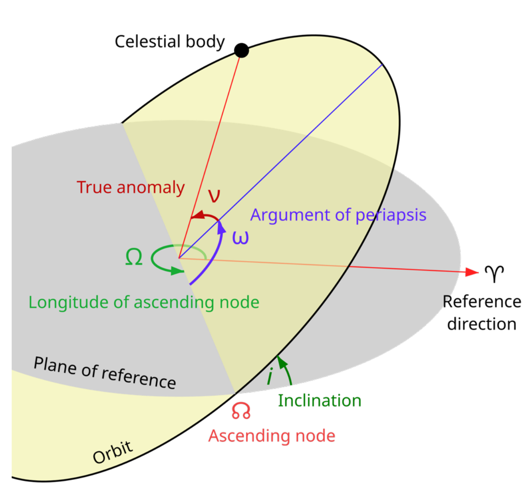
Detumbling takes place when a satellite is initially ejected into orbit, unstable and rotating at high angular velocities. Detumbling stabilizes the satellite and reduces angular velocity to zero [1].

Sun Acquisition orients the satellite's solar panels towards the Sun. During this phase, the satellite locates and continuously tracks the position of the Sun [2].

The path and location of an object in an elliptical orbit can be defined by a set of **six orbital parameters**:

- Eccentricity (e)
- Semi-major axis (a)
- Inclination (i)
- Ascending Node (Ω)
- Argument of Periapsis (ω)
- True Anomaly (θ)

These parameters fully define an orbit and are essential for determining a satellite's position and direction vectors [3].



Six Orbital Elements
Source: [4]

OBJECTIVE

The goal of this project is to **develop a functional algorithm to model satellite Detumbling and Sun Acquisition modes of operation**. This model will serve as a base foundation for future modifications to implement other modes of operation and add additional features to increase accuracy and efficiency.

METHOD

Detumbling is achieved through $\dot{B}$ Control Law, where B represents the local geomagnetic field generated by the Earth. The torque L generated by magnetic torquers is given by

$$L = m \times B$$

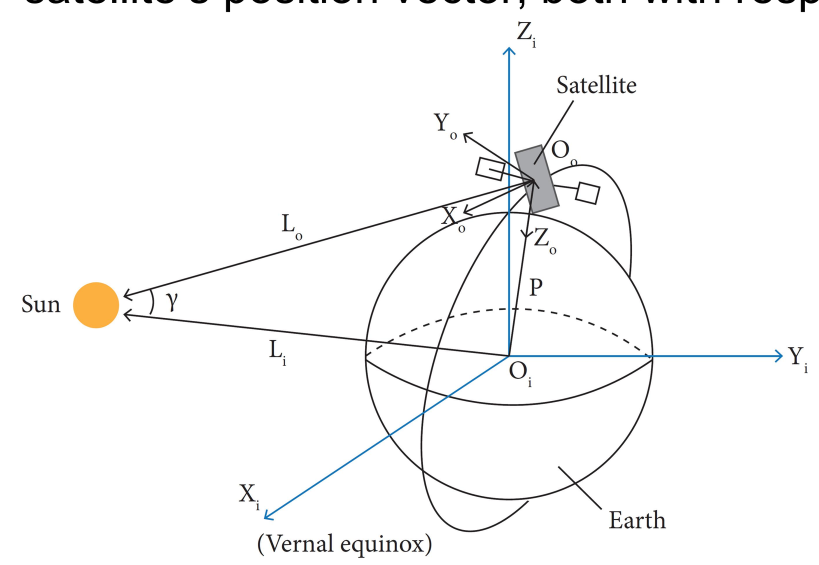
where m is the magnetic dipole moment. For detumbling,

$$m = \frac{k}{\|B\|}(\omega \times b) \times B$$

where k is a positive scalar gain, ω is angular velocity, and $b = \frac{B}{\|B\|}$. Thus, the torque needed for detumbling is given by

$$L = k\,(\omega \times b) \times b \text{ [1].}$$

In **Sun Acquisition**, the desired direction vector from the satellite to the Sun, also called the Sun Vector, is obtained from the difference of two vectors: the Sun's position vector and the satellite's position vector, both with respect to the ECI frame [5].



Sun Vector (direction from satellite to Sun) obtained from Sun and Earth position vectors w.r.t ECI frame, denoted by X_i, Y_i, Z_i. Source: [5]

To orient a satellite's current direction vector towards the desired Sun Vector, a **Proportional-Integral-Derivative (PID) control loop** is utilized to determine the needed torque:

$$Torque_{control} = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{d(e(t))}{dt}$$

where K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively, and $e(t)$ is the error. Over time, a PID control loop decreases the error to zero. For satellite Sun Acquisition, **the error is the angle between the satellite's current direction vector and the desired Sun Vector**.

Quaternions are a 4-D number system, comprised of three imaginary and one real component. **Quaternions can be utilized to represent and calculate orientations and rotations** for 3-D vectors and have multiple advantages over traditional rotation matrices (Euler angles) [1].

Quaternions	Rotation (Euler) Matrices
• One matrix multiplication to model a vector rotation • 4 elements needed • Less operations, less error • No risk of gimbal lock	• Three matrix multiplications to model a vector rotation • 9 elements needed (27 total) • More operations, more error • Risk of gimbal lock

RESULTS

The model is designed in **MATLAB**, ideal due to its numerical computation, simulation, and matrix operation capabilities.

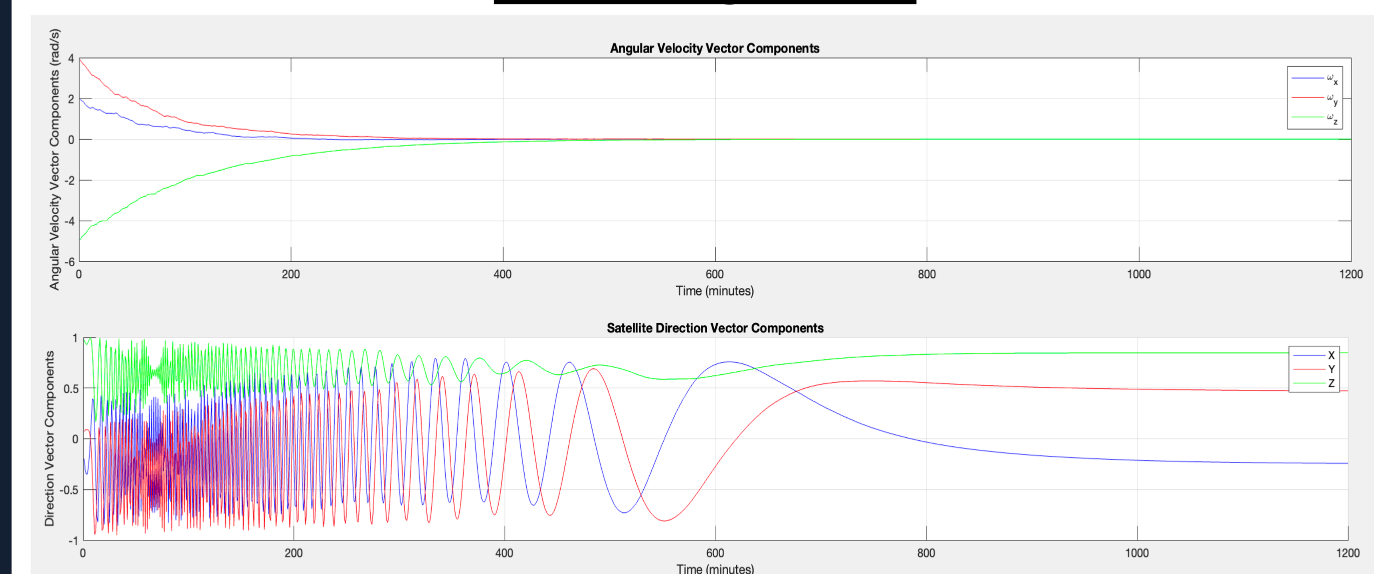
Detumbling Algorithm Structure

- Define parameters for orbit, time, initial velocity
- For every increment in time (iterative loop):
  - Calculate and update new position (orbital parameters)
  - Obtain local geomagnetic field vector b from IGRF model
  - Calculate and apply torque (from $\dot{B}$ Control Law)
  - Update quaternion orientation, time steps
- **Repeat until angular velocity approaches zero**

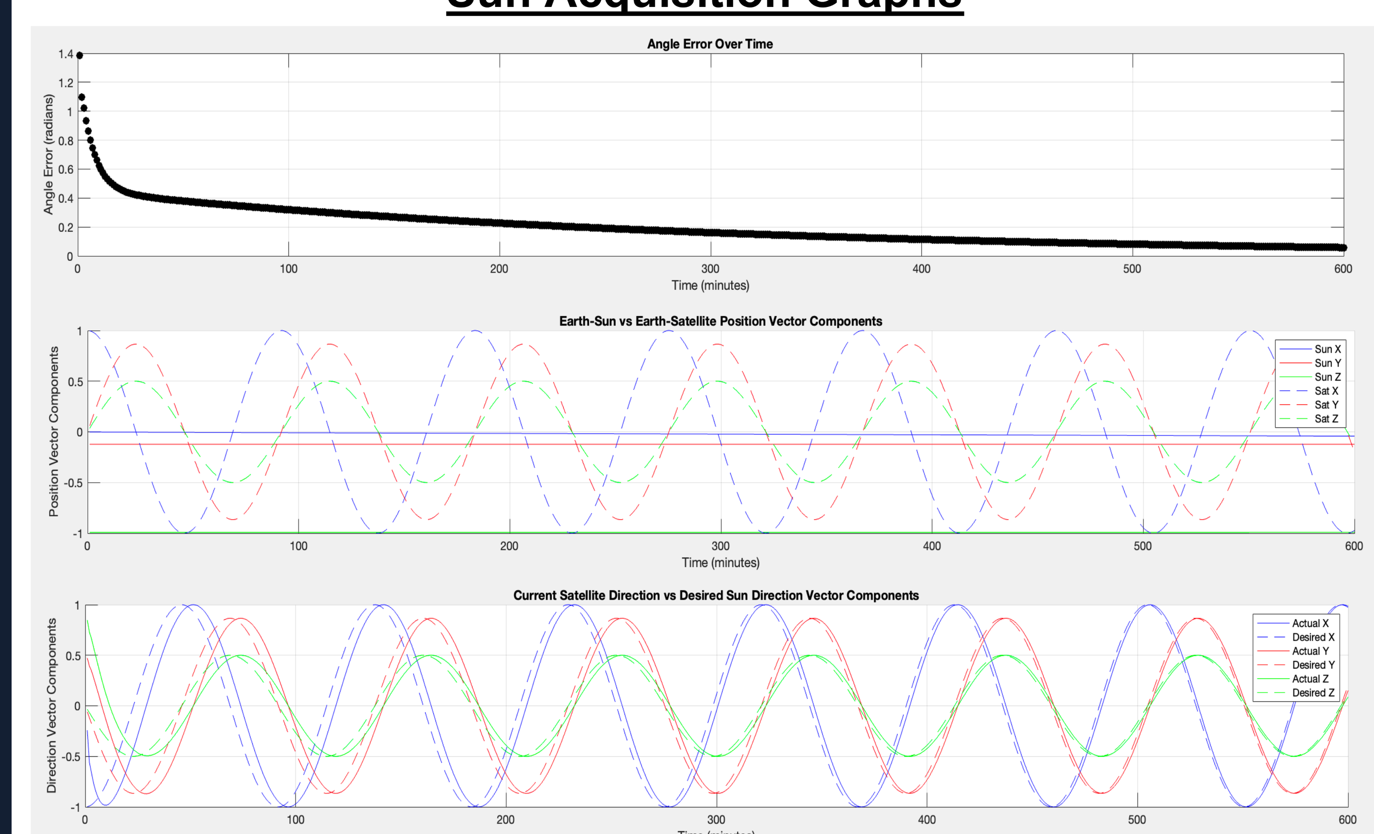
Sun Acquisition Algorithm Structure

- Define PID gains and initial direction (from detumbling)
- For every increment in time (iterative loop):
  - Calculate and update the satellite position vector
  - Calculate the Sun's position vector (given formula)
  - Calculate the desired Sun Vector
  - Calculate error (angle from current to desired vector)
  - Calculate necessary torque from PID equation
  - Convert vectors to quaternion form and apply rotation
  - Update error, current direction vector, time steps
- **Repeat until error approaches zero**

Detumbling Graphs



Sun Acquisition Graphs



RESULTS (CONTINUED)

Detumbling Results
Graph 1: Angular velocity converges to near zero
Graph 2: Satellite's direction vector components converge to stable values

Sun Acquisition Results:
Graph 1: Angle error decreases to near zero
Graph 2: Shows expected vector components – minimal changes in Sun position, oscillations in satellite position
Graph 3: Shows expected oscillations in direction vector components – actual vector converges to desired vector

CONCLUSIONS

The Detumbling and Sun Acquisition algorithms are effective and successfully model their respective purposes. The following features form a solid foundation for further development:

1. Established parameters for orbital path, position, time
2. Iteration loops to simulate changing conditions
3. Quaternion-based attitude tracking and rotations
4. Implementations for $\dot{B}$ and PID Control

FUTURE STEPS

The model can be improved by incorporating additional components to simulate realistic conditions.

- Address sources of error – solar radiation, sensor noise, atmospheric drag, numerical inaccuracies
- Kalman filters, particle filters
- Adjust parameters to model real satellites

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