Attitude Determination and Control for a Low Earth-Orbiting Satellite using Reaction Wheels

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Introduction

The Attitude Determination and Control (ADAC) system is a primary piece of hardware aboard a spacecraft. The ADAC system is responsible for attaining the desired orientation of the spacecraft by calculating the current position with respect to a coordinate frame and then running an algorithm to change the orientation if needed. This poster will describe and simulate the ADAC system for a typical low Earth orbiting (LEO) spacecraft. Specifically the spacecraft simulated will bare similar orbit trajectory properties as the earth observing satellite TERRA [1]. The ADAC system simulation will be created and run in Simulink using MATLAB software. This simulation is comprised of a controller, initial conditions, reaction wheels (RW) and dynamics subsystem. Two tests will be run over the span of one hour, the first with an assumed 0% RW error for the reaction wheels, the second with an assumed 1% RW error. The angular velocity, quaternion and error rate will be monitored.

MATLAB SIMULINK

Image Credit: MathWorks

Attitude Estimation Method

The attitude of a spacecraft can be determined using several different methods. The Euler method is a simple and intuitive 3 dimensional way analyze the attitude of the spacecraft. However, it is limited because of 'gimble lock' when the pitch angle approaches ±90°. While this is an appropriate method for aircraft unlikely to reach a pitch angle of ±90°, it is unsuitable for Earth-orbiting spacecraft.

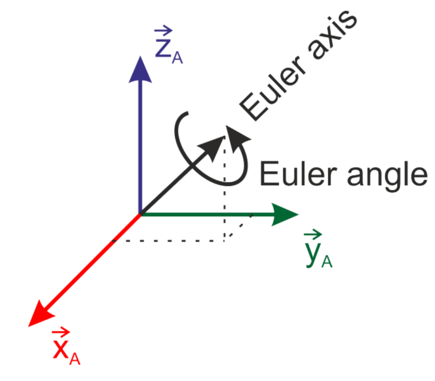


Image Credit: [2]
Technical University of Berlin

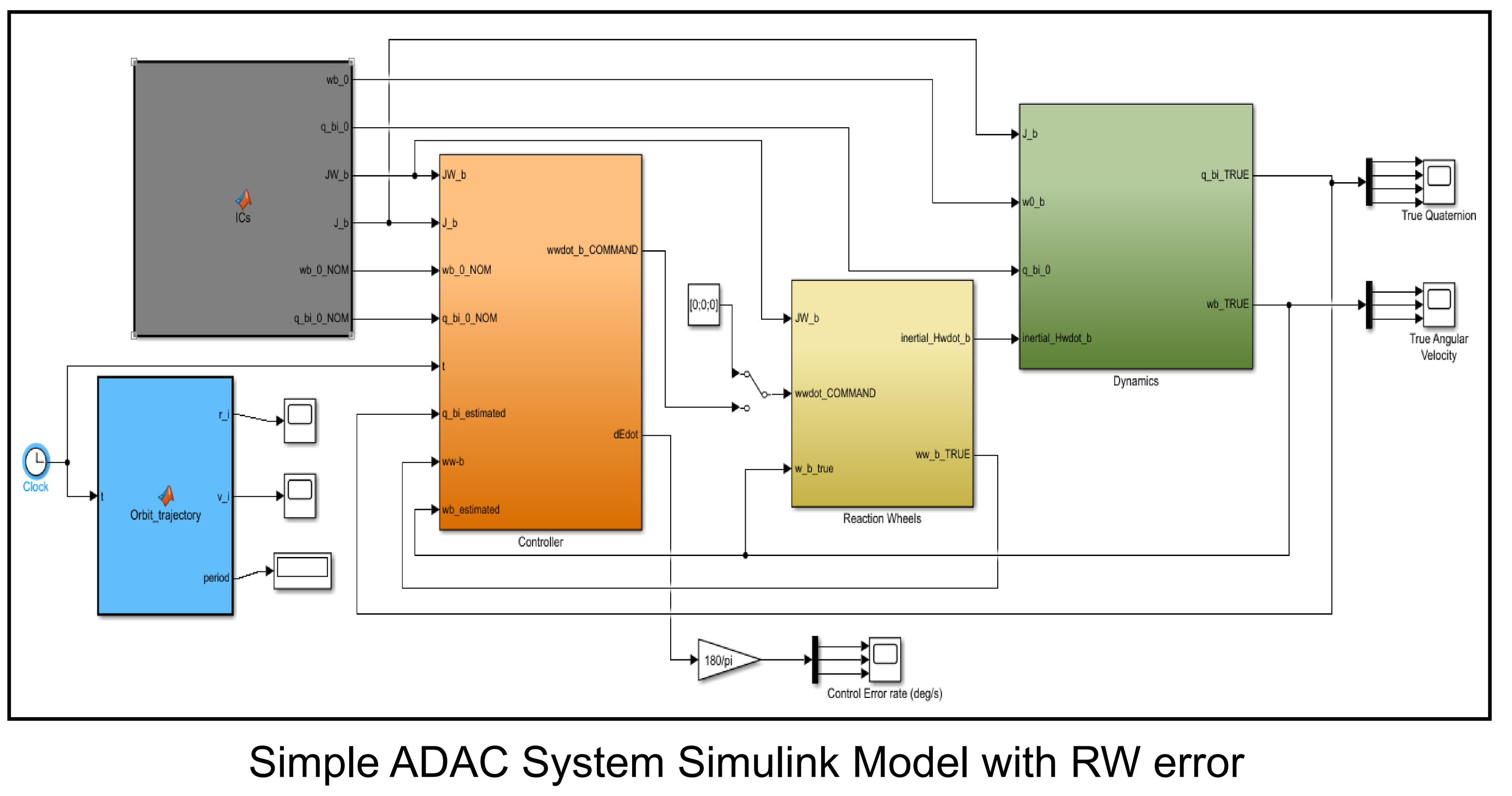
An alternative method is to use quaternions which provide a way to analyze the attitude of the spacecraft without 'gimble lock'. A quaternion is a 4 element vector using the Euler vector.

$$\bar{q} = \begin{bmatrix} -q_s \\ -q_x \\ -q_y \\ -q_z \end{bmatrix} = \begin{bmatrix} \cos\frac{2\pi-\theta}{2} \\ \|-\vec{e}\| \cdot \sin\frac{2\pi-\theta}{2} \end{bmatrix}$$

Equation Credit: [2]
Technical University of Berlin

Modeling an ADAC System

Attitude dynamics generally focuses on rigid body, rotational dynamics such that the spacecraft experiences torques at its center of mass. Common representations in simple attitude dynamics include the use of quaternions or Euler angles relative to a reference frame.



Simple ADAC System Simulink Model with RW error

- [Blue] Orbit Trajectory: Calculates the instantaneous position and velocity of the spacecraft, as well as the orbit period.
- [Grey] ICs: Imported input data related to the spacecrafts center of mass.
- [Orange] Controller: Calculates the torque acted on the center of mass of the spacecraft with respect to the center of mass using the nominal angular velocity and quaternion. It then uses the torque and estimated angular velocity to calculate a RW command, essentially controlling the RWs.
- [Yellow] Reaction Wheels: The primary mechanism responsible for correcting the satellites attitude by using the movement command given by the controller to calculate the rate of momentum.
- [Green] Dynamics: This subsystem calculates the true quaternion and angular velocity to input back into the controller to start the process again.

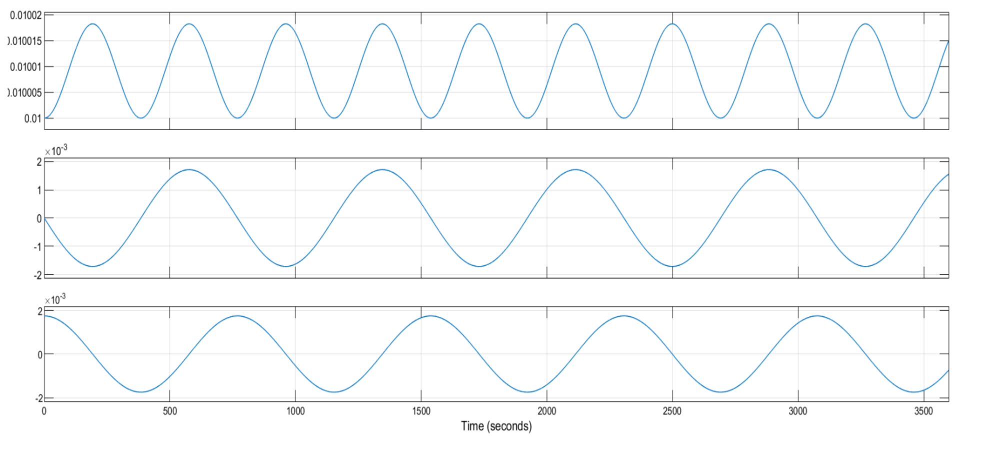
- Note: A sensors subsystem can be added to the system after the dynamics to incorporate actuator, gyro and wheel speed error. This would then require a TRIAD system to efficiently determine the spacecrafts attitude.

Simulation Results for a Low Earth Orbiting Satellite

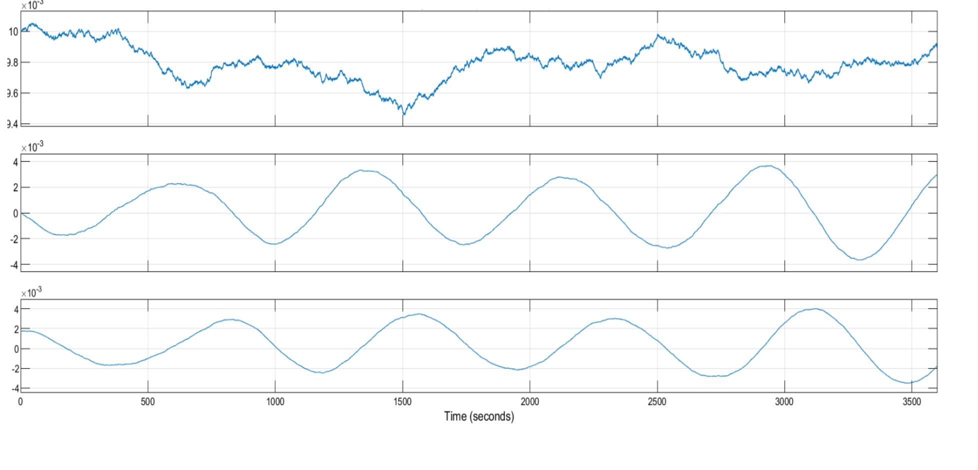
Time Evolution of Spacecraft Angular Velocity

The two plots to the right demonstrate the angular velocity of the spacecraft with or without error over the time span of 1 hour. The X coordinate variation is negligible, which is observable for both plots due to is small amplitude compared to Y and Z. When 1% RW error is introduced, the Y and Z angular velocities are affected more within the first 1000 seconds while still keeping periodical motion. As time progresses the angular velocity recovers to a more stable state.

Angular Velocity (X,Y,Z): 0% Error



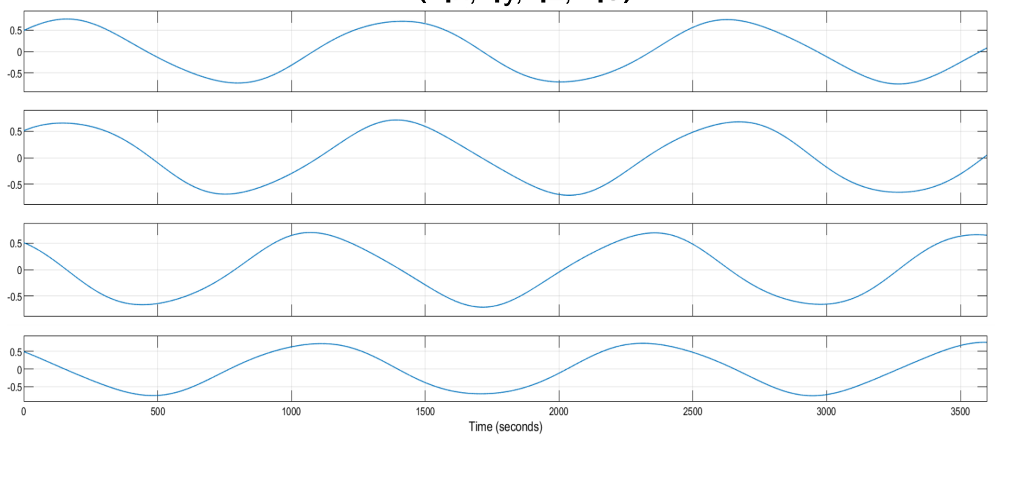
Angular Velocity (X,Y,Z): 1% Error



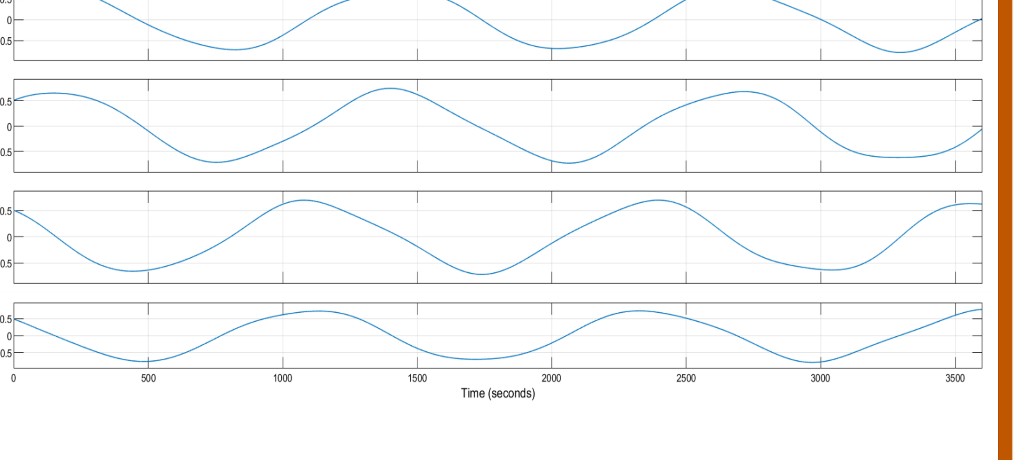
Time Evolution of Quaternion based Attitude

There is little to no observable difference between the 0% and 1% error quaternion vector. This demonstrates why the quaternion method of determining attitude is safer and more reliable compared to the Euler angle method. Euler angles would not be suitable for this simulation due the periodical angle change in each coordinate with the consistent passing of ±90° in the pitch angle.

Quaternion (q_x, q_y, q_z, q_s): 0% Error



Quaternion (q_x, q_y, q_z, q_s): 1% Error

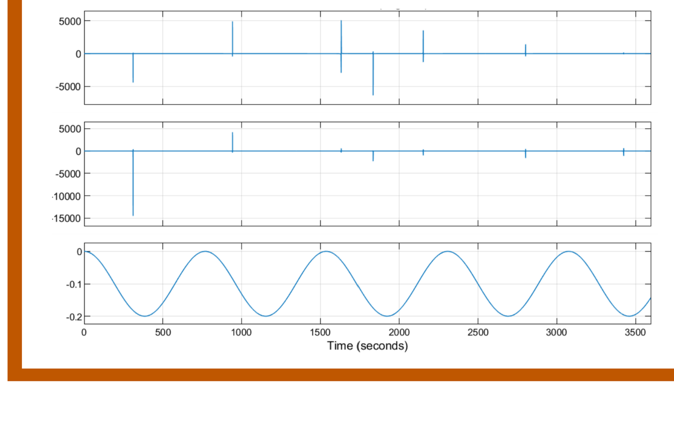


Time Evolution of Controller Error Rate

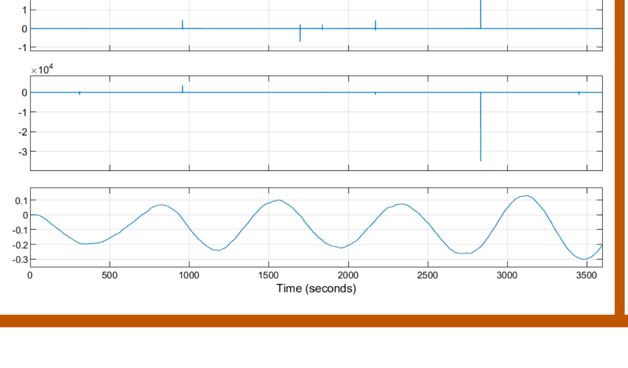
The error in the X and Y direction for the controller is 0 except for the random negligible spikes as time progresses. These are due to conversion error anomalies [3].

The Z coordinate varies similar to angular velocity when error is introduced.

Controller Error Rate: 0%



Controller Error Rate: 1%



Conclusion

The attitude determination and control system designed for spacecrafts best estimates the current attitude through stochastic methods. The model used in the poster is a basic example of how 1% error associated with RW can affect the attitude determination of a LEO spacecraft using the quaternion method. Other methods exist such as the Kalman method which uses a near nonlinear least squares formulation to realistically use signals from the sensor to estimate the attitude. [4]

References

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[3] Microcontroller Division Applications. "UNDERSTANDING AND MINIMISING ADC CONVERSION ERRORS." *AN1636 APPLICATION NOTE*, 2003, www.st.com/resource/en/application_note/cd00004444-understanding-and-minimising-adc-conversion-errors-stmicroelectronics.pdf.

[4] Markley, F. L., & Crassidis, J. L. (2014). Fundamentals of Spacecraft Attitude Determination and Control. Springer New York. https://doi.org/10.1007/978-1-4939-0802-8