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System Design and Controller Interface of Spacecraft Reaction Wheels

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System configuration and design for a three-axis reaction wheel array and corresponding controller for adjusting the rotation of a spacecraft.

Weight and operational lifespan play a critical role when designing a spacecraft. For a short-term use vehicle, such as the Apollo Lunar Module, Reaction Control System (RCS) thrusters were used to rotate the spacecraft and make translational adjustments without using the main engine. RCS thrusters run off either a hypergolic fuel mixture or monopropellant and thus, have a limited number of ignitions. Additionally, fuel tanks, pipelines, and propellant need to be carried onboard.

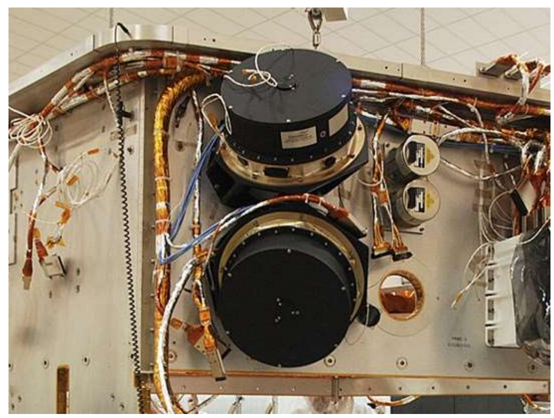

Figure 1: A Pair of Reaction Wheels on the Kepler Space Telescope [1]

For long-term use or smaller spacecraft, such as the Hubble and Kepler Space Telescopes, where translational adjustments are not necessary, reaction wheels can be a better solution. Instead of requiring RCS thruster packs, fuel tanks, and propellants, these wheels run off electricity. This allows ground control to rotate the spacecraft for its full operational lifespan. Additionally, due to thrusters having a minimum thrust magnitude, reaction wheels can provide more accuracy when rotating a spacecraft.

The basis for reaction wheels comes from Newton's Third Law, stating that for every force, there is an equal and opposite force. For example, when a motor spins a wheel left, the system will feel a torque to the right. By using a set of three or more wheels, three-axis rotation can be achieved. Figure 2 shows possible designs for reaction wheel systems, with Figure 2a depicting the three-axis minimum requirement.

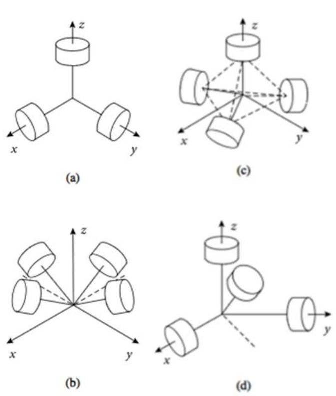

Figure 2: Reaction Wheel Configurations: a) Orthogonal, b) Pyramidal, c) Tetrahedral, d) Skew [2]

Due to the mechanical nature and potential failure of reaction wheel assemblies, spacecraft will often carry backup wheels or use configurations that have more than three wheels. For example, the Kepler Space Telescope carried four reaction wheels in a pyramidal configuration towards the back of the spacecraft, as seen in Figure 1 above. Additionally, if there are external forces applied to a spacecraft, the reaction wheels may become saturated. In this situation, the wheels have reached their maximum RPM, but cannot overcome the torque required to stop the spacecraft. In this case, if the spacecraft is near a strong magnetic field, a magnetorquer could be used to align with this field and desaturate the reaction wheels. If in deep space, other desaturation methods, such as RCS thrusters, could be required.

To operate a reaction wheel system, a controller needs to communicate with both a motor driver for each reaction wheel, along with an Attitude and Heading Reference System (AHRS) or comparable sensor. An AHRS sensor contains gyroscopes, magnetometers, and accelerometers that can determine the attitude angle and the angular velocity of a spacecraft. This data is then fed into a data register that can be read and converted into values needed by the control algorithm. Once the AHRS data has been interpreted and a required torque has been found, the controller will then send the required current for specific motors to the driver to create this torque. This interface and process can be seen in Figure 3 to the right.

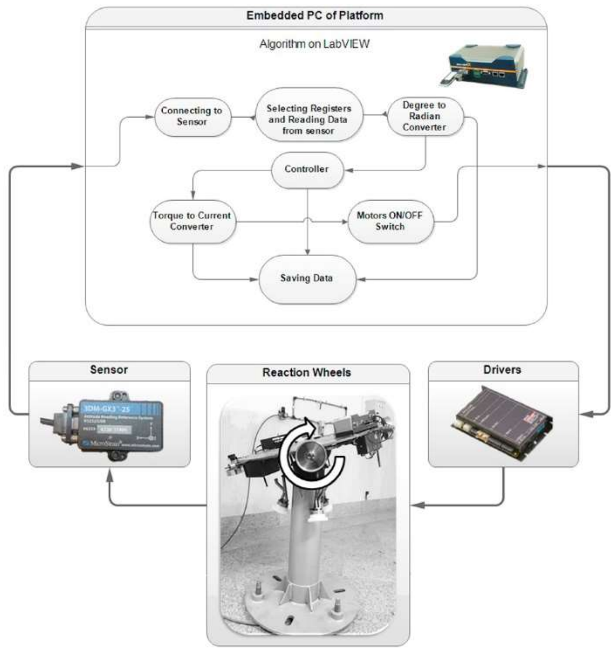

Figure 3: General Structure of a Spacecraft Reaction Wheel Simulator [3]

As mentioned above, reaction wheels can suffer from saturation. One method to reduce the amount of saturation is to ensure that the reaction wheel speed decreases to zero at the end of each maneuver. By adding a momentum feedback loop, using a modified feedback linearization, to the controller above, the controller can ensure that the system accounts for any momentum that could lead to saturation.[3] Additionally, if the reaction wheels keep rotating after the maneuver is completed, the spacecraft could have increased energy consumption and thus, reduced efficiency.

By using at least three reaction wheels, a spacecraft can achieve a three-axis rotation, without the need for RCS thrusters and propellant. This can help save weight and improve rotational accuracy on smaller spacecraft. By using an Attitude and Heading Reference System, a controller, and motor drivers, a reaction wheel system can accurately determine the current position, calculate the required motor adjustments, and rotate the spacecraft to a desired attitude. By adding a momentum feedback loop, this can also ensure that the reaction wheel speeds decrease to zero after each maneuver, which can conserve energy and reduce potential saturation.

[1] J. Foust, "Kepler Space Telescope Reaction Wheel Remains a Concern," *Space News,* Apr 2013. [Online] Available: https://spacenews.com/34692kepler-space-telescope-reaction-wheel-remains-a-concern/

[2] J. Narkiewicz, M. Sochacki, B. Zakrzewski, "Generic Model of a Satellite Attitude Control System," *Int. J. of Aerospace Eng,* vol. 2020, Jul 2020. [Online]. Available: https://doi.org/10.1155/2020/5352019

[3] M. Malekzadeh, H. Sadeghian, "Attitude Control of Spacecraft Simulator without Angular Velocity Measurement," *Control Eng. Practice,* vol. 84, pp. 72-81, Mar 2019. [Online]. Available: https://doi.org/10.1016/j.conengprac.2018.11.011