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Significance of Attitude Control and Control Systems in Satellites

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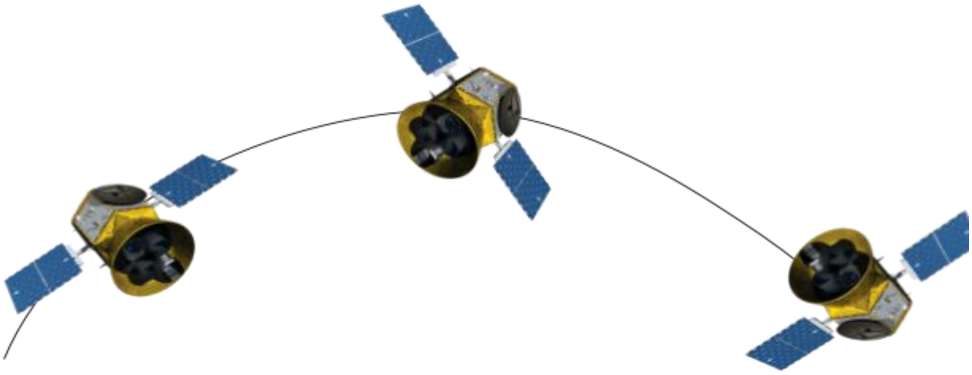
Abstract
This literature paper briefly overviews major topics concerning attitude control systems in satellites. This paper introduces these topics by highlighting the significance of these mechanisms, before elaborating on the physics principles behind attitude dynamics and the needfor recovery strategies through control systems.

This paper, produced after analyzing scholarly articles and incorporating first-hand research of professionals working in this stream, underscores the need for these robust control systems for precise satellite pointing and stabilization in our daily lives to an audience interested in knowingthe basics behind this phenomenon.

In conclusion, this review demonstrates the vital role of attitude control systems in satellite missions and suggests avenues for future research to enhance satellite performance and missionsuccess.

I. Introduction

When you follow Google Maps or change your plans based on the weather forecast, you are relying on an object in space vulnerable to harsh environmental conditions that solely carry out your functions due to its ability to stay on its path and maintain its orientation.



The Attitude of a satellite is nothing but its orientation in space.

The attitude control in any spacecraft is the process by which the spacecraft, or satellite in this case, maintains its orientation with respect to a certain reference frame (a coordinate system to make measurements to). It entails altering the orientation (or "attitude") of an object to maintain a desired orientation or track specified pointing directions. This control ensures that the item maintains the proper alignment required for mission objectives, such as stabilizing a satellite to keep its antennas pointed at Earth or orienting solar panels toward the Sun. To make exact orientation modifications, attitude control systems frequently include components such as reaction wheels, control moment gyroscopes, thrusters, and magnetic torquers. Three vectors that specify an object's rotation with respect to a reference frame are commonly used to characterize its orientation in space. Pitch, roll, and yaw are common examples of these angles: rotation around the longitudinal (front-to-back) axis is called roll, rotation around the vertical axis is called yaw, and rotation around the lateral (side-to-side) axis is called pitch.

There are several reference frames, such as fixed body frames, earth-centred inertial (ECI), and earth-centred fixed frames, which this paper will not elaborate on.

The choice of reference frame is critical because it defines the axes against which orientation is measured, such as a local horizon frame for aerial navigation or a spacecraft body frame in spaceoperations.

We will first review primary concepts like Newtonian mechanics, angular momentum, and conservation principles to understand how a satellite uses sensors, actuators and control systems to achieve attitude control.

Law of Conservation of Momentum

The conservation of momentum is a fundamental principle in physics, stating that the total momentum of an isolated system remains unchanged.
Linear Momentum, is the product of an object's mass and velocity, which characterizes the motion of the object. Momentum can also be understood as the amount of force needed to stop the object over a specific period.

The change in linear momentum can thus be calculated using two possible formulas:

- $\Delta p = m(\Delta v)$ (since mass is constant)
- $\Delta p = F(\Delta t)$ (force/ acceleration is constant)

Conservation of linear momentum states that the total linear momentum before and after anyevent within the system is constant, provided no external forces are acting on it.
Angular momentum is a measure of the rotational motion of an object around a point or axis. It's similar to linear momentum but applies to rotating objects like our satellite in this case.
The angular momentum (L) is given by: $L=I\cdot\omega$

where:

- I is the moment of inertia of the object (a measure of how mass is scattered about the axisof rotation),
- ω\ omega is the angular velocity, which describes how fast the object is rotating.

In a closed system with no external torques applied, the total angular momentum remains constant. This principle is called conservation of angular momentum and it explains the workings of the reaction wheels of satellites to control their orientation.

Newton's Laws of Motion

1. An object in motion remains in motion at a constant speed and an object at rest remains at rest unless acted on by a resultant force
2. The acceleration of the body is directly proportional to the net force acting on the body and inversely proportional to the mass of the body.
3. The forces exerted by two interacting bodies are equal in size and opposite in direction.

Awareness of these concepts is crucial to understanding how a satellite employs components to perform this function.

The Eyes and The Limbs: Sensors and Actuators

Before carrying out Attitude Control the current orientation of the satellite must be determined, and this is done with the help of sensors. This paper outlines the following types of sensors: Sun sensors, StarTracker and Gyroscope.

Sun sensors

In order to determine the spacecraft's orientation with regard to the Sun, sun sensors are essential. They are utilised to track the satellite's attitude with respect to the solar vector while it is in orbit. The solar vector is the angle at which the sun's rays reach the satellite or spacecraft. Sun sensors allow light to enter through gaps on top of the sensor and these consist of photogenic units, these units convert the photons into electrons. This gives rise to the electric current that is made into a signal that sends out information. When the Light enters through the gaps and projects an image onto the base of the device the photosensitive cells measure the amount of light and it can be used to calculate the angle of incidence. Three primary varieties of sun sensors are analogue, digital and coarse sun sensors.

Gyroscope

A gyroscope is an instrument used to monitor or control angular velocity and orientation. A spinning wheel or disc is installed on the gyroscope so that its axis can freely rotate in any direction. With the help of conservation of angular momentum, it can resist changes in its orientation and this makes it useful for stabilizing or measuring direction in navigation systemsand spacecrafts.

Star Trackers

A star tracker is a device used to determine the precise attitude of the spacecraft by the usage of images of stars and comparing the images to a known star catalogue. The patterns of the stars areidentified and the spacecraft's orientation in space based on the stars are calculated.

Once the location and orientation of the satellite is established, the satellite needs to be transferred to the desired orientation and position; this is done with the help of actuators.

This paper will review active attitude control mechanisms (uses external power) through reaction wheels, magnetic torquers, and thrusters.

Reaction Wheels

Reaction wheels are devices used for precise attitude control. They consist of spinning wheels which spin at high speeds to create a counteracting torque, and the spacecraft's orientation is changed based on the conservation of angular momentum. When a reaction wheel spins, the satellite responds by rotating to conserve angular momentum. The change in angular momentum of the wheel is equal and opposite to that of the satellite, ensuring balance. Depending on the system's net angular momentum at a given moment, both the reaction wheel and the satellite can rotate in the same or opposite directions. Reaction wheels allow precise adjustments to the satellite's orientation without relying directly on thrusters for continuous operation. An electric motor powers each reaction wheel, causing it to spin at high speeds. By adjusting the wheel’s speed the spacecraft rotates in response. However, fuel is still required for other purposes.

Since satellite systems are not ideal, unwanted torques—caused by factors like gravitational gradients, solar radiation pressure, or magnetic field interactions—gradually build up angular momentum. Over time, this accumulated momentum must be dissipated to prevent instability.

This process, known as momentum dumping, is achieved using thrusters or magnetorquers. For non-Earth satellites and interplanetary missions, thrusters are the primary tool for this task.

Magnetorquers

Magnetorquers are used for attitude control in spacecraft with usage of the earth's magnetic field without the need for fuel. A magnetic moment is created when current is passed through the electromagnetic coils or rods, this magnetic moment interacts with the earth's magnetic field which in response produces a torque that rotates the spacecraft.

Thrusters

Thrusters are propulsion devices that help in attitude control by providing force and torque. A Pair of thruster rockets on opposite sides of the spacecraft are fired in opposite directions.to rotate or stabilize its orientation. They depend on fuel and are used in deep space where othermethods may not be as effective.

In smaller satellites, passive attitude control mechanisms (no power usage) that exploit prevalent external disturbances created by gravity, aerodynamic or magnetic fields are utilized. An example of this is Gravity Gradient Stabilization which takes advantage of the mass distribution of the satellite body and the gravitational field of the earth. The lower part having more mass will be more attracted to the earth and the satellite will align in its axis of minimum moment of inertiavertically.

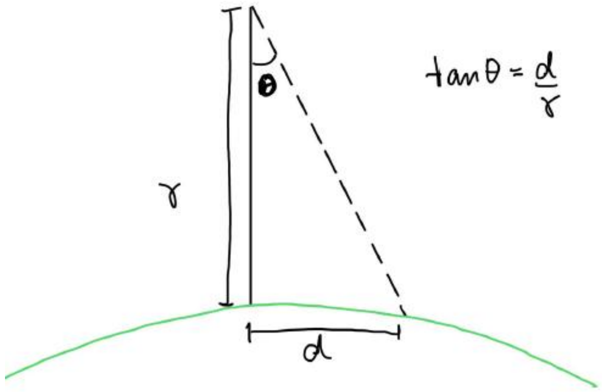
Why do we need attitude control?

Why is precise pointing and orientation even necessary for satellite operations?

The usual functions of a satellite require it to be pointed to a specific body to transmit its signal; this could be a certain celestial body like a star or the sun, a ground station, or a GPS receiver depending on its purpose.

Looking at the image below we can see that when the satellite’s orientation changes even by a 0.00482 rad difference, the location it points at changes.

To calculate the change in distance at Earth’s surface when a satellite changes its orientation by 0.00482 radians, we can use trigonometry since we can treat the angle and distances as part of aright triangle.



Let:

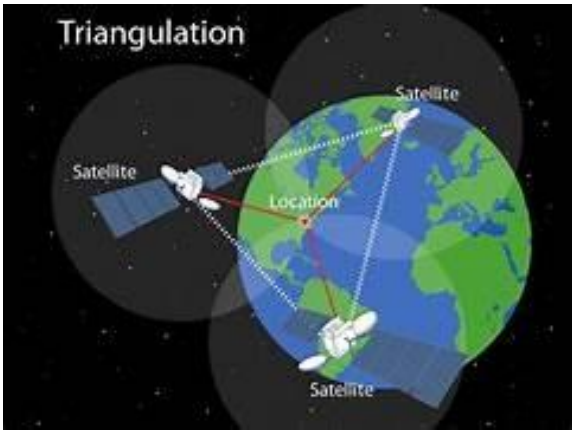
- θ=0.00482 rad (small angular change)

- r = 400 km (distance from the satellite to the Earth's surface).

The change in distance d can be found using tan(θ)=d/rNow, calculate d:
d=tan(0.00482)x400x10^3= 1928m or 2000m

The change in pointing along the Earth's surface for a satellite orientation change of 0.00482 radians is approximately **2 km**, this can cause a huge effect and lead to incorrect results. Hence maintaining the precise angle is very important.

The location of a satellite too is significant to attain its data, especially in the case of GPS or weather forecasting. The triangulation method used by GPS systems determines the location of several satellites with overlapping orbits to continuously update the exact location of the user.



When a satellite travels in its orbit it faces several disturbances, both external and internal, that can deviate it from its path and affect its orientation.

External factors: solar radiation, gravitational, aerodynamic, and magnetic

Solar radiation - Solar radiation can damage electronics, cause thermal stress and deformation, and create static electricity leading to electrostatic discharges that harm communication systems. It also exerts solar radiation pressure, a force from light's dual nature, used in solar sails but adds external torques that affect the satellite's stability.

Gravitational force - Satellites in low Earth orbit (LEO) encounter atmospheric drag, which can lead to orbital decay over time. This decay may result in the satellite re-entering the atmosphere, where it can burn up. Additionally, tidal forces exerted by the Earth and Moon can generate gravitational waves that disrupt the stability of a satellite's orbit.

Aerodynamic forces can hinder a satellite primarily when it operates in low Earth orbit (LEO),

Similar to gravitational force where it experiences drag causing the satellite to eventually re-enter the atmosphere and potentially burn up. Additionally, the varying density of the atmosphere can create unpredictable aerodynamic forces that complicate the satellite's trajectory and require frequent adjustments to maintain its intended orbit.

The interaction between the satellite's own magnetic components and the external magnetic field can cause unwanted rotations or deviations from its intended orientation. The performance and accuracy may be affected when it interferes with strong magnetic fields.

Internal factors: slosh, micro-vibrations and flexible body(deployment of solar panels.)

The movement of liquid propellant within tanks in a spacecraft during acceleration or change in direction can lead to a change in the center of mass affecting the stability and attitude control.

Micro-vibrations can impact delicate instruments, resulting in reduced performance or inaccurate measurements, especially in scientific missions that demand precise data gathering.

The deployment process can cause oscillations or vibrations, potentially leading to unexpected torque and affecting the spacecraft's attitude.

The Brain: Control systems

Control systems can successfully guide a satellite's attitude after sensors have established its orientation and location, overcoming mistakes caused by circumferential torques and other disturbances. To maintain alignment and make the required modifications to guarantee the satellite's proper operation, they employ feedback systems, in which sensors supply the data that prompts actuators to apply forces in the appropriate directions.

Feedback Control:

Feedback control plays a central role by continuously using the satellite's output to adjust its input, allowing it to adapt to unpredictable conditions in space. By detecting deviations in orientation through sensors, the satellite can respond to external disturbances such as gravitational forces or solar radiation pressure. Feedback loops ensure the satellite remains stable and aligned, adjusting automatically to maintain precise orientation.

PID Control:

A **proportional–integral–derivative controller** (**PID)** also known as a **three-term controller**, is a feedback control system widely used to regulate machines and processes that need continuous monitoring and automated adjustments.

In a satellite PID’s control system:

- **Proportional Control** addresses the current error in orientation by making immediate adjustments. If the satellite is off-target by a certain angle, the proportional component applies a force directly related to the size of that angle, aiming to quickly correct it.

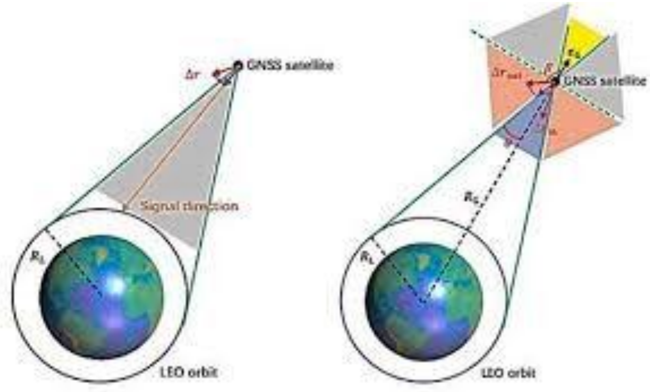
-**Integral Control** accumulates past errors over time, correcting for any consistent drift or bias. For instance, if minor deviations from the target orientation repeatedly occur, the integral term sums these small errors, gradually applying a correction to prevent long-term misalignment.

-**Derivative Control** predicts future errors based on the rate of change in orientation, acting to counter rapid shifts or overshoots. For satellites, this is essential when rapid responses could destabilize the system, as derivative control tempers such adjustments to prevent excessive corrections.

By balancing these three terms, PID control maintains a smooth and stable orientation, allowing satellites to respond to disturbances without consuming excessive energy or overcorrecting. This control strategy is particularly useful for satellites in low Earth orbit, where minor but continuous adjustments are needed to counteract small forces and maintain precise pointing for imaging, communication, or scientific data collection.

LQR Control

An ideal control technique called the Linear Quadratic Regulator (LQR) is made to minimize a cost function, which usually includes both energy consumption and the departure from a desired orientation. Because LQR strikes a balance between accuracy and control effort, it is especially well-suited for satellites that need to be extremely precise. For satellites with certain performance requirements, where precise control and economical energy use are top concerns, this approach works well.



II. Conclusion

Attitude control is a foundational component in the success of satellite missions, ensuring that satellites remain oriented accurately to perform their designated functions. Effective attitude control allows satellites to maintain precise pointing—essential for applications like Earth observation, communication, and navigation—where even minor misalignments can lead to significant errors, compromising data quality or mission success.

The need for sophisticated attitude control arises from the multitude of external and internal forces acting on satellites. Solar radiation pressure, gravitational perturbations, magnetic forces, and internal disturbances (like fuel sloshing and the deployment of solar panels) continuously challenge stability. Attitude control systems—through feedback mechanisms and control strategies such as PID and LQR—work to counter these disturbances, enabling satellites to adaptin real-time to ensure stable, efficient operations.

By providing this stability, attitude control maximizes the satellite's operational lifespan, conserves energy, and supports accurate data collection and transmission. As satellite missions become more complex and expectations for precision grow, the role of advanced attitude control systems is increasingly critical, underscoring their significance in ensuring that satellites meet their mission objectives and deliver value across scientific, commercial, and environmental applications.

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