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WHEN SPACECRAFT WON'T POINT

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The Spacecraft Attitude Dynamics and Control course at Virginia Tech is primarily taken by juniors as an alternative to the aircraft stability and control course. Such a course can be taught in many different ways. On one extreme, one could invoke the powerful machinery of geometric mechanics, including the momentum map, $so(3)$, $SO(3)$, cotangent bundles and symplectic manifolds. At the other extreme, one might use a handbook with convenient sizing formulas for designing ADCS hardware. Somewhere in between these extreme approaches lie the approaches used in most courses. In any case, students can better appreciate the significance of the selected topics covered if they are provided with concrete examples. One particularly interesting type of example is the ADCS failure or anomaly, especially where a failure is caused by the same type of error that the students are being asked to understand and not make.

INTRODUCTION

In this paper, I describe our junior/senior-level course in Spacecraft Attitude Dynamics and Control[1] and describe some illustrative examples of ADCS failures that are used in the course. The paper includes references to failure reports, conference papers and other technical reports that describe these failures in more detail.

The course, AOE 4140 Spacecraft Dynamics and Control, has the following official description:

> Space missions and how pointing requirements affect attitude control systems. Rotational kinematics and attitude determination algorithms. Modelling and analysis of the attitude dynamics of space vehicles. Rigid body dynamics, effects of energy dissipation. Gravity gradient, spin, and dual spin stabilization. Rotational maneuvers. Environmental torques. Impacts of attitude stabilization techniques on mission performance.

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The topics covered in the course are:

Introduction and Overview of attitude control concepts Identify the principal characteristics, applications, advantages and disadvantages of various attitude control concepts

Mission Analysis Understand the geometry of space mission analysis and how it applies to the attitude determination and control subsystem requirements and design

Attitude Kinematics Understand the description of attitude kinematics using reference frames, rotation matrices, Euler parameters, Euler angles, and quaternions

Attitude Determination Understand the measurements required to determine the attitude of a spacecraft. Understand basic attitude determination algorithms.

Rigid Body Dynamics Understand the equations of motion for rigid bodies, including modeling assumptions, angular momentum, Euler's equations, moments of inertia, and the solutions for an axisymmetric body.

Satellite Attitude Dynamics Know the environmental forces and moments affecting satellite motion. Apply basic dynamics analysis to the attitude dynamics of spin, dual-spin, three-axis, and gravity gradient stabilized satellites, including the effects of energy dissipation.

Momentum Exchange Systems Understand and apply basic relations for gyroscopic instruments and for reaction wheel (RW) and control moment gyro (CMG) control systems. Understand the similarities and differences between RW and dual-spin systems.

Attitude Control Understand the application of basic linear control theory to basic attitude control problems.

Possible Additional Topics Tethered satellites, Rotational maneuvers, Effects of flexibility and liquid fuel slosh

Extensive lecture notes are provided to students through the course website.[1]

One useful element of the course is the use of examples of real spacecraft attitude control systems. Some of these are taken from current events. Others are taken from historical data, especially those involving ADCS failures. The operational examples are intended to illustrate the relationship between the mission, the orbit, and the attitude requirements and implementation. These examples then motivate typical homework assignments, which usually require interpretation of a two-line element set[2] and its application to a mission-related pointing problem.

The use of ADCS failures, while interesting in its own right, provides useful lessons in the importance of "trivial" issues such as sign errors and unit inconsistencies, and other issues such as component selection. Earlier this year, Robertson and Stoneking[3] presented a statistical analysis for a wide variety of satellite guidance, navigation and control anomalies. They found that approximately 23% of all GN&C anomalies were ADCS-related, and that ADCS anomalies were the single most common cause in those missions that were a total loss. Another excellent reference for spacecraft failures is the list maintained at the Satellite Digest website.[4] Attitude control system anomalies have also been the subject of investigations on the use of expert systems.[5] In the remainder of this paper we describe several example ADCS failures in some detail. Presentation materials to accompany some of these examples are available on the course website.[1]

Lewis ADCS Problems Led to Total Mission Loss

The Lewis[6] spacecraft was three-axis stabilized, with a zero momentum-biased control system with 0.004° attitude knowledge. It had a hydrazine propulsion system with eight 1-lbf thrusters. System reliability was predicted to be 0.86 for its five-year mission. Lewis was launched on Aug 23, 1997, and after successful on-orbit operations were established, the ground crew went home.

The safe mode design was intended to drive the solar panels to a predetermined orientation, where the x-axis pointed toward the sun, to maintain this orientation using autonomous thruster firings, and to use a single two-axis gyro to sense y and z axis rates. A small thruster imbalance caused spinup around the x axis, which was not sensed by the rate gyro. Eventually the thrusters shut down to excessive firings. The x axis was the intermediate axis axis of the spacecraft, so that the resulting uncontrolled spin was unstable. The spacecraft tumbled to a major axis spin with the solar panels pointed edge-on to sun. By the time the operations crew returned, the batteries were depleted; contact was lost Aug 26, 1997, and the spacecraft re-entered Sep 28, 1997.

Furthermore, there was a flaw in the ADCS simulations. The spacecraft was left untended for 12 critical hours based on unwarranted confidence in the simulation. The simulation had been based on the proven Total Ozone Mapping Spacecraft (TOMS) design. However, the TOMS safe mode had the major axis sun-pointing, whereas the Lewis safe mode had the intermediate axis sun-pointing. The simulation did not include any imbalance or the possibility of an initial spin rate about the intermediate axis. Furthermore, the simulation used a mission operations scenario instead of a transfer orbit operations scenario.

Lewis provides an excellent example of the significance of the moments of inertia, importance of component selection, and perils of placing excessive confidence in simulations.

The Compton Gamma Ray Observatory Was Deorbited Because of a Rate Gyro Failure

At 35,000 lbs, CGRO was, at the time, the largest LEO spacecraft ever launched on the shuttle.[7] The spacecraft was launched on April 5, 1991. One of the rate gyros failed on Dec 6, 1999, probably due to a bearing failure. Although the spacecraft still had an expected life of several more years, NASA decided to initiate reentry to avoid the possibility of uncontrolled reentry in the event of future failures. The decision generated a lot of controversy within the science community, but the de-orbit took place and CGRO re-entered the Earth's atmosphere on June 4, 2000.

The CGRO failure demonstrates how the loss of one component, while not disabling the mission, could lead to mission termination for safety reasons.

Heating Caused Polar BEAR to Lose Sense of Direction

The Polar Beacon Experiment and Auroral Research spacecraft was affected by boom heating problems similar to those that affected other Naval Research Laboratory gravity-gradient satellites.[8] Polar BEAR was gravity-gradient stabilized with a boom and tip mass, and augmented with pitch momentum wheel. The spacecraft was built from a Transit satellite that had been in the Air & Space Museum for eight years, and was launched on November 14, 1986. In February 1987, solar heating of the boom led to large-angle attitude motions, and in May 1987, the spacecraft became inverted and stabilized in an upside down attitude. The recovery approach involved allowing the wheel to spin down, then spinning it back up. After three tries, Polar BEAR was successfully re-inverted. The problem was further analyzed in Ref. 9.

The Polar BEAR story illustrates how unmodelled effects can dramatically perturb a spacecraft's motion. It also provides an excellent example of how ADCS engineers can solve problems that arise with on-orbit spacecraft.

Electronics Design Error Caused WIRE Tumble

The Wide-Field Infrared Explorer (WIRE) spacecraft was launched on March 4, 1999 and was planned to have a four month mission.[10] The short duration was due to the cryogenically cooled infrared telescope: the cryocooler used a bar of solid hydrogen that sublimated to cool the mirror. A pyrotechnic device was included to remove the cover from the telescope. Transient outputs from the pyro electronics box caused the cover to be blown when the box was initially powered up. Since the spacecraft was not yet in its operational orbit and attitude, the telescope was exposed to heating and hydrogen was vented. The vented hydrogen acted as a thruster and tumbled the spacecraft. Eventually the attitude control system was able to detumble the spacecraft, but not before all of the hydrogen was vented. Subsequent checkout of the spacecraft subsystems validated most elements of the spacecraft design, though no infrared images were obtained.[11]

Surface Tension Immobilized Nutation Damper in IMAGE Spacecraft

The Imager for Magnetopause to Aurora Global Exploration (IMAGE) spacecraft was spin-stabilized with a single magnetic torque rod and a partially-filled ring nutation damper.[12] The vehicle's initial nutation did not decay as expected. Evidently, due to the spacecraft's low spin rate (0.5 rpm) surface tension immobilized the liquid mercury in the nutation damper. The nutation was damped by uploading an open-loop damping controller which used the magnetic torque rod. Detailed analysis of the dynamics is presented in Ref. 12.

Rate Gyro Failure in FUSE Led to Brain Transplant

The Far Ultraviolet Spectroscopic Explorer (FUSE) spacecraft[13] was launched on its three-year mission in June 1999, and has been credited with enabling a wide range of discoveries regarding distant stars and galaxies.

The attitude control system uses magnetic coils and flywheels. Two of the four momentum wheels on FUSE failed in 2001 and engineers reprogrammed the attitude control software to combine the magnetic torquers and momentum wheels to continue to provide accurate control. Attitude determination uses a set of six ring-laser gyros. One of the gyros failed in 2001 and the remaining five ”all show signs of age.”

The new software allows the spacecraft to do attitude control with only two reaction wheels and no gyroscopes. Comparing with Compton Gamma Ray Observatory, this capability will extend the life of the mission.

GeoSat Follow-On Sign Error — Partial Credit?

The GeoSat Follow-On (GFO) satellite is three-axis stabilized with momentum wheels, has a single solar array with one-axis articulation, and hydrazine thrusters for orbit maintenance.[14] The 370 kg spacecraft was launched on February 10, 1998. The spacecraft tumbled instead of achieving the correct attitude, and the subsequent analysis of telemetry and the equations of motion led to the conclusion that the momentum and torque were in the wrong direction: a sign error. Fortunately the attitude control system was table-driven so that engineers were able to upload corrected tables. Within hours, the satellite was sun-pointing within 0.02° with attitude rates of less than 0.006°/s.

Other ADCS failures

There are other interesting anomalies that are related to ADCS. For example, Ref. 15 described how a change in adhesive application practices affected environmental disturbance torques on the TDRS spacecraft. The Earth Radiation Budget Satellite (ERBS) experienced an anomaly during a yaw maneuver which resulted in a tumbling rate of more than 2 deg/sec.[16] Clementine[17] was lost due to a software error which caused a thruster to become stuck open, hence the attitude control system propellant was exhausted.

Summary

The paper describes an attitude determination and control course taught to undergraduates at Virginia Tech. An interesting feature of the course is the inclusion of several examples of ADCS failures that illustrate the principles of ADCS analysis and design.

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