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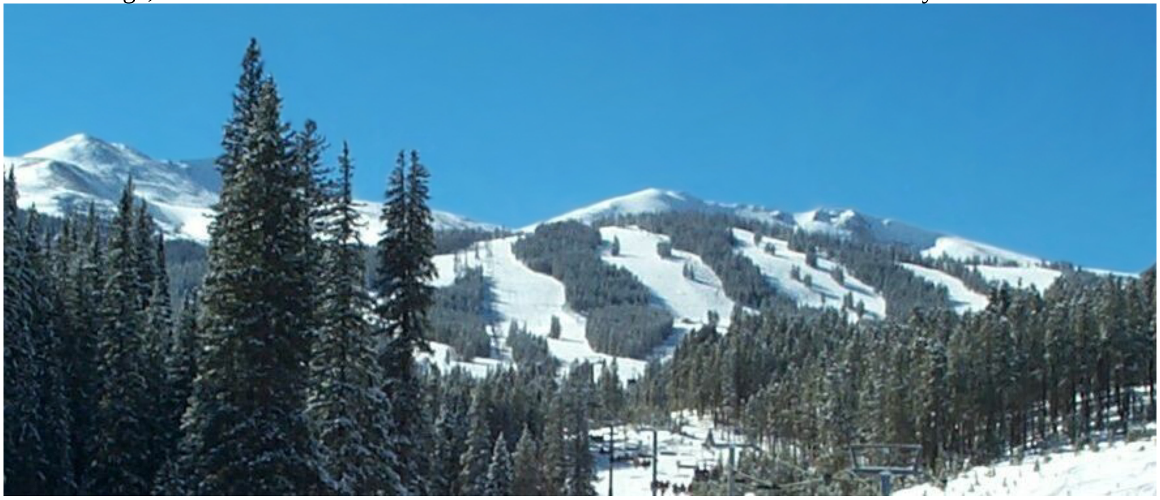

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In this paper, the attitude control issues associated with International Space Station (ISS) loss of automatic thruster control capability are discussed and methods for attitude control recovery are presented. This scenario was experienced recently during Shuttle mission STS-117 and ISS Stage 13A in June 2007 when the Russian GN&C computers, which command the ISS thrusters, failed. Without automatic propulsive attitude control, the ISS would not be able to regain attitude control after the Orbiter undocked. The core issues associated with recovering long-term attitude control using CMGs are described as well as the systems engineering analysis to identify recovery options. It is shown that the recovery method can be separated into a procedure for rate damping to a "safe harbor" gravity gradient stable orientation and a capability to maneuver the vehicle to the necessary initial conditions for long term attitude hold.

A manual control option using Soyuz and Progress vehicle thrusters is investigated for rate damping and maneuvers. The issues with implementing such an option are presented and the key issue of closed-loop stability is addressed. A new non-propulsive alternative to thruster control, Zero Propellant Maneuver (ZPM) attitude control method is introduced and its rate damping and maneuver performance evaluated. It is shown that ZPM can meet the tight attitude and rate error tolerances needed for long term attitude control. A combination of manual thruster rate damping to a "safe harbor" attitude followed by a ZPM to Stage long term attitude control orientation was selected by the Anomaly Resolution Team as the alternate attitude control method for such a contingency.

INTRODUCTION

During Shuttle mission STS-117 in June 2006, when the Orbiter was mated to the International Space Station (ISS) for assembly of ISS Stage 13A, the Russian GN&C computers failed[1]. The result was loss of closed-loop ISS attitude control capability using thrusters. Without this capability, the ISS would not be able to regain attitude control after the Orbiter undocked. This paper presents the operational solutions and control methods developed in order to recover attitude control when automatic thruster control capability is lost.

The ISS uses propulsive and non-propulsive actuators to maintain attitude control. Propulsive capability is provided by thrusters on the Russian Segment (RS) components such as the Service Module (SM), and Progress visiting vehicles. The SM Motion Control System (MCS) is used to command the thrusters for both attitude and translational control. For attitude control the SM MCS uses a Phase Plane based controller. Additionally, a Soyuz vehicle is also docked to the ISS; however, its thrusters can only be activated manually by the crew. This is shown in Figure 1.

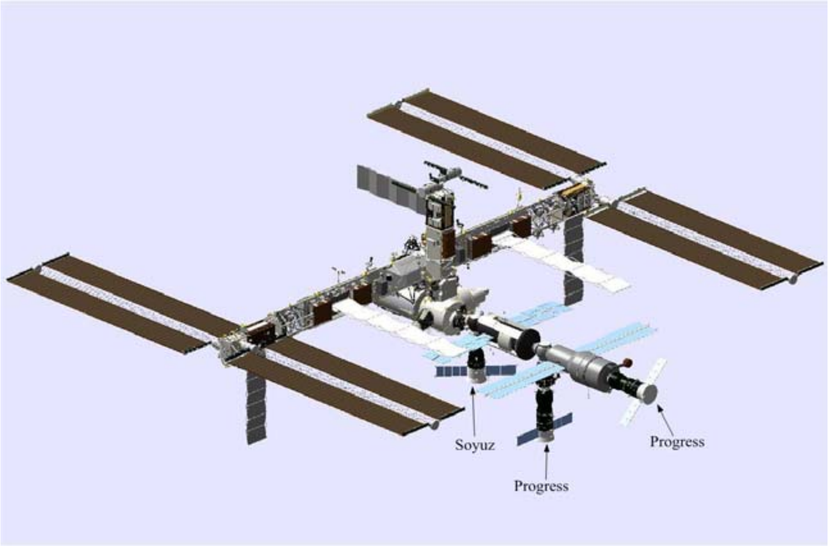

Figure 1. ISS Stage 13A Russian visiting vehicle configurations

Non-propulsive control is provided by Control Momentum Gyroscopes (CMGs) on the US segment. A Momentum Manager[2] (MM) controller is used for long term attitude hold at Torque Equilibrium Attitudes (TEAs). In general, these TEAs are unstable and without MM control the ISS would tumble. For successful MM start-up, thrusters must be used to damp rate errors to less than 0.001deg/s[1]. For larger rate errors, the transient response may cause momentum saturation which leads to Loss of Attitude Control (LOAC). For short term attitude hold and maneuvers, a PID Attitude Hold (AH) controller with an eigenaxis maneuver logic is used. Typically, the integral term is not used; hence it will be referred to as a PD controller. However, holding attitude and maneuvering the ISS will, in general, also cause momentum saturation. As the CMGs have limited torque and momentum capacity, when this limit is reached (i.e. they become saturated), thrusters must be used for momentum desaturation. But due to CMG lifetime issues, momentum desaturation using thrusters is currently prohibited.

There is one more propulsive attitude hold control option, US Thruster Only (USTO), which uses the PD controller in Pulse Width Modulation (PWM) mode to command the Russian thrusters rather than the US CMGs. A graphic of all three attitude control options are depicted in Figure 2. The USTO controller is shown in Figure 3. Briefly stated, the torque command generated by the PD controller is multiplied by the Thruster Assist (TA) period resulting in a momentum change command, deltaH, which is then sent to the RS where it is converted to thruster on-times. Additionally, the minimum and maximum deltaH command can also be specified. The TA period and deltaH limits are uploadable flight software parameters.

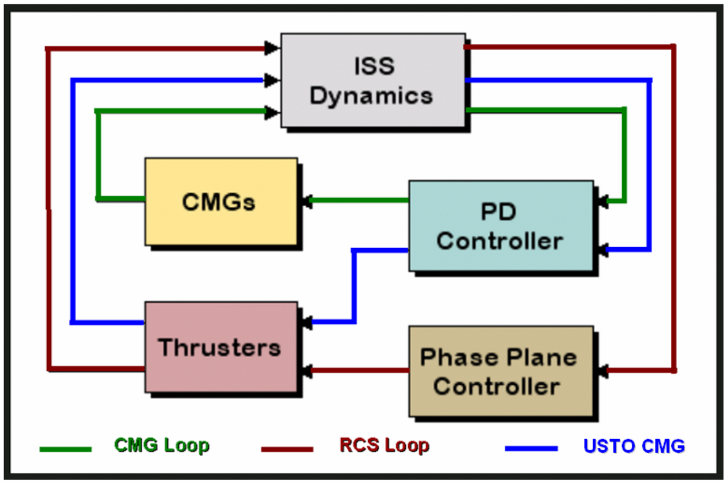

Figure 2. ISS Attitude Hold control options

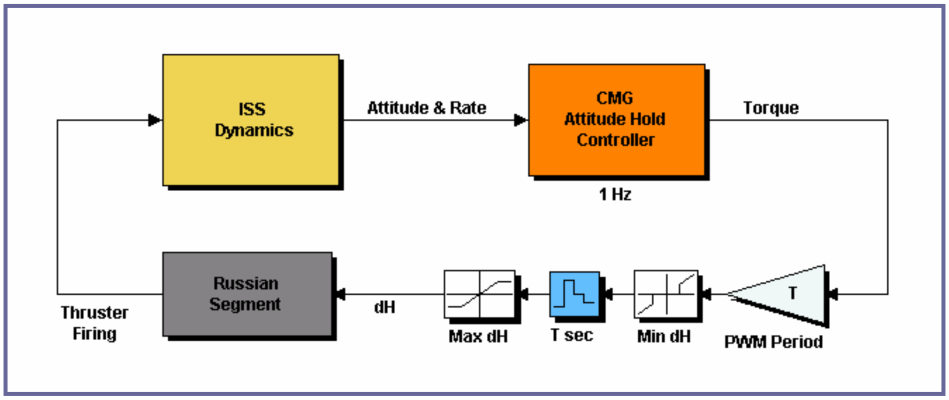

Figure 3. USTO Attitude Hold control mode

It is apparent that without propulsive attitude control the ISS would not be able to regain attitude control after Orbiter undocking. Hence, the core issue is how to undock so that MM control at the Stage TEA can be successfully activated.

ISS ATTITUDE CONTROL RECOVERY OPTIONS

To list the choices from which to select a recovery option, an evaluation of the Orbiter undocking operation was performed in conjunction with remaining attitude control alternatives. Nominally, the Orbiter maneuvers the mated stack to the non-TEA undock attitude [0 0 0]deg with respect to Local Vertical Local Horizontal (LVLH) reference frame. A graphic of the undocking dynamics is shown in Figure 4. After the Orbiter undocks, Russian thrusters are used to maneuver the ISS to the Stage TEA, damp rates, and handoff to MM. The main point of the graphic is that it is difficult to predict reliably the initial conditions for ISS attitude control initiation due to uncertainty in initial conditions, free drift periods and plume impingement effects. Thus biasing the mated stack initial condition prior to undocking is not a viable choice. Free-drift is also not an option as the ISS will tumble.

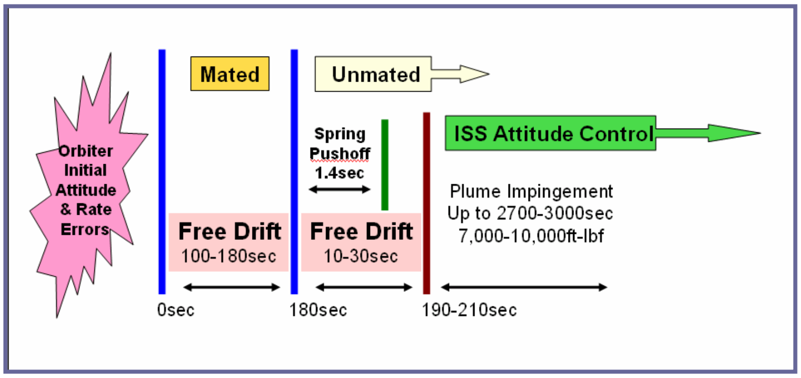

Figure 4. Orbiter undock from ISS procedure

Once the Orbiter has undocked, only two ISS attitude control options remain for rate damping and maneuvers. The first is to manually fire the thrusters on Soyuz and Progress vehicles. The second is a new non-propulsive control method, Zero Propellant Maneuver (ZPM)[4,5] which will be described in the following sections. Therefore, the undocking choices and the predicted likelihood of success are shown in Figure 5. Two basic choices are identified: undocking at a Stable TEA (STEA) or an Unstable TEA (UTEA). For nominal undocking at LVLH attitude or at the nearest Stage UTEA, if thrusters are not available, attitude recovery is not very likely. If manual control is available, direct handover to MM will fail due to its coarse rate control capability. However, if the ISS is maneuvered to an STEA with manual control, followed by a ZPM to the Stage TEA, it is likely that MM start-up will be successful. On the other hand, if the undocking is performed at an STEA, the likelihood of successfully regaining attitude control is substantially increased. Only in the case of no thrusters and high initial rate errors (e.g., greater than 0.1deg/s currently) is it not very likely that attitude control will be achieved. However, with large initial rate errors, it is also unlikely that the ISS will remain at the STEA, i.e. within its basin of attraction.

Thus, it is seen that the highest probability recovery method can be separated into a procedure for rate damping to a “safe harbor” gravity gradient stable orientation and a capability to maneuver the vehicle back to the Stage TEA while meeting the necessary initial conditions for successful MM startup. The Anomaly Resolution Team selected the maneuver to an STEA with manual control followed by a ZPM to Stage TEA as the approach to recover attitude control capability. In the following sections the key issues with manual control and ZPM are discussed.

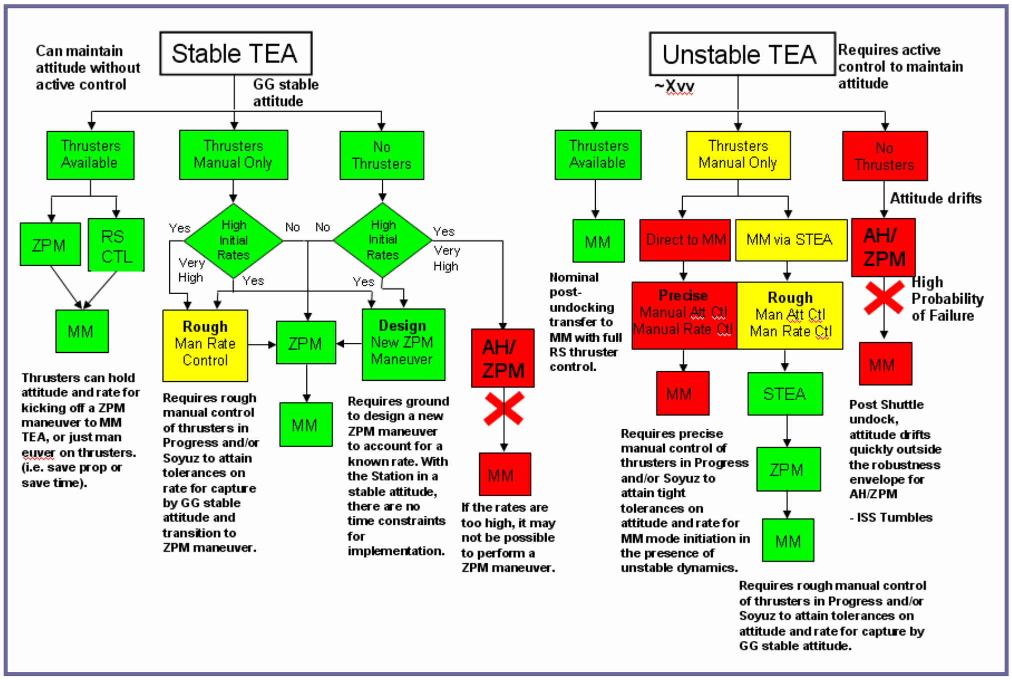

Figure 5. ISS attitude control recovery options

MANUAL CONTROL

In this section, the main issues with implementing such an option are presented and the key issue of manual control stability is identified. Solutions using the existing flight software and a customized approach are presented which address this stability issue from the perspective of largest allowable sampling and delay time in order to minimize astronaut work load. There are two manual control options to be considered. Onboard implementation without ground assistance and a ground-assisted solution. The main issues with an onboard approach include:

- The crew has not been trained for such a contingency and it was desirable to minimize crew involvement.
- There is limited availability of GN&C data and processing tools. Only vehicle state can be accessed.
- Installing new software requires certification which is costly and time consuming.

For these reasons, an onboard solution was rejected. On the other hand, the main issues with a ground-assisted solution are:

- The turn-around time is substantial as it requires coordination between Houston and Moscow Mission Control Centers (MCC).
- Installing new software in MCC requires certification which is costly and time consuming.
- US GN&C provided vehicle state and PD controller torque command is available to the ground.

The basic outline of the manual control capability using a ground-assisted method is for the ground to intermittently issue thruster and on-times commands for the crew to implement using hand-controllers.

As a solution that requires new software be installed in MCC is not feasible within the time frame of the emergency as well as due to cost, an approach that does not require any new software was pursued. The success criteria for the approach were the capability to recover ISS from a tumble and maneuver to a STEA. Further, the recovery operation should not take too long, e.g. more than a few hours, and not require many commands. The main issue that had to be resolved was the closed-loop stability of the manual mode, i.e. what is the maximum time delay that can be tolerated while meeting the success criteria.

As the vehicle state and control torque are available from the US GN&C system via telemetry, a PD-based USTO solution was investigated first. Frequency domain stability margins were computed for various proportional and derivative gains to identify the maximum delay for which stable attitude control could be achieved. For an open-loop bandwidth of $7\omega_o$ and 0.7 damping ratio, stability would be maintained for delays < 2min and TA periods < 4min. Time domain simulation was then performed using the high-fidelity Space Station Multi-Rigid Body Simulation (SSMRBS).[6] A simulation of 7200s duration manual control with a 2min delay and 4min TA period is provided in Figure 6. The initial conditions were chosen from a separate simulation to obtain an estimate of a worst case tumbling rate. Hence a free-drift simulation from the +X-axis in Velocity Vector (+XVV) Stage TEA [0 -8.7 -0.5]deg (YPR order and sequence) was performed resulting in 0.098deg/s rate magnitude at an orientation of [-146.2 -69.2 -67.5]deg (PYR order and sequence). The manual control target is the gravity-gradient stable attitude [-268.6 7.9 -90.4]deg (PYR order and sequence). A two-step maneuver rate and maximum deltaH profile was used with the switch time at 3600s. The maximum deltaH values were 30000ft-lbf-s and 15000ft-lbf-s for the first and second half of the solution respectively, and the maneuver rates were set to 0.05deg/s and 0.01deg/s. It is seen that manual control is successful in recovering the ISS from a tumble and maneuvering it to the STEA. A total of 912 manual commands were issued.

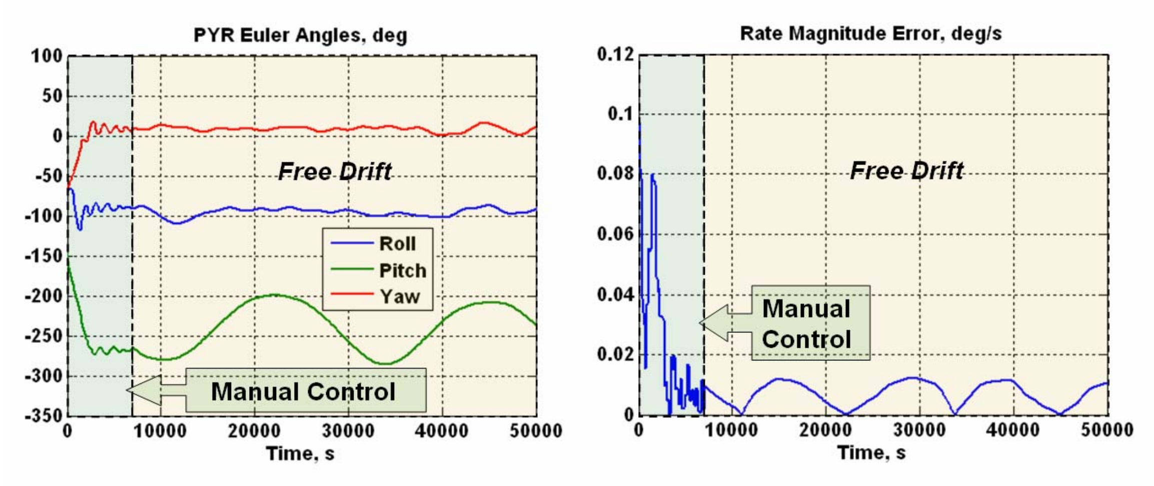

Figure 6. Manual Control with PD Logic – Attitude (deg, PYR sequence, left plot), Rate Magnitude Error (deg/s, right plot)

However, the maximum delay time of 2min between state measurement and thruster actuation was deemed too short for implementation. An eigenaxis-based approach was developed that is stable with a 5min delay and 10min TA period and can be implemented as a USTO controller with zero proportional gain and a derivative gain equal to one divided by the TA period. Figure 7 shows such a two-step solution implemented with maximum deltaH and maneuver rate values of 75000ft-lbf-s and 0.1deg/s respectively for 3600s followed by 15000ft-lbf-s and 0.01deg/s for the next 3600s. A total of 133 manual commands were issued.

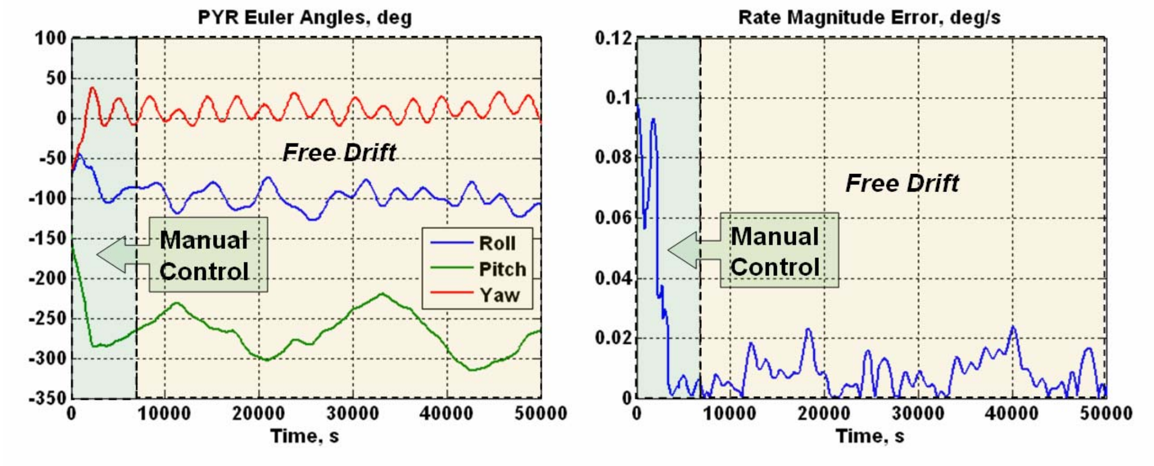

Figure 7. Manual Control with Eigenaxis Logic – Attitude (deg, PYR sequence, left plot), Rate Magnitude Error (deg/s, right plot)

ZERO PROPELLANT MANEUVER (ZPM)

To transition the ISS from a STEA to the Stage TEA and successfully startup MM, a new attitude control concept using ZPM guidance was developed. With ZPM, the operational envelope of ISS CMG PD controller is expanded such that essentially saturation induced

LOAC is eliminated. Put another way, with ZPM, CMG-only attitude control may always be possible without needing thrusters as backup. This is achieved by using computational optimal control to develop the feedforward reference signal the PD feedback controller follows. As it is a model based approach, robustness issues have to be addressed in order to fully exploit its capabilities. With this approach a new class of performance previously thought impossible can now be realized. ZPM enables non-propulsive large angle maneuvers, attitude control with saturated CMGs, and rate damping. These capabilities can be achieved without any flight software changes simply by commanding the controller with a specific attitude trajectory.

This concept has already been successfully flight demonstrated, twice. The first ever flight demonstration was performed on November 5, 2006, when the ISS was maneuvered 90deg in 7200s without using any propellant.[4] The second demonstration was performed on March 3, 2007, when the ISS was maneuvered 180deg in 10000s also without using any propellant.[5] To put the propellant savings in perspective, on January 2, 2007, the ISS performed the exact same 180deg maneuver using thrusters which consumed 50.76kg of propellant with an approximate value of $1,100,000.

The ZPM concept is based on developing a special attitude trajectory to accomplish the desired rotational state transition without exceeding CMG capability, i.e. peak momentum and torque magnitude. The trajectory is shaped in a manner that takes advantage of the nonlinear system dynamics. The key is to coordinate and modulate attitude-dependent environmental torques. Coordination is accomplished by varying the maneuver rate, i.e. speeding up or slowing down. Modulation is achieved by commanding attitude excursions. This is similar to the way a sailboat would tack against the wind. In this analogy, the CMGs represent the ship's "rudder," the gravity gradient torque is the "wind," while aerodynamic torque is the "ocean drag." This is shown in Figure 8. For example, an eigenaxis maneuver is kinematically the shortest path between two orientations. For the attitude controller system to follow the eigenaxis, the nonlinear system dynamics must be overcome, thereby increasing the "cost" of the maneuver. By considering a kinematically longer path and increasing the time to perform the maneuver, path dependence of system dynamics can be exploited to lower the "cost". This allows spacecraft that use momentum storage devices for attitude control, such as the ISS, to perform large angle attitude maneuvers non-propulsively.

To implement the ZPM, the ground-developed trajectory is converted into Greenwich Mean Time (GMT) time-tagged commands for uplink to the ISS Command and Control computer (C&C MDM) prior to the maneuver execution time. As the C&C MDM command buffer was limited to 200 slots, ZPM is allocated 160 slots. This limits the ZPM to 80 quaternion commands and 80 maneuver rate commands. Since the ISS attitude hold controller uses an eigenaxis maneuver logic, the rate command is a scalar maneuver rate required to transition from one attitude command to the next in the specified time.

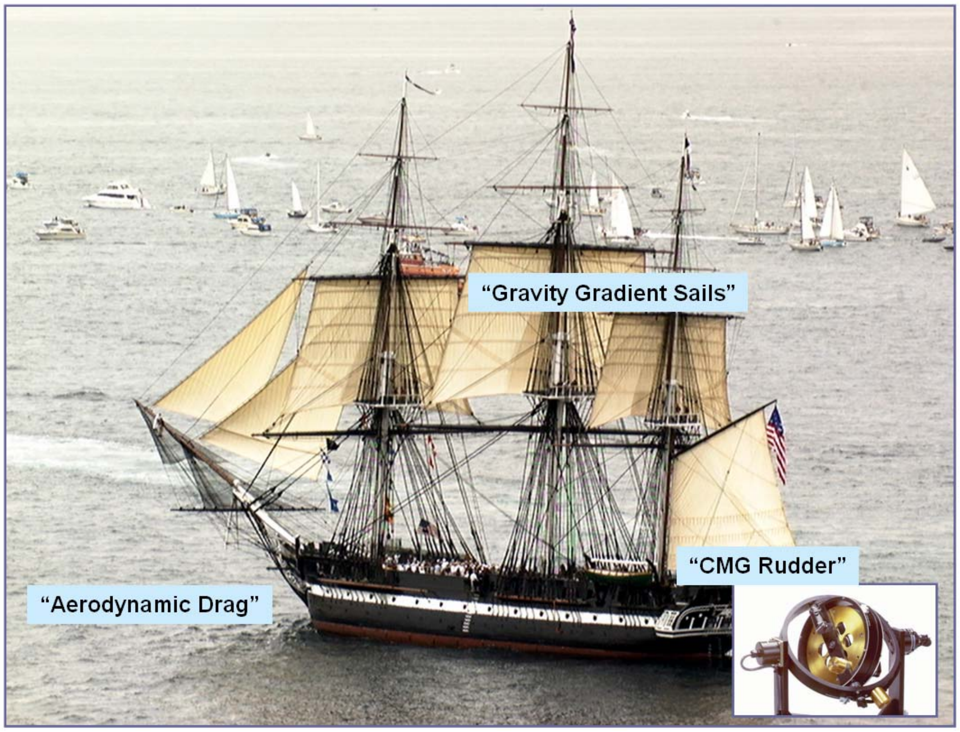

Figure 8. Zero Propellant Maneuver guidance concept sailing analog. CMG image cropped from http://www.ecpsystems.com/controls_ctrlgyro.htm, courtesy of ECP Systems.

ZPM from STEA to Stage TEA

In this section a ZPM from an STEA to the Stage TEA is described. The starting point is the +YVV STEA given by [100.4 82 10.1]deg with respect to LVLH reference frame and in YPR order and sequence. The CMG momentum state is assumed to be at the origin, [0 0 0]ft-lbf-s expressed in body frame and XYZ order. The target orientation is the +XVV Stage TEA, [0 -8.7 -0.5]deg with respect to LVLH and in YPR order and sequence. The MM start-up momentum target is [225 0 0]ft-lbf-s expressed in body frame and XYZ order. The environmental parameters were based on predictions for July 25, 2007. The Solar Array Rotary Joints (SARJs) and PhotoVoltaic Arrays (PVAs) were oriented at 90deg. The Thermal Rejection Rotary Joints (TRRJs) are required to be at 75deg at +YVV and at 0deg at +XVV, and the transition is assumed to occur at 6500s into the maneuver. The maneuver time is 10000s after which MM start-up occurs. The attitude profile and momentum magnitude are shown in Figure 9. It is evident the MM start-up is successful.

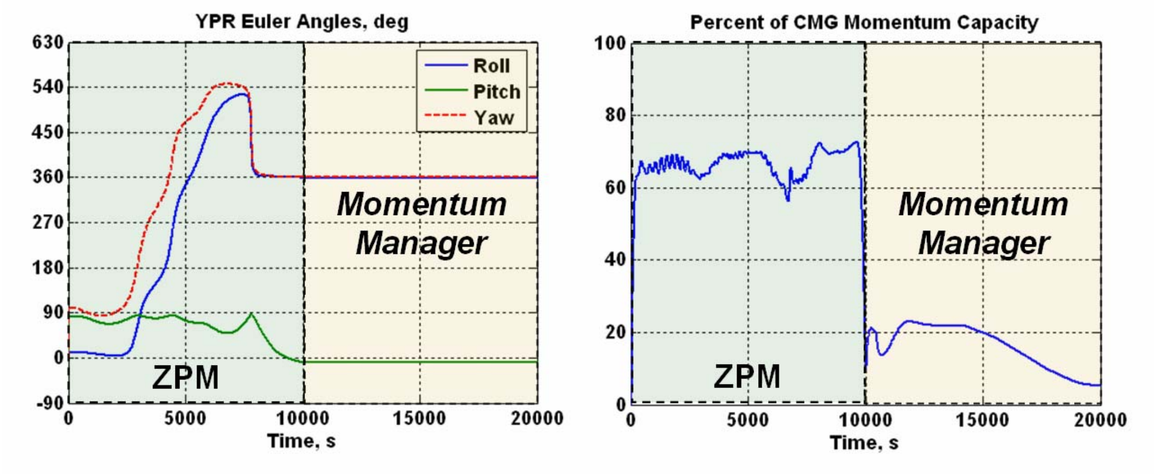

Figure 9. ZPM Trajectory from +YVV STEA to +XVV Stage TEA – Attitude (deg, YPR sequence, left plot), Percent of Momentum Capacity (%, right plot)

ZPM Attitude Recovery For No Thrusters Option

In this section, the use of ZPM is investigated for the contingency scenario when thruster control is not available, i.e. manual control of thrusters is not feasible. It is assumed that the Orbiter undocks at +XVV Stage TEA. For this scenario two alternative strategies can be considered. The first is to directly maneuver to the Stage TEA after the Orbiter undocks. It is assumed that the AH controller is used initially to damp rates which results in momentum saturation. Hence, the objective is to show feasibility of maneuvering the ISS with initially saturated CMGs. The second strategy is to arrest a tumbling ISS and return it to the Stage TEA. In the first phase, ZPM rate damping is performed which is followed by another ZPM to reach the final attitude.

ZPM Attitude Control with Saturated CMGs

To recover attitude control from saturated CMGs, a ZPM is constructed to maneuver the ISS so as to desaturate the CMGs and target the MM initial conditions chosen by the MM design team. In order to design the ZPM, the three-axis saturated momentum state is needed and can be estimated from simulation. Figure 10-Figure 11 show the results of simulating CMG attitude hold (with the PD AH controller) at +XVV until the CMGs saturate, followed by a CMG desaturation ZPM lasting 8000s. In this case, the momentum reaches 3-CMG capacity at [1341 10710 -381]ft-lbf-s. It is seen that ZPM desaturates the CMGs and MM start-up is successful.

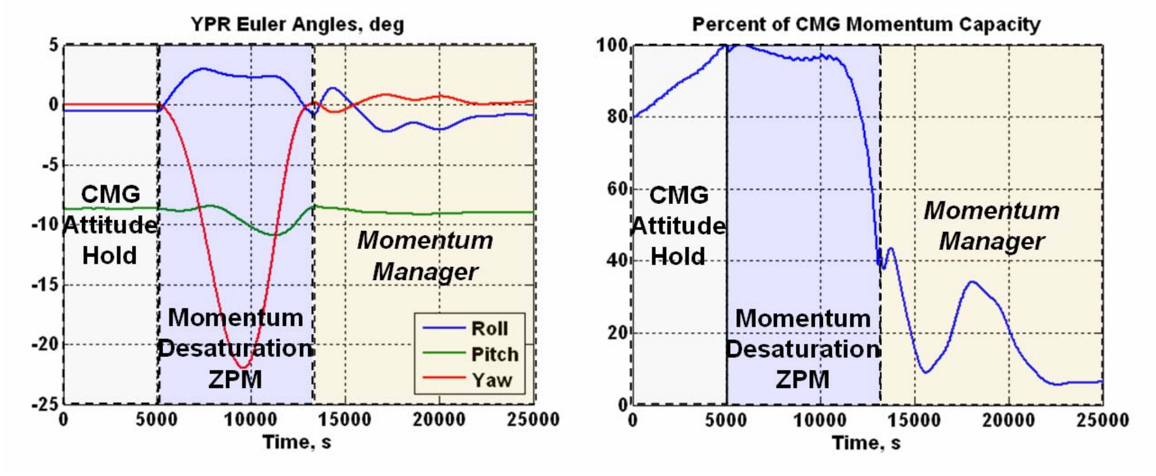

Figure 10. ZPM attitude control with saturated CMGs – Attitude (deg, YPR sequence, left plot), Percent of Momentum Capacity (%, right plot)

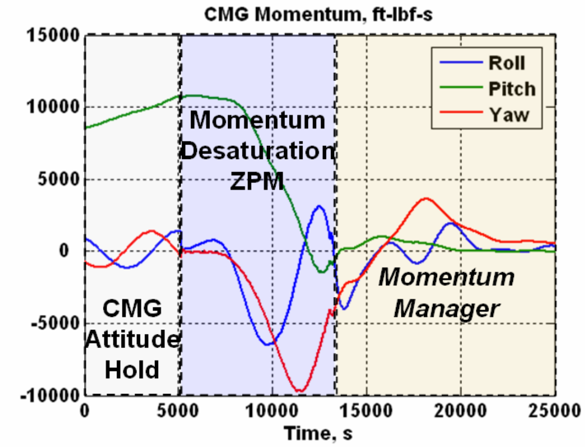

Figure 11. ZPM attitude control with saturated CMGs – CMG Momentum (ft-lbf-s)

ZPM Attitude Control For Tumbling ISS

To recover attitude control of a tumbling ISS, first a rate-damping ZPM is developed. It is then followed by a maneuver to the Stage TEA while targeting MM start-up conditions (e.g., the Stage UTEA and associated momentum vector provided by the MM design team). The estimated worst case tumbling rate magnitude of 0.098deg/s and corresponding attitude obtained from the +XVV Stage TEA free-drift simulation mentioned earlier were used as the initial states for the rate-damping ZPM. The rate-damping ZPM lasted 12000s whereas the ZPM to target MM startup was performed in 5000s. The simulation results in Figure 12Figure 13 show that the ZPMs successfully damp rates and hand-over to MM while staying within CMG momentum capacity limits.

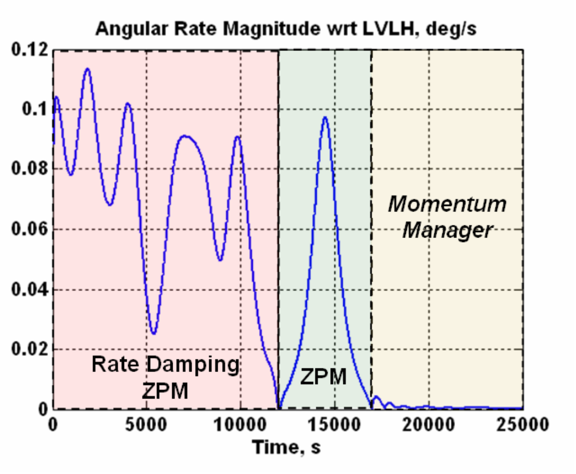

Figure 12. ZPM attitude control for tumbling ISS – Magnitude of Body Rate w.r.t. LVLH (deg/s)

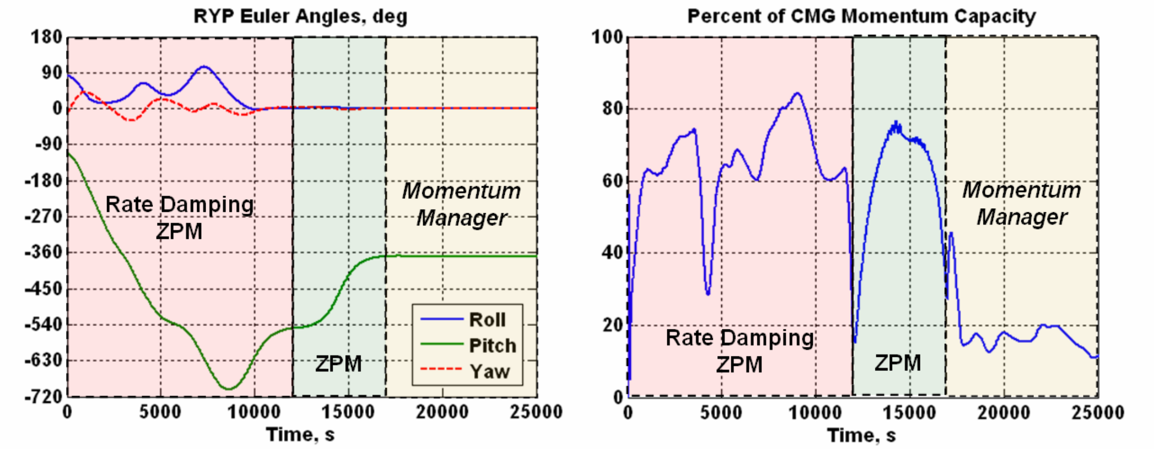

Figure 13. ZPM attitude control for tumbling ISS – Attitude (deg, RYP sequence, left plot), Percent of Momentum Capacity (%, right plot)

Robustness of ZPM

The success of a ZPM in flight depends on uncertainty in initial conditions and system parameters (e.g., mass properties, environmental conditions, etc.). Monte Carlo simulations are performed to estimate robustness bounds for a ZPM. As an example, ZPM performance for a Stage 13A.1 maneuver from an STEA to +XVV Stage TEA simulated with perturbed initial attitudes and rates is given in Figure 14. It is seen that initial errors up to about 2deg in attitude and 0.006deg/s in rate can be tolerated by ZPM without reaching momentum capacity. This ZPM was designed to hand over to MM after the Orbiter undocked from the ISS at a STEA. As stated earlier, the process of undocking (Figure 4) leads to uncertainty in the states. Figure 15 shows the ISS attitude during free-drift for different Orbiter plume profiles. It is apparent that the uncertainty in ZPM initial conditions can be outside of robustness bounds. Thus it is desirable to be able to monitor ISS telemetry to predict states in advance via simulation, design a new ZPM based on the prediction, and upload the new trajectory.

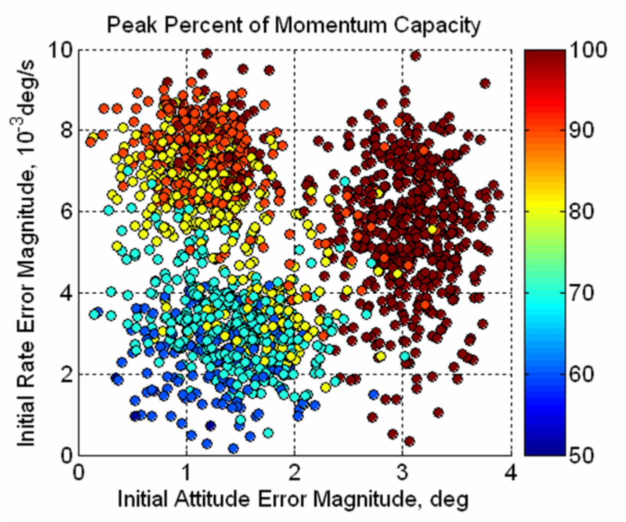

Figure 14. ZPM robust performance in the presence of initial attitude and rate errors

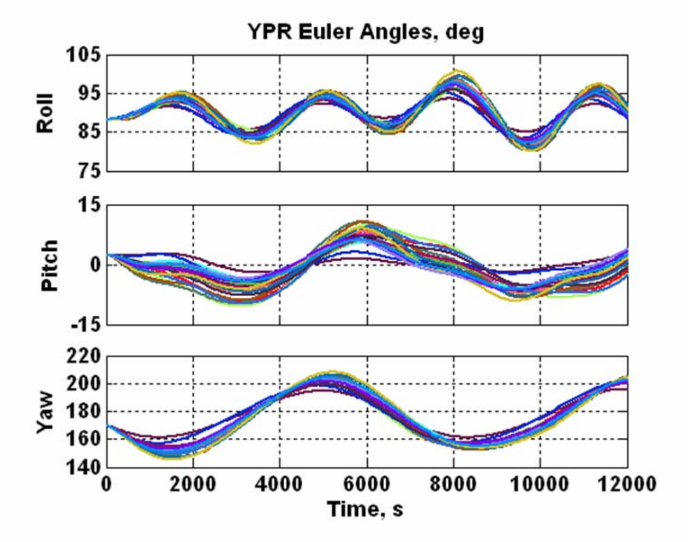

Figure 15. Free-drift attitude for undocking at STEA

CONCLUSION

In this paper, the attitude control issues associated with International Space Station (ISS) loss of closed-loop thruster control capability are discussed and methods for attitude control recovery are presented. This scenario was experienced recently during Shuttle mission STS-117 and ISS Stage 13A in June 2007 when the Russian GN&C computers, which command the ISS thrusters, failed. Without automatic propulsive attitude control, the ISS would not be able to regain attitude control after the Orbiter undocked. The core issues associated with recovering long-term attitude control using CMGs are described as well as the systems engineering analysis to identify recovery options. It is shown that the recovery method can be separated into a procedure for rate damping to a "safe harbor" gravity gradient stable orientation and a capability to maneuver the vehicle to the necessary initial conditions for long term attitude hold.

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