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**SPACECRAFT HYBRID CONTROL AT NASA:
A LOOK BACK, CURRENT INITIATIVES, AND
SOME FUTURE CONSIDERATIONS**

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NASA Engineering & Safety Center (NESC)

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SPACECRAFT HYBRID CONTROL AT NASA: A HISTORICAL LOOK BACK, CURRENT INITIATIVES, AND SOME FUTURE CONSIDERATIONS

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ABSTRACT

There is a heightened interest within NASA for the design, development, and flight implementation of mixed actuator hybrid attitude control systems for science spacecraft that have less than three functional reaction wheel actuators. This interest is driven by a number of recent reaction wheels failures on aging, but still scientifically productive, NASA spacecraft. This paper describes the highlights of the first NASA Cross-Center Hybrid Control Workshop that was held in Greenbelt, Maryland in April of 2013 under the sponsorship of the NASA Engineering and Safety Center (NESC). A brief historical summary of NASA's past experiences with spacecraft mixed actuator hybrid attitude control approaches, some of which were implemented on-orbit, will be provided. This paper will also convey some of the lessons learned and best practices captured at that workshop. Some relevant recent and current hybrid control activities will be described with an emphasis on work in support of a repurposed Kepler spacecraft. Specific technical areas for future considerations regarding spacecraft hybrid control will also be identified.

INTRODUCTION

There is a heightened interest within NASA for the design, development, and flight implementation of mixed actuator hybrid attitude control systems for science spacecraft that have less than three functional reaction wheel actuators. This interest is driven by a number of recent reaction wheels failures on aging, but still scientifically productive, NASA spacecraft. This interest is also motivated as a general means to ensure continued longevity of NASA's scientific spacecraft fleet well past their prime mission lifetimes and into extended mission operations.

In late 2012 the Science Mission Directorate (SMD) Chief Engineer, Dr. Tupper Hyde, requested the support of the NASA Engineering and Safety Center (NESC) Guidance, Navigation, and Con-

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trol (GN&C) Technical Discipline Team (TDT) to plan and conduct a NASA-wide workshop on lessons learned and current developments in “hybrid” (mixed actuator) spacecraft attitude control mode design, test, and operations. A hybrid attitude control mode is a contingency means for controlling the a spacecraft that has lost the use of one or more of its reaction wheel complement such that there are less than three functional operating reaction wheels remaining.

At the time frame the workshop was being planned and conducted there were a number of NASA missions either actively working on designing and implementing hybrid attitude control or at least considering the feasibility of candidate hybrid control techniques In particular the Dawn mission, the Mars Odyssey mission and the Kepler mission were working on or considering the use of such a hybrid contingency attitude control mode for their respective on-orbit science spacecraft. There are also several other missions that may be facing reaction wheel failures as they age and could potentially benefit from contingency hybrid control.

In the following sections of this paper summary level highlights form the NASA Cross-Center Hybrid Control Workshop will be provided. This will primarily consist of set of brief historical summaries of NASA’s work on past spacecraft mixed actuator hybrid attitude control approaches. This paper will also document some of the key lessons learned and best practices captured at the workshop. A number of initiatives were spawned following the April 2013 workshop. Some specific examples of current hybrid control research, design, development and test will be described. Technical areas for future considerations will also be identified.

NASA HYBRID CONTROL WORKSHOP SUMMARY

The primary motivation behind holding the workshop was to identify and capture lessons learned and best engineering practices emerging from the several NASA missions that had in the recent past analyzed, designed, implemented and operated in this type of hybrid attitude control mode.

Therefore in April of 2013, the NASA Technical Fellow for GN&C (assisted by members of his NESC GN&C TDT) conducted what is believed to be the first ever NASA-wide workshop-type meeting focused on both the Agency’s historical experience with contingency spacecraft attitude control using only two reaction wheels (2-RW) and current relevant activities. The two-day workshop also focused on the technical feasibility of 2-RW contingency attitude control for three particular NASA science spacecraft: namely Dawn, Mars Odyssey, and Kepler. In this context, 2-RW contingency attitude control refers to hybrid mixed actuator attitude control modes of operation in which reaction control thrusters and/or magnetic torque actuators are combined with the two remaining functional reaction wheels on a given spacecraft to provide the requisite set of required attitude control torques.

Hybrid Control Workshop Goals

NASA wants to position itself to be as knowledgeable and as prepared as possible for contingency attitude control operations with only two (or possibly one) reaction wheels on missions such as Dawn, Mars Odyssey, and Kepler. The specific SMD goal of the workshop was to help inform and prepare the Kepler, Dawn, and Mars Odyssey ACS teams to better understand the technical challenges, risks, and benefits of potential 2-RW hybrid attitude control mode operations on their spacecraft. It was a mutual goal of the SMD and NESC to have the engineering knowledge in this particular spacecraft GN&C area to be shared amongst the subject matter experts from across the

NASA Centers and our industry and research partners. The identification of specific engineering areas and/or technology ideas for follow-on work in this area of hybrid control that would mitigate design and development risk and on-board implementation risk for future NASA space science missions was also an NESC goal for this workshop.

Specific Hybrid Control Workshop Objectives

The specific objectives of the NASA Hybrid Control Workshop were to:

- 1) Review recent on-orbit reaction wheel failures.
- 2) Review contingency hybrid (2-RW) attitude control past experience, to include re-design analysis and implementation details (e.g., specific attitude control law modifications).
- 3) Capture key lessons learned from historical experiences with hybrid (2-RW) attitude control.
- 4) Discuss the constraints on and limiting factors for hybrid (2-RW) attitude control and review of what is technically feasible with hybrid (2-RW) attitude control.
- 5) Discuss the risks of implementing hybrid (2-RW) contingency attitude control.
- 6) Discuss the current state of the Kepler, Dawn, and Mars Odyssey spacecraft RW attitude control capabilities.
 - Is there an imminent risk of another on-board reaction wheel failure?
 - Are there spacecraft-unique aspects to impending hybrid (2-RW) control on any of these spacecraft?
- 7) Discuss the technical risks/benefits (including a consideration of the degree of difficulty) of implementing hybrid 2-RW contingency attitude control on the Kepler, Dawn, and Mars Odyssey spacecraft.
- 8) Assess the potential for implementing contingency hybrid (2-RW) attitude control on Kepler, Dawn, and Mars Odyssey.

The workshop was purposely conducted in a collegial manner with an open sharing of hybrid control ideas and methods of operating scientific spacecraft with a reduced complement of reaction wheels. As shown in Table 1 twenty-eight attitude control subject matter experts from a combination of commercial industry (both large primes and small businesses), academia, non-profit labs, government labs, and NASA Centers participated in the workshop. Table 1 lists the workshop participants by name/organization and Figure 1 is a group photograph of the workshop participants.

By definition none of the briefings contained any of their organization's proprietary, confidential, or trade secret information. The Orbital Sciences Corporation (OSC) and Johns Hopkins Applied Physics Lab (APL) each provided some hybrid control historical perspective by describing their successful contingency operations for the FUSE and TIMED spacecraft, respectively. OSC and APL reported on how, through a series of innovative and clever engineering approaches they each were successful in enabling the continuation of their science missions for many years beyond their required design life and after having experienced multiple on-orbit reaction wheel assembly (RWA) failures. OSC, Lockheed Martin, and NASA explained their backup plans for possible future RWA failures on Dawn and Mars Odyssey. Engineers from the NASA Jet Propulsion Laboratory (JPL) described their hybrid control work on Cassini and also presented the results of a preliminary hybrid control feasibility study for Kepler. In the following sub-section of this paper a very brief summary will be provide on each of the above topic areas covered during the workshop.

Name	Discipline	Organization
Core Team		
Neil Dennehy	Lead, NASA Technical Fellow for GN&C	GSFC
Patricia Pahlavani	MTSO Program Analyst	LaRC
Frank Bauer	GN&C TDT Member	Emergent
Charles Bell	NASA RWA Tiger Team	JPL
Dominick Bruno	Dawn ACS	Orbital
Bharat Chudasama	NASA RWA Tiger Team	JPL
Brian Class	Orbital CE/FUSE/ ACS Peer Review	Orbital
Wayne Dellinger	TIMED ACS/Peer Review	APL
Bradley Haack	Mars Odyssey ACS	LMC/Denver
Noel Hughes	Mars Odyssey ACS	LMC/Denver
Jack Hunt	STEREO ACS	APL
Lloyd Keith	NESC Chief Engineer	JPL
Torraj Kia	GN&C Engineering	JPL
Jinho Kim	Messenger ACS	APL
Nans Kunz	NESC Chief Engineer	ARC
Kenneth Lebsock	NASA GN&C Deputy	GSFC
Allan Lee	Dawn/Cassini ACS	HQ
Glenn Macala	Kepler/Cassini ACS	JPL
David Mangus	Peer Review	GSFC
Ian Mitchell	GN&C TDT Member	Draper Labs
James O'Donnell	MAP ACS/Peer Review	GSFC
Mike Ruth	FUSE ACS/Peer Review	Orbital Sciences Corporation
John Rackozy	Peer Review	MSFC
Charles Schira	Kepler ACS	Ball Aerospace
Brett Smith	Kepler ACS	JPL
Scott Starin	MAP ACS	GSFC
Eric Stoneking	GLAST ACS	GSFC
Davin Swanson	ACS Peer Review	The Aerospace Corporation
John West	GN&C TDT Member	Draper Laboratory
Consultants		
Joe Pellicciotti	NASA Technical Fellow for Mechanical Systems; NASA RWA Tiger Team	GSFC
Mike Dube	NASA RWA Tiger Team	GSFC
Administrative Support		
Linda Burgess	Planning and Control Analyst	LaRC/AMA
Erin Moran	Technical Writer	LaRC/AMA
Diane Sarrazin	Project Coordinator	LaRC/AMA

Table 1 : NASA Hybrid Control Workshop Participant List



Figure 1: Group Photograph of NASA Hybrid Control Workshop Participants

FUSE HYBRID CONTROL WORKSHOP REPORT

OSC presented a summary level presentation on the work Orbital and JHU/APL engineers performed in 2004, to design and implement a hybrid attitude control system for the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. The FUSE spacecraft (see Figure 2) was launched into orbit in June 1999 and began a three-year prime mission to collect high-resolution spectra in the far ultraviolet wavelength. FUSE flew in a circular Low Earth Orbit (LEO), approximately 725 km in altitude, with an inclination of 25 degrees and with an orbital period of slightly less than a 100 minutes. The spacecraft was equipped with a set of four reaction wheels. Two and a half years after launch, mechanical failures of two out of four reaction wheels reduced the satellite to two-axis control, halting science observations.

In November 2001, the yaw RWA on FUSE suffered dramatically increased drag and ceased spinning, but science operations continued with the redundant skew RWA controlling yaw. In December 2001, the pitch RWA also suffered a similar failure, leaving the spacecraft with only two axes of control. The FUSE spacecraft's zero-momentum three-axis stabilized Attitude Control System (ACS) was reconfigured to use the remaining two functional RWAs to stabilize the

spacecraft in pitch and roll, but science operations were not possible due to an uncontrolled tumble in yaw. Efforts by the FUSE flight operations team to re-start both the yaw and pitch RWAs resulted in no detectable motion. After the yaw wheel failure in November 2001, while still operating in three-wheel mode, preliminary investigations began into the feasibility of using the MTBs to generate attitude control torque in a mixed actuator or ‘hybrid’ actuator configuration. Geomagnetic torque had been used in conjunction with spacecraft spin-stabilization for quite some time, but this approach is clearly incompatible with the existing design and three-axis control requirements of FUSE. It has also been suggested as a method of control for the class of spacecraft whose design provides inherent gravity gradient stabilization, but the science demands required that the FUSE spacecraft observe science targets all over the sky and hold attitudes that did not minimize gravity gradient torques. At any rate, purely magnetic pointing control up till this time had only been applied to missions where the tolerances for attitude control were at the relatively coarse 1° pointing level.

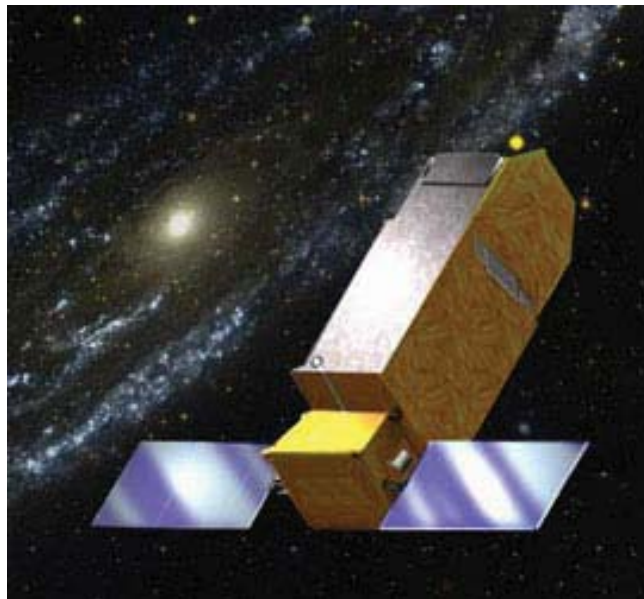


Figure 2: FUSE Spacecraft

Since torque can never be generated about the instantaneous geomagnetic field vector, any mission that uses magnetic control torques must have additional actuators, or accept attitude disturbances about a vector that is moving relative to inertial space. In the case of FUSE, these additional actuators were the two remaining functional reaction wheels. Initial calculations showed that the MTBs could be commanded with sufficiently high bandwidth for fine pointing control within the science requirements, and that they could produce enough torque to cancel external disturbances, but only at some spacecraft orientations. After the second permanent RWA failure, simultaneous efforts began to upgrade the ACS software to accomplish magnetic control, and to develop ground-based models useful for predicting stable spacecraft orientations.

It was described how these reaction wheel failures prompted modification of the FUSE ACS flight software to restore three-axis control using a hybrid configuration of existing magnetic and reaction wheel actuators. Pointing accuracy and stability were once again accomplished at the sub-arc second level, close to the pre-wheel failure performance. The range of stable attitudes is limited, but a new ground-based software model was developed which directed the spacecraft

observation planning process such that that observations and maneuvers stay within the limits of the actuators. Even in the face of all these constraints efficient FUSE science operations could be performed and over the course of a year, the entire sky was made available for observation.

In July 2007, FUSE's final working reaction wheel, the skew wheel, failed and efforts to restart it were unsuccessful. An announcement was made in September 2007 that because the fine control needed to perform its mission had been lost, the FUSE mission would be terminated.

References 1 and 2 contain the details of the FUSE hybrid control (both 2-RW and 1-wheel) design and development process.

TIMED HYBRID CONTROL WORKSHOP REPORT

As part of NASA's Solar Connections Program, the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission has the primary objective of investigating and understanding the energetics and dynamics of the Mesosphere and Lower Thermosphere/Ionosphere (MLTI) region. Launched on 7 December 2001, the TIMED spacecraft was built, and is operated, for NASA by The Johns Hopkins University Applied Physics Laboratory (JHU APL). TIMED is a 600 kilogram spacecraft (see Figure 3) carrying four primary instrument payloads. Launched into a 625 kilometer circular orbit with an inclination of 74.1 degrees, the original mission lifetime for TIMED was two years and has since been granted multiple mission extensions.

As described in Reference 3 the RWA-1 unit on the TIMED spacecraft exhibited an increase in running friction on 15 February 2007 and it was autonomously removed from the attitude control loop. Several attempts to restart RWA were unsuccessful. This failure of RWA-1 appeared to make the remaining wheels on TIMED suspect and mission managers initiated steps to be prepared for any subsequent wheel failure. It was decided to re-design the baseline attitude controller to implement a 2-RW /magnetic torque rod hybrid control approach similar as to what was done on the FUSE mission. The team's objective was to develop and test the attitude control flight software modifications (i.e., 'patches') prior to a subsequent wheel failure.

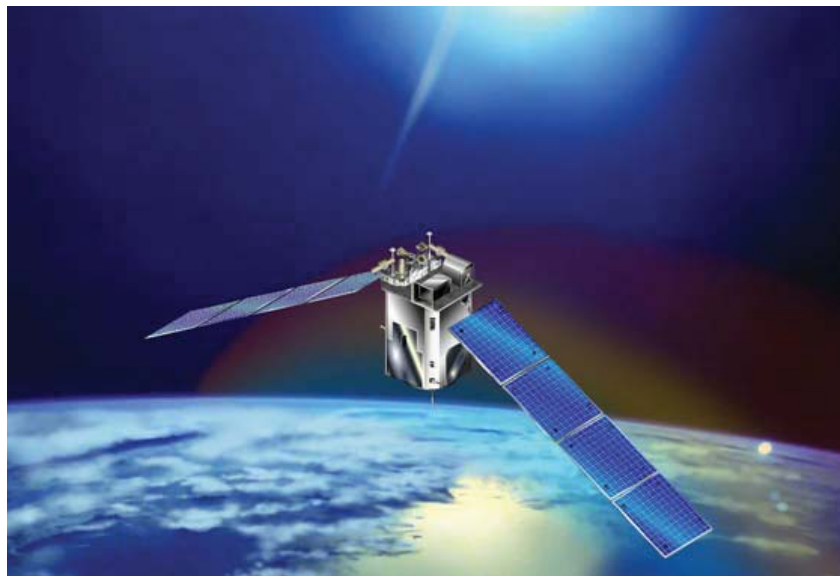


Figure 3: TIMED Spacecraft

However a fundamental difference was that while the FUSE spacecraft was inertially pointed for its science observations the TIMED spacecraft is nominally a nadir pointing platform. Yet another key difference was that while there is a capability to proportionally energize the magnetic torque rods on FUSE the torque rods on TIMED were operated in a basic on/off manner. Since the rods are operated in a ‘on’ (fixed full dipole command) and ‘off’ (zero dipole command) way the capability for ‘fine’ continuous proportional attitude control was reduced. The TIMED spacecraft hybrid controller was designed to “fire” the MTB actuators in an on/off manner using phase plane logic, in a way very similar to how RCS thrusters are typically used. The significant difference being that the TIMED MTBs, unlike RCS thrusters, only ‘consumed’ electrical current and not propellant. -This is one example however of where there is a connection between deep space mission hybrid control applications using thrusters and low-Earth-Orbit (LEO) mission hybrid control using MTBs.

As described in detail in Reference 4 some of the key findings and/or design challenges to the JHU APL team working the TIMED 2-RW hybrid control problem were among the following:

- Any two reaction wheels provided control torque in a plane only. Therefore the use of a Wheel/Rod Control Pseudo Frame would be a good basic first step in designing a new hybrid controller for TIMED.
- There was limited wheel control authority. In particular the torque available on the spacecraft’s x-axis was relatively quite small. There was a maximum control torque of ~13 milli-Nm on the x-axis as compared to ~59 milli-Nm on the y/z axes.
- Limited magnetic torque rod output direction and magnitude causing under/over shoot or torque in undesired direction.
- There was only limited magnetic torque rod control authority. Furthermore the magnetic torque rod authority depended on the in-situ magnetic field and spacecraft orientation. Torque rod output varied during an orbit (even crossing zero or remaining near zero) and also changed from orbit to orbit.
- Only very limited control authority on the spacecraft’s x-axis when the torques from both the y-axis and z-axis torque rods are near zero.
- Significant changes to the existing TIMED spacecraft operations philosophy were required. For example, due to poor slew capability using only two wheels, the vehicle would always remain in nadir-pointing attitude and the sun-pointing attitude was eliminated.
- The TIMED reaction wheel configuration yielded very little x-axis body torque in two of the potential 2-RW configurations, so the magnetic torque rods would be called upon to primarily control the x-axis. It was further noted that another potential wheel configuration provided very little z-axis body torque.
- The autonomous switch from 3-wheel nominal control to contingency 2-RW hybrid control was complicated due to the different autonomy (i.e., fault protection) rule sets involved. The actual switch between the two control algorithms would be done automatically on-board through monitoring of the wheel health flag.
- The flight processor that hosts the attitude control flight software, the spacecraft’s Attitude Interface Unit (AIU), had virtually no code space remaining with which to implement the new 2-RW hybrid control algorithm so hosting the new 2-RW hybrid control algorithm in the AIU was precluded. An approach to change as little as possible inside the AIU was thus adopted.
- There were undesired torques acting on the spacecraft’s x-axis: both precessional torque from wheel momentum due to vehicle’s nominal orbital rotation about the y-axis and a torque from the vehicle’s residual magnetic dipole.

CASSINI HYBRID CONTROL WORKSHOP REPORT

The JPL workshop presenter addressed the engineering performed by that organization on hybrid control for the Cassini spacecraft (see Figure 4). Cassini was launched on 15 October 1997 and

after an interplanetary cruise that lasted almost seven years it entered orbit around Saturn in June of 2004. After completion of its Saturn Orbit Insertion maneuver, Cassini began a complicated set of orbits about Saturn, designed to optimize science collection over not only Saturn itself, but also its icy satellites and moons. As with other spacecraft discussed at the workshop the Cassini spacecraft has certainly demonstrated its longevity. It collected science data throughout its four-year prime mission (2004–08) and has since then been approved for an extended mission through 2017. Also like the other spacecraft addressed at the workshop Cassini carries a set of four reaction wheels: three of which are fixed orientation wheels and the fourth being a so-called “backup” reaction wheel (i.e. RWA-4) that is mounted on top of an articuable platform. If necessary, this platform could be articulated to orient the backup reaction wheel into co-alignment with the degraded wheel. As described in Reference 5 RWA-3 exhibited signs of bearing cage instability in the 2001-2002 time frame. Consequently, the mission managers decided to articulate Cassini’s RWA-4 on its platform to align it with RWA-3. Starting in July of 2003 Cassini was controlled using RWA-1, RWA-2, and RWA-4. The Cassini flight operations team has worked to carefully manage the accumulation of the wheel revolutions. However, starting from their first use in 2000 to the present, RWA-1 and RWA-2 accumulated well over 3 billion revolutions each and there are some indications of increased drag torques of those wheels’ bearings observed in telemetry. Reference 5 describes some guidelines levied on Cassini science observations to extend reaction wheel life.



Figure 4: Cassini Spacecraft

Given this situation, the Cassini mission managers proactively prepare for future reaction wheel degradations or outright wheel failures. Specifically a study was initiated to investigate the feasibility of controlling Cassini using the two remaining reaction wheels (in this case RWA-2 and RWA-4) and four thrusters to meet the science pointing requirements for two different key science operational modes.

The two remaining reaction wheels will not be able to provide precise and stable three-axis control of the spacecraft. In this study, summarized in Reference 6, the performance (e.g., the pointing control error, pointing stability, hydrazine propellant consumption rates, etc.) of the two hybrid controllers used for the two different science data taking operational modes was compared with the performance achieved using an all-thruster controller design. The strengths and weaknesses of the Cassini hybrid control architecture(s) were assessed quantitatively.

DAWN HYBRID CONTROL WORKSHOP REPORT

A representative from OSC presented a summary level talk on the Dawn hybrid control approach and its status. OSC is the DAWN prime spacecraft contractor. Dawn, a low-thrust interplanetary spacecraft (see Figure 5), was launched in September 2007 and is the ninth Discovery mission in NASA's SMD. The program is managed and the spacecraft is operated by JPL. In June of 2010, during its cruise to the asteroid Vesta, the first of its two asteroid destinations, the spacecraft experienced a high friction anomaly on one of its four Reaction Wheel Assemblies (RWAs). The RWA was taken out of the attitude control loop, and some limited testing indicated that it was likely unusable for the approaching Vesta campaign. To preserve the remaining three wheels for science operations at the asteroids, the backup Reaction Control System (RCS) thrusters were activated for attitude control for the remainder of the cruise to Vesta. Simultaneously, as a contingency against an additional RWA failure in the remaining, now non-redundant, 3-wheel complement, an effort was initiated to develop a hybrid control mode that would use only two RWAs in a mixed actuator mode together with the RCS to provide full three-axis attitude control. Compared to the existing backup all-thruster controller, this mixed actuator hybrid control mode was designed to provide better pointing with less propellant expenditure during science operations.

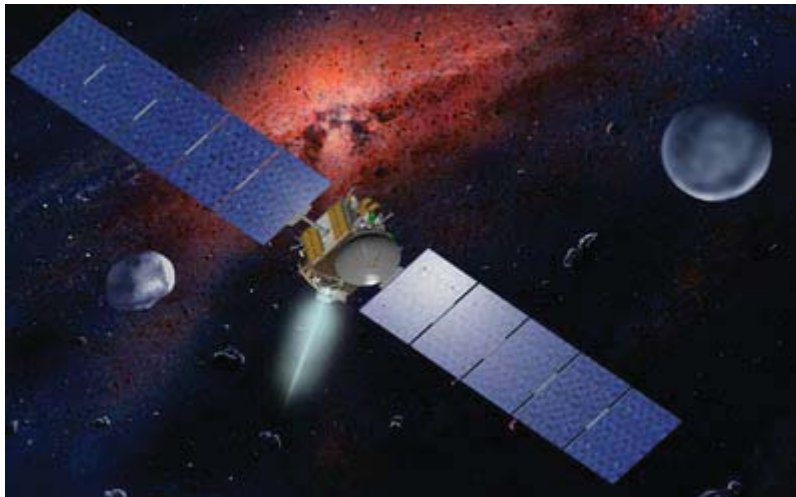


Figure 5: Dawn Spacecraft

OSC mentioned that another motivation for the development was the recognition that the root cause of the RWA anomaly was not entirely understood, and therefore it was not possible to mitigate the risk solely by imposing new operational guidelines/constraints on the remaining RWAs, as had been done on other missions. The hybrid mode needed to have the capability of performing all planned science operations with activation at any time during the mission. It also needed to be designed, implemented, and tested rather quickly, since it required a new version of the flight software that had to be loaded onto the spacecraft well before the beginning of Vesta operations.

Hybrid controller design challenges for Dawn included the requirement to maintain nominal science payload pointing, especially with the relatively large attitude rates required in the low altitude orbits, but also the requirement for maintaining a communications link to Earth with the High Gain Antenna (HGA). The latter requires relatively tight pointing (i.e., less than a degree) on the two axes normal to the HGA's boresight. It was understood that level of pointing may not be possible with only two RWAs depending on the orientation of their torque axes.

As described above a hybrid mixed actuator controller using RWAs together with electromagnetic torque rods had been developed for NASA's FUSE spacecraft, one of OSC's earlier Low Earth

Orbit (LEO) spacecraft that also experienced problems with its wheels and this design formed the basis of the Dawn hybrid controller. A similar implementation was developed for NASA's TIMED spacecraft, which as described above, is another LEO spacecraft using electromagnetic torque rods. Using high-torque thrusters instead of low-torque magnetic control imposed its own set of design challenges, particularly in the need for a low-bandwidth thruster control loop that would minimize thruster pulsing and propellant consumption while still providing acceptable pointing. The thruster control loop was also designed to minimize its coupling into the wheel control loops. The major implementation challenge was to keep changes to the existing flight software to a minimum, both to reduce testing and verification time and to avoid large-scale changes to mission operations procedures, which would impose a risk given the short time to the beginning of the Vesta campaign. Thus, a surgical approach to the flight software implementation was adopted, whereby all changes would be decoupled from the existing software to the maximum extent possible and would have no effect on normal, i.e., non-mixed mode, operations. After relatively short development, implementation, and testing phases the new version of the flight software containing the hybrid controller was uploaded to the spacecraft in early 2011, providing risk mitigation and additional mission flexibility. Dawn arrived at Vesta in May 2011 after a flyby of Mars in February 2009. After a yearlong successful science campaign at Vesta, Dawn departed for its next destination, the asteroid Ceres, with an arrival date planned for in early 2015.

At the workshop OSC described how the 2-RW hybrid controller was designed, developed and implemented on the Dawn spacecraft to provide mission flexibility for the contingency of multiple failures of the primary RWA actuators. Although the pointing performance is less than that achievable with the nominal all-wheel control scheme, it is still sufficient to meet the Dawn science objectives. Since it is a more propellant efficient mode than the backup all-thruster control, reducing the rate of consumption of a limited resource, it allows for a longer duration of the remaining mission. The hybrid controller was implemented well into the Dawn mission, retrofitted into the flight software with one of the constraints being to make it as transparent as possible to normal operations. The OSC representative described some of the operational considerations for preparing Dawn to use a hybrid actuator configuration.

References 7 and 8 provide the details of the DAWN hybrid control experiences. In particular Reference 8, which is companion Mixed Actuator Attitude Control conference session paper to this paper, provides a Dawn hybrid control update with inflight performance results included.

MARS ODYSSEY HYBRID CONTROL WORKSHOP REPORT

The Mars Odyssey spacecraft, launched on 7 April 2001, is an orbiter carrying science experiments designed to make global observations of Mars to improve our understanding of the planet's climate and geologic history, including the search for water and evidence of life-sustaining environments. Lockheed Martin Company (LMC) built and operates the Odyssey Mars Orbiter under contract to NASA, Jet Propulsion Laboratory (JPL). The vehicle has been in orbit around Mars now for well over a decade and in December 2010 it became the longest lived vehicle orbiting Mars. In addition to its science mission Odyssey's other mission is to provide communication relay for NASA's vehicles on the Martian surface. Figure 6 depicts the general configuration of the Odyssey spacecraft in its nominal nadir-pointing orientation. The primary attitude control actuators are three RWAs each aligned with the three vehicle coordinate frame axes, and a nominally inactive fourth "skew" RWA to be employed in case of failure of any one other RWA. Note the relatively long Gamma Ray Spectrometer (GRS) boom, in addition to its single-wing solar array, yields non-symmetric inertial properties for the Odyssey vehicle. This causes non-negligible gravity gradient disturbance torques.

As described in Reference 9, on 8 June 2012 the RWA-1 (i.e., the x-axis wheel) experienced a stiction anomaly causing the Mars Odyssey spacecraft to enter a safe mode. An increase in wheel bearing friction prevented RWA-1 from producing the control torque commanded by the spacecraft's Attitude Control Subsystem (ACS) which in turn allowed an attitude error to grow and exceed the safe mode entry limit. Recovery from this safe hold necessitated activation of the Skew RWA. There is no plan to attempt to use the failed RWA-1 unless another RWA failure occurs.

Shortly thereafter NASA directed JPL and LMC to initiate development of a contingency Thruster Only (all thruster) Controller and a contingency 2-RW Hybrid Controller (with thrusters for accomplishing control on one axis), to maintain three-axis control of the spacecraft in the event of a second wheel anomaly/failure. These contingency modes of operation would be required to accomplish both the nominal nadir-pointing and to maneuver/inertially hold the spacecraft to properly point its High Gain Antenna (HGA) towards Earth for data downlink communication periods once or twice a day.

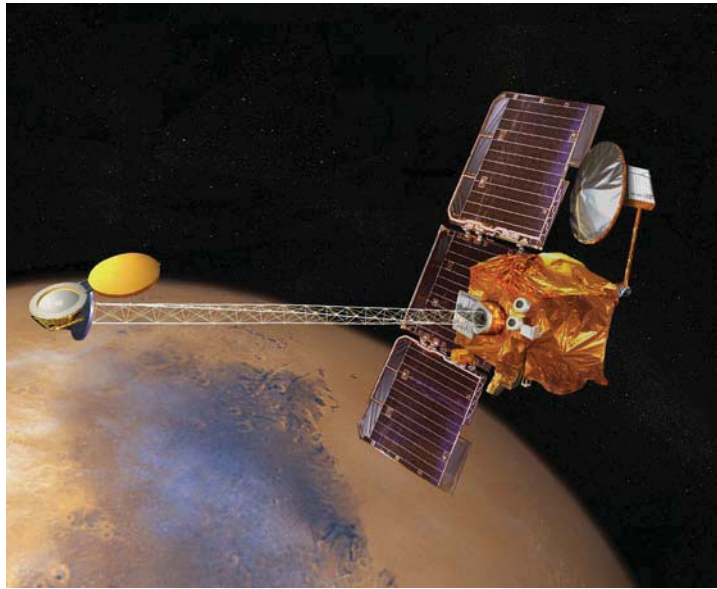


Figure 6: Mars Odyssey Spacecraft

As described in Reference 10 LMC designed a 2-RW hybrid attitude control system in which the 2 functional wheels controlled two of the spacecraft's axes and used thrusters to provide control torques for the third axis. A rotated control reference frame, called the Reaction wheel Control Plane (RCP), was employed such that the axis controlled by the thrusters is orthogonal to the wheels. A very positive implementation aspect was that the Odyssey hybrid controller could be implemented with only ACS data parameter changes, so patching of existing ACS flight software would not be required. This was primarily due to the simplicity and elegance of the baseline attitude controller architecture.

There were however some 2-RW hybrid control issues that emerged from the preliminary analyses and simulations of flying in the nominal nadir-pointing attitude. The momentum stored in each wheel typically cycles up and down as the spacecraft orbits Mars. If one of those axes is controlled by thrusters that wheel momentum cannot cycle up and down, as it is taken out immediately. There were concerns about sensitivity to thruster variations or impingement. Also it was ob-

served that precessional torque (from ‘dragging’ the RWA angular momentum vector around) induced additional thruster firings.

The relative performance, in terms of propellant consumption, of the various possible contingency control modes and actuator hardware configurations were performed. In particular the performance of the two-wheel controller was compared to the Thruster Only controller. Attempts were made to optimize the vehicle’s pitch angle to minimize the gravity gradient disturbance torque disturbance. In addition the hybrid control designers at LMC cleverly aligned the RCP with the spacecraft’s orbit plane to eliminate the undesirable RWA momentum vector precessional torques and to improve propellant efficiency.

Simulation results indicated that the thruster controlled axis would be inefficient due to the thruster configuration so hybrid control could actually be worse, in the sense of more propellant consumption, than the Thruster Only attitude control mode. At the time of the workshop it appeared that there was not much improvement to be gained via the 2-RW hybrid control mode over the Thruster Only mode at least for the nominal nadir-pointing portion of the mission. The team understood that a propellant efficient three-axis Thruster Only contingency attitude control mode, using a one-sided deadbanding approach, would eliminate the need for or any advantage of a 2-RW hybrid mode.

As mentioned earlier the hybrid attitude controller would be required to maneuver the spacecraft to the proper attitude for HGA communication with Earth and to also inertially hold that attitude for the duration of that data downlink period. Initial simulation results showed significant propellant was consumed during the HGA maneuver and inertial hold portion of the mission, when using both the Thruster Only and the 2-RW hybrid controllers. The LMC engineers were subsequently able to develop an improved, more propellant efficient, two-segment approach for maneuvering the spacecraft to the HGA communication attitude. At the time of the workshop there were indications that the greatest potential benefit was to be gained with hybrid slews to the HGA communication attitude. Further investigation of operational optimization was planned, for example re-considering the number of and the specific scheduling of the maneuvers for HGA-Earth communications.

Also further tuning of and comparison of the 2-RW and Thruster Only control modes is planned with particular attention to propellant consumption and operational complexity. One of the Odyssey team’s conclusions expressed at the workshop was that orbiting, non-symmetrical spacecraft make for non-optimal hybrid control due to a combination of precessional torques and gravity gradient torques. Lastly, it was expressed that further efficiency optimization of both 2-RW hybrid control and Thruster Only (all thruster) was probable.

KEPLER WORKSHOP REPORT

The Kepler mission (NASA Discovery Mission #10) was specifically formulated to survey a portion of our region of the Milky Way galaxy to discover dozens of Earth-size planets in or near the habitable zone and determine how many of the billions of stars in our galaxy have such planets. It is NASA's first mission capable of finding Earth-size planets around other stars. The Kepler spacecraft (see Figure 7), which flies in a heliocentric Earth-trailing mission orbit, was launched March 7, 2009 and it completed its 3.5 year prime mission in November 2012.

As described in Reference 11, the Kepler spacecraft, which was designed and built by Ball Aerospace and Technologies Corporation (BATC) of Boulder, Colorado, nominally employs a set of four (4) reaction wheel actuators to generate attitude control torques to slew, point and precisely stabilize the vehicle. A minimum of three reaction wheels is required to provide the zero-momentum three-axis stabilization of the spacecraft. Kepler employs reaction wheels very similar

to the ones flown on the TIMED mission described above.

It was noted that the TIMED reaction wheel failure occurred during the build of the Kepler RWAs and it was decided to rework the Kepler wheels prior to launch.

While there was not any significant discussion on Kepler hybrid control system design efforts at the workshop the prevailing mindset was that this mission would greatly benefit from proactively developing a two-wheel hybrid controller as a protection from another wheel failure. The BATC representative at the workshop did describe (see Reference 12) the way in which the Kepler RWA-2 performed anomalously for a period of time and then eventually failed. In July 2012, Kepler's RWA-2 friction increased beyond the control law's torque command; analysis showed friction torque of approximately 140 mN-m, up from a nominal friction torque of 20 mN-m. Since then, Kepler had continued performing normal mission pointing on the remaining three RWAs with the following mitigations: increased RWA heater set point, increased minimum speed to ensure an all ElastoHydroDynamic (EHD) bearing operating regime, bi-directional wheel spin operation, and implementation of a very propellant efficient Thruster-Controlled Safe Mode.

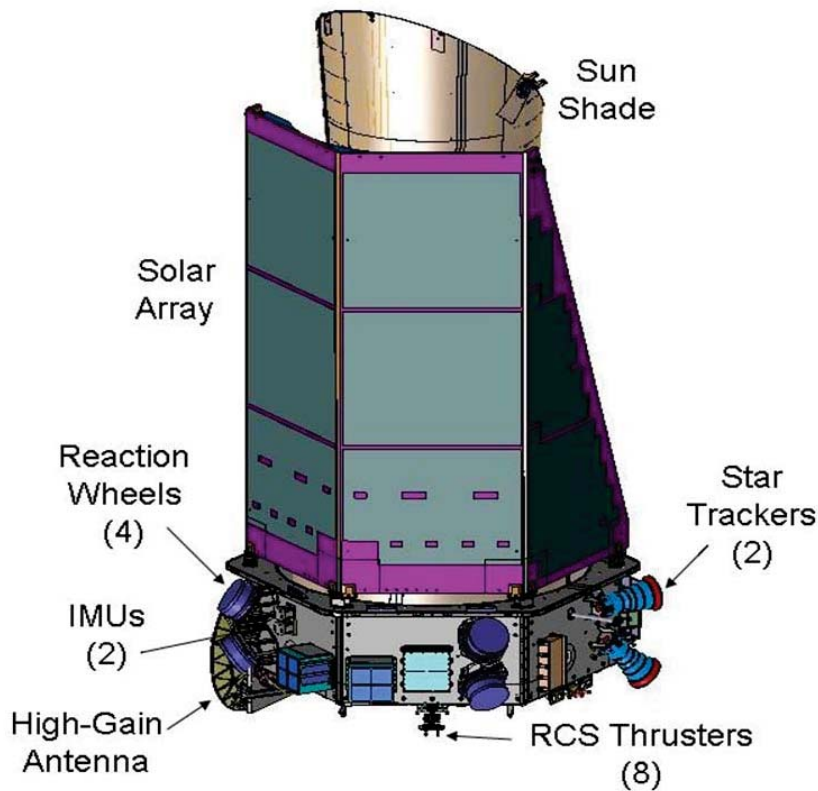


Figure 7: Kepler Spacecraft

At the workshop results were presented from a preliminary technical feasibility investigation performed by Jet Propulsion Laboratory (see Reference 13) which indicated that capability of achieving the mission's original long term pointing stability of 9 milli arc-seconds while staring at the original Cygnus science target field-of-view would not be feasible with a two-wheel (plus

thrusters) hybrid controller primarily because the minimum impulse bit of the spacecraft's propulsion subsystem thrusters was not originally sized for fine attitude control purposes.

HYBRID CONTROL LESSONS LEARNED/BEST PRACTICES FROM WORKSHOP

There were several key lessons learned and/or best engineering practices that emerged from the NASA Hybrid Control Workshop, including the following:

- The creation of a new hybrid control frame (HCF) reference frame, to permit decomposition of the RW control torques from the Thruster/MTB (alternate actuator) control torques, appears to be a good basic first step in designing a new hybrid controller.
- Hybrid control system designers should consider plotting/reporting ACS simulation results in the coordinate frame containing all the control torque from the remaining two RWAs (e.g., the TIMED "Pseudo Frame), rather than normal spacecraft body frame, to provide insights for the hybrid controller tuning process.
- There is an ACS architectural lesson learned from the TIMED hybrid control experience concerning reaction wheel control torque distribution. In the early stages of the ACS design process the analysts should consider the control torque distribution in the spacecraft body frame for all possible 2 RW combinations.
- Analysts should consider ways that wheel orientations should be optimized to balance the remaining 2-RW control torque across all three spacecraft body axes.
- There are advantages of having the 4th RWA be articulable, as was done on Cassini.
- Thruster firings in hybrid attitude control mode or all-thruster control mode creates unwanted spacecraft Delta-V which complicates the mission spaceflight navigation process.
- There appears to be limited need for the development of new, or the enhancement of existing, analytical (modeling and simulation) tools for hybrid controller design and analysis.
- Performing large angle spacecraft attitude slew maneuvers appears to be a common stressing challenge for 2-RW hybrid control.
- If a S/C has already lost one RWA then the need to minimize revolutions on the remaining RWAs is diminished.
- To avoid limitations on the available contingency hybrid control design space, and to achieve potential improvements for future mission applications, ACS designers should consider designing in provisions for the hybrid mode during the normal spacecraft development cycle.

Two other very important considerations when implementing new contingency hybrid attitude control schemes also emerges during the workshop which are worth highlighting here:

- The critical need for and the great benefits of having spare ACS flight software (FSW) table elements, telemetry elements and commands. All the spare FSW table elements, telemetry words, and commands that had been added to the ACS FSW in an early build were used by the time Orbital was done implementing their new hybrid control ACS algorithms. Having these spares made quick FSW patches safer and much easier.
- The critical need to be able to maintain the spacecraft's ACS Engineering Development Units in a FLATSAT laboratory testbed environment so that it could be connected to the spacecraft's ground system to allow testing of the new hybrid control commands, telemetry, operational scripts, operational procedures and also to perform flight controller operations training on the modified ACS.

Lastly there was a general finding regarding ACS operations for long-extended missions: For missions with significantly extended flight operations (well beyond the prime mission duration), it is particularly important for the flight operations team to identify, track/monitor, and carefully manage all on-board flight software clocks, timers, counters and other similar functions that ‘rollover’ at some point in time.

RECENT AND CURRENT INITIATIVES

Although there has been progress on hybrid control on other NASA missions (for example, in-flight performance testing of the Dawn hybrid controller has recently been performed by JPL and OSC as reported in Reference 8) the majority of the activity, at least from the author’s NESC perspective, has been focused on identifying and developing a technically feasible, well performing, operational simple and easily implementable two-wheel hybrid controller for the Kepler spacecraft.

Work on a viable Kepler two-wheel hybrid controller was greatly spurred on by the fact that shortly after the April 2013 workshop a second RWA, that being RWA-4, performed anomalously and subsequently failed. By the end of April 2013, all appropriate mitigation steps to prolong the life of Kepler’s RWA-4 had been taken. Unfortunately the wheel life extension operational mitigations described above were not sufficient to protect Kepler’s RWA-4, which had exhibited symptoms of increasing bearing friction.

At the routine communications contact on 14 May 2013, the Kepler spacecraft was unexpectedly discovered by its flight operations team to be in Thruster-Controlled Safe Mode. In this safe mode the vehicle was in a power-positive/thermally-benign orientation with the solar panels facing the Sun, slowly spinning about the sun-line. A reaction wheel anomaly review team concurred that the telemetry data appeared to unambiguously indicate a failure of RWA4. The Kepler Project Office at NASA’s Ames Research Center and the prime spacecraft contractor (BATC) then turned their collective attention to preserving the remaining propellant, attempting to return the failed wheels to service at reduced performance levels, and investigating attitude control techniques for collecting scientifically meaningful data using the combination of the two remaining functional wheels and thrusters.

As a focused follow-up activity initiated shortly after the April 2013 workshop, controls engineers at NASA’s Goddard Space Flight Center (GSFC) designed, modeled and simulated a momentum-bias based scheme for accomplishing three axis attitude control using only two reaction wheels and no thrusters. The work described in Reference 14, which is another companion Mixed Actuator Attitude Control conference session paper to this paper, was undertaken under direction and sponsorship of the NESC. It is an independent exploration of the feasibility of two-wheel attitude control on a Kepler-class spacecraft and the constraints that inevitably arise which considers the bounding problem: Can spacecraft attitude be maintained indefinitely using only two reaction wheels in the presence of solar radiation pressure torque? Since no thruster usage is a baseline assumption in this work the two reaction wheels are responsible not only for three-axis attitude control, but also angular momentum management. The intent of this work was not to propose yet another candidate control architecture, but rather to understand the conditions that any such architecture must satisfy to be a viable solution. Two complementary algorithms for inertially pointing a representative, but Kepler-like, spacecraft using the wheels only are discussed in Reference 14. The benefits of using a momentum bias are described and that paper serves to quantify and document some of the fundamental hybrid control constraints and limitations.

Reference 15 documents the work performed to date at BATC to design and develop a new two-wheel/thruster hybrid controller for the Kepler spacecraft. A second wheel failed on 11 May 2013, leaving the spacecraft with only two operational wheels, and thus unable to perform three-axis control on wheels alone. The spacecraft is equipped with a set of eight reaction control thrusters which can be used for attitude control. Reference 15, which is another companion Mixed Actuator Attitude Control conference session paper to this paper, discusses the hybrid control architecture that uses momentum biasing of the two remaining wheels and low duty cycle use of the thrusters to provide 3-axis control. It also discusses general guidelines for operating the vehicle in this mode.

In August 2013, after the failure of Kepler's second reaction wheel, the project scientist at NASA ARC issued an open call for science white papers seeking ideas to repurpose a mission for the Kepler observatory. The NESC has supported the Kepler Project Office in the process of identifying hybrid control/science observation combinations for a potential repurposed Kepler spacecraft. NESC engineers provided technical support to define attributes, preliminary performance estimates, and flight implementation challenges of the selected baseline hybrid control concept. In conjunction with the science white paper call, the NESC released, through NASA's Langley Research Center (LaRC), a NASA Request For Information (RFI) seeking new hybrid control concepts and innovative hybrid control approaches for possible application to the distressed Kepler spacecraft. The most desired alternate science operations would involve long term pointing with as much pointing stability as possible. So the challenge was to develop a two-RWA Hybrid mode that could deliver this type of operation and performance while pointed at some other science target(s).

Numerous science ideas and several concepts relevant to two-wheel hybrid control were surfaced through the combination of the science white paper call and the NASA RFI. The NESC reviewed and evaluated all the RFI responses received based on: 1) their relevance to the Kepler 2-RW hybrid control problem, 2) their likelihood of technical implementation success, and 3) their degree of operational difficulty. The NESC also planned and conducted a two-day Kepler Pointing TIM with the Kepler Project Office engineering and science leaders at NASA ARC to help them identify the best baseline approach for a repurposed Kepler spacecraft. Not surprisingly, given their in-depth knowledge of the spacecraft and its operating environment, the BATC-developed 2-RW hybrid control architecture described in Reference 15 has been adopted by the Project Office as the baseline approach for the repurposed Kepler mission.

At the time that this paper was written the Kepler Project Office at Ames was currently in the process of developing their proposal for NASA SMD for a repurposed Kepler mission called K2. The Kepler science, engineering, and flight operations teams believe this new K2 mission is technically feasible and operationally straightforward with the two remaining wheels. K2 apparently has the potential to discover many hundreds of new, small exoplanets around low-mass stars located in or near the ecliptic plane. So the key new operational and science observation constraint here is limiting the K2 science observations to science targets in or near the ecliptic plane where the Solar Radiation Pressure (SRP) disturbance torques can be carefully balanced to minimize boresight roll. Initially there was concerns this approach would be similar to balancing on a knife edge but data from some early on-orbit K2 testing shows the SRP disturbance torque profile to be more benign (i.e., not so steep) as originally suspected. However more testing will be needed to confirm this. The attitude control engineers at BATC have done enough ACS analysis, as reported in Reference 15, and the results of the few early ecliptic-plane K2 performance tests are favorable enough, to support feasibility of this hybrid control scheme. Additionally these tests have allowed the Kepler scientists to develop initial predictions of K2 photometric performance. Trade studies are planned to assess the number of targets, cadence durations, initial fields of view,

and observing strategies. If the Kepler Project's proposal is approved, it is very likely that K2 will observe many different target fields during a sequence of two-month to three-month campaigns over the next few years.

In parallel with all this activity focused on the repurposed Kepler spacecraft research into ways to control under-actuated vehicles is currently on-going at the Naval Postgraduate School (NPS) under NESC sponsorship. The topic of how to control under-actuated vehicles has been studied before (see Reference 16 for example). The researchers at the NPS are challenging the convention wisdom on spacecraft attitude control that says three independent controllers are needed for precision pointing. This wisdom not only is intuitively well-founded as three controllers span a three-dimensional space but also the concept is in agreement with fundamental mathematical theory on linear controllability. NPS maintains that nonlinear controllability (without linearization) is not only practical but it also defies intuition: a linearized system may be controllable but really be uncontrollable due to nonlinear (i.e. practical) effects. Additionally, and more importantly to the case of under-actuated spacecraft control of primary interest here, a nonlinear system may be controllable but the linearized system may be uncontrollable. Thus it is possible to get false positives and negatives on practical controllability using a linear analysis.

In Reference 17, which is another companion Mixed Actuator Attitude Control conference session paper to this paper, NPS addresses nonlinear, and hence, practical controllability without linearization using a combination of well-known and recent results in mathematical system theory. In particular, they consider the particular problem of nonlinear controllability of a spacecraft equipped with just two reaction wheels.

The application of these mathematical results to the Kepler 2-RW hybrid control problem is still ongoing at NPS. Should the results bear out, then it has the potential to offer a new solution to possibly recover the capability to perform the original Kepler mission.

SOME FUTURE CONSIDERATIONS

Beyond the lessons learned and the engineering best practices mentioned above that emerged from the workshop there are several technical areas that appear promising and which should be considered for future hybrid attitude control system applications, such as, but not limited to the following:

- Nonlinear control laws
- Nonlinear optimization
- Improved high fidelity SRP modeling
- Simple and reliable articulation platforms for re-positioning reaction wheels
- Low minimum impulse bit micro-propulsion vernier thrusters
- Linear proportional magnetic torquers

CONCLUSION

This paper describes the highlights of the first NASA Cross-Center Hybrid Control Workshop that was held in Greenbelt, Maryland in April of 2013. In support of risk/benefit assessments for Kepler, Dawn, Mars Odyssey, and other science spacecraft flight operations, the workshop gathered, captured, and disseminated GN&C engineering knowledge and lessons learned regarding contingency spacecraft attitude control techniques using only two reaction wheels. The fundamental driver for holding this workshop was to help inform and prepare the Kepler, Dawn, and

Mars Odyssey attitude control system (ACS) teams better understand the technical challenges, risks, and benefits of potential 2-RW hybrid attitude control mode operations on their spacecraft.

Given its heightened interest in the design, development, and flight implementation of mixed actuator hybrid attitude control systems for science spacecraft NASA will likely be studying past relevant experiences and evaluating new techniques for controlling spacecraft that have less than three functional reaction wheels. This interest is driven by a number of recent reaction wheels failures on aging, but still scientifically productive, NASA spacecraft as well as motivated to ensure continued longevity of NASA's scientific spacecraft fleet well past their prime mission lifetimes.

Some relevant recent and current hybrid control activities were described with an emphasis on work done in support of a repurposed Kepler spacecraft. Specific technical areas for future considerations regarding spacecraft hybrid control were also identified in this paper.

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