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NASA Workshop on Hybrid (Mixed-Actuator) Spacecraft Attitude Control

Cornelius J. Dennehy/NESC, and Nans Kunz/NESC
Langley Research Center, Hampton, Virginia

October 2014

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Space Administration

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Acknowledgments

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1.0	Initial Release	Neil Dennehy, NASA Technical Fellow for GN&C, GSFC	9/11/14

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Volume I: Technical Assessment Report

1.0 Notification and Authorization

Mr. Tupper Hyde, Science Mission Directorate (SMD) Chief Engineer at NASA Headquarters, requested the support of the NASA Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT) to plan and conduct a workshop on lessons learned and current developments in "hybrid" (mixed-actuator) attitude control mode design, test, and operations.

Mr. Neil Dennehy, NASA Technical Fellow for GN&C at the NASA Goddard Space Flight Center (GSFC), was selected to lead this assessment.

The key stakeholders were the SMD Chief Engineer and the NASA Engineering and Safety Center (NESC).

2.0 Signature Page

Submitted by:

Team Signature Page on File - 9/22/14

Mr. Cornelius J. Dennehy Date

Significant Contributor:

Mr. Nans Kunz Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
Neil Dennehy	Lead, NASA Technical Fellow for GN&C	GSFC
Nans Kunz	Co-Lead, NESC Chief Engineer	ARC
Frank Bauer	GN&C TDT Member	Emergent
Charles Bell	NASA RW Tiger Team	JPL
Dominick Bruno	Dawn ACS	Orbital
Bharat Chudasama	NASA RW Tiger Team	JPL
Brian Class	Orbital CE/ACS Peer Review	Orbital
Wayne Dellinger	TIMED ACS Lead/ACS Peer Review	APL
Bradley Haack	Mars Odyssey ACS	LMC/Denver
Noel Hughes	Mars Odyssey ACS	LMC/Denver
Jack Hunt	STEREO ACS	APL
Tupper Hyde	SMD Chief Engineer	HQ/OCE
Lloyd Keith	NESC Chief Engineer	JPL
Torraj Kia	GN&C Engineering	JPL
Jinho Kim	Messenger ACS	APL
Kenneth Lebsock	NESC GN&C TDT Deputy/Peer Review	GSFC
Allan Lee	Dawn/Cassini ACS	HQ
Glenn Macala	Kepler/Cassini ACS	JPL
David Mangus	GN&C TDT Member	GSFC
Sagar Bhatt	ISS GN&C Engineer/ACS Peer Review	Draper Labs
James O'Donnell	MAP ACS/Peer Review	GSFC
Mike Ruth	FUSE ACS/Peer Review	Orbital
John Rackozy	ACS 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
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Erin Moran	Technical Writer	LaRC/AMA
Patricia Pahlavani	MTSO Program Analyst	LaRC
Diane Sarrazin	Project Coordinator	LaRC/AMA

3.1 Acknowledgements

The significant contributions of the NASA Hybrid Control Workshop participants are recognized, in particular all the presenters: Charlie Bell, Brian Class, Wayne Dellinger, Scott Starin, Allan Lee, Sagar Bhatt, Dominick Bruno, Brett Smith, Charlie Schira, Glenn Macala, Noel Hughes, and Brad Haack. Also, Dustin Putnam and Doug Wiemer (both from Ball Aerospace and Technologies Corporation (BATC)), Eric Stoneking (GSFC), and Ken Lebsock (NESC) deserve special recognition for their post-workshop hybrid attitude control work in support of Kepler. Lastly, the contributions from the technical peer reviewers of this NESC final report are gratefully acknowledged.

4.0 Executive Summary

Since 2001, well over a billion dollars of NASA spacecraft mission assets have been rendered non-functional or placed in jeopardy due to reaction wheel (RW) failures. Some of these failures occurred prior to completion of the primary mission. Fortunately, most of the various respective project teams were able to successfully develop and implement a Hybrid Attitude Control System (ACS) that allowed these spacecraft to either return to their prime mission or at least to a worthwhile scientific productive mode. "Hybrid" in this case meaning using a combination of various ACS actuator components such as the thrusters or magnetic torquer bars (MTB) with the remaining RWs, in a way not originally planned, to maintain precision three-axis control of the spacecraft.

Currently, NASA has 57 science spacecraft in extended mission operations. Because of these aging, but scientifically productive spacecraft (and concern over more RW failures in both these existing and in future spacecraft), NASA needs to be proactive into researching possible mitigations.

Therefore, at the request of the Science Mission Directorate (SMD) Chief Engineer, the NASA Technical Fellow for Guidance, Navigation & Control (GN&C) assembled and facilitated a workshop on Spacecraft Hybrid Attitude Control. This multi-Center, academic, and industry workshop, sponsored by the NASA Engineering and Safety Center (NESC), was held in April 2013, to unite nationwide experts to present and discuss the various innovative solutions, techniques, and lessons learned regarding the development and implementation of the various hybrid ACS solutions investigated or implemented.

The fundamental driver for holding this workshop was to help inform and prepare the Kepler, Dawn, and Mars Odyssey ACS teams better understand the technical challenges, risks, and benefits of potential two reaction wheel hybrid attitude control mode operations on their spacecraft. This includes developing hybrid mixed-actuator ACS solutions to maintain productivity of these valuable spacecraft assets. Much of what was learned can be applied to the early development phase of new spacecraft in addition to extending the productive life of the existing spacecraft.

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.

This report attempts to document these key lessons learned with the 16 findings and 9 NESC recommendations provided in Section 8.

The primary findings generated by this workshop included:

- The spacecraft RW failures reviewed in the workshop all, with one exception[1],have been on a single make and model of RW (the Ithaco[2] Type-B RW, which uses stainless steel ball bearings). Significant analysis, test, and evaluation have been performed, by NASA, industry, and the RW provider and they have found multiple failure modes and proximate causes of the Type-B RW failure. However, there was not a 'single' as-built version of the Ithaco Type-B RW; each Type-B RW was of common overall design, but unique in details, such as lubrication, bearings, bearing preload, etc., varied. Therefore, a common root cause of the Type-B RW failures has remained elusive and has not been determined. This information came from the NASA RW Tiger Team's report at the workshop.
- Hybrid (mixed-actuator) attitude control techniques have successfully served to maintain three-axis attitude control and extend science productivity of several NASA spacecraft (including Far Ultraviolet Spectroscopic Explorer (FUSE), Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED), Cassini, and Dawn) that suffered multiple RW in-flight anomalies/failures.
- Of the seven spacecraft discussed in the workshop, there was a range of hybrid control implementation challenges. In some cases, hybrid control was relatively easy to implement and on other spacecraft it was much more difficult to implement. The degree of difficulty in successfully implementing contingency hybrid attitude control is strongly influenced by the mission's operational requirements (e.g., pointing stability), the spacecraft's physical configuration, and the ACS and command and data handling (C&DH) (Avionics) subsystem architectures and design attributes. The available flight processor resources and the flexibility in the ACS flight software (FSW) architecture are particularly important in this context.
- Hybrid control implementation risk was reduced for those cases where FSW testbeds and/or hardware-in-the-loop (HITL) FlatSat testbeds could be employed to validate hybrid controller FSW patches before uploading to the vehicle and executing.
- Robotic science spacecraft typically have at least one all-thruster attitude controller as part of their ACS baseline design, but these controllers were not designed for long-term propellant-efficient precision pointing control or large angle attitude slewing. These all-thruster attitude controllers must be redesigned or, at a minimum, retuned, if they are to be useful as part of a contingency hybrid attitude control scheme, which will reduce the mission lifetime due to increased propellant usage.

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[1] A single Ithaco Type-A wheel failed on the Mars Odyssey spacecraft.

[2] The Type-B reaction wheels (RW) trace their design and manufacturing heritage directly back to the Ithaco Company, which was the original designer of this particular class of RW. In this report, consistent with common practice in the community, the vendor of the Type-B RW will simply be identified as "Ithaco."

- The existing ACS modeling, simulation and analysis tools appear to be adequate for supporting the design and development of new hybrid ACSs.
- Performing large-angle spacecraft attitude slew maneuvers (for science observation re-orientations, science data downlink communications, power/thermal management purposes, etc.) is a common stressing challenge for contingency two RW hybrid control systems.
- The impacts on the baseline spacecraft fault management/safing/safe mode subsystem need to be carefully considered as part of any contingency hybrid attitude control design implementation.
- There have been, and most likely will continue to be, opportunities for performing low-risk on-orbit validation testing of specific hybrid controller concepts on spacecraft nearing the end of their operational lifetimes. An opportunity was missed for performing just such testing on the Microwave Anisotropy Probe (MAP) spacecraft prior to its decommissioning.
- While there may be some common aspects/attributes in the various hybrid control systems implemented to date, it appears that each spacecraft implementation needs to be unique. This makes it difficult and problematic to accurately extrapolate from one set of spacecraft hybrid control system performance metrics to another.
- There are significant differences in the application of hybrid control to spacecraft flying in low Earth orbit (LEO), Mars orbit, flyby trajectories, and/or in orbit around asteroids/small bodies. For example, while spacecraft flying in Mars Orbit must contend with similar environmental disturbances (e.g., gravity gradient torques) as those spacecraft flying in LEO, they lack the advantage of an *in-situ* magnetic field that could be used to generate attitude control torques with the use of an MTB actuator.
- The attitude control engineering practice, as resurrected from the 1960s, of establishing, with the two remaining functional RWs, a momentum bias on the vehicle to provide a gyroscopic restraint about two of the spacecraft axes could form the basis of an efficient hybrid attitude control scheme.

The NESC recommendations that emerged from this workshop included:

- Hybrid (mixed-actuator) attitude control techniques should be considered as a means to recover three-axis attitude control and extend productivity of spacecraft that have experienced RW in-flight anomalies/failures.
- Based on the data presented at the workshop, future NASA missions should avoid using the Ithaco Type-B RW until such time as the root cause of the failures can be been determined and adequate corrective measures can be implemented for this particular make/model of wheel.

- ACS design engineers should perform architectural considerations, of both hardware and software attributes, early in the system conceptual design phase to facilitate hybrid control implementations in the later stages of mission life. Considerations of RW, MTB, and thruster placements and geometric orientations from a potential hybrid control perspective are particularly important, as are considerations of the ACS FSW architecture's flexibility to permit the incorporation of a hybrid controller in the later stages of mission life.
- ACS design engineers should ensure spacecraft fault management/safing/safe mode aspects are carefully considered when designing new hybrid control modes.
- Programs and projects should maintain their ACS FSW testbeds, and/or their HITL FlatSat testbeds, for both hybrid control system development and implementation risk reduction, and for flight-readiness recertification purposes.
- When designing a two-RW-based spacecraft hybrid control system, ACS design engineers should consider the potential advantages of employing a bias-momentum (versus a zero-momentum) approach, similar to what was successfully implemented on the re-purposed Kepler K2 spacecraft.
- The investigation zero propellant maneuver/optimized propellant maneuver (ZPM/OPM) hybrid attitude control approaches for performing large-angle attitude slews, using two RWs only, of the type performed to reorient the spacecraft for science observations and for achieving Earth-oriented attitudes for science data downlink communications. Missions such as Kepler and Mars Odyssey, which both have large angle attitude slew requirements, would benefit from having a ZPM/OPM hybrid control capability that could perform large spacecraft reorientations with only two RWs.
- On-orbit spacecraft, for which hybrid attitude controllers have been designed, should conduct on-orbit testing of these hybrid controllers at their end of life for existing spacecraft prior to decommissioning.

5.0 Assessment Plan

The SMD Chief Engineer requested the support of the NASA GN&C TDT to plan and conduct a workshop on lessons learned and current developments in hybrid attitude control mode design, test, and operations. A hybrid attitude control mode is one in which the spacecraft has lost the use of one or more of its RW complement such that there are less than the typically needed three functional operating RWs remaining. The Dawn and Mars Odyssey spacecraft are considering the use of such a hybrid contingency attitude control mode. Several other spacecraft have been analyzed or operated in this mode in the past, and the SMD Chief Engineer requested the cross-Center engineering lessons learned in this particular GN&C area to be shared amongst the subject matter experts from across NASA.

6.0 Workshop Description

The primary motivation behind holding the workshop was to identify and capture lessons learned 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.

There are several other missions that may be facing reaction wheel failures as they age. For this assessment, the NASA Technical Fellow for GN&C (assisted by members of the GN&C TDT) focused on NASA's historical experience with contingency spacecraft attitude control using only two reaction wheels and examined the technical feasibility of two wheel contingency attitude control for a selected number of NASA's science spacecraft. The contingency attitude control included hybrid attitude control modes of operation in which reaction control thrusters and/or magnetic torquers are combined with the two remaining wheels to provide three-axis attitude control.

In support of risk/benefit assessments for Kepler, Dawn, Mars Odyssey, and other science spacecraft flight operations, a workshop was held April 2 and 3, 2013, to gather, capture, and disseminate GN&C engineering knowledge and lessons learned regarding contingency spacecraft attitude control techniques using only two reactions wheels in combination with other reaction forces/torques.

6.1 Workshop Goals

Currently, NASA has 57 science spacecraft in extended mission operations. Because NASA has many aging, but still scientifically productive spacecraft, coupled with a number of recent RW failures, a heightened interest has been spurred within the Agency for the design, development, and flight implementation of mixed-actuator hybrid systems. These hybrid systems serve to maintain three-axis attitude control and extend science productivity of the spacecraft that suffer RW in-flight failures. Examples of these include Kepler, Dawn, Mars Odyssey, Cassini, and TIMED. Hybrid control is envisioned as a general means to ensure the continued longevity of

NASA's scientific spacecraft fleet well past their prime mission lifetimes and into productive extended science mission operations.

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 two reaction wheel 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.

More generally speaking, 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) RWs on missions such as Dawn, Mars Odyssey, and Kepler. 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 a secondary NESC goal for this workshop.

6.2 Workshop Objectives

The key objectives of this workshop were to:

1) Review recent on-orbit reaction wheel failures.
2) Discuss the ways in which the two remaining reaction wheels can be used for contingency three-axis attitude control in a hybrid (mixed-actuator) mode of operation.
3) Review hybrid attitude control past experiences, to include redesign, analysis and implementation details (e.g., specific attitude control law modifications).
4) Capture key lessons learned from historical experiences with hybrid attitude control.
5) Discuss the constraints on and limiting factors for hybrid attitude control and review what is technically feasible with only two reaction wheels.
6) Discuss the risks of implementing hybrid attitude control.
7) Discuss the current state of the Kepler, Dawn, and Mars Odyssey spacecraft reaction wheel attitude control capabilities.
    - Is there an imminent risk of another reaction wheel failure?
    - Are there spacecraft-unique aspects to implementing hybrid control on any of these spacecraft?
8) Discuss the technical risks/benefits (including a consideration of the degree of difficulty) of implementing two reaction wheel hybrid attitude control on the Kepler, Dawn, and Mars Odyssey spacecraft.

6.3 Workshop Approach

Therefore, in April 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 focused on both the Agency's historical experience with contingency spacecraft three-axis attitude control using only two reaction wheel units and some current relevant activities. The 2-day workshop also focused on the technical feasibility of two wheel contingency attitude control for three particular NASA science spacecraft: namely Dawn, Mars Odyssey, and Kepler. In this context, two reaction wheel 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 wheels on a given spacecraft to provide the requisite set of required attitude control torques.

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 RWs. As shown in Section 3 of this report, 28 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. Figure 6.3-1 is a group photograph of the workshop participants.

Figure 6.3-1. Group Photograph of NASA Hybrid Control Workshop Participants

By definition, none of the briefings contained any of their organizations' proprietary, confidential, or trade secret information. The Orbital Sciences Corporation (Orbital) and Johns Hopkins University (JHU) Applied Physics Lab (APL) each provided some hybrid control historical perspective by describing their successful contingency operations for the FUSE and TIMED spacecraft, respectively. Orbital 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 inflight RW failures. Orbital, Lockheed Martin Corporation (LMC), and NASA described their work on hybrid control techniques for Dawn and Mars Odyssey. Engineers from the Jet Propulsion Laboratory (JPL) described their hybrid control work on Cassini and presented the results of a preliminary hybrid control feasibility study for Kepler. The Ball Aerospace and Technologies Corporation (BATC) representative to the workshop provided an overview of the Kepler ACS and described the history of RW anomalies on Kepler. In the following subsections of this report, a very brief summary will be provided on each of the above topic areas covered during the workshop.

7.0 Workshop Presentation Summaries and Discussion

In the following sections, the high-level information extracted from the technical materials presented at the NASA Hybrid Attitude Control Workshop is summarized. The actual workshop presentations are included in the Appendix. Key information on each of the missions/spacecraft is captured in tabular form in Section 7.1 for easy reference for the reader.

7.1 Summary of Workshop Presentations

NASA Mission							
	FUSE	TIMED	MAP	Cassini	Dawn	Kepler	Mars Odyssey
Nominal purpose of mission	Space Science: Collection of high-resolution spectra in the far ultraviolet wavelength	Earth Science: Investigating the energetics and dynamics of the Mesosphere and Lower Thermosphere/ Ionosphere (MLTI) region	Space Science: Explorer-class follow-on mission to the Cosmic Background Explorer (COBE) making fundamental cosmology measurements	Space Science: Explore the Saturn System	Space Science: Study protoplanets to understand the role of size and water in determining the evolution of planets	Space Science: Survey our region of the Milky Way galaxy to discover Earth-size and smaller planets in or near the habitable zone	Space Science: Mapping amount and distribution of chemical elements on Martian surface
Total Primary Mission Cost (2014 dollars)	~$360M	~$507M	~$220M	>$2B	~$450M	~ $650M	~$350M
Presenter	Brian Class (Orbital)	Wayne Dellinger (APL)	Scott Starin (GSFC)	Alan Lee (JPL)	Dominic Bruno (Orbital)	Charles Schira (Ball) & Glenn Macala (JPL)	Noel Hughes & Bradley Haack (LMC)
Mission Regime	LEO with i = 25 degrees	LEO with i = 74.1 degrees	L2 orbit (the second Sun-Earth Libration point)	Interplanetary cruise, then orbiting Saturn	Interplanetary cruise, then orbiting Vesta and Ceres	Heliocentric Earth-trailing orbit	Mars Orbit

NASA Mission							
	FUSE	TIMED	MAP	Cassini	Dawn	Kepler	Mars Odyssey
Prime Mission Life	3 years	2 years	2 years at L2	7 year cruise phase, 4 year prime science mission	8 years	3.5 years	32 months, 10 years extended mission
Launch Date	June 1999	December 2001	June 2001	October 1997	September 2007	March 2009	April 2001
First RW Failure	November 2001	February 2007	No wheel failures	2001	June 2010	July 2012	June 2012
Second RW Failure	December 2001	N/A	N/A	N/A	August 2012	May 2013	N/A
RW Number, Make & Model	Four Ithaco Type-B	Four Ithaco Type-B	Three Ithaco Type-E	Four L-3 R-15	Four Ithaco Type-B	Four Ithaco Type-B**	Four Ithaco Type-A
Was Prime Mission duration met prior to the failure of the first RW?	No	Yes	N/A	N/A	No	No	Yes
Was hybrid control developed successfully?	Yes ($)	Yes	Yes	No	Yes ($)	Yes ($)	No

NASA Mission							
	FUSE	TIMED	MAP	Cassini	Dawn	Kepler	Mars Odyssey
Does or did Hybrid mode implemented meet original mission pointing/ACS?	Yes	Depends which RW fails next	N/A	N/A	Yes	No	No
Does or did Hybrid mode implemented allow for continued successful science productivity?	Yes	Yes	N/A	N/A	Yes	Yes	No
What is hybrid actuator configuration?	2 RWs + MTBs	2 RWs + MTBs	2 RWs + Thrusters	2 RWs + Thrusters	2 RWs + Thrusters	2 RWs + Thrusters	2 RWs + Thrusters
Status as of Workshop	The last RW on FUSE failed in July 2007, and mission was terminated in September 2007.	As of Jan 2008 APL designed, developed, ground and flight tested new algorithms for Timed hybrid control. Autonomous switch into hybrid	Lost opportunity to perform on-orbit test of hybrid control prior to MAP decommissioning	Cassini was functioning on three RWs. Preliminary feasibility study of hybrid control performed	Planning for in-flight tests of the hybrid control	Functioning on three RWs: two normally operating ones and one anomalous wheel	Trade study to evaluate hybrid controller versus all-thruster controller not completed.

NASA Mission							
	FUSE	TIMED	MAP	Cassini	Dawn	Kepler	Mars Odyssey
		mode will occur should a second wheel fail.					
Current status (as of date of this report): if changed from above: no changes or short description of changes	No Change	No Change	No Change	No Change	In-flight tests of the hybrid control system successfully performed.	Suffered second wheel failure and is now flying on a hybrid mode controller as the re-purposed K2 mission	A fuel efficient all-thruster attitude control mode was selected
Special note or summary: short description of any key points not covered above	N/A	N/A	N/A	N/A	Both RW-3 and RW-4 wheels have failed and they will not be powered either on again during remainder of prime mission.	K2 is collecting scientifically meaningful data under hybrid control	The all-thruster contingency attitude control mode will be used in case of second RW failure

* RW-3 exhibited bearing cage instability anomaly, RW-3 is not considered a failed wheel.
****** The version with modified housing with electronics on opposite side.
$ Successful implementation of hybrid control allowed mission to continue.

7.1.1 NASA RW Tiger Team Presentation Summary

RW technology is a widely and commonly applied approach to provide spacecraft attitude control torque and momentum management functions. RWs provide the physical means to rotate a spacecraft, based on the principle of angular momentum transfer and Newton's Third Law of action–reaction. RWs are frequently used for the purpose of stabilizing, slewing/orienting, and precision pointing spacecraft platforms in a low-jitter inducing mode without using any non-consumables. A typical RW actuator consists of a rotating inertia flywheel, a wheel suspension system (which is almost exclusively lubricated bearing balls), a wheel drive motor, and wheel drive electronics, all encased in a wheel housing/enclosure. RWs are used in Earth and Mars orbiting spacecraft, as well as on interplanetary vehicles. Most often, a complement of four identical RWs, physically mounted on the spacecraft in an optimized geometric arrangement, is used to provide a redundant (4-for-3 configuration) three-axis attitude control capability on spacecraft. In rare cases, some high-value spacecraft employ more than four RWs: for example, the NASA Class A James Webb Space Telescope observatory will fly with a complement of six RWs. Conversely, there are cost/mass/powered constrained missions that fly a non-redundant RW hardware configuration consisting of only three RWs.

RW life is driven primarily by the suspension system performance, i.e., the bearing/lubricant lifetime. Flight experience has shown that bearing and lubricant life are highly dependent on the manner in which a given RW is assembled and tested as well as the shock and vibration dynamics exposure it receives during the relatively brief launch event, how it is operated in-flight, and the nature of the wheel's long-term *in situ* mission thermal environment. A minimum of three RWs is required to provide the zero-momentum, three-axis stabilization of the spacecraft. Therefore, a failure of one on-board RW (out of a four-wheel configuration) can typically be tolerated and three-axis spacecraft attitude control maintained. The failure of two wheels, on a spacecraft with a four-wheel configuration, poses a significant challenge for accomplishing some (most likely, degraded) form of three-axis attitude control. This usually results in an inability to meet the Level 1 science requirements of the mission.

In early 2007, NASA formed a RW Tiger Team to investigate a concerning number of RW anomalies and failures occurring on spacecraft flying the Type-B RWs. These Type-B RWs trace their design and manufacture heritage directly back to the Goodrich Company (acquired by United Technologies Corporation in 2011) and before that, to the Ithaco Company, which was the original designer of this particular class of RW and was acquired by Goodrich in 1999. In the remainder of this report the vendor of the Type-B RW will be identified as "Ithaco," since as mentioned above, the original design of this wheel originates from that company and the wheel is commonly referred to using the Ithaco name. At that time (2007), the driver for forming the team was to assess the risk of using the Ithaco Type-B RWs for the Dawn mission, which was approaching its launch date. The Tiger Team's primary charter was to review design, perform fault tree analysis, identify problem areas, and provide recommendations to minimize risks. Other, additional responsibilities of the team were to review the application/design of the Type-B

RW and to assess risk for Dawn, Kepler, Orbiting Carbon Observatory, ST-8, and other NASA missions using the same type of Ithaco RWs.

The NESC was a member of this JPL-led NASA RW Tiger Team and directly participated in the investigations and deliberations of this team. Tiger Team members were selected to get the best expertise available within the Agency and to assure Agency-wide cooperation and knowledge dissemination. The NASA RW Tiger Team membership was primarily drawn from JPL, Goddard Space Flight Center (GSFC), the NESC, The Aerospace Corporation, the JHU APL, and the Goodrich Company (i.e., the Type-B RW vendor at that time). It should be noted that, in parallel with supporting the NASA Tiger Team, the NESC performed an independent risk assessment of the Kepler RWs.

As described at the workshop by the JPL co-chairperson of the NASA RW Tiger Team, the team was initially concerned in their Phase I work with evaluating failures of RWs designed and manufactured by Ithaco on the TIMED and FUSE spacecraft so as to obtain a better understanding the reliability of the wheels to be flown on the Dawn and Kepler spacecraft. It was mentioned at the workshop that the Kepler ACS design included RWs similar to the ones flown on the TIMED spacecraft. The TIMED RW failure occurred during the build of the Kepler RWs, and it was decided by the project, with the recommendation of the NASA Tiger Team, to rework the Kepler wheels prior to launch. The Tiger Team also was interested in understanding the operation of the wheels on the Fermi (formerly Gamma-ray Large Area Space Telescope (GLAST)) spacecraft, as there have been no wheel anomalies encountered during the Fermi mission. Early on, the Tiger Team's focus was on identifying and implementing design improvements for the Type-B RW. In the 2007 to 2008 time period, a database was created to capture the attributes and details of the individual RW anomalies and failures recently experienced on NASA, Air Force, and commercial spacecraft.

More recently, in subsequent phases of its activity, the Tiger Team's charter was expanded to first update this database to include all available critical parameters and, secondly, to perfume a comprehensive study of the information contained in the database to establish trends and correlations to enhance NASA's ability for early RW problem detection so that proactive corrective actions could be executed in a timely manner. The team also worked to develop a set of in-flight operational recommendations for the Ithaco Type-B RWs that would serve to maximize mission life based on history, usage, elastohydrodynamic (EHD) parameters, lubrication characteristics, operating temperatures, thermal cycles, exposure to dynamic environment, and other such parameters.

The JPL team co-chairperson reported at the workshop that one of the key performance metrics tracked and analyzed by the Tiger Team was the accumulated number of wheel revolutions (i.e., wheel cycles) prior to the first occurrence of an anomaly or failure. Based on an analysis of the wheel revolutions at failure information in the team's database, the Dawn single-RW probability of success was calculated in October 2008 to be at ~0.83 at <2 billion revolutions. With the support of the Tiger Team, the Dawn project developed an approach to reduce wheel revolutions, as well as an operational workaround should more than one RW fail. In actuality, two of the Dawn RWs began to act anomalously at fewer than the predicted number of revolutions. At the workshop it was reported that the Dawn RW-4 unit anomaly occurred at 0.52 billion revolutions and the Dawn RW-3 unit anomaly occurred at 1.07 billion revolutions. It was also mentioned that the Mars Odyssey RW-1 exhibited anomalous drag at "a few billion revolutions." It was noted that the Mars Odyssey project does not keep precise track of wheel revolutions. Lastly, it was mentioned that the Kepler RW-2 unit failed at 1.3 billion revolutions.

For all the spacecraft reviewed in the workshop, all the RW failures have been on a single wheel model, the Ithaco Type-B RW. The root cause of these particular RW failures has not been determined. Much analysis, test, and evaluation has been performed by both the NASA Tiger Team and the RW vendor, but the root cause remains elusive.

During the period from 2007 to 2013, the NASA RW Tiger Team served as a resource for all NASA projects: projects were informed by the team of its most up-to-date understanding of desirable design and operational best practices, with updates as appropriate. The Tiger Team intends to develop a "Reaction Wheel Design and Operations Guideline" handbook-type document for project teams for all project phases.

It was also mentioned at the workshop that the NESC has reconstituted a cross-Agency team of subject matter experts to conduct its own independent assessment underway to analyze and test typical classes of RW bearings under realistic operational conditions. Led by the NASA Technical Fellow for Mechanical Systems, the purpose of this assessment is to 1) identify best practices and advance recommendations intended to impact the design, operation, and mission lifetime of RWs, not only the Type-B wheels, but other RWs as well, based on key parameters identified in the database and results obtained from bearing testing, and 2) perform an independent evaluation of the design and performance of the Moog-Bradford RW used on several European Space Agency (ESA) spacecraft.

7.1.2 FUSE Workshop Presentation Summary

Orbital presented a summary-level presentation on the work Orbital and JHU APL engineers performed in 2004, to design and implement a hybrid ACS for the FUSE satellite. The FUSE spacecraft (see Figure 7.1.2-1) was launched into orbit in June 1999 and began a 3-year prime mission to collect high-resolution spectra in the far ultraviolet wavelength. FUSE flew in a circular LEO, approximately 725 km in altitude, with an inclination of 25 degrees and with an orbital period of slightly less than 100 minutes. Like most zero-momentum three-axis stabilized spacecraft, FUSE employed a RW-based ACS. The spacecraft was equipped with a set of four RWs. Two and a half years after launch, mechanical failures of two out of four RWs reduced the satellite to two-axis control, halting science observations.

In November 2001, the yaw RW on FUSE suffered dramatically increased drag and ceased spinning, but science operations continued with the redundant skew RW controlling yaw. In December 2001, the pitch RW also suffered a similar failure, leaving the spacecraft with only two axes of control. The FUSE spacecraft's zero-momentum three-axis stabilized ACS was reconfigured to use the remaining two functional RWs 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 restart both the yaw and pitch RWs 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. The interaction of MTBs with the Earth's geomagnetic field had been used since the 1960s to provide attitude control for momentum bias spacecraft (see reference 1), 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 until this time had only been applied to missions where the tolerances for attitude control were at the relatively coarse 1-degree pointing level.

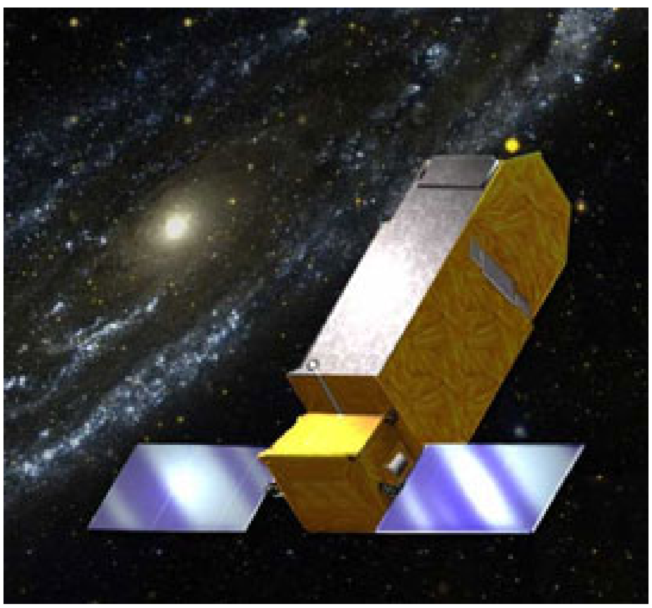


Figure 7.1.2-1. FUSE Spacecraft

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 RWs. 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. The 25-degree inclination of the FUSE orbital plane placed geometrical constraints on the use of magnetic control. The direction of the Earth's magnetic dipole is almost constant in the Earth frame at 11.5 degrees from its spin axis. In a low inclination orbit, a spacecraft will not see as much variation in the local magnetic field direction as it would in a higher inclination orbit. In a polar orbit, there will be a lot of inertial turning around of the field over an orbit. In that polar orbit case, there would be more opportunities to create a magnetic torque in any desired direction. In a low inclination Earth orbit, the magnetic torqueing takes longer because it is less efficient.

After the second permanent RW failure in December of 2001, 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 RW failures prompted modification of the FUSE ACS FSW to restore three-axis control using a hybrid configuration of existing magnetic and RW actuators. Pointing accuracy and stability were once again accomplished at the sub-arc second level, close to the pre-wheel failure performance, and momentum control was still automatically handled. The range of stable attitudes at any given time was limited, but a new ground-based software model was developed, which directed the spacecraft observation planning process such that the observations and maneuvers stay within the limits of the actuators. Even in the face of 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 December of 2004, the roll wheel permanently failed, leaving just the skew wheel and magnetic torque rods for control. FUSE was again able to be used in science operations, but at a reduced pointing accuracy of a couple of arc-seconds. Additionally, the momentum unloading had to be performed via science target selection and swapping, wherein one target would load momentum and the other would unload momentum. At this time, the FUSE team also had to make substantial changes to the safe mode and implemented a number of different modes to use at various times given different initial conditions. There was no longer one “best” safe mode. It was dependent upon a couple factors that were analyzed on-board at the time of the fault.

In July 2007, FUSE's final working RW (i.e., 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 2 and 3 contain the details of the FUSE hybrid control design and development process for both two and one reaction wheel configurations.

7.1.3 TIMED Workshop Presentation Summary

As part of NASA’s Solar Connections Program, the TIMED mission has the primary objective of investigating and understanding the energetics and dynamics of the MLTI region. Launched on December 7, 2001, the TIMED spacecraft was built and is operated for NASA by the JHU APL. TIMED is a 600-kilogram spacecraft (see Figure 7.1.3-1) 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 2 years, and the mission has since been granted multiple mission extensions.

As described in reference 4, the RW-1 unit on the TIMED spacecraft exhibited an increase in running friction on February 15, 2007, and it was autonomously removed from the attitude control loop. Several attempts to restart RW-1 were unsuccessful. This failure of RW-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 redesign the baseline attitude controller to implement a two reaction wheel/magnetic torque rod hybrid hybrid-control approach similar to what was done on the FUSE mission. The team's objective was to develop and test the attitude control FSW modifications (i.e., "patches") prior to a subsequent wheel failure.

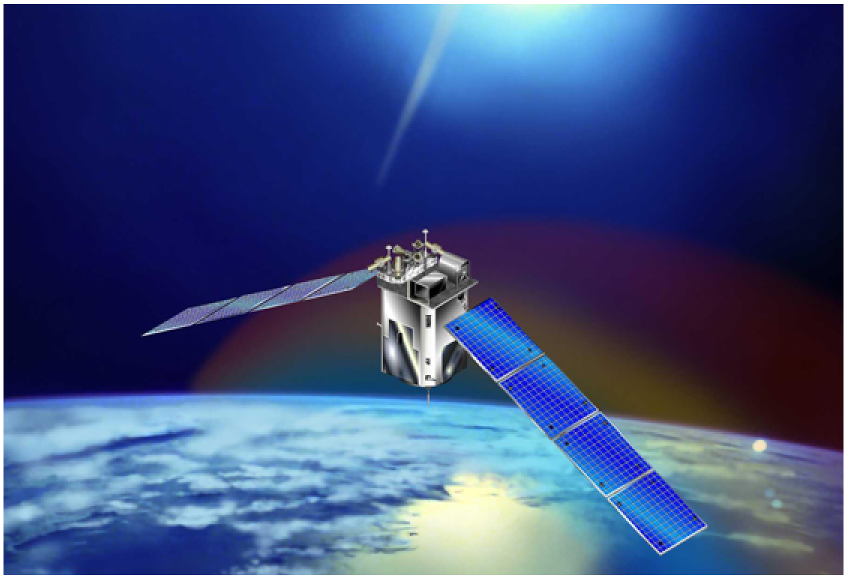


Figure 7.1.3-1. TIMED Spacecraft

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 an "on" (fixed full dipole command) and "off" (zero dipole command) manner, 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. This was done in a manner similar to how reaction control system (RCS) thrusters are typically used. The significant difference here 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 conceptual similarity between deep space mission hybrid control applications using thrusters and LEO mission hybrid control using MTBs.

As described in detail in reference 5, some of the key design challenges to and/or lessons learned by the JHU APL team working the TIMED hybrid control problem were among the following:

- Any two RWs 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 with ~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 changed from orbit to orbit.
- Only very limited control authority on the spacecraft's x-axis when the torques from both the y- and z-axes 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 RW configuration yielded very little x-axis body torque in two of the potential remaining reaction wheel 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 three-wheel nominal control to contingency two wheel 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 FSW, the spacecraft's attitude interface unit (AIU), had virtually no code space remaining with which to implement the new hybrid control algorithm, so hosting the new 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.

Therefore, in summary as described at the workshop, following the failure of a RW the APL team developed, uploaded, and tested new algorithms for hybrid attitude control for TIMED. These hybrid control algorithms were successfully tested for a duration of one orbit in January 2008. APL has configured the onboard ACS FSW to perform an autonomous switch to the hybrid mode controller should a second wheel fail.

The hybrid control analysis performed by APL reveals that maintaining sufficient ACS performance with hybrid control to meet the TIMED mission's science requirements will depend on which RW fails next. There are two configurations where it appears, based on simulation and limited on-orbit testing, that TIMED spacecraft will be able to meet the ACS pointing requirement of 0.5 degrees most of the time (>94% of the time) under hybrid control. If the wrong wheel fails, then ACS pointing requirements are met only 70 to 80% of the time. In all cases, attitude control is maintained, but errors in the 2-degree range may occur for the latter, worst-case two-wheel configuration. APL chose to test the best combination of two wheels, and during this one orbit, the ACS pointing requirements were met.

7.1.4 MAP Workshop Presentation Summary

GSFC presented their contingency attitude control strategy for completing the mission with only two operable reaction wheel which was developed prior to launch. What was designed was hybrid in the sense that it depended on use of both thrusters and wheels. However, in this scheme the thrusters would not be used at the same time as reaction wheels. Rather, the different attitude control actuators were to be used purely in a sequential manner: first establish the momentum bias in the wheels with thrusters, then operate for several days controlling spacecraft nutation with two reaction wheels to achieve the desired scan profile needed for science data-taking. The MAP experience was included in the workshop since the innovative use of two wheels and a momentum bias for contingency attitude control was highly relevant.

The MAP mission was a NASA Explorer-class mission managed by NASA/GSFC that launched in June 2001 to make fundamental measurements of cosmology. MAP was a follow-on mission to the COBE mission, and it collected science data from an orbit near the second Sun-Earth Lagrange (libration) point (i.e., the L2 point).

Due to the project's limited mass, power, and financial resources, a traditional reliability concept including fully redundant components was not feasible for MAP. Instead, the MAP spacecraft design (Figure 7.1.4-1) employed selective hardware redundancy in tandem with contingency software modes and algorithms to improve the odds of mission success. For example, a non-redundant hardware configuration consisting of only three RWs was flown on MAP. As described by the GSFC presenter, the MAP Observatory nominally uses three RWs for most of its attitude control requirements. In the event of a failure of one of the three RWs, it would not be possible to achieve full, three-axis control using the remaining two wheels. The MAP spacecraft did have attitude control thrusters fueled by hydrazine propellant.

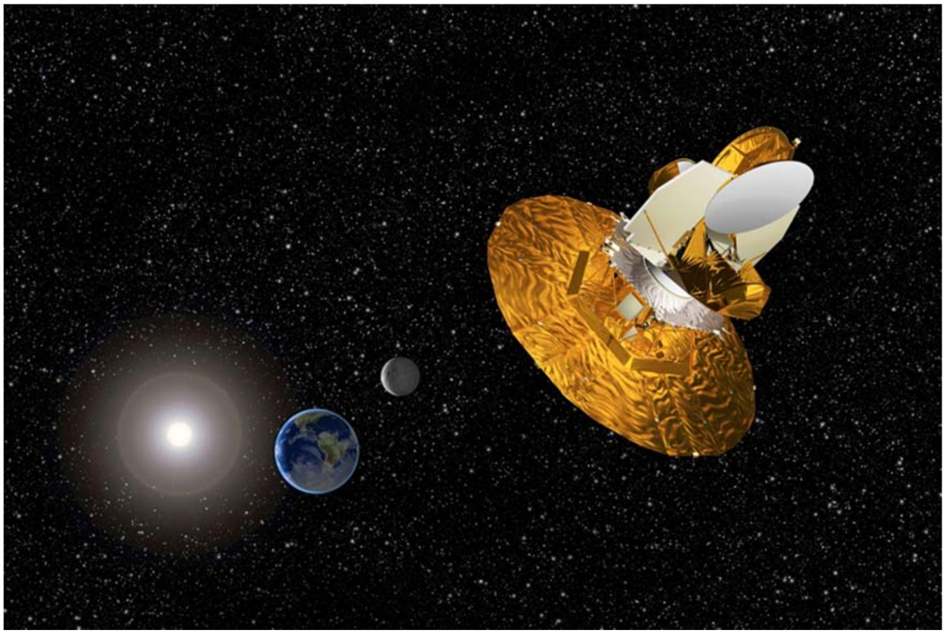


Figure 7.1.4-1. MAP Spacecraft

During early design phase of the MAP Observatory, a system-level cost-benefit analysis led to the elimination of a redundant fourth RW from the spacecraft's ACS design. This impactful design decision was reached in part because a safe hold mode (SHM) for MAP using only two wheels was feasible. However, a means to fulfill the MAP science mission degraded by the loss of a single wheel was needed. Not long before the launch of MAP, as an outcome of a red team review in September 2000, the prelaunch development of a strategy for completing the mission with two only operable RWs became an imperative.

The path taken by the MAP project team was the development of a two reaction wheel backup attitude control strategy. This proactive strategy would allow MAP to position itself for maneuvers and collect science data should one of its three reaction wheels fail.

The GSFC presenter at the workshop described the detailed process the MAP ACS team went through to analyze and evaluate how the various spacecraft ACS modes required to carry out the mission functions would be affected by the loss of a wheel, and what design steps were necessary to prepare for the possibility of two-wheel operations (reference 6). It was determined that two of the baseline attitude control algorithms implemented on the MAP spacecraft would no longer be usable with only two wheels. These two ACS modes would be the inertial mode, which served to slew to and hold a desired inertial attitude, and the observing mode, which served to implement the nominal dual-spin science data collection mode. It was also foreseen that a totally new momentum adjust algorithm would need to be designed to support the two-wheel science mode.

As a result of those analyses and evaluations, a proactive strategy was formulated to develop, along with some associated operational considerations, three new two-wheel-based hybrid attitude control algorithms. These algorithms would use the remaining attitude control actuators (i.e., selected hydrazine thrusters and the two remaining functional RWs) in ways that would achieve control goals while minimizing adverse impacts on the functionality of other subsystems and software.

A brief description of the changes that needed to be made to the MAP onboard FSW for it to fulfill a science mission degraded by the loss of a wheel was provided. In order to deliver and implement a backup two-wheel hybrid control design in a timely manner, a streamlined design philosophy was first adopted. When possible, the existing attitude control algorithms were used with few or no changes to reduce development and testing time. Where new algorithms were needed, they were implemented in a manner consistent with the current FSW design, with the great advantage of having updateable data tables to allow for on-orbit flexibility. Finally, the development of new and changed algorithms was prioritized by when they were needed to maximize the chances of mission success in the event of a wheel failure at any point in the mission. This last strategic tenet also served to maintain proper focus on other spacecraft concerns as the actual launch approached.

Development of two-wheel contingency FSW was completed in two phases. In the prelaunch phase, a software patch to install the thruster-based inertial mode was developed and tested, as this was the only new algorithm needed to get MAP to its L2 operational orbit. In the second phase, the other two algorithms needed for MAP to fulfill the remainder of its science mission in the event of a wheel failure were developed and tested. These are called Two-Wheel Science and Momentum Adjust. The Two-Wheel Science Mode employed a thruster-generated momentum bias, used to sweep the instrument boresights across the sky in a manner similar to the nominal 3-RW science Observing Mode. However, this natural-motion science mode results in a decrease in data density over the sky. The momentum bias required to point at the Sun needed to be adjusted often by the thrusters for the Two-Wheel Science Mode to operate safely and effectively. Therefore, as mentioned above, a totally new Momentum Adjust algorithm was designed to control the thruster during these daily operations. Because of the intractability of the attitude control problem, the Two-Wheel Science Mode algorithm was designed to allow for the on-orbit adjustment of several parameters, including angle error gains and other parameters used to adjust various failsafe modes built into the algorithm. All of these critical parameters could be adjusted in an updateable FSW data table that was part of the existing architecture. At the workshop, it was pointed out that this design philosophy provided the MAP ACS team with a reasonable measure of security against unpredictable dynamical effects that might be encountered when first employing these backup hybrid modes of attitude control.

The GSFC presenter reported that since all three reaction wheel performed nominally during the MAP mission it was never necessary to activate the backup hybrid modes of attitude control. It was also pointed out as a lesson learned that an opportunity was missed to operationally validate these hybrid control modes on-orbit after completion of the science mission and prior to the decommissioning of the MAP spacecraft.

7.1.5 Cassini Workshop Presentation Summary

The JPL workshop presenter addressed the engineering performed by that organization on hybrid control for the Cassini spacecraft (see Figure 7.1.5-1). Cassini was launched on October 15, 1997, and after an interplanetary cruise that lasted almost 7 years it entered orbit around Saturn in June 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.

Figure 7.1.5-1. Cassini Spacecraft

As with other spacecraft discussed at the workshop, the Cassini spacecraft has certainly demonstrated its longevity. It collected science data throughout its 4-year prime mission (2004–2008) and has since been approved for two extended missions through September 2017. Also, like the other spacecraft addressed at the workshop, Cassini carries a set of four RWs, three of which are fixed orientation wheels and the fourth being a so-called “backup” RW (i.e., RW-4) that is mounted on top of an articulable platform, as shown in Figure 7.1.5-2. If necessary, this platform could be articulated to orient the backup RW into co-alignment with the degraded wheel. As described in reference 7, RW-3 exhibited signs of bearing cage instability in the 2001–2002 time frame. Consequently, the mission managers decided to articulate the Cassini spacecraft’s RW-4 on its platform to align it with faulty RW-3 unit.

Figure 7.1.5-2. Cassini's Four RWs

Starting in July 2003, Cassini was controlled using RW-1, RW-2, and RW-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, RW-1 and RW-2 accumulated well over 3 billion revolutions each, and there are some indications of increased drag torques of those wheels' bearings being observed in telemetry. Reference 7 also describes some guidelines levied on Cassini science observations to extend RW life.

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

The two remaining RWs will not be able to provide precise and stable three-axis control of the spacecraft. In this study, which is summarized in reference 8, 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.

The Cassini project does not have a hybrid controller "ready-to-go" for uploading to the spacecraft in the event additional wheel anomalies, and potentially wheel failures, occur. JPL documented the hybrid control feasibility study they first performed in 2003, but the detailed development of a hybrid attitude control capability was not pursued by the project. FSW modifications for hybrid control were not defined and hence no real ground testing has been done. Actually, two separate hybrid attitude controllers would be required for the two different science data-taking modes Cassini flies in. If a second RW were to behave such that it must be removed from the attitude control loop, the Cassini project would power up RW-3 (the wheel that exhibited a bearing cage instability anomaly, but is still working) and use that for attitude control. If RW-3 was to truly experience a hard failure the project would likely revert to thrusters at that point and operate the rest of the Cassini mission in an RCS all-thruster attitude control mode. Implementing the two version of hybrid attitude control on Cassini, which would entail developing and fully ground testing the ACS FSW code modifications as well as defining and training for the associated operational constraints, would likely be a prohibitively costly effort for the project and is not viewed favorably/merited at this point in the mission (2014, just 3 years before the planned end of extended mission in September 2017).

7.1.6 Dawn Workshop Presentation Summary

At the workshop, a representative from Orbital presented a summary-level talk on the Dawn hybrid control approach and its status. Orbital is the Dawn prime spacecraft contractor. Dawn, a low-thrust interplanetary spacecraft (see Figure 7.1.6-1), 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 2010, during its cruise to the asteroid Vesta, the first of its two asteroid destinations, the spacecraft experienced a high-friction anomaly on RW-4. This anomalous RW was taken out of the attitude control loop, and some limited testing indicated that it was likely unusable for the approaching Vesta campaign. There have been three attempts to revive RW-4, none of them successful, so it is highly unlikely that any further attempts will produce different results. To preserve the remaining three wheels for science operations at the asteroids, the backup RCS thrusters were activated for attitude control for the remainder of the cruise to Vesta.

Figure 7.1.6-1. Dawn Spacecraft

Simultaneously, as a contingency against an additional RW failure in the remaining, now non-redundant, three-wheel complement, an effort was initiated in September 2010 to develop a hybrid control mode that would use only two RWs in a mixed-actuator mode together with thrusters to provide full three-axis attitude control. Compared with 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.

At the workshop, Orbital mentioned that another motivation for the development was the recognition that the root cause of the RW 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 RWs, 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 FSW that had to be loaded onto the spacecraft well before the beginning of science operations at the asteroid Vesta.

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 RWs, depending on the orientation of their torque axes.

As described above, a hybrid mixed-actuator controller using RWs together with electromagnetic torque rods was developed for the FUSE spacecraft, one of Orbital's earlier 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 FSW 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 FSW 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 FSW containing the hybrid controller was uploaded to the spacecraft in April 2011, providing risk mitigation and additional mission flexibility. Dawn arrived at Vesta in May 2011 after a flyby of Mars in February 2009. Vesta science operations were performed entirely on three wheels: RW-1, RW-2, and RW-3. After a yearlong successful science campaign at Vesta, Dawn departed for its next destination, the asteroid Ceres, with an arrival date there planned for early 2015.

In August 2012, RW-3 experienced a high-friction anomaly, and Dawn's attitude control was again transitioned to an all thruster mode to preserve life on the remaining two functional wheels. The Dawn project has no plans to power on either RW-3 or RW-4 again during the remainder of the Dawn primary mission. At the workshop it was stated both that the spacecraft would remain in an all thruster control mode until reaching Ceres and it was also mentioned that inflight tests of the Dawn hybrid controller were planned for later in 2013.

Also at the workshop, Orbital described how the two-wheel hybrid controller was designed, developed, and implemented on the Dawn spacecraft to provide mission flexibility for the contingency of a pair of failures in the primary actuator set (i.e., the reaction wheels). 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. Because it is a more propellant-efficient mode than the backup all-thruster control, thereby 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 FSW with one of the constraints being to make it as transparent as possible to normal operations. The Orbital representative described some of the operational considerations for preparing Dawn to use a hybrid actuator configuration.

Reference 9 is a technical paper that provides the details of the Dawn hybrid control experience as described at the workshop. Reference 10, published after the workshop, provides a more recent Dawn hybrid control operations update with inflight test performance results included.

7.1.7 Kepler Workshop Presentation Summary

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-sized 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 7.1.7-1), which flies in a heliocentric Earth-trailing mission orbit, was launched March 7, 2009, and completed its 3.5-year prime mission in November 2012. At the time of this workshop, it was early in the operations of the approved 3-year extension of this primary mission.

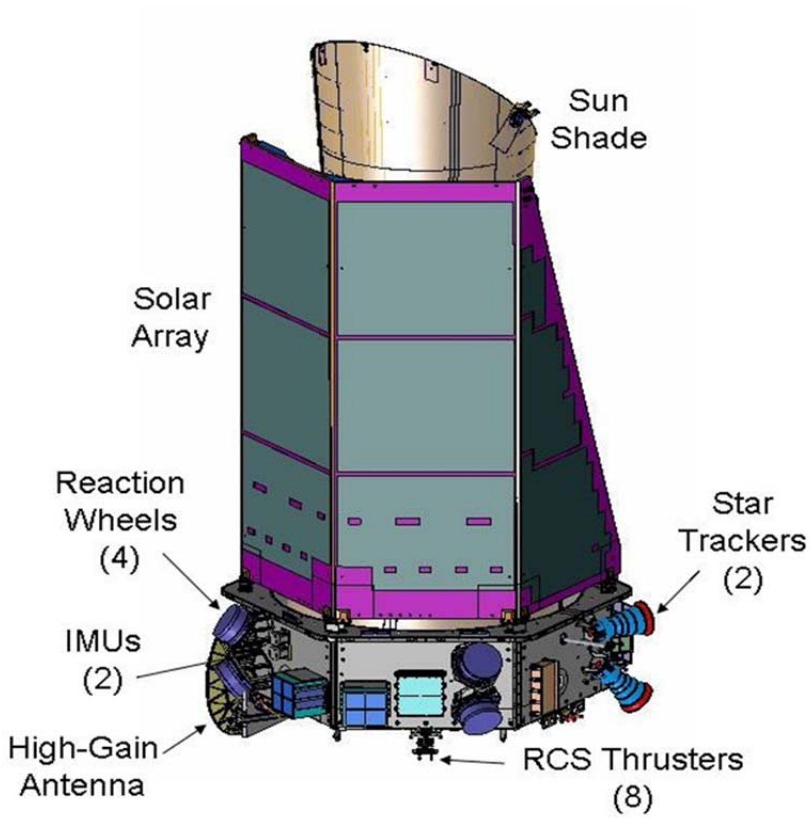


Figure 7.1.7-1. Kepler Spacecraft

While there was not any significant discussion on Kepler hybrid control system design efforts at the workshop, the prevailing participant view was that this mission would greatly benefit from proactively developing a two-wheel hybrid controller as a protection from another wheel failure.

It should be noted that at the time of the workshop BATC had not yet initiated work on the design of a two-wheel hybrid attitude controller. At that point in time (i.e., April 2013), BATC was primarily focused on managing the remaining three wheels, as described above, in order to preserve their remaining life. However, the JPL had conducted a preliminary assessment of a wheel-thruster hybrid controller for the Kepler spacecraft. At the workshop, results were presented by a JPL representative summarizing their preliminary technical feasibility investigation. These results indicated that the capability of achieving the Kepler mission's original long-term pointing stability of 9 milli-arcseconds while staring at the original Cygnus science target field-of-view would not be feasible with a two-wheel (plus thrusters) hybrid controller. This was primarily because the minimum impulse bit of the spacecraft's propulsion subsystem thrusters was not originally sized for fine attitude control purposes.

As described in reference 11, the Kepler spacecraft, which was designed and built by BATC of Boulder, Colorado, nominally employs a set of four RW actuators to generate attitude control torques to slew, point, and precisely stabilize the vehicle. These four RWs are positioned on the spacecraft in a nonorthogonal orientation such that any one of the four RWs can fail and the remaining three can still maintain complete three-axis control of the spacecraft. This is essentially the standard method for modern spacecraft using RWs for ACS to have a spare in case of an RW failure. A minimum of three RWs is required to provide the zero-momentum three-axis stabilization of the spacecraft using only RWs.

7.1.7.1 Kepler RW Anomalies

The make and model of the RWs used on Kepler (Ithaco Type- B) are very similar to the ones flown on the TIMED mission described in a previous section of this report. It was mentioned at the workshop that the TIMED RW failure occurred during the build phase of Kepler. This new knowledge was assessed by the Kepler project team, and the decision was made to keep them, but to rework and take special steps with the bearings/wheels within these RWs to try to avoid a similar failure.

The BATC representative at the workshop described the sequence of RW anomalies and failures that are summarized as follows:

- January 2012, RW-2 friction temporarily increased by about 2 mN-m and returned to normal.
- June 2012, RW-4 friction increased by about 8 mN-m for about 12 hours, dropped to about 2 mN-m above normal for another 3 days, then returned to normal.
- July 2012, RW-2 friction increased beyond the control law’s torque command; analysis showed friction torque of approximately 140 mN-m (so Kepler had the first RW failure prior to completion of the primary mission, with a second RW showing signs of distress).
- Kepler was performing normal mission pointing using the three remaining RWs after July 2012 with the addition of the following changes to try to extend the life of the remaining RWs and protect the Kepler spacecraft in case of another RW failure:
  - Increased RW heater set point
  - Increased minimum speed to ensure all EHD-region operation
  - Bidirectional operation (goal)
  - Implemented thruster-controlled safe mode
- December 2012, RW-4 friction increased by about 2 mN-m.
- January 2013, in an attempt to “heal” the distressed RW-4 bearing, a 10-day “rest” period (thruster-controlled safe mode) was implemented, but the RW-4 friction remained elevated after rest.
- April 2013, at the time of this workshop, Kepler was still performing the primary mission under three-RW control, with RW-4 having elevated friction.

As described in Section 7.3 of this report, shortly after this workshop on May 11, 2013, RW-4 failed such that the Kepler spacecraft could no longer perform its primary mission with the two remaining functional RWs.

7.1.7.2 JPL Preliminary Study of Kepler Hybrid Attitude Control Feasibility

As noted above, at the time of the workshop BATC had not yet initiated work on the design of a two-wheel hybrid attitude controller. At that time (i.e., April 2013), BATC was primarily focused on managing the remaining three wheels, as described above, in order to preserve their remaining life. However, JPL had conducted a top-level assessment of a two-wheel (plus thrusters) hybrid attitude controller for the Kepler spacecraft. Therefore, at the workshop, results were presented by a JPL representative summarizing their preliminary technical feasibility investigation. These results indicated that the capability of achieving the Kepler mission's original long-term pointing stability of 9 milli-arcseconds while staring at the original Cygnus science target field-of-view would not be feasible with a two-wheel (plus thrusters) hybrid controller. This was primarily because the minimum impulse bit of the spacecraft's propulsion subsystem thrusters was not originally sized for fine attitude control purposes.

7.1.8 Mars Odyssey Hybrid Control Workshop Presentation Summary

The Mars Odyssey spacecraft, launched on April 7, 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. LMC built and operates the Odyssey Mars Orbiter under contract to 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 7.1.8-1 depicts the general configuration of the Odyssey spacecraft in its nominal nadir-pointing orientation. The primary attitude control actuators are three RWs, each aligned with the three vehicle coordinate frame axes, and a nominally inactive fourth "skew" RW to be employed in case of failure of any one other RW. Note the relatively long Gamma Ray Spectrometer boom, in addition to its single-wing solar array, which yields nonsymmetric inertial properties for the Odyssey vehicle. This causes non-negligible gravity gradient disturbance torques.

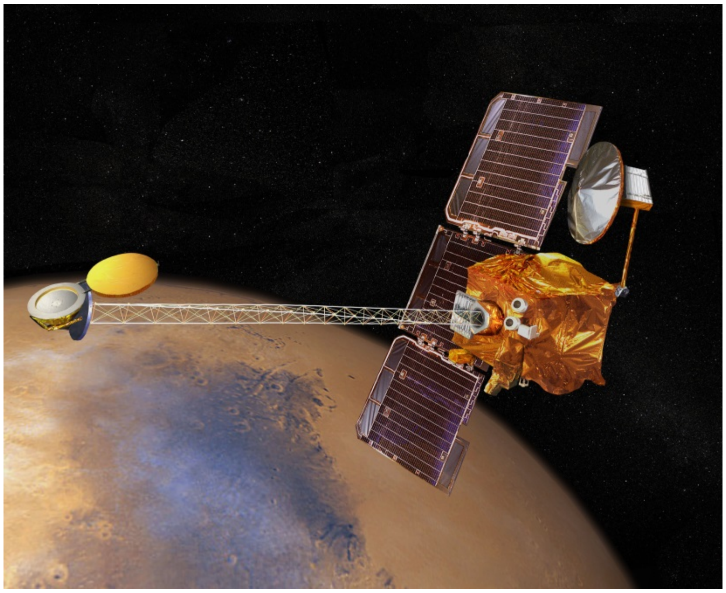


Figure 7.1.8-1. Mars Odyssey Spacecraft

As described in reference 12, on June 8, 2012, the RW-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 RW-1 from producing the control torque commanded by the spacecraft's 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 RW. It was stated at the workshop that there was no plan to attempt to use the failed RW-1.

Shortly thereafter, NASA directed JPL and LMC to initiate development of a contingency thruster only (all thruster) controller and a contingency two-wheel 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 or inertially hold the spacecraft to properly point its HGA towards Earth for data downlink communication periods once or twice a day.

As described in the workshop presentation, LMC designed a two-wheel hybrid ACS that used various combinations of functional wheel pairs (e.g., the RW-2 and the skew wheel pair, the RW-3 and the skew wheel pair, and RW-2 and RW-3 pair) to control two of the spacecraft's axes and used thrusters to provide control torques for the third axis. A rotated control reference frame, called the RW Control Plane (RCP), was employed such that the axis controlled by the thrusters was orthogonal to the wheels. A positive implementation aspect was that the Odyssey hybrid controller could be implemented with only ACS data parameter changes, so patching of existing ACS FSW would not be required. According to the LMC workshop presenter, this was primarily due to the simplicity and elegance of the baseline attitude controller architecture.

Another positive attribute of the Mars Odyssey baseline ACS architecture came into play when the LMC team was addressing a problem that emerged once the spacecraft began to operate on the skew wheel following the failure of RW-1. Initially, it was not possible to cleanly desaturate the skew wheel's x-axis momentum component because of the coupling into the spacecraft's y-axis and z-axis. Hence, a study had been initiated by JPL aimed at determining ACS "algorithm changes" that would allow for x-axis momentum desaturations. After analyzing the ACS architecture, it was observed that a simple change to the contents of a single on-board ACS parameter matrix would allow the skew wheel to be desaturated without affecting the other vehicle axes. Therefore, no ACS FSW algorithm changes were required, which is just another result of the flexibility built into this particular ACS design.

There were, however, some 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, then that wheel momentum cannot cycle up and down, as it is taken out immediately. There were concerns about sensitivity to thruster variations or impingement. It was observed that precessional torque (from "dragging" the RW 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 with 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 RW momentum vector precessional torques and to improve propellant efficiency.

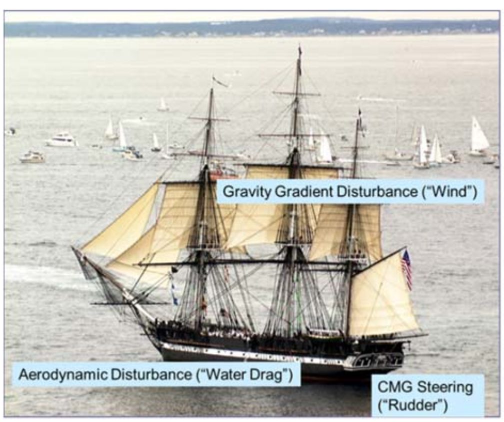
Simulation results indicated that the thruster-controlled axis would be inefficient due to the thruster configuration, so hybrid control could actually be worse in the sense of more propellant consumption than the "Thruster Only attitude control mode. At the time of the workshop, it appeared that there was not much improvement to be gained via the two-wheel 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 two-wheel 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 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 the inertial hold portion of the mission when using both the Thruster Only and the two-wheel 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, reconsidering the number of and the specific scheduling of the maneuvers for HGA-Earth communications.

Also, further tuning of and comparison of the two-reaction wheel 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, nonsymmetrical spacecraft make for nonoptimal hybrid control due to a combination of precessional torques and gravity gradient torques. Lastly, it was expressed that further efficiency optimization of both two reaction wheel hybrid control and Thruster Only was probable. As it currently stands, if another RW fails on the Mars Odyssey spacecraft, then it will revert to the Thruster Only three-axis attitude control mode versus a two reaction wheel plus thrusters hybrid-control mode of attitude control.

7.1.9 ZPM Workshop Presentation Summary

The representative from the Charles Stark Draper Laboratory presented an overview of the ZPM technology developed at Draper over the last several years. The ZPM is a guidance method initially developed for International Space Station (ISS) control motor gyroscopes (CMG) that eliminates the need for thrusters as backup (see Figure 7.1.9-1). By applying ZPM optimal guidance, a new class of CMG capability previously thought impossible can be achieved. The ZPM algorithms are used to compute an optimized subject to carefully defined constraints/cost functions spacecraft attitude profile (i.e., a trajectory made up of a sequence of commanded quaternions) that can then be used as a time-sequenced command input to the spacecraft's ACS. As described by the Draper representative, ZPM can be used to perform large-angle spacecraft attitude slew maneuvers, rate damping, and momentum desaturation. In the applications demonstrated to date, ZPM does not require onboard FSW modifications.



Notional depiction of how the ZPM approach exploits naturally occurring environmental disturbances to formulate optimal guidance trajectories

The ZPM approach has been flight tested on both the ISS and on the TRACE spacecraft"

Figure 7.1.9-1. ZPM Approach

The ZPM is formulated as an Optimal Control Problem (OCP) specifically tailored to a particular spacecraft configuration, ACS architecture, and the spacecraft's particular operational environmental conditions. The ZPM operational implementation consists of a ground-based tool that generates a sequence of optimal attitude and maneuver rate commands. System performance is verified via high-fidelity simulation of the spacecraft's ACS response to the time sequence of optimal commands.

There have been at least two flight demonstrations of the ZPM technique performed on the ISS. The first was a 90-degree ISS attitude slew maneuver performed on November 5, 2006. This 90-degree slew was accomplished in 2 hours by inputting a sequence of ground-computed ZPL commanded quaternions to the ISS ACS once every 90 seconds. In this flight demonstration, only three active CMGs were used for generating attitude control torques as one of the ISS's four-CMG complement (i.e., CMG3) had previously been shut down due to excessive wheel vibrations. A 180-degree ISS attitude slew maneuver flight demonstration of the ZPM was subsequently performed on March 3, 2007, using only three active CMGs. Employing the ZPM technique is a means to conserve ISS thruster propellant: consider that the same 180-degree attitude slew maneuver performed using ISS thrusters in January 2007 consumed approximately 51 kg of propellant.

The ZPM maneuvering capability was considered for "emergency" use when the ISS Russian GN&C computers failed on June 11, 2007, during the STS-117 mission. With the failure of the Russian GN&C computers, closed-loop ISS attitude control capability with thrusters was lost. Lacking a thruster-based, closed-loop attitude control capability, it was feared that ISS would tumble after Shuttle undocking and that the astronaut crew might have to abandon the ISS. Contingency plans and procedures were developed to accomplish ISS attitude recovery under CMG-alone control using the ZPM approach.

On a related note, the Draper representative described how ZPM-type optimization algorithms were used by GSFC, the Naval Postgraduate School (NPS), Draper, and the NESC team to perform flight demonstrations of shortest time maneuvers (STM) on the retired Transition Region and Coronal Explorer (TRACE) satellite in August 2010. TRACE was launched in 1998 and conducted its last science observation in June 2010. Before decommissioning, GSFC made the satellite available to demonstrate time-optimal multi-target large-angle slews. The objectives of these TRACE flight tests were to demonstrate STMs improve performance without any onboard FSW change. The OCP in this case was tailored to compute appropriate STMs attitude profiles to meet the TRACE-specific constraints. Draper was responsible for the design and verification of STM trajectories. A total of 22 STM trajectories were successfully flown under RW control. Some of these STMs performing maneuvers up to ~13% faster than more conventional Eigen axis industry standard type attitude maneuvers.

The Draper representative concluded his workshop presentation by suggesting the ZPM optimal control approach could potentially serve as a solution, or part of a broader solution, for the hybrid control problem using two RWs.

7.2 Summary of Workshop Discussions

Interactive technical discussions were held throughout the course of the workshop. As mentioned above, the workshop was purposely conducted in a technically focused and collegial manner with an open sharing of hybrid control ideas and methods of operating scientific spacecraft with a reduced complement of RWs. The findings, observations, and NESC recommendations provided in Section 8 of this report materialized during the course of these workshop discussions. To stimulate and focus discussion, the following list of thought-provoking questions was developed by the workshop chairs and shared with the participants:

- What are the fundamental constraints/limiting factors/technical boundaries for two reaction wheel hybrid attitude control?
- What level of attitude control performance is feasible under two reaction wheel hybrid attitude control?
- What are the salient hybrid control scheme differences between spacecraft in Flyby-type missions versus spacecraft in LEO missions?
- In addition to the attitude control law redesign aspects, are there mission operational lessons that have been learned as well?
- What are the risks of implementing two reaction wheel contingency attitude control?
- What are the common lessons for future hybrid attitude controller designers?
- What has historically posed the greatest challenges and/or caused the greatest problems?
- Are there impacts to the operational conditions of the remaining RWs?
    - Are RW operations under hybrid control consistent with the recommendations of the NASA RW Tiger Team?
    - Are there more frequent zero wheel speed crossings?
    - Is more time spent in sub-EHD wheel speed regimes?
- What are FSW/ground software impacts?
    - Fault management/fault detection, isolation, and recovery (FDIR) algorithm modifications?
    - Recertification challenges/issues?
    - Command and telemetry changes?
- What are impacts to other flight system/ground system subsystems?
    - Propulsion, especially unanticipated thruster duty cycles and propellant consumption?
    - C&DH, especially on-board computer central processing unit usage changes?
    - Thermal impacts?

- High data rate communications constraints/impacts?
- Mission operations planning and scheduling tool modifications?
- Science data processing changes?

7.2.1 Discussion Points

There were several discussion topics that emerged during the interactive workshop discussions, including the following:

- It was addressed by members of the NASA RW Tiger Team that not all Ithaco Type-B wheels are exactly the same. According to the data collected and analyzed by the RW Tiger Team, there have been a number of Type-B RWs developed and flown with several subtle differences between them in the following areas:
  1) Wheel lubrication (some lubricated with grease and some with oil only)
  2) Wheel bearing preload
  3) Snub nut and snubbers
  4) Snub nut preload (affecting the bearing preload)
  5) Types and orientations of the wave springs ("wavy washers")

  It was noted that the TIMED RW failure occurred during the build of the Kepler RWs, and it was decided by the Kepler Project Office, with the recommendation of the NASA RW Tiger Team, to rework the Kepler wheels prior to launch. One modification was to modify the housing of the wheel. The result of this is the version of the Type-B RW, commonly known as the "Killer-B" version, where the wheel housing was modified to mount the wheel drive electronics on the opposite side from where it is mounted on the typical Type-B RW. This has the effect of making the housing stiffer, which is potentially better for loading the wheel bearing more evenly. This Killer-B version of the Type-B RW was flown on the Kepler spacecraft.

- The effects of new control schemes on the fault management system and safe modes should be thoroughly evaluated to prevent false fault trips and loss of mission time or danger to the vehicle. This includes consideration of the state that the flight computer will reboot in the event of a single event upset reset, dead bus recovery, etc. If the recovery state cannot be modified (i.e., a programmable read-only memory load and constraints on changing reconfiguration data), then operational contingency plans should be considered.

- The need for simple and flexible spacecraft ACS FSW architectures was emphasized. Architectures that permit substitution of hybrid actuators without FSW code modifications reduced the degree of difficulty of hybrid control implementation.

- The creation of a new hybrid control frame 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 RWs (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 RW 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 two reaction wheel combinations.
- The representative from Orbital mentioned the benefit of including an on-board wheel running friction estimation loop in the design of the spacecraft ACS. A simple state predictor/corrector can be designed to track either the true wheel friction, or the error in the *a priori* friction model, depending on the vehicle attitude control loop. The wheel friction estimate can be estimated using the difference between the commanded wheel speed and the tachometer-sensed wheel speed. The commanded wheel speed can straightforwardly be computed by integrating the torque command signal that is generated by the attitude control law. Having an on-board running estimate of the wheel friction can provide an excellent basis for critical wheel-related FDIR tests. The friction estimate also directly serves as a way to monitor wheel health. The friction estimate can be used to adjust/compensate the commanded torque signal that is actually sent to the RW, but care needs to be taken when the wheel speeds are low since the tachometer-sensed wheel speed measurement can become noisy at low speeds. Apparently, Orbital has had significant on-orbit flight experience with this speed/torque with friction compensation wheel commanding approach.
- Analysts should consider ways that wheel orientations should be optimized to balance the remaining two reaction wheel control torque across all three spacecraft body axes.
- There are advantages of having the fourth RW 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.
- Based on the workshop presentation materials, there appears to be no need for the development of new or the enhancement of existing analytical (modeling and simulation) tools for hybrid controller design/analysis.
- Performing large-angle spacecraft attitude slew maneuvers appears to be a common stressing challenge for two reaction wheel hybrid control.

- If a spacecraft has already lost one RW, then the need to minimize revolutions on the remaining RWs 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 important points relevant to implementing new contingency hybrid attitude control schemes also emerged during the workshop discussion; these are summarized here.

1. **The critical need for and the great benefits of having spare ACS 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 FUSE hybrid control ACS algorithms. Having these spares made quick FSW patches safer and much easier.
2. **The critical need to maintain the spacecraft's ACS Engineering Development Units in a FlatSat (i.e., a hardware in the loop configuration) laboratory testbed environment.** Connecting this ACS testbed to the spacecraft's ground system will permit high-fidelity testing of the new hybrid control commands, telemetry, operational scripts, and operational procedures, and will allow the flight operations team to train on the modified ACS. If an extension contract is awarded to operate the vehicle beyond the design life, then that contract should include a requirement to maintain a software testbed, including acquisition of spares testbed elements/components that may run into obsolescence issues and become unavailable many years into the mission.

Lastly, there was a general observation that surfaced during the workshop discussions regarding ACS flight 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 FSW clocks, timers, counters and other similar functions that "rollover" at some point in time.

7.2.2 Promising Technical Areas for Future Hybrid Attitude Control Applications

Beyond the key points mentioned above that emerged from the workshop discussions, there were a number of potential technology investment areas identified that participants believe to be promising and that should be considered for future hybrid ACS applications, such as, but not limited to, the following:

- Nonlinear control laws
- Nonlinear optimization solvers
- Techniques for implementing computationally efficient on-board real-time nonlinear control laws/nonlinear optimization solvers on typical spacecraft flight processors

- Improved high-fidelity disturbance torque modeling, particularly the Solar Radiation Pressure (SRP) disturbance
- Simple and reliable articulation platforms for repositioning RWs
- Ultra-low minimum impulse bit micro-propulsion (cold gas) Vernier attitude control thrusters as potential substitutes for RW
- Linear proportional high-efficiency magnetic torquers

7.2.3 Hybrid Tool Table

During the course of the workshop, there was much time devoted to discussions of the various and different attitude disturbance forces and torques acting on spacecraft as a function of their operational environment/regime. Table 7.2.3-1 was developed during the workshop to show various tools/disturbance forces that can change the orientation/attitude of a spacecraft. While many of these are normally considered as disturbances that require corrective counter forces from spacecraft ACS actuators, these same disturbance forces may become useful as potential corrective forces when considering alternate methods to control the spacecraft, after it has experienced failures of some of the standard spacecraft ACS actuators, such as RWs. The workshop participants recognized that these disturbance forces/torques, usually treated as something negative to be “rejected” by the ACS, could be harnessed in a positive way as a tool and become an intrinsic element of a hybrid ACS.

Table 7.2.3-1. Hybrid Tool Table

Location / Hybrid Control Source of Force/Torque	LEO/HEO	Planet w/Atmosphere (P w/A)	Planet or Mass w/o Atmosphere (P w/o A)	No Planet or Nearby Mass (No P/M)
Hybrid Control Source of Force/Torque				
Atmospheric Drag	X	X	-	-
Magnetic Field/MTB	X	-	-	-
Gravity Gradients	X	X	X	-
Solar Pressure	X	X	X	X
Mechanism movement	X	X	X	X

Mission	Location	Aero Drag	Magnetic Field	Gravity Gradient	Solar Pressure	Mechanism
FUSE	LEO	A	I	A	A	
TIMED	LEO	A	I	A	A	
MAP	L2, No P/M	-	-	-	A	
Cassini	No P/M >Pw/A	?	-	A	A	A
Dawn	P w/o A	-	-	A	A	
Kepler	NNA	-	-	-	A	-
Mars Odyssey	P w/A	A	-	I	A	

A = available; I = available and implemented for Hybrid approach; - = not available

7.3 Post-Workshop Spacecraft Hybrid Attitude Control Related Activities

Although there was progress on hybrid control on other NASA missions (e.g., inflight testing of the Dawn hybrid controller has recently been performed by JPL and Orbital), the majority of the post-workshop activity has been focused on identifying and developing a technically feasible, well-performing, operationally simple, and easily implementable two-wheel hybrid controller for the Kepler spacecraft. Design of a viable Kepler two-wheel hybrid controller was greatly spurred on by the fact that shortly after the April 2013 workshop, a second Kepler RW, that being RW-4, performed anomalously and subsequently failed.

By the end of April 2013, all appropriate mitigation steps to prolong the life of Kepler's RW-4 had been taken. Unfortunately, the wheel life extension operational mitigations described above were not sufficient to protect Kepler's RW-4, which had exhibited symptoms of increasing bearing friction. At the routine communications contact on May 14, 2013, the Kepler spacecraft was unexpectedly discovered by its flight operations team to be in its 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 RW anomaly review team concurred that the telemetry data appeared to unambiguously indicate that RW-4 failed on May 11, 2013. The Kepler Project Office at NASA's Ames Research Center (ARC) 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 proactive follow-up activity initiated shortly after the April 2013 workshop, controls engineers at GSFC designed, modeled, and simulated a momentum-bias approach for accomplishing three-axis attitude control using only two RWs and no thrusters. The work described in reference 13 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 RWs in the presence of solar radiation pressure torque? Since no thruster usage is a baseline assumption in this work, the two RWs are responsible for not only three-axis attitude control, but also angular momentum management. The intent of this work was not to propose yet 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 13. The benefits of using a momentum bias are described, and the results reported in reference 13 serve to quantify and document some fundamental hybrid control constraints and limitations.

Shortly following the failure of RW-4, ACS engineers at BATC designed a new two-wheel/thruster hybrid controller for the repurposed Kepler spacecraft. Reference 14 discusses the BATC hybrid control architecture that uses momentum biasing of the two remaining wheels and low duty cycle use of the RCS thrusters to provide three-axis control. It also discusses general guidelines for operating the vehicle in this mode.

Because the pointing stability of 9 milli-arcseconds required for the primary Kepler mission appears to not be achievable with only two RWs, after the failure of Kepler's second RW in August 2013 the Kepler 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 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. Therefore, the challenge was to develop a two reaction wheel hybrid attitude control mode that could deliver this type of operation and three-axis performance while pointed at 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 hybrid control problem, 2) their likelihood of technical implementation success, and 3) their degree of operational difficulty. The NESC also planned and conducted (in September 2013) a 2-day Kepler Pointing Technical Interface Meeting with the Kepler Project Office engineering and science teams at NASA ARC to help identify the best hybrid attitude control approach for a repurposed Kepler spacecraft. Not surprisingly, given their in-depth knowledge of the spacecraft and its operating environment, the BATC-developed two-wheel hybrid control architecture has been adopted by the Project Office as the baseline approach for the repurposed Kepler mission [ref. 14].

The Kepler Project Office at ARC has proposed to the NASA SMD a repurposed Kepler mission called K2. At the time of this final report was issued, SMD had accepted the ARC K2 proposal. 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. Therefore, 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 SRP disturbance torques can be carefully balanced to minimize boresight roll. Initially, there was concern that this approach would be similar to balancing on a knife edge, but data from some early inflight K2 testing shows the SRP disturbance torque profile to be more benign (i.e., not so steep) as originally suspected. However, more inflight testing will be needed to confirm this. The attitude control engineers at BATC have done enough ACS analysis and the results of the several early ecliptic-plane K2 performance tests are favorable enough to demonstrate the 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 2- to 3-month campaigns over the next few years.

It is worth noting that two of the lessons learned that emerged from the NASA Spacecraft Hybrid Attitude Control Workshop came very much into play in the design of the K2 ACS by BATC. The BATC K2 ACS design will employ a momentum bias about the spacecraft z-axis. That momentum bias will be oriented normal to the Kepler spacecraft's orbit plane such that inertial targets in that plane can be tracked simply by modulating the bias. Kepler is unusual because of its tight roll pointing stability requirement; most science telescopes would most likely have the momentum bias along their optical boresight axis rather than perpendicular to it, as will be done on K2. Secondly, it should be noted that K2 will be pointed in the ecliptic plane to exploit the SRP disturbance torque rather than fight it. This followed serendipitously from the best engineering practice of using the momentum bias mentioned above. These two concepts were suggested to BATC by the NESC in support of their hybrid controller design work to enable Kepler repurposing.

In parallel with the activity focused on the repurposed Kepler spacecraft, research into ways to control under-actuated vehicles is currently ongoing at the NPS under NESC sponsorship as part of a separate NESC assessment to evaluate hybrid attitude control concepts specifically for Kepler. The topic of how to control under-actuated vehicles has been studied before, as described in reference 15. The researchers at the NPS are challenging the conventional 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 the concept is in agreement with fundamental mathematical theory on linear controllability. NPS maintains that nonlinear controllability (without linearization) is not only practical, but 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 16, the NPS researchers address 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 problem of nonlinear controllability of a spacecraft equipped with just two RWs.

The application of these mathematical results to Kepler is still ongoing at NPS with a recent re-focusing of that work, after technical consultation with the Kepler Project Office at ARC, to develop nonlinear two-wheel control laws for large-angle spacecraft slews as a propellant-saving measure.

There is one other post-workshop update worth mentioning in this report. The Mars Odyssey attitude dynamics and control analyses performed by LMC subsequent to the workshop indicated that there was a better option than either the hybrid controller or the specific Thruster Only type of all thruster controllers that were under consideration at the time of the workshop. Some background on the Mars Odyssey propulsion subsystem is helpful here. The Mars Odyssey spacecraft has two sets of reaction control subsystem thrusters. The first set are four 0.2-pound-force (lbf) RCS thrusters that are the primary three-axis control set for attitude control. Unfortunately, two of these 0.2-lbf thrusters impinge on the spacecraft's HGA except in the configuration when the HGA is stowed in a position that precludes Earth communication. The second set consists of four 5-lbf thrusters, aligned with the spacecraft z-axis; these are used for propulsive delta-velocity maneuvers. None of these 5-lbf thrusters impinges on the HGA. Analysis showed that the 5-lbf thrusters can be used to control the spacecraft x- and y-axes attitude. By disabling the two 0.2-lbf thrusters that impinge on the HGA, the two remaining 0.2-lbf thrusters could be used to control the z-axis attitude of the Mars Odyssey spacecraft while the 5-lbf thrusters controlled the x- and y-axes, thus allowing for HGA communication. LMC refers to this as the "six-thruster controller." The downside of this "six-thruster controller" method of contingency attitude control is that it is very fuel inefficient. The concept that emerged for operation following a second RW failure is to fly the majority of the time on the four 0.2-lbf RCS thrusters, collecting science observations and, more importantly, receiving and storing data from Mars-landed assets, then switching to the six-thruster control for relatively short periods and pointing the HGA for data downlink to Earth. All operations can be performed without leaving our nominal, fuel-efficient nadir-pointing attitude. This is the Mars Odyssey Project's current baseline controller and operational concept in case of a second RW failure.

8.0 Findings, Observations, and NESC Recommendations

8.1 Findings

The following findings were identified:

F-1. Significant analysis, test, and evaluation have been performed by NASA, industry, and the RW provider to determine proximate cause of the Type-B RW failure; however, a common root cause has remained elusive and has not been determined.

F-2. Several spacecraft RW failures have occurred on-orbit over the period 2001 to 2013. For all the spacecraft reviewed in the workshop, with the single exception of the Ithaco Type-A wheel failure on Mars Odyssey, all the RW failures have been on a single make and model of RW (i.e., Ithaco Type-B).

- A conservative estimate of well over a billion dollars-worth of NASA mission assets was rendered nonfunctional or placed in jeopardy due to reaction wheel anomalies and/or failures that exceeded typical wheel redundancy provisions.

F-3. Hybrid (mixed-actuator) attitude control techniques have successfully served to maintain three-axis attitude control and extend the science productivity of several NASA spacecraft that suffered multiple RW in-flight anomalies/failures.

F-4. Of the seven spacecraft discussed at the workshop, with the exception of the MAP spacecraft and possibly the Cassini spacecraft, there had been no prelaunch considerations of implementing hybrid attitude control.

F-5. Of the seven spacecraft discussed in the workshop, there was a range of hybrid control implementation challenges. In some cases, hybrid control was relatively easy to implement, and on other spacecraft it was much more difficult to implement. The degree of difficulty in successfully implementing contingency hybrid attitude control is strongly influenced by the mission's operational requirements, the spacecraft's physical configuration, and the ACS and C&DH (Avionics) subsystem architectures and design attributes, among them the following:

- Requirements for spacecraft reorientation attitude slew maneuvers for communications or other purposes
- RW/Thruster/MTB control actuator placement, orientation geometry, and the control authority and performance characteristics of the available alternates attitude control actuators (e.g., thrusters and MTBs)
- Spacecraft mass properties, in particular the mass moment of inertias
- Available flight processor resources
- ACS FSW architecture

F-6. Hybrid control implementation risk was reduced for those cases where FSW testbeds and/or HITL FlatSat testbeds could be employed to validate hybrid controller FSW patches before uploading to the vehicle and executing.

F-7. For spacecraft flying in Earth orbit or in orbit around a planet that has a magnetic field, MTBs can be part of an efficient hybrid control implementation as demonstrated by the FUSE experience.

F-8. Robotic science spacecraft typically have at least one all-thruster attitude controller as part of their ACS baseline design, but these controllers were not designed for long-term propellant-efficient precision pointing control or large-angle attitude slewing. These all-thruster attitude controllers must be redesigned or, at a minimum, retuned, if they are to be useful as part of a contingency hybrid attitude control scheme.

F-9. Thruster firings in hybrid attitude control mode or in an all-thruster control mode will create unwanted spacecraft Delta-V, which can complicate the mission spaceflight navigation process.

F-10. The existing ACS modeling, simulation, and analysis tools appear to be adequate for supporting the design and development of new hybrid ACSs.

F-11. Performing large-angle spacecraft attitude slew maneuvers (for science observation re-orientations, science data downlink communications, power/thermal management purposes, etc.) is a common stressing challenge for contingency two RW hybrid control systems.

F-12. The impacts on the baseline spacecraft Fault Management/Safing/Safe Mode subsystem need to be carefully considered as part of any contingency hybrid attitude control design implementation.

F-13. There have been and most likely will continue to be opportunities for performing low-risk on-orbit validation testing of specific hybrid controller concepts on spacecraft nearing the end of their operational lifetimes. An opportunity was missed for performing just such testing on the MAP spacecraft prior to its decommissioning.

F-14. While there may be some common aspects/attributes in the various hybrid control systems implemented to date, it appears that each spacecraft implementation needs to be unique. This makes it difficult and problematic to accurately extrapolate from one set of spacecraft hybrid control system performance metrics to another.

F-15. There are significant differences in the application of hybrid control to spacecraft flying in LEO, Mars orbit, flyby trajectories, and/or in orbit around asteroids/small bodies. For example, while spacecraft flying in Mars orbit must contend with similar environmental disturbances (e.g., gravity gradient torques) as those spacecraft flying in LEO, they lack the advantage of an *in-situ* magnetic field that could be used to generate attitude control torques with the use of an MTB actuator.

F-16. The attitude control engineering practice, resurrected from the 1960s of establishing, with the two remaining functional RWs, a momentum bias on the vehicle to provide a gyroscopic restraint about two of the spacecraft axes could form the basis of an efficient hybrid attitude control scheme.

8.2 Observations

The following observations were identified:

O-1. For missions with significantly extended flight operations (i.e., 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 FSW clocks, timers, counters, and other similar functions that "rollover" at some point in time. With so many of NASA's science spacecraft operating past their prime mission duration, the NESC should consider sponsoring a NASA-wide workshop devoted to the care and handling of obsolescence spacecraft.

O-2. Hybrid attitude control has a background that dates back more than a decade, and it is still a dynamically evolving area of research and practice. The NESC should consider sponsoring a second NASA Workshop on Hybrid (Mixed-Actuator) Spacecraft Attitude Control in fiscal year 2015 to understand the lessons learned from, among other projects, the recent work to design and implement hybrid control on K2, the repurposed Kepler spacecraft. Inviting representatives from the ESA to participate and collaborate in this suggested future workshop should be considered as well, especially in light of ESA's recent work on developing a hybrid attitude control system for their Rosetta spacecraft (see reference 17).

8.3 NESC Recommendations

The following NESC recommendations were identified and directed toward the SMD Chief Engineer; the Kepler, Dawn, and Mars Odyssey projects; other NASA Earth/space science projects experiencing RW and failures; and, more generally, the NASA GN&C community of practice:

R-1. Consider hybrid (mixed-actuator) attitude control techniques as a means to recover three-axis attitude control and extend productivity of spacecraft that have experienced multiple RW in-flight anomalies/failures. ***(F-3, F-7, F-10)***

R-2. Avoid using the Ithaco Type-B RW for future NASA missions until such time as the root cause of the failures can be been determined and adequate corrective measures can be implemented for this particular make/model of wheel. ***(F-1, F-2)***

R-3. Perform ACS architectural considerations of both hardware and software attributes early in the system conceptual design phase to facilitate hybrid control implementations in the later stages of mission life. (***F-4, F-5, F-7)***

- Consider RW, MTB, and thruster placements and geometric orientations from a potential hybrid control perspective.
- Consider the ACS FSW architecture's flexibility to permit the incorporation of a hybrid controller in the later stages of mission life.

R-4. Ensure spacecraft fault management/safing/safe mode aspects are carefully considered when designing new hybrid control modes. ***(F-12)***

R-5. For hybrid control system development and implementation risk reduction, programs and projects should maintain their ACS FSW testbeds and/or their HITL FlatSat testbeds for flight-readiness recertification purposes that permit extended spacecraft productivity in the face of multiple RW in-flight anomalies/failures. ***(F-6)***

R-6. Consider the potential advantages of employing a bias-momentum (versus a zero-momentum) approach when designing a two-RW based spacecraft hybrid control system, such as what was successfully implemented on the repurposed Kepler K2 spacecraft. ***(F-16)***

R-7. Investigate ZPM/OPM hybrid attitude control approaches for performing large-angle attitude slews, using two RWs only, of the type performed to reorient the spacecraft for science observations and for achieving Earth-oriented attitudes for science data downlink communications. ***(F-8, F-9, F-11)***

- Missions such as Kepler and Mars Odyssey, which both have large-angle attitude slew requirements, would benefit from having a ZPM/OPM hybrid control capability that can perform large spacecraft reorientations using only two RWs.

R-8. Conduct on-orbit testing of spacecraft hybrid attitude controllers whenever possible, but especially near the end of life for existing spacecraft prior to their decommissioning, for the benefit of future missions. ***(F-13)***

R-9. Specific technology investment areas should be considered for enabling future hybrid ACS applications such as, but not limited to, the following:

- Nonlinear control laws
- Nonlinear optimization solvers
- Techniques for implementing computationally efficient on-board real-time nonlinear control laws/nonlinear optimization solvers on typical spacecraft flight processors
- Improved high-fidelity disturbance torque modeling, particularly the SRP disturbance
- Simple and reliable articulation platforms for repositioning RWs

- Ultra-low minimum impulse bit micro-propulsion (cold gas) Vernier attitude control thrusters as potential substitutes for RW
- Linear proportional high-efficiency magnetic torquers
- Intelligent RWs with built-in speed/torque commanding and running friction estimators

9.0 Alternate Viewpoint

There were no alternate viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

10.0 Other Deliverables

The deliverables from this assessment included the results of the workshop presentations and deliberations between the participants to include the capture of knowledge from historical hybrid control past experiences, all identified lessons learned to date, and the recommendations of the participants relative to any future risk reduction technical work needed in this specific area.

The results and recommendations were presented in a stakeholder briefing to the SMD Chief Engineer and documented in a NESC final report.

11.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified as a result of this assessment.

12.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Lessons Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure.

Observation	A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions. Avoid squeezing all of this information into a finding or observation

13.0 Acronym List

ACS	Attitude Control System
AIU	Attitude Interface Unit
AMA	Analytical Mechanics Associates
APL	Applied Physics Laboratory
ARC	Ames Research Center
BATC	Ball Aerospace and Technologies Corporation
C&DH	Command and Data Handling
CMG	Control Motor Gyroscope
COBE	Cosmic Background Explorer
EHD	Elastohydrodynamic
ESA	European Space Agency
FDIR	Fault Detection, Isolation, and Recovery
FSW	Flight Software

FUSE	Far Ultraviolet Spectroscopic Explorer
GLAST	Gamma-ray Large Area Space Telescope
GN&C	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center
HGA	High Gain Antenna
HITL	Hardware-in-the-Loop
HQ	Headquarters
ISS	International Space Station
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
L2	Second Sun-Earth Libration Point
LaRC	Langley Research Center
LEO	Low Earth Orbit
LMC	Lockheed Martin Corporation
MAP	Microwave Anisotropy Probe
MLTI	Mesosphere and Lower Thermosphere/Ionosphere
MSFC	Marshall Space Flight Center
MTB	Magnetic Torque Bar
MTSO	Management and Technical Support Office
NESC	NASA Engineering and Safety Center
NPS	Naval Postgraduate School
NRB	NESC Review Board
OCE	Office of the Chief Engineer
OCP	Optimal Control Problem
OPM	Optimized Propellant Maneuver
Orbital	Orbital Sciences Corporation
RCP	Reaction Wheel Control Plane
RCS	Reaction Control System
RFI	Request for Information
RW	Reaction Wheel
SHM	Safe Hold Mode
SMD	Science Mission Directorate
SRP	Solar Radiation Pressure
STM	Shortest-time Maneuvers
TDT	Technical Discipline Team
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics
TRACE	Transition Region and Coronal Explorer
ZPM	Zero Propellant Maneuver

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16.0 Appendices (standalone Volume)

A. NASA Reaction Wheel Tiger Team Workshop Presentation
B. FUSE Workshop Presentation and Technical Papers
B-1. FUSE Workshop Presentation
B-2. FUSE Technical Papers
C. TIMED Workshop Presentation and Technical Papers
C-1. TIMED Workshop Presentation
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D. MAP Workshop Presentation and Technical Papers
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E. Cassini Workshop Presentation and Technical Papers
E-1. Cassini Workshop Presentation
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F. Dawn Workshop Presentation and Technical Papers
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F-3. Dawn Technical Paper
G. Kepler Workshop Presentations and Technical Papers
G-1. Kepler/Ball
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G-3. Kepler Technical Paper
H. Mars Odyssey Workshop Presentation and Technical Papers
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I. ZPM Workshop Presentation and Technical Papers

- I-1. ZPM Workshop Presentation
- I-2. ZPM Technical Papers

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14. ABSTRACT
At the request of the Science Mission Directorate Chief Engineer, the NASA Technical Fellow for Guidance, Navigation & Control assembled and facilitated a workshop on Spacecraft Hybrid Attitude Control. This multi-Center, academic, and industry workshop, sponsored by the NASA Engineering and Safety Center (NESC), was held in April 2013 to unite nationwide experts to present and discuss the various innovative solutions, techniques, and lessons learned regarding the development and implementation of the various hybrid attitude control system solutions investigated or implemented. This report attempts to document these key lessons learned with the 16 findings and 9 NESC recommendations.

15. SUBJECT TERMS
Spacecraft Hybrid Attitude Control; NASA Engineering and Safety Center; Attitude Control System; Attitude Interface Unit; Mixed-Actuator; Reaction Wheel

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