This article is an excerpt from the NESC 2014 Technical Update

Tackling Hybrid Control is Right in the GNC Wheelhouse

The NESC's Guidance, Navigation, and Control (GNC) Technical Discipline Team (TDT) is sharply focused on the development of hybrid attitude control approaches and techniques for NASA spacecraft. The necessity for such hybrid techniques has grown in the last several years as science spacecraft, some working in extended mission operations, have been rendered nonfunctional or placed in jeopardy after crippling reaction wheel failures. ***See "Reaction Wheel Basics" – page 16.***

"Failures have occurred both before and after primary mission completion," said Mr. Neil Dennehy, the NASA Technical Fellow for GNC. "Fortunately, many project teams were able to successfully develop and implement a hybrid attitude control scheme, using both the remaining functional wheels and the thrusters. This allowed these spacecraft to continue in a scientifically productive mode using nonstandard mixed-actuator techniques to obtain three-axis control with only two wheels."

The story of hybrid control

The challenge in implementing hybrid attitude control, said Dennehy, is manipulating the physics of an under-actuated space vehicle, harnessing the remaining attitude control actuators, and often exploiting naturally occurring disturbance torques. "The project teams that have faced the challenges of dealing with failed reaction wheels have responded with clever and implementable solutions for hybrid attitude control. What they accomplished is a great feat of engineering and flight operations innovation," Dennehy said. The end result is a restructured, but effective, configuration and operating mode for these spacecraft, though one likely not envisioned by the designers of the original attitude control system (ACS).

With billions of dollars invested in spacecraft assets, which are collecting invaluable science data, the need to keep those spacecraft operational for as long as possible, in today's economic climate, is a clear-cut goal. "NASA has a history of trying to squeeze more and more out of its science spacecraft," said Dennehy, putting the development of successful hybrid ACS at the top of the GNC "to do" list.

Since reaction wheel problems began emerging in 2001, efforts have been underway to address the issue. In early 2007, NASA formed a tiger team to investigate the wheel anomalies and failures occurring on spacecraft, and in spring 2013, the NESC sponsored a NASA workshop on Hybrid (Mixed-Actuator) Spacecraft Attitude Control, gathering key personnel from across NASA Centers and industry for a 2-day delve into contingency spacecraft attitude control techniques.

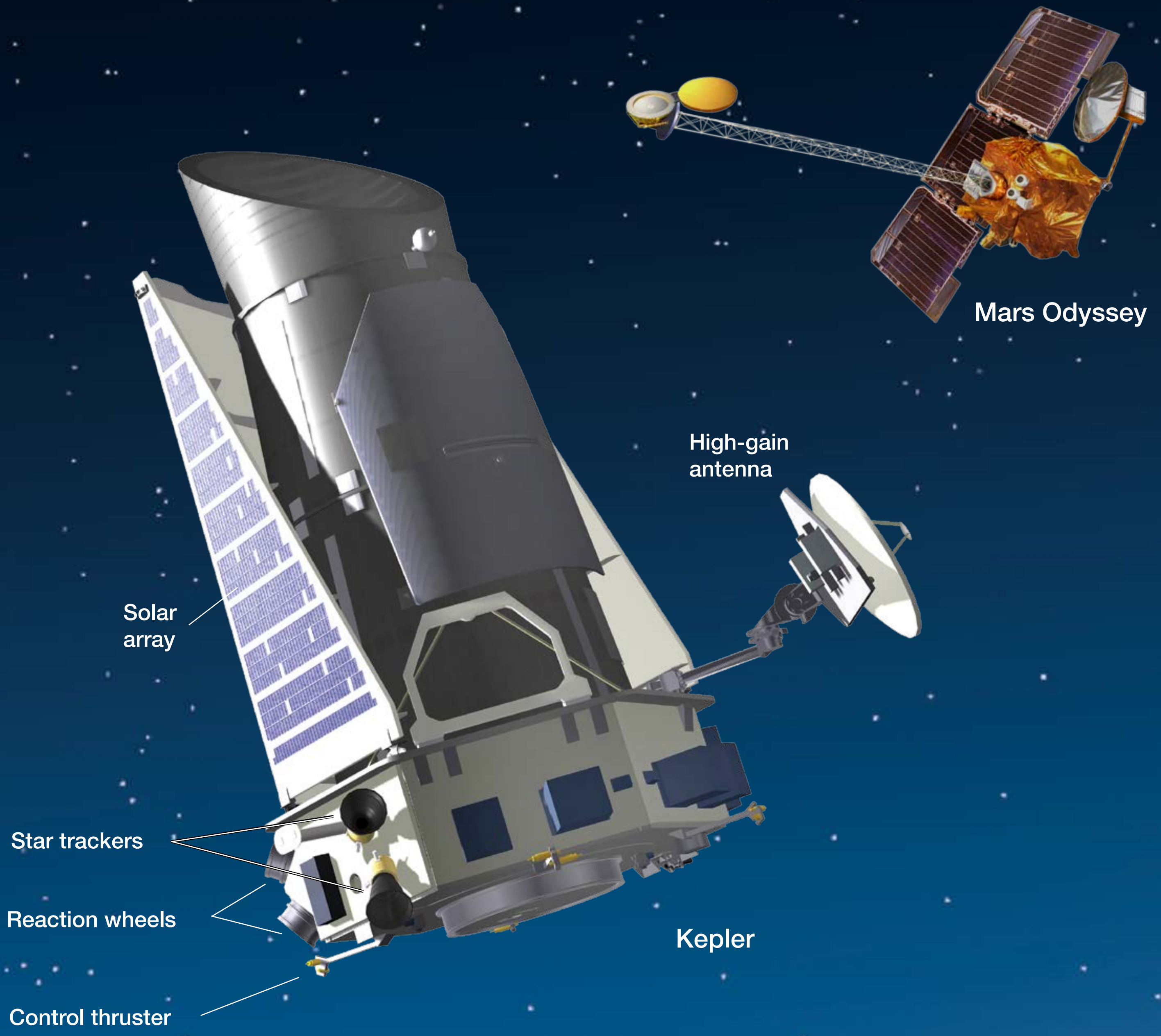
At the workshop, discussions revolved around previously successful hybrid control techniques developed by the ACS teams for spacecraft such as Far Ultraviolet Spectroscopic Explorer (FUSE) and Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED). Brainstorming sessions were held to tackle current issues faced by Kepler, Dawn, and Mars Odyssey spacecraft.

Seven different spacecraft were discussed at the workshop, and Dennehy said that the range of hybrid control implementation challenges was just as varied. What they quickly discovered was that a mission's operational requirements, a spacecraft's physical configuration, ACS architectures, and more, all play a huge role in the development of a successful hybrid approach. As presentations and discussions ensued, a revealing list of lessons learned emerged, some of which came into play sooner than expected. ***See "Top Five Takeaways for Hybrid Control" – page 16.***

Extending the Kepler Mission

Not long after the workshop, Kepler suffered the loss of a second reaction wheel, leaving the spacecraft with only two operational wheels. After issuing an open call seeking innovative hybrid attitude control ideas for possible application in repurposing Kepler for new science objectives, the NESC coordinated a spacecraft pointing

DAWN



technical interchange meeting (TIM) to evaluate those ideas. Today, after the successful development of a new two-wheel/thruster hybrid controller by the spacecraft's prime contractor, Kepler is once again collecting valuable science data. ***See "About Kepler" – page 16.***

"Initially it looked like the Kepler Mission was done," said Dennehy. "But the project team and the GNC community felt something could be done to regain three-axis attitude control. We used the pointing TIM as a forum for the project to hear and evaluate a wide variety of hybrid control ideas from the community that could potentially help accomplish new types of Kepler science observations. It was a real group effort to get Kepler back on the air, pointing sufficiently to perform science. Collectively we were able to accomplish that, and that's a big deal. Kepler isn't collecting exactly the same science data as it was originally, but it's doing some very scientifically valuable observations."

The future of hybrid control

Following Kepler's success, research continues at the Naval Postgraduate School, under NESC sponsorship, to evaluate nonlinear hybrid attitude control concepts, ideally for Kepler, but which may have broader applicability to other NASA under-actuated spacecraft. These concepts would work without the use of propellant-consuming thrusters, employing only the two remaining functional wheels.

In the near future, Dennehy envisions a second workshop to continue efforts in developing hybrid ACS techniques. "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," he said. "This is the kind of challenging problem a GNC engineer likes to work on." □

Reference NASA/TM-2014-218539

TIMED

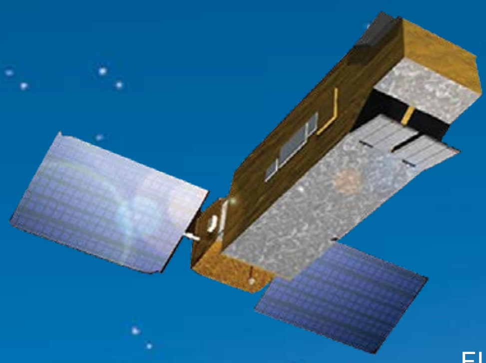
About Kepler

Launched in March 2009, the Kepler spacecraft was tasked with performing a photometric survey of approximately 100,000 stars in a section of the Milky Way near the constellation Cygnus. Its mission was to detect planets and determine the prevalence of Earth-sized planets in or near the habitable zone. Planet detection required Kepler to maintain a pointing stability of better than 9 milliarc-seconds for science observation periods longer than 30 minutes.

Near the end of Kepler's 3.5-year prime mission, a reaction wheel failed when its friction increased beyond the attitude control law's torque command. A second wheel was lost in May 2013, which prompted the Kepler Project to request support from the NESC GNC TDT and spurred the development of a two-wheel hybrid controller at Ball Aerospace (the Kepler prime contractor). A known challenge, GNC engineers at Jet Propulsion Laboratory had already conducted a hybrid control feasibility study that showed achieving Kepler's original long-term pointing stability with only two wheels would be unlikely.

In parallel with Ball Aerospace, members of the GNC TDT independently worked to analytically demonstrate the feasibility of a bias-momentum hybrid control approach for Kepler. Results obtained by Ball engineers and the GNC TDT compared favorably, and the new Ball-designed two-wheel/thruster hybrid controller was implemented on the repurposed Kepler observatory, called K2.

K2 is now successfully collecting science data using this hybrid attitude control. The momentum bias, created by the combination of the two remaining wheels, will be oriented normal to the Kepler spacecraft's orbital plane so targets in that plane can be tracked by modulating the bias. K2 will be pointed in the ecliptic plane to exploit the solar radiation pressure disturbance torque rather than fight it. In December 2014, the K2 mission logged its first exoplanet discovery of a planet 2.5 times the diameter of Earth, named HIP 11645b, proving K2 is once again performing valuable science.



FUSE

Reaction wheel basics

Reaction wheel (RW) technology provides spacecraft attitude control torque and momentum management functions. RWs rotate the spacecraft and are frequently used for stabilizing, slewing/orienting, and precision pointing spacecraft platforms. Typical RW actuators consist of a rotating inertia flywheel, a wheel suspension system (almost exclusively lubricated bearing balls), a wheel drive motor, and wheel drive electronics encased in a wheel housing/enclosure. RWs are used in Earth and Mars orbiting spacecraft as well as on interplanetary vehicles, with a typical complement of four RWs providing a redundant three-axis attitude control capability. While the failure of one RW can typically be managed, the failure of two wheels poses a significant challenge for accomplishing some form of three-axis attitude control.

Top five takeaways for hybrid control

No one hybrid solution is applicable to all spacecraft, but some key lessons learned are applicable to all ACS hybrid design.

1. While successful hybrid (mixed actuator) ACS techniques have extended the science productivity of several NASA spacecraft, prelaunch considerations for implementing hybrid attitude control were nearly non-existent. ACS architectural considerations early in system development may facilitate hybrid control implementations in the later stages of mission life.

2. There are advantages to considering a bias-momentum approach when designing a two-wheel-based hybrid control system, as was successfully implemented on the repurposed Kepler.

3. Spacecraft fault management/safing/safe mode aspects should be carefully considered when designing new hybrid control modes.

4. Maintaining ACS flight software testbeds whenever possible will aid in flight readiness recertification efforts in the face of wheel in-flight anomalies.

5. On-orbit testing of spacecraft attitude controllers in hybrid ACS configurations, especially near the end of life, is wise and will likely benefit future spacecraft missions.