Reaction wheels ensure satellites maintain the right attitude: Part 2

MARCH 3, 2022 BY BILL SCHWEBER

Electrically driven reaction wheels use conservation of angular momentum to keep a satellite pointed in the right direction, eliminating the need for fuel-powered and limited thrusters.

Part 1 was an introduction to reaction wheel basics. This part continues the investigation into their performance and construction.

Physics and analysis

Although the basic principle of reaction wheels is relatively simple, it's no surprise that a fully functioning precision unit includes much more than just controlling a spinning rotor. As with the gyroscope, error and imperfection sources include friction, damping, flexing, and other factors. Detailed models using these real-world factors are needed to fully analyze error sources and their magnitude **(Figure 1)**. This is especially the situation as the reaction wheel usually functions in closed-loop, autonomous system design, and in-use "calibration" or fine-tuning is both impractical and undesirable.

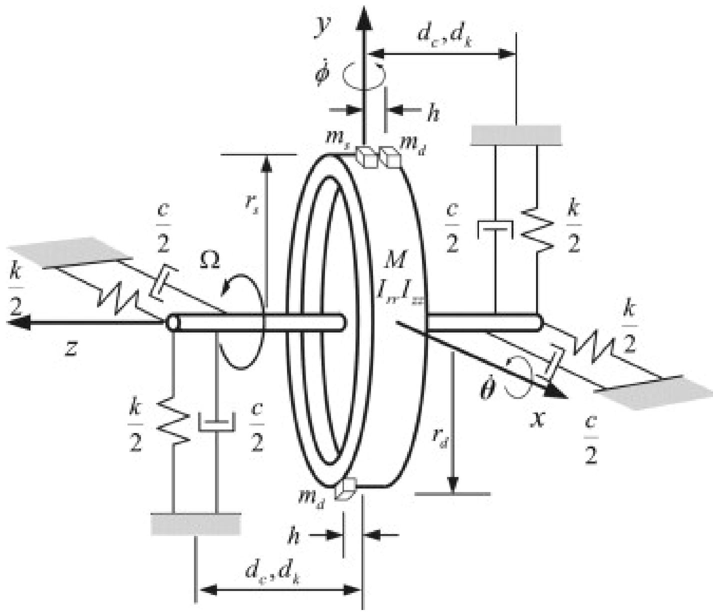

Fig 1: To achieve the performance and precision needed, the reaction wheel must be modeled in great detail, with all possible error sources analyzed and taken into account. (Image: Science Direct/Journal of Sound and Vibration)

Make or buy

Reaction wheels are used in nearly all orbiting space vehicles. For example, the Hubble space telescope was launched with six for redundancy. Over its long life, four of them have been replaced by Space Shuttle astronauts, as they failed due to wear-out beyond their service life. (Those failures actually gave scientists a good opportunity to study long-term lubricant performance in the vacuum of space on the returned units.)

The Kepler space telescope was launched in 2009, and in 2012, one of its four reaction wheels failed **(Figure 2)**. Since it required only three reaction wheels to aim the telescope accurately, its mission continued, but a second reaction wheel failed in 2013, this ending Kepler's primary mission. Despite this loss, its primary mission goal was re-directed, and a clever "hack" was used to keep Kepler viable until its official retirement in 2018 (more on this later).

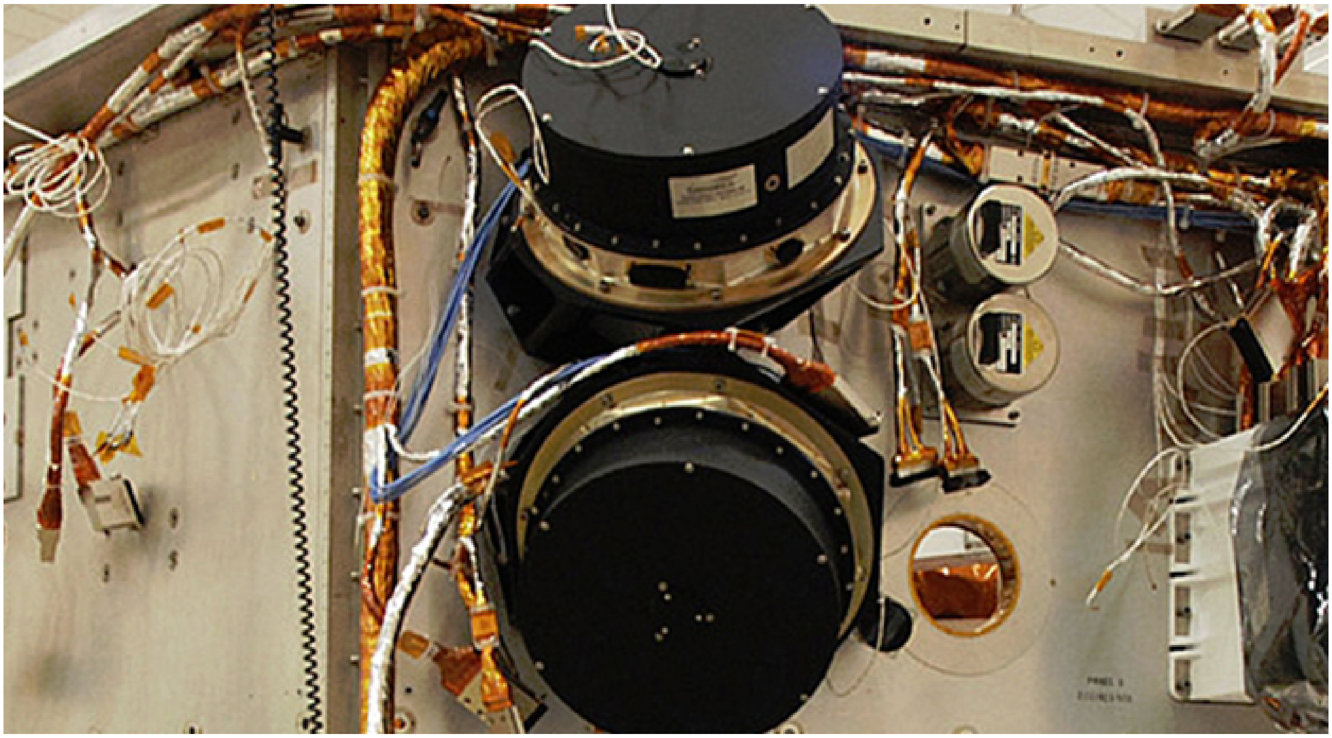

Fig 2: The installation showing two of the four reaction wheels on the Kepler space telescope shows the modular, enclosed nature of these devices. (Image: Space News)

Of course, the recently launched James Webb Space Telescope (JWST) has multiple primary and backup reaction wheels to maintain its attitude. These are built by Rockwell Collins Deutschland GBMH (Formerly Teldix) and are descendants of the Teldix reaction wheels used on NASA's Chandra, EOS Aqua, and Aura Missions.

However, reaction wheels are not limited to large or one-of-a-kind satellites. Due to their fairly simple construction ("simple" only in the relative sense), small versions are also used in the very popular CubeSats; some of these are tested and controlled via a PC and USB interface **(Figure 3)**.

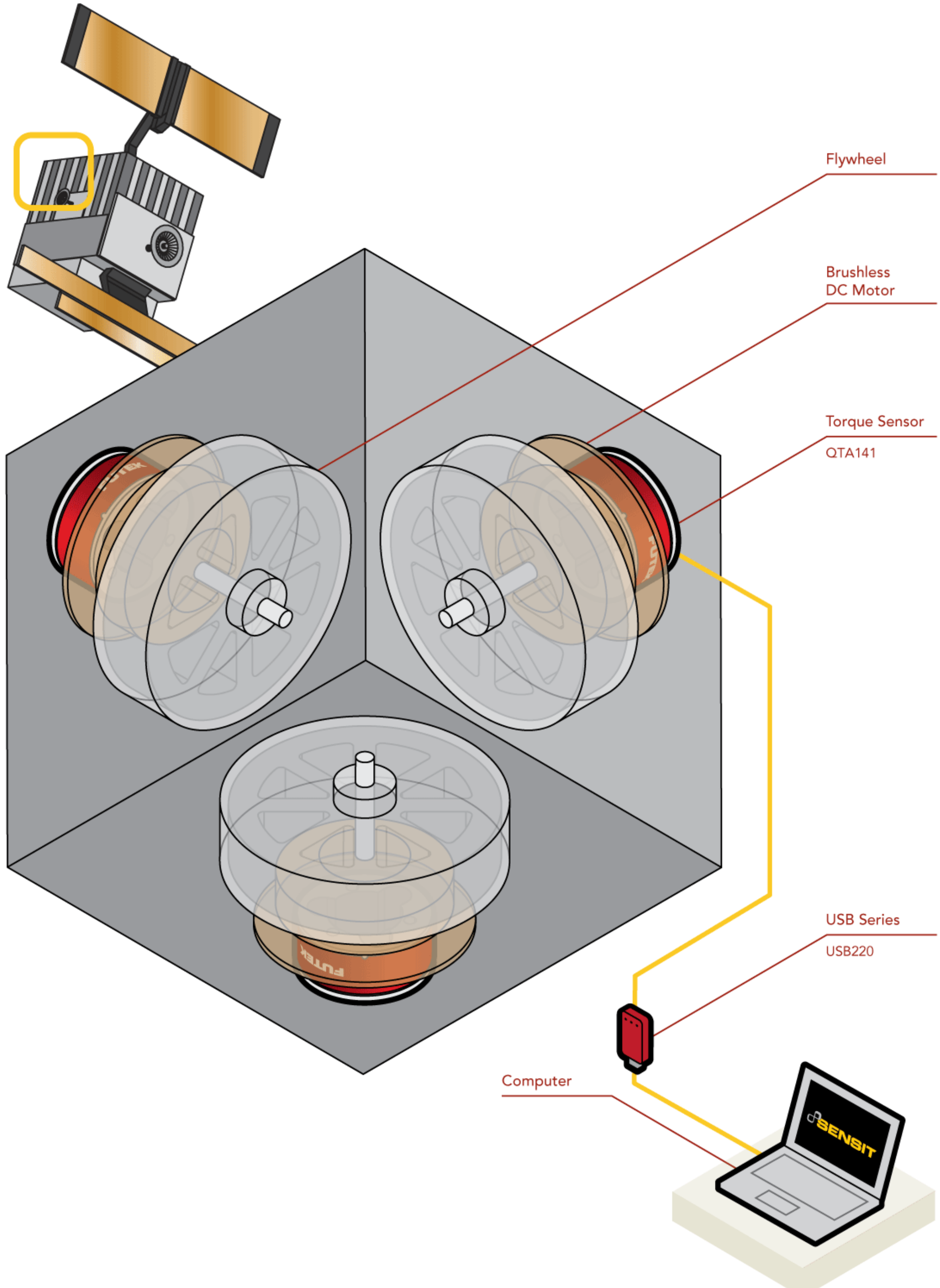

Fig 3: Small reaction wheel sets are used on some CubeSats and include a USB interface for bench test and operation. (Image: Futek Advanced Sensor Technology)

Another example is discussed in a PowerPoint presentation from the University of Toronto Space Flight Laboratory (UTSFL) (see **External Reference 1**). This presentation illuminates some of the design insights and tradeoffs explored as their team had about one year to design and build a modest run of 15 reaction-wheel units for their CanX satellite program **(Figure 4)**. These include issues related to the use of standard versus custom electric motors, magnetic design, enclosure, bearings, and final achieved performance specifications; in the end, they built 20 units on schedule.

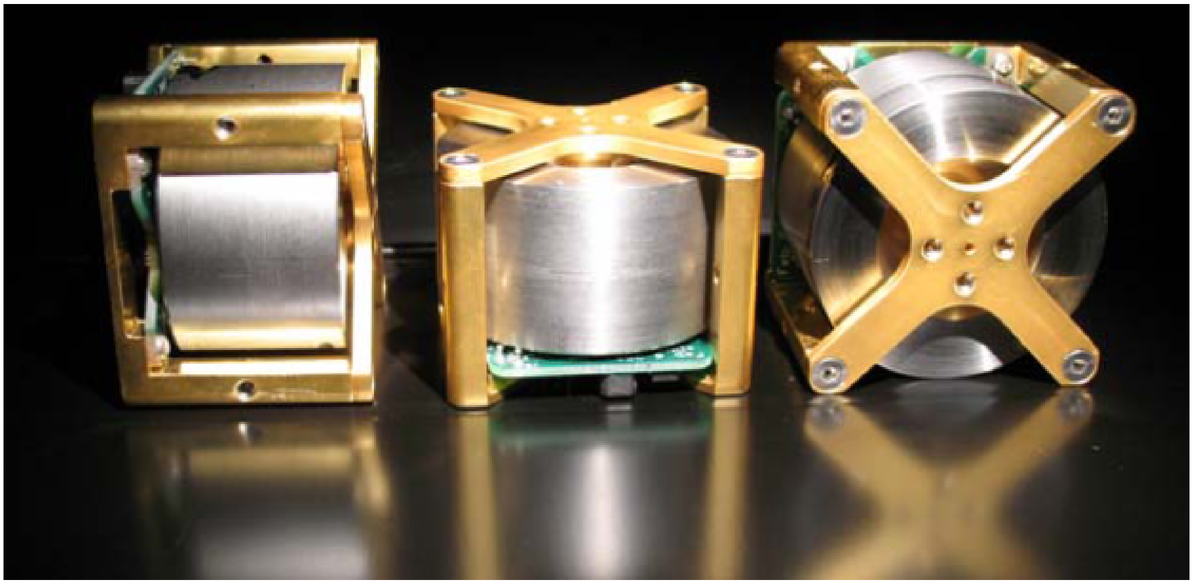

Fig 4: Twenty of these small reaction wheels were designed, analyzed, and built-in a year, using both standard and custom components. (Image: University of Toronto Space Flight Laboratory)

Standard "off the shelf" commercial reaction-wheel units are available for small to medium satellites from vendors such as Honeywell Aerospace, among others. Their 7-inch diameter HC7 and 9-inch HC9 are complete, enclosed reaction wheel assemblies (RWAs) offering 6 and 11.5 newton-meter-seconds of momentum, respectively; these units are complete with integral electronics and have a single RS-422 connector for signals and power **(Figure 5)**.

Fig 5: Reaction wheels are available as complete, packaged standard units such as these 7- and 9-inch ones; they have a single connector for power and signal. (Image: Honeywell Aerospace)

A look at their top-level specifications shows other key parameters such as power requirements, mass, size, and anticipated operational life **(Figure 6)**.

PARAMETER	UNIT	CAPABILITY*	
Model (Gen 1)		HC7	HC9
Momentum	Nms	6	11.5
Reaction Torque	Nm	0.2	
Standby Power. nominal	Watts	5	
Peak System Power. max	Watts	130	
Steady State System Power. max	Watts	25	
Mass	Kg	<4.5	<5.5
Envelope. H x D	Cm	10.5 x 20	11.5 x 25
Integral Electronics	No/Yes	Yes	
Mission Life	Years	7	

Fig 6: The specifications of the Honeywell units show the similarities and differences between the HC7 and HC9 models. (Image: Honeywell Aerospace)

For those situations where the designers prefer to provide their own electronics, the Honeywell HR04 reaction-wheel core is also available **(Figure 7)**; again, the top-tier specifications are revealing **(Figure 8)**.

Fig 7: This dual reaction wheel, model HR04, is the system's core; the user provides the associated electronics. (Image: Honeywell Aerospace)

PARAMETER		UNIT	CAPABILITY*
Momentum, per RWA		Nms	1 Nms @ 9000 rpm
Net Output Torque, per RWA		Nms	.030 Nm
Quiescent System Power		Watts	2.0
Peak System Power, max at 9000 rpm		Watts	48
Steady State System Power, max	at 9000 rpm	Watts	<17
	at 3000 rpm	Watts	<8
Mass Integrated Array		kg	< 2.6
Envelope, H X W Integrated Array		cm	16.0 x 21.2 x12.9
Integral Electronics		No/Yes	Yes
Mission Life		Years	5 minimum
Storage Life		Years	1 minimum

Fig 8: Even without the electronics, the specifications of the HR04 show what it can do. (Image: Honeywell Aerospace)

Whether for an LEO such as a CubeSat, an MEO satellite, or even a geostationary one, the reaction-wheel design and operation life match the satellite's expected operational life. Keep in mind that an LEO has a life of about a year before its orbit decays, an MEO may have several years, and a geostationary satellite life would be on the order of a decade. A unit designed for a longer life than needed would be more costly, heavier, more complicated, and harder to evaluate for long-term performance – in other words, overdesigned at a cost in time, money, intricacies, and mass.

Make your own at home?

Some advanced experimenters even build their own reaction wheels simply for the experience and experience of doing so. One amazing example is described in **Reference 2** from Charles' Lab in France (don't worry, the English is perfect!). It shows the full electronic and mechanical design, construction, evaluation, and more, including parts fabricated via 3-D printing after CAD modeling **(Figure 9)**.

Fig 9: This advanced amateur designed and built a complete reaction-wheel system that included designing and fabricating some parts using 3D printing. (Image: Charles' Labs)

The electronics of this "homemade" reaction wheel has three primary functions:

- Measure the current angular speed via the **MPU6050** gyroscope/accelerometer MEMS chip,
- Drive the stepper motor using a **DRV8825** module,
- Run the control algorithms on **ATmega328** microcontroller, on an Arduino Nano board.

Their roles are detailed in the electronics wiring diagram **(Figure 10)**:

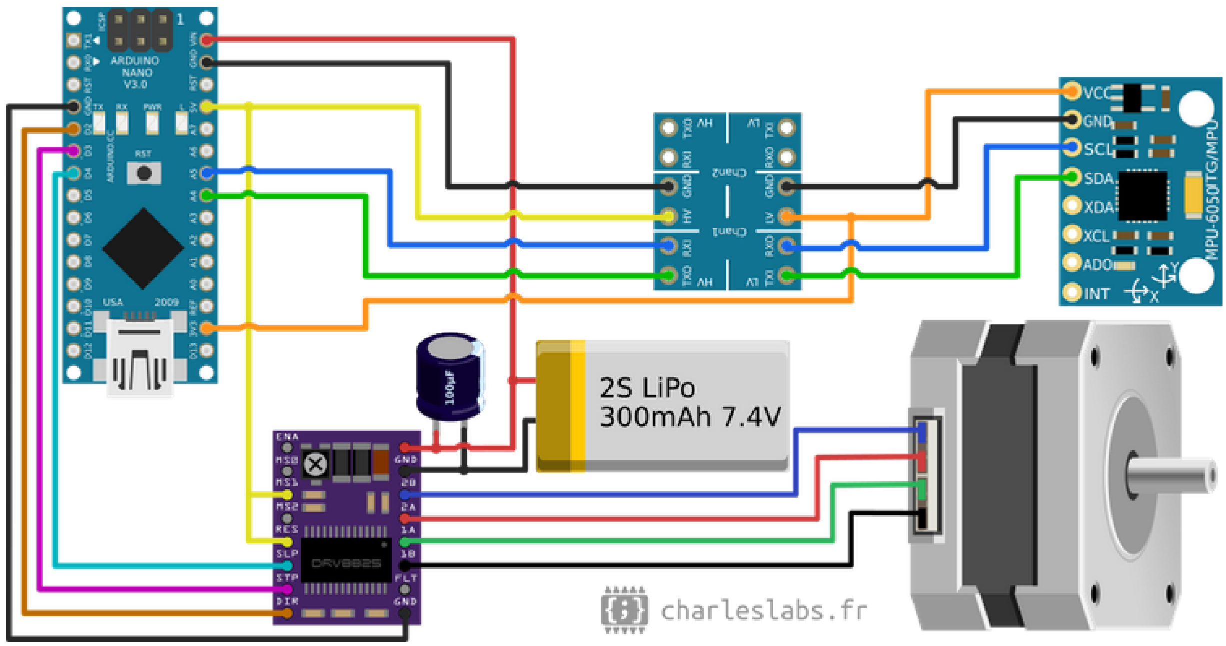

Fig 10: The associated electronics for the homemade reaction wheel uses standard, low-cost ICs, and related electronics in well-defined roles. (Image: Charles' Labs)

Issues and alternatives

Reaction wheels are widely used, but, as with all solutions, they have some shortcomings and can degrade or fail. In addition to these, they can "suffer" from a condition called "saturation." If there is a small continuous torque on a satellite (which may be from solar radiation pressure), the reaction wheels spin continuously, faster and faster, to counteract it.

There needs to be a way to "dump" the momentum, analogous to deliberately discharging a capacitor to counteract this. The usual technique, used by the Hubble Space Telescope and other satellites, is to use a set of electromagnets (again, the virtues of electrically powered functions) in a "magnetorquer" to exert a weak countering torque against the Earth's magnetic field as the satellite "cuts through" that extended field.

The countertorque generated by this technique is a function of magnetorquer's size and power, of course, as well as the satellite's altitude, as the Earth's magnetic field drops off rapidly with distance. There are even cases where a reaction wheel has failed, so the magnetorquer alone was being used to aid in attitude adjustment and control, although it is not as effective or efficient as the reaction wheel – it has been done.

Similarly, the radiation pressure, which is partially responsible for the changes in satellite attitude, can also be leveraged to counteract some problems. By adjusting the orientation of the vanes on the satellite, the radiation pressure can be managed and employed beneficially to some extent; this is somewhat analogous to tacking a sailboat against the wind, although there is a "cost" in power usage and accuracy. But sometimes difficult times call for difficult solutions: this technique was used on the Kepler space telescope to maintain attitude for its refined mission after two of its four wheels failed.

Conclusion

Reaction-wheel systems show how basic physics principles can offer creative solutions to challenging problems. At the same time, taking these ideas and making them into practical, effective, high-performance solutions requires detailed analysis, modeling, and simulation, all followed by careful consideration of the operating environment, materials, electronics, fabrication, and installation.

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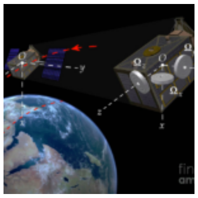
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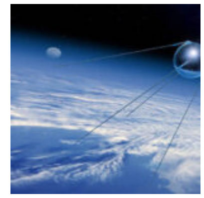
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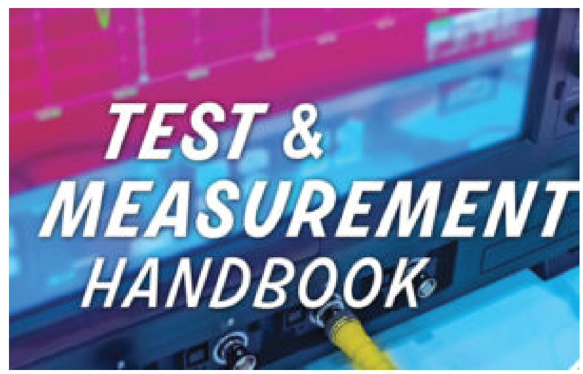

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