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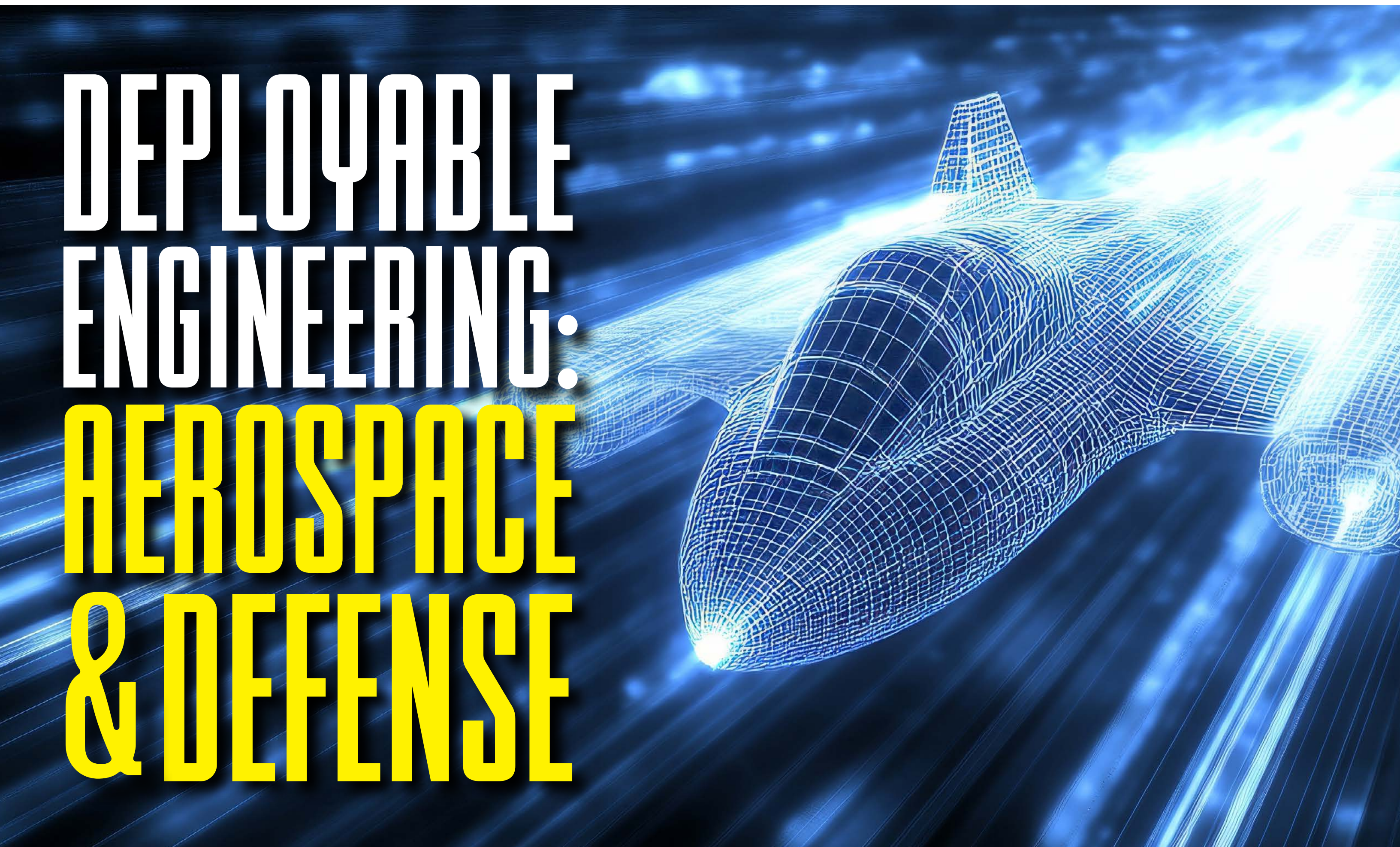
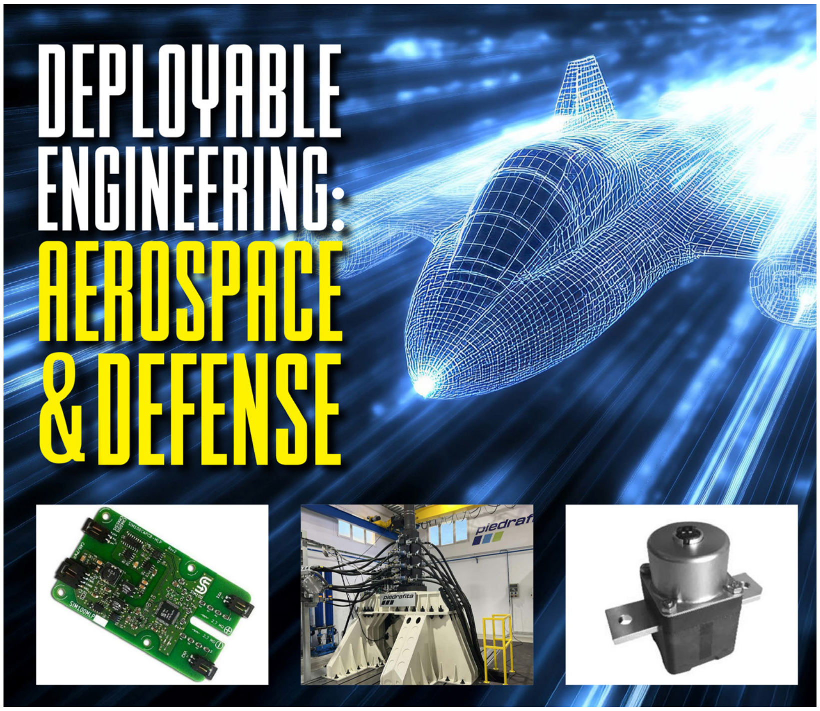


DEPLOYABLE ENGINEERING: AEROSPACE & DEFENSE



Rehana Begg,
Editor-in-Chief
Machine Design

CONTENTS

Editor's Note: DESIGNING FOR MISSION SUCCESS

Next-generation technologies can be transformative. This is the driving force behind this collection of articles. Contributors dig into the product requirements and solutions shaping the fundamental mechanisms of high-precision motion control. Drawing from cross-sector deployments in designing, prototyping and producing componentry, these articles highlight emerging trends and proven technologies that bolster reliability in the most demanding environments.

Reach me directly if you have questions or comments: rbegg@endeavorb2b.com

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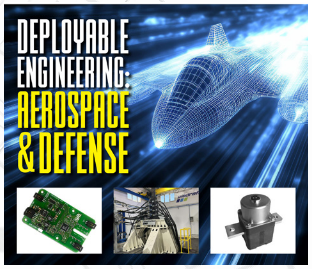


Moog

CHAPTER 1:

R&D Spotlight: Designing a Test Bench for Armored Vehicle Suspensions

REHANA BEGG, Editor-in-Chief, *Machine Design*

Engineers at Moog and Piedrafita Systems custom-designed a test rig that simulates the movement of a hydraulic vehicle's tracks over uneven terrain.

Test engineers undoubtedly agree on the need for a test rig that can evaluate the reliability of a vehicle's suspension system. However, developing and building a high-performance fatigue bench that could be used in the design and specification of armored vehicle suspensions raises the bar on the unique specifications needed for combat scenarios.

Designed for battlefield tasks, these formidable machines are heavyweight and move in terrains with many obstacles at high speed and low visibility. The requirements are highly demanding due to the vehicle characteristics and usage.

Armored vehicles are designed to "make high velocity movements with high forces within the suspension elements, said Luis Barrada, technical director, Piedrafita Systems. "There is a high frequency and low amplitude movement present, caused by the track pitch. It is imperative to have a reliable system that can withstand those hard conditions and deliver the correct suspension characteristics over the lifetime of the system. A fatigue bench or rig that could handle these conditions would be necessary to ensure this."

Cue the engineers at Moog's industrial segment who routinely combine electric, hydraulic and hybrid technologies to design and manufacture applications in energy, industrial machinery, simulation and test markets.

Spain-based Piedrafita Systems, which develops rotary suspension solutions for military land platforms, worked closely with Moog engineers to design the Merlin test bench, a high-performance test rig that would be used in designing heavy-duty vehicle suspensions. Piedrafita Systems specified the need for a fatigue test system capable of delivering forces up to 500 kN (80,000 joules per meter) at a speed of 8m/s and up to 200 Hz.

"Piedrafita asked Moog how to make feasible this new system," said Juan Carlos Molinero, project manager for Simulation & Test at Moog. "After our study and performance tests, we collaborated with Piedrafita to develop a concept that could test an armored vehicle's suspension."

The Merlin test bench was unveiled in July 2023, bringing to market a system capable of simulating intense vibrations, and was deemed crucial for assessing shock absorbers and suspension systems in combat scenarios.

Not the First Rodeo for Fatigue Test Bench Design

The parameters may have been unprecedented, but it would not be the first time Moog had worked with Piedrafita on pioneering a novel solution. The companies collaborated in 2013 on the design of a fatigue test bench for developing a shock absorber. Back then, the pair designed a fatigue test bench for military ground vehicles operating in extreme

A custom-designed test bench developed by Moog and Piedrafita Systems simulates the movement of a hydraulic vehicle's tracks over uneven terrain. The system incorporates hydraulic actuators with digital servo valves, a test controller, power cabinet, digital pumps and an accumulator bench with piping. Moog

Hydraulics Unit	System Pressure	280 bar
	Accumulator Capacity	900 litres
	Pumps Power	280 kW
Suspension Testing	Maximum elastic + damped force	533 kN
	Total Stroke	700 mm
	Maximum Suspension Vertical Velocity	8 m/s
	Maximum Acceleration	100 G
	Frequency Response (Large Displacement)	Up to 40 Hz
	Frequency Response (Small Displacement)	Up to 140 Hz
Controller	MOOG Controller Type SmarTESTOne closed loop with *Replication Software*	

Piedrafita and Moog collaborated on developing the Merlin test bench, a system capable of simulating intense vibrations. Suspension test bed features are specified to assess shock absorbers and suspension systems in combat scenarios. Moog

conditions that could deliver up to 80kN at 5 m/s velocity.

This time, however, Piedrafita and Moog's design and test engineers went above and beyond to deliver a test bench system that not only simulates the movement of an armored vehicle's tracks over uneven terrain but can reach five times higher forces at twice the velocity and double the frequency range. This level of vibration is crucial for evaluating the resistance and performance of shock absorbers as well as suspension systems in combat scenarios.

The system combines the heavy-duty loading typically found in a high-capacity hydraulic press with the speed and fidelity of a motorsport 4/8-poster rig.

According to the engineers, the test rig is designed to replicate the movement of an armored vehicle over an APG track, as the vibrations experienced during the run are critical in assessing the resistance and related capabilities of the shock absorbers and suspension during combat. The test bench includes a high-performance controller and customized actuators that can reproduce vibration up to 100 G, according to Moog's chief engineer, Ian Whiting. Nonstandard turbocharged valves were used to achieve the 500kN, 8m/s, 200Hz and 100 G corners of the operating envelope.

"Our new test system is capable of carrying out tests for 70-ton tracked vehicles, with a weight of around 5.5 tons per wheel," added Piedrafita's Barrada. "Our engineers can test wheel stations under very demanding profiles for main battle tanks such as the Abrams, Challenger, Leclerc and Leopard."

A Better Design for a Rotary Hydropneumatic Suspension System

The test rig's delivery is a milestone feeding into a larger project intended to improve heavy armored vehicles mobility, particularly new and legacy main battle tanks.

Piedrafita Systems has been developing a rotary hydropneumatic suspension system for armored vehicles in consortium with [Repack-S] and IB Fischer CFD+Engineering GmbH. The SRB Project is backed by a grant from the European Defence Industrial Development Programme (EDIDP).

Piedrafita Systems acts as the coordinator on the collaboration and leverages its expertise in designing and validating damping systems. The test bench enhances the company's proficiency when it comes to standing up to the challenges of designing suspension solutions and improving mobility of heavy armored vehicles and battle tanks.

Optimizing Lifecycle Efficiency

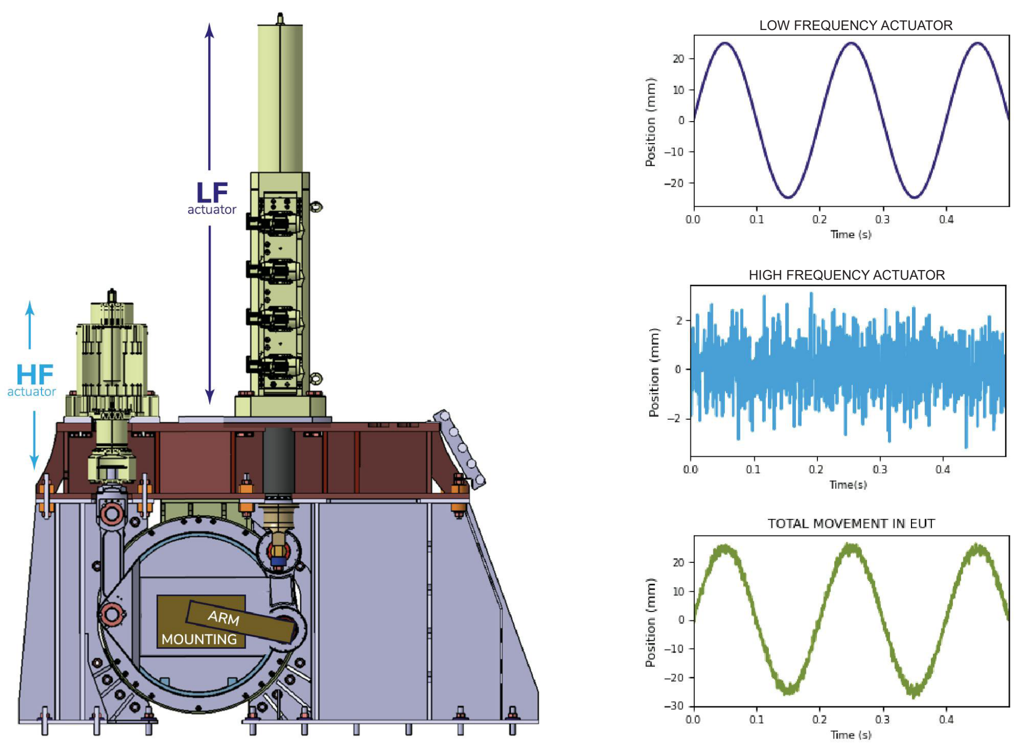
Essential components making up the test system include: a Moog test controller, two hydraulic actuators with Moog digital servo valves, an HPU with Moog digital pumps and a power cabinet, and an accumulator bench with the required piping.

Moog's Analysis and Simulation Toolbox was also used to demonstrate the likely per-

THE WORKING PRINCIPLE

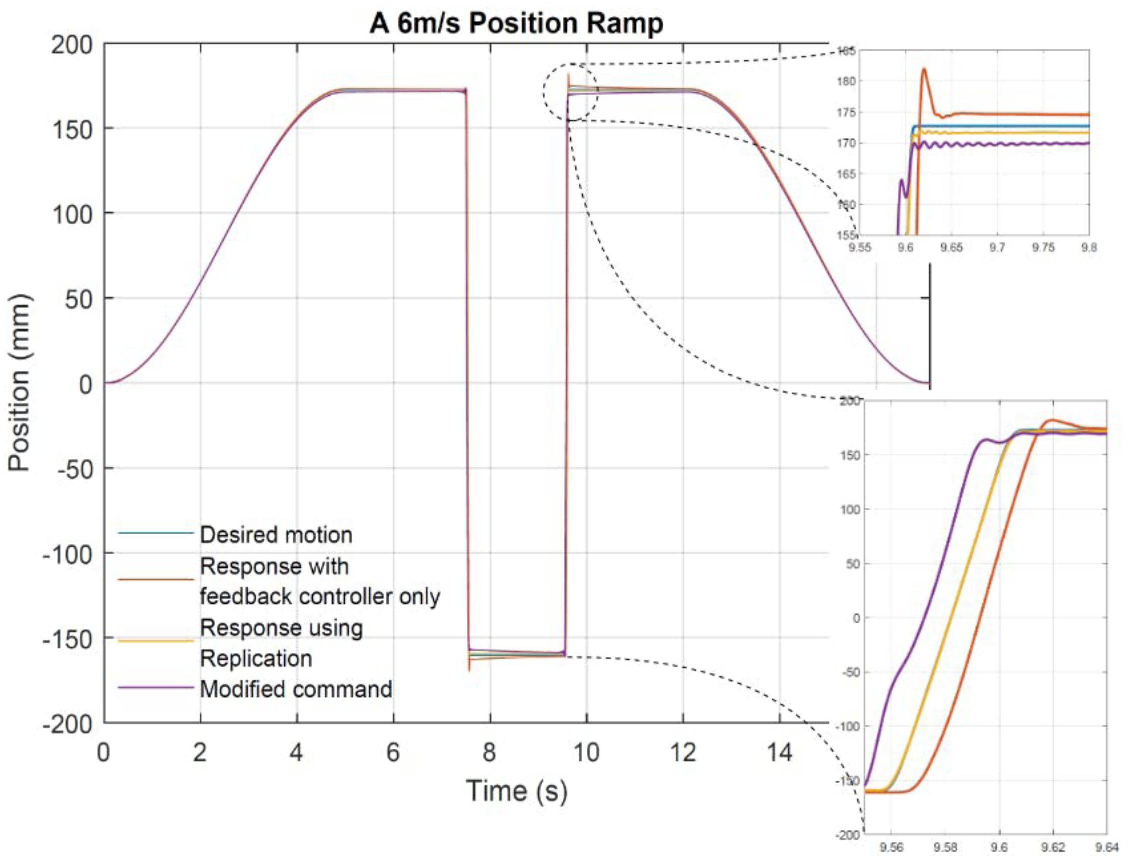
#1 Low Frecquency actuator for large suspension displacements up to 30 Hz

#2 High Frecuency actuator for small suspension displacements from 30 Hz to 140 Hz



The signal imposed in the LF actuator (**dark blue signal**) is overlayed with the HF actuator movement (**light blue signal**) to result in the **green signal** to which device under testing (DUT) is subjected.

The "working principle" behind Moog and Piedrafita's innovative test rig is that the signal imposed in a low-frequency (LF) actuator is overlaid with the high-frequency (HF) actuator movement to result in "total movement" to which the device under testing is subjected. Moog



Piedrafita and Moog designed a fatigue test bench for military ground vehicles. The test bench includes a high-performance controller and customized actuators that can reproduce vibration up to 100 G. This schematic depicts the desired motion response, response with feedback controller only, response using replication and the modified command.
Piedrafita Systems

formance of the proposed twin-actuator servo system. Typical functions of the software include processing customer data, building Simulink models (a MATLAB-based graphical programming environment) and running model cases studies. The simulation software was used to relay the required motions and forces to the test article, according to Moog's engineers.

In addition to the task of selecting and sizing the test system's respective components, Moog was tasked with commissioning and training the Piedrafita team on how to operate the system.

"The Merlin test bench is a high dynamic system with high energy accumulated, so it must be operated correctly," said Federico Gil, lead engineer of Dynamic Testing for Piedrafita Systems. "The software that Moog provides for operating the system (Moog Integrated Test Suite and Replication) are user friendly, even though it is a complex system to operate. This advantage, plus a well-designed training session in the test bench/rig, allowed Piedrafita Operators to learn fast how to operate it and take the most out of all the capabilities the system has to offer."

Investing in ROI and Reliability

The high-performance test bench minimizes costs and enables tests in a controlled manner. In addition, it waylays the need for driving over a proving ground, "thereby protecting a crew who would otherwise have to be on board a vehicle," said Barrada.

Proving grounds are generally large terrains used for testing the durability, the weaknesses and probable life of operating equipment under various conditions.

The use of the rig is scalable to other manufacturers in the aerospace and defense segments, too. "Manufacturers such as General Dynamics and KNDS can also test their vehicles' suspension on our new test system," said Barrada.

The next phase of this project (SRB2) is well underway. According to a European Defence Fund (EDF) 2023 note, Rotary Suspension for Armoured Vehicles 2 is a follow-on project developing a fully rotary hydropneumatic suspension system for heavy armored vehicles. The objective is to integrate a toroidal piston as the elastic element and a fully rotary hydraulic damper as the damping element. The new suspension, state the engineers, would improve mobility in heavy armored vehicles, and new and legacy main battle tanks in particular.

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CHAPTER 2:

Powering the Skies: The Critical Sensor Requirements for Advancing Air Mobility

DARREN MAGAS, Senior Product Manager Aerospace Business, *Sensata Technologies*

Sensor technology companies are leveling up sensor capabilities that best support advanced air mobility capabilities.

Advanced air mobility (AAM) is reshaping industries that have defined human progress for decades. Consider aerospace and automotive. At the heart of the industries' transformation lies electrification, which has become the driving force behind the revolution in air travel. This shift doesn't just impact vehicles—it extends to every corner of the supply chain, encouraging suppliers and manufacturers to embrace innovation that makes air travel safer, cleaner and more efficient.

Today's traditional aircraft contribute nearly 3% of global emissions, proving the urgent need for a greener alternative. At the same time, rapid urbanization has heightened the demand for solutions to reduce traffic congestion. Advanced air mobility—fueled by breakthroughs in battery and fuel cell technologies—seeks to address both challenges by reducing carbon footprints and providing a sustainable alternative for urban and regional transportation.

But as this exciting future unfolds, the success of AAM depends on more than just propulsion systems and flight designs. To achieve truly transformative outcomes, the aerospace industry must ensure next-generation sensor technologies are developed and deployed. These sensors are the "eyes and ears" of the aircraft, delivering the critical data needed for autonomous flight, collision avoidance, air traffic management and even passenger comfort.

The question now is: What must the aerospace industry do to equip itself with the right sensors to support the development of advanced air mobility?

Electric aircraft use similar components to electric vehicles but have some unique requirements when it comes to component weight, safety and system design. Flight range and payload capacity are directly tied to weight, prompting engineers to make intricate changes to remove even a tenth of a pound from systems and components. Electric aircraft typically have many more electric motors and battery modules or fuel cells, all cross-tied to prevent total loss of electric propulsion in case of failure, which needs additional electrical safety components.

Additionally, the systems and components need to function reliably at high voltage and power (up to 450A and 1,000 Vdc) over a long lifespan. Finally, they must operate under extreme temperatures (−55°C to +85°C), at altitudes from 10,000 to 35,000 ft, and withstand high levels of vibration and shock.

This article will address the product requirements and solutions for high-voltage system circuit protection, isolation monitoring for safety and electric propulsion unit efficiency using example within Sensata Technologies' portfolio:

High voltage system protection. For high voltage-high power systems, commutation functions are managed by high voltage contactors. These devices handle switching during startup and shutdown and provide short circuit protection. They are often paired with a pyrofuse switch, which can quickly disconnect the battery in a short circuit event.

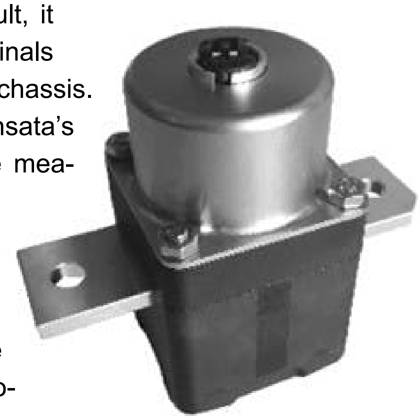
Sensata Electrified Flight (SELF) contactors offer a lightweight solution with a ceramic to metal brazed header for a hermetic seal that is ideal for EVTOL applications. These contactors are rated from 12 Vdc to 1,000 Vdc, with continuous current ratings up to 600, and meet the DO-160 aerospace standard. The SELF pyrofuse switch provides a fast disconnect time of less than 1 millisecond, with a maximum breaking capacity of 1,000 Vdc, 16kA, and a continuous current carry rating of 500 amps.

Sensata SELF-EDP-00x
Courtesy Sensata Technologies

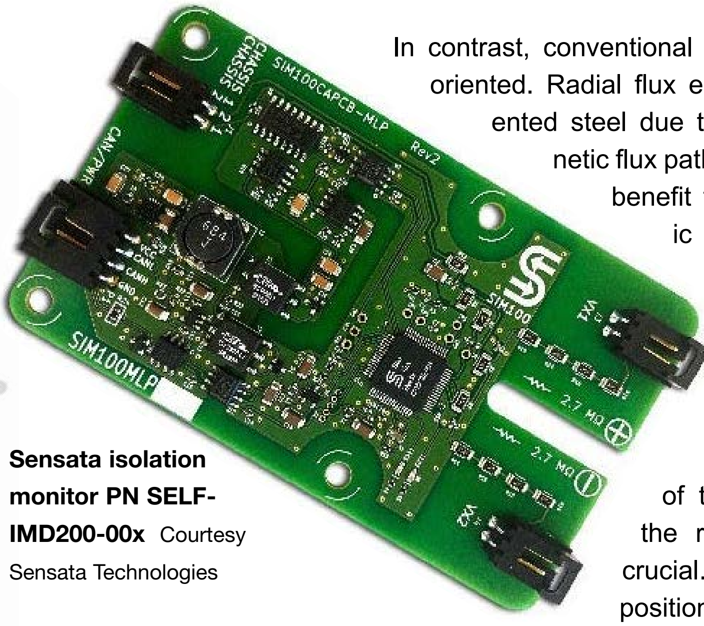
Isolation monitoring for safety. The Insulation Monitoring Device (IMD) operates effectively even with active batteries experiencing large voltage variations. It detects all leakage sources, including multiple simultaneous symmetrical and asymmetrical faults, and resistive paths between the chassis and battery points with the same potential.

The IMD continuously monitors and uses an algorithm for high noise rejection, estimating new isolation resistance values twice per second. In case of an insulation fault, it identifies the fault's relative position to the battery terminals and measures capacitance from each terminal to the chassis. The IMD's enhanced performance demonstrates Sensata's capability in addressing complex current and voltage measurement challenges.

Electric propulsion unit efficiency. The adoption of electric motors (e-motors) in aircraft such as UAM, AAM and eVTOL has created an immediate demand for accurate, low-profile position sensors that achieve efficiency similar to axial flux e-motors. Axial flux e-motors feature a gap between the rotor and stator, with the direction of magnetic flux parallel to the axis of rotation.



Sensata electrified flight pyrofuse switch Courtesy Sensata Technologies



Sensata isolation monitor PN SELF-IMD200-00x Courtesy Sensata Technologies

In contrast, conventional e-motor magnets are radially oriented. Radial flux e-motors require non-grain-oriented steel due to their two-dimensional magnetic flux path. However, axial flux e-motors benefit from a unidirectional magnetic flux path, allowing the use of grain-oriented electrical steel, which has higher permeability and reduces iron losses, thereby increasing motor efficiency.

To ensure optimal efficiency of the axial flux motor, knowing the rotor's positional accuracy is crucial. Sensata's SELF-EDP rotary position sensor offers a revolutionary solution compared to traditional resolvers. Unlike resolvers, which are heavier, have a higher profile, and require off-board electronics, the SELF-EDP sensor is lightweight, low-profile, magnet-free and can have a built-in redundant channel. It provides accuracy of ≤±1 deg. over its lifespan and is adaptable to custom motor diameters, pole-pair counts, and mounting positions. Additionally, it is robust against vibration, dust, humidity, oil and wear debris.

Sensata SELF-EDP-00x
Courtesy Sensata Technologies

The Advanced Air Mobility (AAM) market is experiencing rapid growth, with production rates expected to reach thousands of aircraft per year. In addition to sensor technologies, charging infrastructure will play a pivotal role in this transformation.

Sensata Technologies is addressing these infrastructure needs through its comprehensive range of high voltage components, including Dynapower charging infrastructure and a broader Contactor portfolio. These components and systems will play a vital role in enhancing eVTOL performance.

Traditional aircraft produce 3% of global emissions. At the same time, population growth in large cities is creating demand for transportation methods to relieve congestion. Over the last decade, advances in battery and fuel cell technology are enabling the advanced aircraft air mobility revolution. This movement aims to reduce the aircraft emissions, address congestion in large cities, and create more cost effective regional air transportation.

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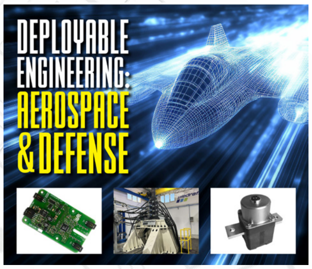


From Experiment to Application:

PARTNERSHIP WORKS TOWARD DEFENSE SOLUTION

CHAPTER 3:

Forging the Future of Defense with Modern Methodologies

SHARON SPIELMAN, Technical Editor, *Machine Design*

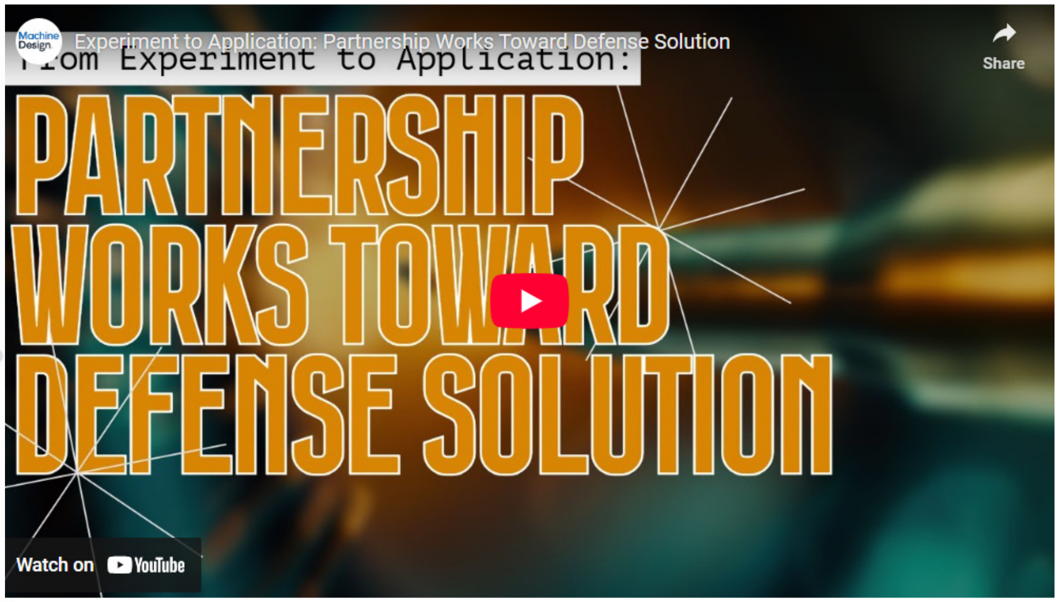
A collaboration between Element U.S. Space & Defense and Texas Tech's Mechanical Engineering Department focuses on propellant ignition studies for modern defense solutions.

Since the 1960s, Element U.S. Space and Defense has worked with the U.S. government in the realm of space exploration and defense technologies. Dr. John Granier, chief engineer of munitions and energetics at Element, along with Dr. Michelle Pantoya, J.W. Wright Regents Chair in mechanical engineering and professor at Texas Tech, are focusing on specific areas of research—particularly propellant research studies—to tackle the challenges that define the development of modern defense solutions.

In this first of a five-part series, *Machine Design* spoke with Granier and Pantoya about their cutting-edge research. Understanding the ignition processes in a range of ammunition systems—from small arms to large tank rounds—will help improve the performance and safety of munitions.

We learn that to achieve this understanding, they are using diagnostic techniques such as digital tomography and high-speed cameras to understand energy transfer during ignition. Advanced methodologies allow researchers to gain insights into how heat moves during the ignition process.

At the heart of this partnership is a commitment to student development and mentorship. By actively involving students in meaningful research projects, Element and Texas Tech are creating a dynamic educational environment. Hands-on experience with industry veterans equips the students with skills and knowledge needed to tackle real-world problems in the defense sector. We learn that Granier was one of Pantoya's students, and now they are collaborators helping to diagnose and solve problems in the aerospace and defense sectors.



Watch additional parts of this interview series with Dr. John Granier and Dr. Michelle Pantoya:

- [Part 2: The Role of Advanced Sensors in Propellant Technology]
- [Part 3: Prototyping Solutions for the Defense Industry]
- [Part 4: Assessing Effectiveness and Reliability in Prototype Development]
- [Part 5: The Future of Defense Engineering: Trends and Insights]

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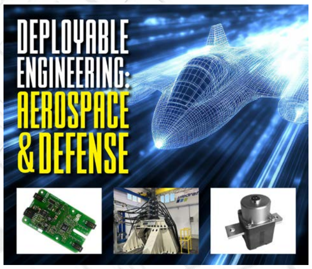

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CHAPTER 4:

Exploring the Universe with Strain Wave Gearing

Contributed by HARMONIC DRIVE

Discover how Harmonic Drive's strain wave gears—trusted in satellites, spacecraft and rovers—are designed and engineered for extreme environments, high torque and maintenance-free performance.

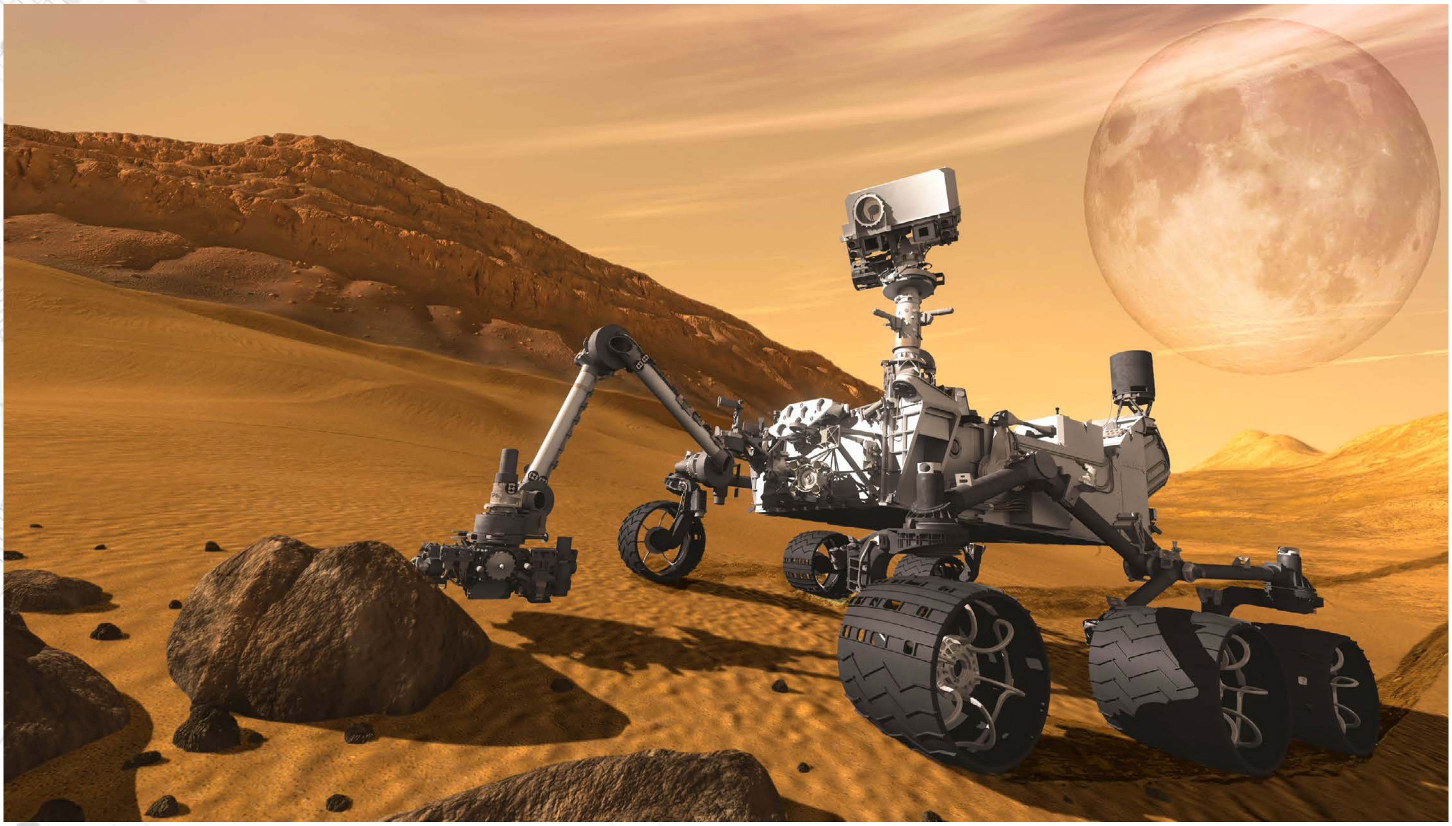
Behind every step humankind takes toward understanding and inhabiting our universe are smaller choices that ensure safety, longevity, and operational efficiency. For over 60 years, NASA has relied on reliable, compact, robust strain wave gearing from Harmonic Drive® to ensure the success of many space missions.

The concept at the heart of strain wave gearing—making use of elastic dynamics rather than increasing gears' rigidity—was developed by C. Walton Musser in 1955. Musser designed a motor-driven elliptical hub that engages the teeth of a flexible spline with those of a rigid circular spline. Because the tooth count on the flexible spline is slightly lower than that of the circular spline, the wave-like motion produced by the ellipse progresses around the circumference resulting in a greatly reduced output speed and high power density, that is, the ability to generate significant torque in a compact footprint. These attributes make strain wave gearing indispensable for satellites, interplanetary spacecraft, rovers on the moon and Mars, robots, and more.

Satellites Take the Long View

We rely on satellites that employ strain wave gearing for everyday information and insights into our universe. Your summer road trip is likely powered by the 31 Global Positioning System (GPS) satellites, each of which circles Earth twice daily from a height of 12,550 miles. Geostationary Operational Environmental Satellites (GOES) orbiting at 22,300 miles above Earth fuel your morning weather forecast, predict space weather, and support SARSAT emergency beacons. Both kinds of satellite drives employ Harmonic Drive strain wave gears to orient the solar arrays that power the transmission of vital data throughout the satellites' 15-year operational lifespan.

Strain wave gears are central to space telescope operations, too. On the Hubble Space Telescope (HST), Harmonic Drive strain wave gears manipulate the main shutter that's



Fukume | Dreamstime.com

responsible for many of the 1.6 million observations HST has recorded since its 1990 launch into low Earth orbit. The James Webb Space Telescope (JWST), situated 1 million miles from Earth since 2021, uses Harmonic Drive strain wave gearing in Its near-infrared camera and to orient its down-link antennae. With help from a dry-lubricated strain wave gear set that can operate consistently at temperatures as low as -253°C, the camera images faint objects like extrasolar planets and galaxies in formation in the early universe and then transmit the data back to Earth.

Interplanetary Spacecraft go Boldly

When humans have sent probes to other planets, Harmonic Drive strain wave gears have been integral to the missions' successes. Strain wave gears on the Cassini spacecraft helped deploy a shield that protected the main engine from micrometeorites. The high reduction ratios and high power density supplied by Harmonic Drive components ensured that the spacecraft, launched toward Saturn in 1997 on a 20-year mission, could journey the 4.9 billion miles safely.

Harmonic Drive delivered the same reliability on the Mercury MESSENGER, launched in 2004 for a 10-year mission to the planet closest to the sun. Like GPS and GOES satellites, MESSENGER used Harmonic Drive strain wave gearing in its solar-array drives. The antenna that enabled communications with Earth throughout MESSENGER's 107.5-million-mile journey was positioned with help from strain wave gearing on its gimbal's elevation and azimuth drives. The strain wave gearing compact footprint, lightweight design, and ability to operate reliably between 268°C and 371°C minimized launch weights and let

MESSENGER fit behind its sunshade, ensuring mission success in the harsh interplanetary environment.

Rovers and Robots Lead Close-Up Exploration

Strain wave gears have also landed on other bodies in our solar system since the 1970s. Each wheel of the Lunar Rovers that accompanied Apollo missions 15, 16, and 17 contained a hermetically sealed Harmonic Drive strain wave gear set that added an 80:1 reduction stage to a DC series-wound, 0.25-hp, 10,000-rpm motor. Together, the three rovers took astronauts more than 56 miles across the lunar surface.

Many of Harmonic Drive strain wave gears have also traveled to Mars. Landing in 2004, Mars Exploration Rovers Spirit and Opportunity had multiple strain wave gear units, including 10 for wheels and steering, two for deploying and positioning a high-gain antenna, and three in a robot arm on each rover. Opportunity drove 28 miles, including the record-breaking traverse of a 32°-slope, over its 14 years in operation. Spirit traveled 4.8 miles over six years. Both rovers remained operational for far longer than expected, a testament to the reliability of Harmonic Drive strain wave gears along with other components.

Also on Mars, in 2008, the Phoenix lander used a 2.5-m robotic arm with Harmonic Drive strain wave gears in the shoulder and elbow joints to confirm the presence of water ice on the red planet. A similar robotic arm allows the Perseverance rover to collect rock samples for future study on its four-plus-year mission.

Strain wave gears provide the power-dense precise, backlash-free motion needed for robotics in any environment, but these attributes are even more critical when robots operate in space environments that are inhospitable to humans. Robonaut 2, a humanoid robot deployed aboard the International Space Station from 2011 to 2018, used 26 Harmonic Drive strain wave gears in its arms, legs, waist, and head. Robonaut 2 and its unlaunched successor, Valkyrie, were designed to relieve human astronauts of dangerous or repetitive tasks, including some spacewalks. In addition to operating virtually maintenance-free, these strain wave units were adapted to use the dry lubrication required in zero-g and vacuum environments.

For over 60 years, Harmonic Drive has built the strain wave gears needed to explore our universe on satellites, interplanetary spacecraft, and rovers. These gears deliver high torque and high reduction ratios in a compact footprint. Harmonic Drive engineers designed these components for long, maintenance-free lives and adapted them for lighter weight, extreme-temperature operation, and dry lubrication. With these capabilities, Harmonic Drive strain wave gears will be part of humankind's future spaceflight and exploration missions to the moon, Mars, and beyond.

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