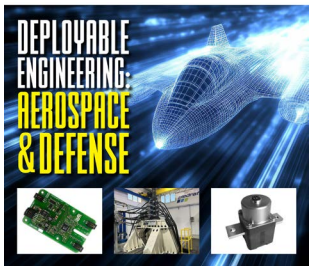

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Exploring the Universe with Strain Wave Gearing

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.

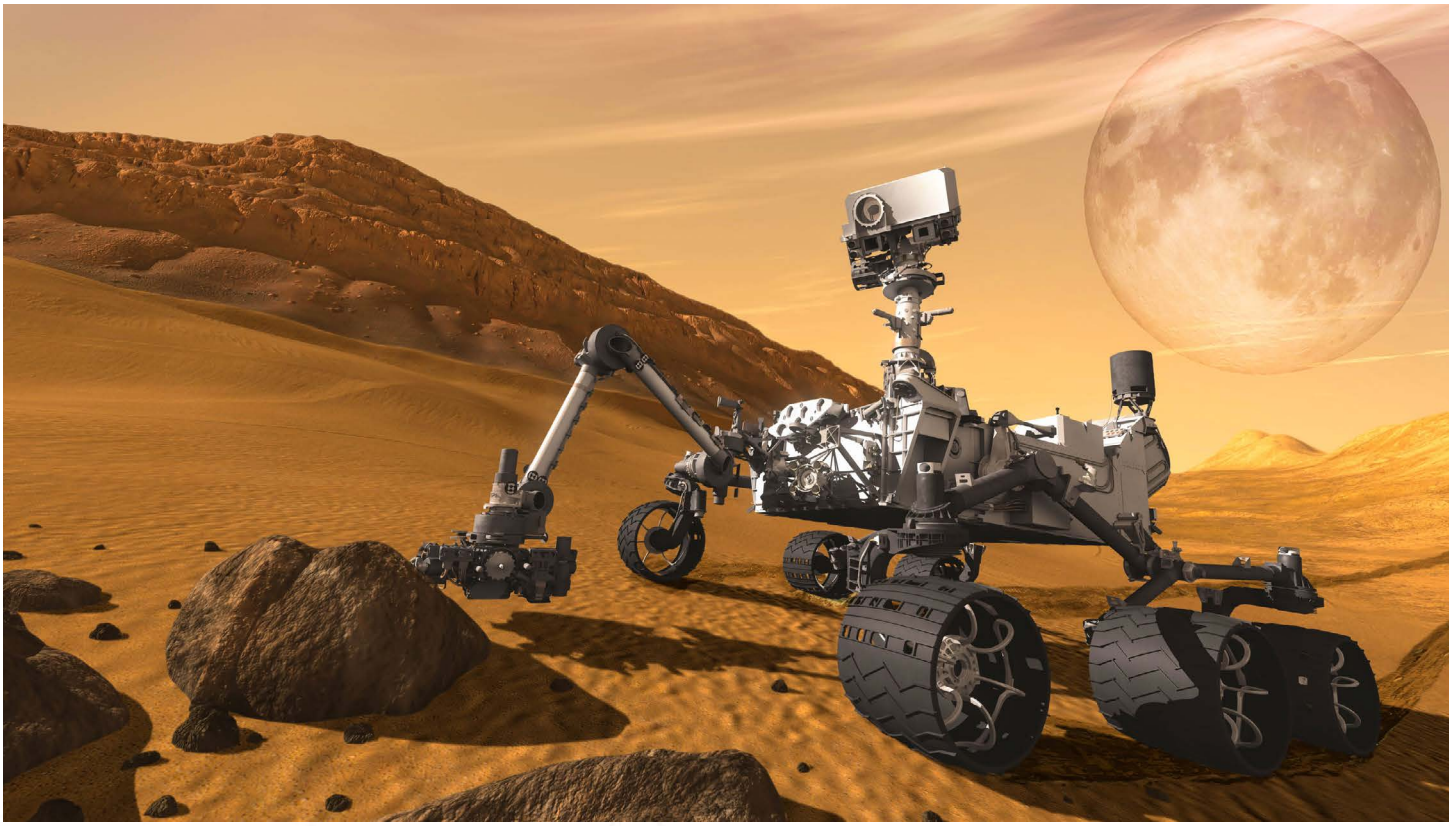
Behind every step humankind takes toward understanding and inhabiting our universe are smaller choices that ensure safety, longevity, and operational efficiency. For over 60 years, NASA has relied on reliable, compact, robust strain wave gearing from Harmonic Drive® to ensure the success of many space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



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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.