Lightweight Gears and Actuators Help Improve the Productivity of Factory Automation Systems

After sliding from its peak more than 30 years ago, U.S. manufacturing appears to be on the way back. More and more companies are deciding to make their products here, giving rise to a new buzzword in industry, reshoring, which represents the repatriation of manufacturing to North America from lower-wage nations.

The reasons behind the renaissance in U.S. manufacturing are as diverse as the companies involved, but one key to the trend is worker productivity. As manufacturing employment declined from 1977 to 2010, factory output more than doubled. In short, U.S. workers became more productive.

The rise in productivity is not only attributed to people working smarter but also to investments in factory automation products that have helped workers become three times more productive than their Asian counterparts. Factory automation is a critical element enabling U.S. manufacturing companies to effectively compete in the global marketplace.

To maintain this competitive trend, modern robotic and automation systems require higher precision and faster speeds than ever before. And a crucial component in providing the high accuracy and smooth operation required lies in the gear mechanisms that move and position the robot arm or machine structure.

A typical robot can have upwards of six axes, each with its own gear reducer. Gearing has a significant effect on the acceleration, positioning accuracy, and dynamic performance possible from the robot. Gear units and actuators greatly impact performance, enabling robots to reach their full potential in boosting manufacturing output.

What is High Performance?

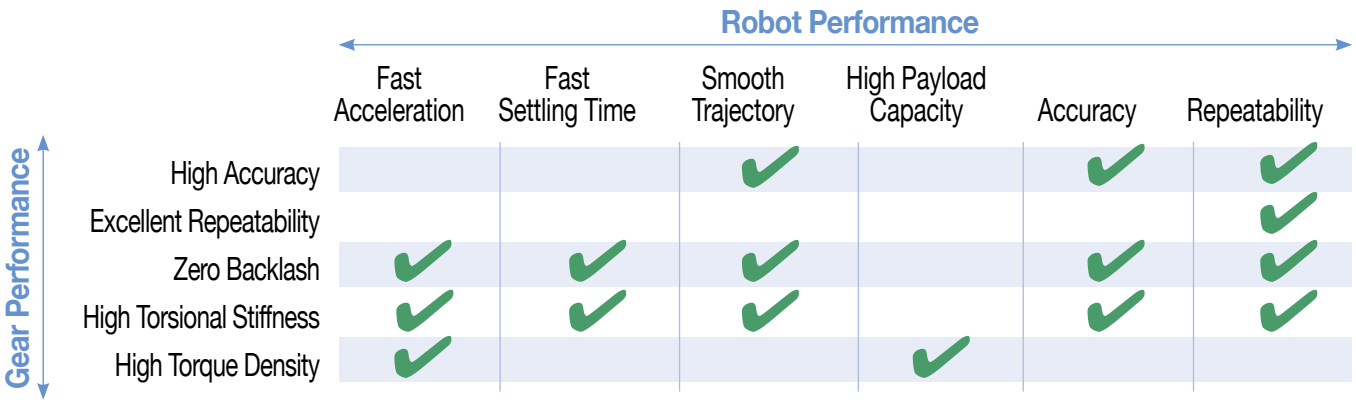
High performance means different things to different people. In the world of factory automation, high performance means superior dynamic performance of the robot. Dynamic performance is defined by fast cycle times (high acceleration/deceleration, high speed, and short settling time), smooth trajectory, and large payload capacity for a robot of a given size. In addition, both positioning accuracy and repeatability are typically essential for high-performance automation.

Accuracy is how closely a robot can reach a commanded position. The difference or error between the actual position of the robot and the commanded position is defined as accuracy.

Repeatability, on the other hand, is how closely the robot returns to that programmed position after moving to another position. Repeatability is related but different from accuracy and is typically the more important criterion for a robot.

A repeatability specification of ± 0.02 mm for a robot with a 700-mm reach translates to an angular repeatability of just ± 5.9 arc-sec at the base axis. Backlash, inherent in most gear technologies, makes it impossible to achieve this level of repeatability without using expensive high-resolution absolute encoders on

Gear Characteristics vs Robot Performance



the output of each axis.

What then are the performance requirements for a gear or servo actuator to achieve high-performance automation? These requirements can be summarized as High Accuracy, Excellent Repeatability, Zero Backlash, High Torsional Stiffness, and a combination of High Torque and Light Weight (called Torque Density). The effect of these gear characteristics on robot performance can be understood from the matrix above.*

Limitations of Spur and Planetary Gearing

Some conventional spur or planetary gears can be accurate for single-direction positioning, but they fall short in terms of repeatability, which can present system control issues. The main culprit is backlash, a feature that is deliberately designed into these gears to provide proper tooth clearance, minimize tooth wear, and allow the drives to operate smoothly. Backlash has a negative impact on robot performance and is most significant when present in the first and second axes.

Planetary and spur gears can also be very heavy, thereby reducing robot payload capacity, decreasing allowable acceleration rate due to high inertia of the robot arm, and decreasing energy efficiency. The impact of these factors on robot performance is increasingly notable when these gears are used in the third through sixth axes.

While the negative effects of gear backlash become smaller toward the last axis of the robot, the effects of using a heavy gear system become much greater. Heavy gears within the robot arm require the robot to use much of its available torque simply to move the arm itself, rather than moving a payload. Additionally, the resulting high inertia of the arm limits maximum acceleration.

Harmonic Gearing

A gear technology known as harmonic gearing eliminates the problems inherent in spur and planetary gearing to provide exceptional positioning accuracy and repeatability within a few arc-seconds. This technology allows for lighter and more compact gear and servo actuator designs that enable robots to perform at their best. (See *Harmonic Gear Operating*

*Although this article refers primarily to robots, the same basic principles and challenges apply to all types of precision automation.

Principle to learn more about the technology used in Harmonic Drive products.)

The majority of the world's leading robot manufacturers use Harmonic Drive gears and actuators to take advantage of their superior performance including:

- **High Accuracy –** Standard accuracy of Harmonic Drive gears is <1 arc-minute, but they are commonly manufactured with <30 arc-second accuracy per customer request.
- **Excellent Repeatability –** Typical repeatability is ± 5 arc-seconds.
- **Zero Backlash –** Harmonic Drive products inherently have true zero backlash. Lost motion (defined as hysteresis in the low torque region) of the gear is measured by applying ± 4% of rated torque to the output while the input is rotationally locked. Lost motion in Harmonic Drive gears is <1 arc-minute and is maintained for the life of the gear.
- **High Torsional Stiffness –** Up to 30% of the gear teeth are engaged at all times, resulting in high torsional stiffness.
- **High Torque Density –** The simplicity of the gear technology results in gears and actuators that have very low weight, yet deliver very high torque. This combination results in gears with exceptionally high torque density and actuators with exceptionally high power density.

Performance Benefits for Robotic Applications

As indicated in the matrix, the zero-backlash characteristic provides a multitude of performance benefits. As a robot moves through a typical motion profile, it experiences multiple accelerations and decelerations, causing reversing loads on the gear. *Any* backlash present in the gears allows a shock load to be generated in the gear system during acceleration or deceleration, causing jerky motion. The shock load also creates a disturbance in the servo system, creating overshoot and causing the robot to stray from its planned trajectory.

Over time, these reversing loads, combined with backlash in spur or planetary gears, cause tooth wear, further degrading positioning accuracy and repeatability. These effects can be minimized by reducing acceleration rate, which, in turn, increases robot cycle time.

The inherent zero-backlash characteristic of Harmonic Drive gears eliminates the issues described above. The gearing allows the robot to accelerate and decelerate very quickly without the shock loads experienced by traditional gear systems. In addition, the use of zero-backlash Harmonic Drive gears or actuators allows the servo gain to be set higher, improving the dynamic performance and positioning accuracy and reducing the following error.

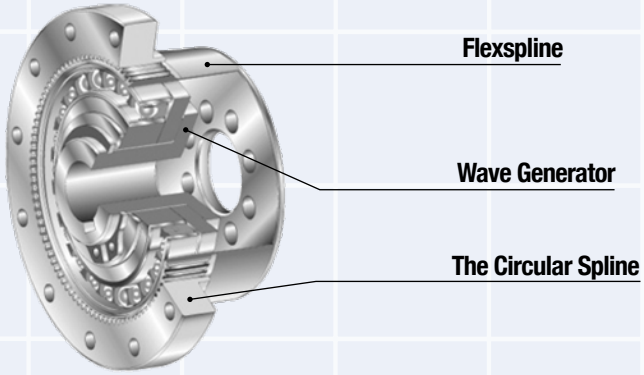
The high accuracy of harmonic gears minimizes velocity ripple at the output, leading to smooth motion. In addition to the obvious benefit of high positioning accuracy of the robot, the high accuracy of the gear also contributes to its outstanding repeatability.

In most applications, automation equipment using a Harmonic Drive gear or actuator relies on a single encoder mounted on the motor side to control both velocity and position. The high accuracy and repeatability of this precision gearing eliminates the need for a costly second absolute encoder at the output of the robot joint. This simplifies the mechanical design as well as the wiring and control since both the velocity and position loops can be closed using a single encoder.

Unlike other gearing, harmonic gears offer a high reduction ratio in a single stage. This helps reduce the size and weight of both the gear and motor. The high ratios reduce the amount of output load inertia

Harmonic Gear Operating Principle

The harmonic gear principle of operation is both unique and simple. It is based upon non-rigid body mechanics and employs just three concentric parts to produce high mechanical advantage and high reduction ratios.

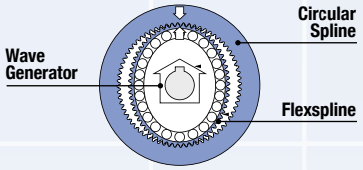


The **Wave Generator** is a thin ball bearing fitted onto an elliptical hub. This is generally mounted onto the input or motor shaft. As the hub is rotated, a pair of moving waves is produced on the outside of the non-rotating outer race of the bearing.

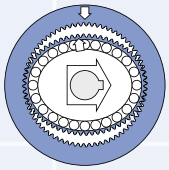
The **Flexspline** is a cylindrical cup with external teeth on the open end of the cup. The Flexspline is torsionally stiff, yet radially compliant. It fits over the Wave Generator and takes on its shape creating an elliptical gear. The Flexspline is generally used as the output of the gear.

The **Circular Spline** is a rigid ring with internal teeth. It engages the teeth of the Flexspline along the major axis of the Wave Generator ellipse. The Circular Spline has two more teeth than the Flexspline and is generally fixed (not rotating) and mounted within a gear housing.

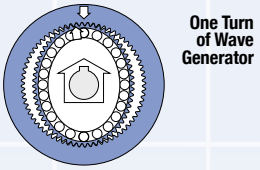
Operating Principle



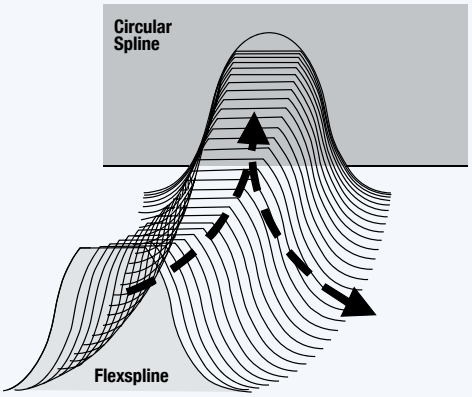
The Flexspline is slightly smaller in diameter than the Circular Spline and usually has two fewer teeth than the Circular Spline. The elliptical shape of the Wave Generator causes the Flexspline to engage the Circular Spline at two opposite regions along the major axis of the ellipse.



As the Wave Generator rotates, the teeth of the Flexspline engage with the Circular Spline at the major axis. For every 180-degree clockwise movement of the Wave Generator, the Flexspline rotates counterclockwise by one tooth in relation to the Circular Spline.



Each complete clockwise rotation of the Wave Generator results in the Flexspline moving counterclockwise by two teeth from its original position relative to the Circular Spline.



The harmonic gear has a unique tooth engagement that results in a zero-backlash gear mesh that provides high positioning accuracy and high torque with a compact form factor. Unlike the involute tooth profile used in conventional gears, the optimized Harmonic Drive® gear tooth profile (S tooth) enables about 30% of the total number of teeth to be engaged at the same time. This technological innovation results in high torque, high torsional stiffness, long life, and smooth rotation. The S tooth profile virtually eliminates stress concentration by widening the tooth root and providing a large tooth root radius. The figure (left) shows the progression of the Flexspline tooth engagement as it meshes with the teeth of the Circular Spline.

reflected back to the motor so the motor is able to respond quickly.

The torque density of Harmonic Drive products is exceptionally high. This is a significant benefit when the gears are used on a robotic arm. The low weight of the gear reduces both the mass and inertia of the arm, allowing faster positioning and/or higher payloads. This benefit has a cascading effect when moving from the sixth axis back toward the first axis, reducing the torque required merely to support or accelerate the mass of the gearing.

Finally, because of the operating principle that virtually eliminates tooth wear, Harmonic Drive gears provide zero backlash for life and have a long, maintenance-free life, reducing costly downtime.

Design Features

Some of the design features that make Harmonic Drive products particularly well-suited to factory automation systems include:

- **Through-Hole Design –** Many of our gearheads and actuators feature a large hollow shaft that allows cables, pipes, or coaxial shafts to pass through the center of the gear or actuator. This can greatly simplify a design and improve reliability.
- **Flanged Output –** Many Harmonic Drive gear and actuator products feature a flanged output for direct mounting of the load. A large bolt circle diameter ensures secure mounting with no worry about the output shaft connection slipping.
- **Cross Roller Output Bearings** are widely integrated in the products and provide high axial, radial, and moment load capacities in a compact space.
- **No Change in Size or Weight with Gear Ratio –** Unlike other gear technologies, harmonic gears have the same size, weight, and form factor regardless of gear ratio. This feature allows design flexibility or revisions without the need to redesign the entire mechanism. Reduction ratios of 30:1 through 160:1 are commonly available.

Single-Stage, High-Reduction Ratio

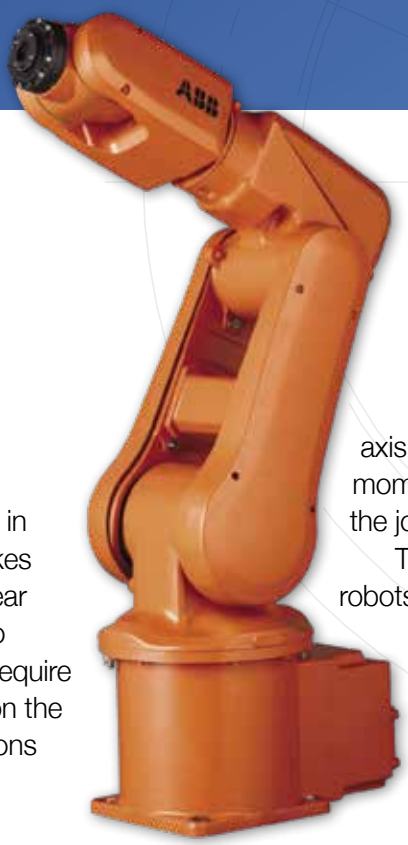
In the typical harmonic gear configuration, the Wave Generator is the input element, the Circular Spline is static, and the Flexspline is the output. When using this configuration the reduction ratio can be calculated from:

$$\text{Ratio} = \frac{Nf}{Nf - Nc}$$

Where: Nf = Number of teeth of the Flexspline

Nc = Number of teeth of the Circular Spline

The reduction ratio can be changed simply by changing the number of gear teeth on the Flexspline and Circular Spline. Gear ratios typically available include: 30:1, 50:1, 80:1, 100:1, 120:1, and 160:1. These ratios are offered in a single stage without any change to the weight or size of the gear. Harmonic gears can achieve high ratios in a single gear stage, whereas most other types of gears need multiple stages. Therefore, size and weight of the harmonic gear need not be increased to produce these higher ratios. Ratios up to 320:1 are built in a single stage.



Gears and Actuators in Action

Harmonic Drive® gears and actuators are used in a wide range of applications, each of which takes advantage of a different characteristic of the gear technology. Some applications depend on zero backlash and high positional accuracy. Some require a high torque-to-weight ratio. Others depend on the unique configurations available. A few installations utilize all of these attributes.

Industrial robotics is one of the major application areas for Harmonic Drive gear components. These applications require zero-backlash gears with high torque capacity, high torsional stiffness, and excellent repeatability. Hollow-shaft designs also are favored because they make cable routing easy, neat, and reliable. Gear units with high-capacity, cross roller bearings are sometimes selected due to their compact form and are particularly well-suited for use in the robot axis, which places significant tilting moments on the output bearing of the joint.

The primary axes of six-axis robots must be capable of providing high peak torques during the acceleration and deceleration phases of a cycle. The primary axis gears must also exhibit high repeatability and high positioning accuracy to enable the robot to execute precise assembly tasks or accurate path-following applications, such as arc welding or adhesive application. Harmonic Drive gears and actuators routinely meet these demanding requirements.

Medical equipment advances have continually driven the requirements for high-precision motion control. This is exemplified in gear units used in the rotary axes of a stereotactic manipulator used for brain surgery. The manipulator is a six-axis robotic arm that supports the operating microscope used by the surgeon. As the operation progresses, the microscope superimposes computer data on the actual viewpoint of the operating area, acting as a head-up display to guide the surgeon through the operation. Harmonic Drive precision and reliability are crucial to successful surgical procedures.

Another interesting medical application is a nuclear medicine camera for general-purpose, SPECT, and planar imaging, which can produce as many as 15 different image sets using physician-specified protocols. The nuclear camera's unusual open design can accommodate patients on gurneys, in hospital beds, and even in wheelchairs. Harmonic Drive®

gear units are used to safely, reliably, and accurately position the gamma cameras.

Sadly, many combat veterans serving overseas have endured injuries resulting in the loss of limbs. Additionally, cancer survivors have lost limbs in their battle to defeat the disease. Although no technology today can replace the aesthetics and full function of the human body, Harmonic Drive LLC has been working closely with several innovative companies to make breakthroughs in the form, performance, and function of powered prosthetics.

These prosthetic devices, of which several have already received FDA approval, deliver functionality never before achieved with passive devices. People have regained the ability to easily sit and stand, climb stairs, and walk up and down sloped pathways without tiring. Others have regained their independence by using a six-axis robotic prosthetic arm.

The low weight of the Harmonic Drive LLC gears enables the overall weight of the prosthetic limb to be similar to that of a human limb. This is critical for the comfort, usability, and battery life of the prosthetic. Harmonic Drive LLC is proud to be involved in the design of these devices that serve people in need.

Articulated robots are frequently used for welding, manufacturing, and packaging. Harmonic Drive gears reduce inertia of the robot arm to improve dynamic performance through faster acceleration and faster settling time. They also increase payload capacity and reduce power requirements.

Machine tool manufacturers often rely on Harmonic Drive products for their high-accuracy, compact form, and hollow shaft features. Common applications are in the fourth and fifth axes of milling heads for vertical machining centers and routers. Here, machine designers consistently use the hollow shaft to route wires to the spindle drive motor.

Manufacturers of waterjet machines also use Harmonic Drive® gears and actuators for the linear axis and to compensate for the natural tapered cutting angle caused by dispersion of the waterjet stream. Harmonic Drive actuators used in the fourth and fifth axes enable not only straight cuts (without any taper) but also complex shapes with precision tapers and bevels.

Like all other machine tools, CNC grinding machines need the precision, repeatability, and zero-backlash features. In addition, they need superior dynamic transmission accuracy and smooth motion. Without these performance characteristics, the mirror-like finishes produced in grinding operations could not be possible. Besides being used in general-purpose grinding machines, Harmonic Drive actuators are even used in specialty grinders for lenses and crystals.

The natural preloading of harmonic gears means there is no increase in backlash during their operating life, eliminating the need to re-adjust gears to remove backlash, as is common with worm gears or planetary gears. This means the machine tools maintain their design specification, reducing the number of service calls and increasing customer satisfaction.

Additionally, Harmonic Drive actuators are well-suited to applications in the peripheral axes of large machine tools, such as in tool changers. The simple, compact design of the actuators, with their high-stiffness cross roller output bearings, makes them ideal for these applications.

Mobile robots have the capability to move around in their environment and are not fixed to one physical location. Because they are powered by a battery, compact size and light weight are often the primary design considerations for any component used in them. When used in the arm of a mobile robot, such as for an explosive ordinance disposal (EOD) robot, harmonic gearing allows the payload capacity of the arm to be increased.

In mobile robot wheel drives, the lighter-weight gearing reduces overall robot weight, thereby reducing power requirements and improving battery life. The reduced weight is also helpful in improving the portability of robots used by law enforcement and defense forces.

Conclusion

Precision gear and actuator products from Harmonic Drive LLC deliver highly accurate, backlash-free positioning for sophisticated motion control applications in both industrial and surgical robots as well as semiconductor manufacturing equipment, factory automation equipment, medical equipment, and automation systems. The gears deliver high torque in a lightweight, compact package, allowing faster response and higher payloads.

If your robotic or automation system can benefit from the advantages provided by Harmonic Drive LLC products, please contact us at 800-921-3332, or visit our website at **www.harmonicdrive.net.** ■

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