

# Improve the Productivity of Robotics & Automation Systems with Lightweight Gears and Integrated Actuators

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**HarmonicDrive®**

# Lightweight Harmonic Drive® Gears and Actuators Help Improve the Productivity of Factory Automation Systems

**A**fter sliding from its peak more than 25 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. To achieve optimum productivity, each gear unit must minimize those design factors that degrade performance. Harmonic Drive® Gear units and actuators provide this 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  $\pm 0.02$  mm for a robot with a 700-mm reach translates to an angular repeatability of just  $\pm 5.9$  arc-sec at the base axis.

## Gear Characteristics

		Resulting Robot Performance					
		Fast Acceleration	Fast Settling Time	Smooth Trajectory	High Payload Capacity	Accuracy	Repeatability
Great Performance ↑	High Accuracy			✓		✓	✓
	Excellent Repeatability						✓
	Zero Backlash	✓	✓	✓		✓	✓
	High Torsional Stiffness	✓	✓	✓		✓	✓
	High Torque Density	✓			✓		

Backlash, inherent in most gear technologies, makes it impossible to achieve this level of repeatability without using expensive high-resolution absolute encoders on 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. Harmonic

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

Drive® motion control products incorporate this technology to produce lighter and more compact gear and servo actuator designs that enable robots to perform at their best. (See the sidebar *Harmonic Gear Operating 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  $\pm 5$  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  $\pm 4\%$  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 of Harmonic Drive products 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.

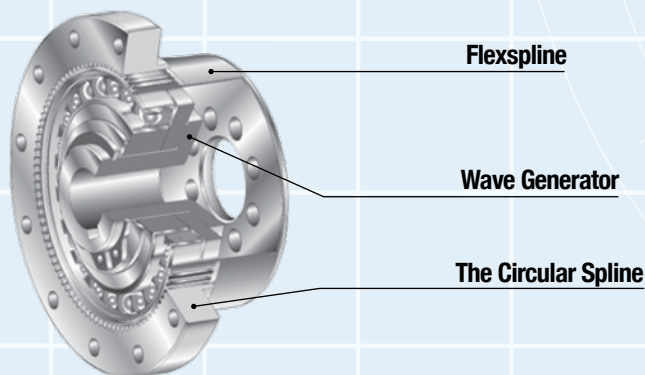
The inherent zero-backlash characteristic of Harmonic Drive gears eliminates the issues described above. The gearing allows the robot to accelerate and decelerate very quickly without the shock loads experienced by traditional gear systems. In addition, the use of zero-backlash Harmonic Drive gears or 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 Drive 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

# 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.

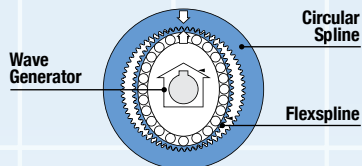


The **Wave Generator** is a thin ball bearing fitted onto an elliptical hub. This is generally mounted onto the input or motor shaft. As the hub is rotated, a pair of moving waves is produced on the outside of the non-rotating outer race of the bearing.

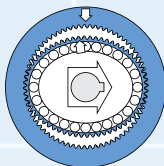
The **Flexspline** is a cylindrical cup with external teeth on the open end of the cup. The Flexspline is torsionally stiff, yet radially compliant. It fits over the Wave Generator and takes on its shape creating an elliptical gear. The Flexspline is generally used as the output of the gear.

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.

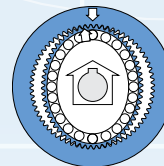
## Operating Principle



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.

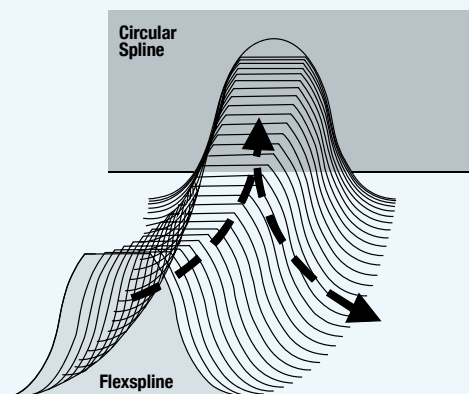


As the Wave Generator rotates, the teeth of the Flexspline engage with the Circular Spline at the major axis. For every 180-degree clockwise movement of the Wave Generator, the Flexspline rotates counterclockwise by one tooth in relation to the Circular Spline.



One Turn of Wave Generator

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.

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 available in Harmonic Drive® gears reduce the amount of output load inertia 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 of Harmonic Drive Products

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.

## New Lightweight / High-Torque Products

Several new series of Low Weight Harmonic Drive gear units have been introduced, using lightweight housing materials and an optimized design. These gear units, based upon existing product lines, maintain the same torque capacity with up to 30% lower weight. Additionally, a new small Harmonic Drive hollow shaft actuator has been developed, expanding the size range of the SHA Series of brushless actuators. All these new products deliver the performance advantages described below.



**CSG-LW**



**CSF-LW**

**CSG-LW** and **CSF-LW** gearheads are 30% lighter than previous designs without reducing the torque rating or significantly changing interface dimensions. They incorporate a Harmonic Drive component set in a lightweight housing and have an integral high-capacity cross roller bearing and output flange to support the load.



### **SHG-LW & SHF-LW**

**SHG-LW** and **SHF-LW** are compact hollow-shaft gearheads that are 20% lighter than standard SHF units. In addition to the hollow shaft feature, the gearhead incorporates a high-capacity cross roller bearing and an output flange to mount the load directly without the need for an additional support bearing.



### **SHD-LW**

**SHD-LW** is a compact, lightweight, hollow shaft precision gear unit. The gearhead incorporates a Harmonic Drive® component set in an aluminum housing. It is 15% shorter and 30% to 40% lighter than the SHF series. It features a high-capacity cross roller bearing and flanged output to mount the moving load without the need for additional support bearings. The large hollow shaft allows cables, shafts, or pipes to pass directly through the axis of rotation.



### **SHA-20**

The new **SHA-20 Actuator** is the smallest actuator in the SHA family. Measuring just 94 mm in diameter and 108 mm in length, the actuator delivers up to 120 N-m of peak torque. It features a 17mm hollow shaft and a robust cross roller bearing capable of supporting a 187 N-m moment load. The actuator is driven with a brushless servomotor and has a 16-bit multi-turn encoder. An optional failsafe brake is available without increasing the outside dimensions. Compatible servodrives are available with several control protocols, including EtherCAT.

## **New Lightweight Products for Robotic Applications**

Harmonic Drive LLC continuously strives to develop new products that advance the performance and capabilities of our customers' machines. Our goal is to make our customers successful. These new lightweight products were developed to enhance the performance of robots and automation equipment. The improved torque density provides significant benefits to articulated robots, as well as mobile robot applications.

**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.

**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.

## 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

# 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:

$$\text{Ratio} = \frac{N_f}{N_f - N_c}$$

**Where:  $N_f$  = Number of teeth  
of the Flexspline**

**$N_c$  = 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.



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.

**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.

## Conclusion

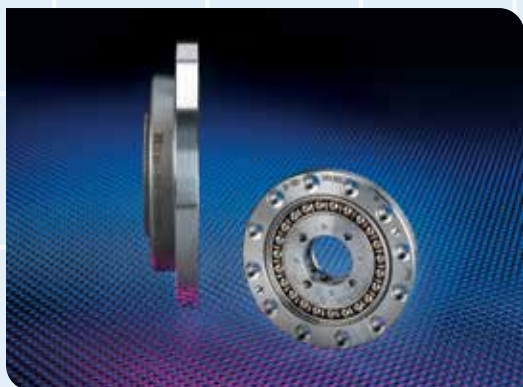
Precision gear and actuator products from Harmonic Drive LLC deliver highly accurate, backlash-free positioning for sophisticated motion control applications in both industrial and surgical robots as well as semiconductor manufacturing equipment, factory automation equipment, medical equipment, and automation 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](http://www.harmonicdrive.net)**. ■

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# Component Sets and Gearheads

Harmonic Drive® products are divided into three basic categories: gear component sets, gearheads (gear units), and actuators. The features and form factors differ, but all provide the performance benefits and reliability for which Harmonic Drive is known.



**Component Sets** are the core gear mechanisms used in Harmonic Drive products, and they offer the greatest design flexibility. Several component set product lines are available featuring different sizes, reduction ratios, and configurations, including ultra-flat and hollow shaft designs. This selection allows designers to choose the gear set with the optimum dimensions and performance, based on their requirements and space available in their custom-designed housings.

These high-accuracy gear components can be used as the core of custom high-performance mechanisms. Designing with component sets offers the best opportunity to reduce the weight and size of machines or robot arms because the machine itself can serve as the gear housing. However, significant effort is required by the customer to design a suitable precision housing and bearing support structure, and to provide proper sealing. Although this requires time and effort, the benefits are great and the engineering staff at Harmonic Drive is always available to assist in the design process.



**Gearheads** are supplied as either a close-coupled gearhead that connects directly to a servomotor or as a completely sealed unit with an input shaft. These products greatly simplify the design effort because the precision housing, output flange (or shaft), and bearing structure are already provided in an optimized design. Cross roller bearings are commonly used because they are axially compact and provide both high precision and high load capacity.

Many product lines are available that provide different form factors and features such as hollow shaft or the ability to quick-connect to any servomotor, similar to conventional gearboxes in the market. Sizes range from 0.625 inches to over 10 inches in diameter with reduction ratios ranging from 30:1 to 160:1. Precision Harmonic Planetary® gearheads and hollow shaft gear units are also available with gear ratios from 3:1 to 45:1 and backlash maintained below 1 arc-min.



**RSF-5 Integrated**



**RSA-8 Integrated**



**FHA Mini Integrated**



**SHA Integrated**

## Actuators

**Actuators** are the easiest to use in any application. It combines a precision Harmonic Drive® gear with a high-performance servomotor and encoder. Integral brakes are also available. Because Harmonic Drive manufactures its own cross roller bearing, gear component set, servomotor, and encoder, we have complete control over every element of the design to maximize performance and minimize both size and weight. These actuators have a compact form factor and a high torque-to-weight and torque-to-volume ratio.

Hollow shaft designs are available in several product lines that allow easy routing of cabling directly through the axis of rotation. Combined, these features provide a significant advantage over a solution based on purchasing and assembling a gearhead and motor separately.

All Harmonic Drive® actuators feature zero backlash, high accuracy, and fast response times and are available in a wide range of sizes. Harmonic Drive also offers a complete range of digital servo drives for these actuators.

### Integrated Actuators

Harmonic Drive has introduced several new actuators that integrates the servo drive inside the actuator. These actuators are extremely compact and are typically only 1 or 2mm longer than the standard actuator and heavier by only a few grams. The integrated drive eliminates the need for an external servo drive so the wiring is greatly simplified. Communicating via CANopen, a cable with only 4 conductors are needed and up to 127 axis can be run off a single four conductor bus.

The FHA mini and SHA series also feature dual absolute encoders - one at the motor and one at the output of the actuator. With this feature, homing can be eliminated when powering up in most cases. These new actuators are ideal for use in robotics where precision, weight and reliability are essential.