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Position Yourself for SUCCESS

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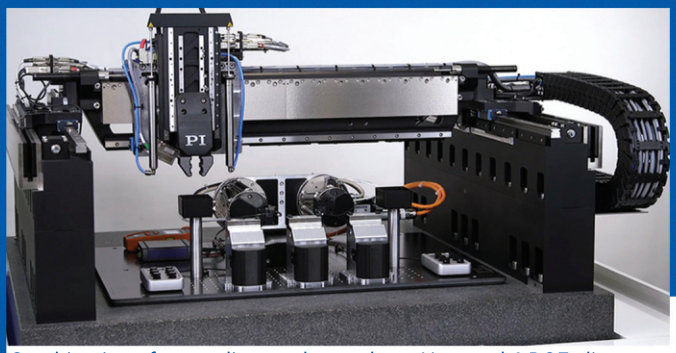
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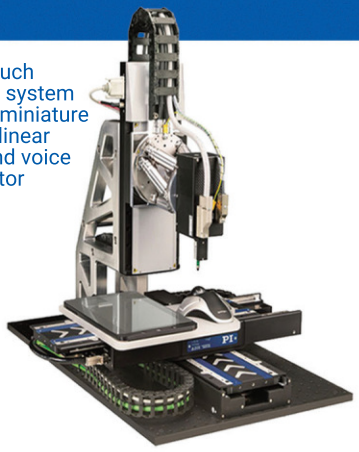


Combination of gantry linear robot and two Hexapod 6-DOF alignment systems for fast automated testing of photonics components

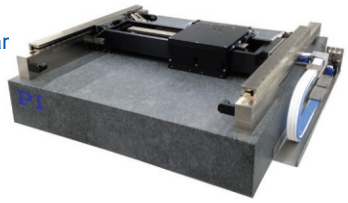
Motion & automation solutions based on:

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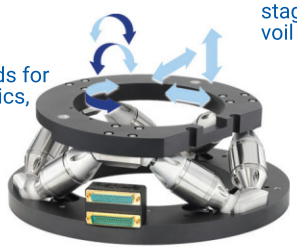
10-axis touch panel test system based on miniature hexapod, linear stages, and voice voil actuator



3-motor planar XY air bearing stage with yaw control



6-axis hexapods for alignment, optics, stabilization, photonics, and metrology



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Pinpointing Your Goals



Bob Vavra,
Content Director for Machine Design and Power & Motion

The dime is the smallest of all U.S. coins, so the ability of anyone to be able to "turn on a dime" was considered a pretty impressive feat.

In a sophisticated manufacturing facility, that's no longer good enough.

Precise motion control means being able to deliver not anything as pedestrian as a dime's size, but one thousandth the thickness of the dime—and when it comes to semiconductor manufacturing, divide that by another thousand. As part of an interconnected system that includes robotics, motors and multi-axis assemblies, the need for precision is paramount. As a result, the work done by engineers to refine and focus motion control and positioning now needs a pinpoint as its guiding principle.

So much of this discussion, as this e-book will demonstrate, is about the application of these motion control principles. From encoders and air bearings to aligned and turned XYZ assemblies, the engineering continues to deliver a precise and productive motion control system.

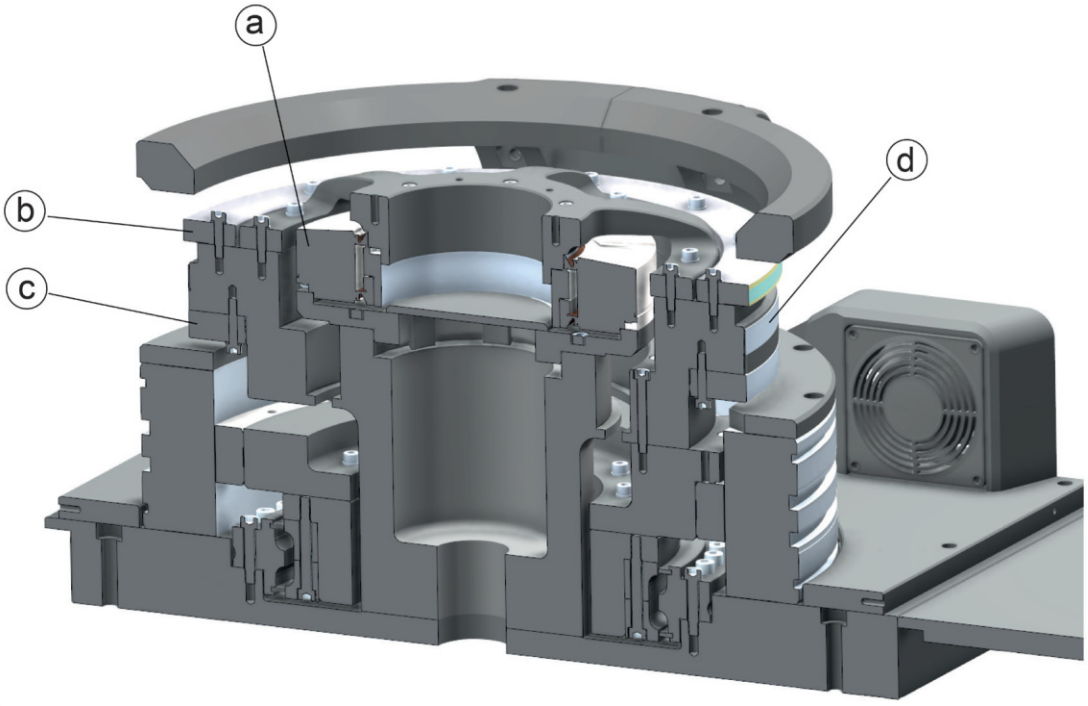
One such application is the use of motion control technology to replace a back brace used to correct spinal curvature with a robotic system that improves the way patients can improve range of motion while their treatment continues. In this way, motion control replaces a statis process of a hard brace with an intuitive and interactive system that helps while it heals.

Another area where motion control's precision applications are essential is additive manufacturing. The use of 3D printing to create complex and dynamic products and systems requires not just control of nozzles and lasers but also the mixing of materials to create a strong, flexible part.

The work of engineers to develop and further refine the mechanics of motion control continues. I look to a future day when such solutions are a dime a dozen—and where a pinpoint is no longer adequate to define such precision.

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CHAPTER 1:

Evaluating Angle Encoders' Effects on Motors

HEIDENHAIN STAFF

Choosing the right encoder is critical for reliable, stable and accurate machining processes.

Why are there so many different angle encoders on the market? Why do they use different scanning and measuring methods? And which one should a designer choose?

To answer those questions, engineers at *Heidenhain* set up a torque motor commanded by a CNC controller hooked up to four different angle encoders to see how they differ. The four absolute angle encoders included a sealed optical encoder for rotary tables and swivel heads; a modular optical encoder with a steel scale drum for wide-axis rotary tables and swivel heads; a contamination-tolerant modular magnetic encoder; and a compact inductive scale-tape encoder.

The controller simulated positioning tasks for each angle encoder while technicians analyzed how signal quality affects dynamic performance and how the measuring principle affects accuracy. They also examined how using data from the motor, encoder and sensor could improve process reliability.

Signal Quality

In direct drive motors, the encoder's signal quality plays a critical role in the amount of electrical current noise, which affects the motor's dynamic performance and possible power dissipation. The noise is a retroactive effect of interpolation errors and affects the dynamic performance of an axis. Interpolation errors, in turn, are rapid changes in the position value that cause errors in calculating the speed calculation. These errors lead to more current noise. To avoid instability in the drive system, the increase in noise must be counteracted by reducing the loop gain, which will in turn lower the motor's dynamic performance.

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Noise also affects a motor's thermal behavior. Low noise levels translate into lower power dissipation and motor temperatures. High noise levels, on the other hand, increases the motor's power dissipation and significantly raise its temperature.

Comparing the noise from different encoders reveals their behavioral differences. Optical encoders cause low, steady noise, whereas magnetic and inductive encoders cause higher, much more heterogeneous noise, even with a low-pass filter. This makes



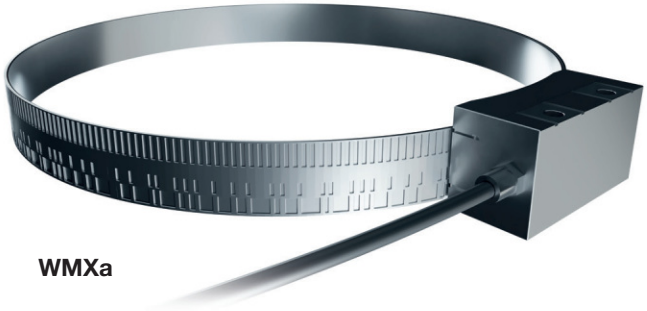
ECA



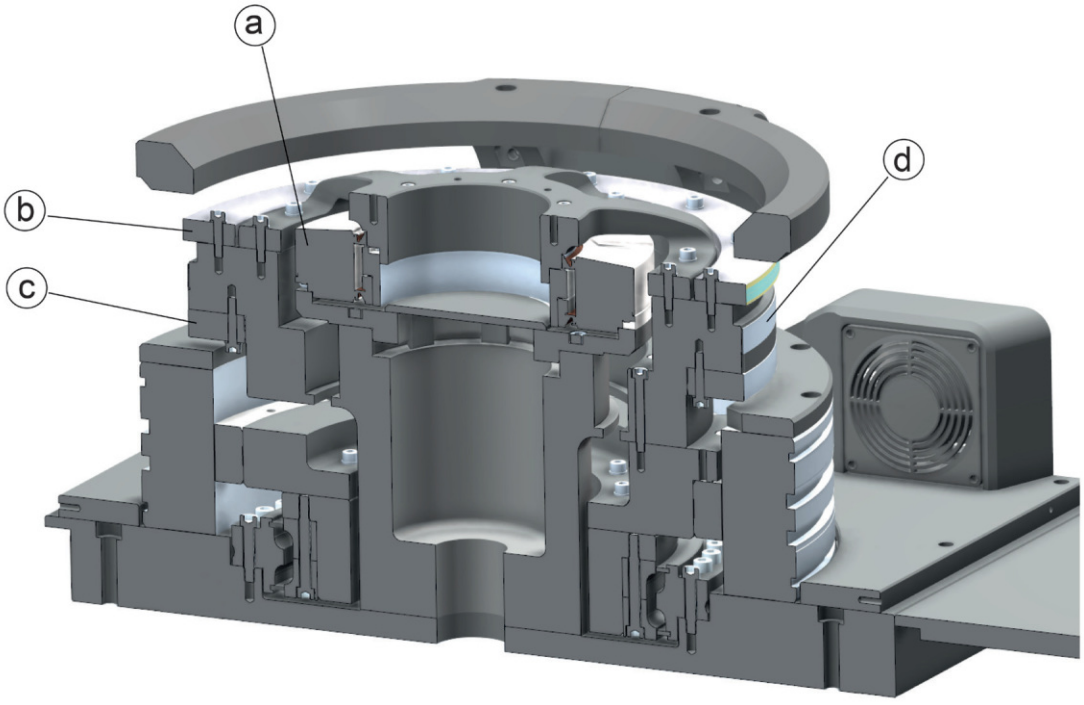
ECM



RCN



WMXa

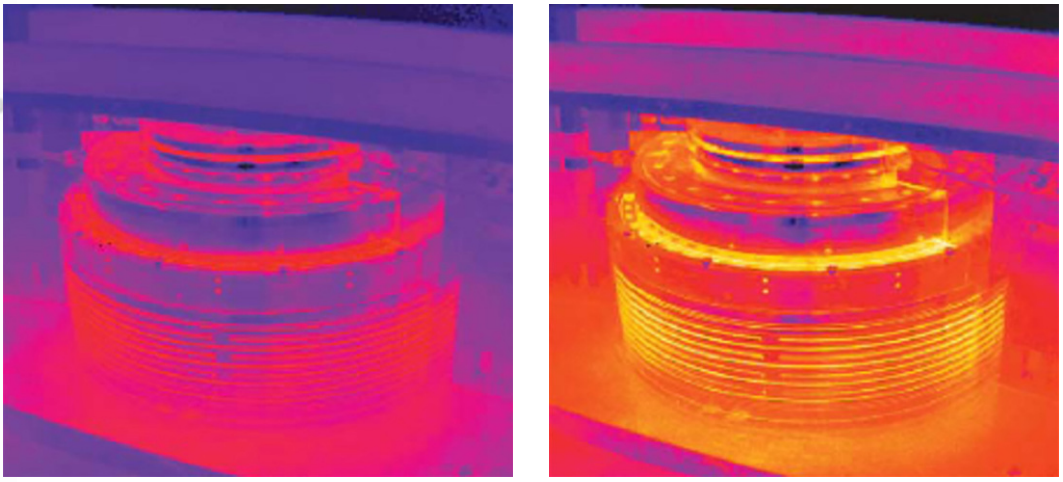


This device was used to test and evaluate the different encoders using a TMB+ torque motor from ETEL. The cutaway shows the positions of the different absolute angle encoders: (a) a Heidenhain RCN 8311, a typical sealed encoder for rotary tables and swivel heads in high-accuracy machine tools; (b) a Heidenhain ECA 4410, a typical optical encoder with a steel scale drum for wide-axis rotary tables and swivel heads; (c) a Heidenhain ECM 2410 magnetic encoder; and (d) AMOS’s WMxA 1010 inductive encoder, a scale-tape version that is compact and contamination-tolerant.

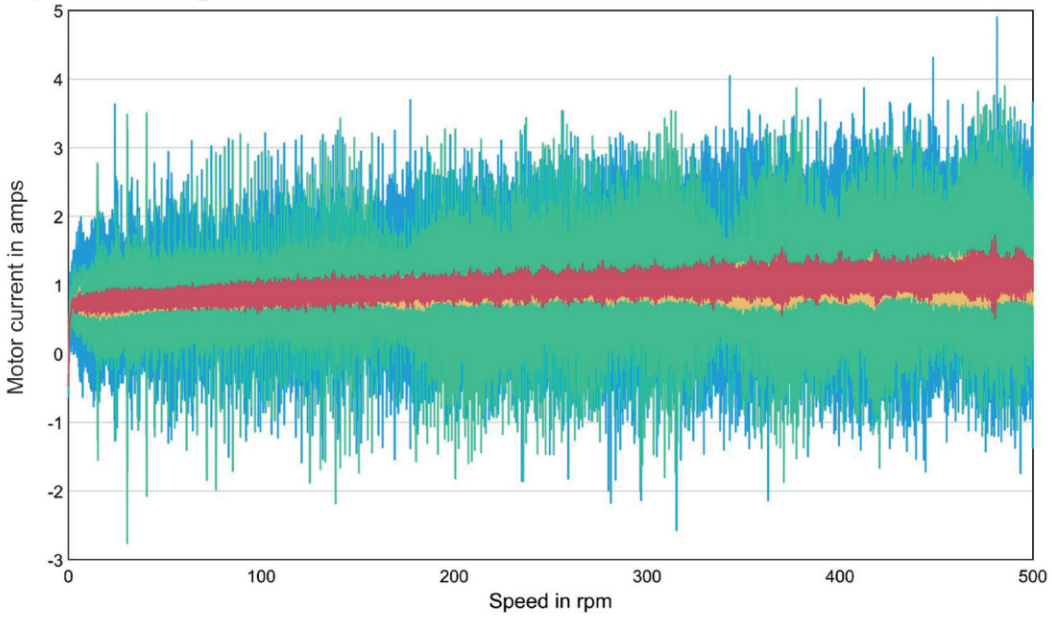
optical encoders the best choice for getting the most out of a motor's performance potential and getting the best-surface quality.

Actual Versus Desired Position

Whether or not the actual position of a rotary table coincides with the desired position can be evaluated based on statistical measurement of positioning accuracy in accordance



The thermal image on the left shows the lower motor temperature for an optical angle encoder used for position control compared to the higher temperatures created by a non-optical encoder, as seen at right.



	Type	Scanning	Line count	Resolution (in bits)	Max. speed in rpm	Applied TNC filter
	RCN 8311	Photoelectric	32768	29	1500	None
	ECA 4410	Photoelectric	25993	28	900	None
	ECM 2410	Magnetic	2600	25	4500	FIR=2
	WMxA 1010	Inductive	1024	24	520	FIR=2

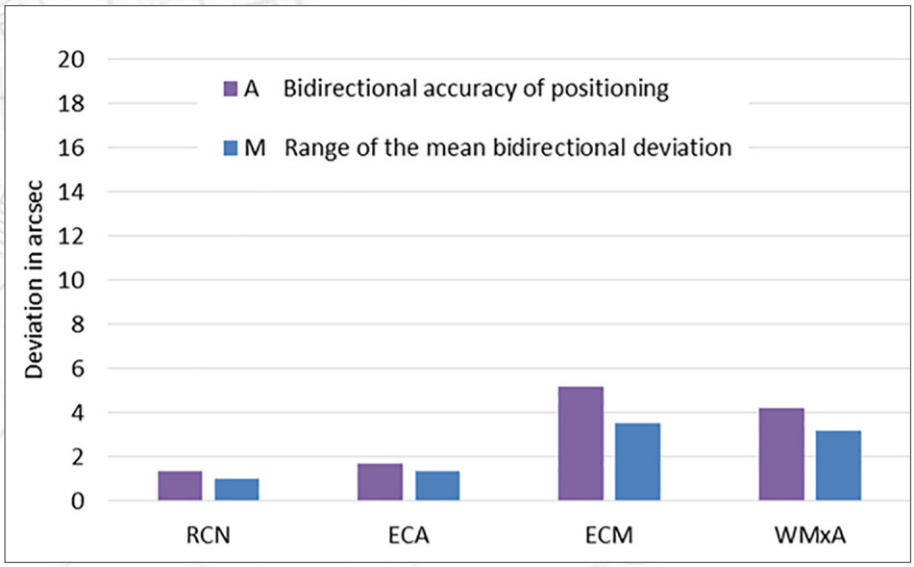
This graph shows the noise levels generated by the four different encoders.

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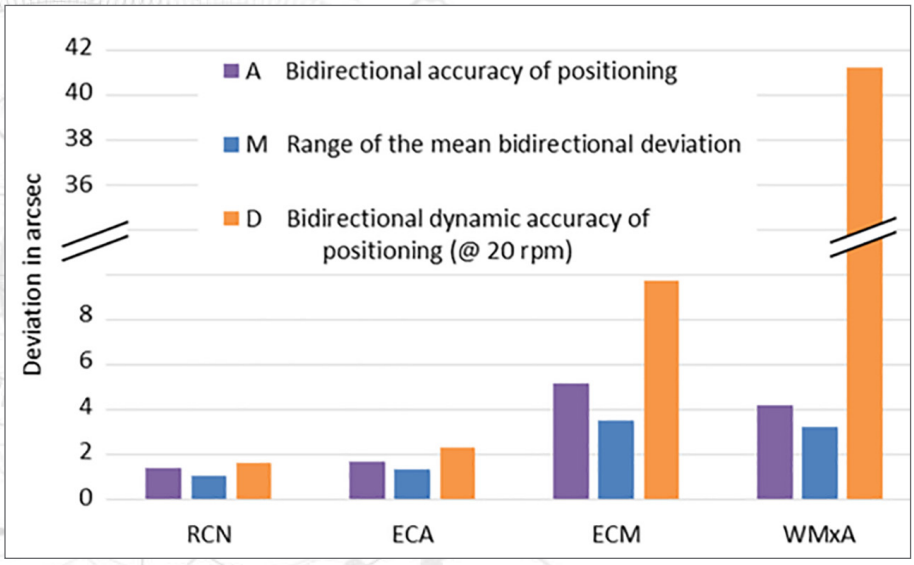
with ISO 230-2. This calls for five clockwise and five counterclockwise revolutions of the rotary table, with 12 measurements taken at 30-deg. steps over each revolution.

Key metrics for evaluating encoders are Parameter A (the bidirectional positional accuracy) and Parameter M (the range of the mean bidirectional positional deviation). Parameter A is comparable to the accuracy of an angle encoder and Parameter M to the graduation accuracy, each taking into account the error from the application.

To evaluate the contouring accuracy at a given maximum speed, the evaluation went beyond ISO 230-2 criteria and added dynamic accuracy of positioning (designated by the letter D). As in ISO 230-2, measurements are once again taken over five clockwise and five counterclockwise revolutions of the rotary table. This time, however, the measurements are taken at a scanning rate of 5 kHz and a speed of 20 rpm.



This chart compares the encodes' bidirectional accuracy of positioning and the range of the mean bidirectional positional deviation. The RCN and ECA optical angle encoders exhibit much less deviation between the actual and desired position than the magnetic (ECM) and inductive (WMxA) encoders.



This chart compares the encoders' dynamic accuracy of positioning, a parameter that determines their achievable contouring accuracies. It shows the high deviation for the inductive encoder.

Measuring the dynamic positioning accuracy at the contouring accuracy uncovers high deviations for inductive angle encoders. (Contouring accuracy refers to the changes in accuracy measured at speed by comparing desired position to actual position.) The deviation is a byproduct of inductive scanning that causes accuracy to vary with speed. In contrast, optical encoders demonstrate hardly any deviation between desired and actual positions. The magnetic encoder showed mid-level performance without extreme deviation.

Motor Protection

Torque motors provide high performance in a compact device. But overheating is a risk if current distribution in the windings becomes asymmetric during certain machining operations, causing a surge in temperature of a single winding. Sending sensor data on thermal behavior around the motor to the controller protects the motor, as well as increases the reliability and efficiency of machining processes.

The sensor box used in the evaluation monitors all three motor windings, providing the temperature data for immediate use. The box is installed next to the motor and between the encoder and controller.



The EIB 5200 sensor box from Heidenhain offers intelligent motor protection for the machining process. With minimal cabling, additional data from the motor system are immediately usable.

If the motor's thermal model is already known, as is the case with the torque motor, the sensor box will rapidly detect sudden temperature rises and preventing damage to the motor windings and protecting the motor from overheating.

Choosing the right encoder and using the various data available from the machining process are important for reliability, stability and accuracy of machining processes. Knowing the characteristics of different encoders lets designers and developers choose the most suitable encoder for an application. After all, choosing the right encoder isn't just about dynamic performance and accuracy; designers and developers must also take design-related factors such as the shaft diameter and mounting into account, not to mention cost-effectiveness.

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CHAPTER 2:

Advantages of Air Bearings

MATT RECK

For straightness, high speed, or high resolution, air bearings might be the solution you're looking for.

Most motion applications use mechanical bearing guidance. However, there are many cases in which precision, angular repeatability, and geometric performance must be optimal, or submicron-bearing rumble is problematic. Air bearings offer distinct advantages in precision positioning, such as lacking backlash and having no static friction.

Friction is the Enemy

Frictionless drive and bearing technology is a prerequisite for vibration-free precision motion with nano-scale resolution, repeatability and guiding accuracy. There are several ways to achieve frictionless motion. Piezo drives and flexure guidance work well for short travel ranges typically below 1 mm. Another principle is based on magnetic levitation (magnetic bearings). These motion systems are more complex in terms of control, and designed for multi-axis motion applications. The most mature solution for long travel ranges consists of air bearings driven by electromagnetic linear and torque motors.

Air-bearing stages are rotary or linear positioners that float on a cushion of air, using one of several preload mechanisms, thus nearly eliminating mechanical contact, and in turn, wear, friction, and hysteresis effects. They deliver maximized throughput while providing higher precision than conventional bearings, especially for multi-axis motion. That's because an XY stage can be designed with one base rather than by stacking individual stages with accumulative errors.

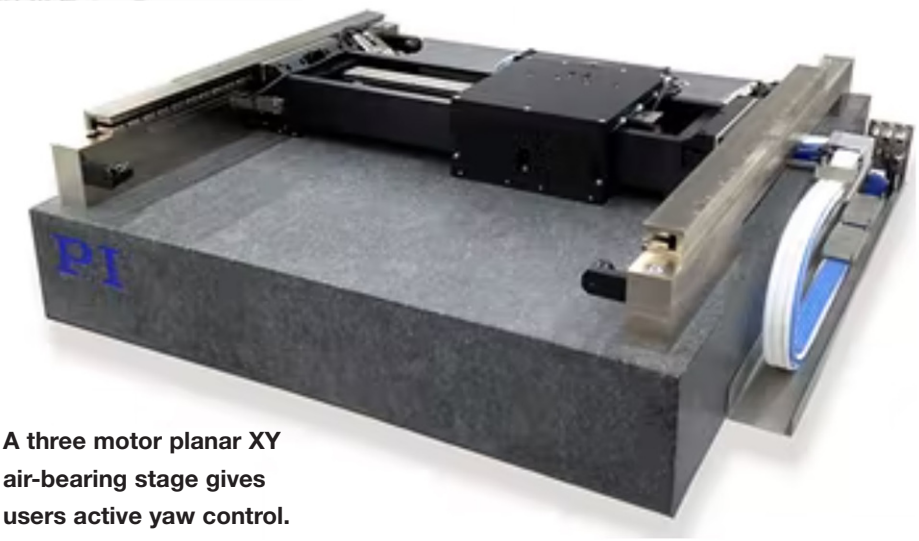
Benefits of Air Bearings

The most common factors supporting the use of air-bearing stages in motion-control applications are:

Frictionless High-Performance Positioning

A direct-drive motor and high-resolution encoder can position a moving carriage supported by an air bearing to within 1 nm in a linear application, or within 0.1 arc-seconds in rotational applications. The lack of friction and mechanical contact means there is minimal

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A three motor planar XY air-bearing stage gives users active yaw control.

hysteresis or reversal error. As a result, it's highly repeatable and ideal for many inspection and manufacturing operations, such as flat-panel inspection, semiconductor metrology, and laser machining. Air bearings virtually eliminate stiction, which improves resolution capabilities and reduces in-position "hunting"(limit cycling). In addition, position repeatability within a few fundamental encoder counts is possible. Piezo flexure guided stages can achieve similar precision, though over much smaller travel ranges. Magnetic levitation is another option.

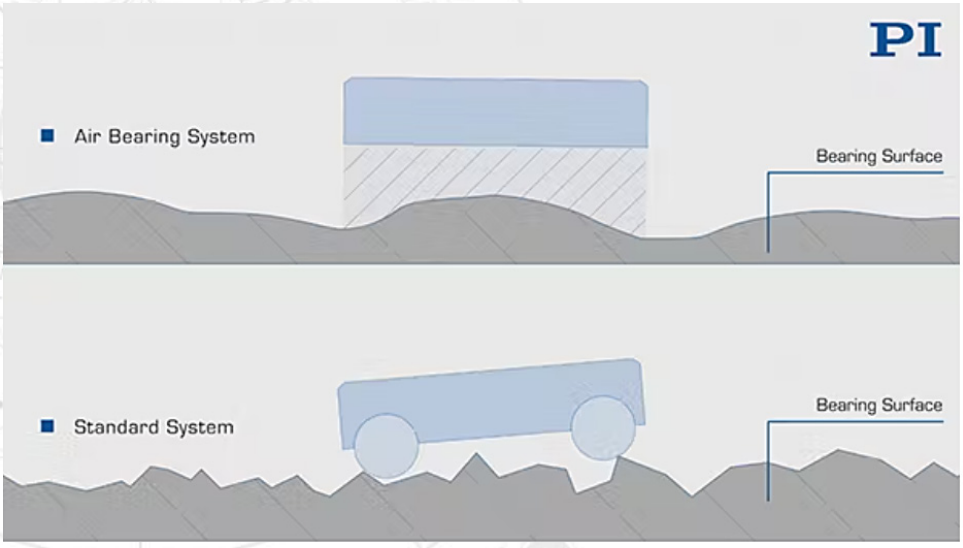
Velocity Stability and Scanning

Inertial sensor testing, tomography, wafer scanning, and surface profiling require continuous motion at tightly controlled speeds. These types of experiments and processes are best served by air-bearing systems because the lack of mechanical-bearing elements means nothing can get in the way of smooth, controlled velocity (stability to better than 0.01%).

Very Low Error Motions Due to Surface-Averaging Effect

Air bearings offer high accuracy because not only components are manufactured with extremely tight tolerances, but also due to the air film's averaging effects (check out *this video*). Linear air-bearing stages have extraordinarily straight and flat travel. Pitch, roll, and yaw errors about 1 arc-second per 100-mm travel. Rotary stages achieve tilt (wobble) errors in the range of 0.1 to 1 arc-second.

Furthermore, the angular performance of an air bearing is repeatable. For manufacturing and measuring, this means a very high repeatability of the same process and the feasibility to compensate for deviations of the ideal trajectory. Considering that tolerances of current semiconductor features are approaching single-digit nanometers, and even some components in the latest automotive engines need to surpass submicron precision, this type of performance guarantees repeatable part quality and measurement reliability for applications from precision machining to optics inspection.



The surface-averaging effect of an air bearing improves straightness/flatness of motion and reduces high-frequency bearing rumble.

Travel Requirements are Greater than a Flexure Stage

Piezo-driven flexure stages and

actuators can satisfy many high-precision positioning applications. However, these designs are usually limited to a few millimeters of travel. Air-bearing linear stages can be used for travels of 25 mm or more. Manufacturers such as *Physik Instrumente (PI)* provide linear air bearings with travels up to a meter, and can offer longer lengths with custom design.



Wobble-Free or High-Speed Rotary Motion

Rotary air bearings are stiff and are able to deliver highly precise rotary motion. Radial, axial, and wobble error motions are typically 10 times smaller than what's possible with most mechanical-bearing solutions. Also, the rotary motion is smoother since there are no roller elements.

Rotary positioning stages generally can achieve speeds up to 600 RPM, while air-bearing spindles used in higher-speed applications can rotate up to 100,000 rpm and more. Rotary-bearing designs mounted with the plane of the table can work in either the horizontal (i.e., turntable) or vertical orientations to suit applications from optical testing or machining.

Minimal Maintenance

Air bearings require no regular maintenance procedures or lubrication. Moreover, the system is highly stable—without the effects of wear, performance characteristics should not change over the life of the system. There is little need for recalibrating the positioning accuracy, as can be the case when mechanical bearings wear out over time and lose guiding precision. Moving cables and hoses are often the only wear items in an air-bearing system.



Spherical air bearings can simulate zero gravity to maintain high-precision positioning.

Cleanliness

Because air bearings are wear-free, they generate virtually no particulates that can become airborne. This makes them ideal for cleanroom applications like optics inspection, wafer inspection, bio-pharma research, and flat-panel display inspection. For extremely clean applications, air bearings can operate using 99.9% pure nitrogen.

Precise Force Control and Sensing

Air bearings are virtually frictionless when coupled with a direct-drive motor or voice coil. They are ideal for micro- and nano-Newton-force control applications. Such applications can include pick-and-place of delicate items, materials testing, and coordinate measuring.

Non-Conductive Environments

Air bearings are not ideal for all operating environments:

- *Vacuum environments:* Though not impossible to operate an air bearing in a vacuum, it is challenging. Vacuum applications should generally be avoided; instead use stages based on mechanical bearings, magnetic levitation, or flexure guiding systems.
- *Dirty, dusty applications:* An application for air bearings is often clean environments. Avoid applications where heavy amounts of dust, dirt, debris, and fluids are present.
- *Unavailable pressurized air or nitrogen:* Air bearings require a continuous supply of clean compressed air or nitrogen.

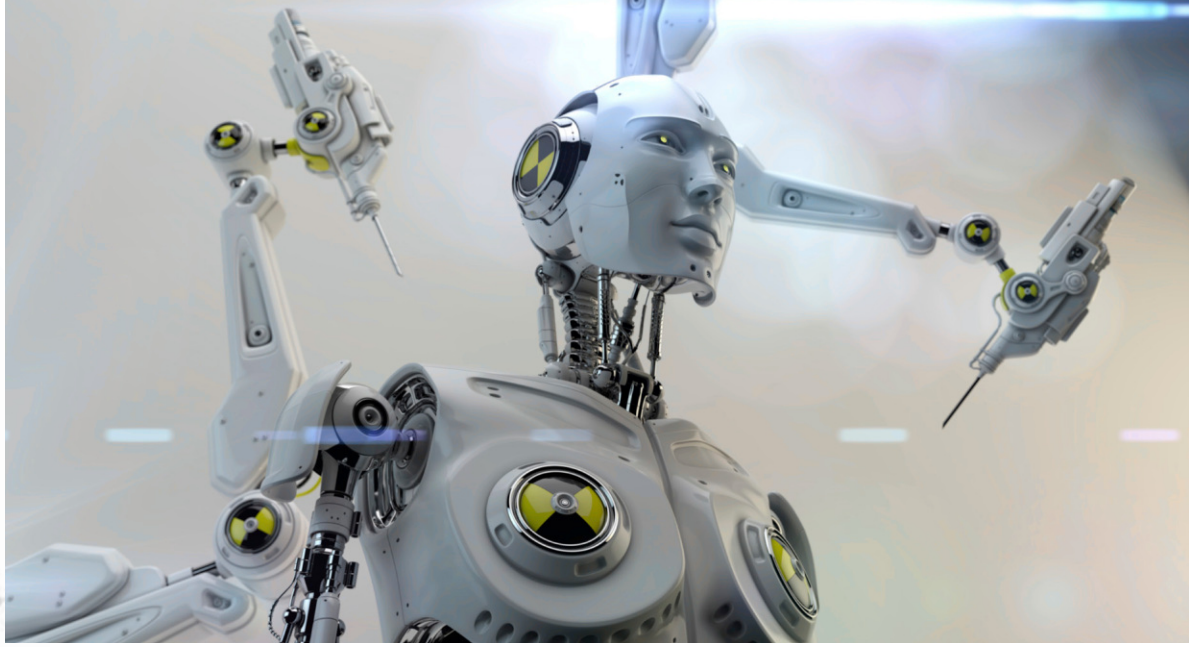
Matt Reck is Air Bearing Product Line Manager at PI. He holds a B.S. in Mechanical Engineering from the University of Pittsburgh. He has extensive knowledge in design and applications of precision positioning equipment, having spent the past years working at a number of motion-control companies including Dover Instrument, Danaher Corp., and Aerotech, Inc. Additionally, as a program manager for several top engineering companies, Mr. Reck gained experience in the medical device and lab automation fields, leading the development of a wide range of products and systems.

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CHAPTER 3:

Solving the Hunchback with a Robotic Exoskeleton

CARLOS GONZALEZ, Contributing Technical Editor

Researchers from Columbia University look to modernize the back brace with a dynamic robotic system in hopes of correct spinal deformities.

New research from Columbia University looks to solve the limitations in spinal curve correction treatment. Spine deformities are characterized by an abnormal curve in the spine. The medical terms for such conditions are idiopathic scoliosis or kyphosis, commonly referred to as being "hunchbacked." These conditions affect children in development, and the common treatment for any spinal deformity is to wear a brace that fits around the torso and hips. The brace helps to correct the abnormal curve, and it been shown to prevent the progression of the curve to avoid future surgery.

The bracing used has not changed in 50 years, however. While it stops or slows down the progression of the curve, it imposes a number of limitations and restrictions on the children. The braces are rigid, static, and analog, meaning there are no feedback sensors or technology that can monitor the patient's progress. Also, most braces are uncomfortable and can cause skin irritation from prolonged use. The braces also do not adapt well over time, resulting in diminished effect until a new brace is made for the patient—which can be costly.

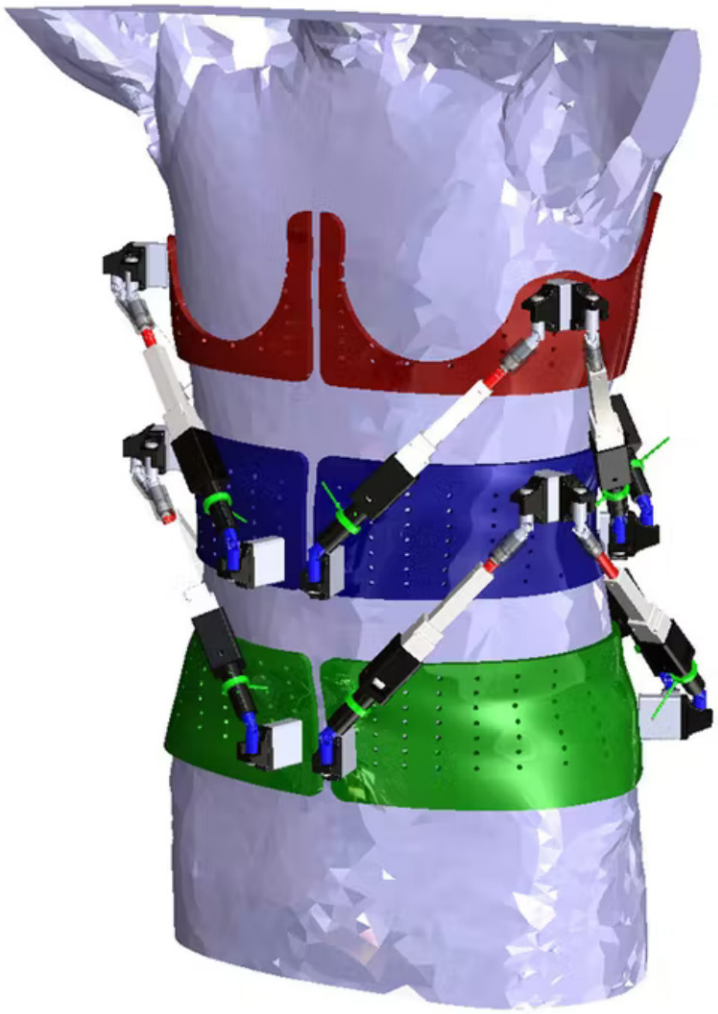
To modernize the brace, Columbia Engineering researchers have invented a new Robotic Spine Exoskeleton (RoSE). RoSE looks to solve the limitations of current brace technology and hopefully lead to new treatments for spine deformities.

Designing of the RoSE

The RoSE is a dynamic spine brace that looks at in vivo measurements of torso stiffness and characterizes the three-dimensional stiffness of the human torso. The first study was published online March 30 in *IEEE Transactions of Neural Systems and Rehabilitation Engineering*.

"The RoSE is the first device to measure and modulate the position or forces in all six degrees of freedom in specific regions of the torso," says the study's principal investi-

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The Robotic Spine Exoskeleton (RoSE) consists of two six-degrees-of-freedom, parallel-actuated modules connected in series, each with six actuated limbs. (Image Credit: Sunil Agrawal/Columbia Engineering)

gator, Sunil Agrawal, professor of mechanical engineering at Columbia Engineering and professor of rehabilitation and regenerative medicine at Columbia University Vagelos College of Physicians and Surgeons. "This study is foundational and we believe will lead to exciting advances both in characterizing and treating spine deformities.

"To our knowledge, there are no other studies on dynamic braces like ours," Agrawal continues. Prior to developing the RoSE technology, brace studies were performed on cadavers, which did not provide a complete dynamic picture.

The RoSE was developed by Agrawal's Robotics and Rehabilitation (ROAR) Laboratory and consists of three rings placed on the pelvis, mid-thoracic, and upper-thoracic regions of the spine. A six-degrees-of-freedom, parallel-actuated robot is used to control the motion of two adjacent rings.

The system has 12 degrees of freedom overall that is controlled by 12 motors. With the RoSE, researchers have the ability to control the motion of the upper rings with respect to the pelvis ring or apply controlled forces on these rings during the motion. The system design can also apply corrective forces in specific directions without restricting the free motion in other directions.

The RoSE First Case Study

In the first study conducted by the team, eight male subjects without spine deformities and two male subjects with spine deformities were selected. The purpose of the pilot study was to characterize the three-dimensional stiffness of their torsos. The RoSE controlled the position/orientation of specific cross sections of the subjects' torsos while simultaneously measuring the exerted forces/moments.

Spinal abnormal curves are three-dimensional, meaning that the stiffness characteristics are curve-specific and depend on the locations of the curve apex on the human torso. The results from the study showed that the three-dimensional stiffness of the human torso can be characterized using the RoSE, and that the spine



This video describes the design and fabrication process used in creating the RoSE. (Image Credit: Sunil Agrawal/Columbia Engineering)

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The image above is an illustration of the design and fabrication steps used in developing the RoSE. (Image Credit: Sunil Agrawal/Columbia Engineering)

deformities induce torso stiffness characteristics that were significantly different from the healthy subjects.

Joon-Hyuk Park, who worked on this research as a Ph.D. student and a team member at Agrawal's ROAR laboratory says that, "In order to characterize the three-dimensional stiffness of the human torso, the RoSE applies six unidirectional displacements in each DOF of the human torso, at two different levels, while simultaneously measuring the forces and moments."

"Our results open up the possibility for designing spine braces that incorporate patient-specific torso stiffness characteristics," adds the study's co-principal investigator, David P. Roye, a spine surgeon and a professor of pediatric orthopedics at the Columbia University Irving Medical Center. "Our findings could also lead to new interventions using dynamic modulation of three-dimensional forces for spine deformity treatment."

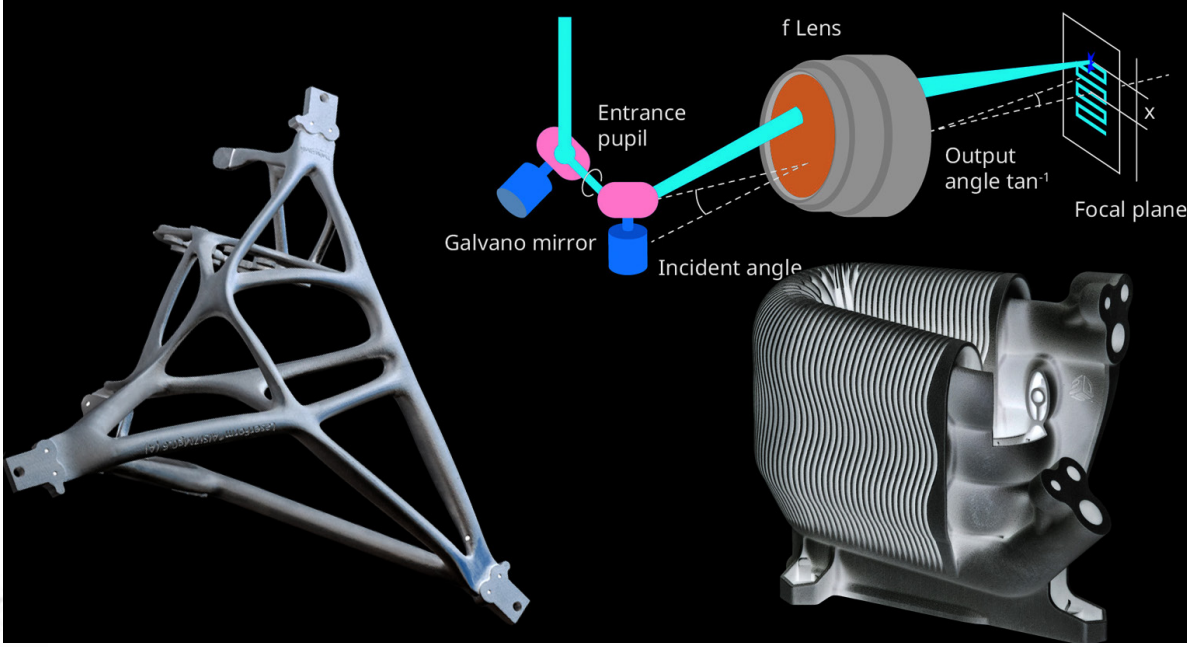
The next phase of study is to use the RoSE on female patients. In young females, idiopathic scoliosis is 10 times more common than males. "Directional difference in the stiffness of the spine may help predict which children can potentially benefit from bracing and avoid surgery," says Agrawal.

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CHAPTER 4:

Five Considerations for Building a Metal AM Business Case

MARK COOK

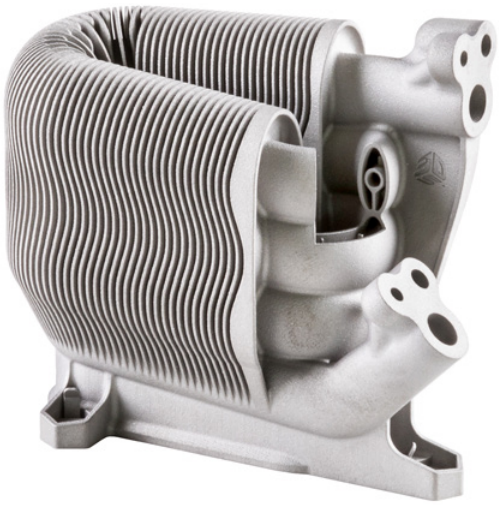
Digital manufacturing solutions fuse metal 3D printing workflows to produce repeatable, high-quality parts from the most challenging alloys.

Additive manufacturing (AM) is becoming a core element of production workflows for manufacturers looking to improve efficiencies, better manage their supply chains and maintain competitive advantage. In a recent EY study, "*3D Printing: Hype or Game Changer*," it is confirmed the adoption of additive is ramping with nearly 75% of companies either already embracing the technology or considering its integration into their manufacturing workflow. However, the introduction of these technologies into existing business models and workflows can be challenging for those who are new to AM. Drawing on the know-how of AM experts can help companies plan for and execute successful implementation.

The Business Case for Metal AM

Metal AM is a design-driven manufacturing process that uses high-powered lasers to selectively weld powdered material where prescribed and leave it to be evacuated where unwanted. Companies typically invest in metal AM to take advantage of the benefits unlocked by the nearly unlimited design flexibility of a digital workflow.

Metal AM also enables creation of parts that would be nearly impossible to produce in any other way, featuring custom exterior or interior geometries that lower weight (which translates to cost reduction



Metal AM is a design-driven manufacturing process that makes possible many organic shapes and features, such as this lamellar heat exchanger part.

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in production and implementation, or both) or improve functionality (which can also have significant economic ramifications). Additionally, metal AM makes it possible to consolidate multiple parts into a single design and replace complex assemblies of components, which limits associated labor costs and contributes to enhanced structural integrity through the elimination of weak joining points.

Beyond the economic values already listed, metal AM opens the door to more agile manufacturing, mass customization and supply chain consolidation. Increasing productivity, reducing inventory and accelerating time-to-market become tangible and strategic opportunities with the correct metal AM solution.

Five Factors that Impact Metal AM Quality & Repeatability

One of the key components at the heart of a metal digital manufacturing solution is the metal 3D printer that transforms metal powder materials into final metal parts. Every piece of the metal 3D printing process has an impact on the outcome. How these pieces interact and are managed influences overall AM quality and repeatability.

There are several metal AM printers available that use a laser-based process to deliver parts, including laser powder bed fusion (LPBF), direct metal printing (DMP), selective laser melting (SLM) and direct metal laser sintering (DMLS). The trick is finding a system that enables consistent quality and repeatability. In selecting the appropriate system for an application, it is imperative the following five factors are considered.

1. Premium Laser Control

The chain from the laser source to the melting of powder particles is at the core of every metal 3D printer. Any concession made in this chain can degrade the quality and accuracy of the additive manufacturing process, resulting in a negative impact on parts produced.

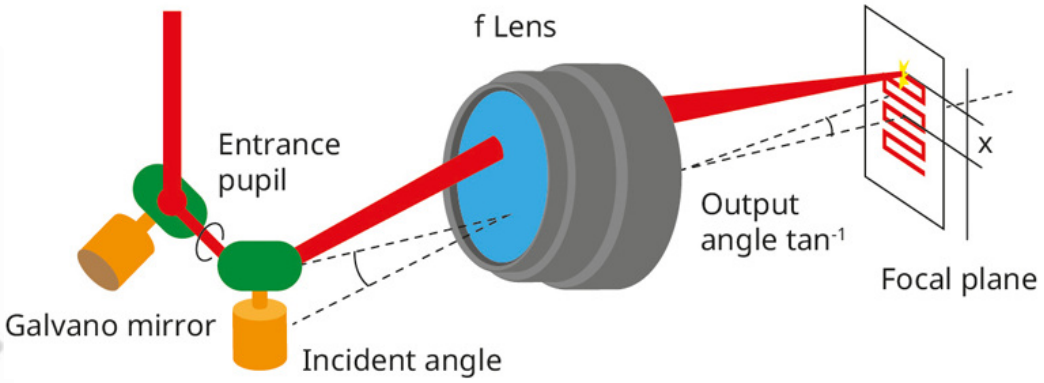
As mentioned above, metal AM is an optical process. Therefore, the laser source and the entire optical chain must be accurate and robust. The laser source must emit a high-intensity laser beam to feed sufficient energy into the optical chain. An optimal laser beam of 50 or 65 µm will ensure proper melting and high accuracy AM. The quality achieved by such a system typically translates into a 150 µm achievable wall thickness and standard deviations as low as 25 µm.

2. Qualitative Powder Use & Process Emissions Evacuation

Process emissions resulting from improper argon flow management are detrimental to quality in metal AM. Likewise, the use of metal alloy powder that is suboptimal in quality or purity—which is inadequately matched with printing parameters—will also diminish the printing process. It is advised to use ready-to-run metal alloy powders, which are specifically developed and supplied for metal AM purposes.

Operating metal AM printers with optimized, tuned powder types contributes to higher-quality part outcomes and an increased first-time-right experience. The print file, which tells the 3D printer what and how to print, is based on extensively developed algorithms for each material. The quality of these algorithms heavily influences the final part quality and radically reduces the time customers need to achieve the targeted properties for any specific part.

Because metal AM is essentially a welding process using powder, it is important that argon flow in the print chamber be properly managed. If argon flow is mismanaged, emit-



An accurate, robust optical chain from the laser source to the melting powder particles ensures a dynamic, qualitative metal printing process.

ted particles are at risk of absorbing laser energy. To avoid quality issues, a robust and highly controllable argon flow system is necessary.

3. Inert Atmosphere with Steady, Ultra-Low Oxygen Level

An inert gas environment inside the 3D printer plays an important role in metal AM quality. More specifically, the AM process will be affected by oxygen and moisture content. Air trapped between powder particles, even in low quantities, is likely to have an impact and introduce metal oxidation, which leads to weaker, more brittle materials.

Applying a vacuum is an effective approach to removing air. A vacuum is achieved from executing multiple inerting cycles to obtain an ultra-low oxygen atmosphere in the 3D printer's build area and material storage space. A proven process used in critical welding applications, the vacuum concept removes air from the build chamber and actively extracts air and humidity from between the powder particles.

Inerting processes that use and print inside a vacuum chamber consistently achieve <25 ppm of O_2. Other inerting processes achieve between 500 and 1,000 ppm. As a result of extremely low oxygen pickup, such a printer enables considerable savings on raw materials due to the full reusability of the recycled metal powder. Beyond the cost savings on argon, the savings enabled by powder reusability are extremely valuable over time, allowing users to make full use of materials at full quality.

4. Real-Time Process Monitoring & Automated Quality Analysis

Quality analysis of the final part is key in serial part production, and many companies looking into the technology underestimate the cost and time factor currently required. Metal 3D printers that capture visible light images of the powder bed both before and after scanning—as well as visible light images of the melt pool—are ideally suited for process monitoring and non-destructive quality control of the parts being produced.

Additionally, to support traceability, look for a metal 3D printer that automatically records all graphical data, including backup to a server. Access to this wealth of data supports informed decision-making. Established process traceability and related documentation are proven to be useful and are mandatory within highly regulated industries such as aerospace and healthcare.

While most available systems on the market gather tremendous amounts of data (gigabyte upon gigabyte) and offer some kind of representation, this approach is rarely as helpful as it seems because it requires the intentional allocation of time and attention to sort through and analyze it. To combat this shortcoming, some manufacturers offer graphs of certain quality parameters. A problem arises when defining these quality parameters, as they do not sync to industry quality controls in terms of factors that define the mechanical integrity of the part, such as porosity, location of voids, and surface defects. Perhaps even more significantly, many software programs provide no guarantee of the accuracy of the data.



Using an all-in-one software solution that integrates structure optimization capabilities enables users to create lighter weight parts for aerospace, such as this satellite bracket.

Look for a solution that includes tools that enable users to see and analyze defects in the correct size and at the correct location with high accuracy for defect detection (99.9% for pore detection of pores 200 um or larger). This can help users reduce or eliminate the number of bad parts going through downstream quality inspection steps.

5. Software that Spans the Entire AM Workflow

Achieving successful prints is the key objective of the AM workflow. Getting from design to a repeatable manufacturing process with optimized cost structure is key and requires a software solution that integrates the entire workflow of preparation, optimization and manufacturing of 3D CAD models. There are many software solutions available that address a portion of these steps, but only a select few cover the entire workflow.

An integrated all-in-one solutionwill allow users to easily move from one stage to another without file format conversion, thus saving a lengthy, error-prone iterative process. Other key features that will facilitate the 3D printing process include:

- Native data import, eliminating the need to convert to STL, maintaining design integrity and saving time on fixing error-prone data format conversion issues
- Structure optimization capabilities that enable users to save on weight, material and printing time
- Integrated build simulation within the design environment minimizes try-outs, shortens lead time and cuts production cost
- Optimized slicing and hatching ensure repeatable, high-quality prints while minimizing print time
- Programing of post-processing operations like machining and drilling tools to remove

supports; machine high-quality surface areas; and drill, tap or ream holes. Additionally, applying smart machining templates enables smooth integration of additive and subtractive processes for best final part results and lowest achievable cost per part.

Integrated Solutions Fuel Innovation

Metal AM has become an important technology for end use production applications—especially for the aerospace and healthcare industries. This is due in large part because of its benefits: part cost reduction, increasing efficiency of designs, light weighting of parts, assembly consolidation and the ability to design and produce unique parts that would not be possible with traditional manufacturing technologies.

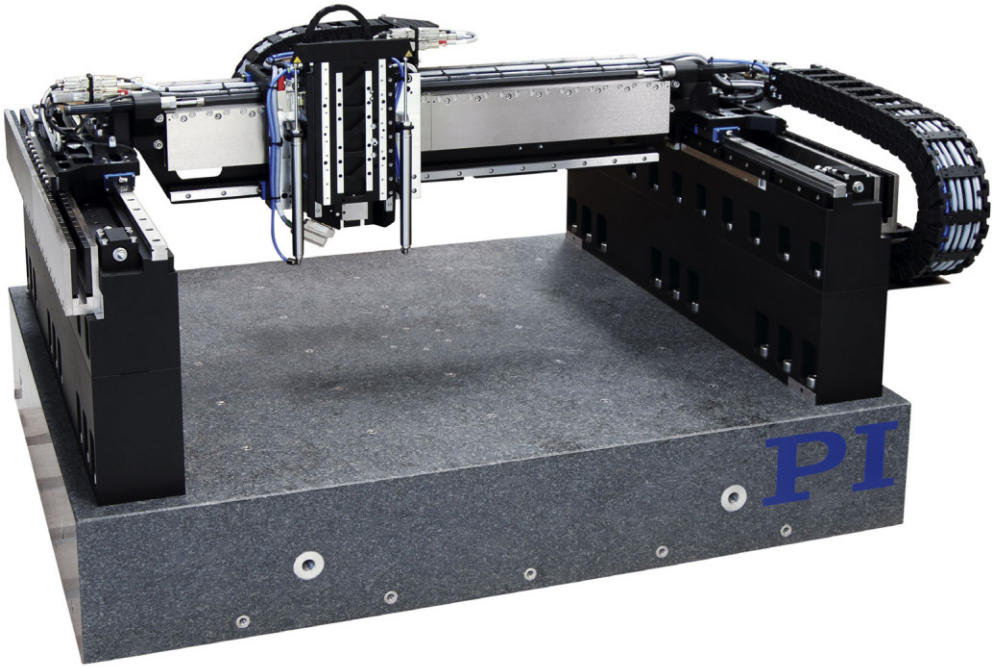
The most successful digital manufacturing solutions complete metal 3D printing workflows tailored to a specific application—optimized for scalability, high throughput and low total cost of operation—to produce repeatable, high-quality parts from the most challenging alloys. As adoption of metal AM increases, companies will transform how they create new, improved products while gaining efficiencies that place them well ahead of their competitors.

Mark Cook started his career as a design engineer developing new products for the aerospace, consumer, industrial and medical markets. In 2005, Cook joined Z Corporation to develop full-color 3D printers used for rapid concept modeling, and then joined 3D Systems in 2012 when Z Corporation was acquired. He earned a B.S. in mechanical engineering at Northeastern University and an MBA from the D'Amore-McKim School of Business at Northeastern University.

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Position Yourself for SUCCESS



CHAPTER 5:

Simple, Fast, Accurate, and Flexible Control in Laser Materials Processing

DR CLIFF JOLLIFFE, Head of Automation Market Segment at PI (Physik Instrumente)

How to make it easier for system integrators to design and build advanced systems for a new age of laser applications

1. Introduction

Lasers have been used for welding and cutting applications in materials processing for many years. However, laser technology has frequently been considered a specialist area, requiring complex control systems for accurate positioning, as well as significant investment and expertise. Recently, the cost of lasers has collapsed, opening this powerful technology up to new applications; even the latest extremely fast ultrashort pulse lasers are now feasible options for machine builders who would typically have used 'less risky' laser setups.

The commoditization of lasers means that system integrators must do more to gain and maintain an advantage, and that positioning and control – as integral parts of any laser system – are important elements of this. The newer technologies work in a slightly different way, so it makes sense that positioning and control also need to be different; the basic ability to fire the laser in the right place has become more challenging, and a simpler approach is even more important than ever, especially for those who are completely new to the technology.

Novel solutions are now available that take a uniquely modular approach to laser control, making it far easier and faster for system integrators to design and build systems in the first place, whether or not they have previous experience of lasers. The use of industrial control networks such as EtherCAT makes this modular solution even more flexible, as other items – such as sensors, or nonmotion devices – can be easily incorporated.

This white paper looks at positioning and control of lasers in detail, at the challenges

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that system integrators face, and, more importantly, at the solutions that are available to them that simplify system builds.

2. Why choose laser processing?

There are many significant advantages to using lasers instead of traditional machining processes, not least their capacity for much higher throughputs. Lasers are not susceptible to the same wear and tear that can lead to breakdown disruption and costs in mechanical components, and are often efficient at processing materials that are otherwise notoriously difficult to deal with. The fine beams of lasers also give a level of elaborate detail and accuracy that is near impossible to create using other methods, which is ideal for applications, such as those generating high aspect ratio holes or other features requiring similar high precision. High intensity short pulse lasers, in particular, are incredibly precise; the low thermal energy deposition around the beam of these lasers means there is negligible damage to the surrounding areas. Lasers can even process below the surface of a material, depending on where the beam focuses, examples of which can be commonly found in microelectronics devices, such as light-emitting diodes and flexible displays.

2.1. Striking the right balance of speed, power, and precision

Whatever the application, fast shuttering and accurate firing of laser pulses is essential to ensure consistent, high-quality processing. Precise placement and energy control are crucial for this and can be achieved by linking the automation and motion system directly to the laser output. It is extremely important to be able to make sure that the laser is focused on the right place, for the right amount of time, and delivering the right level of power in order to prevent damage to the material or the production of inaccurate parts.

One option is to link laser power to pulse rate and modulation; if the power is fixed, then the motion system will need to run at a constant speed to ensure that the correct level is delivered across the surface. This suits some operations, such as raster scans where the laser is fired following the motion in one direction, or during the constant velocity phase between acceleration and deceleration phases. However, cutting and welding applications may also need the laser pulses to overlap at a consistent ratio, even when the motion path speed is not constant, and laser pulses occur at a fixed frequency. **Figure 1** shows an example of this; 1a shows the laser pulse placement during a constant speed profile, and 1b when the velocity changes. This could result in a nonuniform pulse delivery, where

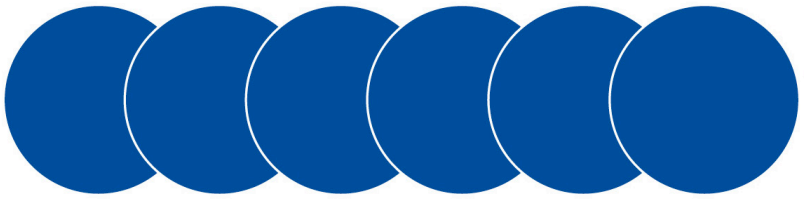


Fig. 1a. Laser pulse placement during a constant speed profile.

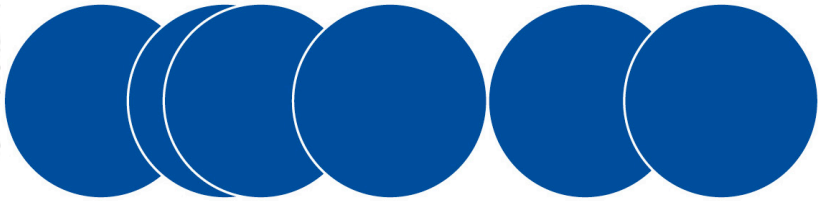


Fig. 1b. Non-uniform pulse delivery.

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too much energy to a particular area could create HAZ (heat affected zones) and too little could cause weak regions or breaks in the cut or weld path.

The problem of HAZ occurs even more frequently with multi- axis systems, simply because of the nonlinear path of corners or arcs. The best analogy is that of a sports car driving around a racing track – when it gets to a corner, it must slow down, otherwise it wouldn't be able to follow the racing line and would probably run off the track; the same is true for an XY table. However, if the motion path slows down too much, but the laser pulsing rate remains constant, too much power is delivered into the corners as the laser pulses bunch up (**Figure 2**). Some G-code capable CNC machines have 'look ahead' capabilities to address this, allowing the motion controller to look for changes in speed that exceed predetermined limits.

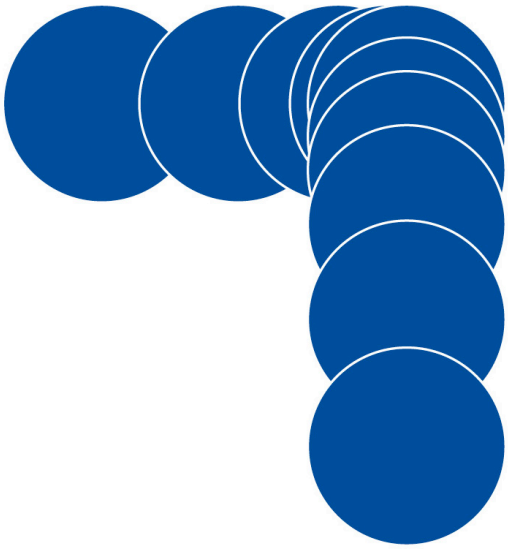


Fig. 2 Pulses bunching up around corners.

3. Linking laser control to speed and position

One of the simplest methods of controlling laser power is to link it to the velocity of the motion path. This can be simply achieved by linking an analog output in the controller to that of the vector speed of the motion path and linking this to the laser power; the analog output is connected to the power input connection on the laser, for example, a 0-10 Vdc range. Typically, the motion controller will allow you to define a scaling factor so that the maximum output is relative to the maximum power of the laser required for the process – a lower limit may also be set. It is important to remember that if the motion is badly tuned, jerks may result in bad processing. Poor placement accuracy could also create a bad quality part. This is a simple but effective process, for example, for welding.

Another approach is to precisely control the laser by pulse placement along the motion path, regardless of the vector velocity. It is also possible to combine these two methods to control scaling of the power output, which overcomes undesired features of the laser electronics or optic path.

There are several technologies available in the industry that can generate such accurate, high-speed, position-based events linked to electronic outputs, for example, laser pulses. Although subtly different from each other, they essentially do the same thing for motion in a single axis; some are better suited to galvo technology, others are more aimed at motorized positioners. Now, with the development of a new modular controller from PI's ACS range, Position Event Generation (PEG) is emerging as an exciting and flexible solution for linking a laser to multi-axis positioning.

4. The challenges of controlling multiple axes

Paths that create three dimensional trajectories can be created from three or more axes. Examples are simple dual vector tracking – generated from two axes and widely

used for linear XY table contouring, including circles or arcs and straight lines – a linear theta combination for processing tubing, or any combination of linear and rotary stages, for example, producing helical motion for drilling. Until recently, controlling the motion path for lasers across multiple axes has come with certain limitations relating to performance, speed, practicalities, and, not least, higher complexity and costs.

4.1. Restricted application, performance, and speed

Many of the drives available for precision motion and laser processing have to be predefined, depending on the feedback device used on the stages or the table used in the motion system. Positional feedback means a device that is capable of reading the stage's position, but also allows the controller to calculate the speed of such a device. Some motion stages do not use any feedback; they rely on the principle that the commanded motion request equals the actual response. Typically, feedback systems are either incremental or absolute; incremental encoders require a reference point or known position when the system starts up, often a homing switch. In comparison, an absolute encoder system has the positional data built into the feedback measurement scale. This positional data is available at startup and therefore removes the step of physically moving the system to a reference device.

4.1.1. Incremental feedback systems

There are two types of incremental encoders, square wave or sinusoidal (sin/cos wave) (**Figure 3**). Square wave encoders provide the system with discrete digital steps of a fixed distance. For example, a square wave encoder on a rotary motor may output 1,000 steps per revolution; if the rotary motor was driving a 1 mm pitch screw, the system resolution would be 1 mm/1,000, i.e. a 1 µm resolution. A potential problem with a square wave encoder is when it has a high count output to obtain resolution, and the system also requires high speed. The output frequency could potentially exceed the maximum frequency input of the controller's feedback circuit, resulting in position loss. Sine wave encoders are able to provide much higher resolution with higher stage speeds because the controller inputs the data at the fundamental frequency of the encoder, which is much lower than the square wave equivalent. The controller feedback circuit internally subdivides the sine wave into digital steps to produce the internal digital steps; this process is called multiplication.

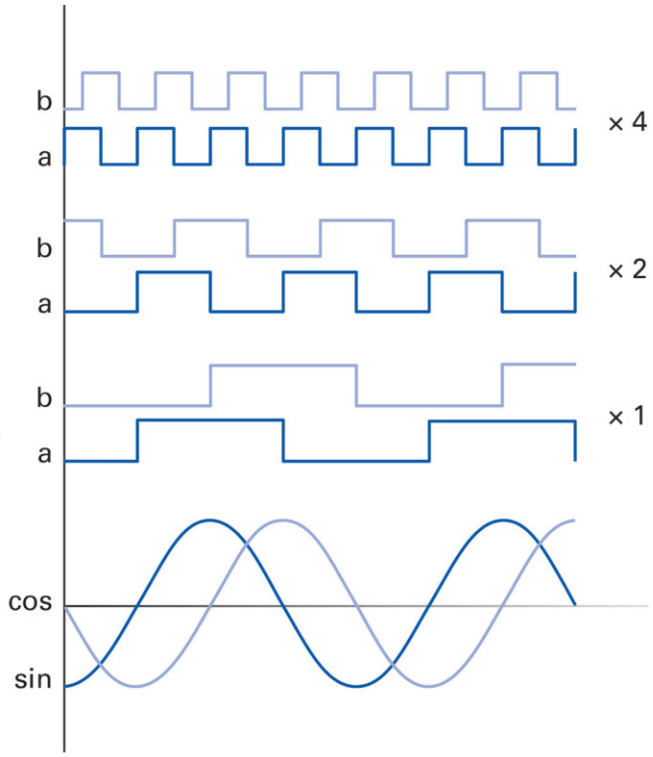


Fig. 3. Sine wave encoder subdivision (encoder multiplication)

In practice, a square wave encoder may start out as a

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sinusoidal encoder, and the key difference is where the digitization or multiplication takes place – at the feedback device in the case of a square wave or in the controller.

However, many laser firing controllers unfortunately cannot use sinusoidal feedback to produce an output that will trigger the laser – their electronics require digital square wave signals – and this may limit their usability to low speed systems with high feedback resolutions or to high speed systems with low feedback resolutions.

4.1.2. Multiple feedback in multi-axis systems

Laser synchronizing technologies use encoder data for single axis path motion to trigger, for example, one-to-one firing so that there is a single laser pulse with every millimeter or micron moved. When it comes to multi-axis, for example pulsing in a circle, the same principle can be applied – data is taken from the individual encoders of each axis and fed into on-board electronics hardware, where the combined vector output is calculated. This has been the accepted norm for many years and, in theory, its accuracy comes from the fact that it is based on real-time positional information from the encoders. However, in reality, if the motion system is not adequate in performance, then this approach will produce poor results. For example, a constant speed circle on an XY table is made up of sinusoidal changes in velocity for each axis. A change in velocity means there must be an acceleration associated with the motion. Acceleration is directly proportional to following error (the difference between the commanded path and the actual path). Therefore, the path will always deviate from what was commanded, and it is the user's responsibility to ensure the error is below the threshold for the required accuracy. The path may be longer or shorter because of the deviation, which would mean the laser pulsing could be activated at incorrect positions.

Additionally, the electronic circuitry used for processing multiple feedback devices, and creating the output vector used for firing, can result in a significant delay (latency) to the output; the more encoders that are tracked, the more dramatically the speed of the output reduces, consequently the data input rate (tracking) of each feedback is reduced.

4.1.3. Non-incremental, non-direct, or non-feedback systems

Firing hardware that requires encoder data obviously cannot be used to generate events for motors that have no feedback, for example, stepper motors. Similarly, they are not appropriate for serial communication-based absolute encoders; these encoders don't need to be 'homed' when they start up, which can be a significant advantage with regard to safety and convenience for some advanced systems. Kinematic systems like hexapods are also challenging; the encoder data is not directly linked to the position or motion in a parallel direction, or may be a combination of data from multiple axes that requires calculation, and so does not generate direct triggering for paths in Cartesian coordinates. There are very few automation controllers on the market that can handle this level of complexity to ensure that the motion system not only has the correct motion performance, but also the ability to read in and trigger out the encoders used for these applications. With this in mind, users should consider pulsing strategies that do not rely solely on direct feedback.

Whichever method is chosen, the machine builder should always consider the motion performance of the mechanics and controller. Motion systems have other system issues, such as resonances, low bandwidth, under-powered motors, or mechanical inadequacies (accuracy, roll, pitch, yaw, flatness, straightness, and stacking areas) that need to be appropriately matched to the system requirements so that the work piece or the laser head is in the right place when firing occurs.

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4.2. The drawbacks of repurposing drive systems

Laser processing puts additional hardware requirements onto an automation system and the system designer needs to be aware of the input and output needs of connecting a laser to a controller. In theory, every time a system integrator designs a new system with advanced laser control abilities, they must take the input/output capability of the master controller or the master drive unit into consideration. This is frustrating because the focus shifts from the servo performance required to the laser connection functionality. Typically, the machine builder has to literally rebuild the entire control system to take account of these additional requirements. This may involve replacing the first drive unit with a physically larger, much more complex, and more expensive drive that combines such capabilities (**Figure 4**). This can have a significant impact on cost, including time for redesigning the system, additional hardware, stock of spare parts, and larger electrical cabinets.

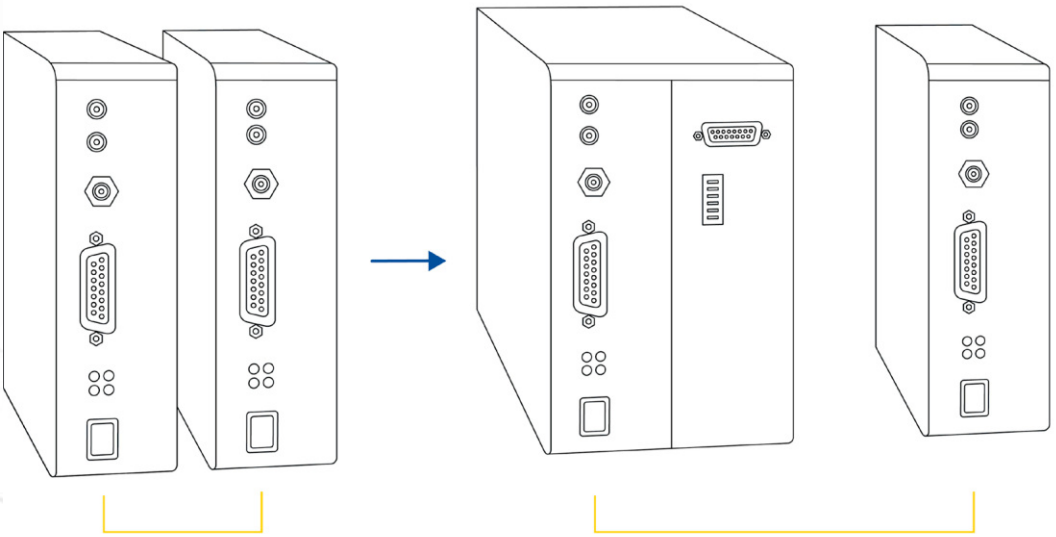


Fig. 4. Replacing the first drive to create a multi-axis control system.



Fig. 5. PI's modular ACS Laser Control Module.

5. The advantages of modular design

PI's ACS Laser Control Module (LCM) introduces a modular way to construct motion systems, based on the EtherCAT industrial network. It does not rely on encoder data and allows drives to select specified axes requirements. This new approach offers system integrators – particularly those who are new to the field – a far quicker and easier way to significantly expand their capabilities when it comes to laser control and gives them the flexibility to add high performance multi-axis capabilities only when they are needed, greatly simplifying the system architecture of the drives.

The LCM does not change the types of drive used for motion but simply connects to the existing network. The simple architecture of an add-on module is ideal for laser control; there is no need to change the drive types, which greatly simplifies the cabinet design (**Figure 6**); there are no changes to the existing hardware, which reduces stock requirements for spare parts; and there is no additional wiring except a simple Ethernet cable. The time saved in design and build is also economically sound. This approach makes it really quick, easy, and extremely cost effective to construct a universal drive offering high performance that covers every eventuality.

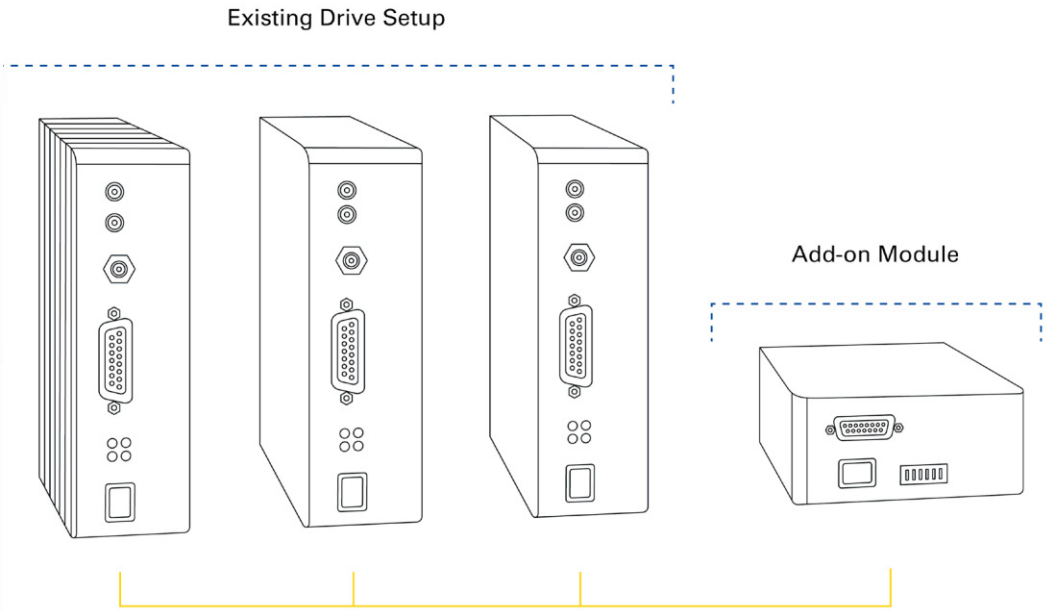
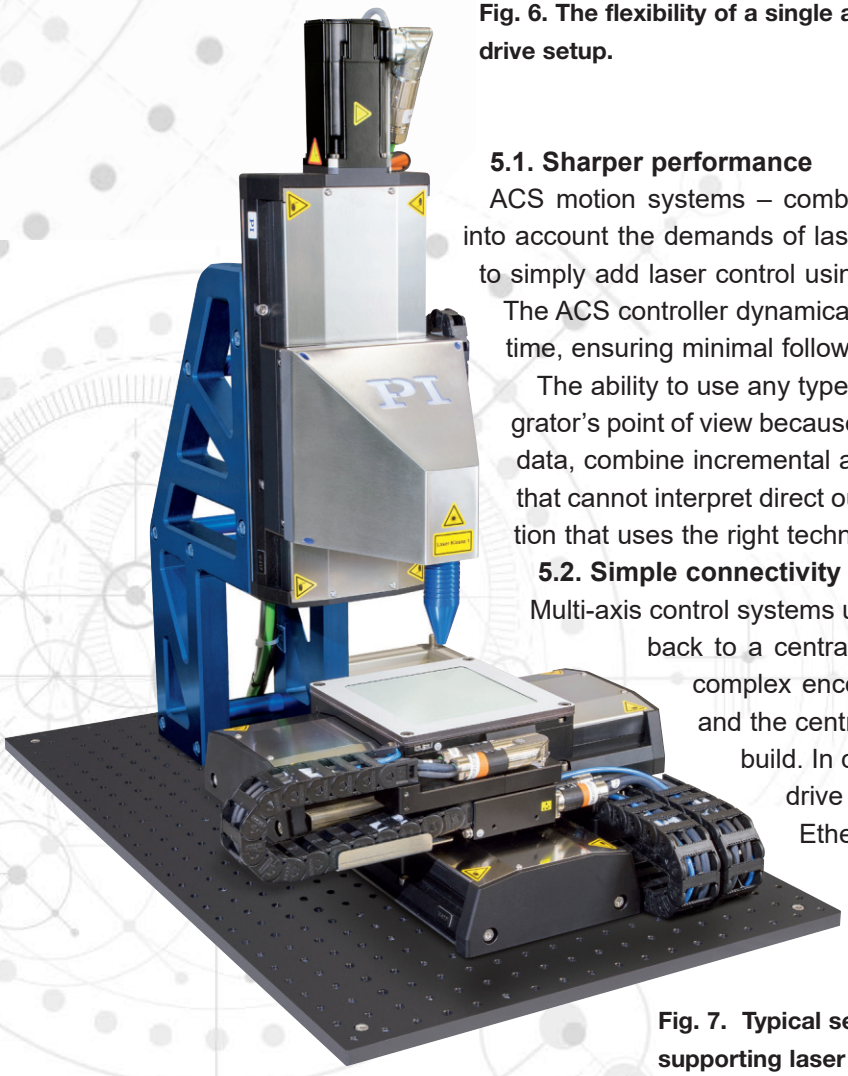


Fig. 6. The flexibility of a single add-on module, which does not impact on the existing drive setup.



5.1. Sharper performance

ACS motion systems – combined with well-designed mechanical platforms that take into account the demands of laser processing (PI's V-41X stage series) – allow the user to simply add laser control using the LCM module, to fire along a highly accurate path. The ACS controller dynamically corrects disturbances and vibrations that occur in real time, ensuring minimal following errors.

The ability to use any type of feedback is hugely advantageous from a system integrator's point of view because it offers the potential to mix axes with or without encoder data, combine incremental and absolute encoders, or incorporate kinematic systems that cannot interpret direct output from encoders. This means that a total system solution that uses the right technology to solve the problem can be created.

5.2. Simple connectivity

Multi-axis control systems use output encoder pulses from each axis and feed these back to a central location by means of wiring. This sometimes involves complex encoder cables that split the signal between one axis drive and the central controller, adding complexity and wiring to the system build. In contrast, the new modular concept adds PEG to an entire drive system using the well-recognized industry standard EtherCAT (**Figure 8**) – integrated with a simple Ethernet cat5e cable – taking the individual path information directly from each motion device on the EtherCAT bus and linking the positional information from multiple

Fig. 7. Typical setup of XY linear motor stages and vertical stage supporting laser head.

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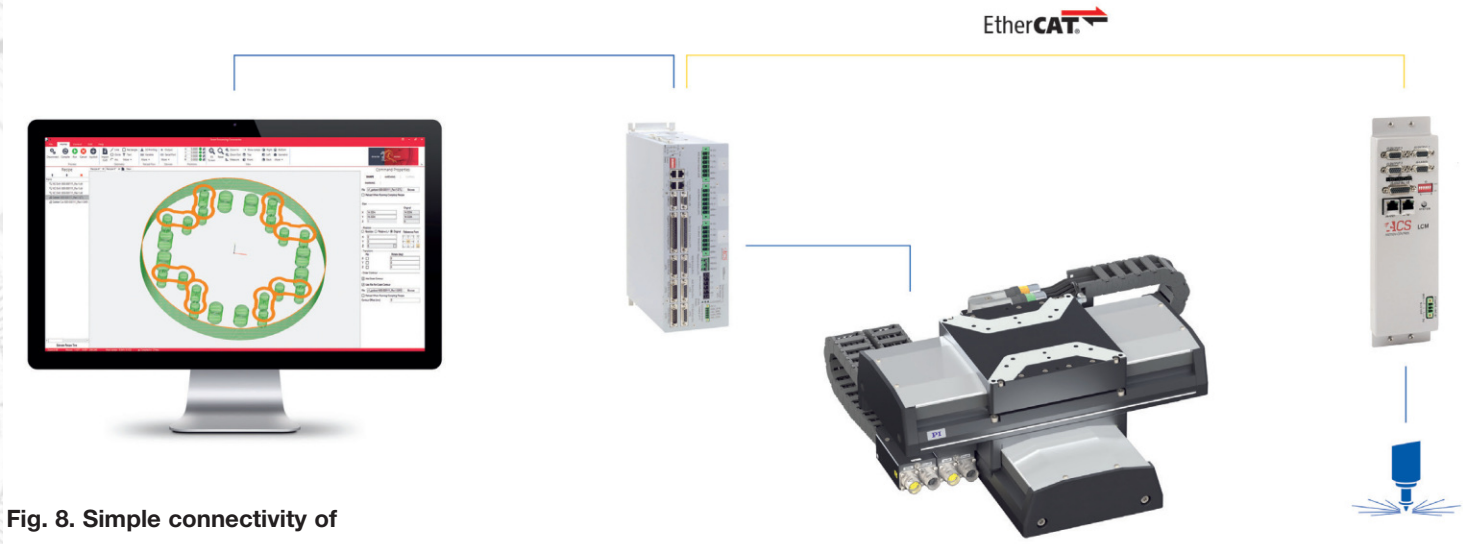


Fig. 8. Simple connectivity of an Ethernet cable.

axes to a single PEG output. This data is then used to generate laser control events along the combined vector path, controlling the laser attached to the system.

5.3. No feedback, absolute encoders, and kinematic transformation

Using stepper-motor-driven stages for laser control must be undertaken with caution; open-loop positioning does not provide information when a motor has lost position due to a potential fault but it does open up the method for lower cost and less demanding motion applications. In addition, there are certain situations where absolute encoders are ideal because they do not require referencing at machine power- up. This can help avoid collisions of stages or parts with obstacles in the machine layout, allowing the system to intelligently create regions where the stages should not enter, or provide additional flexibility when unusual or oversized parts need to be processed.

In systems where the three-dimensional coordinate system is made up from complex kinematics, or paths created from nonlinear devices such as rotary stages, it is necessary to create motion path data that is not related directly to encoder feedback.

The LCM can function without the use of encoder data, so it is ideal for either of these scenarios.

5.4. Gantry control

In general, gantries have two motors to move the bottom axes, guided by two encoders directing the base of the system. Other control signals also come from side encoders. However, these encoders may generate different readings and there is the potential for firing in the wrong place. The risk of this happening increases with wider gantry systems with a long cross axis or high dynamics. The LCM combines the data from the two encoders in line with the carriage (laser) and effectively

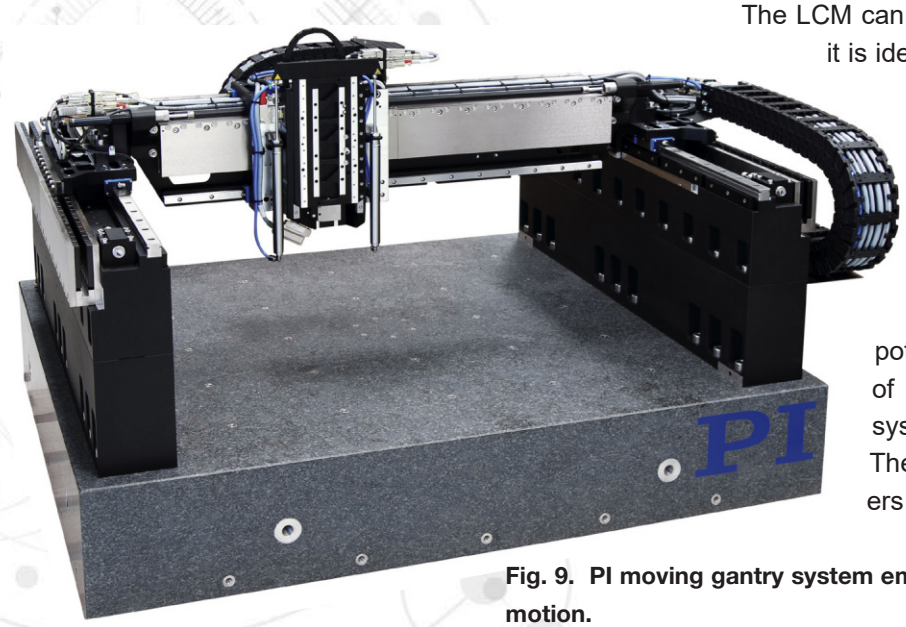


Fig. 9. PI moving gantry system employing two independent encoders for base motion.

removes the effect of having potentially two conflicting feedback sources that could lead to inaccurate firing. ACS controllers provide PI gantries with additional controller algorithms that, in real time, enhance stability and positional accuracy across the whole travel ranges of the system. These facilitate low following error and disturbance rejection that again ensure the laser is fired at the right position.

6. Opening up control options for the new laser technology

Laser material processing is now a significant aspect of industrial manufacturing – used for tasks ranging from heating for hardening, melting for welding and cladding, and the removal of material by drilling and cutting – and many of the new technologies would benefit from a system that could synchronize laser pulse control with motion.

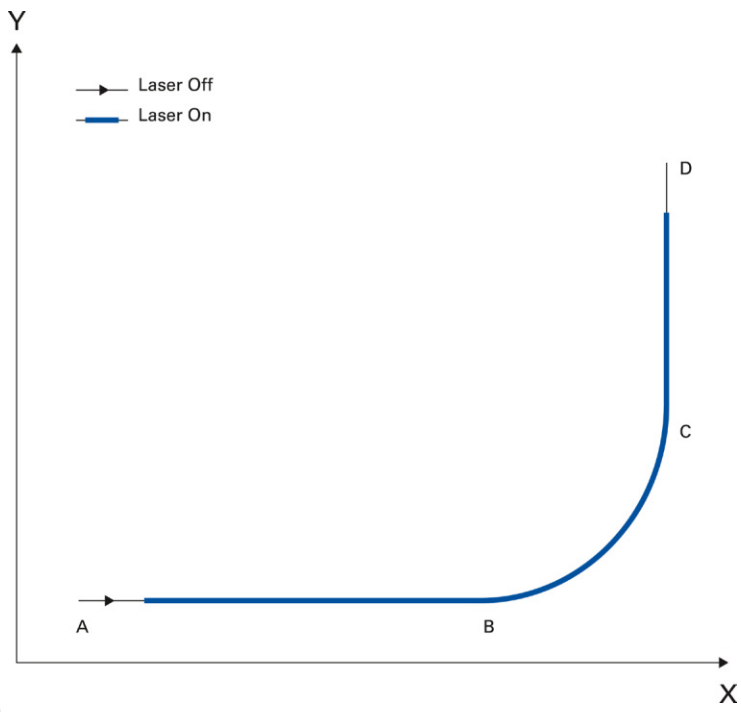


Fig. 10. A laser-on profile

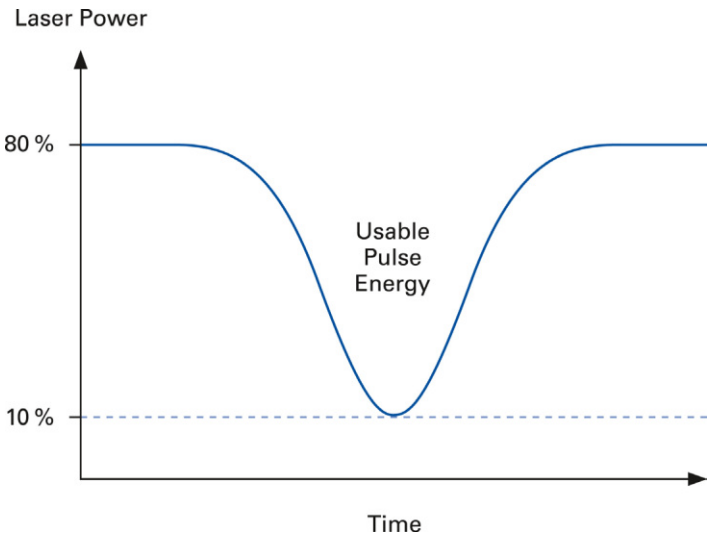


Fig. 10b. Speed according to minimum and maximum laser power

For example, high intensity femtosecond laser processing, which is becoming more common as more industry-proven commercial lasers become available, is considered a 'cold' process because the material being processed does not heat up during the interaction. This type of processing includes texturing of surfaces to decrease reflectivity, provide hydrophobic surfaces, or create chemically-reactive surfaces. It is of particular interest in the automotive industry, where the push for improved efficiency is driving the reduction of friction of moving components, to lessen the use of lubricant consumables and improve durability.

Another useful property of the 'cold' ablation of high intensity lasers is the ability to drill clean, small, deep holes in materials without damaging the surrounding material. This technology is now commonly used in the medical industry for fabricating vascular stents and it has been widely adopted for holes with diameters of microns and a large depth-to-diameter ratio.

Other applications include the dicing of glass that allows the processing of the back of a surface without damaging the front. This application is simply not possible using conventional mechanical diamond blade dicing techniques.

Micromachining and welding are commonly carried out by nanosecond fiber lasers. Although the fiber laser has longer pulse duration than femtosecond lasers, it can be used with careful control of pulses and processing parameters. In this type of laser processing, the energy is eventually converted into heat that dissipates out of the laser spot, beyond the duration of the laser pulse. Essentially fiber lasers keep costs lower, so, if the process is controlled and

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the results are suitable for the application, they make a lot of sense.

In all of these applications and more, controlling the pulse duration, frequency, and placement is key to changing the laser process capabilities, quality, and intermolecular interactions.

6.1. Basic modes of operation

The most simple method of laser control is to define the switch-on and switch-off positions. Here, the laser power control is set by the laser itself or an additional analog input is used as described in section 3, for power related to speed (**Figures 10a and b.**)

The next method to consider is distance-based pulse control, which is when the laser expects to see a trigger at a fixed distance, along the path. The user defines the switch-on and switch-off positions as before but the firing signal is not continuously on. The controller may use this pulse to create a single shot from the laser or a combination of pulses for a particular laser processing recipe. Another method is based on the fact that the pulse trigger positions are not at a fixed distance but at user-specified points along the path. This is typically called random position pulsing or array-based pulsing. Some lasers have quite capable internal pulsing mechanisms and would prefer a simple gating or on/off; others require a PWM-type input. This is useful for controlling laser power based on speed.

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To improve application and process throughput, both pulse and PWM input can be controlled by advanced laser control capabilities from the laser firing controller. The different methods can also be combined to offer even greater flexibility, precision, and throughput. The following section shows graphical examples of the different methods of control (**Figures 11-16**).

6.2. User-specified output pulse generation

6.2.1. Fixed-distance firing

The combination of high resolution, multiple axes, and high speed within one system can be problematic for a user to calculate the distance along the outputting vector path. Fortunately, laser firing modules like the LCM calculate the vector path for you. This makes it simple to define a fixed distance along the path, even when the path may be physically in one direction or a combination of multiple axes. In addition, modules like the LCM can subdivide the resolution of the encoder so that the firing position occurs below the natural resolution of the system, potentially improving placement accuracy.

It is also possible to define a series of pulses that occur after the initial pulse (**Figure 12**). This can be used where an event may require a series of pulses or a laser may expect an addition excitation pulse, or multiple pulses to build an average power level from the laser.

6.3. Firing at defined positions along a path (array-based or random firing)

Rather than telling the system to fire at fixed discrete positions, it is also possible to define an array of positions where firing occurs. This can be used when an event may trigger a single shot or an alternative processing regime, for example, due to a material or process change (cutting versus welding).

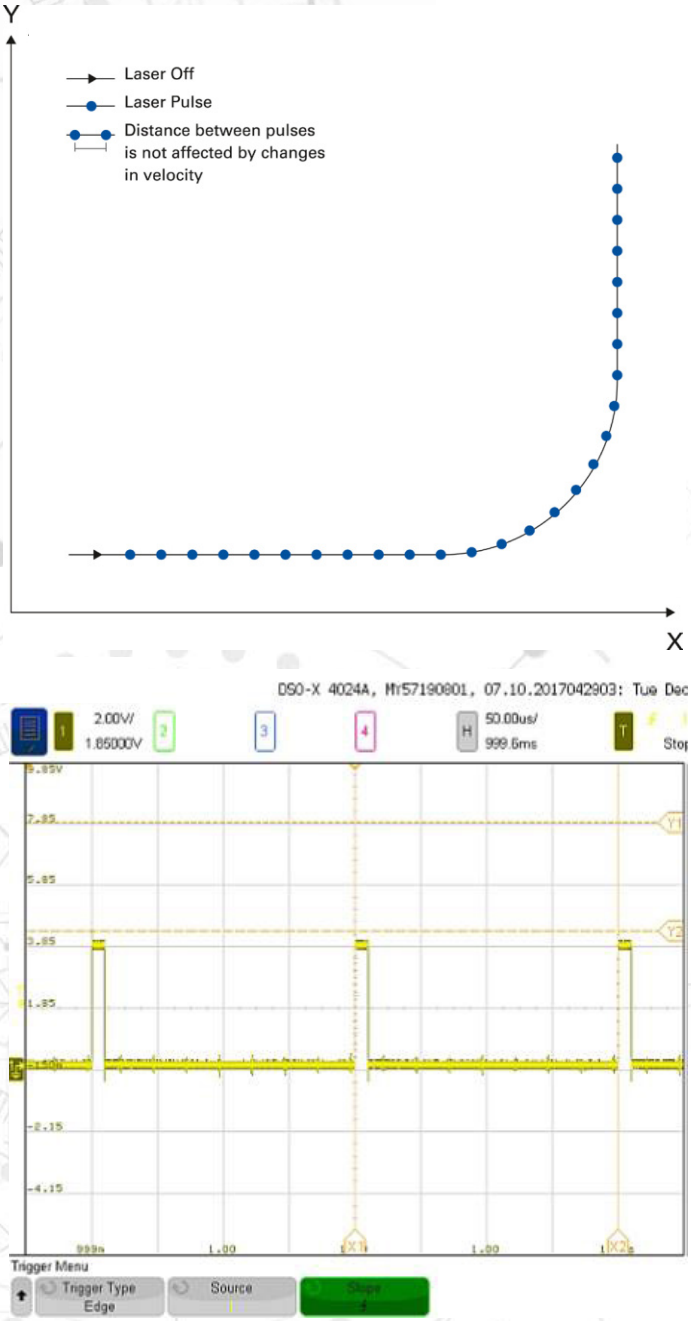


Fig. 11. LCM fixed-distance firing – defined by distance not time.

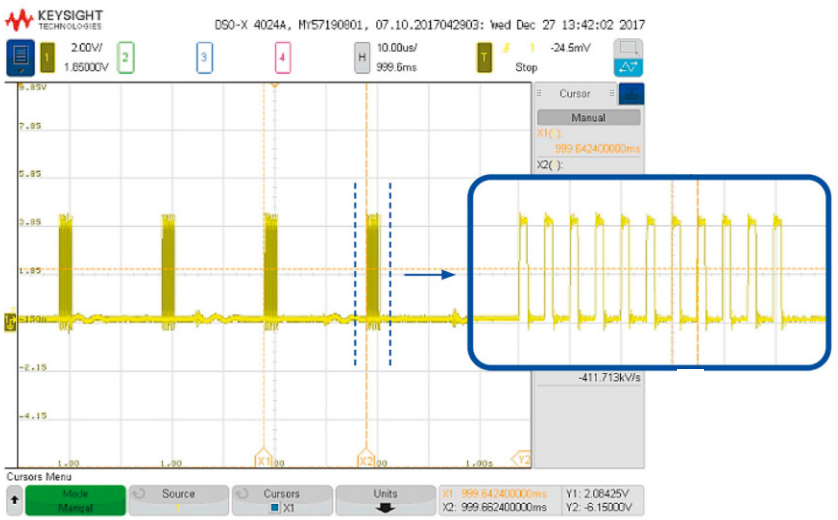


Fig. 12. Example of multiple pulses generated from single fixed distance event.

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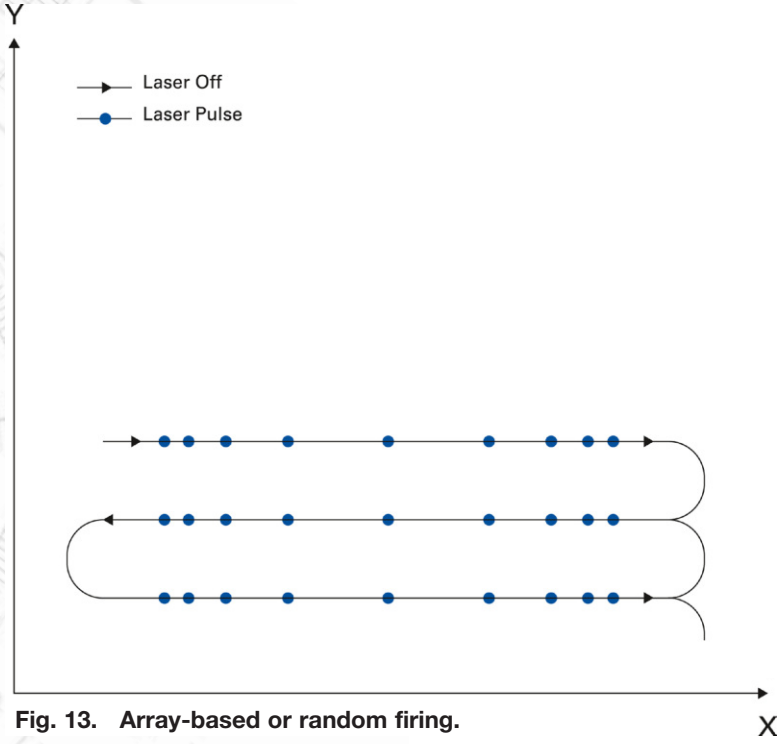


Fig. 13. Array-based or random firing.

6.4. Isolating an area of interest (windowing)

Some users may simply need to tell a laser where to turn itself on or off. The laser power may be controlled, for example, by an analog input (typically a 0-10 V signal). Alternatively, laser power can be controlled by a combination of modes, for example, fixed-distance pulsing or PWM. Windowing can be overlaid with these methods to simplify the laser processing areas. This typically uses an array method to define the start and end of the window.

6.5. PWM mode

This method is very common in electronics, directly controlling laser power by using PWM to adjust the duty cycle. Hybrid modes are also available that combine PWM with pulsing at user-defined intervals, allowing nonlinear or varying firing events. In addition, zones of operation can be created, giving even tighter control over where firing or modulation takes place.

The following diagram shows when windowing and PWM are combined to provide discrete areas of laser firing.

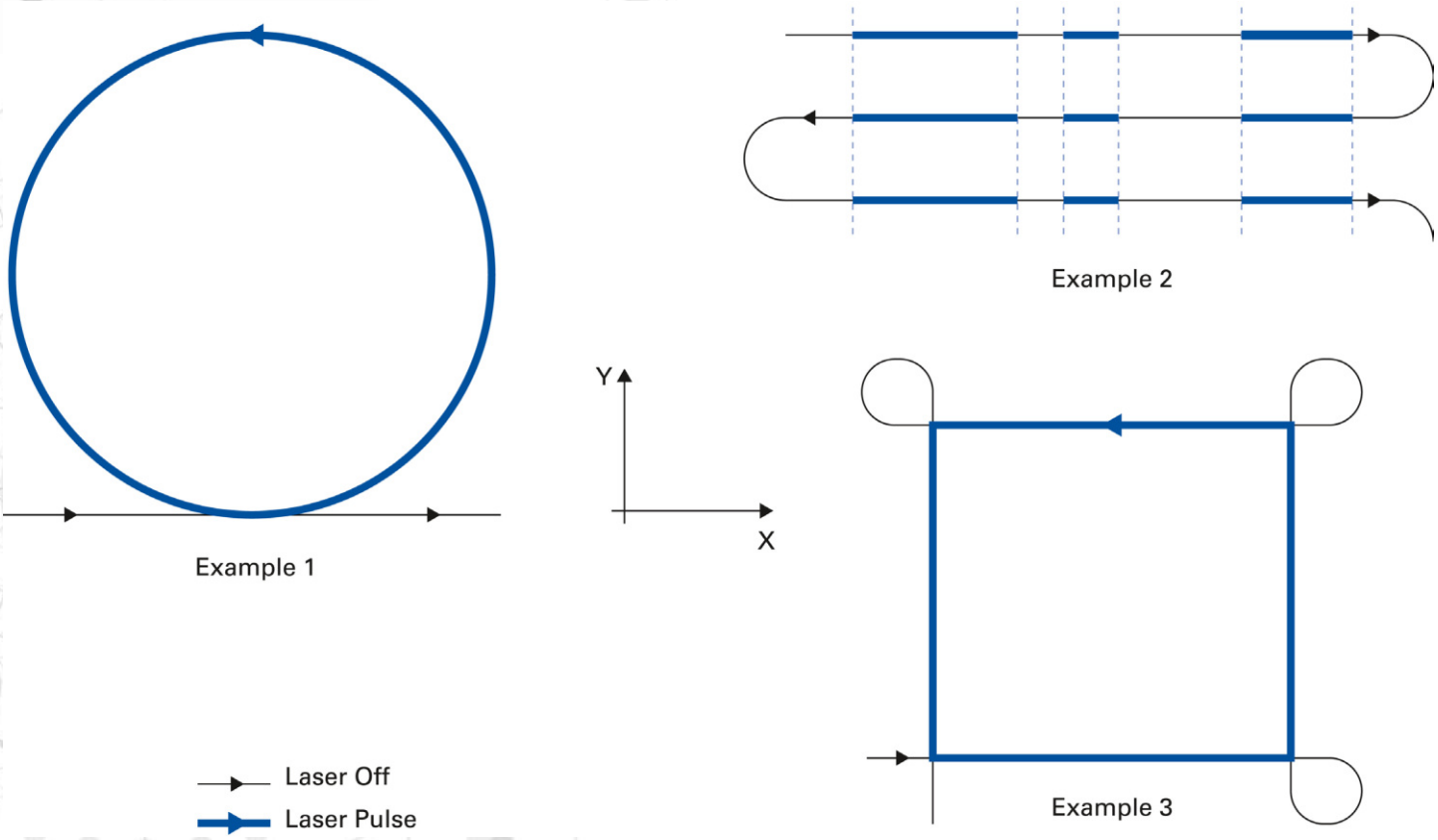


Fig. 14. Turning the laser on/off at predefined positions along the path.

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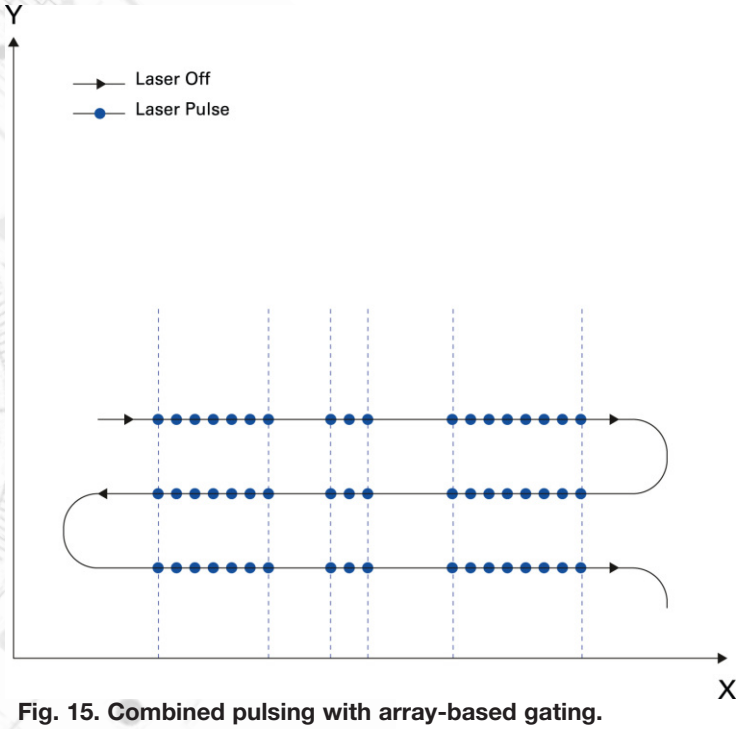


Fig. 15. Combined pulsing with array-based gating.

7. Summary

The latest fast and ultrashort laser sources are now available at a reasonable cost, opening up many opportunities for system integrators to incorporate these innovative technologies into new applications. New tools offer faster solutions and the ability to process smaller features in a different way that was not previously possible with conventional methods. However, for processes which require motion in the form of linear, rotary, and nonlinear kinematics, it is essential that the laser firing is synchronized accurately with the motion path positioning. Electronics that allow this have been available in specialized motion controllers for some time, but now the industry is moving more towards networks such as EtherCAT that make it far simpler to add or link laser pulsing hardware. The significant advantages for the system integrators and builders of electrical cabinets brought by this level of connectivity allow them to choose the appropriate motion amplifiers and controls for the motion and the right interfacing for the laser, giving them simple, fast, accurate, and flexible control of their laser processing.

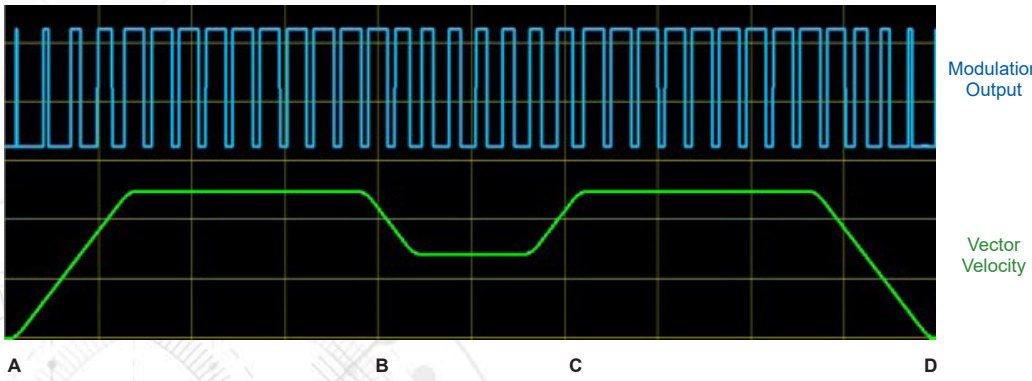


Fig. 16. Increasing duty cycle based on increased speed.

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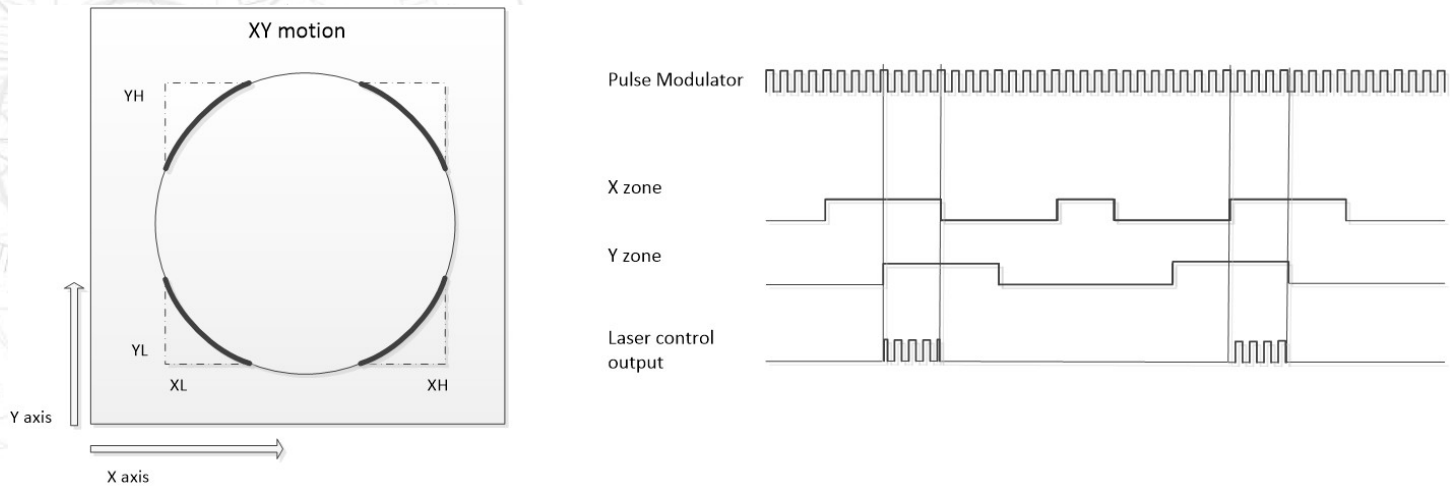


Fig. 17. Hybrid mode with PWM modulation and array gating (windowing).

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