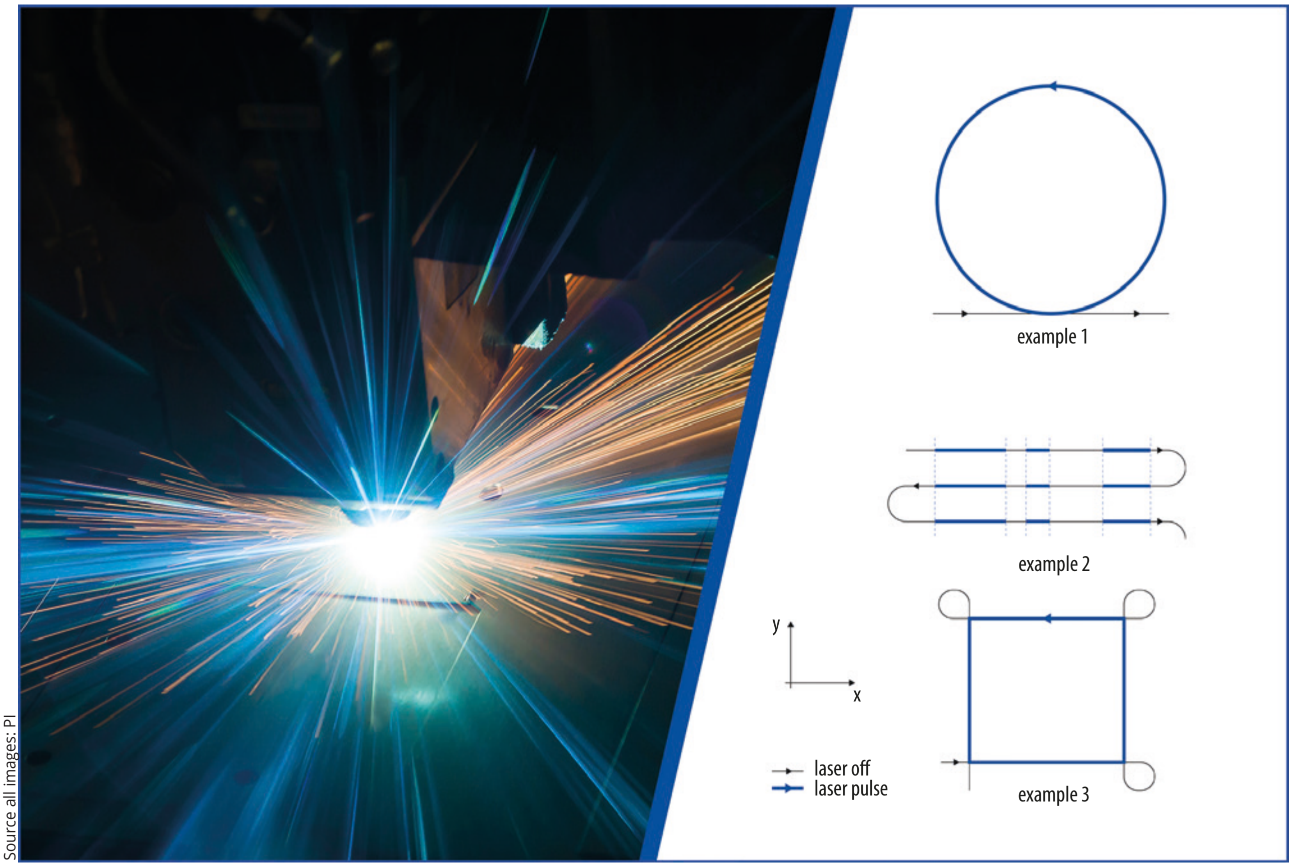
Simple, fast, accurate, and flexible control in laser materials processing

Linking laser control to speed and position – the challenges of controlling multiple axes

Cliff Jolliffe



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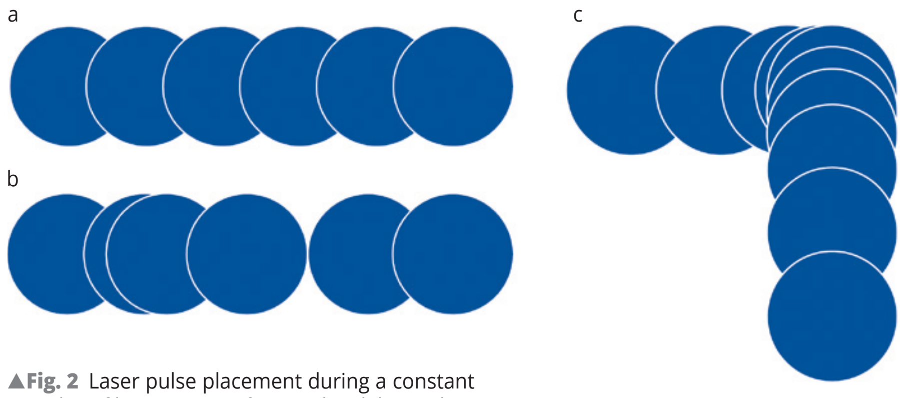
▲ **Fig. 1** Turning the laser on/off at predefined positions along the path.

Until recently, controlling the motion path of lasers across multiple axes has come with certain limitations in performance, speed, practicalities and, on top, higher complexity and costs. With the development of new modular controllers, flexible solutions that enable a laser to be combined with multiaxis positioning are making it easier for system integrators to design and build advanced systems for a new era of laser applications.

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



▲Fig. 2 Laser pulse placement during a constant speed profile (a), non-uniform pulse delivery (b), pulses bunching up around corners (c).

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 because other items – such as sensors or non-motion devices – can be easily incorporated.

This paper looks at the positioning and control of lasers in detail, the challenges that system integrators face and, more importantly, the solutions that are available to them that simplify system builds.

Why choose laser processing?

There are many significant advantages to using lasers instead of traditional machining processes, not least their capacity for much higher throughput. Lasers are not susceptible to the same wear and tear that can lead to breakdown disruption and costs in mechanical components, and they 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 almost impossible to create using other methods, which is ideal for applications 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.

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. Fig. 2 shows an example of this: Fig. 2a shows the laser pulse placement during a constant speed profile, and Fig. 2b when the velocity changes. This could result in non-uniform pulse delivery where too much energy to a particular area could create heat-affected zones (HAZs), and too little could cause weak regions or breaks in the cut or weld path.

The problem of HAZs occurs even more frequently with multiaxis 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 x-y 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 (Fig. 2c). 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.

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 V_{DC} 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 in 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 the 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 such as 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 Physik Instrumente's (PI) subsidiary ACS Motion Control, the Position Event Generation (PEG) is emerging as an exciting and flexible solution to provide a laser with multiaxis positioning.

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 x-y table contouring, including circles or arcs and straight lines – a linear theta combination for processing tubing, or any combination of linear and rotary stages, producing helical motion for drilling for example. Controlling the motion path of lasers across multiple axes has, until recently, had some limitations in performance, speed and practicality along with higher complexity and costs.

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. Feedback systems are typically either incremental or absolute – incremental encoders require a reference point or known position when the system starts up, often provided by 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 point.

Incremental feedback systems

There are two types of incremental encoders, square wave or sinusoidal (sin/cos wave).

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 is 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; this process is called multiplication.

In practice, a square wave encoder may start out as a 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 restrict their usability to low-speed systems with high feedback resolution or to high-speed systems with low feedback resolution.

Multiple feedback in multiaxis 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. The same principle can be used for multiaxis motion, for example pulsing in a circle – 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. In reality however, if the motion system is not adequate in performance, then this approach will produce poor results. For example, a constant speed circle on an x-y 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 the following error (the difference between the commanded path and the actual path). The path will therefore always deviate from what was commanded, and it is the user's responsibility to ensure that 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 to process multiple feedback devices, and to create the output vector used for firing, can introduce a significant delay (latency) to the output; the more encoders that are tracked, the more dramatically the speed of the output reduces, and consequently the data input rate (tracking) of each feedback is reduced.

Fig. 3 Typical setup of x-y linear motor stages and vertical stage supporting a laser head.

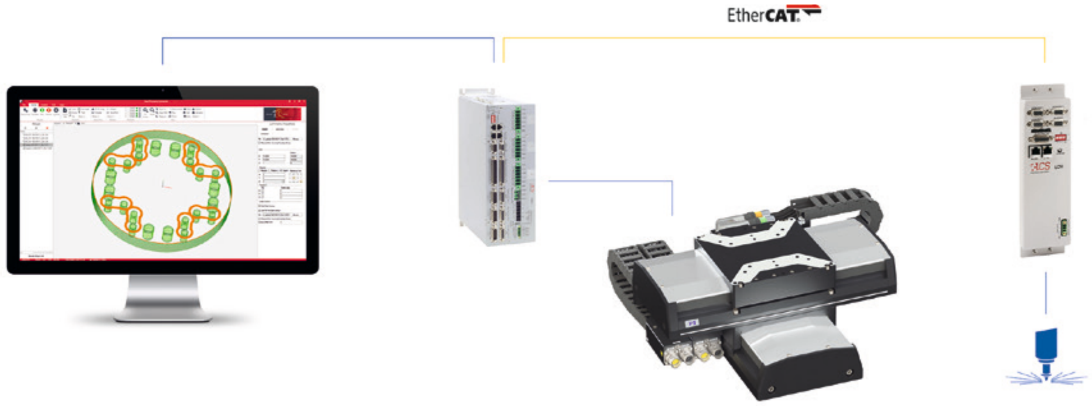


Fig. 4 Simple connectivity of an Ethernet cable

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, such as stepper motors. Similarly, they are not appropriate for serial communication-based absolute encoders. These encoders do not 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 it 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 have the ability to read in and trigger out the encoders used in 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, underpowered 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.

The drawbacks of repurposing drive systems

Laser processing brings additional hardware requirements to 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 completely 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. This can have a significant impact on cost, including the time required to redesign the system, additional hardware, stock of spare parts, and larger electrical cabinets.

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 in laser control, and gives them the flexibility to add high-performance, multi-axis capabilities as and 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

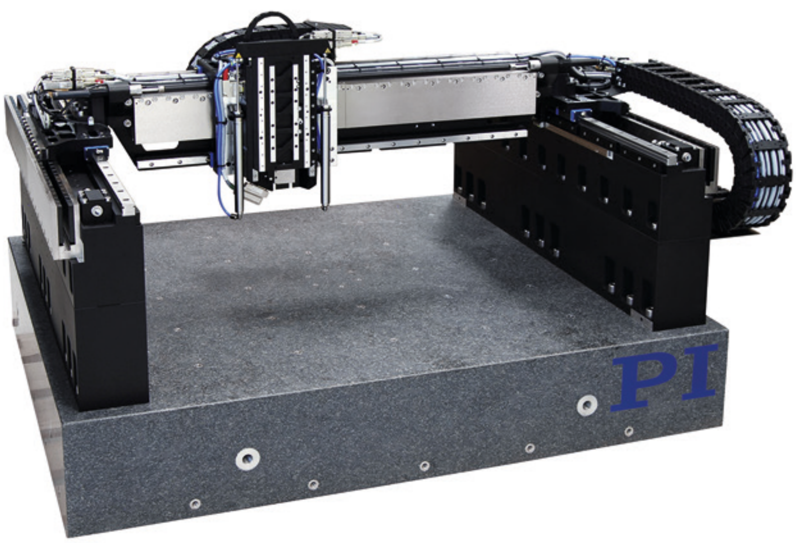


Fig. 5 PI moving gantry system employing two independent encoders for base motion.

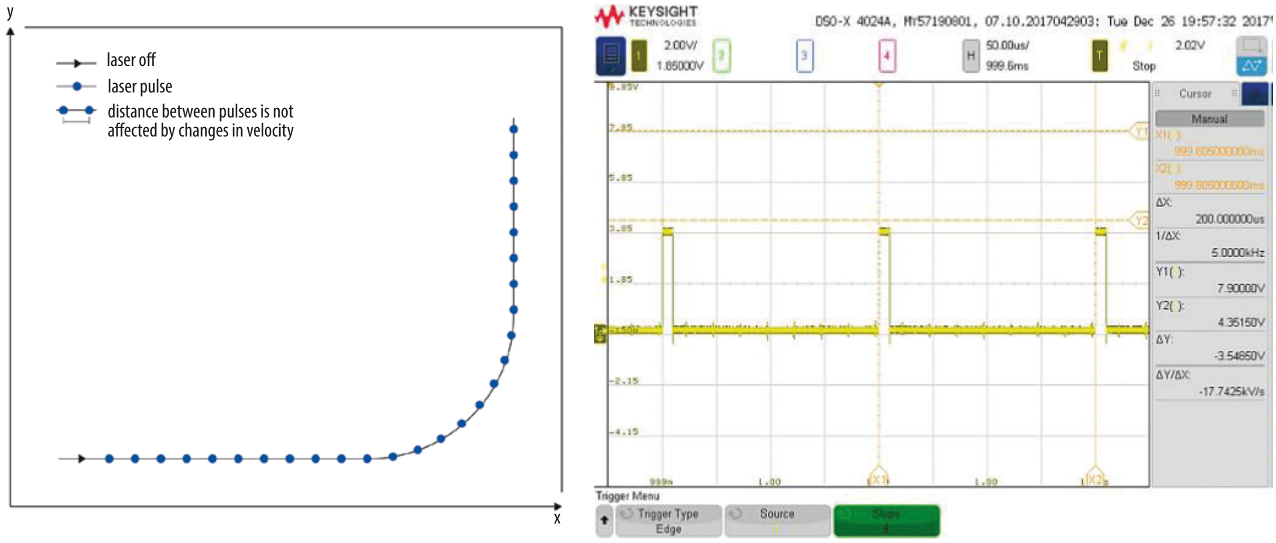


Fig. 6 LCM fixed-distance firing – defined by distance, not time.

simplifies the cabinet design. There are no changes to the existing hardware, which reduces stock requirements for spare parts. There is no additional wiring except a simple Ethernet cable. The time saved in design and build is also economically beneficial. This approach makes it really quick, easy, and extremely cost effective to construct a universal drive offering high performance that covers every eventuality.

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 be able 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.

Simple connectivity

Multiaxis 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 EtherCAT industry standard (**Fig. 4**) – integrated by using 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 axes to a single PEG output. This data is then used to generate laser control events along the combined vector path and to control the system's laser.

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 to 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 to 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 are 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.

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 that have a long cross axis or high dynamics. The LCM combines the data from the two encoders in line with the carriage (laser) and effectively removes the effect of having two potentially conflicting feedback sources that could lead to inaccurate firing. ACS controllers provide PI gantries with additional controller algorithms thatenhance stability and positional accuracy across all travel ranges of the system in real time. These facilitate low following error and high disturbance rejection, which again ensure that the laser is fired at the right position.

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.

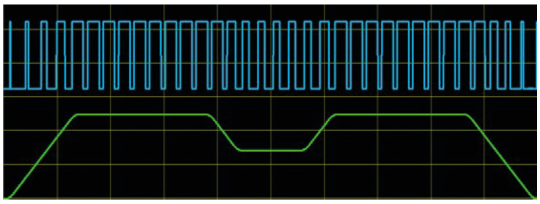


Fig. 7 Increasing duty cycle based on increased speed

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 the 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 to 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 to fabricate vascular stents and it has been widely adopted to produce holes with diameters of microns and a large depth-to-diameter ratio.

Other applications include the dicing of glass that allows the back of a surface to be processed 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 a 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 the results are suitable for the application, they make a lot of sense.

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

Basic modes of operation

The simplest method of laser control is to define the switch-on and switch-off positions. The laser power control is set by the laser itself or by an additional analog input as described in **section 3**, for power related to speed.

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 prefer simple gating or on/off commands; others require a pulse-width modulation (PWM) type of input. This is useful to control the laser power based on speed.

To improve application and process throughput, both the pulse and PWM inputs 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 (**Figs. 1, 6, 7**).

User-specified output pulse generation

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. 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.

Firing at defined positions along a path

Rather than telling the system to fire at fixed discrete positions, it is also possible to define an array of positions where firing occurs (array-based or random

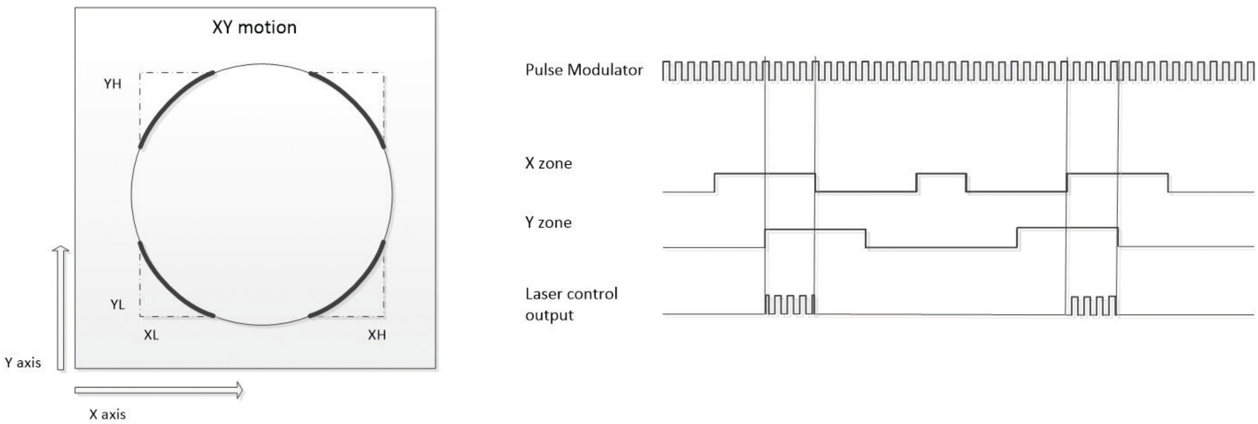


Fig. 8 Hybrid mode with PWM modulation and array gating (windowing)

firing). 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).

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, such as 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.

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.

Fig. 8 shows when windowing and PWM are combined to provide discrete areas of laser firing.

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 that 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 to 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.

DOI: 10.1002/phvs.202200048

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