VISION INSIGHTS

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Motion Control for Vision Professionals

How to Deploy Motion Control in Machine Vision Applications

In this edition of Vision Insights, Vision Systems Design offers practical advice on how to approach motion control in machine vision systems. Motion control is a key element of many automated optical inspection systems and vision-guided manufacturing processes. The precise movement of cameras and their targets is critical for rapid, high-quality production.

The author of the three-part series is VSD Contributor Mike Fussell at Zaber Technologies (Vancouver, BC, Canada).

Whether you work at an OEM, system integrator or end-user organization, we've provided insights here to help fuel your next project.

Linda Wilson,
EDITOR IN CHIEF
VISION SYSTEMS DESIGN

Introduction to Motion Control for Vision Professionals: Part 1

Motion control is a key element of many automated optical inspection systems and vision-guided manufacturing processes.

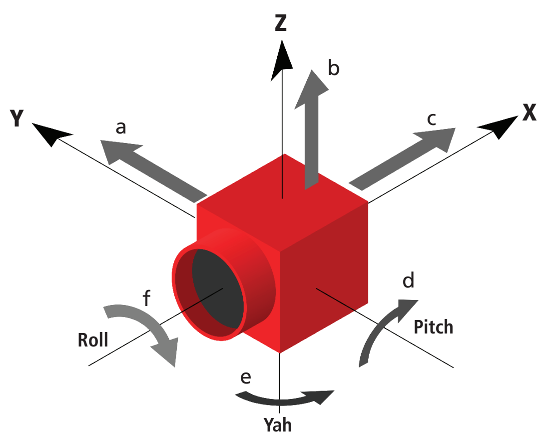
Motion control is a key element of many automated optical inspection systems and vision-guided manufacturing processes. The precise movement of cameras and their targets is critical for rapid, high-quality production. Motion control can also create more flexible vision systems that can be quickly and automatically reconfigured to match the ever-changing product mix in industries including plastics and packaging.

Machine learning and inference-based vision system performance can also be improved by adding motion control. Ensuring that targets are consistently positioned in a camera's field of view eliminates a major source of variability between images. This can reduce the required dataset's size for training neural networks and will also yield smaller networks that will run faster on low-power embedded systems.

The enormous diversity of motion control technologies can make getting started overwhelming. This article is the first in a three-part series that will cover the fundamentals of motion control for vision professionals. It will introduce several common types of motion control hardware; what their key specifications mean; and how to use those specifications to select motion control devices that will improve the performance, reliability, and cost of your system.

Types of Motion

The first step in determining your vision system's motion control requirements is identifying the type of motion required. There are six degrees of freedom. They are based on translation, which is the linear pushing, pulling, carrying, or lifting of a load along an axis (Figure 1, a, b, c), and rotating or tilting a load around an axis of motion (Figure 1, d, e, f). In general, motion control components are designed to provide rapid and accurate movement in a single degree of motion while minimizing unwanted movement in all others.



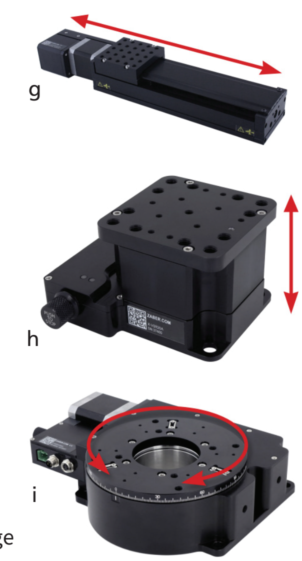


FIGURE 1. The six degrees of movement are based on translation (a, b, c) and rotation (d, e, f). Examples of linear and vertical translation stages (g, h) and a rotary stage (i). (Photos and figures courtesy of Zaber Technologies.)

Anatomy of a Motion Control Device

Moving an object on its intended axis requires five key components:

- Mechanics to securely mount a load to and guide it along its axis of movement.
- A motor to produce the mechanical force to move the load.
- A motor driver to supply the motor with the correct currents at precise timings.
- A controller to provide a data interface with the driver.
- Sensors to calibrate and measure positioning along the axis of travel.

While each of these components can be sourced and integrated independently, Zaber's (Vancouver, BC, Canada; www.zaber.com) X-Series devices combine all of these components into a single positioner (Figure 2).

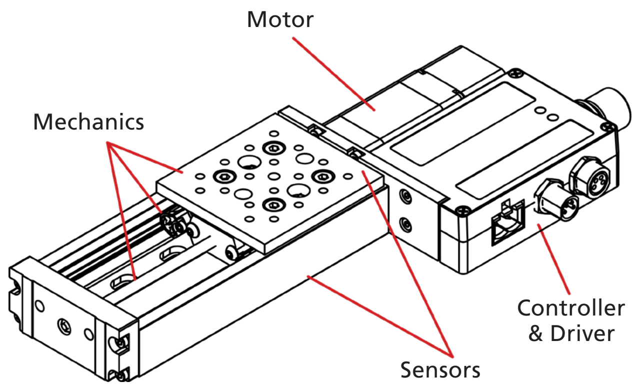


FIGURE 2. A Zaber X-LSM050 linear stage, which integrates mechanics, a motor, a motor driver and a controller into a single device.

Key Specifications

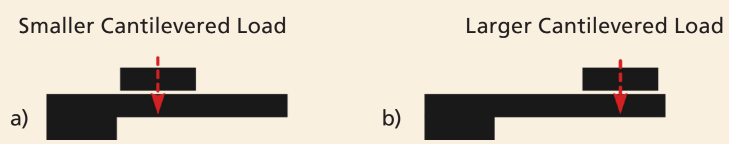
Matching the capabilities of the available motion control options to your vision system's requirements will ensure your system can perform its intended task quickly and reliably without adding unnecessary cost or complexity. For example, a semiconductor packaging system will have different requirements for accuracy and repeatability at different points in the system. It will require nanometer-level accuracy and repeatability for picking and placing chiplet dies but may only require millimeter-level positioning for placing the completed ICs into carrier tape reel pockets. This section will cover the key specifications used to define the capabilities of motion control devices. The factors influencing these specifications will be the focus of Part 2 in this series.

Accuracy is the maximum error possible when moving between any two positions on an axis of travel (Figure 3) when both positions are approached from the same direction.

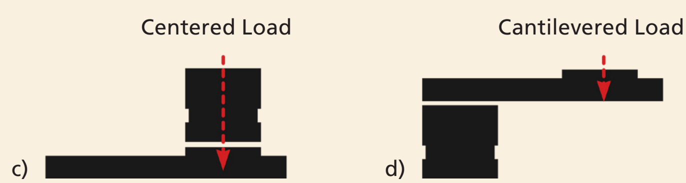
Repeatability is a measure of how accurately a stage can return to the same position over multiple movement cycles from the same direction. It is the maximum deviation in actual position.

For automated inspection and control of high-throughput industrial processes, where minimizing cycle times is critical, repeatability is frequently more important than accuracy. High

Tip: Review the cantilevered loads in your system at both ends of its travel. The cantilevered loading on the stage (a) will increase as the load is moved along its range of travel (b).



When combining multiple devices, consider how they are mounted to each other. A vertical stage mounted on top of a linear stage will apply a centered load to the linear stage (c). A linear stage mounted on top of a vertical stage will apply a cantilevered load to the vertical stage (d).



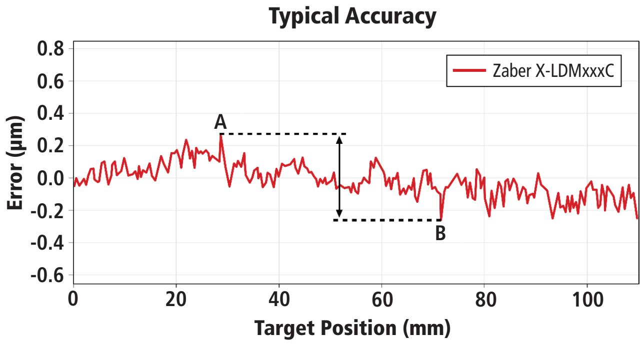


FIGURE 3. Sample accuracy plot for a linear stage. The plot shows the difference between the expected and actual position of the stage across its range of travel. The maximum error possible is 0.6 µm, which is the difference between points A and B.

repeatability ensures that once a system has been calibrated, it will carry out a repeated sequence of motions with a high degree of consistency, eliminating the need for fine repositioning, which would increase cycle times and reduce throughput.

For vision systems that rely on the movement of the target or the camera to achieve fine focus control, backlash is a key performance specification. Backlash is a measure of the slack in a mechanical system (Figure 4), which can have a significant impact on the accuracy and repeatability of small movements. Backlash has its greatest impact on the accuracy and repeatability of stage positioning when the direction of travel is reversed, as the slack in the drive system must be

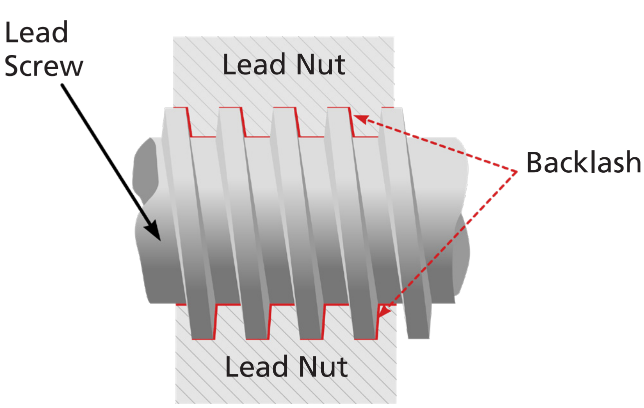


FIGURE 4. In systems driven by a lead screw, mechanical slack results from the minute gap between threads of the lead screw and the corresponding threads of the nut.

taken up before the load will be moved. An inspection system attempting a fine focus change smaller than the backlash of the motion control device that drives it will not result in any change of camera or sample positioning. Note that some manufacturers do not use the term backlash; they report it as the difference between unidirectional and bidirectional repeatability.

To ensure your system will perform as required, selecting a stage that can effectively support and move the required load is critical. The maximum centered load (Figure 5) is the largest force that can be applied to the stage perpendicular to the axis of travel while maintaining reasonable performance and device lifetime. Load measurements are given in force units (Newtons) rather than mass (kilograms), as loading could come from a combination of a mass, gravitational loading, and other sources. The magnitude of these forces will depend on the mass of the object mounted on a stage and the way it is moved. A light object moved very quickly can result in greater forces than a much heavier object moved slowly.

The maximum centered load can be calculated with the following formula:

F(in Newtons) = Mass (in kg) x Acceleration (in m/Sec2)

Under most conditions the acceleration of a centered load will only be due to gravity which can be approximated as 9.8 m/s^2.

Cantilevered loads apply torque to a stage around the intended axis of movement (Figure 5) and will result in uneven loading of its bearings and increased friction. You can calculate the magnitude of the cantilevered load with the following formula:

Cantilevered Load (in N m) = Force (in N) x Distance (in m)

Speed and thrust are key selection criteria for any motion control device. High speed and thrust are particularly important for high-throughput

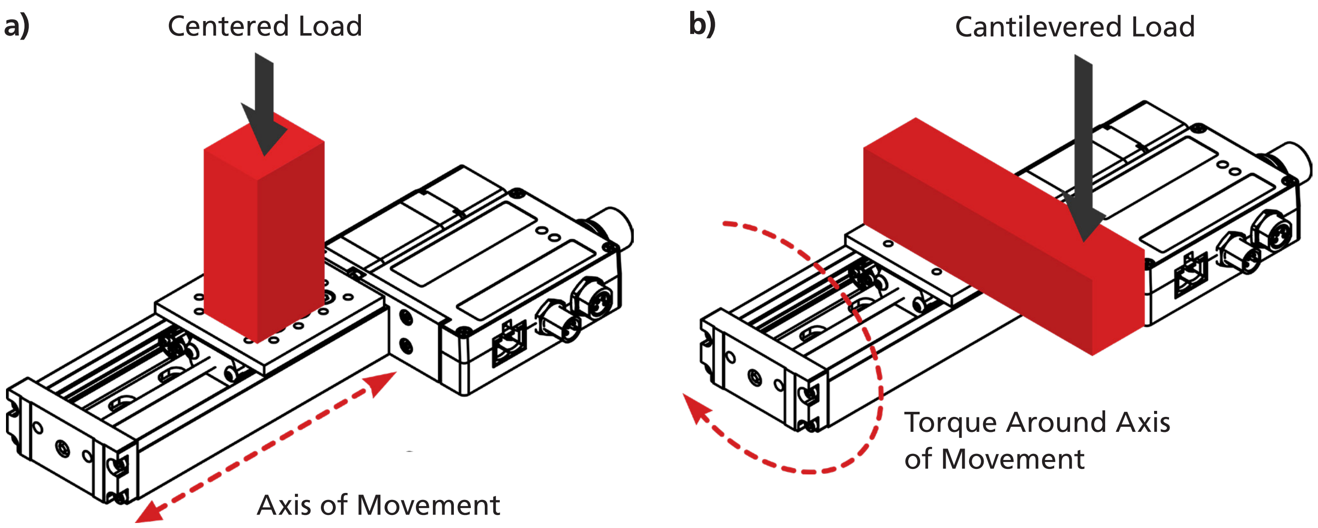


FIGURE 5. A centered load applies force perpendicular to the axis of motion (a). A cantilevered load applies torque about the axis of motion (b).

applications where minimizing cycle times is essential. Maximum thrust is measured in Newtons and is the largest force that the stage can apply in the direction of travel. Maximum speed is the fastest the stage can move with no load.

Extremely high speed and high thrust devices are available. However, if image acquisition or processing times are the bottleneck of your vision system, paying more for faster motion control devices will not yield a decreased cycle time or increased throughput.

Motion control devices with high thrust and speed may unlock significant cost savings for cameras, particularly when high-resolution cameras are required. If a target can be rapidly decelerated and accelerated again, it may be possible to use rolling shutter cameras in place of cameras with much more expensive global shutter sensors without negatively impacting cycle times or system performance.

The combination of thrust and speed will impact the lifespan of the stage. Greater loads moving at higher speeds will exert greater forces on the stage. This will generate more heat in the drive mechanism, leading to faster wear of the mechanical components. For applications requiring long-term operation at high speed and thrust, paying more up front for a device with significant overhead on the maximum speed and thrust specifications can yield significant long-term savings. Uprated motion control devices will deliver longer service lives and reduced maintenance requirements. The relationship between speed and thrust and the factors that influence them will be discussed in greater detail in Part Two.

While mechanical specifications are clearly important for motion control devices, electrical specifications should not be overlooked as they will impact the ease of system integration. Controllers with IO lines are ideal for use in high-throughput machine vision applications. Output lines enable highly reliable, low-latency camera triggering with little setup effort. Cycle times can be minimized by immediately triggering cameras when a stage has reached its target position. IO triggering is an easy way to ensure that your production or inspection system's motion control, lighting, and imaging components remain synchronized.

Care should be taken to match the nominal voltages of the IO between devices. +5V TTL is common for the

> **"Understanding the key specifications of motion control devices can help you optimize your designs and get the most from your vision system—and your vision system budget."**

digital outputs of many motion control devices but may exceed the recommended input voltage of some low power +3.3V single-board computers that lack optoisolated inputs. Most machine vision cameras from major manufacturers have optoisolated input pins and will support +5V inputs.

Advantages of Integration

While it is possible for vision system designers to source and integrate discrete image sensors, FPGAs, image signal processing IP cores, and interface back ends, most users prefer the convenience of preassembled cameras. The same is true for motion control. Sourcing, determining compatibility, configuring, and calibrating discrete stages, motors, drivers, and controllers can be a complex and time-consuming process. Motion control devices with integrated controllers and drivers simplify the device selection and setup processes.

Devices with integrated drivers and controllers that share a common control protocol further simplify system design. By working together seamlessly, out of the box as motion control building blocks, such devices can quickly be combined and recombined as your automation needs change.

Building systems requiring the coordination of movement across multiple axes with lighting, image acquisition, and processing is faster and easier with integrated controller devices sharing a common control protocol and API. Minimizing the number of libraries required for custom application development can result in smaller, more efficient applications, which are more easily maintained and are better suited for running on embedded systems with limited resources. Devices that share a common control protocol can also support daisychained configurations. Daisychaining enables multiple devices to be powered and controlled via a single cable from the host, simplifying cabling and reducing costs. The single wire connection also saves space and frees ports or IO pins, which are frequently limited on embedded systems.

Another advantage of integrated devices is that their unified design allows for streamlined, easy-to-use documentation. Troubleshooting an unexpected issue using a single comprehensive document is much easier than working out the potential conflicts between multiple independent components each with their own documentation.

Motion control is an essential element of automated production and inspection systems. Understanding the key specifications of motion control devices can help you optimize your designs to get the most from your vision system—and your vision system budget. Selecting the right motion control devices can help you quickly design, build, and deliver systems with faster cycle times, increased throughput, and greater reliability—all at a lower cost.

Part Two of this series builds on the fundamentals covered here to explain the impact that different motor, drive, and bearing types can have on vision system performance. It will give you knowledge you need to further optimize your vision system designs.

Introduction to Motion Control for Vision Professionals, Part 2

Selecting motion control devices with the appropriate combination of motors, encoders, bearings, and drive mechanics can have a major impact on your vision system's accuracy, throughput, reliability, and cost.

Welcome to Part 2 of a three-part series covering the essentials of motion control for vision professionals. Part 1 covered the types of motion, the advantages of devices with integrated drivers and controllers, and their key specifications. Part 2 builds on those topics to help you optimize your vision system performance and cost by selecting devices with the most suitable motors, encoders, bearings, and drives for your application.

Motor Types

Motors are the foundation of all motion control devices. There are two main classes of motor: rotary motors, which include stepper and servo motors, that require drive mechanics to convert their rotary motion into linear motion and linear motors that produce linear motion directly with no additional drive mechanics.

Stepper Motors

Stepper motors generate rotary motion using electromagnets arranged in opposing groups around a toothed permanent magnet rotor. When one group of teeth is aligned with the closest electromagnet, the adjacent teeth are partially aligned with the electromagnets near them. By energizing the electromagnets sequentially, the teeth of the rotor will step from aligning with one group of magnets to the next.

The more teeth a stepper motor has, the smaller its movement steps. Stepper motor controllers like those integrated into Zaber's (Vancouver, BC, Canada; www.zaber.com) X-series motion control devices can enable microstepping by partially energizing several groups of electromagnets simultaneously, moving the rotor to intermediate position steps.

Stepper motors deliver excellent torque at low

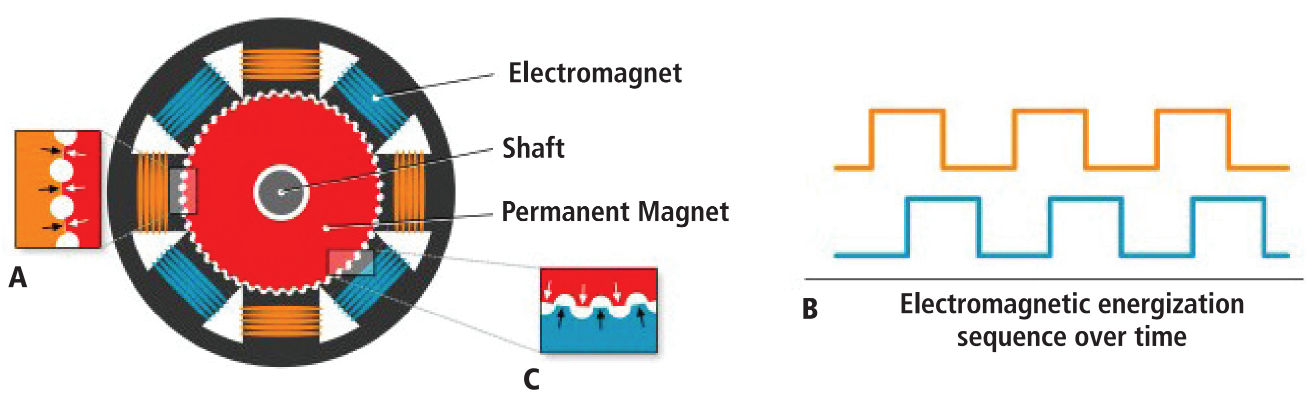


FIGURE 1. The basic design of a stepper motor (A). As the electromagnets are sequentially energized (B), teeth on the rotor are pulled into alignment with teeth on the energized electromagnet (C), while teeth on adjacent electromagnets are pulled out of alignment, setting the motor up for the next step. (Drawings courtesy of Zaber Technologies.)

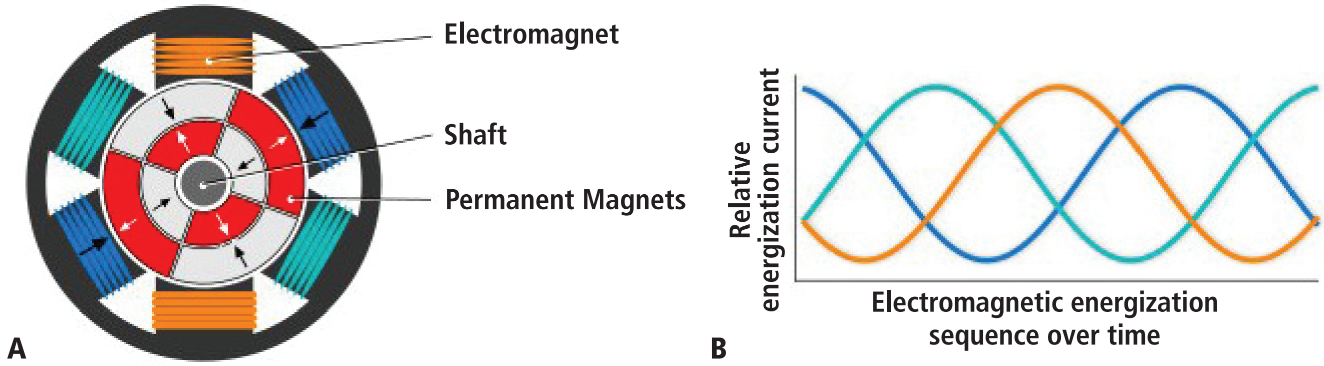


FIGURE 2. The basic design of a servo motor (A). As the electromagnets are sequentially energized (B), they pull permanent magnets on the rotor into alignment with electromagnets fixed to the motor body.

speeds, which enables them to hold loads in a static position. This makes them ideal for stabilizing and positioning cameras on unmanned aerial systems (UAS) as they can hold cameras and optics in place against the force of gravity and the acceleration of the UAS as it moves. By producing high torque at low speeds, stepper motors can accelerate loads quickly. This is useful for applications like imaging of biological samples in microplates that require the sample to be rapidly moved between positions in a sequence of small and precise movements. The small, rapid, and repeated movements of a 3D printer nozzle are also very well suited to stepper motor drives. At high speeds, the maximum torque of stepper motors falls off (Figure 4) because of the high number of magnetic field changes per revolution.

Servo Motors

Servo motors generate rotary motion with electromagnets arranged around a set of permanent magnets attached to the rotating shaft. The electromagnets engage sequentially, pulling the permanent magnets in one direction. To operate efficiently and generate maximum force across a broad range of speeds, servo motors require additional electronics, increasing their cost relative to stepper motors.

Servo motors produce constant torque across their speed range, enabling them to deliver high torque at high speeds. This makes them ideal for driving high-speed continuous flow processes like printing and thin film production. The high-speed tooling including routers and drills found in some industrial vision-guided automated manufacturing systems rely on servo motors. When moving a light load such as a mirror for a laser beam profiling scanner or LiDAR, servo motors generate less heat than stepper motors making them useful for space-constrained embedded systems like mobile robotics where managing heat from cameras and processors is frequently a concern.

Linear Motors

Linear motors use a line of sequentially energized electromagnets to force a mover over a track of permanent magnets. They produce linear motion directly without requiring any additional mechanical components. Eliminating these drive components eliminates the main sources of friction and backlash. This enables linear motors to accelerate extremely quickly and achieve very high accuracy and repeatability. Linear motors are more expensive than rotary motors, but their combination of high accuracy, high acceleration, and virtually unlimited service lives

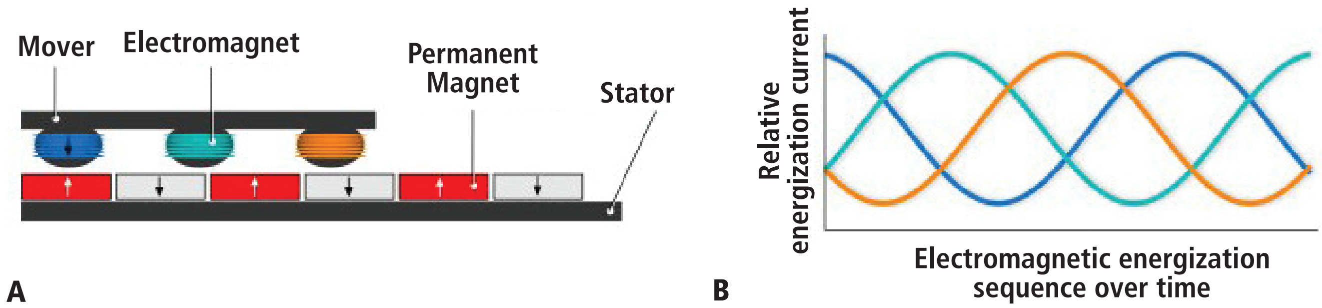


FIGURE 3. The basic design of a linear motor (A). As the electromagnets on the mover are sequentially energized (B), they are pulled into alignment with permanent magnets fixed to the stator.

makes them well worth the investment. They reduce maintenance and unscheduled down time costs while increasing throughput.

When unpowered, linear motor devices can move freely. They must remain powered to hold a load in place. When using a linear motor in a vertical configuration, such as for an autofocus system, a counterbalance like those offered with linear motor devices will offset the force of gravity. This will reduce the power consumption of the system and reduce the heat it generates. The combination of high accuracy and thrust has made linear motors the actuator of choice for many new high-performance consumer camera lenses from Canon, Sony, and Nikon. The rapid-acceleration linear motors can distort larger liquid lenses. Reducing their acceleration will mitigate this effect.

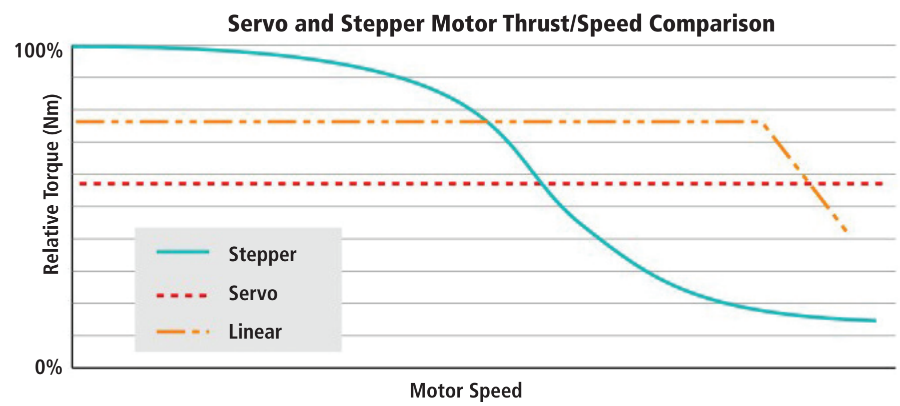


FIGURE 4. Speed vs. thrust of stepper, servo, and linear motors.

The high accuracy and repeatability of linear motors makes them ideal for PCB population and inspection, which requires very high repeatability for accurate positioning of components, and where the requirement for high throughput demands many short, fast moves that would cause rapid wear of the components in a rotary-motor-driven device. The nanometer-level minimum incremental move of quality linear motors can deliver the fine control necessary for semiconductor packaging. These systems require extremely high accuracy and repeatability to ensure stacked chiplets are aligned with the correct interconnects.

Encoders

Encoders are sensors that detect mechanical movement. There are many different types of encoders. Optical encoders are the best for most vision system applications because of their high resolution, repeatability, and accuracy. Encoders enable tight synchronization between target movement and image acquisition. A digital output signal driven from an encoder will enable accurate high-speed triggering

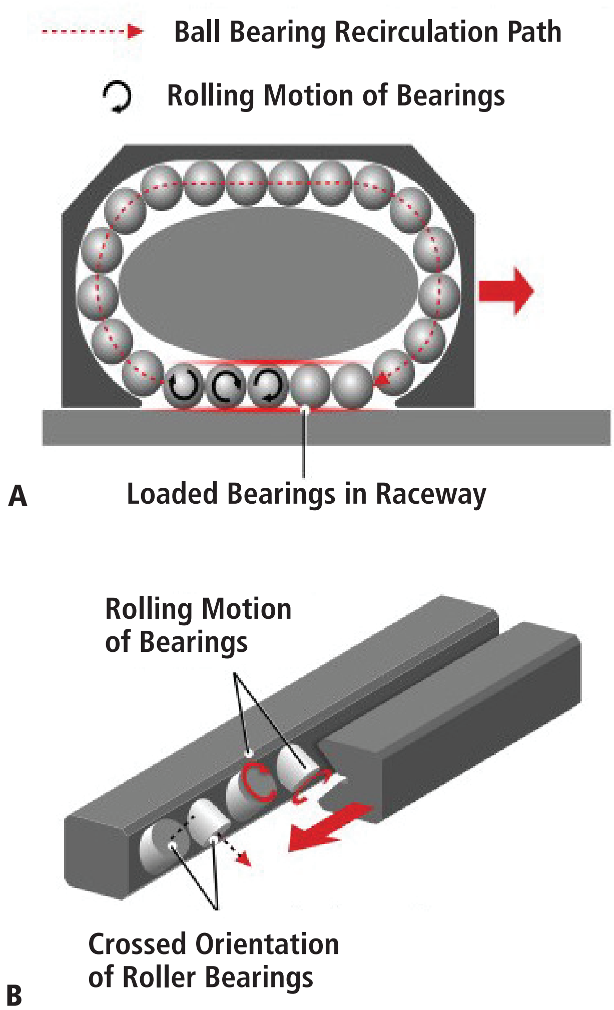


FIGURE 5. Recirculating bearings are contained within a bearing block that moves along a raceway. Travel is limited by the length of the raceway. Crossed roller bearings (B) move smoothly in one axis, while their bearing orientation gives them excellent stiffness in all other directions.

of line scan cameras. Synchronizing line scan camera triggering to an encoder signal eliminates distortion caused by fluctuations in system target movement speed. A camera trigger signal directly driven by the system movement will automatically compensate for variations in system speed, while a camera operating at a fixed line rate will not.

Motor encoders measure the rotation of the drive motor. They do not measure the absolute position of the carriage along its travel, so imperfections in the mechanical conversion of motor rotation to carriage position will affect the accuracy of the reported position. Motor encoders can detect if a stepper motor has slipped or stalled. If a high-speed optical filter wheel in a multispectral imaging system operating near the limits of its drive motor stalled, a motor encoder would allow the system to detect the issue and recover automatically (for example, reducing the speed) without loss of position reference.

Direct encoders measure the absolute position of linear stages and the angle of rotary stages. Direct position measurement means the accuracy of the reported position will not be impacted by mechanical imperfections in the conversion of motor rotation to the final carriage position. Motor controllers can use this data to approach the target position, improving stage accuracy and repeatability.

Direct encoders with resolutions of 1 nm can help maximize the throughput of semiconductor wafer and packaging inspection systems that rely on high-magnification optics. High-resolution encoders enable device controllers to measure system vibrations and trigger cameras immediately upon settling below a target vibration threshold rather than waiting for an arbitrary settling time, which would add an unnecessary delay and reduce system throughput.

Bearing Mechanics

Bearings ensure moving parts travel efficiently and smoothly in one axis while constraining them to prevent unwanted movement on all other axes. Incorrect bearing selection may result in friction and jerking movements of inspection targets, causing unwanted distortion of line scan images. Inadequate bearing stiffness could result in blurring of long-exposure images because of vibrations. Appropriate bearing selection could eliminate the need for more expensive, wider aperture optics or higher power lighting.

Plain Bearings

Plain bearings are the simplest form of bearing. They use low-friction sliding elements running on smooth surfaces that constrain motion to just the desired axis. The simplicity of plain bearings keeps them lightweight, compact, and inexpensive. Dry running polymer plain bearings are chemically inert and self-lubricating, making them virtually maintenance-free. Plain bearings' simplicity enables easy customization. Simple diverters in a quality inspection system may use plain bearings.

While low-friction materials are used in plain bearings, their sliding motion is still much higher friction than the rolling motion of ball or roller bearings. This makes plain bearings a poor choice for applications like vision-guided gemstone cutting where fine, smooth and highly repeatable movements are required. The higher friction of plain bearings may necessitate the use of more powerful and more expensive motors than would be required from more expensive, but lower friction, ball or roller bearings. This friction can cause them to bind under cantilevered loading so if cameras are moved on plain bearings, mounting them close to the bearing is recommended. Plain bearings cannot be preloaded to the extent that ball or roller bearings can be, resulting in less effective constraint of unwanted movement.

A lightweight camera and S-Mount lens may perform well on a plain bearing system, however a large 10GigE camera and high-quality F-mount lens may cause the bearing to bind. Excessive heat from friction can quickly degrade plain bearings if they are pushed beyond their speed and load design limits.

Recirculating Bearings

The rolling motion of ball bearings makes them much lower friction than the sliding motion of plain bearings. By containing ball bearings within a closed path, they will recirculate around the load-bearing surface. This design provides "infinite travel" if there is a hardened steel raceway for the recirculating bearing block to travel along. Recirculating bearings would be ideal for a cartesian robot performing vision-guided adhesive application in automotive production. Integrating recirculating bearings into the moving applicator and guidance head would eliminate the need for bearings along full length of the system's travel, reducing its cost.

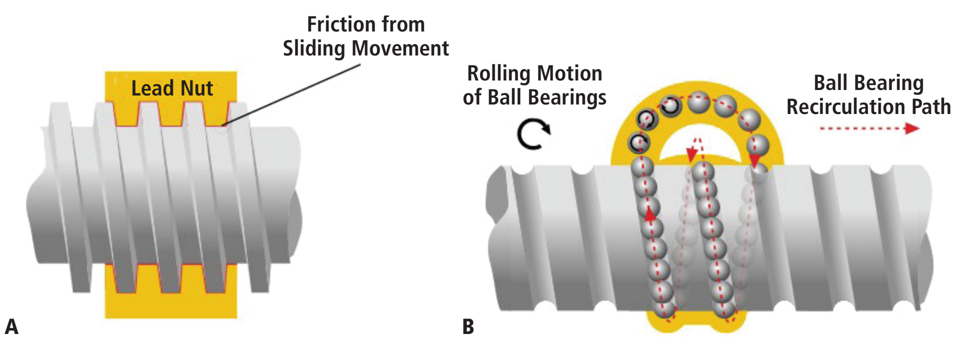


FIGURE 6. A lead screw and lead nut (A). The threads of the lead screw and lead nut slide over each other. Rotary motion of the lead screw is converted into linear motion of the lead nut. A ball screw drive (B) uses recirculating ball bearings which roll in grooves. Rolling is much lower friction than sliding. Rotary motion of the screw is converted into linear motion of the bearing block.

With much lower friction than plain bearings, recirculating ball bearing devices are better suited for high-speed motion. They can also provide much greater accuracy and repeatability than devices relying on plain bearings. These properties make recirculating bearings ideal for use in long-travel systems supported by gantries such as those for inspecting randomly oriented parts on a conveyor and in the inspection of welds.

As bearings circulate, they move in and out of the raceway. Minute differences in ball bearing size and surface imperfections in the raceway can result in acoustic noise and vibration of the carriage. Recirculating bearings require lubrication to roll smoothly. This necessitates periodic maintenance, adding to their lifetime cost.

Crossed-Roller Bearings

Crossed-roller bearings combine low friction in their axis of movement with very high stiffness in all other axes. Their friction force is extremely consistent and predictable, making them a good choice for metrology applications where velocity stability, high accuracy and high repeatability are required. They are ideal for inspection systems using high-magnification optics for mobile phone OLED display inspection where returning to saved positions with micrometer-level repeatability is essential to guarantee that key inspection target features are imaged consistently and reliably.

Crossed roller bearings' excellent rigidity minimizes vibrations to achieve rapid settling times between movements. Faster settling times translate into higher throughput, particularly with high magnification optics where even small vibrations can result in blurred images. Roller bearings distribute their loads over a larger area than ball bearings, making them better for supporting heavy loads or for working at higher thrust. These bearings are commonly used on a wide range of robots to provide smooth, efficient, and accurate movement while lifting large workpieces like engine blocks or aircraft parts. The mechanical performance of crossed roller bearings demands high-precision manufacturing, which increases their cost relative to ball bearing designs.

Drive Mechanics

Many vision systems are based on Cartesian robots that combine several axes of linear motion to move targets and cameras relative to each other. Linear X and Y axes may be combined to move a camera in a plane over the cylinder heads of an engine block to inspect the surface machining. To produce this linear motion, the rotary motion of stepper and servo motors must be converted into linear motion by a drive mechanism. The type of drive mechanics used by a motion control device will determine the applications it is suited for and its cost.

Lead Screw

In lead-screw-driven-devices, a rotating screw drives a lead nut fixed into the carriage, moving it along its travel. The basic lead screw design is extremely versatile, allowing it to be optimized for specific applications. Lead screws are available in a wide range of sizes, pitches, manufacturing tolerances, and materials depending on your requirements for travel, speed, repeatability, and chemical resistance. Lead screws are very compact, making them ideal for integration into space-constrained designs. Self-locking lead-screw devices cannot be easily back-driven and will remain in place when unpowered. This makes them excellent for lifting vertical loads, as once their load has been positioned, it will stay in place. They are used in many smaller-volume and higher-precision additive manufacturing systems.

The accuracy and repeatability of lead screws depends on the precision of their manufacturing and their length. Higher-precision lead screws are more expensive. A lead screw's accuracy decreases proportionally to its length, while its repeatability is independent of its length.

The threads of the lead screw and the lead nut slide across each other. As seen with plain bearings, this sliding movement is inherently higher friction than the rolling motion found in other drive mechanisms. Higher friction requires more torque and larger, more expensive motors to drive. Heat can build up quickly if the recommended limit of speed and load is exceeded, leading to increased wear. Accuracy is reduced, and backlash is increased as drive components wear over time. Wear is accelerated by extended operation at maximum speed, so while an inexpensive lead-screw drive may yield a lower upfront system cost, the increased long-term costs because of maintenance and process drift reducing yields may outweigh the short-term savings . Lead screws pair well with stepper motors as their performance is best at lower speeds. Stepper-motor-driven lead screw stages are versatile and cost-effective, delivering a good balance of accuracy, repeatability, and speed. This makes them a popular choice for prototyping vision systems and in research and development for structured light and multicamera depth sensing solutions for robot guidance, as camera positioning can be quickly and accurately adjusted remotely.

Table 1. Summary of properties

	Stepper Motor	Servo Motor	Linear Motor
Speed	+	++	+++
Thrust	+++ (low speed) + (high speed)	++	+++
Holding	+++	+	++
Accuracy	++	+	+++
Service Life	++	++	+++
Cost	$	$$	$$$

Ball Screw

A ball-screw-drive mechanism combines the basic design of a lead screw with a recirculating ball bearing path. Unlike a lead screw that slides over its lead nut, ball screws use ball bearings that roll, greatly reducing friction. The increased mechanical complexity of ball screws relative to lead screws makes them more expensive and less easily customized. However, their lower friction makes them much better suited for high-speed and high-throughput applications like SMT pick-and-place machines. Lower friction also enables ball screws to make smaller incremental movements than lead screws, making them well suited for driving the hexapod platforms used to position aspherical lenses during inspection.

Ball screws are not self-locking and will not remain in place when unpowered. They require a brake to hold a vertical load. Ball screws require more maintenance than lead screws and must be lubricated to function correctly. This makes them more sensitive to environmental contaminants and necessitates ingress protection in dusty or dirty environments. Correctly maintained ball screws have much longer service lives than lead screws. Their lifespans are also much more predictable as they are much less impacted by speed and load compared to lead screws.

Belt Drive

Belt drives are widely used in many industrial applications as they are cost-effective solutions for moving light loads at high speeds over long distances. These systems generally use a toothed polyurethane timing belt reinforced with steel, aramid, or glass fibers and are driven by either a stepper or servo motor. Belt-drive systems have low friction and high mechanical efficiency, enabling them to be driven by smaller, less expensive motors. These systems are not self-locking and can be easily back-driven. For vertical movements, such as camera positioning on passport control kiosks, a brake may be required to hold the camera at the desired height. Belt drives are ideal for gantry-mounted vision systems tracking randomly oriented parts on fast moving conveyors including selective laser ablation of anodization on electronic device chassis parts for EMC control. Many additive manufacturing systems operate with belt drives, particularly large-volume and low-cost systems.

Belt drive systems cope well with debris like sawdust, making them ideal for many manufacturing processes. They have significantly lower maintenance requirements than ball screw systems. As they wear over time, belts stretch, reducing both the accuracy and repeatability of movements. Belt wear is not as speed-dependent as lead-screw wear is. Therefore, the service life of these devices is more predictable. Belt-drive systems can be customized easily (Figure 7) to meet specific requirements for travel, as their costs scale slowly with length. The "infinite travel" design of recirculating ball bearings pairs with belt drives and can further improve the cost-effectiveness of long travel belt drive systems.

Selecting motion control devices with the appropriate combination of motors, encoders, bearings, and drive mechanics can have a major impact on your vision system's accuracy, throughput, reliability, and cost. Understanding the advantages and the limitations of different motion control device components, and how they can work together will help you ensure your vision systems deliver excellent performance and competitive pricing.

The final article in this three-part series provides two detailed case studies of how the motion control systems supporting an automated cell imaging system and a vision-guided laser etching system were developed.

Introduction to Motion Control for Vision Professionals, Part 3

Two machine vision systems show how key motion control specifications and drive and bearing mechanics can be applied to guide the selection of motion control components.

Welcome to the final installment of a three-part series covering the essentials of motion control for vision professionals. The previous articles covered the key specifications of motion control devices, and those specs were impacted by different motor, drive, bearing, and encoder types. This article demonstrates how that knowledge can be applied to optimize the design of real-world vision systems. It will examine a vision-guided laser ablation system and a high-magnification automated optical inspection system, explaining how the functional requirements are translated into specifications that can be used to select the ideal motion control components for each application.

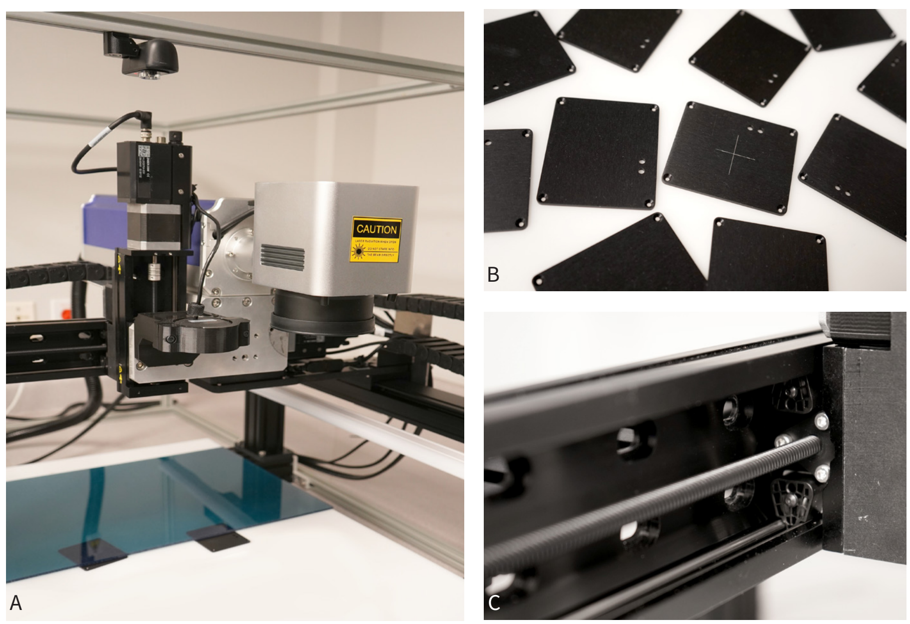


FIGURE 1. The laser ablation system is built on an XY gantry stage, a Z axis stage for focus control, a laser scanning head, and attached camera and ring light (A). Precision laser etching (B) on sample target parts. Lead screw and recirculating ball bearings (C). The mounting of the vertical stage results in a cantilever load. (Photos/charts courtesy of Zaber Technologies.)

Vision-Guided Laser Ablation System

A reliable conductive path between metal parts of an electronic device's casing is critical for achieving its specified electromagnetic emission performance. Selectively removing nonconducting anodization from aluminum parts to create a conductive path between parts is a common manufacturing technique. Automating this procedure can improve manufacturing yields and throughput. A vision-guided system that can accept a mix of randomly oriented parts is ideal for a high-mix, low-volume production environment. It improves production efficiency by eliminating many time-consuming setup steps like changing positioning jigs when switching between different product parts.

To successfully deliver the desired improvements in first-pass yield and production efficiency, the motion control components of this system must fulfill the following key functional requirements:

- Rapidly move a heavy laser scanning head and camera across X and Y axes to locate target parts

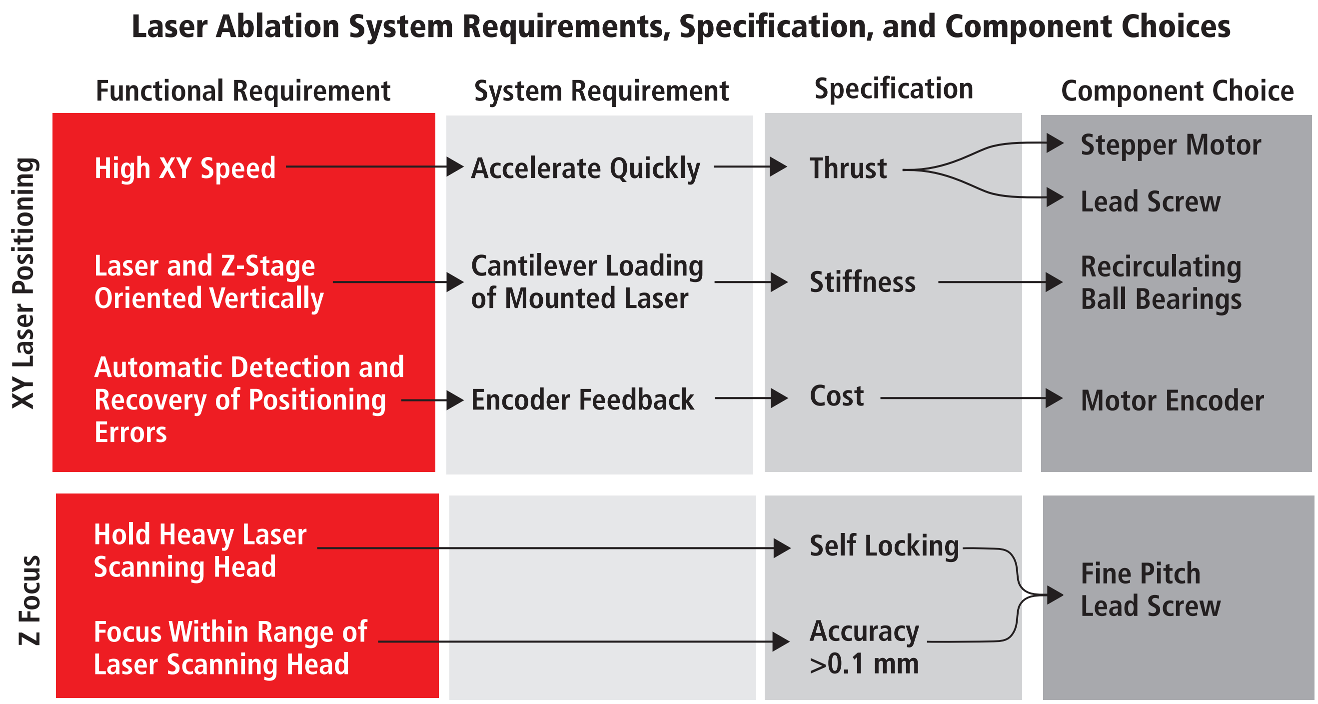


FIGURE 2. Functional requirements driving motion control component choice for laser ablation system.

within a 200- × 200-mm area covered by the laser's scanning head.

- Cover a large area so that many parts can be ablated in a single batch.
- Position the laser along the Z axis to a target height with a precision of 0.1 mm to achieve optimum focus and maximum power delivery.
- Maintain the Z axis position in the event of power failure.
- Automatically detect and recover from positioning errors.

Translating Functional Requirements to Component Choices

The 200- × 200-mm area covered by the laser's integrated scanning head is much larger than the 5-mm screw holes, which are the system's target, resulting in a low accuracy requirement on the X and Y axes. This provides design freedom to prioritize other specifications. Maximizing the number of parts that can be processed in a single run requires a large working area. X and Y stages must therefore have sufficiently long travel to cover the working area (Figure 1a). Recirculating ball bearings are a good choice for long-travel stages in production environments. They can support large cantilevered loads and have long service lives, which reduces long-term maintenance costs and unplanned downtime. Wiper seals surrounding the recirculating bearings provide ingress protection from potentially damaging debris.

The next key functional requirement is speed. The system must move the laser scanner and fine guidance camera from one screw hole to the next, pausing at each hole to perform the ablation operation. The ideal balance between maximum speed and acceleration is different for every application. Over the short distances between target screw holes, high acceleration will contribute more to throughput than

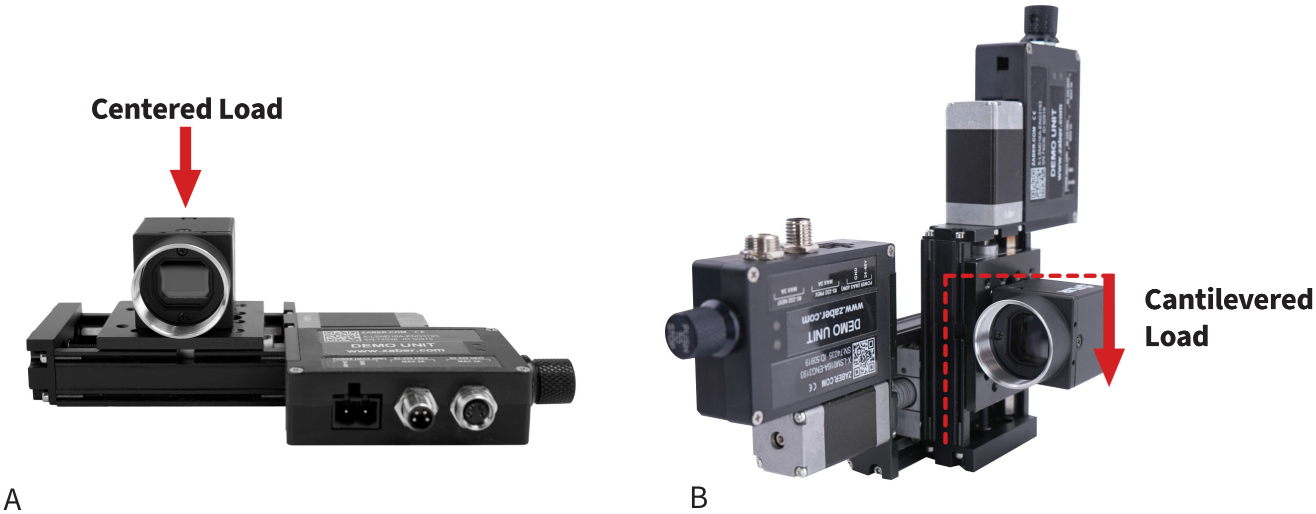


FIGURE 3. In the standard horizontal orientation, the largest load that is recommended for a stage is defined by the maximum centered load specification (A). In a vertical orientation (B), the cantilevered loading must be considered. A vertically oriented stage must have sufficient thrust to lift the load at its required rate against the force of gravity.

maximum speed. For high acceleration from a fixed position, a stepper motor drive is recommended as these motors produce much higher torque at low speeds than servo motors that would require gearboxes that add complexity and cost to the stage. A lead screw or belt drive are both cost-effective options for longer-travel stages, however, the higher peak thrust of a lead-screw-driven stage (Fig. 1c) will allow faster acceleration of the heavy laser scanning head.

The narrow focus range of the laser necessitates greater positioning accuracy in the Z axis than the X or Y axes. The vertical orientation of the stage must be considered since the load will be lifted by the stage, rather than simply sitting on the stage. In this vertical orientation, the thrust generated by the stage must be sufficient to lift the combined mass of the laser scanning head, attached camera, and lighting components. A stepper motor and lead screw drive is an excellent choice thanks to the high low-speed torque of stepper motors relative to servo motors and the low backlash of lead screws relative to belt drives.

Ensuring the laser assembly maintains its Z axis focus position when unpowered requires a self-locking stage. Linear motors require power at all times to hold their loads, while coarse-pitch lead screw and ball-screw-driven stages can be back-driven. A fine-pitch lead-screw-driven stage is therefore recommended.

The vertical orientation of the stage introduces an additional design consideration compared with stages used in a horizontal orientation. In this system, the mounting of the laser scanning head and vision guidance components will produce cantilevered loading of the focus stage (Fig. 3). The bearings must not bind as the resulting friction may cause the motor to stall. Roller bearings or recirculating ball bearings will perform much better under cantilever loads than plain bearings.

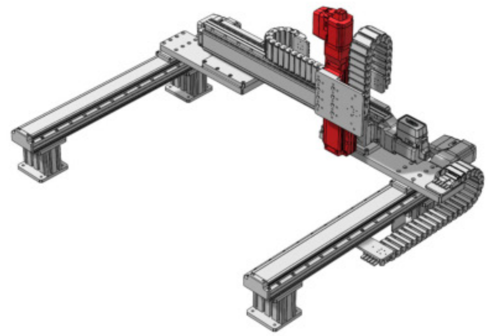
The balance between price and performance must also be considered. Over-specifying a system can greatly increase its cost without delivering any meaningful improvements in its functional performance. Selecting stages with specifications closely aligned to the functional requirements will keep costs in check. Encoder feedback can provide a more cost-effective solution to guaranteeing that 100% of the target screw holes are processed than selecting more expensive stages with a performance

1. XX-Axis | 2. Y-Axis | 3. Z-Axis (Optional) | 4. Y-Axis Orientation | 5. Risers | 6. Cable Guides | 7. Optional Accessories

Step 3: Select device for Z-axis

Depending on your selection below, the most suitable controller, data cables, mounting hardware, and power supplies will be added (see pricing in 'Parts, Cables & Hardware' on the right).

If you choose to separately add any of Zaber's linear, rotation, tilt, and/or gripping devices to this gantry's cart, we will review your configuration to ensure you have all the required accessories.



LRT-EC *(Dust Covers)* | LSQ-EC *(Hard Covers)* | LSQ-E

	Parts	Travel Range (mm) *Change Spec*	Maximum Speed (mm/s) *Change Spec*	Peak Thrust (N) *Change Spec*
◉	LRT0100HL-E08CT3A	100 mm (3.937")	240 mm/s (9.449"/s)	1200 N (269.1 lb)
○	LRT0250AL-E08CT3A	250 mm (9.843")	45 mm/s (1.772"/s)	1200 N (269.1 lb)
○	LRT0250BL-E08CT3A	250 mm (9.843")	175 mm/s (6.890"/s)	600 N (134.6 lb)
○	LRT0250DL-E08CT3A	250 mm (9.843")	700 mm/s (27.559"/s)	200 N (44.9 lb)
○	LRT0250HL-E08CT3A	250 mm (9.843")	240 mm/s (9.449"/s)	1200 N (269.1 lb)
○	LRT0500AL-E08CT3A	500 mm (19.685")	45 mm/s (1.772"/s)	1200 N (269.1 lb)
○	LRT0500BL-E08CT3A	500 mm (19.685")	175 mm/s (6.890"/s)	600 N (134.6 lb)

FIGURE 4. Example image from a configuration tool for planning multi-axis motion control systems. These tools provide step-by-step guidance to ensure the correct devices are selected and all the required cabling, supports and brackets to mount each device in the appropriate orientations are also included.

buffer. Encoders enable automatic compensation for slipping or stalling of a system that is operating close to its performance limits. Since direct position measurement is not required, motor encoders are the most cost-effective option. Once the system requirements and specifications are defined, online tools make designing a system to meet those requirements easy.

The vision guidance system uses two 2.3-MPixel, 30-fps USB 2.0 cameras. One camera is stationary and mounted above the system to detect the boundaries of each part. A second camera is mounted beside the laser's scanning head and moves with it to provide fine guidance for the laser's galvo scanning head. LED bar lights provide illumination for the coarse positioning camera while an LED ring light surrounds the fine positioning camera.

Like many industrial systems, the machine vision and motion control elements of this system depend on each other for their effective operation. Neither can operate independently of the other. Without input from the coarse-guidance camera, the motion control system cannot position the laser scanning head and fine-guidance camera accurately. Without motion control, the fine-guidance camera and laser cannot be positioned over the part to be processed. Coordinated operation of these systems is achieved through software. The application was implemented in Python to support rapid development and ease of updating and adapting the system as requirements

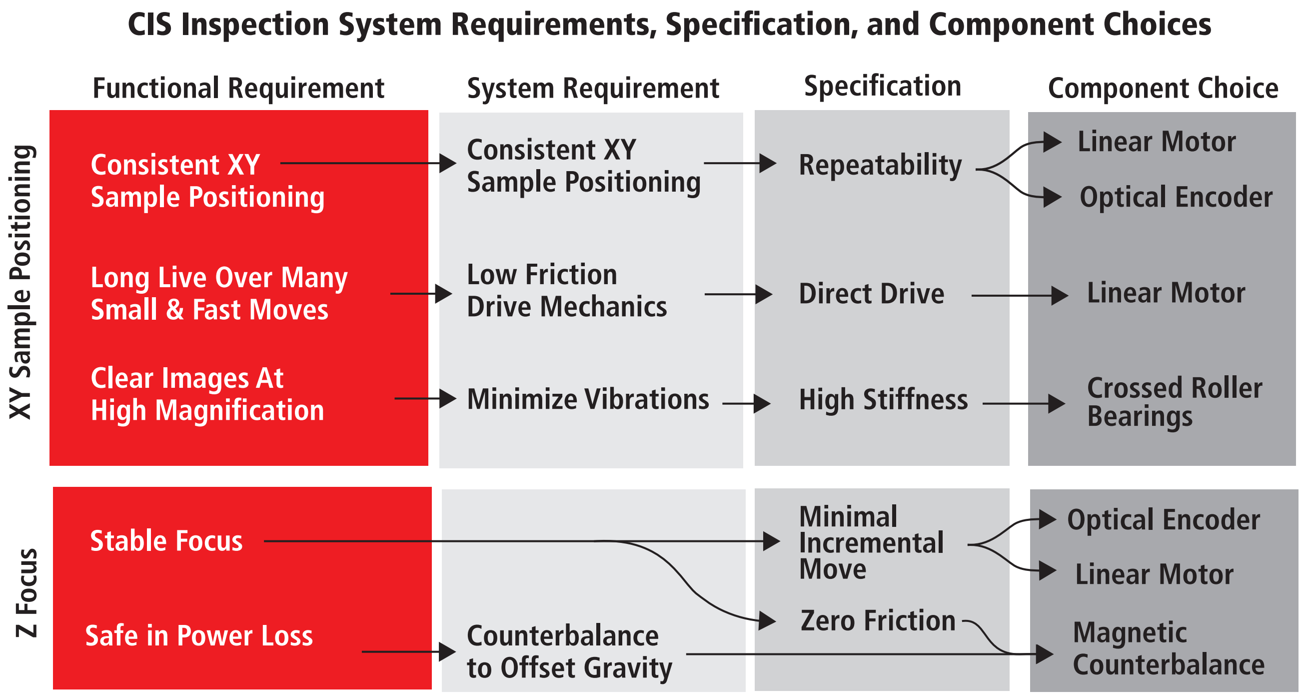


FIGURE 5. Functional requirements driving motion control component choice for microscope ZY stage.

evolve. Image analysis is performed using OpenCV, while motion control uses the Zaber Motion Library.

High-Magnification Automated Optical Inspection System

Semiconductor devices like CMOS image sensors (CIS) are subject to stringent quality control processes to ensure they will operate correctly and that the materials and processes used to manufacture them are within specified tolerances. Inspecting semiconductor devices requires high-magnification optics to clearly resolve micron-scale features. Precision motion control is necessary to localize those small features consistently.

A demonstration CIS inspection system based on a Zaber MVR automated microscope was constructed. This system was optimized for low-mix, high-volume inspection of small parts. It shows how the same principles used to guide the selection of components in the large format, high-mix, low-volume system can be applied to the opposite end of the spectrum.

To capture actionable images of the micron-scale features on a CIS in a high-throughput production environment, the following functional requirements must be met:

- The CIS must remain at a consistent distance from the objective lens so that focus is held constant across the entire area of the part.
- The system must have a long service life when operating continuously in a high-throughput environment.
- Key features on the sensor must be reliably positioned to simplify automated image analysis.
- The system must capture sharp, clear images.
- Objectives must not be damaged if power is lost.

Translating Functional Requirements to Component Choices

Inspection systems with high magnification optics pose unique challenges to vision system designers. These systems are extremely sensitive to vibrations. Shallow depths of field of less than 1 µm make finding and maintaining accurate focus much more demanding than with standard machine vision optics.

Minimizing motion blur caused by vibrations is essential to capturing sharp images at high magnifications. Vibrations can be reduced by selecting components with high mechanical stiffness. Crossed roller bearings are recommended for high magnification applications because of their higher stiffness and repeatability compared with recirculating ball bearings or plain bearings. Minimizing vibrations with high-stiffness components, which also have very low and highly consistent friction, will greatly improve imaging throughput by reducing the time required for the system to settle after moving between inspection locations or loading the next part to be inspected into the system.

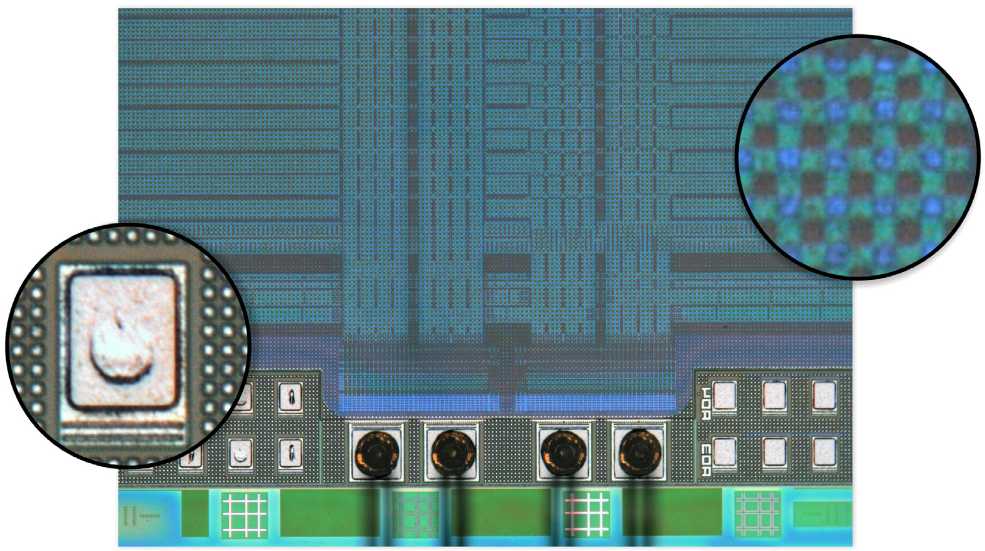


FIGURE 6. 20x magnified view of the edge of a CMOS image sensor shows the wire bonding to the sensor die and Bayer pattern color filter array over 2.74 ¬µm pixels.

The faster the system can settle between movements, the higher its throughput can be. The high stiffness of crossed roller bearings also improves system performance by ensuring that once focused, the target will remain at the correct focal distance over its entire area. Rapid settling times can also help reduce costs by enabling less expensive rolling shutter cameras to capture distortion-free images, eliminating the need for more expensive global shutter cameras.

Consistently imaging the same point across thousands of inspection targets requires very high repeatability. Stages with a smaller minimum incremental move specification will benefit most from positioning feedback as they will be capable of smaller positioning corrections. Smooth and low-friction crossed roller bearings and low-friction, zero-backlash linear motors can achieve minimum incremental movement distances as low as 20 nm, ensuring consistent results even for 24/7 high throughput applications.

Minimizing unscheduled down-time is critical for industrial processes. Unlike stepper-motor-driven stages, linear motors produce linear motion directly and do not require additional mechanical components to convert rotary motion into linear. This eliminates sources of friction, backlash, and mechanical wear, yielding extremely long service lives. This is crucial for systems like this that will operate continuously at high thrust making many small fast moves between target imaging positions.

A 24.5-MPixel Teledyne FLIR (Richmond, BC, Canada; www.flir.com/machine-vision) BFS-U3-244S8C-C camera based on the Sony (Atsugi-Shi, Kanagawa, Japan; www.sony-semicon.co.jp/e/) IMX428 CMOS image sensor was selected for its high resolution and large sensor size which delivers excellent detail across a wide area (Figure 4). Reflected darkfield illumination

> **"Consistent control of focus requires a small minimum incremental move and high repeatability. These requirements line up well with the capabilities of linear motors."**

was provided by a Zaber X-LCA4 lighting controller and Zaber MLR3B LED epi-illuminator. The objective lens was a Zeiss (White Plains, NY, USA; www.zeiss.com) EC Epiplan 20x/0.25 HD. Automation of motion control and image acquisition was achieved using µManager software.

Accurate control of the focus shares many of the same requirements as the XY positioning stage. Consistent control of focus requires a small minimum incremental move and high repeatability. These requirements line up well with the capabilities of linear motors. The high stiffness and smooth motion of crossed roller bearings, which help minimize vibrations and achieve highly repeatable movement, make these bearings an ideal choice here.

Like with the laser ablation system above, the vertical orientation of the focus stage must be considered. Linear motors must remain powered to hold their loads in place, but a self-locking lead-screw stage will not deliver the required repeatability, backlash, and minimum incremental move performance. This problem can be solved using a counterbalance to offset the force of gravity and lower the stage gently in the event of a power loss.

Many microscopy applications use autofocus systems to quickly find the best possible focus. Most software-based approaches for autofocus work by capturing a series of images at different Z positions then selecting the image with the highest contrast. Generally, this means overshooting the best focus position, then moving back to it. Applications where a target must be approached from alternating directions with a high degree of repeatability are best served by linear motors which have effectively zero backlash. Optical encoders can further improve repeatability by providing positioning feedback. Further improvements in autofocus performance can be achieved by selecting a focus stage with an integrated controller supporting IO triggering. Such stages can be triggered to step to the next Z position directly via a camera's digital output line.

Two very different machine vision systems show how the key motion control specifications introduced in part one and the drive and bearing mechanics introduced in part two can be applied to guide the selection of the motion control components that best support the functional requirements of those systems. This knowledge helps vision systems designers make informed decisions to balance the tradeoffs between specifications and build cost-effective and reliable systems that meet their performance targets.