

Optimizing Motion Systems for the High-Precision, High-Throughput Laser Cutting of Cylindrical Medical Products

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Introduction to Cylindrical Medical Products

One of the most universal challenges in precision engineering and machine design involves making tradeoffs and design compromises. This is especially true in cylindrical medical product manufacturing. Engineers, managers and business leaders regularly have to choose between making parts quickly – but with errors that lead to extensive post-processing scrap rates – and making highly precise parts in lower volumes at higher costs.

What if they could produce significantly more parts in a given amount of time without compromising quality? Using fundamental strategies for optimizing laser cutting motion systems, it's possible to minimize these tradeoffs – enabling cylindrical medical product and device manufacturers to more readily reach their goals, improve operations and gain a competitive edge.

Many cylindrical medical products and devices are laser-cut from tube stock, including:

- Structural heart components, which augment or completely replace damaged heart valves in procedures such as transcatheter aortic valve replacement (TAVR), transcatheter mitral valve repair (TMVR) and bicuspid aortic valve (BAV) procedures.
- Coronary stents, which hold open major blood vessels to improve the supply of blood to the heart as a treatment for coronary artery disease. Stents are placed in the patient's body through a procedure called percutaneous coronary intervention (PCI), during which a catheter guides the stent and places it in the appropriate location. Some stents are drug-eluting, meaning they are coated with a time-release medication that helps to keep the artery clear.
- Neurovascular stents, which are very fine-featured products delivered through the patient's vascular system into the brain. Their principal function

is to treat aneurysms, intracranial atherosclerotic disease (ICAD) and similar neurological conditions.

- Peripheral vascular devices, which include stents used to treat conditions that affect blood vessels outside the heart or brain. Peripheral stents are commonly used to treat conditions such as deep-vein thrombosis (DVT) and pulmonary embolism.
- Minimally invasive instruments, which include hypotubes, catheters, hypodermic needles and more. They are used in a variety of surgical procedures to navigate a patient's blood vessels, deliver and place stents, and support various laparoscopic, endovascular and robotic surgeries.

These laser-cut cylindrical medical products feature diameters ranging from sub-millimeter to a few centimeters, with total part lengths spanning a few millimeters to more than one meter.

Core Elements of Motion Systems for Cylindrical Laser Processing

Designing a highly dynamic motion platform requires system-wide consideration, including positioning stages for workpiece manipulation; a laser cutting head and a means to position it; mechanics to facilitate workpiece holding and feedthrough; and a structure including a machine base, vibration isolation system, frame and enclosure. The linear and rotary stages, which dynamically position the tubular device or workpiece under the laser cutting head to produce the desired feature geometry, are essential to the economical production of tubular devices in high quantities. As shown in Figure 1, key elements of the part manipulation system include the linear axis, rotary axis, collet chuck, gripper for tube advance, bushing and laser-cutting head.

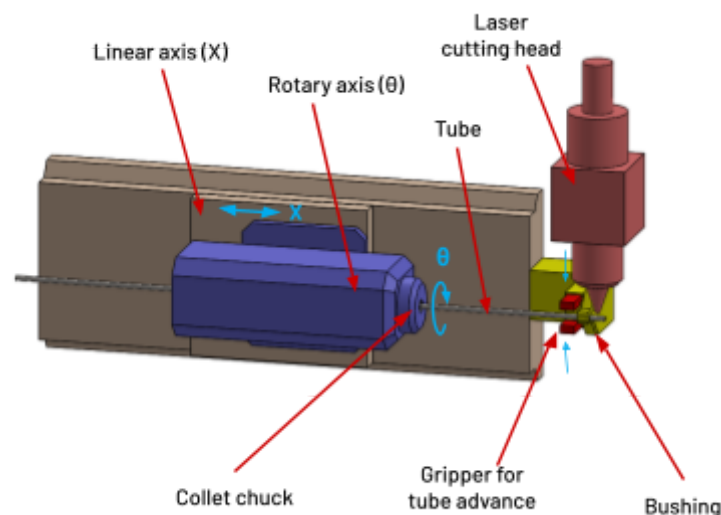


Figure 1. Mechanical components of a precision tube-cutting motion system for part manipulation.

The linear and rotary axes need to exhibit outstanding accuracy, repeatability and speed:

- Accuracy describes how closely the motion system can reach a commanded target position. High accuracy is essential to achieving the desired cut geometry on the workpiece, including precise dimensions, tolerances and feature locations.
- Repeatability characterizes the variability in the motion system's achieved position compared to the commanded position, when the motion axes are commanded to the same position many times. Outstanding repeatability is critical to manufacturing highly reproducible parts and can minimize the time required for post-processing and part inspection.
- Speed is a function of dynamic properties such as velocity and acceleration and the required accuracy and repeatability, to which speed is inversely proportional. Maximizing the machine's processing speed helps users to produce more parts per hour, and this contributes to lower manufacturing costs.

Simultaneously achieving excellent accuracy and repeatability plus high dynamics is extraordinarily challenging. Like driving a vehicle, it is difficult to maintain lane position while rapidly negotiating a tight curve. Slowing down is the obvious solution, but by how much? A tractor trailer will need to slow down more than an SUV, which in turn would have to slow down more than a sports car. Similarly, in cylindrical laser processing, the equipment manipulating the tube under the laser has a major influence on the system's ability to cut precise, reproducible components with extremely high throughput. Thus, the "sports car" of motion systems ought to have low moving mass and inertia, plus copious amounts of force and torque, all while being able to maintain position dynamically within a defined error window.

Characterizing Accuracy and Repeatability

While accuracy and repeatability are important characteristics of a cylindrical tube-cutting motion system, repeatability is fundamentally more important than accuracy. Repeatability, which characterizes the range of positions attained when the motion system is commanded to a given position multiple times, is a function of the system's construction, including component tolerances, properties of the motor and feedback device, bearing and drive-screw component grades, build quality and more. A repeatable axis isn't necessarily accurate, but if the axis is inherently repeatable it can be made accurate through a variety of calibration techniques. Figure 2 illustrates this concept.

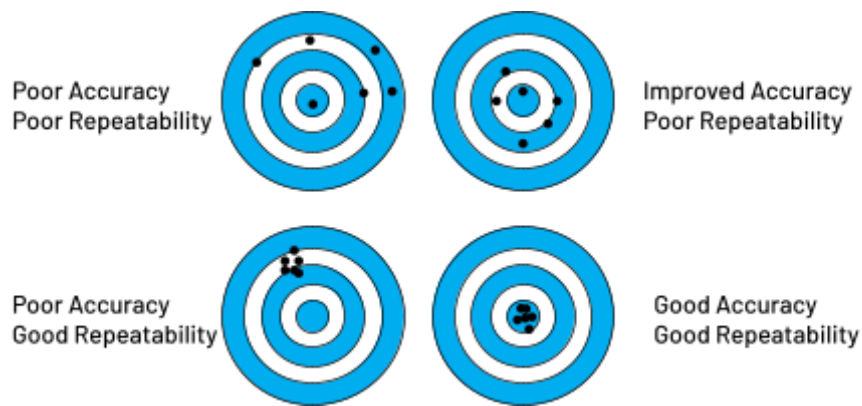


Figure 2. Good repeatability is a prerequisite for good accuracy.

Defining and understanding stage specifications like repeatability and accuracy is necessary to quantify and compare performance criteria to application requirements or even other stages. There are several different evaluation methods, including metrology standards such as:

- ISO 230-2: Test code for machine tools
- ASME B5.64: Methods for the performance evaluation of single-axis linear positioning systems
- ASME B5.54: Methods for performance evaluation of computer numerically controlled machining centers
- VDI 3441: Statistical testing of the operational and positional accuracy of machine tools
- JIS B 6192: Test code for machine tools

These standards quantify accuracy and repeatability by applying statistical treatments to a defined dataset. Beyond this, many motion suppliers have their own methods and definitions of testing and reporting. This variation makes it challenging to directly compare specifications across different suppliers. For instance, Supplier A may report according to ISO 230-2; Supplier B might use a plus-or-minus 1.5-sigma treatment; Supplier C might report root-mean-square (RMS) values; and Supplier D may report typical values only. For the exact same data set, each supplier's reported accuracy and repeatability values would differ from the others. Always ask potential suppliers how they report their specifications.

When suppliers specify and report transparent, easily understandable peak-to-peak values for accuracy, repeatability and more over a stage's full range of motion, the buyer knows every purchase will meet or surpass the published catalog specifications. This conservative approach ensures 100% guaranteed performance, mitigating risk and uncertainty.

How Motion Errors Effect Stage Performance

Realistically, no stage will ever exhibit "perfect" motion, free of all errors. However, it's important to understand error sources and how they contribute to the motion system's

overall performance. On-axis errors occur in the direction of motion, directly impacting accuracy and repeatability. Common sources of on-axis errors include:

- Feedback device (e.g. encoder) errors
- Drivetrain inaccuracies
- Motor cogging
- Torque and velocity ripple
- Abbe errors

Abbe error, named after Dr. Ernst Abbe, characterizes how angular errors are magnified over a distance, resulting in what appears to be linear, on-axis errors. In a linear stage, Abbe error can be caused by motion errors in the pitch direction. As the functional point offset (also known as the work point) increases in height above the stage, the magnitude of the Abbe error also increases. This principle is illustrated in Figure 3, along with a depiction of the five off-axis error directions of a linear stage.

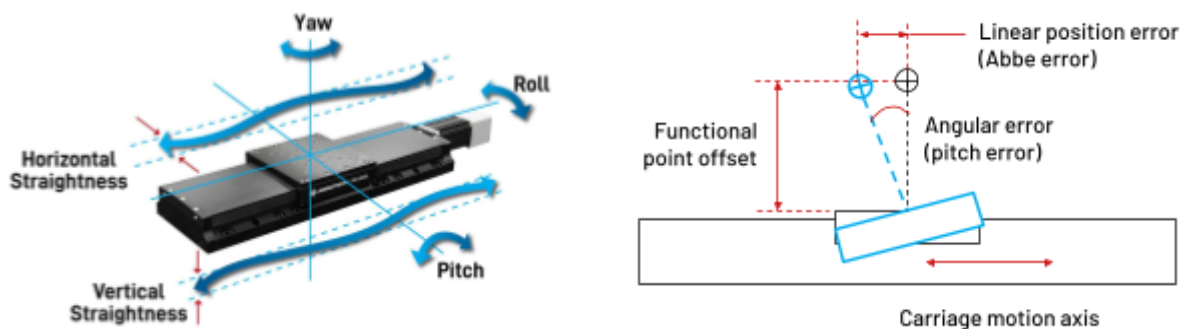


Figure 3. A depiction of the five off-axis errors of a linear stage (left) and illustration of the Abbe error principle (right).

Off-axis errors, however, present themselves in the five remaining degrees of freedom, also depicted in Figure 3. For a linear stage, these off-axis errors include horizontal straightness, vertical straightness (sometimes colloquially and incorrectly referred to as flatness), pitch, yaw and roll. For a rotary stage, the off-axis errors include axial, radial (two directions) and tilt (two directions). There are many sources of off-axis errors, and the most pervasive include:

- Bearing form error
- Base/carriage geometry and tolerances
- Assembly tolerances and alignments
- Bimetallic effects
- Frictional effects
- Externally applied forces

Although it's impossible to eliminate these errors completely, they can be managed and mitigated through a combination of best practices, including:

- Careful stage selection and configuration
- Minimizing the offset distance to the functional point
- Measuring and error-mapping the stage at the functional point

On-axis errors, including Abbe error, can be directly compensated out by implementing various accuracy calibration techniques. Off-axis errors are trickier to correct. It's relatively straightforward to measure, quantify and even map these off-axis error motions, but additional axes of motion are typically needed to physically correct for them because a single-axis stage can only be commanded in the on-axis direction.

Understanding Centers of Action in Stage Performance

In precision stage design, a center of action refers to a point or axis around which a force, motion or load is effectively applied. Understanding this concept is crucial because it directly affects the stage's positioning performance under real-world operating conditions. Even though the vast majority of cylindrical medical device manufacturers will not be designing stages from scratch, understanding key underlying principles is useful in discussions with potential suppliers and during product comparisons and selection.

Figure 4 illustrates an axial cross section of a generalized stage layout with relevant components including the moving carriage, linear guide bearings, linear motor forcer, cable management loop and a user payload. In this example, these components are secured to the moving carriage, resulting in a composite center of mass located above the carriage. In addition to the center of mass, it is necessary to consider the center of force, center of stiffness and center of friction.

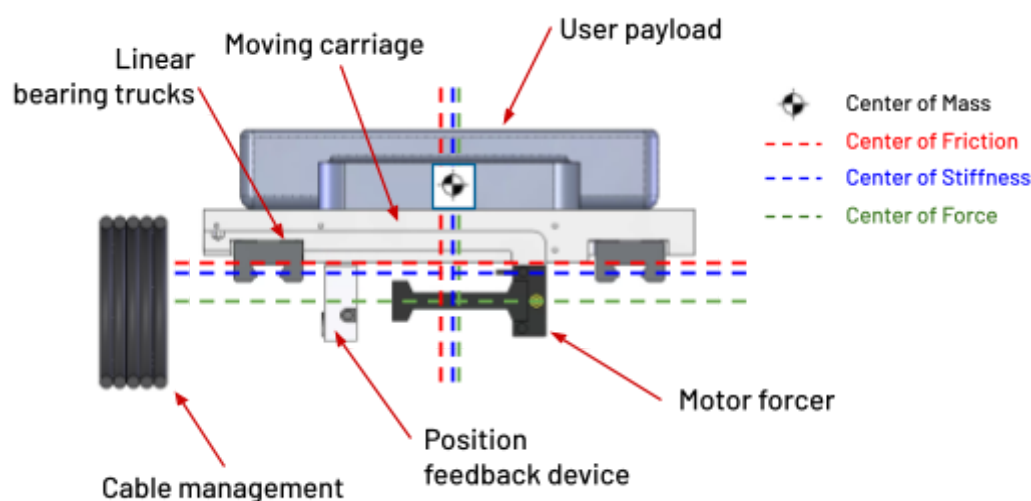


Figure 4. Illustration of a generalized linear stage cross-section with centers of action indicated.

In this case, identifying the center of force is reasonably straightforward: it's located coincident with the plane corresponding to the motor forcer's centerline. Note there is an offset distance between the center of force and the center of mass. This means the motor is applying not only a linear force in the direction of motion, but also a moment load in the pitch direction. The linear bearings counteract most of this moment load, but there is measurable deflection because bearings are not infinitely stiff. This deflection can be characterized as an error in the pitch direction.

The center of stiffness is the location around which the stage exhibits balanced stiffness in all directions. Because the bearings are a primary contributor to axis stiffness, it becomes apparent that the center of stiffness is located within the plane of the linear bearing trucks. Under ideal conditions, when a force is applied axially at the center of stiffness, the carriage will undergo purely translational motion with no rotational motion and therefore no angular errors result from the applied force.

Similar to the center of stiffness, the center of friction describes the location at which the resultant frictional force acts. It's important to notice the center of friction differs in location from the center of stiffness. While the bearings are the primary source of friction, the cable management system imparts additional frictional disturbances to the carriage and thus the center of friction is offset slightly from the center of stiffness.

The highest performing stage designs align these centers of action as closely as possible to optimize performance. In practice, however, it's unrealistic to expect a design to meet this condition completely. There are typically design tradeoffs made between performance and other factors such as stage width or footprint, cost, manufacturability and more. Still, the clever placement of stage components shown in Figure 4 increases the stage's first resonant frequency and minimizes its excitation. Selecting bearings with high pitch stiffness further improves dynamic performance capabilities. This is key to enabling higher throughput without significantly compromising precision.

What happens when the center of force does not align perfectly with the other centers of action? Applying an offset force, misaligned from the other centers, induces an unwanted moment load. These moment loads cause the stage to move in a direction other than intended (i.e. in an off-axis direction). This often causes dynamic pitch error and other errors that result in accuracy and repeatability errors at the functional working point.

Navigating Bearing and Motor Selections

Bearings constrain motion to the desired degrees of freedom and help to prevent unwanted motion in other directions. The most common types of linear bearings used in precision stages offer different properties depending on the design intent, including:

- Linear guides (truck-and-rail style) with recirculating ball or roller elements
- Crossed-roller bearings with a cage of orthogonally oriented rollers slides between two bearing rails
- Air bearings, which involve maintaining a very precise cushion of air between the stage base and its moving carriage

Motion is smoother with crossed-roller bearings because the absence of recirculating rolling elements results in less noise and other disturbances. Stiffness is also superior in crossed-roller bearings, although they provide a more limited range of travel than linear guides. Additionally, linear guides tend to be less costly than crossed-roller bearings.

Although air bearings nearly always outperform both linear guides and crossed-roller bearings in smoothness of motion and geometric performance, they aren't commonly found in tube-cutting systems because of the higher risk of contamination from laser processing debris and any fluid that may be used in the process. Further, air bearings tend to be the costliest of the three variants discussed here.

In terms of motors, there are two fundamental motor types commonly found in precision stages:

- Slotted iron-core motors
- Slotless ironless motors

Both linear and rotary motors can be built as slotted iron-core or slotless ironless variants. Both slotted and slotless motors are comprised of a forcer (or stator, in the case of a rotary motor) containing wound copper coils typically encapsulated in epoxy and a magnet track made of a steel structure to which rare-earth magnets are carefully applied (with rotary motors, this is called the rotor).

In a slotted iron-core motor design, the copper wire is wound through slots, or teeth, in a stack of laminated steel sheets. Slotted iron-core motors exhibit higher force densities than their slotless ironless counterparts because the slots help to concentrate the magnetic flux within the air gap between the magnets and the windings. This results in increased flux density and consequently delivers higher amounts of force or torque.

However, slotted iron-core motors can be more error-prone than slotless ironless motors because of the interaction between the forcer and magnet track (for rotary motors, between the rotor and stator). Each tooth in an iron-core motor has a naturally preferred position relative to each magnet. A detent force is required to move the tooth away from this position. This is commonly referred to as cogging force. Cogging force is independent from the force applied by the motor and the stage velocity. It causes small but observable force or torque ripples as it traverses. Cogging can be problematic when manufacturing tubular medical products with micrometer-level features and tolerances because of the velocity errors it can introduce, which result in part position errors and incorrectly located or dimensioned tube features. Although techniques exist to help mitigate cogging effects, it's impossible to fully eliminate them from slotted iron-core motors.

Slotless ironless motors, conversely, are inherently free from cogging effects and therefore do not exhibit velocity errors in this manner. The forcer lacks steel teeth and consists only of tightly wound copper coils. Motion is considerably smoother, resulting in higher-accuracy cuts and more highly reproducible tubular medical products. Drawbacks of ironless motors include higher cost due to the increased manufacturing complexity and lower force density compared to iron-core motors; however, in demanding applications like stent cutting, where the final product resides in a patient's body, the higher part quality and reproducibility nearly always outweigh these subtle drawbacks.

Key differences in the construction of slotted iron-core motors and slotless ironless motors are readily apparent in Figure 5.

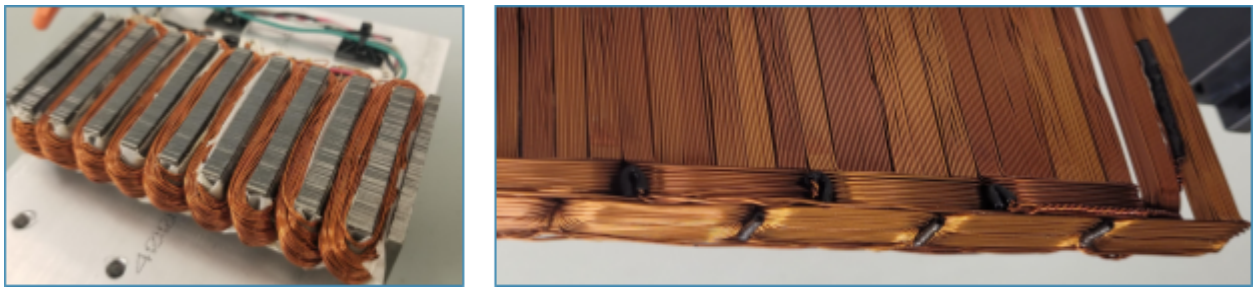


Figure 5. An example of a slotted iron-core linear motor forcer (left) and a slotless ironless linear motor forcer (right). Note the presence of the steel teeth in the iron-core forcer and the absence thereof in the ironless forcer.

For bearing and motor selection, as with many aspects of precision engineering, tradeoffs must be evaluated and decided upon as a function of the design priorities. Well-versed motion suppliers can provide valuable, application-specific guidance to aid in these configuration decisions.

Workholding Considerations

Another crucial element of optimizing motion systems for cylindrical medical device manufacturing involves how the tube stock is held and manipulated by rotary stage or spindle. Once again, this involves evaluating several tradeoffs, and the decision is based on factors such as the workpiece diameter (or range of possible diameters), the final length of the finished part and the machinery's intended use case (e.g. will the tube-cutting system be used to make only a few different types of parts in a full-scale production setting; is it intended more for research, development and rapid prototyping efforts; or will it be used in a job shop environment?).

Tube stock is most commonly held and advanced using a collet mechanism or a three-jaw chuck. Collets can be categorized into two classifications: floating and dead-length. Examples of each are provided in Figure 6.



Figure 6. ER-style floating collets (left), TF- and W-type dead-length collets (center), and a pneumatic three-jaw chuck (right).

ER-style floating collets are often used in tube-cutting applications. The collet itself is a flexure-like cylindrical sleeve with a taper on one end that mates with a corresponding taper inside a collet nut. When the collet is forced axially into the mating nut, it compresses radially to close on the tube. Because the collet must be actuated in the axial

direction in order to close it, it's common to observe unwanted axial motion of the tube on the order of a few hundred micrometers. This makes it more challenging to produce longer parts that require tube advancement and regripping within the length of the part. This unwanted axial motion can result in errors on the part, which in turn may require extensive reworking or even scrapping of the part. It is possible to mitigate these effects by measuring the tube displacement and compensating for it in the part program, but this added complexity slows down the process cycle time. Floating collets can cause surface damage to the tube stock due to the relative axial motion of the collet and the tube during opening and closing, which is especially troublesome for specialty materials that are easily scratched or damaged.

Nonetheless, floating collets are popular for their versatility and relatively wide clamping range (typically 0.5 mm to 1.0 mm range for a single collet), allowing a greater variety of part diameters to be processed without having to change collets. They are reasonably affordable and widely available, making it easy to maintain a full set of collets to address nearly any tubular medical device. This makes floating collets particularly useful in job shop environments where the operator may need to produce many different parts over a short amount of time. And even though floating collets are prone to wear over time, their economical and ubiquitous nature makes them simple to replace.

In contrast, dead-length collets – including type-C, type-D, type-W and Swiss lathe collets – remain virtually still during opening, closing and tube advance operations. Users can expect less than 10 micrometers of tube motion. However, these collets are less versatile because they are “on-size,” meaning they are manufactured to the exact nominal diameter of the workpiece. The machine operator needs to change the collet every time the workpiece diameter changes. Operators who process many different diameter workpieces must maintain a significant quantity of dead-length collet sizes on hand. Some dead-length collet types are costly, which can make it financially challenging to keep a full set on hand. Still, there are several dead-length collet types that are reasonably affordable. Regardless of cost, dead-length collets help to increase process quality and throughput by minimizing the effects of unwanted axial tube motion during tube advancement and regripping.

Both floating collets and dead-length collets have relatively low inertia, which is beneficial to achieving good dynamic performance. They also exhibit low radial runout, which ultimately helps to bolster part quality. An illustration of the differences between floating collet and dead-length collet architecture and operation is provided in Figure 7.

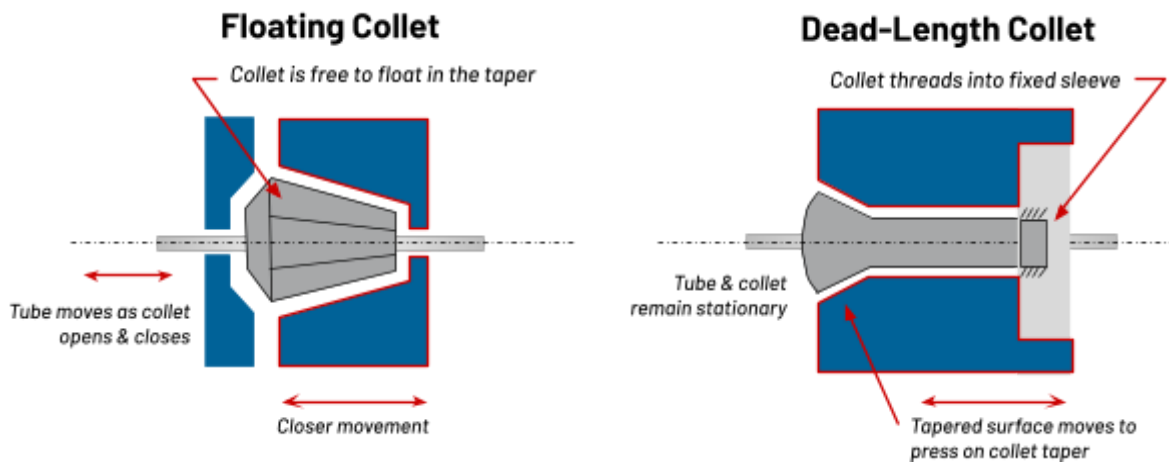


Figure 7. An ER-style floating collet (left) is free to move on the order of hundreds of micrometers within the taper region when open, resulting in axial collet and tube motion during closing. A dead-length collet (right) is threaded into a fixed sleeve, greatly reducing the axial motion of the tube during opening and closing to within single-digit micrometer levels.

Three-jaw chucks are an alternate means of holding the tube. Commonly used on lathes, they hold parts between three jaws that are actuated by a scroll mechanism. A primary advantage of three-jaw chucks is their extremely wide range of permissible tube diameters. The stroke of the grippers can be up to tens of millimeters, allowing for a significant amount of versatility in producing different part sizes using a single chuck — no collet changes required. However, three-jaw chucks are prone to higher levels of radial runout than collets, potentially compromising part quality and reproducibility. Three-jaw chucks are further plagued by relatively high inertia, which limits dynamic performance and increases part cycle time.

Once again, a well-versed motion supplier or machine builder can assess the application requirements and provide guidance on the choice of workholding mechanism.

System Integration and Optimization

At first glance, pairing and integrating a cylindrical tube-cutting system's linear and rotary stages may seem simple. In practice, however, there are many subtle details that must be considered to achieve a high-precision, high-throughput motion platform, including:

- Design of the linear-rotary mounting interface
- Alignment of the linear and rotary axes in relation to one another
- Mounting height of the rotary axis above the linear axis
- Cable management design
- Metrology and calibration
- Advanced tuning

A thoughtfully designed mounting interface between the linear and rotary stages should be sufficiently stiff, especially in the pitch direction. If the interface is excessively compliant, it can be a source of vibration in the system. Maximizing this interface's stiffness helps to boost the first resonant frequency, thereby reducing vibration-related errors. The

mounting interface should also be adequately flat to avoid distorting key components and inducing errors.

Joining the linear and rotary stages together also demands precision. Simply bolting the rotary stage to the linear stage is not enough; rather, it's crucial to precisely align the axis of rotation to the axis of translation, especially in the pitch and yaw directions, because alignment errors will result in imprecise and incorrectly located cuts. This alignment can be done with a precision test pin and a measurement device such as a digital indicator.

Another important design consideration involves locating the rotary stage's axis of rotation as close as reasonably possible to the linear stage. This results in a lower-profile motion system, but more importantly it reduces the offset between the center of gravity of the moving mass and the linear stage's centers of action. This generates elevated resonant frequencies, consequently allowing for higher-speed operation without exciting these frequencies. Achieving precise alignment can be challenging when competing design goals are considered. Reducing the height of the rotary axis and making the corresponding optimizations of the centers of action can result in a wider footprint of the linear stage, for instance, and can even make compromises to the linear-rotary interface's stiffness. Design engineers must carefully weigh the system requirements and choose an ideal balance.

Furthermore, designers need to take care in implementing a cable management system (CMS). The CMS influences the center of friction's location, so steps should be taken to reduce its frictional influences. The CMS can also induce disturbance forces resulting in yaw errors. An effectively designed CMS minimizes these non-symmetric disturbances, reducing their influence on the stage's motion performance.

Following assembly and alignment, metrology must be performed on the linear and rotary stages. It's possible to perform an accuracy calibration by measuring the on-axis accuracy and repeatability errors and generating an error map, from which a table of positional corrections can be generated. Using a laser interferometer and autocollimator, skilled technicians can map out repeatable errors and generate a correction file for the controller. It's important to perform the metrology and calibration as close to the working point as possible to compensate for some amount of off-axis errors such as Abbe error. Figure 8 depicts a metrology technician using a laser interferometer to perform an accuracy calibration on a linear stage.



Figure 8. A technician performs metrology and calibration on a linear stage.

Servo tuning, one of the final system-level optimizations to complete, involves determining a set of servo-loop gains that most closely align with the desired performance criteria. For tube-cutting systems, optimized tuning means that a system exhibits its highest possible bandwidth. Unlike other types of systems, where one might optimize for maximum servo stability under varying loading conditions, tube cutting systems have a payload that is relatively small with respect to the total moving mass; therefore, employing an aggressive tuning scheme usually offers more advantages than downsides.

Tuning is both a science and an art. It can be modeled, categorized and automated to an extent; however, there is often room for additional enhancement at the hands of a servo-tuning expert. Some motion controllers have the ability to autonomously assess a system's properties. Ideally, this kind of autotuning tool directly measures and compensates for resonances and nonlinear system behavior and applies optimized servo gains, filters and other loop-shaping procedures. This makes it possible to optimize system tuning with a single mouse click. Even with an autotuning tool, it's still important for a technician to confirm and validate the automatically determined parameters, then make small manual adjustments and optimizations as needed. In any case, an aggressive, stiff tuning scheme is necessary to achieve the optimal combination of speed and precision in cylindrical medical device manufacturing applications.

As with advanced tuning, additional controller features such as enhanced tracking control, position-synchronized output and look-ahead capabilities can further aid in system optimization and effectiveness,

Summary

Optimizing motion systems to transform cylindrical tube stock into life-saving medical devices can be challenging, especially when the process needs to be both fast and precise. The key to success lies in identifying and optimizing machine design elements so the whole is greater than the sum of the parts.

In precision machine design everything matters, and some aspects matter more than others. It's crucial to identify the on- and off-axis error motion sources, particularly those that significantly contribute to dynamic errors, and use clever design techniques to minimize their influence. This involves identifying and understanding error sources; selecting machine components such as bearings, motors collets and more that lessen the contribution of these errors; and applying advanced control techniques to further optimize performance.

Key to achieving both excellent precision and high speed simultaneously are:

- Identifying and mitigating error sources
- Making design decisions that enable high-dynamic performance
- Selecting an optimal workholding mechanism
- Pairing the mechanics with a controller that has performance-optimizing features and technology
- Recognizing that a purpose-engineered motion system will nearly always outperform individual stages and drives that are pieced together as components

By addressing these considerations, manufacturers of cylindrical medical products and devices – whether they are OEM machine builders, system integrators or job shops – can increase production rates while maintaining or even improving part quality and consistency, enabling them to better compete in the market.



About the Author

Brian Fink is Aerotech's product manager for stages, motors, hexapods and other mechanical devices. With 15+ years of experience in precision motion control, he's held roles in research and development, applications engineering, sales and marketing. Fink holds master's degrees in mechanical engineering and business administration from the University of Pittsburgh.