

# ACHIEVING PRECISION & HIGH THROUGHPUT IN LASER PROCESSING

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Laser stent micromachining

Almost everyone familiar with large-scale industrial laser processing has seen high-throughput CNC machines cutting large sheets and tubes of steel or aluminum at impressive speeds. Those involved in laser microprocessing, where part quality depends on micrometers of processing accuracy, wonder whether such feats of machine throughput can be achieved while still producing high-precision parts. The answer is yes—and the question then becomes “how?” This article explores fundamental considerations in machine design and control to maximise throughput in precision laser microprocessing.

## THE ROLE OF ERROR BUDGETS

Part tolerances in manufacturing are generally non-negotiable. These tolerances, required for parts to function properly and safely, dictate the allowable error budget for the manufacturing process. This error budget is “used up” by various error sources: the machine’s design, controller capabilities, and laser-material interactions during processing.

The key to maximising throughput while maintaining high precision is to preserve as much of this error budget as possible for dynamic

tracking errors. Following sound system and structural design principles and selecting a highly capable motion controller—one that makes optimal use of the dynamic tracking error budget—will maximise throughput and strengthen the economic justification for a laser micromachining system.

## STRUCTURAL DESIGN AND STIFFNESS

A manufacturing system’s structural design is fundamental to high-throughput performance. To reject and minimise errors, control systems depend on sensors to observe relative motions between the tool and the part. In most systems, these sensors do not directly observe the tool tip’s motions (i.e., the laser spot); instead, they rely on optical read heads and encoder scales embedded within the motion system mechanics.

To preserve error budget for dynamic tracking, designers must minimise unobservable errors caused by bending or vibration in the machine frame. The key to minimising these errors is maximising structural stiffness. One approach is to minimise the length of the machine’s structural loop—the path through which forces produced by machine

movement transfer to the ground or to opposing structural elements.

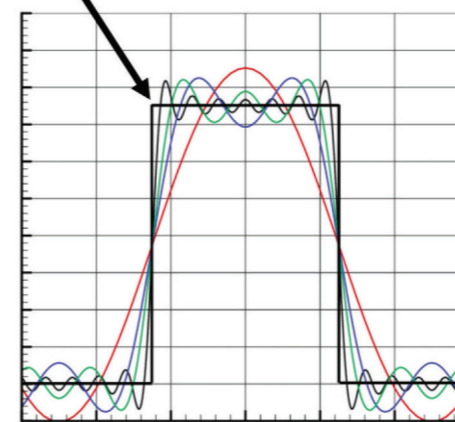
Imagine the machine’s structural elements as thousands of microscopic springs in a serial chain. Adding more springs in series lowers the chain’s stiffness, whereas adding springs in parallel increases stiffness. Designers should shorten the structural “chain” and add redundant structural elements in parallel to support inertial forces. The stiffer the machine, the more energy can be injected into its structure without causing unwanted movement. This allows higher speeds, accelerations, and energy while minimising unobservable processing errors.

## MACHINE DYNAMICS AND MOTION BANDWIDTH

A stiffer motion platform and frame will also exhibit a higher natural frequency. As natural frequency increases, so do controllability and the ability to produce parts faster.

Every motion trajectory—the path needed for a laser spot to manufacture a part—has spectral content across all axes involved. Commands to each axis can be broken down into sine waves of varying frequencies, which together approximate the motion profile.

Desired Profile



$$x(t) = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{\sin(2\pi f(2n-1)t)}{2n-1}$$

Approximate Profiles

- $\sum_{n=1}^1$  1 Frequency
- $\sum_{n=1}^2$  2 Frequencies
- $\sum_{n=1}^3$  3 Frequencies
- $\sum_{n=1}^4$  4 Frequencies

Figure 1: Approximation of a step function using a series summation of sine waves. The more frequencies of sine waves used in the approximation, or bandwidth, the closer the approximation matches the step function.

Figure 1 illustrates this concept using a step function and its approximations with limited sine wave bandwidths. A perfect step requires infinite bandwidth because it contains instantaneous changes and high-frequency content extending to infinity. No real machine can deliver infinite bandwidth, as mechanical stiffness and controller response impose limits. When bandwidth is limited, the step is approximated by a smooth transition.

This principle applies to all motion commands. Discontinuities introduce high-frequency content that exceeds the machine’s capability to respond, leading to dynamic errors and poor part quality. Motion programmers therefore avoid discontinuities and create smooth profiles.

In multidimensional trajectories, such as circular motion, traversal speed directly affects frequency content. Faster speeds require higher frequency sine waves from each axis. To maintain precision at higher speeds, the motion system’s bandwidth—set by structural stiffness and controller dynamics—must encompass these frequencies.

## CONTROL SYSTEMS AND REACTION RATE

Control systems rely on feedback signals, servo loops, and motors to ensure actual motions match

commanded motions. The speed at which the control system can react depends on:

- Trajectory generation rate: How quickly motion profiles are computed.
- Current loop closure rate: The speed at which motor drives can adjust currents.
- Motor peak force: Determines how quickly accelerations can be achieved.

While a capable control system improves reaction rate, the mechanical system’s stiffness also plays a critical role. The combination of the platform’s stiffness and the controller’s bandwidth determines the system’s dynamic capabilities.

## ACCELERATION COMMANDS AND TRACKING ERRORS

The signal of prime importance in motion control is the acceleration command. Acceleration correlates directly with motor current, which produces force. Tracking error arises when parts of the commanded acceleration bandwidth exceed the system’s motion bandwidth.

A car attempting to corner faster than its suspension and engine allow will skid off track; similarly, a laser machine pushed beyond its dynamic limits will produce processing errors. Understanding both the

acceleration command bandwidth and the system’s dynamic bandwidth is crucial for ensuring high-quality production at maximum throughput.

Some advanced motion controllers offer features that automatically consider the system’s bandwidth, self-limiting acceleration commands to prevent excess errors.

## MAXIMISING THROUGHPUT AND MAINTAINING PRECISION

Combining these concepts creates a meaningful message for machine designers.

- The stiffer the machine frame’s structure, the less the process results will be affected by machine bending and vibration, leaving more error budget on the table for dynamic tracking errors.
- The stiffer the motion system’s mechanical design, the higher the motion system’s bandwidth will be.
- The higher the capability of the control products used, the higher the motion system’s bandwidth will be.
- The higher the motion system’s bandwidth, the larger the bandwidth of acceleration commands it can respond to while producing the same level of part errors.
- The higher the bandwidth of allowable acceleration commands without making bad parts, the faster a machine can be commanded to traverse a desired profile during part production.

Thus, machine designers should look at every possible way to maximise machine stiffness and control system bandwidth to maximise process throughput without impacting part quality.

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