



GAC 2.0 ANALOG GALVANOMETER CONTROLLER OPERATOR'S MANUAL

1-1-3290-950-00

REV D

May 15, 2014

Please check with the factory for latest version of this operator's manual

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1.0 Introduction

The GAC 2.0 Analog Galvanometer Controller is a complete solution to the control of galvanometers. Its compact format derived from the latest in surface mount technology allows it to be conveniently located near the motor.

The GAC 2.0 has a Power Connector, Motor Connector, I/O Connector and Galvo Position Connector that the user is required to interface to. The GAC 2.0 is addressed through a USB communications connector.

The purpose of this manual is to familiarize the user with the functionality of the GAC 2.0 driver and Galvanometer (the "System"). This manual also touches on topics such as servo tuning and troubleshooting. When buying a complete line scan engine (scanner, driver, and mirror) the servo should arrive with a factory tune. *Do not attempt to retune the servo unless the tuning instructions in Section 6 and Appendix A are fully understood.*

IMPORTANT: Line Scan Engines (Scanner, Driver, and Mirror) are normally tuned, serialized and warranted as a matched set for optimized performance. Mismatched components negatively affect performance and void the warranty. A Line Scan Engine matched set typically consists of the galvanometer motor, mirror load, and electronic driver. Customer supplied / designed mirrors must be characterized in terms of inertia and resonance and vetted by the factory in order to maintain warranty coverage.

Be sure to follow proper Electrostatic Discharge (ESD) precautions when handling line scan engines to prevent driver board electronic failures.

1.1 ESD Warning

The OEM electronics that the Company manufactures - including galvanometers and servo controllers - are sensitive to electrostatic discharge (ESD). Improper handling could therefore damage these electronics. Lincoln Laser Company has implemented procedures and precautions for handling these devices and we encourage our customers to do the same. Upon receiving your components, you should note that it is packaged in an ESD protected container with the appropriate ESD warning labels. The equipment should remain sealed until the user is located at a proper static control station.

Note: Any equipment returned to the factory must be shipped in anti-static packaging.

A proper static control station should include:

1. A soft grounded conductive tabletop or grounded conductive mat on the tabletop.
2. A grounded wrist strap with the appropriate (1 Meg) series resistor connected to the tabletop mat and ground.
3. An adequate earth ground connection such as a water pipe or AC ground.
4. Conductive bags, trays, totes, racks or other containers used for storage.
5. Properly grounded power tools.
6. Personnel handling ESD items should wear ESD protective garments and ground straps.

2.0 Specifications

Specifications are subject to change.

2.1 Servo Controller

Command Input Characteristics

Analog Input:

Differential Voltage Range	+ / - 5 Volts (Default) +/- 10 Volts with JP9 Shorted
Input Impedance	5 K differential
<i>Command Input</i>	XY2-100 Protocol (Optional)

Power Supply	Voltage ± 15 to ± 24 volts DC
Motor Drive Power	10 Amps Peak
	5 Amps RMS
	Quiescent Current < 200mA
Control I/O Characteristics	USB; A (male) to Mini B (male)
	Cable Not Supplied
Protection	Automatic Shutoffs:
	Over-position
	Over Current
	Over Temperature
Temperature Range	0°C to 50°C Operating
Size W x L x H (Approx. with Mount)	4.1" x 2.5" x 1.5"
Weight	122 grams, 4.3 oz

All systems are shipped pretuned, either to factory specifications or custom tunings requested by the customer.

Factory Tuning Parameters (Random Access Applications)

Power Supply Voltage = ± 24 Vdc, ± 6 Amps

Analog Command Input = ILDA 12/30K 1996 Test Pattern

Speed = 30 Hz (5000 points per second for Light Show Applications)

Size = 100mVP-P (+/- 7.5 degrees optical for Light Shows)

Motor Response = 1 °P-P optical Scan Angle with $\leq 1\%$ Overshoot

Load = 0.6 gm-cm².

2.2 Galvanometer

The GAC 2.0 Servo Controller drives several models of Galvanometers with a broad range of specifications; refer to the documentation included in the shipment for the specifications of your particular Model.

O&M SPECIFICATIONS GALVANOMETER ANALOG CONTROLLER GAC-2.0

REV B 1-2-3290-006-00 NR
SCALE: 1:1 WEIGHT: N/A SHEET 1 OF 1

DATE 12/12/2012
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UNLESS OTHERWISE SPECIFIED:
REMOVE ALL BURRS, BREAK DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONS DECIMALS
ALL EDGES AND CORNERS .015
HOLE LOCATIONS ±.015
DO NOT SCALE DRAWING ROUNDED TO .005
ANGULAR ±1°

CONTROL NAME TAG WITH SERIAL NUMBER

SOFT TUNE NAME TAG SHOWING PAIRED GALVOMETER SERIAL NUMBER (AS REQUIRED)

FACTORY TUNED FOR MODEL S/N XXXXX

LINCOLN LASER
234 EAST MOHAVE STREET
PHOENIX, ARIZONA 85004

GAC-2.0
S/N XXXXX

DIMENSIONS:

- Top View: Overall width 4.13 [105.0], overall height 3.78 [96.0]. Pin headers J1, J2, J3, J4 are spaced 1.38 [35.0] apart. Mounting holes are .12 [3.0] diameter. A control name tag is located at the bottom left.
- Front View: Shows the profile of the unit with a total height of 1.34 [34.0]. The pin header J4 is 2.07 [52.5] from the bottom edge. Mounting holes are .18 [4.5] diameter.
- Side View: Shows the depth of the unit as .12 [3.0]. The pin header J4 is 1.54 [39.0] from the front face. Mounting holes are .12 [3.0] diameter.

Pin Header Labels:

- J1: CUR
- J2: M/F
- J3: GND
- J4: PDBK
- J5: GND

Other Callouts:

- 4X Ø .18 [4.5] THRU (Mounting holes)
- 3X Ø .18 [4.5] THRU (Internal mounting holes)
- .60 [15.2] (Distance between J2 and J3)
- .18 [4.5] (Distance between J3 and J4)
- .12 [3.0] (Hole diameter for J1, J2, J3, J4)
- 2.56 [65.0] (Distance from J1 to J2)
- 1.38 [35.0] (Pitch of pin headers)
- 1.54 [39.0] (Distance from front face to J4)
- 2.07 [52.5] (Distance from bottom edge to J4)
- 3.78 [96.0] (Overall height)
- 4.13 [105.0] (Overall width)

3.0 Connections

3.1 Power Supply

The Power Connector is J1. It is used to supply power to the GAC 2.0. The electronic architecture of the GAC 2.0 requires that a bipolar (\pm DC Voltage) be supplied to it and is connected directly to the output amplifier. The GAC 2.0 has onboard regulators to make all other necessary voltages. A mating connector is typically provided. The mating five-circuit plug is an AMP 6400456-5.

The GAC 2.0 is typically configured to use up to ± 24 VDC supply. For many applications ± 15 VDC is sufficient. For most scanning applications the amplifier draws large current peaks when the motor accelerates then draws very little current at constant position or constant velocity. The current peaks can be as high as ± 8 amps for a few milliseconds, but ± 4 amps for one millisecond are more typical. The required RMS current rarely exceeds 4 amps but the supply(s) must be capable of supplying the peaks. Lincoln Laser recommends using linear supplies rather than switchers. The linear supplies typically have lower noise and are equipped with large output capacitance. *Twisting the Power Supply leads is HIGHLY recommended.*

Switching power supply output architecture varies widely from manufacturer to manufacturer, so instabilities in the GAC 2.0 may be encountered depending on the power supply manufacturer. In general switching power supplies for this application will require a large output capacitance to supply the peak current demand. Use of toroids to smooth output ripple for improved performance is also recommended.

The Lambda DLP180-24-1/E has demonstrated acceptable performance for many applications.

Table 1: Power Connector (J1) Pinout

Pin #	Signal	Description
1	+ V	Positive DC Supply Voltage to the Controller
2	+ V	Positive DC Supply Voltage to the Controller
3	COM	Common
4	-V	Negative DC Supply Voltage to the Controller
5	-V	Negative DC Supply Voltage to the Controller

3.2 I/O Connector

The I/O Connector is J2, used to provide interface with desired Command Signal source. An XY2-100 Protocol option is available. The connector is an AMP 1-640456-0

Table 2: I/O Connector (J2) Pinout

Pin #	Signal	Description
1	COM	Common
2	Fdbk	Analog Position Feedback
3	-EnR	-Enable Request
4	+ Fault	Fault Condition
5	Cmd +	+ Analog Command Input (XY2-100 Data +)
6	Cmd -	- Analog Command Input (XY2-100 Data -)
7	Sc +	XY2-100 Protocol Input (Optional)
8	Sc -	XY2-100 Protocol Input (Optional)
9	Clk +	XY2-100 Protocol Input (Optional)
10	Clk-	XY2-100 Protocol Input (Optional)

3.3 Motor Connector

The Motor Connector is J3, used to interface the motor to the GAC 2.0. The connector is a Molex 39-30-1039.

Table 2: Motor Connector (J3) Pinout

Pin #	Signal	Description
1	SHIELD	Shield Ground
2	COIL +	Positive Motor Current
3	COIL -	Negative Motor Current

3.4 Galvanometer Position

The Galvanometer Position is connected at J4. The connector is AMP 292207-8.

Table 3: Galvanometer Position (J4) Pinout

Pin #	Signal	Description
1	I1	POSITION DETECTOR A
2	I2	POSITION DETECTOR B
3	COM	POSITION DETECTOR COMMON
4	LED	LED CATHODE
5	LED	LED ANODE
6	Shield	SHIELD/CHASSIS GND
7	N/C	
8	N/C	

3.5 Test Points

Test Points are located on the front right edge of the Controller and provide access to monitor the following signals

Table 5: Test Points

Name	Description
CMD	Commanded Position – Post Slew Rate
FDBK	Motor Position Feedback
GND	Common
MTR	Motor Voltage
CUR	Motor Current (Scale 10:1)

3.6 QUICK START INSTRUCTIONS

1. Connect Power to GAC 2.0 Power Connector J1
2. Connect Command Signal to GAC 2.0 I/O Header J2 as necessary per **Table 2 I/O Description**
3. Pull –EnR (Enable Request) “LOW”
4. Connect the galvanometer to the GAC 2.0 at J3 and J4 per Pinout Tables
 - When power is turned on the scanner will begin to respond to the commanded input.
 - When no command input is present, the command is interpreted as zero, so the galvanometer will servo to zero position.
 - The Scanner can only be stopped by turning the power off, or by unplugging the galvanometer.
 - **See Section 7.0 for Troubleshooting Information**

3.7 Communication

Typically a PC will be used to communicate to the GAC 2.0 thru the USB Port (Mini B) using a Hyper Terminal application.

3.7.1 Interfacing to the GAC 2.0 through HyperTerminal

Communications between the GAC 2.0 and a Windows based system can be easily achieved using the Windows supplied HyperTerminal application. Note that sometimes this application is not loaded as part of the “Normal” Windows build process. Refer to the Control Panel “Add/Remove Programs” section if the application is not present.

If HyperTerminal is not installed, an acceptable version can be downloaded at <http://www.chiark.greenend.org.uk/~sgtatham/putty/download.html>

The first screen presented during the Windows HyperTerminal startup process is the “Connect To” screen as shown in Figure 1: HyperTerminal “Connect To” Screen. The only item of interest on this screen is the “Connect using” list box. Select the Serial Communications port number that is connected to the GAC 2.0 from the list. Make sure that no active application such as “HotSync” is using the target port, as it will prevent a successful connection to the GAC 2.0. When done click on the “OK” button.



Figure 1: HyperTerminal "Connect To" Screen

The HyperTerminal application will then display the "Properties" screen as shown in Figure 2: HyperTerminal "Properties" Screen. Every field within this screen is relevant and critical to the successful communications with the GAC 2.0. The "Bits per second" should be set to 115200, the "Data bits" set to 8, the "Parity" set to None, the "Stop bits" set to 1 and finally the "Flow control" set to None. Figure 2: HyperTerminal "Properties" Screen shows the proper settings. Once all settings have been properly set the "OK" button should be pressed.

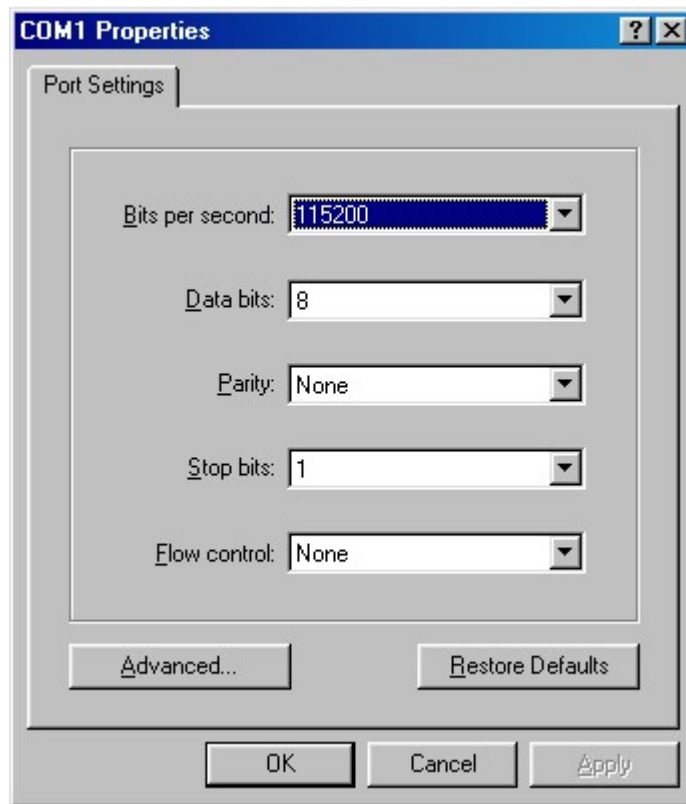


Figure 2: HyperTerminal "Properties" Screen

The HyperTerminal application will then present its "Terminal" page as shown in Figure 3: HyperTerminal "Terminal" Screen. The application will also automatically connect the assigned serial port to the GAC 2.0. At this point communications with the GAC 2.0 should be possible. As a quick test of the communications link a character can be typed at the PC. If the communications link is valid the GAC 2.0 should receive that character and echo it back to the PC. The HyperTerminal application should intercept that character and display it on its Terminal screen.

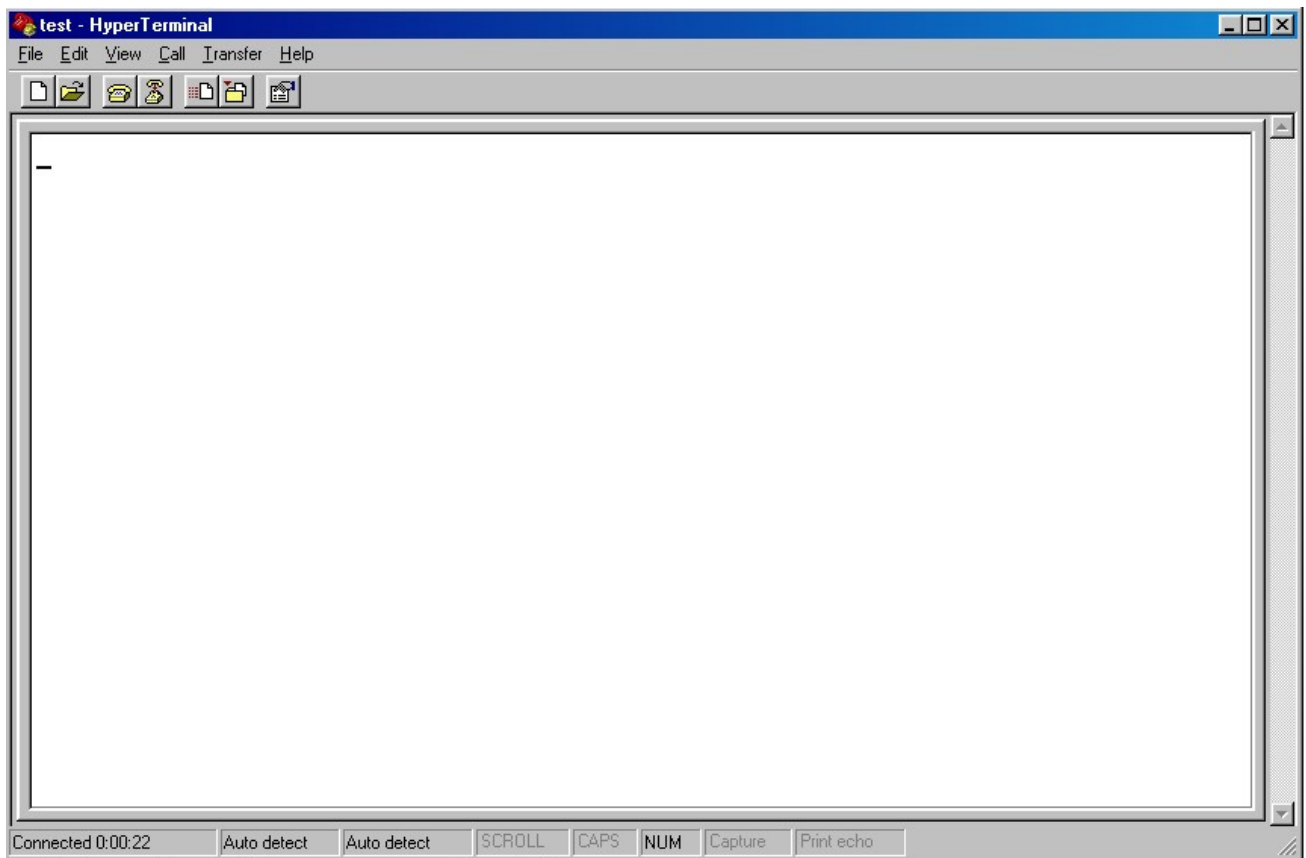


Figure 3: HyperTerminal "Terminal" Screen

If the entered character is not displayed the failure can be explained by several possibilities including; the physical port connected to the PC does not match the port just selected, the port was not properly configured, another application is using the port, the USB cable is defective, the GAC 2.0 is not powered up or functional. See Appendix B for Command Set.

4.0 Protection Circuitry

A Red LED on the GAC 2.0 indicates the Power Amplifier is "Disabled", and/or a Fault condition exists.

4.1 Fault Detection

**Amplifier Over Temperature* - Causes Shutdown when Power Amplifier temperature becomes too high – Automatically Resets when temperature falls to an acceptable level

**Over travel* – Factory set to correspond to maximum travel for the Galvanometer.

**Over Current* – Shutdown occurs when current exceeds 10 Amps and automatically resets when the condition clears

5.0 MOUNTING SCANNERS and CONTROLLERS

Notice: Scanners should be clamped into a rigid mount. Failure to do so can cause an increase in jitter and wobble.

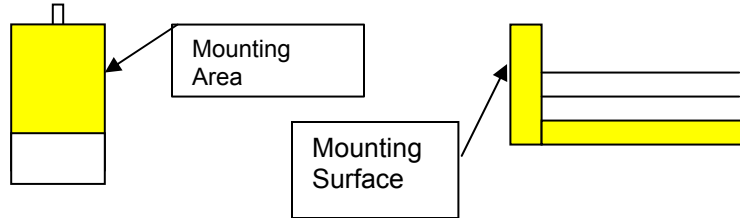


Figure 3. Scanner Mounting Area

Figure 3a: Controller Mounting Area

Temperature management of the system (galvanometers and controller components) can provide a significant reduction of inaccuracies resulting from thermal drift. However, achieving this performance improvement requires careful consideration of the system's thermal environment and proper design of the system's thermal impedance. In applications requiring the highest available accelerations and duty cycles the ability to conduct heat from the system becomes a primary concern. Raster scanning and laser display applications are typically in this category. For these high-power applications, thermal management needs to be given careful consideration early in the system design process. Maximum scan acceleration and efficiency will be primarily a function of the heat sinking provided.

5.1 Temperature Management

NOTE: Thermal Management is critical to proper operation of both the scanner and controller. Analysis should be performed for both, substituting the power amplifier for the scanner coil where appropriate.

Galvanometric scanners and controller components are typically exposed to temperature variations resulting from changes in both the ambient temperature and the power dissipated in the system. Scanner accuracy is adversely affected as the temperature of the position detector and some controller electronic parts change. Although these parts and the position detector have been extensively engineered to minimize their sensitivity to temperature changes, the thermal effects cannot be entirely eliminated. Most low duty cycle or vector applications such as laser marking or rapid prototyping can readily achieve improved performance provided the proper thermal design analysis is performed. While some level of thermal sensitivity reduction can usually be achieved with even a careless implementation of thermal regulation, maximum performance improvement will be realized only with appropriate design analysis.

5.1.1 Thermal Analysis

The first step in the thermal analysis is to determine the minimum and maximum power dissipation in the scanner coil (power amplifier) and the minimum and maximum expected ambient temperatures. Using the maximum coil power dissipation and the maximum ambient temperature, the scanner-to-ambient thermal resistance is designed to provide sufficient heat sinking with the maximum allowable thermal isolation. The thermal time constant of galvanometric scanners and controllers is typically in excess of several minutes and the maximum power dissipation should be calculated as the average dissipation over this time period. The average dissipation, along with knowledge of the expected maximum ambient temperatures can be used to design the optimum scanner-to-ambient thermal resistance

5.2 Heat sinking

5.2.1 The Problems with Heat

The primary concern with high power operation of moving magnet scanners is controlling the motor coil /power amplifier temperature so that destructive failure does not occur. One failure mechanism associated with overheating is a swelling of the stator until interference is created with the rotor. A second potential heat related failure is permanent thermal demagnetization of the rotor. Excessively high temperatures can also result in the permanent failure of the power amplifier and associated components.

There are also less damaging problems associated with scanner / controller heating, such as related gain and offset drift of the position detector and some electronic components. Improper heat sinking can adversely affect dynamic performance and in some cases convection currents created by excessively hot scanners / controllers and mirrors can cause optical path distortions.

5.2.2 Analyzing Heat sinking Requirements

Proper thermal analysis is essential to achieving high reliability and optimal performance in high power applications. An electrical circuit equivalent can model the heat transfer from the scanner / controller, through the heat sink, to the ambient environment. The temperature difference between the motor winding / power amplifier and ambient can be equated to a potential difference, or voltage. The flow of heat is analogous to an electrical current. Thermal impedance is the ratio of temperature drops to power dissipation and is modeled as an electrical resistor. Winding / Power Amplifier temperature rise is dependent on the operating power level and the ability of heat to flow heat away from the winding /amplifier to the motor / controller case, heat sink and the ambient atmosphere. The rate of heat removal depends primarily upon the thermal resistance of the materials involved. The temperature of the winding / amplifier will increase until the rate of heat generated by the power dissipation is equal to the rate of heat flow away from the winding /amplifier. At that point, thermal equilibrium is reached.

$$T_w = P_d (\theta_{wc} + \theta_{cs} + \theta_{sa}) + T_a$$

Where:

T_w = motor winding / amplifier temperature

T_a = ambient temperature

P_d = power dissipation

θ_{wc} = motor / amplifier thermal resistance (to case)

θ_{cs} = interface thermal resistance (case to heat sink)

θ_{sa} = heat sink thermal resistance (heat sink to ambient)

5.2.3 Power Dissipation

Power dissipation is an essential parameter in the determination of winding operating temperature. The power delivered to the scanner can be calculated by multiplying the RMS current and voltage measured using the Test Points. RMS current and voltage measured at the power supply is used to calculate power dissipation by the power amplifier.

5.2.4 Thermal Runaway

The decrease in torque constant and increase in winding resistance as scanner temperature rises can work together to create a thermal runaway effect. Both the torque constant and resistance changes will increase power dissipation. This will, in turn, further increase the temperature of the scanner. If the scanner does not have sufficient heat sinking, it is possible that this cycle will not reach equilibrium at a temperature below the maximum specified winding temperature. It is especially important during the evaluation phase to carefully monitor the power dissipation and scanner case temperature to assure steady state conditions are achieved at an acceptable winding temperature.

5.2.5 Scanner Mounting

In high power applications the scanner should be mounted by the motor case in a manner that assures good thermal conductivity. Supplemental heat sinking can also be provided but its effectiveness is usually small compared to the heat sinking provided by the scanner mount. A typical mount will utilize an aluminum bracket designed to clamp around the scanner body. In order to maximize heat flow from the motor case to the heat sink, the surface area of the interface should be made as large as possible. The unclamped clearance between the mounting bracket and the scanner should be limited to 0.003" in order to prevent excessive air gaps or line-contact interfaces. Excessively rough surface finishes can also degrade heat flow and therefore should be kept to 64 micro inches or better. Thermal compound should be used between the scanner and heat sink, as well as in any additional interfaces between the scanner mount and the Environmental ambient. Thermal compound has an impedance approximately 20 times lower than that of air and will significantly reduce the effects of minor air gaps present even in well designed mounts.

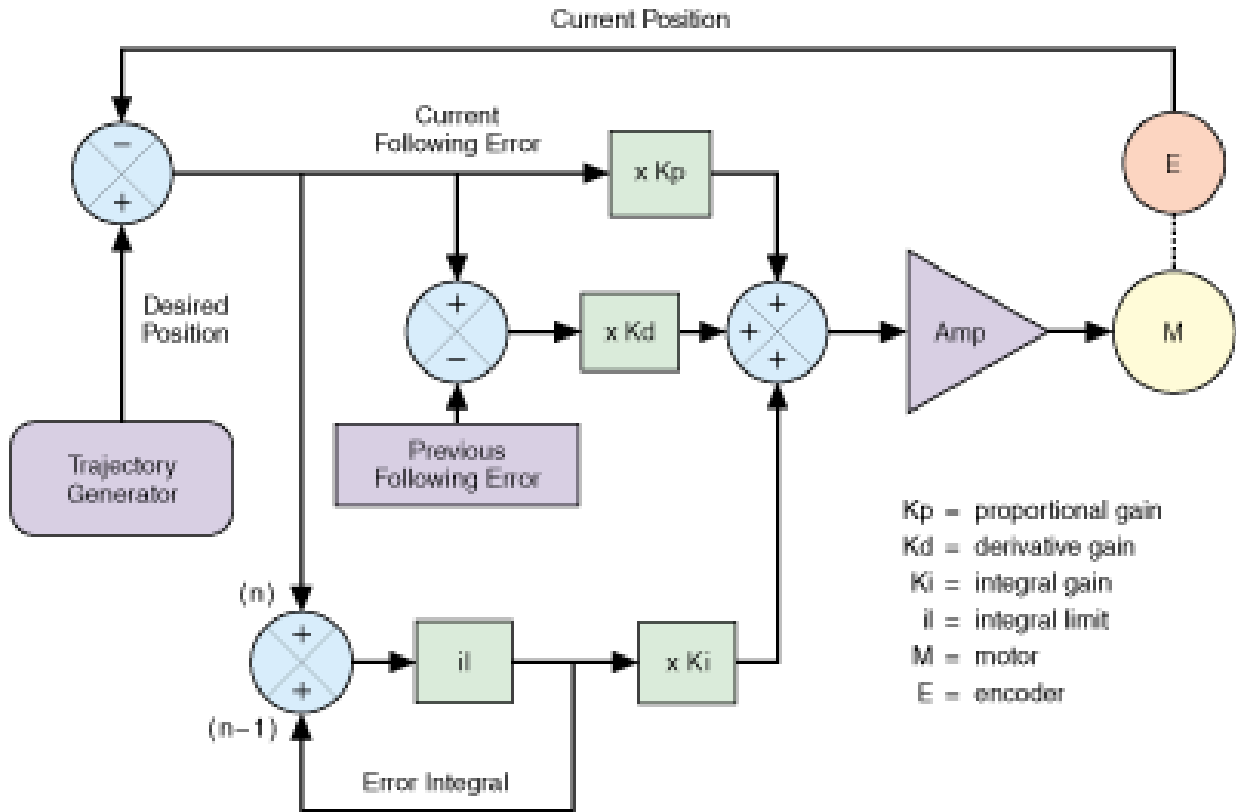
5.2.6 Servo Controller Mounting

The servo controller should be mounted to as large a surface area as possible (capable of dissipating at least 70 Watts), as near the scanner as possible. Use of a thermal compound between the controller and the heat sink is highly recommended. As with the scanner, air gaps and rough surfaces should be minimized.

6.0 Servo Tuning Principles

For more aggressive scanning applications, the servo tuning plays a greater role in determining the speed and accuracy of a system. Servo tuning requires the user to be familiar with equipment such as the oscilloscope and function generator. If not familiar with this equipment, you should contact your sales representative to order a factory custom tuning.

Servo tuning sets the K_p , K_i and K_d of the PID algorithm, also called the *PID filter*. A feedback controller is designed to generate an output that causes corrective effort to be applied to a process so as to drive a measurable process variable towards a desired value known as the setpoint. Shown is a typical feedback control loop with blocks representing the dynamic elements of the system and arrows representing the flow of information, generally in the form of electrical signals. Virtually all feedback controllers determine their output by observing the error between the setpoint and the actual process variable measurement.



Conceptually, that's all there is to a PID controller. The tricky part is "tuning" it; i.e., setting the P, I, and D tuning constants so that the weighted sum of the proportional, integral, and derivative (damping) terms produces a controller output that steadily drives the process variable in the direction required to eliminate the error. The GAC 2.0 provides 2 damping terms. One is the traditional derivative term, which tends to be quite noisy. The second is a synthesized velocity damping term that is preferable to derivative damping.

How to best tune a PID controller depends upon how the process responds to the controller's corrective efforts. Consider a sluggish process that tends to respond slowly. If an error is introduced abruptly (as when the setpoint is changed), the controller's initial reaction will be determined primarily by the derivative term in equation (1).

$$CO = P \cdot e(t) + I \cdot \int_0^t e(\tau) d\tau + D \cdot \left(\frac{d}{dt} e(t) \right)$$

Equation (1)

This will cause the controller to initiate a burst of corrective efforts the instant the error changes from zero. The proportional term will then come in to play to keep the controller's output going until the error is eliminated.

After a while, the integral term will also begin to contribute to the controller's output as the error accumulates over time. In fact, the integral term will eventually come to dominate the output signal, since the error decreases so slowly in a sluggish process. Even after the error has been eliminated, the controller will continue to generate an output based on the history of errors that have been accumulating in the controller's integrator. The process variable may then overshoot the setpoint, causing an error in the opposite direction.

If the integral tuning constant is not too large, this subsequent error will be smaller than the original, and the integral term will begin to diminish as negative errors are added to the history of positive ones. This whole operation may then repeat several times until both the error and the accumulated error are eliminated. Meanwhile, the damping term will continue to add its share to the controller output based on the derivative of the oscillating error signal. The proportional term too will come and go as the error waxes and wanes.

Now suppose the process responds quickly to the controller's efforts. The integral term in equation (1) will not play as dominant a role in the controller's output since the errors will be so short lived. On the other hand, the damping term will tend to be larger since the error will change rapidly.

Always start the tuning process using the default values supplied with the controller. These values are usually very conservative, favoring safe, oscillation-free operation for a tighter, more responsive system that minimizes following error. To achieve the best dynamic performance possible, the system must be tuned for the specific application. Load, acceleration, scanner orientation and performance requirements all affect how the servo loop should be tuned for best results.

As a rule of thumb for tuning systems:

- *Always start tuning with proportional gain K_p to get adequate response speed*
- *Next, increase the value for K_v to decrease the overshoot and stabilize the system*
- *Finally, increase the value for K_i to eliminate steady-state error*
- *To avoid stability problems, never use K_p and K_i without K_v*

Servo tuning is usually performed to achieve better motion performance (such as reducing the following error statically and/or dynamically) or because the system is malfunctioning (oscillating and /or shutting off due to excessive following error).

Acceleration plays a significant role in the magnitudes of the following error and the overshoot, especially at start and stop. Asking the controller to change the velocity instantaneously amounts to an infinite acceleration, which, since it is physically impossible, causes large following errors, and overshoot. Use the smallest acceleration (K_i) the application can tolerate to reduce overshoot and make tuning the PID filter easier.

6.1 Servo Tuning Setup

Position the Visible Wavelength Laser to reflect from the mirror to the Optical Scale in order to monitor the scan line while tuning, *Do Not* exceed the scanner's maximum rated angle. Verify presence of the feedback signal by observing deflection at the Test Point

6.1.1 Equipment

The following equipment is required to properly tune the GAC 2.0

- PC to adjust tuning parameters
- Power Supply (see "Specifications")
- Oscilloscope (analog or digital, 2-channel minimum)
- Signal Generator
- Optical Scale
- Visible Wavelength Laser
- Scanner Mount

6.1.2 Do's and Don'ts

1. Do not attempt tuning without monitoring the position signal on an oscilloscope
2. Do not allow the input command signal to produce a greater deflection than the maximum recommended by the scanner's datasheet.
3. Do not allow the scanner to operate in an unstable manner. If the scanner loses control, turn the power off immediately to avoid damage
4. Do not allow the scanner to be driven into the stops. If this occurs, turn the power off immediately to avoid damage.

Do have patience. Tuning can require a great deal of practice!!

6.2 Tuning Procedures

Each System is shipped pre-tuned, either to the factory standard tuning or the custom tuning requested by the customer. Only technical personnel familiar with servo controllers and galvanometer operation should perform tuning operations. Under normal conditions, if 'fine tuning' of the galvanometer response is desired, adjustment of the parameters listed in Table 1 should provide satisfactory results.

If adjustment of "Factory Set" parameters is desired, contact Lincoln Laser for detailed instructions before proceeding. A complete list of parameters is contained in Appendix B.

Prior to commencing any tuning we recommend recording the stored parameter values be made for future reference. This record can be obtained by typing "d", then press the "Enter" key, the current value of the tuning parameters will then appear in the Hyperterminal screen and may then be printed.

The current value of any given parameter can be obtained at any time by simply typing the appropriate Control Screen Symbol and pressing "Enter". For example to query the current value of the Proportional Gain:

1. Type A
2. Press "Enter"

The value returned is the current value of Proportional Gain.

For the Motor Position (H) and Motor Current (I) parameters the returned value will correspond from left to right to those listed in Appendix B from top to bottom. The first four values are the set points; the fifth value is the current measured value of the parameter.

For Temperature Fault (L) the first value is the set point, the second value is the current temperature.

Should a Fault condition occur, indicated by the Red LED the Fault mode can be determined as follows:

1. Type L
2. Press "Enter"
3. The returned number will correspond to a Fault Mode as shown in Appendix B, under the L command

To alter a tuning parameter proceed as follows:

1. Type the letter for the desired parameter to be altered (See Table 1 for a list of the common Tuning Parameters and their Control Screen Symbols).
2. Enter the desired value (typically 0 to 255)
3. Press "Enter".

Control Screen Symbol	Gain Factor	Description
A	K_p	Proportional Gain
B	K_i	Integral Gain – Improves long term accuracy
C	K_d	Derivative Gain – Traditional derivative (Low Frequency Damping) term , tends to be quite noisy
D	K_v	Velocity Gain – synthesized velocity damping (High Frequency Damping) term, preferable to derivative damping
N	Notch Filter	Filter for reducing mirror assembly resonant frequencies. N0 corresponds to highest frequency ≈ 7 kHz, N255 corresponds to ≈ 1.4 kHz
U	Slew Rate	Command Slew Rate Limit – should be used only by experienced technicians as an improper setting will cause the galvanometer to become unstable.
d	Data	Retrieves stored tuning parameters

6.2.1 Stabilizing Axis Oscillation

If an axis oscillates, this indicates that the gain K_p may be too large. Leave K_v alone, reduce the proportional/ integral gain factors K_p and K_i by 50% and reduce K_d to near zero. If the oscillation does not stop, reduce K_p and K_i again, reduce K_d to zero, and increase K_v 10 %.

When the axis *stops* oscillating, the system response is probably very soft. The following error may be quite large during motion and non-zero at stop. You should continue tuning the PID with the steps described in the next paragraph.

6.2.2 Improving Stable Performance

If the system is stable and you want to improve the performance, start with the current parameters. The goal is to reduce the following error during motion and to eliminate it at stop. Depending on the performance starting point and the desired outcome, here are some guidelines for further tuning.

6.2.2.1 Following Error Too Large

This is a case of a soft loop. It is especially common if you just performed the steps described under axis oscillations. The proportional gain K_p is probably too low and K_i and K_d are near zero. Start by increasing K_p by 10% to 20%. Continue this operation while monitoring the following error until it starts to exhibit excessive ringing characteristics (more than 3 cycles after stop). To reduce the ringing, add some damping by increasing the K_v parameter.

Start with a K_d at near zero, increase by 1 while monitoring the following error. As K_d is increased, the overshoot and the ringing will decrease.

NOTE

Remember that if the acceleration is set too high, the overshoot cannot be completely eliminated with K_v , K_d . If K_d , K_v are further increased, at some point the oscillation will reappear, usually at a higher frequency. Avoid this by keeping K_d low and K_v at a high value, but not so high as to reintroduce oscillations.

Next, add more gain. Increase the K_p value by 10% at a time until signs of excessive ringing appear again. Alternately increase K_v and K_p until K_v cannot eliminate the overshoot and ringing at stop. This indicates K_p is larger than its optimal value and should be reduced. Ultimately, optimal values for K_p and K_v depend on the stiffness of the loop and how much ringing the application can tolerate.

6.2.2.2 Errors After Stop

If you are satisfied with the dynamic response of the PID loop but the motion device does not always stop accurately, modify the integral gain factor K_i . As described before, this term of the PID reduces the following and steady state error to near zero. Unfortunately, it can also contribute to oscillation and overshoot. Always change this parameter carefully and in conjunction with K_v .

Start, if possible with a value for K_i that is at least one order of magnitude smaller than K_p . Increase its value 10% at time and monitor the overshoot and the final position at stop.

If intolerable overshoot develops, increase the K_v factor. Continue alternately increasing K_i and K_v until an acceptable loop response is obtained. If oscillation develops, immediately reduce the K_i . Remember that any finite value for K_i will eventually reduce the error at stop. It is simply a matter of how much time is acceptable for the application. In most cases it is preferable to wait a few extra milliseconds to stop in position rather than have overshoot or run the risk of oscillations.

6.2.2.3 Following Error During Motion

This is caused by a K_i value that is too low. Follow the steps in the previous paragraph, keeping in mind that it is desirable to increase the integral gain factor as little as possible.

Points to Remember

- *Use the lowest acceleration the application can tolerate. Smaller acceleration generates less overshoot.*
- *Use the default values provided with the system for all standard motion devices as a starting point.*

Use the minimum value for K_i that gives acceptable performance. The integral gain factor can result in overshoot and oscillations.

6.2.3 Notch Filter (N)

In applications requiring high gains for tuning, the load's resonant frequency may become excited and must be "Notched" out

Improper adjustment of the Notch Filter can cause mirror breakage and potentially damage the galvanometer.

Physical properties such as mounting, material and geometry will determine the natural resonant frequency of the mirror / load. When the servo controller excites the resonant frequency it may become audible and /or observed as a component in the position signal at TP2 and must be removed. In extreme situations the scanner may oscillate out of control due to excitation of the resonant frequency.

While the Notch Filter is used to remove a narrow band of frequencies corresponding to the resonant frequency of the mirror / load, its use may degrade scanner performance in very demanding applications. The frequency to be "Notched" out can be varied in the same fashion as the other tuning parameters.

With the scanner commanded to the 0V position, adjust the Notch Filter to 0 (this corresponds to the highest frequency, therefore should be least disruptive) then adjust as necessary to eliminate the frequency. *No amount of electronic adjustment can completely compensate for a poorly designed mirror*

7.0 Troubleshooting (Most Common Causes of Malfunction)

Tuning should only be performed by the factory or technical personnel familiar with tuning and operation of galvanometers / servo controllers.

The Red LED on the GAC 2.0 indicates the Power Amplifier is “Disabled”, and may be due to a Fault condition.

Before going further, check the following:

- a. Check the power supply connections, verify proper voltage and sufficient current ratings
- b. Check to make sure the connections between the scanner, driver and PC are properly seated.

1. On power up, scanner rotor pins to one side with no Command signal.

Warning: Turn the power supply off immediately. Failure to do so may result in the scanner overheating.

- a. The scanner may rest against a stop on one side when the Amplifier is disabled. The mirror shaft should easily rotate side to side by hand.
- b. Could be an indication of an un-tuned servo.
- c. When accompanied by excessive heating of the motor and controller, leave power supply off and contact customer service.
- d. Verify that the position circuitry is functioning properly. To do so, disable the Motor by unplugging J3 then rotate the mirror shaft by hand and then observe the position signal on an oscilloscope by monitoring FDBK Test Point. Rotating the mirror shaft should cause the position voltage to fluctuate between $+/- 5\text{ V}$

2. On power up, the scanner does not “torque up” hard to the center position, with a 0V Command signal

- a. Check for blown fuse on the Galvanometer. The motor fuse is measured on the motor connector P1, Pin 8 to Pin 9, normal reading would be $\sim 1.5\text{ ohm}$
- b. Could be an indication of an un-tuned servo.

3. Scanner oscillates when powered up.

Warning: Do not operate the scanner and driver without the load that it was tuned to. Changing the load inertia will most likely change the tuning performance and can cause oscillation or instability. Prolonged operation in this condition can cause severe damage to the controller / galvanometer.

- a. Check to be sure that the load is securely fastened to the shaft.
- b. Check to see if the notch filter setting is correct. Try adjusting the notch filter slightly in each direction to see if the oscillation disappears. (See section 6.2.3 on Notch Filters).
- c. Verify that the position circuitry is functioning properly. To do so, disable the Motor by unplugging J3 then rotate the mirror shaft by hand and then observe the position signal on an oscilloscope by monitoring FDBK Test Point. Rotating the mirror shaft should cause the position voltage to fluctuate between $+/- 5\text{ V}$
- d. Could be an indication of an un-tuned servo.

4. Scanner becomes unstable when powered up.

Warning: Do not operate the scanner and driver without the load that it was tuned to.

- a. Check to be sure that the load is securely fastened to the scanner rotor.
- b. Be sure the power supply current ratings are enough to supply the scanner and driver
(See Section 2.0 for power supply requirements)
- c. Could be an indication of an un-tuned servo.

5. Scanner becomes unstable when commanded to perform larger steps or does not follow the command input adequately.

Warning: Do not operate the scanner and driver without the load that it was tuned to.

Tuning plays a critical role in determining scanner performance, Line scan engines tuned for vector and small-step applications may require a structured command (acceleration limited) to maintain stability over large steps.

- a. Be sure the power supply current ratings are enough to supply the scanner and driver.
- b. The servo is improperly tuned for the large step. Some applications require custom tuning. Tuning should be performed by the factory or by a technical person familiar with the tuning of galvanometers / servo controllers. (See Section 6.0 and Appendix A for a discussion on tuning).

6. Scanner and/or driver become hot when operating.

- a. Make sure scanner rotor is not pinned against the stop. If so, see 1d above.
- b. For high RMS power applications, review the mounting and heat sinking requirements discussed in Section 5.0.
- c. Verify that the position circuitry is functioning properly. To do so, disable the Motor by unplugging J3 then rotate the mirror shaft by hand and then observe the position signal on an oscilloscope by monitoring FDBK Test Point. Rotating the mirror shaft should cause the position voltage to fluctuate between + / - 5 V

7. Scanner is not responding to instructions from PC.

- a. Ensure HyperLink properly established.
- b. Check to make sure the connections between the scanner, driver and PC are properly seated.

Appendix A

Control Theory Terminology

Common motion systems use three types of control methods. They are *position control*, *velocity control* and *torque control*.

Position control: moves the load from one known fixed position to another known fixed position. Feedback, or closed-loop positioning, is important for precise positioning.

Velocity control: moves the load continuously for a certain time interval or moves the load from one place to another at a prescribed velocity. A system can use both encoder and/or tachometer feedback to regulate velocity.

Torque control: measures the current applied to a motor with a known torque coefficient in order to develop a known constant torque.

Following Error: instantaneous difference between actual position as reported by the position feedback device and the ideal position, as commanded by the controller.

Settling Time: amount of time elapsed between when a stage first reaches a commanded position and when it maintains the commanded position to within an acceptable pre-defined error value (Figure 1).

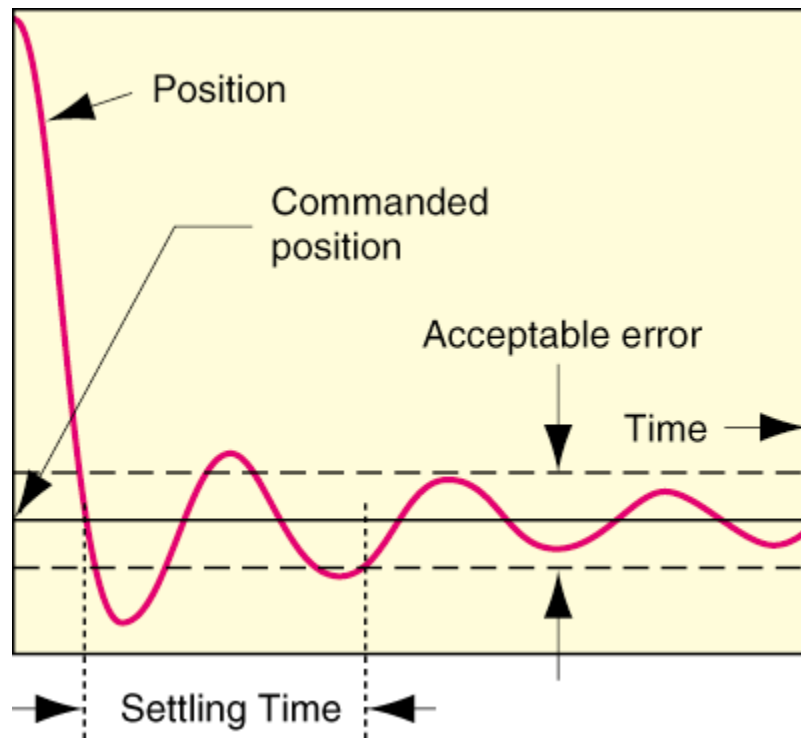


Figure 1: How settling time is defined.

Overshoot: The amount of over-correction in an under-damped control system (Figure 2).

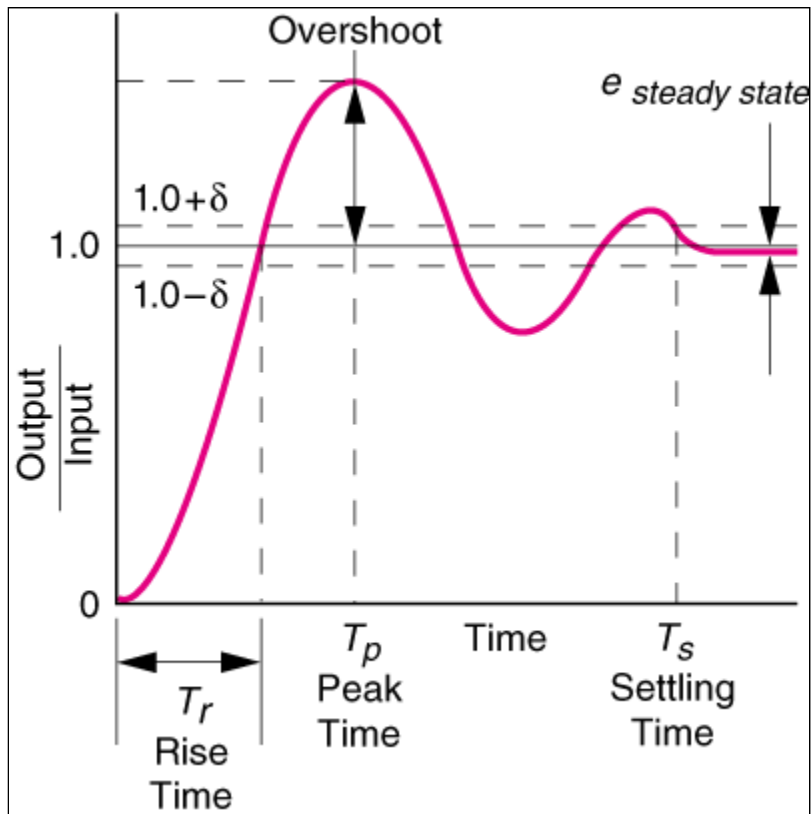


Figure 2: Response for a system using only proportional control leads to overshoot and non-zero steady-state errors.

Steady-State Error: The difference between actual and commanded position after the controller has finished applying corrections (Figure 2).

Vibration: When the operating speed approaches a natural frequency of the mechanical system, structural vibrations, or ringing, can be induced. Ringing can also occur in a system following a sudden change in velocity or position. This oscillation will lessen the effective torque and may result in loss of synchronization between the motor and controller.

Settling times and vibrations can best be dealt with by damping motor oscillations through mechanical design and use of the Notch Filter. Some additional methods that can change resonance vibration frequencies are:

- Half stepping or micro stepping the motor
- Changing the system inertia
- Accelerating through the resonant frequency ranges.

Velocity Profiles: In order to achieve smooth high-speed motion without over-taxing the motor, the controller must direct the motor driver to change velocity judiciously to achieve optimum results. This is accomplished using shaped velocity profiles to limit the accelerations and decelerations required.

Trapezoidal Profile: The trapezoidal profile changes velocity in a linear fashion until the target velocity is reached. When decelerating, the velocity again changes in a linear manner until it reaches zero velocity. Graphing velocity versus time results in a trapezoidal plot (Figure 3). Advanced controllers allow user modification of the acceleration/deceleration with more advanced controllers allowing individual settings for acceleration and deceleration.

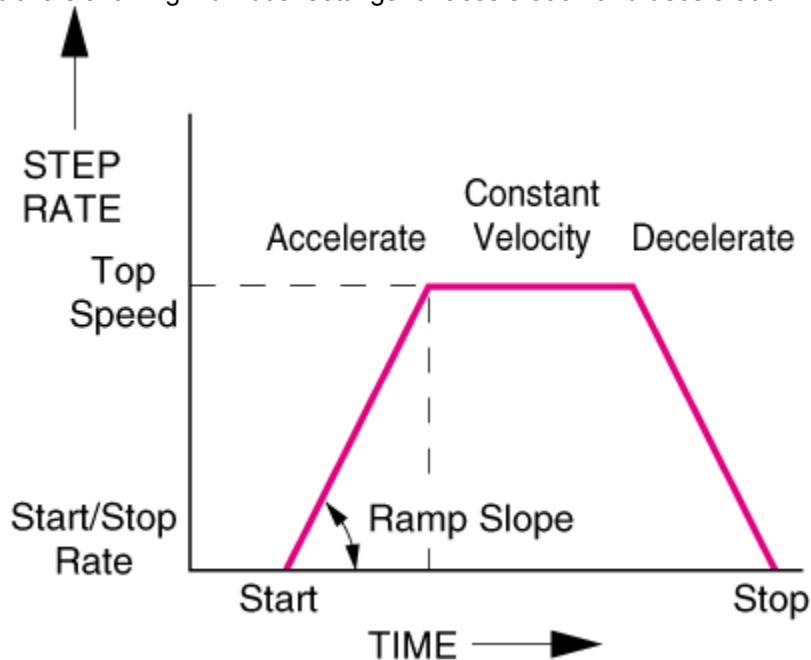


Figure 3: Trapezoidal motion profiles are required to obtain higher speeds without skipping steps or stalling.

S Curve Profile: A trapezoidal velocity profile is adequate for most applications. Its only disadvantage is that it may cause some system disturbances at the “corners” that translate in small vibrations, which extend the settling time. For demanding applications sensitive to this phenomenon, the velocity profile can be modified to have an S shape during the acceleration and deceleration periods. This minimizes the vibrations caused in a mechanical system by a moving mass.

Control Loops

Open Loop Control

Open loop refers to a control technique which does not measure and act upon the output of the system. Most piezoelectric systems and inexpensive micrometer-replacement actuators are open-loop devices. Open-loop positioners are useful when remote control is desired for improved accessibility or to avoid disturbing critical components by touching them.

Stepper and ministepper motors are also often used open loop. The count of pulses is a good indicator of position, but can be unpredictable unless loads, accelerations and velocities are well known. Skipped or extra steps are frequent problems if the system is not properly designed. Open loop motion control has become very popular. Advances in ministepping technology and incorporation of viscous motor-damping mechanisms have greatly improved the positioning dependability and reduced vibration levels of today’s highest quality stepper devices.

Open loop is by no means a synonym for crude. Even inexpensive open loop devices can achieve very fine incremental motions. Nanometer-scale incremental motions are achievable by open loop piezo- and electrostrictive-type devices.

Open-loop systems infer the approximate position of a motion device without using an encoder. In the case of a piezo device, the applied voltage is an indicator of position. However, the relationship is imprecise due to hysteresis and non-linearities inherent in commonplace piezo

materials. More recently developed electrostrictive materials operate in a similar manner with greatly reduced hysteresis.

Closed-Loop Control

Closed-loop refers to a control technique which measures the output of the system compared to the desired input and takes corrective action to achieve the desired result. Electronic feedback mechanisms in closed-loop systems enhance the ability to correctly place and move loads.

Closed-Loop Control Techniques

Depending upon how the feedback signals are processed by the controller, different levels of performance can be achieved. The simplest type of feedback is called proportional control. Other types are called derivative and integral control. Combining all three techniques into what's called PID control provides the best results.

Proportional Control

A control technique that multiplies the error signal (the difference between actual and desired position) by a user-specified gain factor K_p and uses it as a corrective signal to the motion system. The effective result is to exaggerate the error and react immediately to correct it. Changes in position generally occur during commanded acceleration, deceleration, and in moves where velocity changes occur in the system dynamics during motion. As K_p is increased the error is more quickly corrected. However, if K_p becomes too large, the mechanical system will begin to overshoot, and at some point, it may begin to oscillate, becoming unstable if it has insufficient damping.

K_p cannot completely eliminate errors since as the following error, e , approaches zero, the proportional correction element, $K_p e$, disappears. This results in some amount of steady-state error.

Integral Control

A control technique, which accumulates the error signal over time, multiplies the sum by a user specified gain factor K_i and uses the result as a corrective signal to the motion system. Since this technique also acts upon past errors, the correction factor does not go to zero as the following error, e , approaches zero allowing steady-state errors to be eliminated.

The integral gain has an important negative side effect. It is a destabilizing factor for the stability of the control loop. Large values or used without proper damping could cause severe system oscillations.

Derivative Control

A control technique which multiplies the rate of change of the following error signal by a user specified gain K_d and uses the result as a corrective signal to the motion system. Since this type of control acts to stabilize the transient response of a system, it may be thought of as electronic damping.

Increasing the value of K_d , increases the stability of the system. The steady-state error, however, is unaffected since the derivative of the steady-state error is zero.

PID Control

A proportional-integral-derivative or "PID" controller looks at the current value of the error, the integral of the error over a recent time interval, and the current derivative of the error signal to determine not only how much of a correction to apply, but for how long. Those three quantities are each multiplied by a tuning constant and added together to produce the current controller output $CO(t)$ thusly:

$$CO = P \cdot e(t) + I \cdot \int_0^t e(\tau) d\tau + D \cdot \left(\frac{d}{dt} e(t) \right)$$

Equation 1

In equation (1), P is the proportional tuning constant, I is the integral tuning constant, D is the derivative tuning constant, and $e(t)$ is the error between the setpoint $SP(t)$ and the process variable $PV(t)$ at time t .

$$e(t) = SP(t) - PV(t)$$

Equation 2

If the current error is large, has been sustained for some time, or is changing rapidly, the controller will attempt to make a large correction by generating a large output. Conversely, if the process variable has matched the setpoint for some time, the controller will leave well enough alone.

For motion systems, the PID loop has become a very popular control algorithm (Figure 4). The feedback elements are interactive and knowing how they interact is essential for tuning a motion system. Optimum system performance requires that the coefficients, K_p , K_i , and K_d , be tuned for a given combination of motion mechanics and payload inertias.

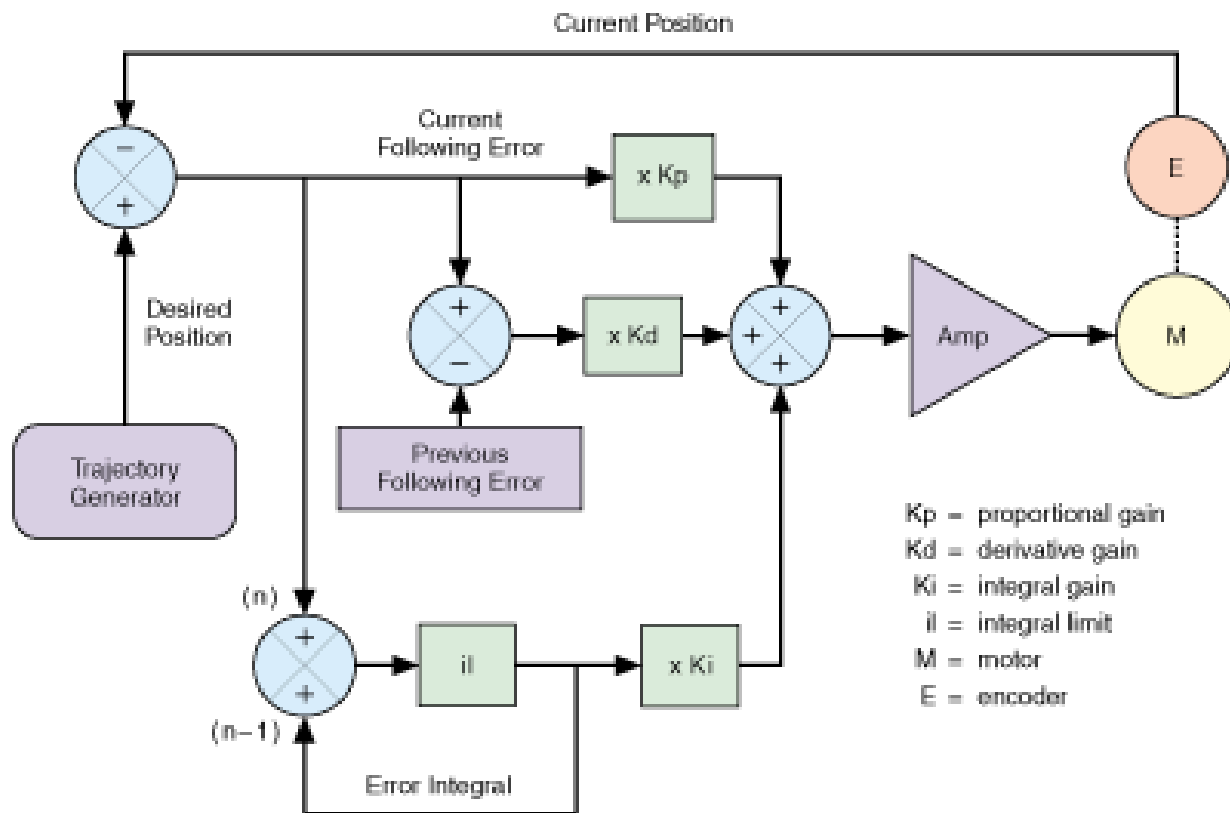


Figure 4: PID control implemented using position feedback.

Positioning Trajectory Options

Motion Without Interpolation

There are three types of non-interpolated motion: single-axis, simultaneous, and synchronized motion. Simultaneous and synchronized motions are both multi-axis (Figure 5). The difference between them is that simultaneous motion is unsynchronized (Figure 6).

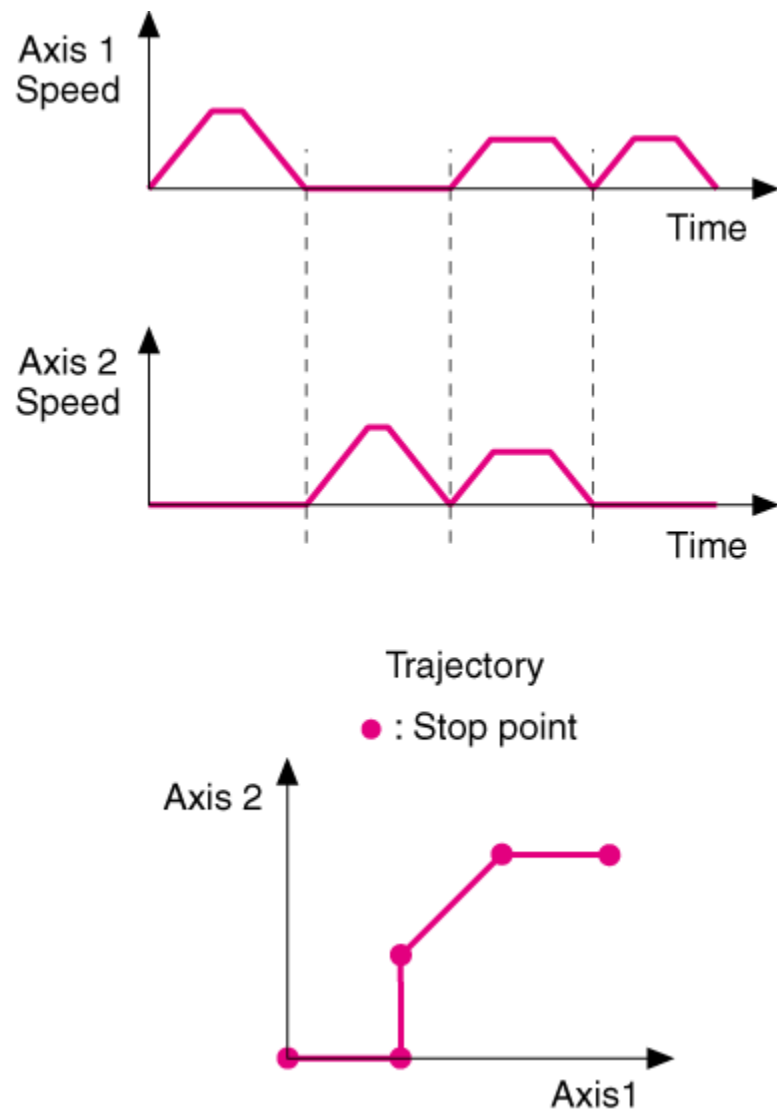
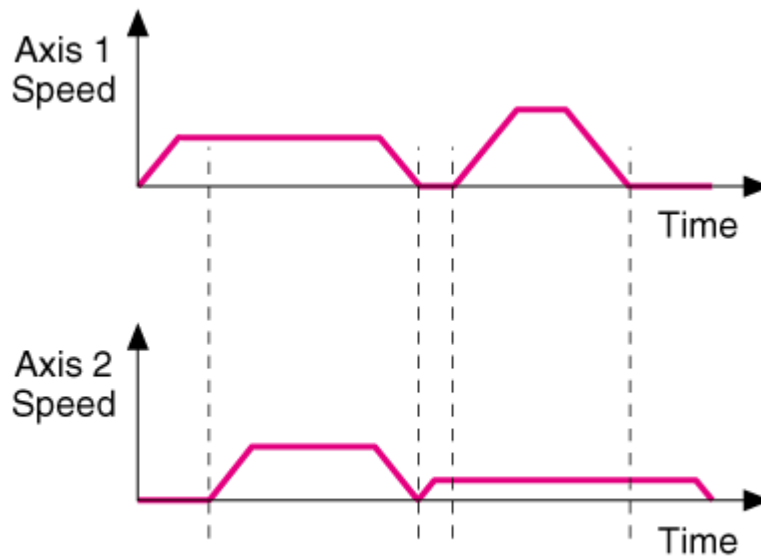


Figure 5: With synchronized motion, multiple axes may or may not move together.



Trajectory

- : Stop or start point (*axis 1*)
- △ : Stop or start point (*axis 2*)

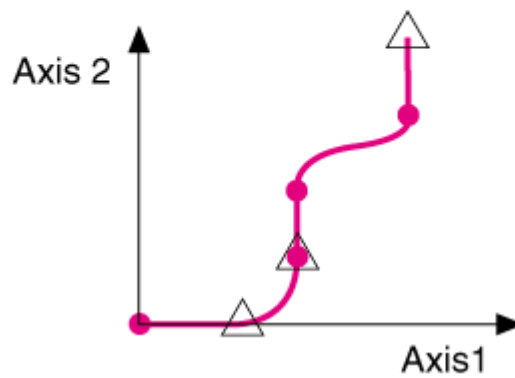


Figure 6: With non-interpolated motion several axes can move simultaneously, but are not coordinated.

Motion with Interpolation

When the controlled load must follow a particular path to get from its starting point to its stopping point, the coordination of axis movements is said to be interpolated. There are two types of interpolation, linear and circular.

Linear Interpolation

Linear interpolation is required for multi-axis motion from one point to another in a straight line. The controller determines the speeds on each axis so that the movements are coordinated. True linear interpolation requires the ability to modify acceleration. Some controllers approximate linear interpolation using pre-calculated acceleration profiles (Figure 7).

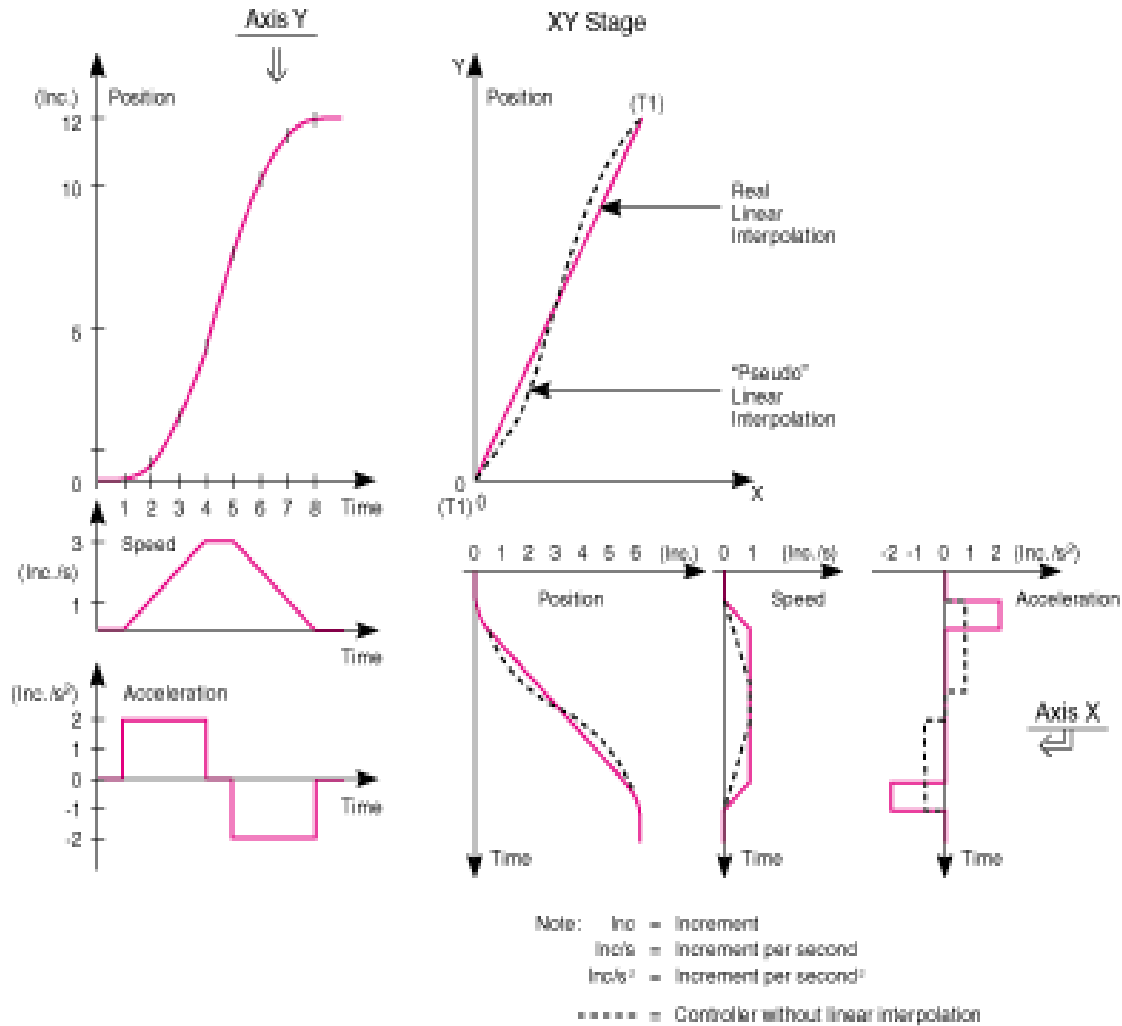


Figure 7: "Pseudo" linear interpolation is obtained with controllers using precalculated acceleration ramps.

Circular Interpolation

Circular interpolation is the ability to move the payload around a circular trajectory. It requires the controller to modify acceleration on the fly (Figures 8 & 9).

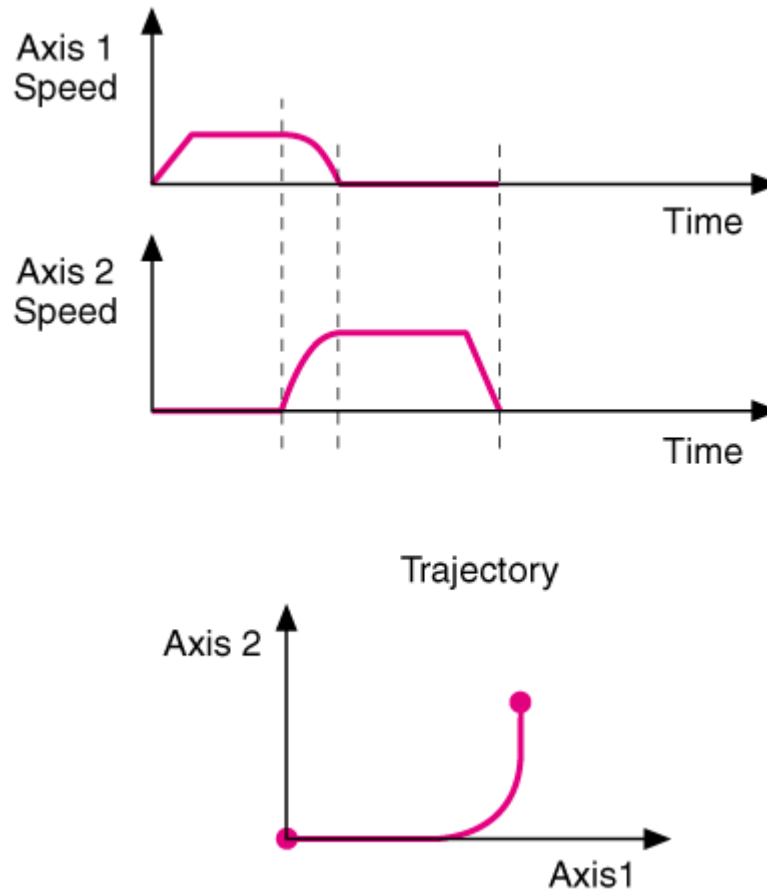


Figure 8: Simple circular interpolation.

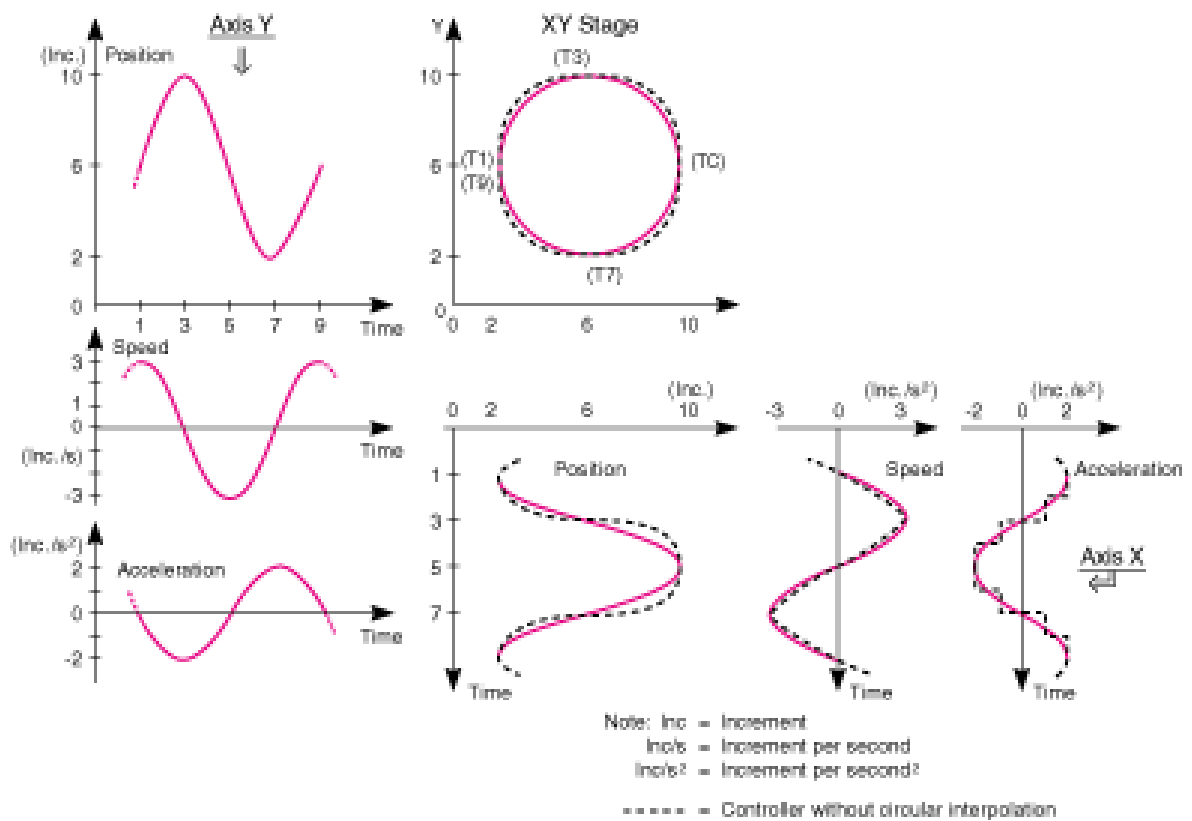


Figure 9: To be able to control stages in “real” circular interpolation, a controller must be able to modify the acceleration on the fly.

Contouring

With contouring, the controller changes the speeds on the different axes so that the trajectories pass smoothly through a set of predefined points. The speed is defined along the trajectory and can be constant, except during starting and stopping (Figure 10).

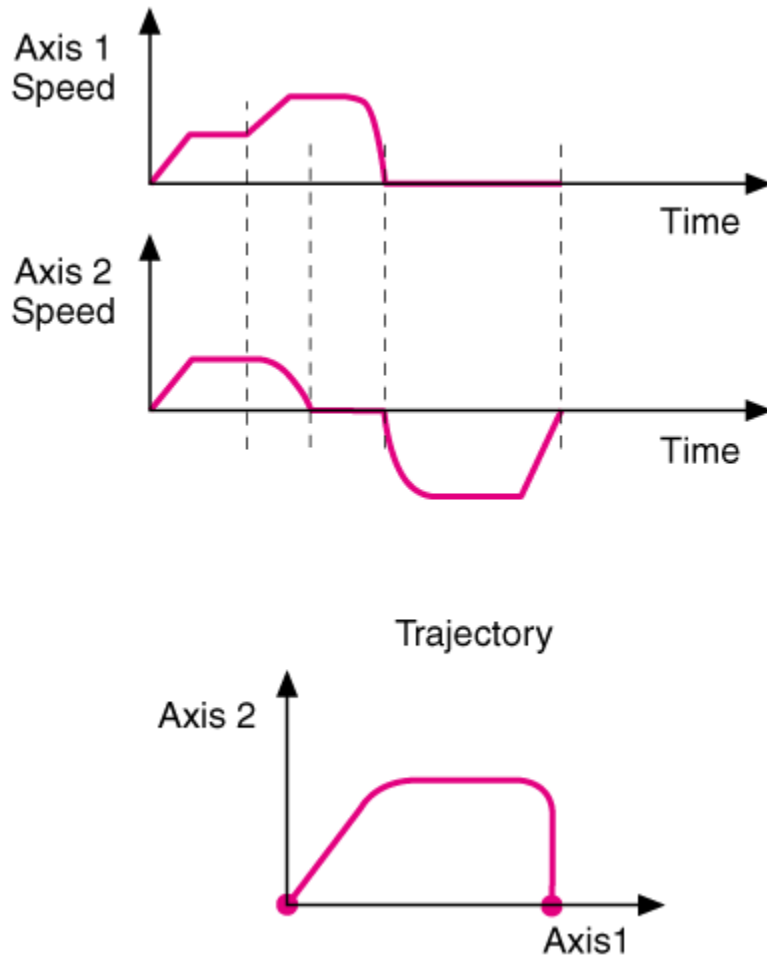


Figure 10: Applications such as laser writing require unusual trajectories executed at constant speed.

APPENDIX B

GAC 2.0 Firmware Command Set.

The device drivers required to address the digital pots can be downloaded from the Galvanometer Scanners page at www.lincolnlaser.com, (GAC 2.X driver zip folder)

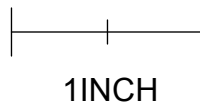
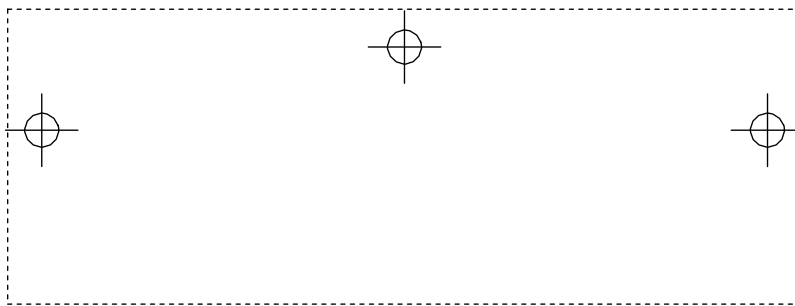
Function	Command	Description / Parameters
Proportional	A	Proportional Pot (0..255)
Integral	B	Integral Pot (0..255)
Derivative	C	Derivative Pot (0..255)
Velocity	D	Velocity Pot (0..255)
Command (Special applications only)	F	Command Position DAC (0...65535)
Position (Factory Set)	H	Negative Limit (0...65535) Positive Limit (0...65535) Limit Count (0..65535) Start Up Delay Count (0...65535) Current Position (0...65535)
Motor Current (Factory Set)	I	Negative Limit (0...65535) Positive Limit (0...65535) Limit Count (0...65535) Start Up Delay Count (0...65535) Current Position (0...65535)
Temperature Fault (Factory Set)	J	Temperature Fault Data (0...65535) Actual Temperature (0...65535)
Amp Fault (Information Only)	L	Fault Mode 0= No Fault 1=Over Current 2=Position Limit 3=Over Temp
Notch Frequency	N	Notch Filter Pot (0...255)
Compiler*	O	Compiler Version used to generate firmware
Version Date Time*	P	Date/Time Firmware was created
Restart Control (Factory Set)	R	Restart Attempt Count (0...255) Servo Start Up Done Count (0...255)
Feedback Scale (Factory Set)	S	Feedback Scale Pot (0...255)
Feedback Offset (Factory Set)	T	Feedback Offset Pot (0...255)
Slew Rate (Factory Set)	U	Slew rate Pot (0...255)
DAC Configuration*	Z	DAC Configuration 0= None 1= LTC 1655 2= XY2 - 100
Dump Variables	d	Dump current variable values
Enable Control*	k	Software Enable Request State (0...1) Start State (0...1) Enable Source (0...1) Hardware Enable State (0...1)

* Not Typically User Adjustable

APPENDIX C

HEAT SINK MOUNTING TEMPLATE

Maximum Recommended Screw Size: # 8



NOTES: