

Mach-DSP Servo Driver and associated software Users Manual



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1.0 Introduction

Pangolin has been using the word “Mach” (pronounced mock) as a model designation for our industrial-grade servo drivers since 1998. Back then, we introduced a unique servo amplifier having four separate coil drivers for a custom industrial galvanometer, and dubbed the project “Mach 4”.

Completely setting aside the fact that the word Mach is a cool word – one which conjures images of the fastest fighter jet airplanes, the word is actually entirely applicable to the field of galvanometer scanning. Indeed, ScannerMAX scanners utilize unusual materials and techniques in their rotor construction, and while choosing these materials we often consider the speed of sound through these materials (i.e. the Mach number). For this reason, we continue to use the word Mach for our servo drivers.

The Mach-DSP servo driver is Pangolin's latest and most advanced development in servo control technology. By taking advantage of high-speed floating-point digital signal processors, 16-bit data converters, direct digital command input, and highly-configurable servo algorithms, the Mach-DSP provides full-function, two-axis servo driver electronics in a cost-effective and compact package. Many advanced techniques and user-customizable features are embodied within the Mach-DSP hardware and software which, when combined with Pangolin's ScannerMAX scanners, provide a level of speed, accuracy and convenience that were unattainable before now.

The Mach-DSP can be accessed and configured using a PC-based Graphical User Interface software package, where the built-in Test Signal Generator, Oscilloscope and Dynamic Signal Analyzer can be used to monitor and adjust the more than 50 performance parameters per axis. These performance parameters can be stored in four separate memory areas (called “tunings”) for instant access and recall at any time. Additional features and behavioral customizations can be added via firmware updates that take only a few minutes to download using the PC-based software, helping to make the Mach-DSP a “future-proof” product. Moreover, since the current version of Mach-DSP firmware uses only a fraction of the on-board memory and only around half of the CPU bandwidth, it is possible that customized applications may also be loaded into the Mach-DSP, helping to reduce the size, power consumption and cost of an overall laser system. (Contact us about how customization could be done for your application.)

The Mach-DSP servo driver was created with OEMs in mind, incorporating a simple yet comprehensive and flexible interface structure. This, together with the modest power requirement and compact size allows laser system manufactures to package the servo driver electronics, the scanners, and often the power supply as well, directly into the laser projector head.

The purpose of this manual is to familiarize you with the functionality of the Mach-DSP servo driver. This manual also provides a brief introduction to the process of servo tuning, although when buying a complete system (scanners, mirrors, mount, servo driver, and cables) the Mach-DSP should arrive already tuned at the Pangolin factory. We also offer tutorial videos on our website that provide more in-depth information.

2.0 Specifications, Dimensions and Mounting

Analog and Digital Command Input

- ◆ Analog Differential Voltage Range ± 10 volts differential for full scale (other voltage ranges are also possible)
- ◆ Analog Input Impedance $20K\Omega$ differential
- ◆ FB4 and XY2-100 digital serial 3.3V direct-connect or RS-422 differential

Position Test Point Output

± 10 volts; scanner-dependent scale

Current Test Point Output

± 10 volts; full scale (1 volt per amp)

AGC Test Point Output

0 to -15 volts, full scale

User-assignable Analog Outputs

six outputs; ± 5 volts; user-adjustable scale

Digitizing resolution

16-bits for all analog inputs and outputs

Enhanced resolution

up to 18-bits for Command; 17-bits Position

Input Power

- ◆ Voltage $\pm 12V$ to ± 30 Volts DC (version dependant)
(Standard version requires $\pm 24V$. See Power Supply section for information.)
- ◆ Quiescent Current $+200mA$, $-230mA$
(servo enabled, galvos at rest)

Motor Drive Power

- ◆ Dynamic Current (per axis) up to 5 Amps RMS; 10 Amps Peak
(scanner and power supply dependant)

Control I/O

- ◆ Programmable on-off "TTL" Inputs two separate optically-isolated inputs
- ◆ Programmable on-off "TTL" Outputs two separate optically-isolated outputs
- ◆ Bi-directional USB/Serial Ports two accessible 3.3V-compatible ports

Fault Monitoring and Protection

- ◆ Fast-blow fuse protection X- and Y-axis motor outputs
- ◆ Fault monitoring shutoff / soft-start Over-position, Over current, Over temp.,
Power supply under- and over-voltage,
Scanner AGC fault or cable unplugged

Operating Temperature Range

$0^{\circ}C$ to $60^{\circ}C$

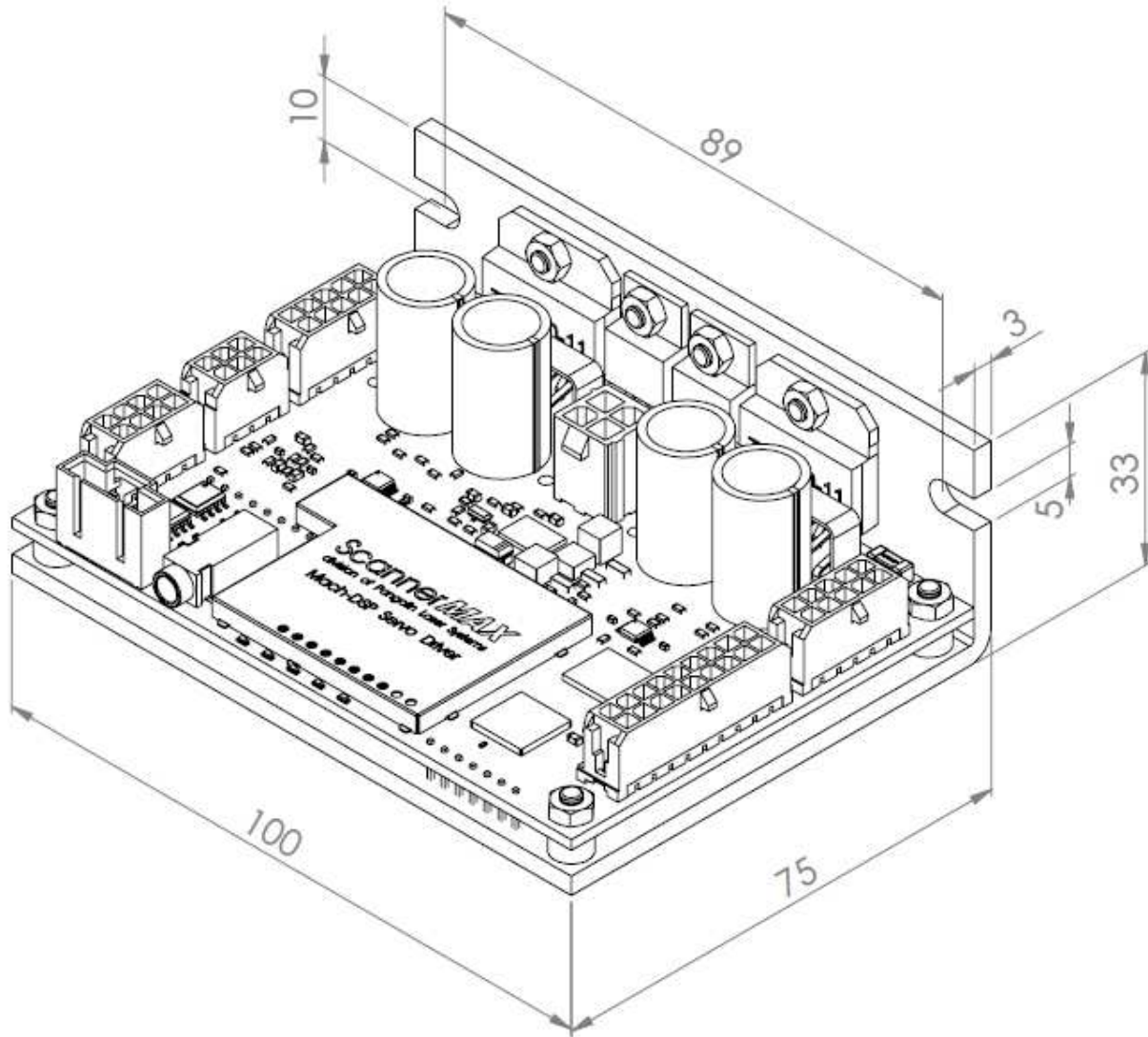
Size

W x L x H
 $2.95" \times 3.94" \times 1.3"$
(75mm x 100mm x 33mm)

Mass

170 grams

Mach-DSP Package Dimensions (millimeters)



2.1 *Mounting the Mach-DSP servo driver*

To transmit heat that is generated during operation, the Mach-DSP servo driver should be mounted to the chassis of a projector or other enclosure. Two semi-circular cutouts are provided on the rear surface of the Mach-DSP servo driver for mounting purposes.

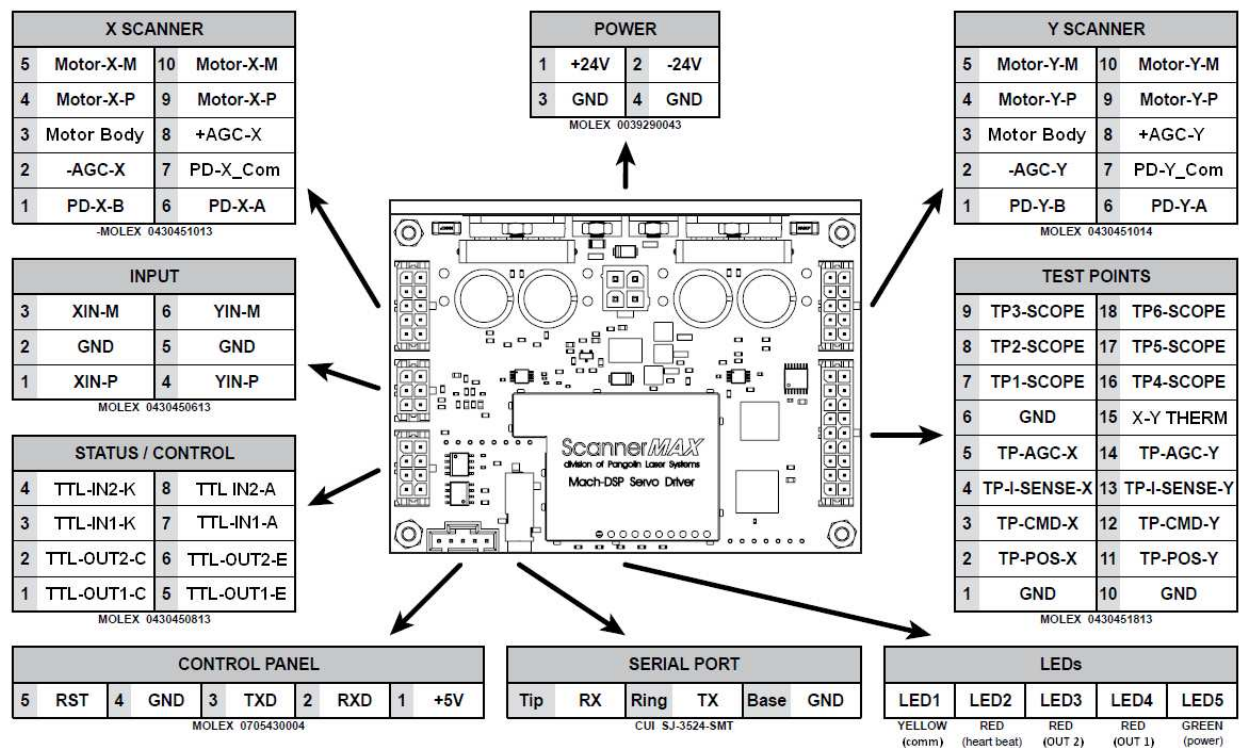
Since the rear surface of the Mach-DSP may not be completely flat, and the projector housing may also not be flat, Pangolin provides thermal interface material consisting of heat sink compound filled with aluminum nitride or silver. That heat sink compound should be spread onto the rear surface of the Mach-DSP servo driver before being mounted onto the projector chassis.

Note that all heat sink compounds include oil as a retaining element, and this oil may evaporate over time. Therefore if the Mach-DSP will be used inside the same projector housing along with sensitive optics, it may be desirable to use a different thermal interface material, such as Sil-Pad made by Bergquist.

Once the Mach-DSP is operational, you should watch the "Servo board temperature" as reported by the Mach-DSP PC application program. Ideally, the Mach-DSP board should be operated at temperatures of 50C or less. However, the Mach-DSP will continue to operate at temperatures well above that. Nevertheless, if the temperature reported exceeds 50C on a regular basis, it might be wise to revisit the thermal interface material between the Mach-DSP and the projector housing, or increase the surface area, to which the Mach-DSP is mounted, to improve heat dissipation.

3.0 Connector locations and functions

Please refer to the diagram below for an overall view of the location and function of each connector. Note that each connector on the Mach-DSP is unique, thus helping to prevent signals from becoming accidentally mismatched or misconnected.



3.1 Power Supply

Power is supplied to the Mach-DSP through a connector that is located approximately in the middle of the board, toward the rear (near the power amplifier components). The connector pin functions are shown in Table 3.1.

The standard version of the Mach-DSP can be operated with power supplies ranging from $\pm 18\text{V}$ to $\pm 30\text{V}$. However, $\pm 24\text{V}$ is required for optimal large-signal performance. Operating the standard version with higher power supply voltages will not provide any increase in scanning performance, but will generate more heating of the servo driver. However, operating the standard version at lower power supply voltages will incur a decrease in large-signal performance.

Note that the component values in the power amplifier section are optimized to operate at specific power supply voltages you specify at the time of purchase. When these components are matched to the power supply used, this results in the best possible large-signal performance. Upon request, the Mach-DSP can be special-ordered to operate *optimally* with power supply voltages as low as $\pm 12\text{V}$ or as high as $\pm 30\text{V}$.

The actual power supply current requirements are dependent on the application, and will vary as a function of the magnitude and duty cycle of galvo acceleration required. Idle current is around 200mA from each of the supply rails, so this represents the minimum current requirement. Laser marking and material processing applications typically draw well under 1 amp from each supply rail while some raster imaging applications and laser lightshows may require several amps continuous.

The Mach-DSP servo is rated for a maximum $\pm 5\text{A}$ RMS and $\pm 10\text{A}$ peak output currents, per axis.

Table 3.1: Power Connector

Pin	Function
1	Positive supply
2	Negative supply
3	Ground
4	Ground

Mating Connector Housing: MOLEX Mini-Fit Jr: 0039012040

Mating Connector Pins: 0039000073 or 0039000074

Specified Wire Size: AWG #18-#24

The Mach-DSP was designed with some degree of protection on the power supply pins. Nevertheless, **YOU MUST OBSERVE POWER SUPPLY POLARITY NOTED IN THE TABLE ABOVE, AND OBSERVE THE MAXIMUM OPERATING VOLTAGE FOR EACH MACH-DSP. APPLYING ELEVATED VOLTAGES, OR NEGATIVE VOLTAGE TO PIN 1, AND/OR POSITIVE VOLTAGE TO PIN 2 MAY RESULT IN IRREPARABLE DAMAGE TO THE MACH-DSP AND WILL VOID THE WARRANTY!!!**

3.2 *Analog and Digital Command Input*

Using the Mach-DSP PC application software (described in Section 7 of this manual), each axis of the Mach-DSP may select either Analog Input or Digital Input as the source of the Command signal. Analog Input is the most common, and is the default.

When the Input Source is set to Analog, then the Mach-DSP will receive its Command signal as a digitized version of the voltage appearing on the 6-pin Analog Command Input connector. When the Input Source is set to Digital, then the Mach-DSP will receive its Command signal from through-hole pads (or an optional XY2-100 Interface Daughterboard) located just to the right of the Status/Control connector.

3.2a *Analog Command Input*

The Analog Command Input connector is located on the left side of the board. The connector pin functions are provided in Table 3.2a:

Table 3.2a: Analog Command Input

Pin	Function
1	+ X-axis command input
2	Ground (see below for details)
3	- X-axis command input
4	+ Y-axis command input
5	Ground (see below for details)
6	- Y-axis command input

Mating Connector Housing: MOLEX Micro-Fit Jr: 0430250600
Mating Connector Pins: 0430300001 through 0430300012
Specified Wire Size: AWG #20-#30, depending on pin type

Analog Command Input Description

The analog command input to the Mach-DSP is a true differential input that accepts a full-scale command of $\pm 10\text{V}$ differential (i.e. $\pm 5\text{V}$ for the + input and $\pm 5\text{V}$ for the – input, or $\pm 10\text{V}$ for the + input and 0V for the – input). For noise sensitive applications, a true differential signal should be provided through a twisted and shielded wire pair.

Important Information about Use with a Single-Ended Signal Source

Some industrial clients and university clients use common off the shelf DAC boards from National Instruments and the like, which offer only a positive (+) signal output and ground, and do not offer a negative (–) signal output. Clients commonly ask us how to make the connections between this kind of signal source and the Mach-DSP.

It occurs often that clients mistakenly believe they should connect their “ground” from the source to pins 2 and pin 5 of the Analog Input connector of the Mach-DSP. (After all, pins 2 and 5 are labeled “ground” above...) While this will sort of work, it will also very likely cause inaccurate scanning as well as cross-talk between X and Y axes. The reason is not obvious, and is covered in the book *LASER SCANNERS: Technologies and Applications*, by William R. Benner, Jr (designer of all ScannerMAX products including the Mach-DSP servo driver). See the chapter that covers *Making the Right Connections for Perfect Laser Images*.

Nevertheless, **if you have a single-ended source, in most cases the best way to connect it to the Mach-DSP is** to connect the + output of the DAC board to pin 1 (the +X-axis command input) and/or pin 4 (the +Y-axis command input), and connect the “ground” from the signal source to *both* pin 3 (the -X-axis command input) *and* pin 6 (the -Y-axis command input) on the Analog Command Input connector. Doing this will take maximum advantage of the differential receiver in the Mach-DSP, allowing it to remove any noise picked up between the signal source and the Mach-DSP, and more importantly, allowing it to subtract out any “ground bounce” and other phantom power supply ground currents.

In most cases, do not connect to pins 2 and 5 on the Analog Input connector

It is very rare indeed that clients should make any connections to pins 2 and 5 of the Analog Input connector. (Again, for all of the reasons why, please read the book mentioned above.) Pins 2 and 5 are connected to the other pins labeled “ground” on the Mach-DSP, including the Scanner interface and Power Supply connector. In most cases, best performance will be had using a single-point-grounding-scheme, with that single point being located at (or very close to) the power supply.

Voltage level of the input signal, and corresponding scan angle

The “Input Scale” is fully adjustable using the Mach-DSP Servo Control software application, and it is possible to accommodate input voltage levels ranging from $\pm 1\text{V}$ to $\pm 10\text{V}$ differential, and have that correspond to any scan angle up to the maximum provided by the scanner connected (greater than 100 degrees optical peak-to-peak with ScannerMAX scanners).

However, to take full advantage of the dynamic range provided by the 16-bit Analog-to-Digital converter front end of the Mach-DSP, the input signal should have a voltage level of $\pm 10\text{V}$ differential. (When using a single-ended source, this corresponds to a voltage range of -10V to $+10\text{V}$ at the + axis inputs, and 0V at the – axis inputs.) Of course the Mach-DSP can be special ordered for other full-scale signal ranges. If you have any questions or concerns about this, please contact us to discuss your requirements.

Input voltage range and common-mode rejection

The inputs are true differential, and as long as each of the + and – inputs do not exceed 20V , the system will provide high common-mode rejection.

3.2b 3.3-volt TTL-level Digital Command Input with Status Feedback

The Digital Command Input and Status feedback signals (and a few unrelated signals) are provided on unpopulated 100-mil-spaced through-hole pads located directly to the right of the Status / Control connector. Table 3.2b below describes the signals:

Table 3.2b: Digital Command Input

Pin	Function
1	Ground (pin 1 indicated with square pad)
2	(reserved "Power Amp Enable active low")
3	Serial Port Y-axis data input (Position Feedback output for FB4)
4	Serial Port X-axis data input (XY-axis data input for FB4)
5	Serial Port Frame Sync input
6	Serial Port Clock input
7	(reserved "PWM power amp clock")
8	(reserved "PWM power amp clock")

Signal description

As implied by Table 3.2b above, Digital Command Input communication is presently facilitated through a multi-wire serial interface consisting of Clock, Frame Sync, one or two axis inputs, and an optional Status feedback output. The XY2-100 protocol uses separate inputs for X-axis data and Y-axis data. The FB4 protocol uses a single input for both X and Y data, and uses a single output for Position Feedback.

Voltage Levels

The digital signals found on these unpopulated through-hole pads use 3.3V TTL signal levels. These signals may be connected directly to other 3.3V microprocessor-based equipment that is located physically close to the Mach-DSP. For equipment located farther (such as typical equipment that uses the XY2-100 standard), an optional daughterboard (described later in this manual) can be fitted to the Mach-DSP, which adapts RS-422 differential signals to the 3.3V signal levels.

Additional unpopulated through-hole pins nearby

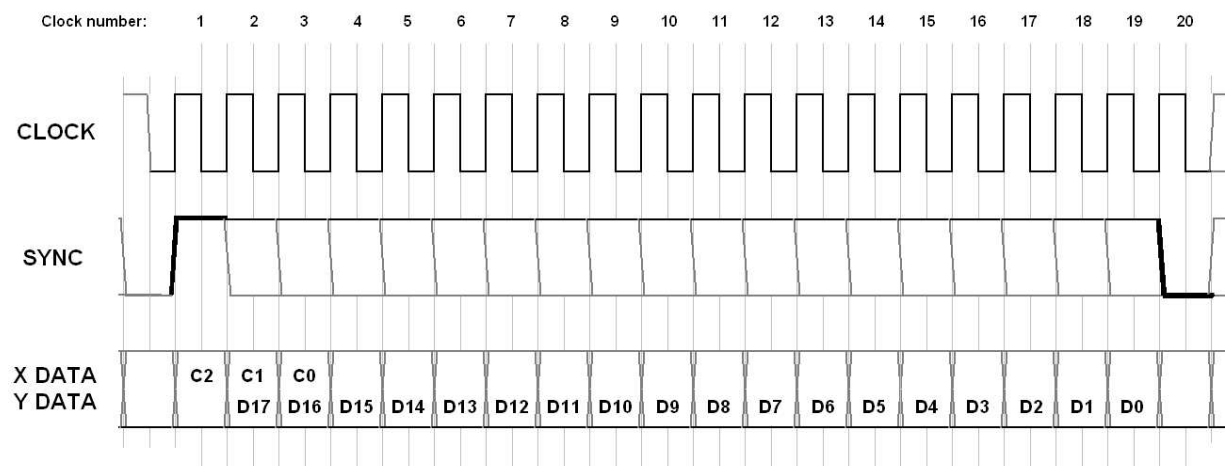
In addition to the 8 unpopulated through-hole pads mentioned above, there may be additional unpopulated pads nearby, such as 5 or 6 pads, depending on the date of manufacture. Those are reserved for future use and you should not connect to them.

Available cables

Digikey part numbers 1528-1964-ND and 1528-1967-ND may be soldered to those unpopulated pads, and thus used to connect your digital signals to the Mach-DSP.

XY2-100-compatible protocol

Refer to the diagram below, which illustrates the signals and phase relationships.



Looking at the diagram above, you will note that signals that are *sent to* the Mach-DSP must change on the low-to-high transition of the clock; signals are *observed by* the Mach-DSP on the high-to-low transitions of the clock.

Reception of a new Input Command begins when the Frame Sync line is brought high, followed by a high-to-low transition of the Clock line. During this same high-to-low clock transition, the first bit of data is also latched by the Mach-DSP. (Technically this is called “active-high, late frame sync” because the sync signal coincides with data reception.)

Once the Frame Sync line has been detected high, it can remain high during the next 18 clocks, or it may be brought low again. In any event, the Frame Sync line must be brought low by clock number 20, as shown in the diagram above, otherwise a Frame Sync Error will occur, and data will not be communicated correctly. In essence, all of this means that the data is “framed” in 20-clock sequences.

The Clock line can be any frequency up to a theoretical maximum of 25MHz, with any reasonable duty cycle. The data frames described above may occur in sequence, one after another (called “coherent frames”), or they may be sporadic (called “isolated frames”). If they are sporadic, the Clock line may continue clocking in between data frames, or it may be quiescent (preferably held in a low state). In all cases, whether the clock is operational or not, the Frame Sync line must be held low when data is not sent.

The “frame rate” may be anything that the Clock and Frame Sync signals allow – ranging from slower than one frame per hour up to a theoretical maximum of 1,250,000 frames per second. The data communicated via this serial port is absorbed by the Mach-DSP at the rate that it is sent, and – unless Synchronous Sampling is selected (as described several pages below), there is no attempt to synchronize the Mach-DSP’s servo sample clock (typically 100kHz to 300kHz) to the serial port signals.

You will note that 19-bits of data per axis (and per returned status) are communicated using this protocol, although the entire sequence requires 20 clocks. And although parity is not used by this protocol, some data integrity is provided by "Control Bits".

You will also note that the first three bits received by the Mach-DSP are designated "C2, C1, C0". These first three bits are called "control bits", and they designate the function of the data that is contained in the bits that follow. The table below describes the control bits and associated functions:

Table 3.2c: Control Bit Definitions

Control Bits [2:0]	Function
000	(reserved for future use)
001	16-bit position data follows
010	(reserved for future use)
011	(reserved for future use)
1xx	18-bit position data follows

As shown in the table, only Control Bit patterns 001, and 1xx are presently used, designating either 16-bit or 18-bit position commands, and therefore there is room for future expansion as well as flexibility to implement custom protocols for individual clients.

For 16-bit position data, a value of 0 (all bits cleared) normally represents the far-left and far-bottom of the scan field; a value of 32768 represents the middle of the scan field; and a value of 65535 (all bits set) normally represents the far-right and far-top of the scan field.

For 18-bit position data, a value of 0 (all bits cleared) normally represents the far-left and far-bottom of the scan field; a value of 131072 represents the middle of the scan field; and a value of 262143 (all bits set) normally represents the far-right and far-top of the scan field.

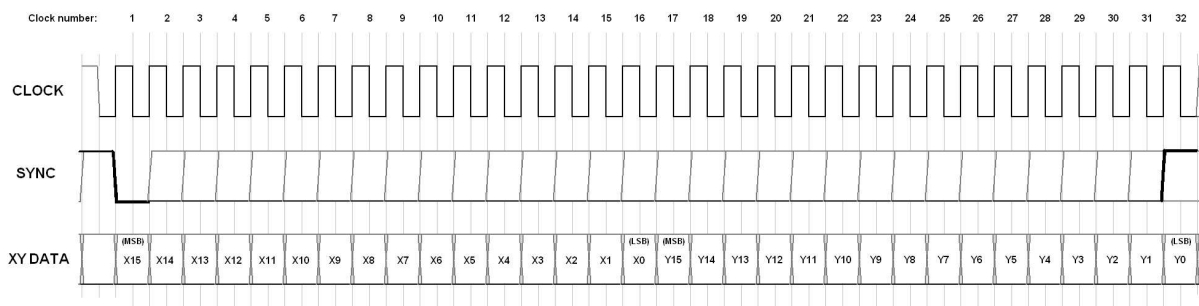
Of course the relationship of the data to the polarity of axis motion (insomuch as far-left / far-right as well as far-bottom / far-top) depends on whether you are using a left-handed or right-handed X-Y mount, and each axis may be inverted by changing the "Input Scale" on the Mach-DSP application software, as described in section 7.3.

XY2-100 Status Return signal

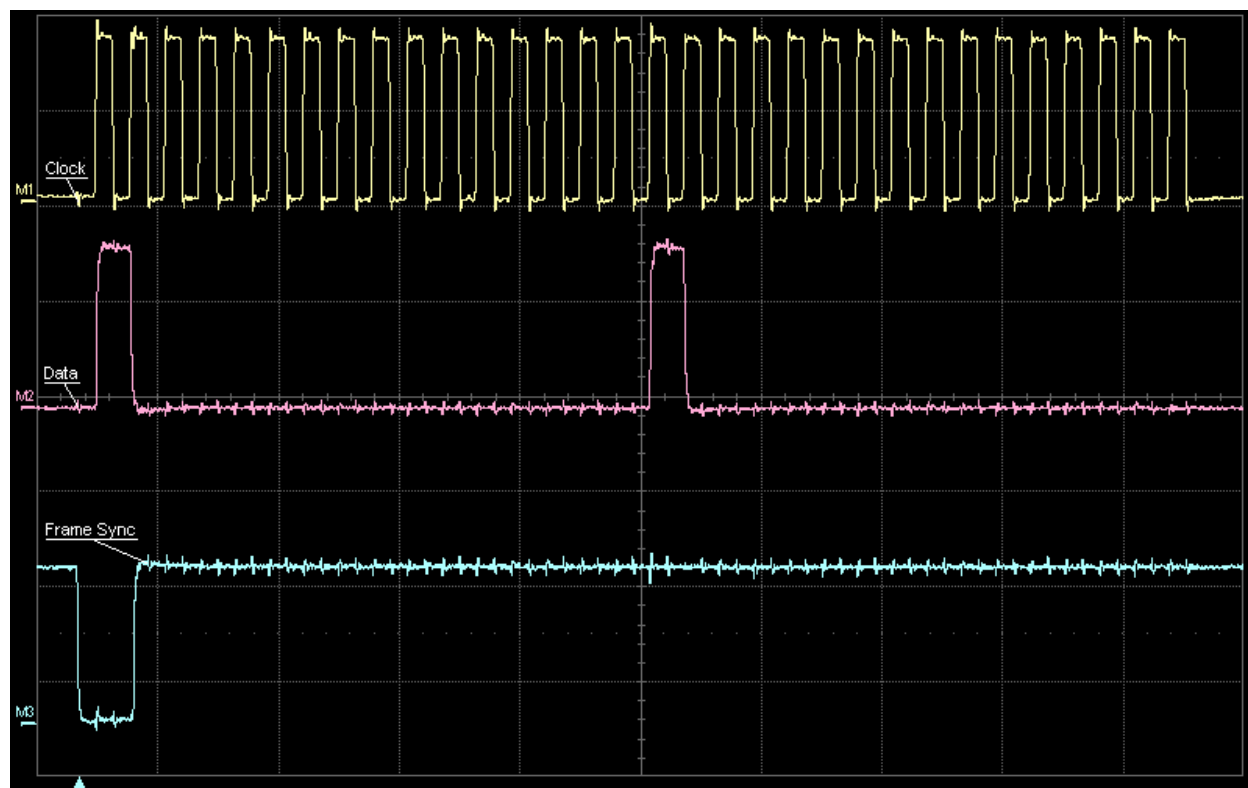
The Mach-DSP includes a single serial port line (the RST signal located on the Control Panel Serial Interface connector), which may be used to communicate status data back to the microprocessor-based equipment. Presently this is not implemented and is reserved for future use. Note that there is great inconsistency among XY2-100-based equipment on the use (and even presence) of the Status signal.

FB4 protocol (only available in certain Mach-DSP firmware versions)

The FB4 protocol combines both X and Y into a single 32-bit data word, with X being the most significant 16-bits, and Y being the least significant 16-bits as shown below.



As is the case with XY2-100, signals that are *sent to* the Mach-DSP must change on the low-to-high transition of the clock; and signals are *observed by* the Mach-DSP on the high-to-low transitions of the clock. Below is an oscilloscope screen shot showing the simplest implementation of the FB4 protocol. Yellow is the clock. Pink is data. Blue is Frame Sync. The numeric data representation is the same as XY2-100. In the picture below, the most significant bits for both X and Y are high, and the rest of the bits are low. This represents +32768, which is equivalent to the center of the scan field.



Once the Frame Sync has been detected low, it can remain low during the next 31 clocks, or it may be brought high again after the first clock as shown above. In any

event, Frame Sync must be brought high by clock number 32, as shown in the diagram above, otherwise a Frame Sync Error will occur, and data will not be communicated correctly. In essence, all of this means that the data is “framed” in 32-clock sequences.

The Clock line can be any frequency up to a theoretical maximum of 25MHz, with any reasonable duty cycle. The data frames described above may occur in sequence, one after another (called “coherent frames”), or they may be sporadic (called “isolated frames”). If they are sporadic, the Clock line may continue clocking in between data frames, or it may be quiescent (preferably held in a low state). In all cases, whether the clock is operational or not, the Frame Sync line must be held high when data is not sent.

The “frame rate” may be anything that the Clock and Frame Sync signals allow – ranging from slower than one frame per hour up to a theoretical maximum of 781,250 frames per second. The data communicated via this serial port is absorbed by the Mach-DSP at the rate that it is sent, and – unless Synchronous Sampling is selected (as described below), there is no attempt to synchronize the Mach-DSP's servo sample clock (typically 100kHz to 300kHz) to the serial port signals.

You will note that 16-bits of data per axis are communicated using this protocol, and the entire sequence requires 32 clocks. X-axis data is first with the MSB during clock number 1. Y-axis data is next with MSB during clock number 17.

FB4 Position return data

The FB4 protocol uses one of the data lines to return the XY position that was read by the Analog to Digital converters. And unless Synchronous Sampling is selected (as described below), there may be a several sample delay between the instantaneous position and the value of the position that is communicated by the return signal.

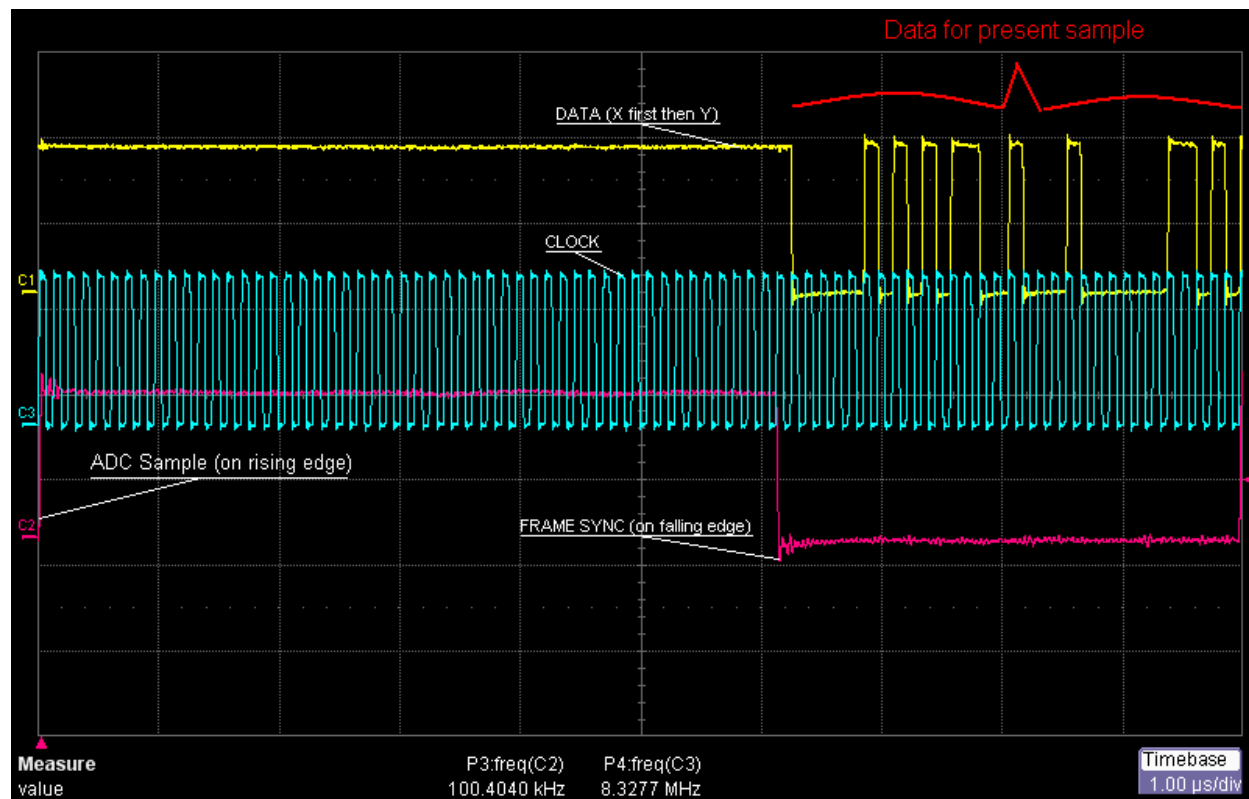
Synchronizing the servo sampling with data communication

It may be desirable to synchronize the servo sampling with the actual serial data communication. This allows for consistent and fresh position data to be returned from the servo, and prevents aliasing of the digital command and position signals that otherwise occur when the servo sampling happens asynchronously to serial data.

Before synchronous sampling can be enabled, the ***Digitizing sample rate*** must be set in accordance with the expected serial data frame rate, and the servo tuning must be optimized for that particular sample rate. The ***Digitizing sample rate*** is found in the ***Digitizer parameters*** section of the ***Pangolin only*** tab. We would also recommend testing bi-directional data communication, and making sure that everything is working perfectly, before enabling synchronous sampling.

When you are ready, check the box ***Synchronize sampling with Serial Input Frame Sync***. When this is done, the Analog to Digital Converters on the Mach-DSP will start their conversion cycle on the rising edge of Frame Sync, and serial communication begins on the falling edge of Frame Sync.

Note that it takes roughly 5.75uS for the analog-to-digital conversion to be completed, and for the data to be read and processed. If Frame Sync is brought low after 5.75uS (as shown in the screen shot below), then the position data that is returned will correspond with the immediately preceding rising edge of the Frame Sync signal.



In this screen shot, Frame Sync is brought high for around 6.1 microseconds, then Frame Sync is brought low and serial communication commences. The command input data and the returned position data are both communicated at the same time, and on the same edges of the clock.

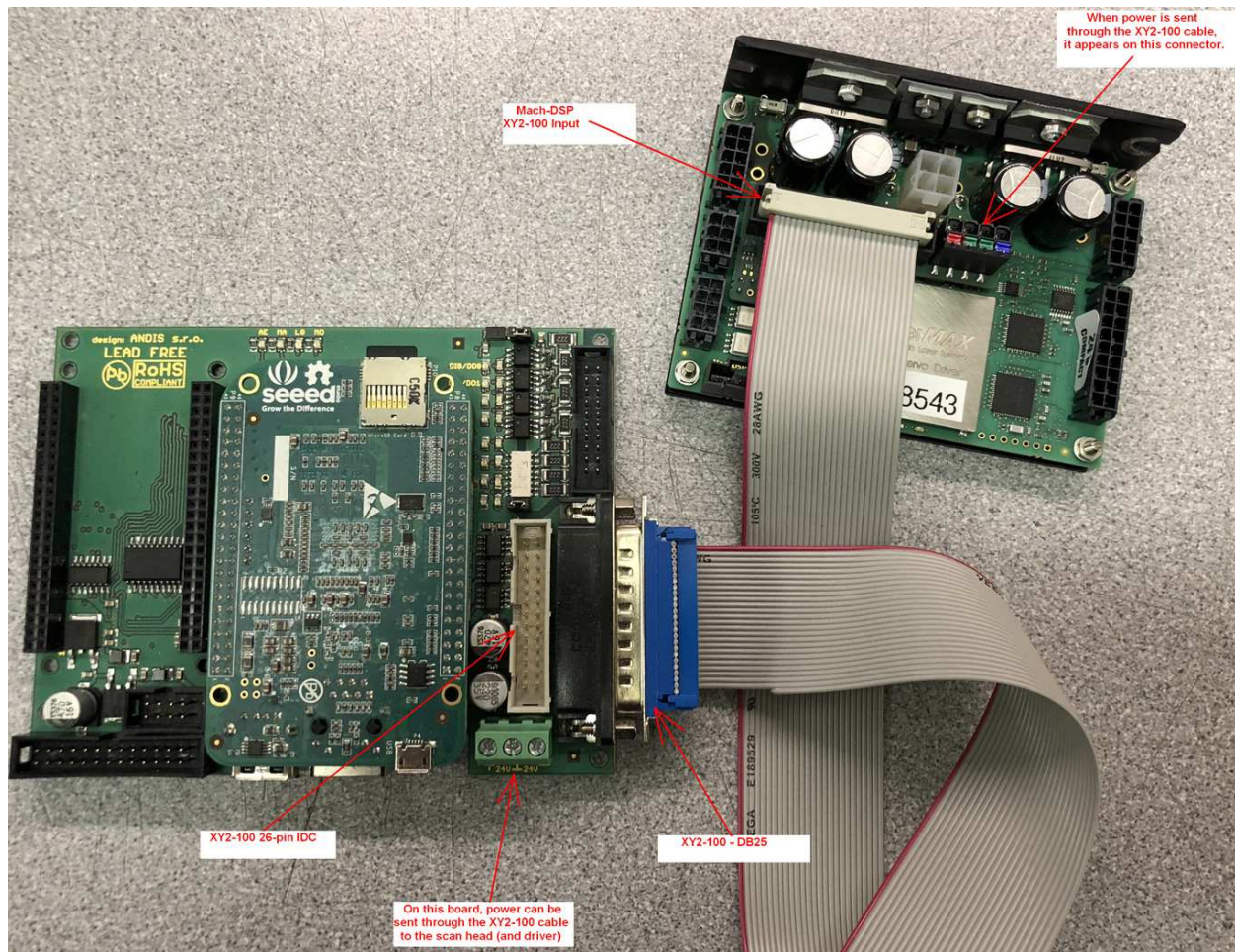
The screen shot above shows 100kHz sample rate, which is reasonable for most applications. To provide for synchronized sampling as well as complete data transmission during the present frame, the clock rate needs to be at least 8.3MHz for a 100kHz sample rate.

Future Expansion and Alternative Protocols

It should be obvious that there is a great deal of flexibility built into the Mach-DSP, and a variety of custom applications and alternatives are possible. The number of bits used and the polarity of Clock and Frame Sync signals are all easily changed. Please contact us if you have special requirements, since they may be accommodated via firmware updates, which are easily performed by users in the field.

3.2c Differential Signaling (XY2-100) Interface Daughterboard

An optional Differential Signaling Interface Daughterboard can be fitted onto the Mach-DSP, providing XY2-100-compatible differential signaling with RS-422 voltage levels. This allows the Mach-DSP to be used with standard laser-marking-style laser controllers that output XY2-100. This is shown in the picture below, with the laser-marking controller appearing in the lower left of the picture and Mach-DSP in the upper-right.



The XY2-100 interface daughterboard uses a 26-pin IDC connector, which can be connected through a ribbon cable directly to a laser-marking controller that also uses a 26-pin IDC connector. Alternatively, the ribbon cable can be terminated in a DB-25 connector, as was typical many years ago when the XY2-100 standard was developed.

When it is desirable to run the Mach-DSP from power sent through the XY2-100 cable, you should connect the power wires from 4-pin power connector (discussed in section 3.1 of this manual) to the Red, Green, and Blue terminals on the right side of the daughterboard (or terminals designated +, -, and ground if they're not colored). Red indicates positive voltage, Green indicates ground, and Blue indicates negative voltage.

Be sure to select a *Digital Input* as the *Input Source*, as discussed in section 7.3.

3.3 Status and Control signals

The status/control signal interface is located in the left side of the board near the front. System I/O includes optically-isolated inputs and outputs facilitated through optical isolators having part number MOCD207M. The pin functions are described in Table 3.3:

Table 3.3: Status / Control Interface

Pin	Function
1	Collector of isolated output 1
2	Collector of isolated output 2
3	Cathode of isolated input 1
4	Cathode of isolated input 2
5	Emitter of isolated output 1
6	Emitter of isolated output 2
7	Anode of isolated input 1
8	Anode of isolated input 2

Mating Connector Housing: MOLEX Micro-Fit Jr: 0430250800
Mating Connector Pins: 0430300001 through 0430300012
Specified Wire Size: AWG #20-#30, depending on pin type

Optically-isolated Inputs

The Mach-DSP features two separate TTL-level inputs, facilitated as LED inputs of optical isolators. These inputs that can be programmed to respond in a variety of ways, using the “Control” tab of the Mach-DSP PC application. For example, these inputs may be used as an external “SERVO ENABLE” signal that will enable the servo driver when the laser Machine is ready for use, but disable the servo driver and place it in standby otherwise. Another example use is to use one or both of these inputs to select scanner-tunings on the fly. **(Although the isolation offered is greater than 500 volts, you should not exceed greater than +/- 6V across the Anode/Cathode terminals.)**

Optically-isolated Outputs

The Mach-DSP also features two separate “TTL” outputs, facilitated as open-collector phototransistor outputs of optical isolators. These TTL outputs that can be programmed to respond in a variety of ways, using the “Control” tab of the Mach-DSP PC application. For example, one or both of these outputs can be used as a “Fault” indication – to indicate that the servo has encountered an over-temperature or over-position fault. Another example use is to use one or both of these outputs as a “Settled” indicator, to indicate when the servo position error has reached a suitably low value, indicating that the mirror has reached its commanded position. **(Although these “TTL” outputs will typically be used with TTL-level voltages, they support up to 30V across each phototransistor, and up to 150mA flowing through each phototransistor.)**

3.4 Control Panel Serial interface

The Mach-DSP includes a 3.3V-TTL-level RS-232 serial port, which can be used to select and adjust scanner tunings as well as monitor the overall health of the servo driver. This connector is located on the left / front side of the board. The connector pin functions are provided in Table 3.4:

Table 3.4: Control Panel Serial Interface

Pin	Function
1	+5V Output
2	RXD (data toward Mach-DSP)
3	TXD (data from Mach-DSP)
4	Ground
5	(reserved / XY2-100 Status)

Mating Connector Housing: MOLEX SL: 0050579405
Mating Connector Pins: 0016020082 or 0016020088
Specified Wire Size: AWG #22-#30, depending on pin type

As expressed above, the RXD and TXD signals use 3.3V signal levels. These signals are protected by series resistors and Schottky diodes, and therefore applying higher voltages, or applying voltages while power is not applied to the Mach-DSP should not cause any harm.

This manual does not include details of the communications protocol used by this connector, but the communications protocol is available to OEMs who agree to the terms of our NDA.

Note that in addition to serial communications signals found on this connector, the Mach-DSP also provides regulated +5V as well. This may be used to power an external control panel including OLED display, or it may be used to provide power for the optically-isolated TTL inputs or TTL outputs described in the Status / Control Interface section of this manual.

3.5 Test and Thermistor interface

The Test and Thermistor interface connector is located on the right / front side of the board. This connector provides 1K-resistor-buffered analog output signals that may be used during servo tuning, and may also be monitored by external equipment if desired. This connector may also be used to connect a thermistor as described below. The connector pin functions for the test interface connector are provided in Table 3.5.

Table 3.5: Test Interface

Pin	Function
1	Ground
2	X-axis Position (not scaled)
3	X-axis Command input (after filter)
4	X-axis Motor drive current (1 V/A)
5	X-axis AGC drive voltage (negative)
6	Ground (usually used for thermistor)
7	User-defined analog output 1
8	User-defined analog output 2
9	User-defined analog output 3
10	Ground
11	Y-axis Position (not scaled)
12	Y-axis Command input (after filter)
13	Y-axis Motor drive current (1 V/A)
14	Y-axis AGC drive voltage (negative)
15	NTC Thermistor (10K $\beta=3300$ nominal)
16	User-defined analog output 4
17	User-defined analog output 5
18	User-defined analog output 6

Mating Connector Housing: MOLEX Micro-Fit Jr: 0430251800
Mating Connector Pins: 0430300001 through 0430300012
Specified Wire Size: AWG #20-#30, depending on pin type

Position, Command, Current and AGC signals

The Test Interface connector includes a number of signals that are referred to as “analog”, but the only truly analog signals are the Position, Command, Current and AGC outputs for both the X- and Y-axes. These are measured and processed purely in the analog domain. As such, they offer maximum resolution in both time and range.

The Position signal has a scale factor that varies somewhat from scanner to scanner, but tends to be approximately 2.45 mechanical degrees per volt for systems that are not customized. The Command signal output is a direct reflection of the Mach-DSP analog command input. The Current signal has a fixed scale factor of 1-volt-per-amp. The AGC signal is a reflection of the voltage seen by the galvo position sensor LED driver.

User-defined analog output signals

For most users, the most important thing to understand about these signals is that the voltage level and actual servo signal that is assigned to be output by each user-defined analog output can be chosen in the *Oscilloscope and Analog Output Controls tool*, found in the Mach-DSP Servo Control Application program. This is described in Chapter 8 of this manual.

When these signals are merely directed to an external oscilloscope, to probe the internal workings of the Mach-DSP servo, probably no additional information is needed. However, when these signals are used by external equipment, such as safety-analysis circuitry or data acquisition systems, the additional details presented below may be critical for the overall success of the system.

The user-defined analog outputs are derived from a 16-bit digital to analog converter. As such, they have limited resolution in both time and range/delta. Note that, with the exception of a single 1K-ohm buffer resistor placed in between each DAC output and the associated Test Interface Connector pins, no filtering or other signal conditioning is performed on these outputs. This has several implications, including:

- Since the DACs are 16-bits, the smallest possible voltage delta is approximately 153 microvolts (+/-5V range over 65536 DAC counts)
- All DAC outputs are updated at the same time (simultaneous sampling), and all outputs are updated at the sample rate that is used by the servo, which is user-adjustable between 100kHz and 300kHz, with 160kHz being typical.
- Albeit nearly all DACs experience some “glitching” between major code transitions, the DAC used on the Mach-DSP (Texas Instruments part number DAC8728) was specifically chosen to be a “low-glitch” type (4nV-S, 5mV max).

Given the points described above, it may be desirable to low-pass filter these signals – at the very least to remove glitches, or possibly as an anti-aliasing portion of the data-acquisition system. Moreover, apparent “code repeating” and “sample repeating” will be sensed if these signals are fed into an ADC that has greater than 16-bit resolution, or one that digitizes a higher sample rate than the servo is operating. This too may be mitigated by the use of low-pass filtering.

Scanner body temperature sensing via Thermistor

An NTC thermistor may be connected between pins 6 and 15 and then attached to the X-Y mount. This will give the Mach-DSP servo an accurate measurement of the scanner's body temperature. (Without the thermistor, the Mach-DSP will assume that the body temperature is a constant 30 degrees C, which may lead to incorrect estimates of the overall scanner coil temperature). The Mach-DSP's temperature calculation will be based on a thermistor having a 10K nominal resistance and β value of 3300K. (Note that thermistor manufacturers report β values differently, and therefore the β values shown in thermistor datasheets are not a consistent indicator of performance...) Nevertheless, our testing revealed that 10K / β =3300 matches pretty well with Cantherm part number CWF4B103G3380, as well as Vishay part number NTCALUG01T103G501.

3.6 Scanner interface

Each scanner is connected to the Mach-DSP through a single cable that provides both the position sensor and motor drive wires. The connector pin functions are provided in Table 3.6:

Table 3.6: Scanner Interface

Pin	Function
1	Position sensor photodiode current "B"
2	LED cathode drive (negative current)
3	Motor body / shield
4	Motor drive +
5	Motor drive -
6	Position sensor photodiode current "A"
7	Position sensor photodiode common
8	LED anode drive (ground)
9	Motor drive + (redundant)
10	Motor drive - (redundant)

Mating Connector Housing: MOLEX Micro-Fit Jr: 0430251000
Mating Connector Pins: 0430300001 through 0430300012
Specified Wire Size: AWG #20-#30, depending on pin type

Note that the LED drive on pin 2 presents a negative current instead of a positive current, which is more common in the industry. This is because most often, the large body of an LED is the positive terminal, and the small bond wire is driven with a negative voltage. This means that the large body ("positive" contact) of the LED is more sensitive to RF interference from walkie-talkies, cell phones and the like. Thus, by driving the LED with a negative current, the largest portion of the LED (the body) becomes grounded, thus this improves the RF immunity of the position sensor portion of the scanner, and also improves signal-to-noise ratio of the position sensor, and of the entire servo system.

Likewise, the Photodiode currents on pin 1 and 6 are expected to be positive currents, not negative currents as are more common in the industry. However, unlike the LED current drive, which is always negative, the Mach-DSP can be configured to expect either a positive current or negative current on the photodiode input pins, depending on how components are populated at the factory.

4.0 Fault monitoring and other protection circuitry

4.1 *Fault Detection*

The Mach-DSP includes protection circuitry that will disable the servo loop and optionally set one or both of the user-defined TTL outputs to a prescribed logic level if any of several monitored error conditions are detected.

The Mach-DSP protection circuitry monitors scanner position, scanner current, scanner coil temperature (and body temperature if you use a thermistor as described in Section 3.5), servo board temperature, and scanner Position Sensor AGC health (including scanner connector unplugged). The Mach-DSP protection circuitry may also optionally monitor one or more user-defined TTL inputs.

When one of the monitored parameters goes outside of the prescribed maximum range (whose range is user-adjustable for most parameters), the servo will shut down. Once all faults are cleared, the servo will automatically reset in a controlled power-up sequence that resets the integrator, enables the servo loop, and then gradually enables the command input, and optionally indicating that the servo is ready using one or both user-defined TTL outputs.

4.2 *Fuses*

Both of the X and Y Scanner drive outputs of the Mach-DSP are fuse-protected, to prevent damage to either the scanner or the servo system in the event of a severe electrical fault. Pangolin installs fuses whose rating is selected based on the RMS power handling capability of the scanner being driven. The fuse is a Nano2 type, series 0453 made by Littelfuse.

4.3 *LED Indicator Lights*

The Mach-DSP includes five separate LED indicator lights that may be used to determine the operational status of the servo driver. These lights are located on the front of the board and shown at the beginning of Section 3 above.

LED1 will illuminate yellow whenever there is communication between the Mach-DSP and the PC (or external serial data interface).

LED2 will illuminate red several times per second, and gives an indirect indication of how much time is spent in the servo algorithm and how often the power supply voltages are being checked. This may be used for troubleshooting if called upon to do so by Pangolin.

LED3 will illuminate red whenever TTL Output 2 is *active*. (See section 7.6 for more info.)

LED4 will illuminate red whenever TTL Output 1 is *active*. (See section 7.6 for more info.)

LED5 will illuminate green when power is applied to the board.

4.3a *Error Indications*

Note that in addition to their roles of indicating communication and servo activity, LED1 and LED2 are also used together to indicate when faults occur during the operation of the Mach-DSP. Faults are indicated by LED1 and LED2 flashing back and forth, in a kind of railroad-crossing manner. The number of back-and-forth flashes will indicate the error number in accordance with the table below.

Errors indicated by railroad-crossing flashes of LED1 and LED2

Flashes	Problem that occurred
1	RS-232 Reception Error (probably wrong baud rate)
2	RS-232 data does not conform to protocol
3	Inability to read system voltages and temperatures
4	XY2-100 or FB4 data error, or loss of Frame Sync
5	RS-232 command is not supported by present firmware
6	Inability to correctly read or interpret the coil temperature

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5.0 Servo Overview

The servo class, servo configuration and servo tuning all play a role in determining the speed and accuracy of an overall scanning system. This chapter describes the ways in which the Mach-DSP may be configured to drive a scanner, as well as the overall servo architecture. Scanner tuning is covered in Chapter 10 of this manual.

5.1 *Servo Class, terminology, and configurations*

The Servo “Class” refers to the number of error integrators that are used within the servo loop. A Class 0 servo is a configuration that does not have an integrator. This is known as simple “PD” since only the Proportional and Derivative terms are used to control the scanner.

A Class 1 servo is a configuration that involves a single integrator. This is most often known as “PID” since Proportional, Integrator and Derivative terms are used to control the scanner.

(There are also Class 2 servos that involve two separate integrators in the loop before the summing node, but these are not used on galvanometer scanners. Also note that just because a galvanometer servo driver – including Mach-DSP – uses an integrator to convert scanner current to velocity, this doesn't mean that it is a separate integrator for the purposes of “classification”).

Note that the word “PID” may actually be more of a euphemism than a definitive description of what is actually happening inside the servo loop. Indeed, modern galvanometer servo drivers more commonly implement servo configurations such as PIV, or PI+ as well as PDF, rather than a true PID as shown in servo textbooks or described on Wikipedia. All of these are different ways of configuring the scanner's position error signal (proportional), the scanner's velocity (derivative) and an integration of the scanner's position signal (integral) to drive a power amplifier and move the mirror in response to a command input. Since PIV, PI+, PDF and PDFF all involve the use of proportional, integral and derivative terms, people very often use the word “PID” as a kind of blanket terminology.

5.2 *Servo configurations possible with the Mach-DSP*

The Mach-DSP provides control over the gain of five fundamental signals, which are ultimately fed into a summing node, including:

- A signal proportional to the error between the commanded and actual position (Error Proportional gain)
- A signal proportional to the integral of the position error (Error Integrator gain)
- Two separate signals proportional to the velocity of the scanner (Low Frequency Damping and High Frequency Damping gain)
- A signal proportional to the position of the scanner (Position-proportional gain)

By adjusting the level of each gain control described above, the following servo configurations are possible with the Mach-DSP servo driver:

PD (Proportional and Derivative): Error Proportional (servo) gain, used along with one or both Damping terms. PD is the fastest type of servo configuration and the easiest to tune. Because of this, it is usually used for laser displays and laser light shows, since these applications consider speed to be the most important criteria in scanning.

PID (Proportional, Integral and Derivative): The PD configuration as described above, plus a small amount of Error Integrator gain. PID adds a little bit of integrator, which will reduce the error (difference between commanded position and actual position) to zero. To control overshoots, the Error Integrator must be used along with a small amount of Position Proportional. This PID configuration allows the integrator to force the mirror to its final target position, but due to the low integrator gains used in this configuration, the error integrator is only used for relatively low frequency and slow moving signals. PID could be a good choice for certain point-and-hold applications.

PDF (Pseudo Derivative Feedback): Error Proportional is not used at all. Instead, the Error Integrator gain is used exclusively to create acceleration. To prevent the servo from going unstable, Position Proportional is also used (in similar proportions) which acts as a strong “spring” against the Error Integrator. One or both damping terms are also used with PDF. The result is that the integrator is always operational and always correcting the servo, driving the error to zero. Thus, PDF provides the greatest accuracy of the servo configurations possible with the Mach-DSP. However, since the only signal path from the command signal to the power amplifier is through the integrator, this generally results in slower operation than is possible by PD or PID. PDF is also much more difficult to tune than PD or PID. Some manuals refer to a servo configuration that uses Error Integrator, Velocity and Position Proportional as a “third-order servo”.

PDFF (Pseudo Derivative Feedback, with Feed Forward): The PDF configuration described above, but additionally the Error Proportional term is also used. Since Error Proportional (i.e. “Servo Gain”) is used in this configuration, it provides a more direct (i.e. “feed-forward”) path from the command signal to the power amplifier. Thus the PDFF configuration is faster than PDF, and is a great alternative when both high speed and high accuracy are needed. It is also the hardest to tune of all configurations.

5.3 Servo architecture and digitizing resolution

The Mach-DSP is essentially a digital implementation of an analog servo driver, but one that has much greater flexibility and utility. An overview of the architecture, including block diagrams is presented further below.

Digitizing resolution and implications

The $\pm 10V$ differential analog input command signal is filtered in the analog domain, and then digitized at 16-bits. For most applications, this input signal range corresponds to an optical deflection of either 40 optical degrees or 60 optical degrees peak-to-peak. Thus, from a command input standpoint, the corresponding digitized command resolution is:

40 optical degrees / 65,536 = 0.00061 degrees per bit (11 microradians)

60 optical degrees / 65,536 = 0.00092 degrees per bit (16 microradians)

The scanner's position signal is also digitized at 16-bits. However, in order to accommodate applications that require scan angles of 80 degrees optical or even greater, generally speaking, the 16-bit full scale digitizing range corresponds to around 90-degrees on the position signal. The corresponding digitized position resolution is:

90 optical degrees / 65,536 = 0.00138 degrees per bit (24 microradians)

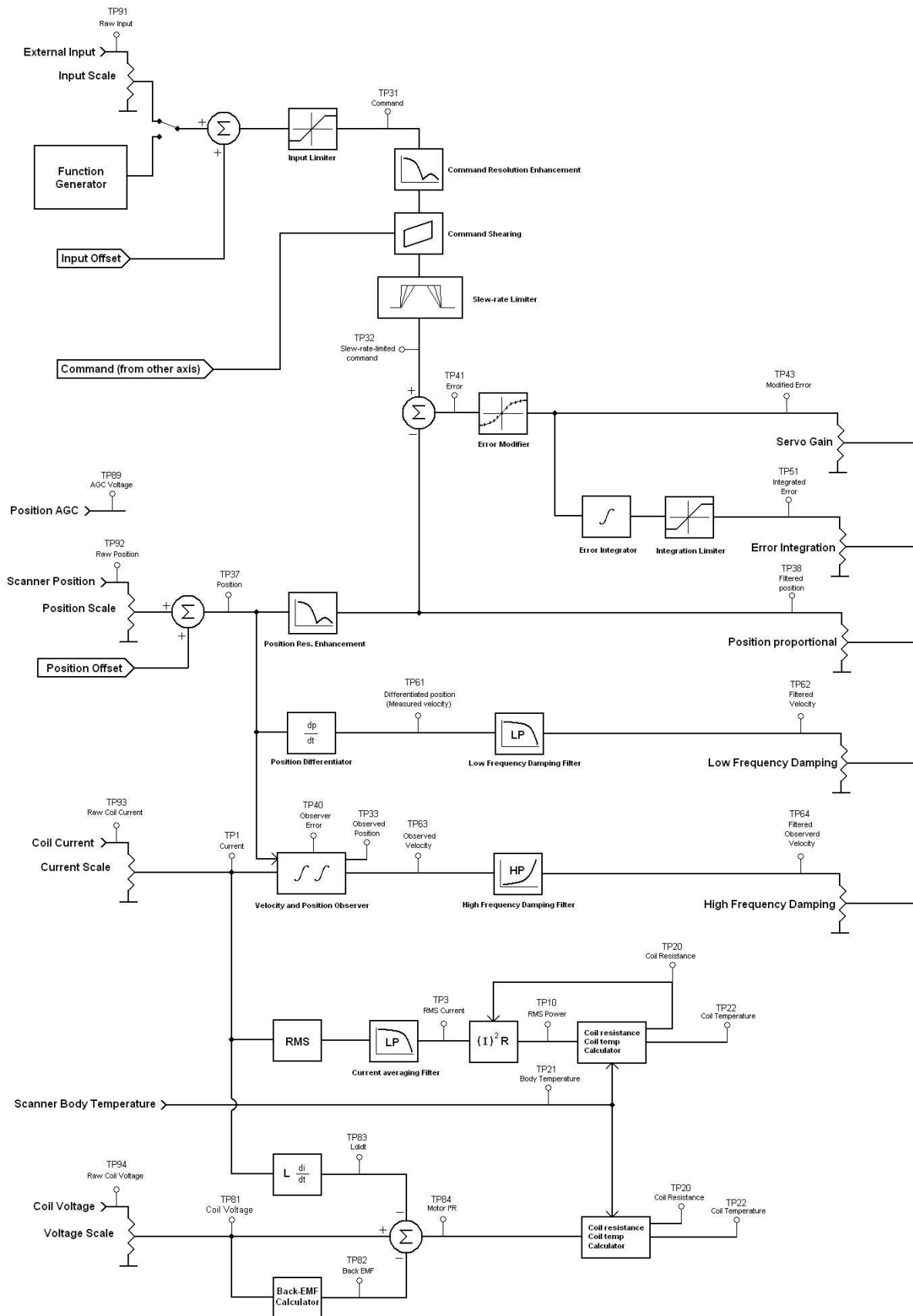
The numbers above, in microradians, represent the best-case resolution that is possible with any digital servo driver that uses 16-bit converters with these full-scale signal ranges. Certain noise sources (including quantizing noise) may effectively reduce this resolution even further. However, the Mach-DSP does incorporate a "Resolution Enhancement Filter", which averages several samples of the Command and Position signals, thus providing better precision than the figures above would suggest. Nevertheless, for applications requiring very fine positioning and low dither, testing will need to be performed using various settings of the Resolution Enhancement Filter, to determine whether the Mach-DSP can deliver the precision required by the application.

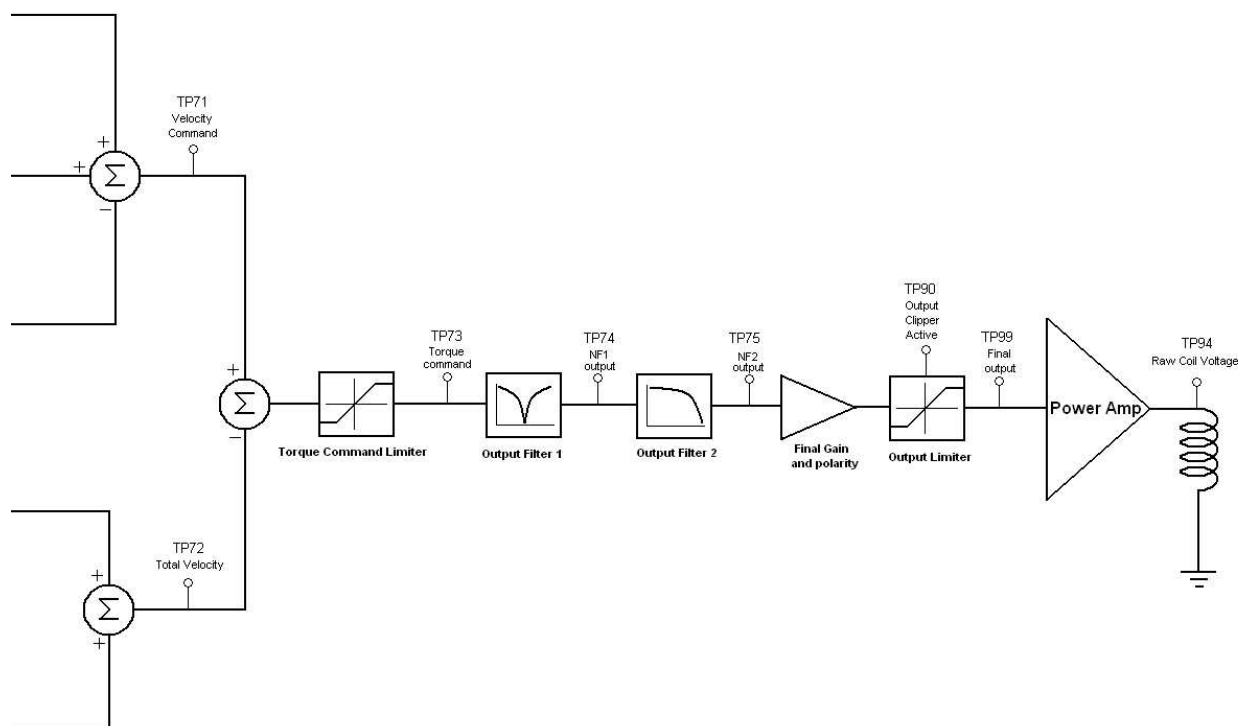
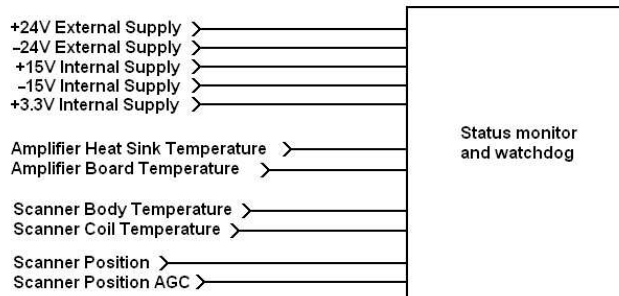
Servo architecture overview and block diagram

A complete block diagram of the Mach-DSP servo is shown on the next two pages. This diagram can also be accessed on the HELP menu of the Mach-DSP program.

Test Points on the diagram

The "TP" numbers are test points that can be accessed in the Oscilloscope portion of the Mach-DSP program. These test points can also be routed to any of six separate user-defined analog outputs on the Mach-DSP servo driver. The Mach-DSP program, oscilloscope function, and analog outputs are all discussed in Chapter 9.





Notes about test points and scope scale factors

Test points are scaled before being output to the scope or virtual scope. This lets you adjust the view. Each test point does not have its own scale factor. Instead, related test points are scaled using a single scale factor for the group.

Test points 1-9 are current related. These use the Current scale factor.

Test point 10 is power related and uses a fixed scale factor of 20 watts per volt (or division).

Test point 20 is resistance related and uses a fixed scale factor of 1 ohm per volt (or division).

Test points 21-29 are temperature related. These use the Temperature scale factor.

Test points 31-39 are position related. These use the Position scale factor.

Test point 40 is observer error and uses a fixed scale factor of 0.2 degrees per volt (or division).

Test points 41-49 are error related. These use the Error scale factor.

Test points 51-59 are integrator related. These use the Integrator scale factor.

Test points 61-69 are velocity related. These use the Velocity scale factor.

Test points 71-79 are output related. These use the Output scale factor.

Test points 81-89 are voltage related. These use the Voltage scale factor.

Test points 90-99 are not scaled and read raw signals. Typically these are A/D inputs or digital signals.

Test point numbers correspond with the X-axis. Add 100 to the number to get to the Y axis.

Simplified block diagram, and the five main tuning parameters

By looking at the complete diagram found on the previous two pages, it is clear that the Mach-DSP servo allows for the adjustment of many different operational parameters. However, there are five primary gain controls that are most fundamental to servo tuning. As described above, the tunable parameters are: Servo Gain (Error-Proportional), Error Integrator Gain, Position Proportional Gain, Low-frequency Damping, and High-Frequency Damping. Below you will find a simplified diagram showing how these five parameters sum together.

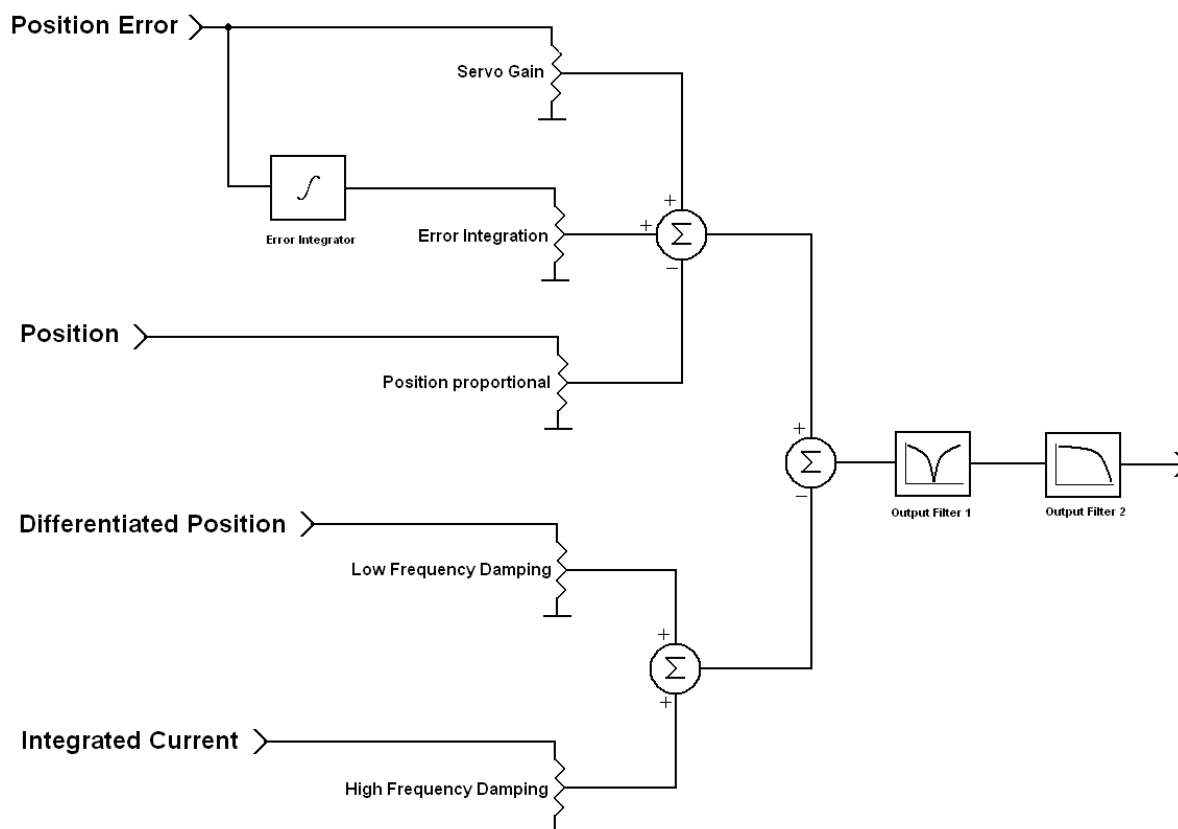


Figure 5.3: Simplified servo parameter diagram

The function of each of these parameters is described below:

Servo Gain: (Error Proportional)	The Servo Gain term provides current to the scanner in proportion to the difference between the commanded and actual position (i.e. proportional to the position error). This allows quick acceleration of the scanner.
Error Integrator Gain:	The Integrator Gain term provides nearly infinite gain at DC, allowing the servo to achieve zero error for a constant or slowly-changing input command, and maintains a constant tracking offset for a constant velocity command.
Position-Proportional Gain:	The Position-Proportional term feeds an inverted portion of the scanner position signal into the servo loop. This tends to act like an electronic spring, having a K factor equal to the Position Proportional Gain setting. Position Proportional can serve to balance the Error Integrator and keep it from winding up. This is particularly useful for PDF and PDFF servo configurations.
Low-Frequency Damping (Differentiated Position):	The low frequency damping term is obtained by differentiating the position signal, thus deriving a primary source of scanner velocity. This is used to maintain loop stability.
High-Frequency Damping (Integrated Current):	The high frequency damping term is obtained by integrating the drive current flowing through the scanner coil, thus deriving a secondary source of scanner velocity. High-frequency Damping is generally not accurate down to DC and therefore most often both Low-frequency damping and High-frequency damping are used together.

These five servo parameters allow the Mach-DSP to be configured as a Class 0 PD amplifier, a CLASS 1 PID amplifier, a CLASS 1 PDF amplifier, or a CLASS 1 PDFF amplifier. For the Mach-DSP, the only difference between all of these different servo configurations is which of the servo parameters above are used, and to what level they are tuned.

5.4 Dual Output Filters (low-pass, notch, or phase-lead)

Every scanner and mirror combination has one or more torsional resonances. The frequency and severity of these resonances is a function of the rotor components (including the rotating magnet, the bearings, the moving element of the position sensor, and the shafts which connect all of these elements) as well as the size and shape of the mirror being driven by the scanner. In many cases, if a notch or low-pass filter is not used, oscillation will occur at the torsional resonant frequency of the rotor/mirror system. This is especially true when driving mirrors for apertures larger than around 4mm.

In addition to the five main servo parameters described above, the Mach-DSP incorporates two separate output filters that may each be enabled and adjusted to prevent oscillations from occurring in the servo loop. (Although the Mach-DSP allows these filters to be configured as either low-pass, notch, or phase-lead, a notch filter is the type most often used, and chosen when there are a small number of well-defined resonances. When needed, the phase-lead filter can be used to improve damping.) The output filters allow for the use of high servo gains for fast response times. Figure 5.4 below gives a graphical example of the scanner's rotor/mirror resonance characteristic along with a notch filter response that would attenuate the resonance.

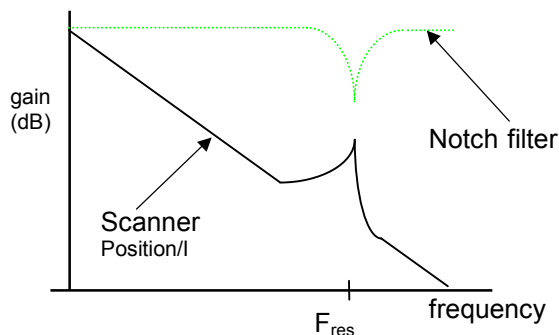
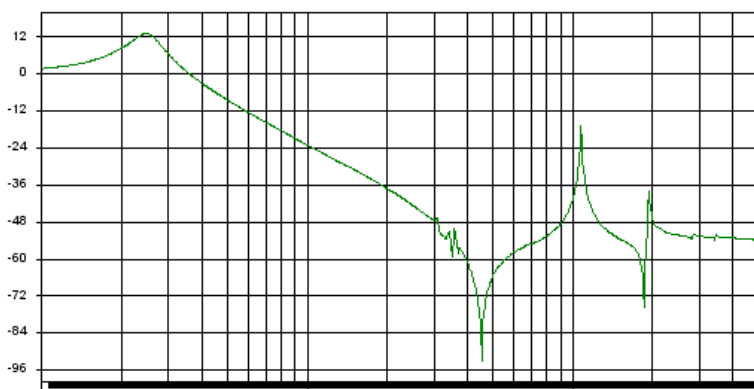


Figure 5.4: Notch Frequency Response

When there are many successive resonances as shown below, it may be more handy to use a low-pass filter instead of a notch. For that reason, the Mach-DSP allows you to choose a single-pole low-pass or two-pole low-pass, having adjustable cut-off frequency and Q settings, allowing the user to make appropriate trade-offs while adjusting tuning.



6.0 Command Input waveforms and implications

The Mach-DSP command signal may come from the built-in test signal generator, but more commonly it will come from the external analog command input connector. The type of waveform and amplitude of the command signal affects how the servo should be configured and tuned for optimal performance. This chapter gives an overview of the types of waveforms that the servo may encounter, and implications of each type of waveform.

6.1 *Large-Signal and Small-Signal waveforms*

The first things that must be understood are the terms “small-signal” and “large-signal”. Although optical scanners are used in a wide variety of applications, the command waveforms can be grouped into two broad categories: *small-signal* and *large-signal*. This terminology does not refer to the angular excursion of the mirror, but rather to signal levels internal to the servo amplifier, and particularly, whether or not the power amplifier saturates while moving the scanner. The power amplifier will saturate if the commanded acceleration exceeds the system’s linear range. Thus, it is power amplifier saturation that defines the transition between small- and large-signal commands.

A full-field step would be deemed a “large-signal” command, if the acceleration required to follow the waveform can not be accommodated. On the other hand, the same full-field step would be deemed a “small-signal” command, if the waveform were structured such that the maximum linear acceleration limit of the scanner/mirror/driver combination is not exceeded. These are illustrated in Figure 6.1:

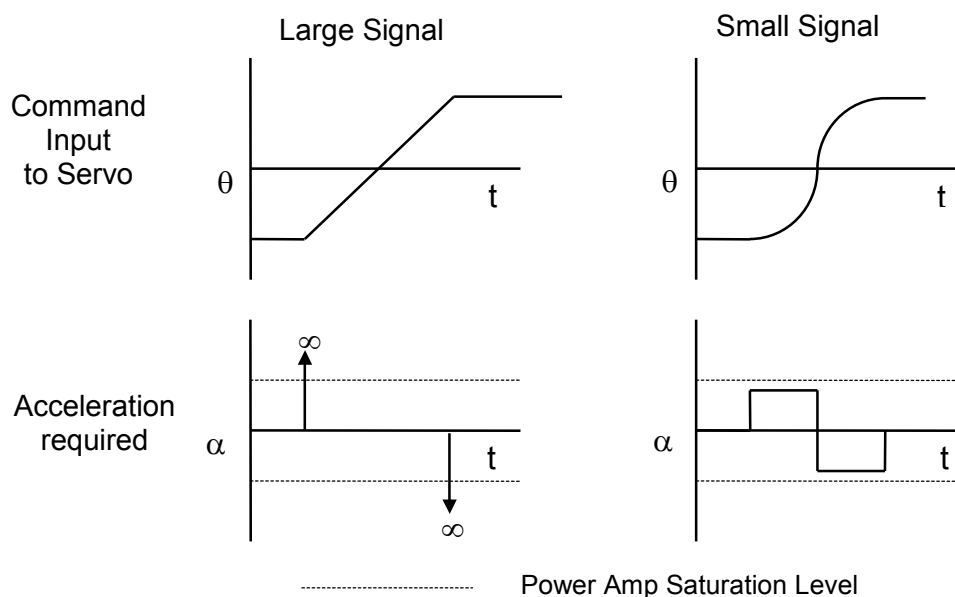


Figure 6.1: Large Signal and Small Signal Commands

6.2 Step waveforms

The servo tuning can be adjusted to optimize the step time to the settling accuracy and step size (sizes) required by a particular application. Servo response to a step command can be characterized as under-damped, critically damped, or over-damped. See Figure 6.2 below.

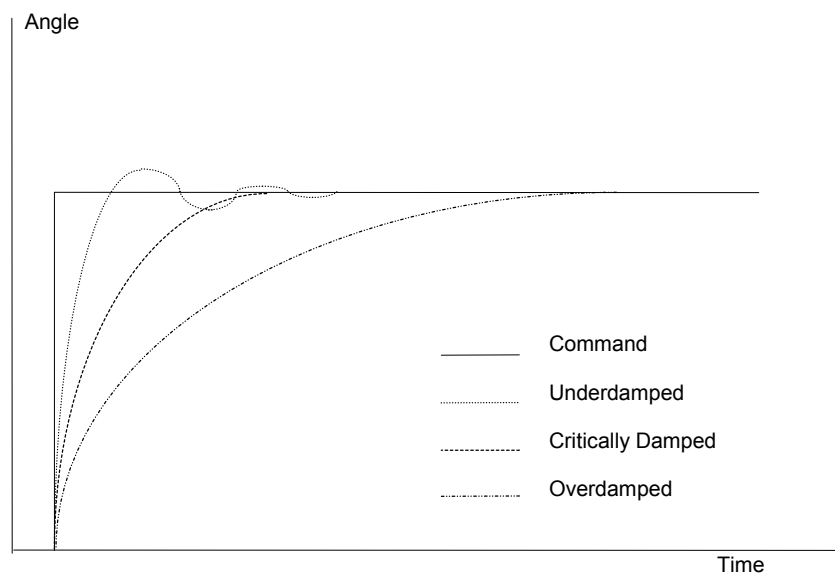


Figure 6.2: Types of Step Responses

With the scanner operating at the required step angle, the settling performance can be monitored on the position test point with the aid of an oscilloscope, or using the oscilloscope built into the Mach-DSP Servo Control application.

Rise times can be minimized by increasing the servo gain control. Typically the smoothness of settling can be improved by increasing the Low-Frequency Damping and High-Frequency Damping. For applications requiring settling to very small tolerances (200 microradians or less) an over-damped response frequently gives the fastest overall settling, even though the rise time is slower, because an over-damped tuning is gentler to the scanner and tends to excite fewer high-frequency resonances, allowing the tight settling to be achieved more readily.

Since large step commands may tend to saturate the power amplifier of the servo controller, it may be difficult to optimize the tuning for more than one large-signal step size. Therefore if consistent performance is required for a variety of different large steps, we recommend that you enable the slew rate limiter as well as possibly using the Error Signal Modifier. These help to eliminate the non-linearity's associated with saturating the power amplifier. Alternatively, you may structure (also known as micro-vector) the command waveform.

6.3 Raster (saw-tooth) waveforms

There are three types of raster command waveforms (See Figure 6.3). The easiest to generate and lowest performance command is a waveform that commands an instantaneous retrace of the scanner. The scanner cannot follow an instantaneous retrace, which causes it to operate at an angle that is smaller in amplitude than commanded. Performance can often be improved by the use of a dual slope command waveform. The slope of the retrace portion of the command is generally determined through trial and error, but a good starting point is 70% of the expected retrace time. The ideal raster command waveform is determined by taking the second integral of a square acceleration profile of a magnitude equal to the maximum unsaturated acceleration of the scan system.

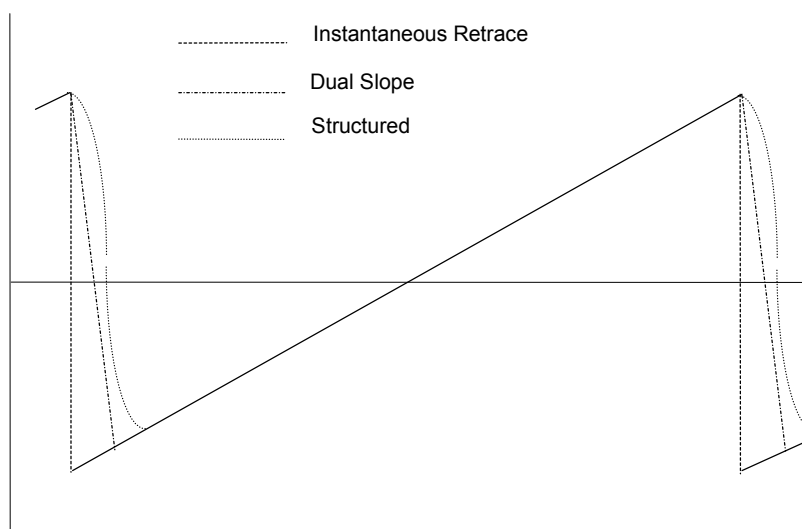


Figure 6.3: Raster Waveforms

The parameters of interest for a raster waveform are typically velocity linearity and retrace time. The velocity of the scanner can be observed by monitoring the velocity signal using the built-in oscilloscope, or by routing a velocity signal to one of the external user test points. The position signal can also be overlaid on the oscilloscope to determine the active scan angle.

Retrace time is typically minimized by increasing the *error* gain, while using the *damping* adjustment to maintain a smooth settling on the velocity waveform. The integrator term is used to maintain a constant velocity over the active scan region.

6.4 Vector Waveforms

Vector waveforms consist of a series of small steps that are updated at a frequency high enough such that they create a waveform that appears continuous to the scanning system. Vector waveforms should be structured so that the commanded acceleration and velocity do not exceed the scan system saturation limits. Typical vector applications include laser marking and 3D printing, where accurate tracking of complex waveforms is required.

It is frequently difficult to choose an optimization waveform for applications such as marking due to the complex, non-repetitive waveforms processed. In these cases a typical optimization waveform is a constant velocity command broken by a series of stop and start points over the full field. (See Figure 6.4) The velocity chosen should be the maximum velocity expected in the application. If the vector waveform is repetitive, such as a structured raster or step, the actual scan waveform should be used during the tuning process.

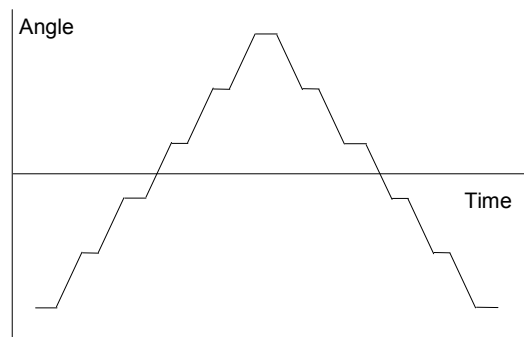


Figure 6.4: Vector-optimized waveform

7.0 Mach-DSP Servo Control Application program

The Mach-DSP servo driver can be setup and adjusted using the Mach-DSP Servo Control Application – a program that runs on Windows-based PCs.

(Within the rest of this manual, the Mach-DSP Servo Control Application is referred to as the “Mach-DSP program”).

In the picture below, you can see what the Mach-DSP program looks like when it is first started.



7.1 Setting up communications

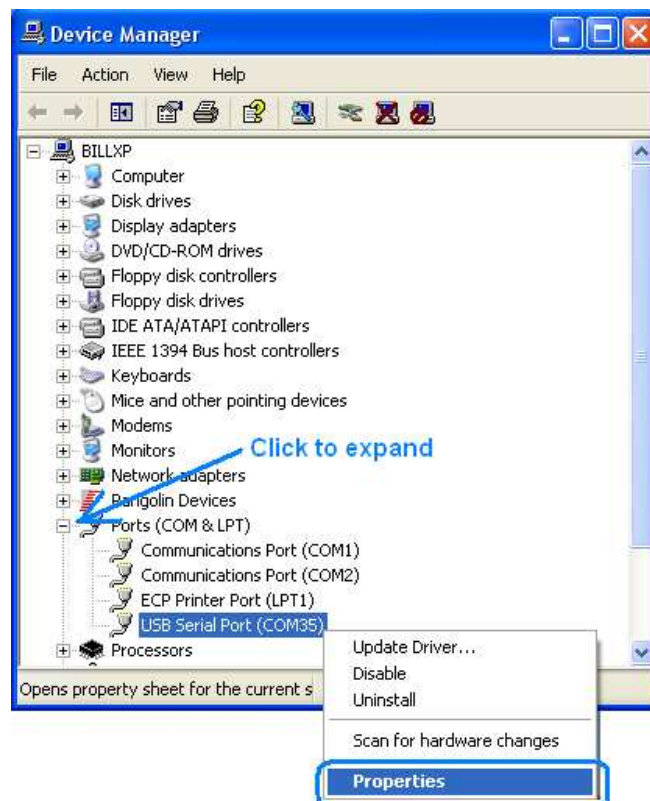
The Mach-DSP program communicates with the Mach-DSP servo using a serial port. To aid in the connection of a personal computer to the serial port, Pangolin supplies a special serial port cable that has a USB plug on one end, and a 1/8-inch phono-jack-style connection on one end.

Before you can begin using the Mach-DSP program, you must plug the special cable into both the computer's USB port and the Mach-DSP servo. If you are using Windows VISTA or later, the driver will be automatically installed on your computer and the cable will be recognized virtually instantly. If you are using Windows XP, you will need to obtain a driver from Pangolin.

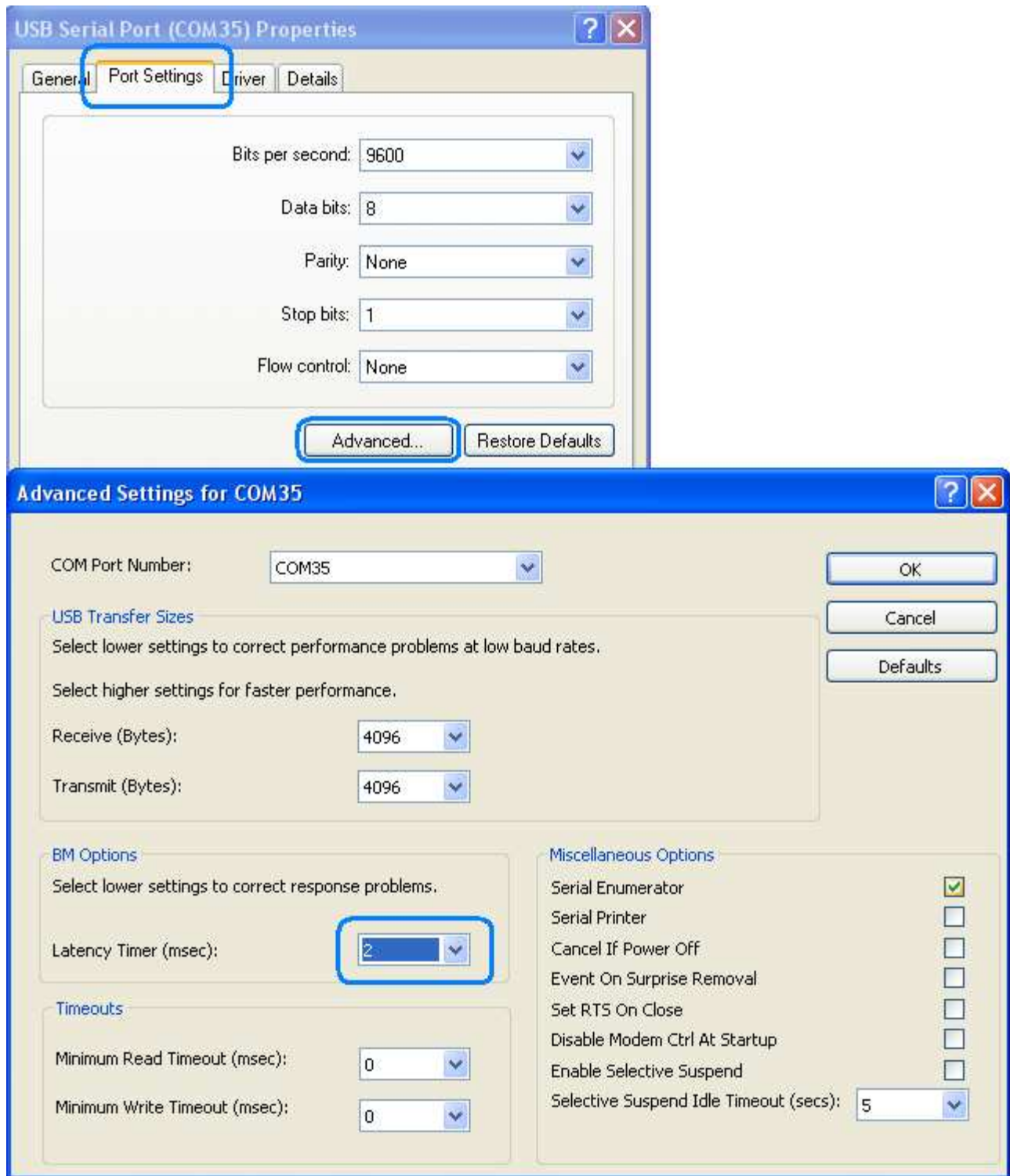
In any event, once the cable is plugged into the computer and the driver is installed on the computer (either automatically for newer versions of Windows, or manually in the case of Windows XP), Pangolin recommends changing a few settings on the driver. The cable will work as-is, but performance is a bit sluggish until the change is made.

To make the change, open the Windows Control Panel and click on the System icon. Then open Device Manager portion of Windows. (Device Manager can be opened several ways, depending on the version of Windows you are using.)

Once Device Manager is opened, click on the + next to "Ports (COM & LPT)". You should see "USB Serial Port" as shown below. Right-click on the USB Serial Port and choose Properties.



This will show another window similar to that shown below. Click on the Port Settings tab, and then click on the Advanced button, which will display yet another window...

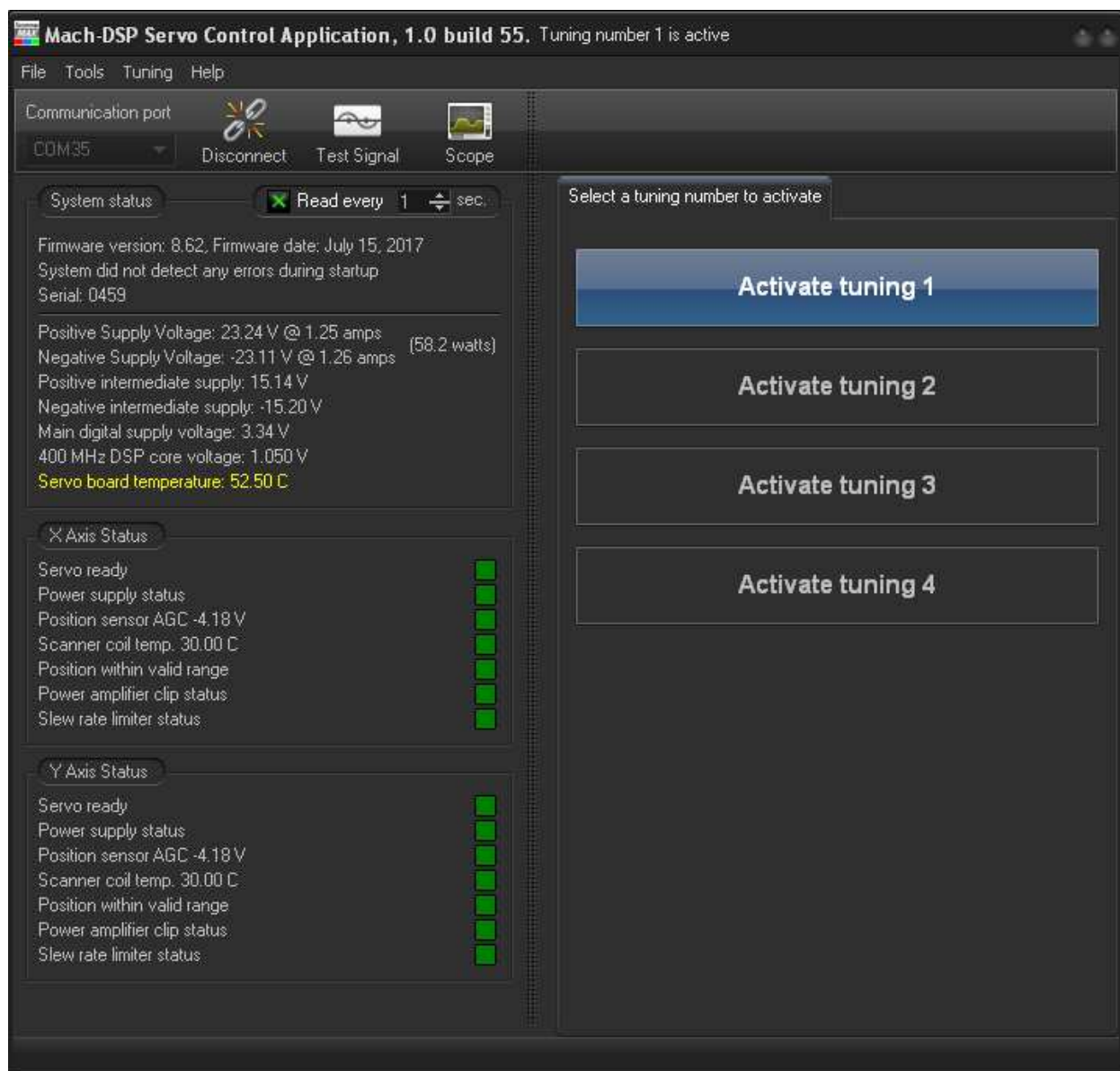


Locate the Latency Timer setting. The default is 16, which is quite slow. Set this to either 1 or 2 to greatly improve performance. Then click OK, and then OK again. After that, we recommend restarting the computer so the changes can take effect.

Once the cable is connected, you can start the Mach-DSP program, and then select the COM port that corresponds to the USB cable. (Note: With “legacy free PCs” that have been sold during the past decade, these PCs do not have native COM ports of their own. With this being the case, the COM port that is automatically chosen by the Mach-DSP program will probably be the correct port.)

Once the COM port is selected in the Mach-DSP program, you can press the “Connect” button. The Mach-DSP program will then attempt to connect to the Mach-DSP servo, and read the status and tuning information.

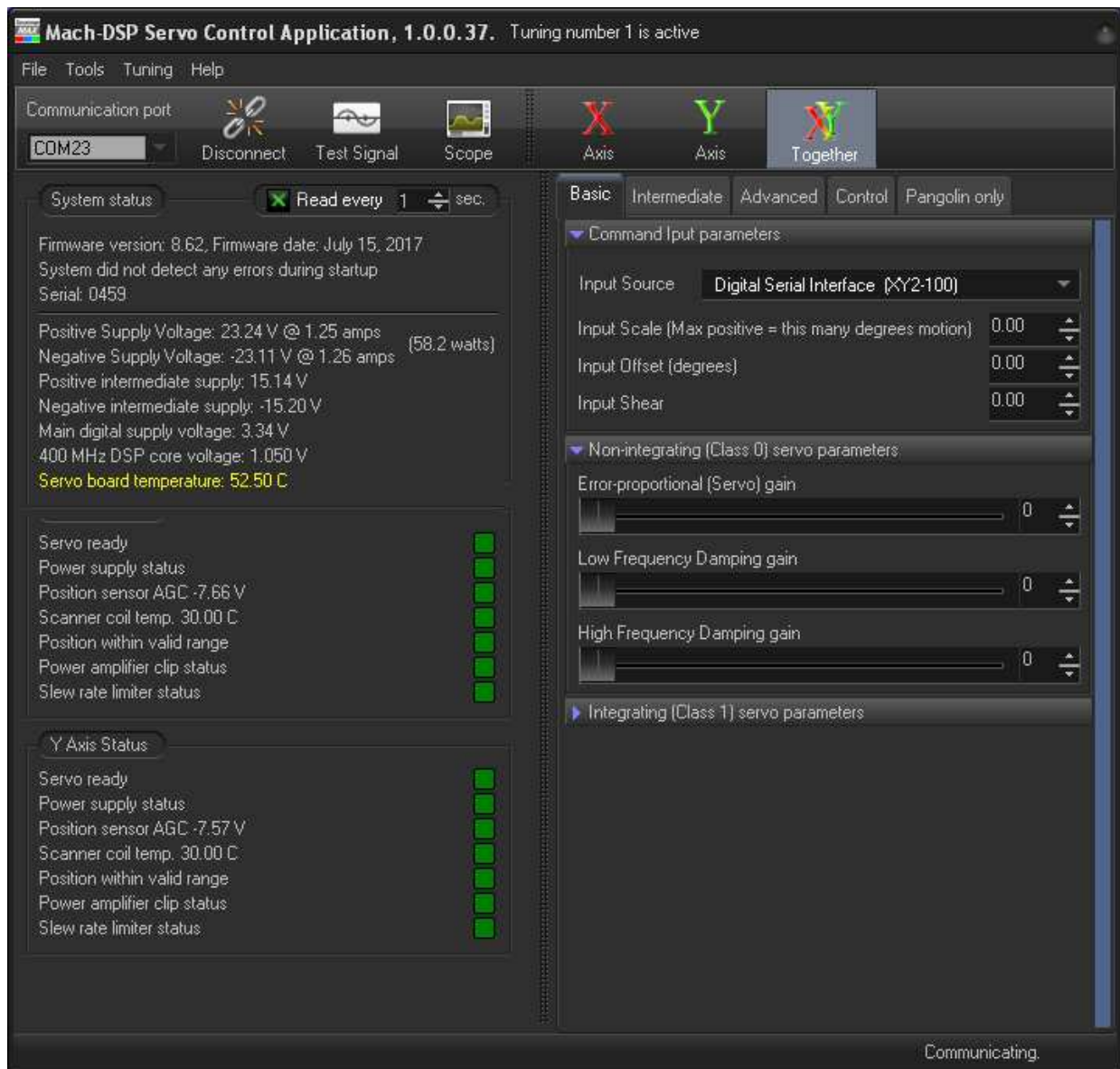
If you are in “User mode”, the window should look similar to that shown below. This window gives you status information and allows you to easily select built-in scanner tunings.



If you are in “Expert mode”, then the window will look different – allowing access to all of the servo parameters.

Because adjusting servo parameters incorrectly could potentially damage the scanners, “Expert mode” is restricted to those customers who really need to be able to access and modify operational parameters.

Note that Pangolin does not publish how to go from “User mode” to “Expert mode”. Customers must contact Pangolin to find out how to change modes.

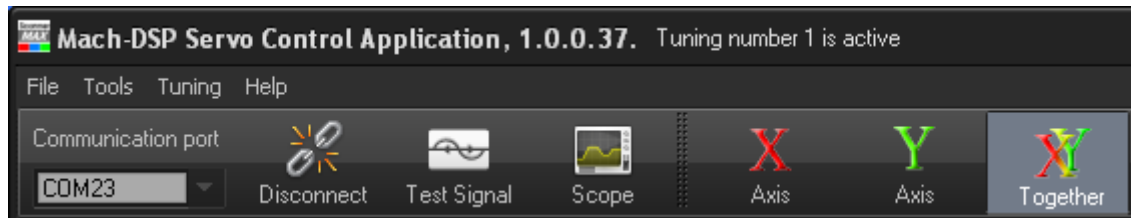


In any event, if the status area shows a problem, it might be due to the wrong COM port being selected. If this happens, simply press Disconnect, choose a different COM port, then press Connect again.

7.2 Menus, toolbar, status area, and control parameters

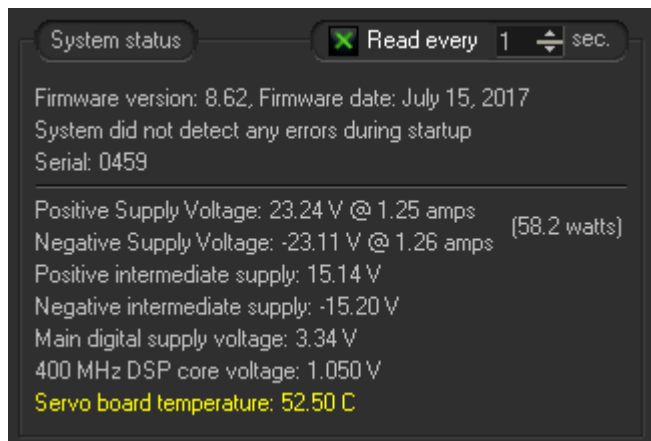
The Mach-DSP program is divided into several different sections, with each section providing a specific function. The sections are described below.

Menus and toolbar (top portion) of the Mach-DSP program



Along the top of the Mach-DSP program you will find various menus and a toolbar. The toolbar allows for quick access to the built-in Oscilloscope, quick access to the Test Signal Generator, and (if you are in "Expert mode") access to buttons that allow you to select whether you are tuning only the X-axis, only the Y-axis, or both X and Y axis at the same time.

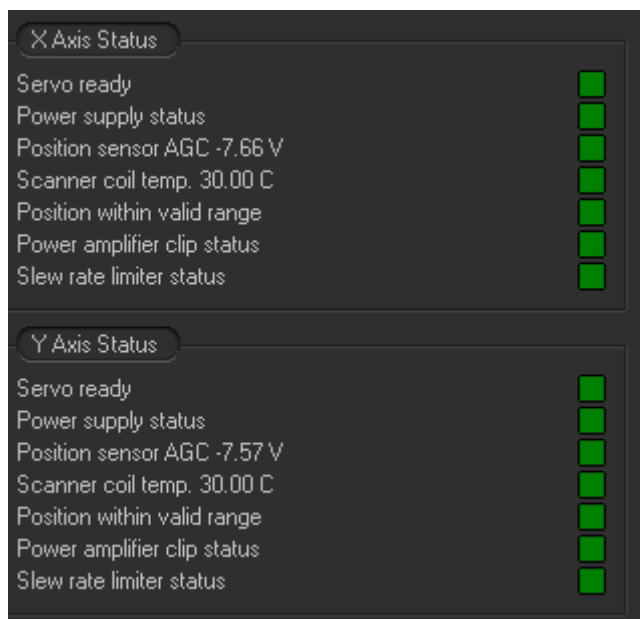
Status area (left side) of the Mach-DSP program



The entire left side of the Mach-DSP program shows status information, including information about the firmware loaded on the Mach-DSP servo driver and its serial number, along with the external and internal power supply voltages and even the temperature of the Mach-DSP servo driver board itself. This information could be important for troubleshooting.

Note that the values expressing power supply currents (i.e. the "@1.25 amps") and total power consumption (i.e. the "58.2 watts") shown next to the Positive Supply and Negative Supply voltages are estimates based on the known quiescent current behaviors of the Mach-DSP along with the measured coil currents flowing through each scanner. Nevertheless, although these are only estimates, the values reported should be good enough for gauging power consumption, and thus power supply requirements.

X and Y Axis status indicators



Below the main status area at the top, there are status indicators for each axis. The status indicators give a text-based description along with a color, so that you can see – at a glance – whether everything is working properly, or if there is a problem. When a colored block is green, this is an indication that the particular parameter is normal, or quiescent (i.e. idle). When a colored block is yellow, that is an indication that the item is operational. When a colored block is red, this is an indication of a problem that will prevent the axis from working properly. Each status indicator is discussed below:

Servo ready: When the colored block is green, this indicates that the servo for this axis is fully initialized and operational. When the colored block is red, this indicates that the servo on this axis is either purposely disabled (by user controls) or that it is not operational due to a problem, such as a scanner not being plugged in, a blown fuse, or an electrical fault of some kind.

Power Supply Status: When the colored block is green, this indicates that the external power supplies feeding the Mach-DSP as well as the internal power supplies (+/-15V and +3.3V) are receiving voltage sufficient to operate the servo successfully. When this colored block is red, this indicates that there is a power supply problem of some kind, in which case looking at the power supply voltages in the section above this should reveal the source of the problem.

Position Sensor AGC: This shows you the actual position sensor AGC voltage being used to operate the scanner, as well as a colored block that can indicate whether or not the voltage is within a normal range. The position sensor voltage can give you an indication of scanner health as well as an indirect indication as to its temperature. You will notice that as a scanner gets hotter, the position sensor AGC voltage will also rise. When the colored block is green, this indicates that the AGC voltage is within a normal

range. When the colored block is red, this indicates either that the scanner is not connected, or that there is an electrical fault with the scanner or the connecting cable.

Scanner coil temp: This shows you an estimate of the scanner coil temperature. Depending on the settings found in the “Coil Temperature Calculator” section of the Advanced tab, the estimate can either be based on the amount of current flowing through the scanner, or the estimate can be based on the measured coil resistance during servo operation. For more information see the “Coil Temperature Calculator” section of this manual.

The “Scanner coil temp” label will change color, depending on the temperature of the coil. For example, when the coil temperature reaches 50C, the label will become yellow. When the coil temperature reaches 60C, the label will become orange. When the coil temperature becomes 80C, the label will become red. This color change is meant to be an additional indication of coil temperature.

In addition to the label color providing an indirect indication of temperature, there is a colored block to the right of the label. When the colored block is green, this indicates that the scanner coil has not exceeded the maximum that is specified in the “Pangolin only” tab. When the colored block is red, this indicates that the “Maximum temperature before servo fault” has been exceeded, in which case the servo will be shut down for several seconds, before it is re-started. The temperature itself will also change color depending on the coil temperature.

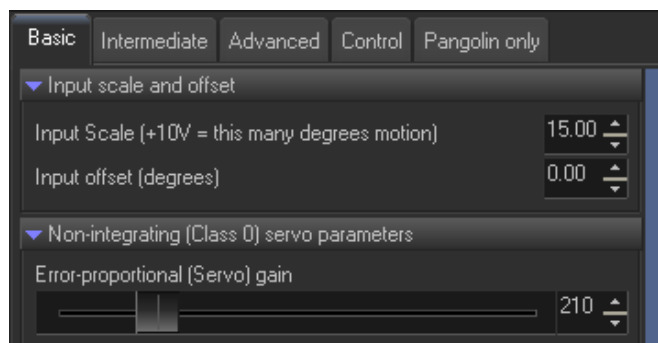
(Note that the estimated temperature will be more accurate if you attach a thermistor to the X-Y mount and connect it to the Test Interface connector, as described in Chapter 3.5 of this manual.)

Position within valid range: When the colored block is green, this indicates that the position signal is within a normal operating range. When the colored block is red, this indicates that the position signal has exceeded the range indicated by the “Position fault detector” portion of the Advanced tab.

Power amplifier clip status: When the colored block is green, this indicates that the power amplifier that drives the scanner is operating completely within its linear range. When the colored block is yellow, this indicates that the power amplifier is saturated. For many applications (for example laser displays), power amplifier saturation is completely expected. For applications that require completely linear and deterministic servo behavior, this could be an indication that the command signal requires structuring, or that the slew rate limiter and/or error modifier need to be adjusted.

Slew rate limiter status: When the colored block is green, this indicates that the input command signal has not exceeded the slew rate limiter settings, and thus, that the slew rate limiter has not had to take action and modify the command signal. When the colored block is yellow, this indicates that the slew rate limiter is actively modifying the input command signal.

Adjustable parameters (right side) of the Mach-DSP program



The entire right side of the Mach-DSP program has sliders and other user interface elements that allow you to control the behavior of the Mach-DSP servo. These controls are separated into sections on tabs. These tabs separate not only the functions, but also the user experience level expected to use the controls. The tabs are described more below.

The **Basic** tab includes the tuning controls that are typically found on most servo drivers on the market. These include Input Scale and Input Offset, Servo Gain, Damping, and Integrator settings. Many users have experience with adjusting controls of this nature, and so they are put on this first, and most basic tab.

The **Intermediate** tab includes controls expected to be used by intermediate-level users. These include Slew Rate Limiter parameters, as well as some filter parameters.

The **Advanced** tab includes controls expected to be used only by the most advanced users, and indeed, these controls should only be used when setting up a brand new scanner on the Mach-DSP servo.

The **Control** tab includes user interface elements that are used to specify how the TTL Inputs and TTL Outputs behave.

The **Pangolin Only** tab includes controls that are related to the Mach-DSP servo itself, and have to do with the calibration and customization of the Mach-DSP for particular applications. Adjustment to these parameters should only be done with the supervision and assistance of Pangolin.

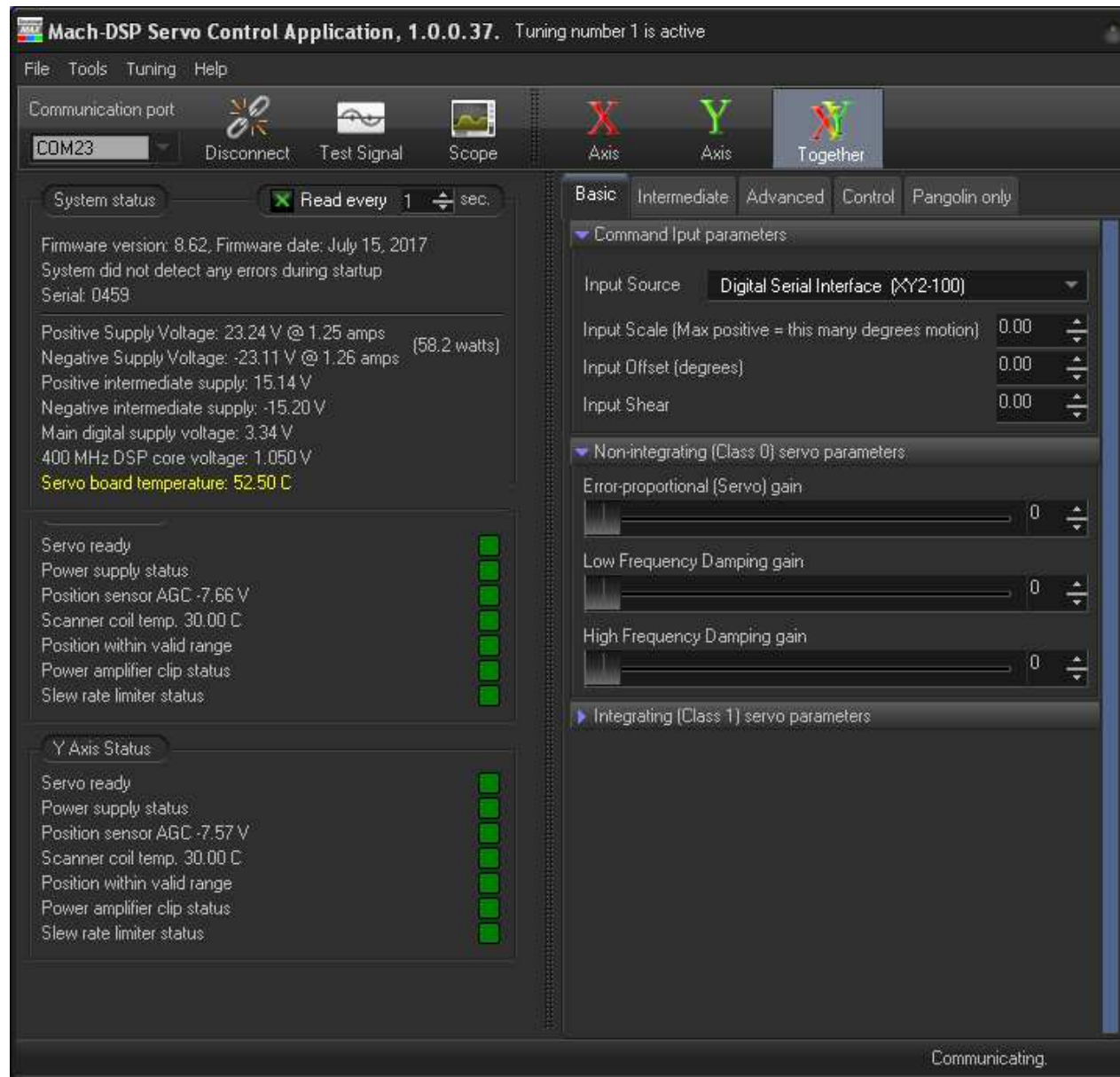
Specifying which axis is affected by controls on the tabs

It is important to understand that the axis being adjusted is signified by the X, Y, and XY buttons found on the toolbar. Indeed, these buttons are located immediately above the control parameters to help reinforce that these buttons apply to Control Parameters.



7.3 Basic control parameters

The controls that are found on the Basic tab are separated into three categories – those controls that adjust Command Input; those controls involved in Class 0 servo configurations; and those controls involved with Class 1 servo configurations.



Input Command parameters

In this section, you will find the parameters related to the input command signal.

Input Source (analog or digital serial input)

This selects whether the Input Command signal is derived from the 6-pin Analog Input connector, or the 8-pin header (with or without XY2-100 daughterboard) providing serial-digital command input, using either the XY2-100 protocol or FB4 protocol.

Input Scale (mechanical degrees motion for maximum positive input)

This controls the amount of mechanical motion caused by the input command voltage (or digital signal). For example, if this is set to 15.00, then an input command signal having +10V DC (or a 16-bit signal having a value of 65535) will create +15.00 mechanical degrees of deflection (+30 optical degrees of motion). This also implies that -10V (or a 16-bit signal having a value of 0) will create -15 mechanical degrees (-30 optical degrees) of deflection. Thus, 20V peak to peak (or the full scale digital signal range) will create 30 mechanical degrees peak-to-peak (or 60 optical degrees peak to peak) deflection. To invert the polarity of input versus motion, this can be set to a negative number. For example, if this is set to -15.00, then an input command signal having +10V DC (or a 16-bit signal having a value of 65535) will create -15.00 mechanical degrees of deflection. This control allows values up to 150.00, thus providing increased sensitivity in the form of smaller input command signals that create large optical deflection angles.

Input Offset (mechanical degrees of offset added to the input)

This controls the mechanical degrees of offset that will be applied to the servo input.

Input Shear (geometric image rotation)

This controls the amount of signal from the X-axis that is fed into the Y-axis (and vice-versa). This is usually used to compensate for small misalignments in mirror mounting or misalignments of the beam entering the X-Y mount. This can also be used to perform geometric correction. (Although it's not intuitive or obvious why, the servo algorithm requires somewhat more processing time when shear on the **X-axis** is not zero.)

Non-integrating (Class 0) servo parameters

In this section, you will find the main three parameters used by many servos found on the market – most especially PD servos.

Error-proportional (Servo) Gain

This controls the amount of position error signal that is fed into the summing node. Some servo drivers call this “Servo Gain”, and others call this “Error-proportional gain”.

In general, this controls the acceleration that the scanner will experience, therefore when greater speed is needed, this should be increased. Error-proportional (Servo) gain is used in PD, PID and PDFF servo configurations.

Low Frequency Damping Gain

This controls the amount of velocity (derived through differentiated position) that is fed into the summing node. Some servo drivers call this “Low Frequency Damping” or just “Damping”. In general, this controls the deceleration that the scanner will experience, therefore when overshoots are happening on steps of all amplitudes, increasing this control may help. Low Frequency Damping Gain is used in all servo configurations (PD, PID, PDF, and PDFF).

High Frequency Damping Gain

This controls the amount of velocity (derived through integrated current) that is fed into the summing node. This works in a similar way to Low Frequency Damping Gain, but the way that this servo term is derived, High Frequency Damping is typically applicable only to fast-changing signals. If your application involves only slow-changing signals (closed-loop bandwidths lower than around 2 kHz), High Frequency Damping Gain may not be needed at all – in which case it can be left at zero. In other cases both Low Frequency Damping Gain and High Frequency Damping Gain must be used (normally not in equal proportions) to achieve critical damping. Thus, High Frequency Damping Gain may be used in all servo configurations (PD, PID, PDF, and PDFF).

Integrating (Class 1) servo parameters

In this section, you will find additional parameters used by integrating servos, including PID, PDF and PDFF servos.

Error Integral Gain

This controls the amount of integrated position error, which is fed into the summing node. When this is set to zero (thus creating a Class 0 servo), a small amount of error may remain when comparing the commanded position and actual position. When this is set to a relatively low gain, position errors lasting more than a few milliseconds will be minimized. When this is set to a relatively high gain, position errors can be reduced more quickly, but this servo term must be increased slowly and carefully. Generally high integrator gains also require high values of Position-proportional gain in order to maintain stability.

Position-proportional gain

This controls the amount of position signal that is fed into the summing node. Generally this should be left at zero for Class 0 servos, and will be higher (in many cases around double) the Error Integral Gain setting.

Anti-windup type

When the servo is configured for PID or PDFF, it is possible that the integrator may cause overshoots, especially when the input command signal involves large squarewave-like steps. The anti-windup system can be used to eliminate such overshoots, by controlling when, and in what amount error integration happens when the power amplifier becomes saturated (as indicated by the "Power amplifier clip status"). It is generally recommended that you consult Pangolin about your application before adjusting this.

Enabling and Disabling the X-axis or Y-axis servo

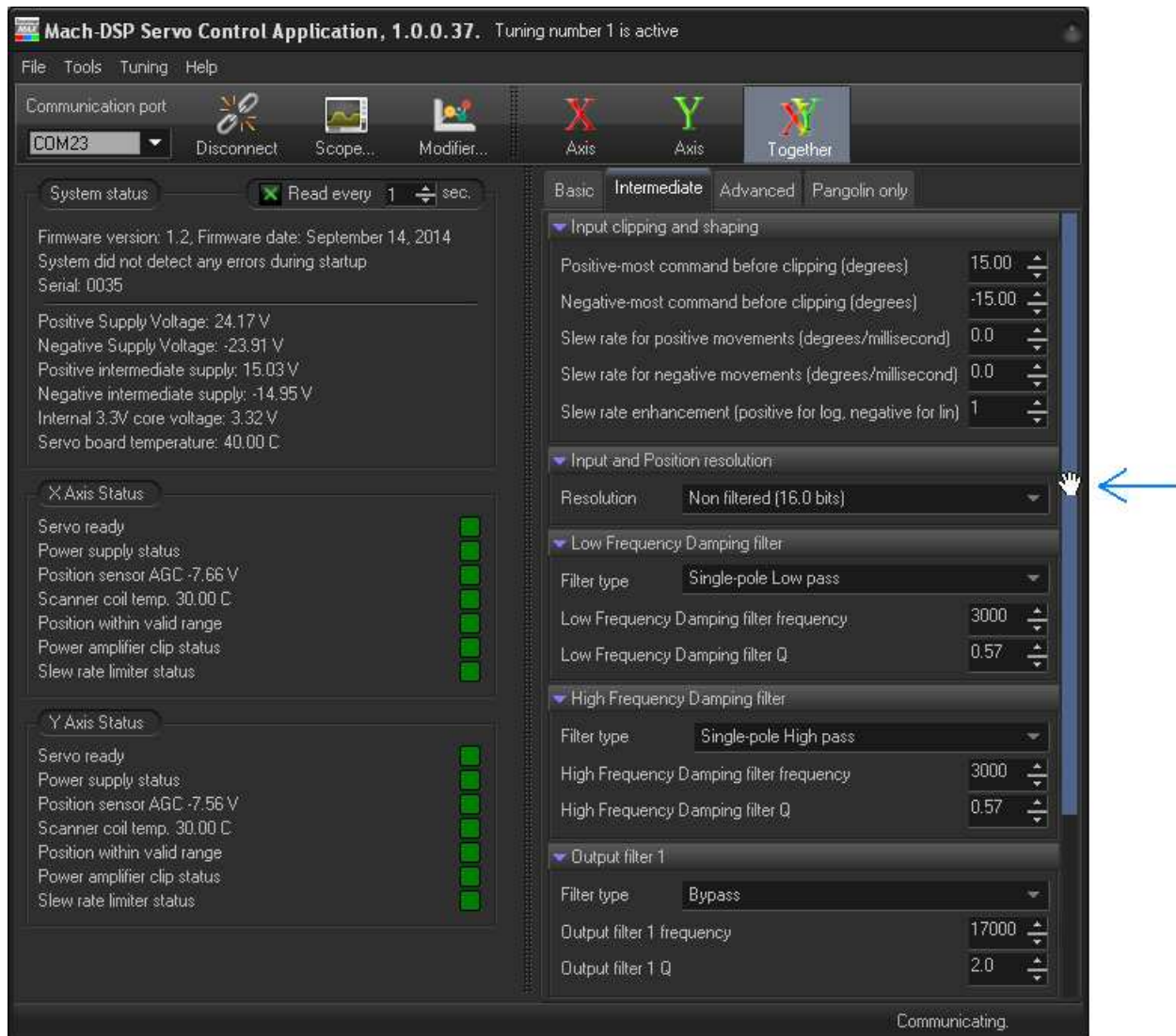
When Servo Gain, Low Frequency Damping, High Frequency Damping, Error Integral and Position Proportional gains are all set to zero, the servo driver for that axis is disabled. This could be handy for running the Mach-DSP as a single-axis servo driver. When a single axis is disabled, the processor does not spend much time doing calculations for the disabled axis.

Up to 200kHz sample rate is possible when both the X- and Y-axis are enabled and relatively few servo parameters are used. Up to 300kHz sample rate is possible when only a single axis is enabled and when relatively few servo parameters are used.

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7.4 Intermediate control parameters

The controls that are found on the Intermediate tab are separated into several categories, including controls involved in Input command signal, position signal filtering, damping filtering, and power amplifier drive signal filtering.



Note that there are more controls in the Intermediate section than in any other section. Because of this, not all of the controls can be shown on the screen at the same time if the window is not resized and made taller. To help with this, you will notice that there is a blue rectangular area on the right (highlighted by the blue arrow). This area works like a scroll bar. When you move the mouse over this area, you will notice that the cursor turns into a Hand icon. If you click and drag in the blue area, you will be able to scroll the panel and access other controls.

Input clipping and shaping

In this section, you will find the parameters related to the input command signal.

Slew rate for positive movements (degrees per millisecond)

This controls the slew rate limiter for scanner motion that corresponds to signals having a rising slope. If you experience overshoots on very large step inputs but small step inputs are well controlled, then the slew rate limiter may be used (or may be used in conjunction with the error signal modifier) to eliminate overshoots on such large-step inputs. (Note that if this is set to zero, then the slew rate limiter is completely disabled.)

Slew rate for negative movements (degrees per millisecond)

This controls the slew rate limiter for scanner motion that corresponds to signals having a falling slope. Although typically this would be set to the same number as the “Slew rate for positive movements”, the slew rate limiter in the Mach-DSP servo driver allows separate values for positive and negative slopes, for special applications.

Slew rate enhancement (positive for logarithmic; negative for linear enhancement)

A conventional slew rate limiter is well known to control overshoots, but is also known to impose a speed penalty on scanning, because the rate-of-change-of-command is effectively limited to a pure triangle-function. To provide better performance, the Mach-DSP includes a “Slew rate enhancement”, which allows the slew to *accelerate* either logarithmically (if it is set to a positive number) or linearly (if it is set to a negative number) based on input amplitude. The ultimate benefit is the elimination of overshoots while minimizing the speed penalty normally associated with a slew rate limiter.

Input and Position Resolution Enhancement

The Mach-DSP includes the ability to successively average several samples, thereby effectively increasing the resolution of the Command and Position signals. (To learn more about [how averaging several samples can effectively increase ADC resolution](#), search the Internet using the underlined/highlighted text above.) Selecting enhanced resolution can reduce the quantization noise of the analog-to-digital converters on the Mach-DSP (as well as other external noise sources) and thus decrease dithering of static mirror positions. However, this comes at the cost of reducing command signal bandwidth and increasing tracking error (also known as tracking delay). Nevertheless, if dither and noise are greater priorities than bandwidth and tracking error, this feature may be helpful. Moreover, since this feature allows user-selectable averaging of anywhere between 2 samples (for 0.5 bit resolution enhancement) and 4 samples (for 1.0 bit resolution enhancement), you can try different resolution enhancements to balance the tradeoff between dither/noise reduction and bandwidth/tracking error. Note that the damping parameters will need to be adjusted when this value is changed. Also note that if *Input Shear* is not zero on both the X- and Y-axis, then you should use the same *Input and Position Resolution Enhancement* setting for both X- and Y-axis.

Low Frequency Damping filter

Within the Mach-DSP, low frequency damping provides gain over a Velocity term that is derived from differentiating the position signal. Differentiating an electrical signal essentially is a high-pass filter and thus, this tends to exacerbate noise in the system. For that reason, this velocity term is passed through a low-pass filter.

As was the case with the Position-proportional filter, you can choose to bypass the filter, or you may choose a single-pole low-pass or two-pole low-pass filter. Bypassing is not recommended. As the cutoff frequency is reduced, noise in the servo is also reduced, but an additional phase delay is also introduced into the servo, which could affect the quality of motion. Normally this phase delay is compensated using High Frequency damping, and appropriately adjusting the High Frequency damping filter. Nevertheless, the filter frequencies must be adjusted carefully and there is a tradeoff between noise that exists in the servo and the quality of motion that results.

High Frequency Damping filter

Within the Mach-DSP, high frequency damping provides gain over a Velocity term that is derived from integrating the current flowing through the scanner coil. (This integrated current may optionally be combined with the scanner's actual position so that the Mach-DSP provides true observed velocity.) Although this provides a very good estimate of velocity, and one that does not contain noise, this kind of velocity is normally not usable for very low velocities. For that reason, this velocity term is passed through a high-pass filter.

As was the case with the Low Frequency damping filter, you can choose various filter types and cutoff frequency to optimize and tradeoff noise in the servo and position quality. Best results are usually obtained when the cutoff frequency of the High Frequency Damping filter is set somewhat higher than that of the Low Frequency Damping filter.

Output filter 1 and Output filter 2

The approach presently used in galvanometer scanning is to place a mirror on the end of a motor shaft. This creates a two-mass, one-spring mechanical system (with one mass being the scanner's moving magnet rotor, another mass being the mirror, and the spring being the shaft and mirror mount that connects the rotor to the mirror). This type of mechanical system will always have multiple resonances. In the case of small mirrors (for example 3mm or 4mm aperture), these resonances may have a sufficiently high frequency and sufficiently low Q that they will not be noticeable. But generally when the mirrors become large enough to accommodate a 5mm or larger aperture, these resonances will cause instability in the servo, especially at high servo gains.

(Note that the actual frequencies of these resonances can be determined using the Dynamic Signal Analyzer feature within the Mach-DSP program.)

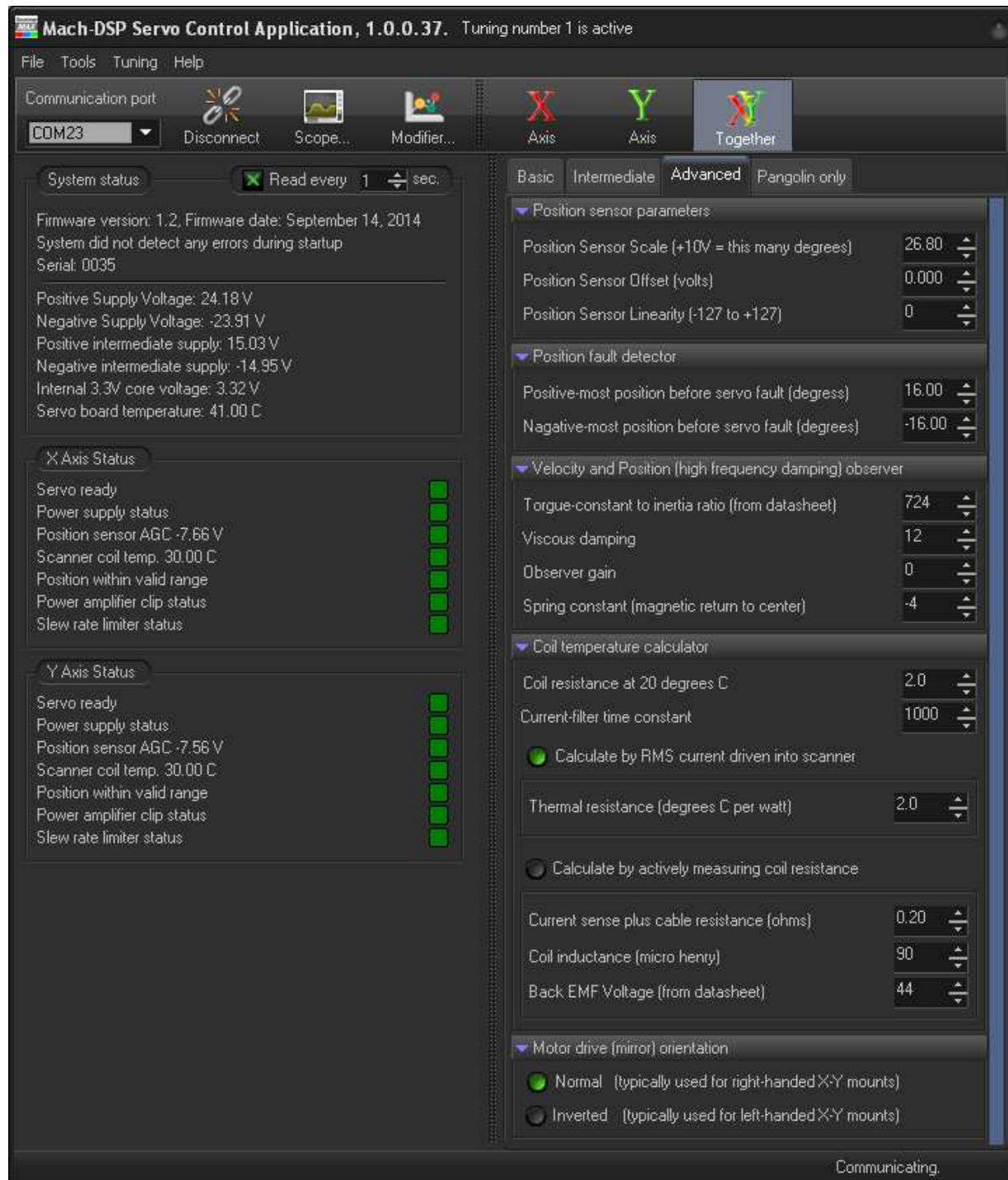
For that reason, the Mach-DSP incorporates two separate filters, which may optionally be employed to control these resonances. Each filter may be bypassed (saving computational time) or may be selected as a single-pole low-pass, a two-pole low-pass, notch, or phase-lead filtering. Of the four types of filters, the notch filter is used most often, and has the lowest impact on scanner position motion quality.

The filter frequency and filter Q are adjustable along with the filter type. Generally the use of a lower Q allows for better control over resonances, but unfortunately also imposes a greater phase delay in the servo loop, which may affect the quality of motion. Thus the filter type, filter frequency and filter Q must all be adjusted carefully, while monitoring the result using the Dynamic Signal Analyzer as well as the Oscilloscope, to eliminate any resonances while at the same time minimizing impact on position quality.

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7.5 Advanced control parameters

The controls that are found on the Advanced tab are separated into several categories, including controls involved in position sensor scaling and fault detection, high frequency velocity derivation, coil temperature calculation, and motor drive orientation. Normally these controls only need to be used when scanners are being assembled along with a Mach-DSP servo for the first time.



Position sensor parameters

Galvanometer scanners use LEDs and silicon photodiodes to detect the position of the rotor. Although the LEDs and photodiodes are made of high quality materials, there are small differences between each LED and photodiode inside the scanner. To accommodate these differences, the Mach-DSP provides controls to precisely calibrate the amount of beam deflection created by the scanner.

Position Sensor scale (mechanical degrees motion for +10V electrical signal)

This controls the amount of mechanical motion of the scanner to cause +10V to appear at the input of the Mach-DSP digitizer (and to appear on the test interface connector). For example, if this is set to 25.0, then a mechanical deflection of 25.0 degrees will create +10V DC on the digitizer. This also implies that -10V corresponds to -25.0 degrees of deflection. Thus, 20V peak to peak position signal will correspond to will create 50 mechanical degrees peak to peak (or 100 optical degrees peak to peak) deflection.

Position Sensor offset (degrees)

This controls the amount of amount of offset that must be added to the position signal in order to make a zero-volt command signal to correspond to the center of the projection surface. This may be used to fine-tune the zero position of the X-Y system, since it is difficult to precisely achieve centering through mechanical adjustment alone...

Position fault detector

All mirror sets provided by Pangolin are designed to deflect a beam over a prescribed projection angle. Deflection beyond the prescribed angle will, at the very least, cause the laser beam to overfill the mirror surface, creating a loss of projected beam power. Moreover, in some cases if mirrors are deflected well beyond their prescribed range of angles, they may crash into each other, causing pieces of the mirror to chip away. To prevent this, the Mach-DSP includes a fault detector, which will shut down the servo (momentarily) if the position signal exceeds a specified projection angle. Normally this would only happen accidentally while tuning up a servo, or as a result of some electrical fault.

Positive-most position before servo fault (degrees)

This specifies the positive-most position signal that will be allowed before a "servo fault" is triggered, specified in mechanical degrees.

Negative-most position before servo fault (degrees)

This specifies the negative-most position signal that will be allowed before a "servo fault" is triggered, specified in mechanical degrees.

Note that once a servo fault is triggered, the Mach-DSP servo will shut down, and then go through a controlled startup sequence, which takes several seconds.

Also note that these controls are related to the internal position signal (viewable on the built-in oscilloscope). A “positive” position signal may correspond to right-ward or left-ward beam deflection, depending on the orientation of the X-Y mount and other factors. It is this reason that these are referred to as “positive” and “negative” instead of “clockwise”, “right-ward”, or some less-definitive quantity.

Velocity and Position (high frequency damping) observer

The Mach-DSP servo includes a flexible means of deriving high frequency velocity information. Depending on the adjustment of the parameters in this section, simple current integration could be used for high frequency damping, or alternatively, velocity information may come from a “rigid body observer” built into the Mach-DSP servo. (For more information about “observers”, see servo text books.)

Torque-constant to inertia ratio

In general, this controls the amount of current that is integrated to ultimately create the high frequency velocity signal, which is then controlled using the “High Frequency Damping gain” described above. Greater amounts of “Torque-constant to inertia ratio” will allow lower amounts of High Frequency Damping gain.

When “Observer gain” is set to zero, this control only influences the amount of High Frequency Damping gain that is needed. Stated another way, this works like a gain control over the High Frequency Damping gain. However, when Observer gain is set above zero, it is important that the Torque-constant to inertia ratio be set correctly, otherwise the observer will not function correctly and velocity errors will result (making it difficult or impossible to achieve perfect damping).

To correctly set this control, you should look for the “Torque constant” and “Rotor Inertia” specifications found on the scanner's datasheet. Add the mirror's inertia to the rotor inertia specified on the datasheet, and then perform a division.

For example, the Saturn 1 torque constant is 18,000, and its rotor inertia is 0.010. A typical 3mm mirror's inertia is 0.0027. Adding the 0.0027 mirror inertia to the 0.010 rotor inertia sums to a total system inertia of 0.0127. Performing a division provides: $18,000 / 0.0127 = 1,417,322$. This control does not allow numbers in the millions – only in the thousands. Because of this, the optimal number to enter is 1417 (the actual torque constant to inertia ratio of the system divided by 1000).

Viscous damping

Galvanometer scanners that use ball bearings will experience viscous damping, due partially to the balls riding in the raceway, and due partially to the lubricant in the

bearings. The Viscous damping control allows you to specify the amount of damping that the bearings are contributing to the system. This can be used to fine-tune the observer, to deliver precise estimates of high-frequency velocity.

When Observer gain is set to zero, this must be set to at least 1. Generally speaking, Viscous damping numbers between 1 and 20 are reasonable.

Observer gain

This sets the gain of the “rigid body observer” used in the Mach-DSP. When this is set to zero, then the observer is not used, and high-frequency velocity is derived simply as a result of integrating the coil current. (The implications of this are described below.) When Observer gain is increased above zero, a servo loop is formed which compares the predicted (observed) galvanometer position and actual measured galvanometer position, the gain of this servo loop being controlled by the Observer gain setting. High amounts of Observer gain will force the predicted position to match the actual position very closely, and thus force predicted (i.e. observed) velocity to be very accurate. However, high observer gains may also inadvertently inject noise into the main servo loop. Therefore, there is a tradeoff between Observer gain and the quality of the predicted velocity. Generally an Observer gain setting of around 20 is reasonable.

Spring constant (magnetic return to center)

Some galvanometer scanners have a natural tendency to return the rotor to a central rotation angle when coil current is removed. This is especially true of the ScannerMAX Compact series of scanners, as well as older moving iron galvanometers that used a torsion bar. Other galvanometer scanners will not impose any torque on the rotor when coil current is removed. When constant coil current is required to maintain the position of a galvanometer (as is the case with the Compact series), this constant coil current will result in a DC offset that appears in the derived high-frequency velocity signal. For that reason, the Mach-DSP servo allows you to specify the Spring constant (both positive and negative) so that this can be taken into account and subtracted from the coil current, ultimately providing a more accurate derived high frequency velocity.

A final note about observers...

For more than two decades, conventional galvanometer servo drivers have derived high-frequency velocity information by simply integrating coil current. This involves simple circuitry and provides reasonable results. However, integrating the coil current almost always results in a DC offset, as well as low-frequency AC signals riding on the derived high-frequency velocity. These extraneous signals may extend mirror settling-time (as is the case with most conventional servo drivers on the market). Setting the Observer gain higher than zero will engage the rigid-body observer, which in turn eliminates this DC offset as well as the low-frequency AC signal, thus improving mirror settling-time. Therefore the use of an observer can be very valuable. However, it will only work correctly if the Torque-constant to inertia ratio, Viscous damping, and Spring constant settings are all set correctly. Therefore, although the use of an observer may provide better settling time if adjusted correctly, it can actually cause more problems if

not adjusted correctly. For that reason, these controls should be adjusted and tuned using the built-in oscilloscope, while monitoring the Observed Velocity (TP63), Observed Position (TP36) and Observer Error (TP40).

Coil temperature calculator

As current is driven into the scanner to create beam deflection, the temperature of the coil and that of the inside the scanner may rise. The actual temperature rise depends on the waveform of the command input signal, as well as the scanner tuning. The temperature inside the scanner also depends on the X-Y mount and other factors that are external to the scanner (including the ambient temperature).

Galvanometer scanners are generally designed to operate with their coil having a maximum temperature of around 100 degrees C, while the outside of the scanner body having a maximum temperature of around 50 degrees C. If the coil temperature is allowed to exceed the maximum specified on the datasheet, permanent damage to the scanner may result. Because of this, the Mach-DSP servo includes a Coil Temperature Calculator, and systems to make sure that the coil temperature is not exceeded.

On the Pangolin-only tab, there are adjustments that control the manner in which the Coil Temperature Calculator will react. The normal manner is to greatly impede scanner acceleration (and thus drive current) when the motor's coil temperature has approached the maximum, and then to temporarily shut down the servo if the maximum temperature is greatly exceeded.

The Mach-DSP servo driver implements two modes in which the coil temperature may be calculated by the servo. "Mode 1" is to measure only the coil's RMS drive current, and then estimate the temperature of the coil, given assumptions about the scanner's mounting configuration and environment. This is essentially an open-loop approach. "Mode 2" is to actively measure both the coil's instantaneous drive current and drive voltage, and derive the coil's actual resistance, and then calculate the actual temperature of the coil. This is essentially a closed-loop approach.

For decades, manufacturers of conventional servo drivers have used RMS current alone to estimate coil temperature. This is simple and effective, but possibly error-prone, because assumptions are made that the scanner is mounted to a compression-style X-Y mount that is bolted to an infinite heat sink, and that the scanner's body will never exceed 50 degrees C. When this is not the case, these simple coil temperature calculators will underestimate the actual coil temperature – and in a worst-case scenario, this will result in scanner destruction. On the other hand, the Mode 2 approach of actively measuring the coil temperature using both coil voltage and coil current may result in a very accurate estimation of coil temperature – and one which does not rely on any assumptions about the X-Y mount or other environmental factors. However, as was the case with the velocity observer described above, this mode requires additional information to be entered (cable resistance, coil inductance, and Back EMF voltage) and if these are not entered correctly, the coil temperature calculator will not estimate coil temperature correctly. This second mode also requires more computational power

to be exerted by the Mach-DSP. Therefore when the X-Y mount and environment are all well-known and controlled, or when input command waveform is never expected to cause scanner heating (for example, in laser marking or other small-signal applications), the first mode (Calculate by RMS current) should be chosen. (Note that the precision of the coil temperature calculator is greatly enhanced when using a thermistor attached to the X-Y mount, as described in Chapter 3.5 of this manual.)

Coil resistance at 25 degrees C

Enter the coil resistance as specified on the scanner's datasheet.

Current-filter time constant

The RMS calculation requires a time constant over which to average the RMS current. This is unitless, and may be fine-tuned by using the built-in oscilloscope while observing the Coil Temperature (TP22). As the value increases, the speed of the filter also increases (i.e. the amount of time over which the current is averaged decreases). Setting this to a value of 300 to 1000 is reasonable for ScannerMAX galvanometers.

Thermal resistance (degrees C per watt)

When the X-Y mount is a compression-style mount that is supplied by Pangolin, and it is bolted to a large aluminum heat sink, then you can enter the thermal resistance as specified on the scanner's datasheet. Otherwise, you should enter a higher number to take into account the sub-optimal mounting.

Current sense plus cable resistance (ohms)

When the Coil Temperature Calculator is operating in Mode 2, the Mach-DSP must know the total resistance to expect, including not only the resistance of the scanner's coil, but also any additional resistance such as that of the current sense and even the cable that connects the scanner to the servo driver.

The Mach-DSP uses a 0.1 ohm current sense resistor. A short cable may add an additional 0.1 ohms, but a longer cable may add an additional 1 ohm.

You should enter the value corresponding to the cable resistance, and then add 0.1 to that number to account for the built-in current sense resistor.

Coil inductance (micro henry)

Enter the coil inductance found on the scanner's datasheet.

Back EMF Voltage

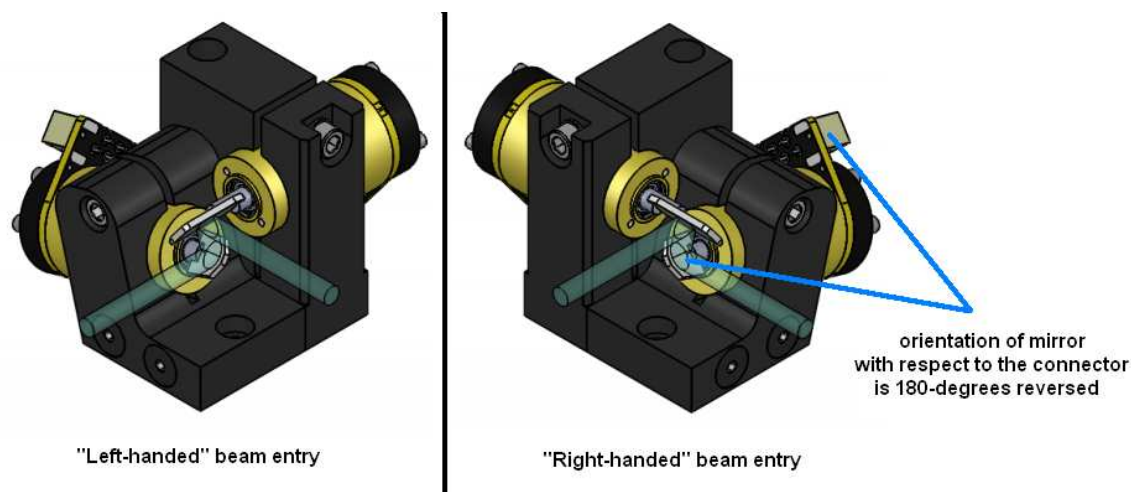
Enter the Back EMF voltage found on the scanner's datasheet.

A final note about using Mode 2...

Although the cable resistance, coil resistance, coil inductance, and Back EMF voltage may be known, we recommend that these values be fine-tuned using the built-in oscilloscope, while monitoring Motor I*R (TP84) and Coil Temperature (TP22). Also note that Mode 2 **will not** work properly with the ScannerMAX Compact 506 scanner.

Motor drive (mirror) orientation

Depending on whether you are using an X-Y mount configured for right-handed beam entry, or left-handed beam entry, the rotational orientation of the X and Y mirrors needs to change (with respect to the connector on the scanner). See the picture below for further clarification.



Most manufacturers of galvanometers require you to remove the mirrors from the scanners and orient the reflective surface of the mirror on the other side of the scanner shaft itself. This is because other manufacturers of scanners use a "stopping pin" which prevents the rotor from rotating all the way around.

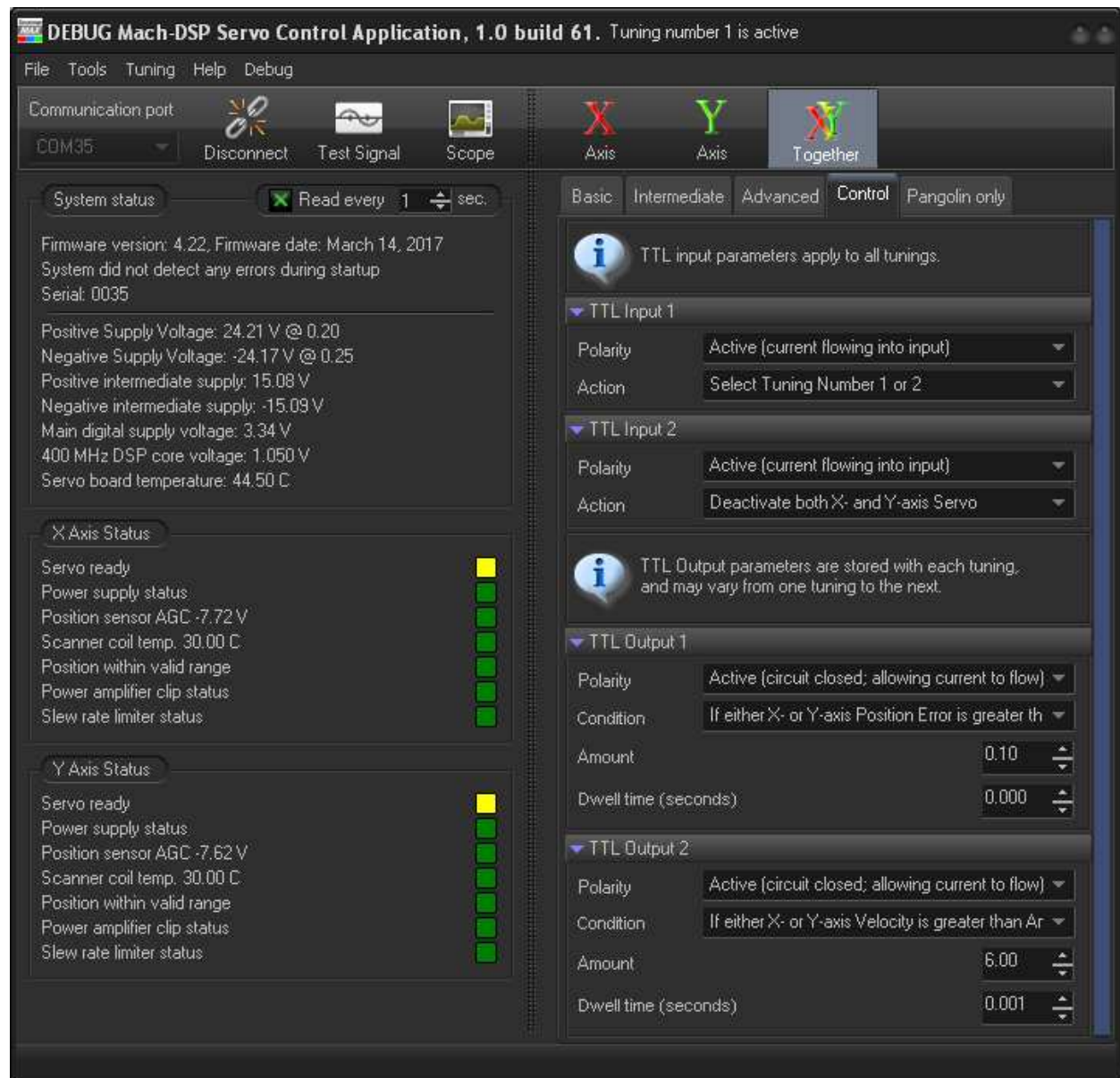
However, the Compact and Saturn series of scanners manufactured by ScannerMAX have rotors that can rotate all the way around (a feature used to exercise bearings). For this reason, accommodating left-handed mounts or right-handed mounts becomes easy, and is accomplished by merely changing the polarity of the motor drive signal.

The Mach-DSP servo driver allows you to set the motor drive polarity, to accommodate right-handed or left-handed mirror orientation.

CAUTION! It is recommended that Servo Gain, Low Frequency Damping, Error Integral Gain and Position-proportional gain all be set to zero, and that any external mirror bumpers are applied correctly before changing this setting!

7.6 Control-related (TTL Input and Output) parameters

The controls that are found on the Control tab affect how the Mach-DSP responds to TTL Inputs, and how the Mach-DSP influences the TTL Outputs.



The Mach-DSP includes two optically-isolated TTL Inputs, and two optically-isolated TTL Outputs found on the Status / Control connector (described in Table 3.3 of this manual). The function of the TTL Inputs does not change with the scanner tuning selection, but the function of the TTL Outputs can change from tuning to tuning.

The following paragraphs describe how to adjust the TTL Inputs and TTL Outputs.

TTL Input 1 and TTL Input 2

In this section, you will find the parameters related to TTL Input 1 and TTL Input 2.

Polarity

The TTL Inputs are implemented through optical isolators. This is done so that current can be passed through them from far away in a factory, without concern for ground loops or voltage differences that might exist over long distances. With this being the case, it is impossible to discuss the inputs in terms of “high” or “low”. What matters is whether current is flowing into the optical isolator or not. When current is flowing, we consider the input to be “active”. When current is not flowing, we consider the input to be “inactive”. (For most application, “Active” will correspond with TTL High, but this depends on how the input is actually connected at the source (controlling) device.)

The *Polarity* control allows you to specify whether the “Action” (described below) is initiated as a result of the TTL Input being “Active” or “Inactive”.

Action

The *Action* specifies what the Mach-DSP will do when the TTL Input is in the condition described by *Polarity*. Possible actions are:

- Ignored (the TTL Input has no affect on the Mach-DSP)
- Deactivate X-axis servo
- Deactivate Y-axis servo
- Deactivate both X-axis and Y-axis servo
- Mute X-axis Command Input
- Mute Y-axis Command Input
- Mute both X-axis and Y-axis Command Input
- Select Tuning 1 or 2
- Select Tuning 3 or 4
- Select Tuning 1-2-3-4
- Request exercise of X-axis scanner
- Request exercise Y-axis scanner
- Request exercise both X-axis and Y-axis scanner

(Note that the “exercise” actions will only have an effect if exercising has been setup in the scanner tuning, using the parameters on the Pangolin-only tab. Exercising is also only possible if the scanner does not have any external mirror bumpers in place, because exercising involves continuous rotation of the scanner.)

TTL Output 1 and TTL Output 2

In this section, you will find the parameters related to TTL Output 1 and TTL Output 2.

Polarity

As was the case for TTL Inputs (and for the same reasons) the TTL Outputs are implemented through optical isolators. And as was the case with TTL Inputs, the terms “Active” and “Inactive” are used for TTL Outputs as well.

The *Polarity* control allows you to specify which TTL Output State will be asserted as a result of the “Condition” (described below).

Condition

The *Condition* specifies which signals and behaviors the Mach-DSP will be observing, before asserting of the respective TTL Output. Possible conditions are:

- Never (the TTL Output is placed in the opposite state specified by *Polarity*)
- Always (the TTL Output is placed in the exact state specified by *Polarity*)
- If X-axis servo is Ready
- If Y-axis servo is Ready
- If both X-axis and Y-axis servo are ready
- If either X-axis or Y-axis servo is ready
- If Power Amplifier is enabled
- If Servo board temperature is greater than *Amount*
- If X-axis coil temperature is greater than *Amount*
- If Y-axis coil temperature is greater than *Amount*
- If X-axis coil temperature is greater than *Amount*
- If X-axis scanner is being exercised
- If Y-axis scanner is being exercised
- If either X-axis or Y-axis scanner is being exercised
- If either X-axis or Y-axis coil temperature is greater than *Amount*
- If X-axis Position Error is greater than *Amount*
- If Y-axis Position Error is greater than *Amount*
- If either X-axis or Y-axis Position Error is greater than *Amount*
- If X-axis Velocity is greater than *Amount*
- If Y-axis Velocity is greater than *Amount*
- If either X-axis or Y-axis Velocity is greater than *Amount*

(As explained above in the TTL Input section, the “exercise” actions will only have an effect if exercising has been setup in the scanner tuning, using the parameters on the Pangolin-only tab.)

Amount

The *Amount* is a qualifier that is used with some of the *Conditions* above. The value that the *Amount* corresponds to depends on the selected condition. For example, if the *Condition* is set to “If Servo board temperature is greater than Amount”, then the *Amount* is used to specify the temperature in degrees. For Position Error and Velocity related conditions, you can use the built-in Oscilloscope feature to determine appropriate values to enter into *Amount*.

Dwell time (seconds)

The *Dwell time* specifies the amount of time that the TTL Output will be maintained in the state specified by *Polarity*, even after the *Condition* no longer exists. For example, if Condition and Amount are set to “If X-axis coil temperature is greater than 60 degrees”, then the TTL Output will become asserted immediately upon that condition. But lets say that the coil temperature is 60 degrees for only a split second, and then it goes back down to 59 degrees. For safety reasons, you might want the Mach-DSP to continue to assert this condition for some number of seconds.

Dwell time takes on a more important and more meaningful role in applications that evaluate whether or not scanning is taking place (i.e. as a “scan-fail safeguard”). In these applications, it is often the case where scanning occurs, then pauses, then resumes scanning, and then pauses (for example, pausing on the corners of letters or graphic shapes). These pauses typically occur for less than one millisecond. For evaluating whether or not scanning is happening, the *Condition* could be set to “If either X-axis or Y-axis Velocity is greater than 6”, and *Dwell time* can be set to 0.001 or 0.002.

The *Dwell time* allows you to specify zero (for immediate assertion and de-assertion of the TTL output), or 0.001 (for 1 millisecond of dwell time) or values up to 15 seconds.

TTL Indicators on the Mach-DSP board

The Mach-DSP board has two red LEDs, which correspond to the two TTL Outputs, and are each illuminated when the corresponding TTL Output is “Active”. See section 5.0 for more information.

IMPORTANT NOTICE ABOUT TTL OUTPUTS AND LASER SAFETY

Since the TTL Outputs are delivered to external machinery and devices through a connector, it is possible that the connector can become unplugged, and then the external machinery may be led to believe that the monitored condition remains permanently in a safe state!

Likewise, since the TTL Outputs are delivered via optical isolators, these optical isolators do not conduct any current when power is not applied to the Mach-DSP. Therefore external machinery will not receive the correct signaling based on a non-powered Mach-DSP servo driver, possibly leading to an unsafe condition.

Moreover, all of the parameters of the TTL Outputs are saved with each scanner tuning. If you specify a *Condition* in one scanner tuning, but a different *Condition* in another scanner tuning, then the machinery that is monitoring TTL Outputs may be fooled into believing that the scanning or system is in a safe state when it isn't...

And finally, the TTL Output signals themselves are ultimately controlled and activated by software, which (although we make every effort in our programming and testing to ensure reliability) may have unknown flaws.

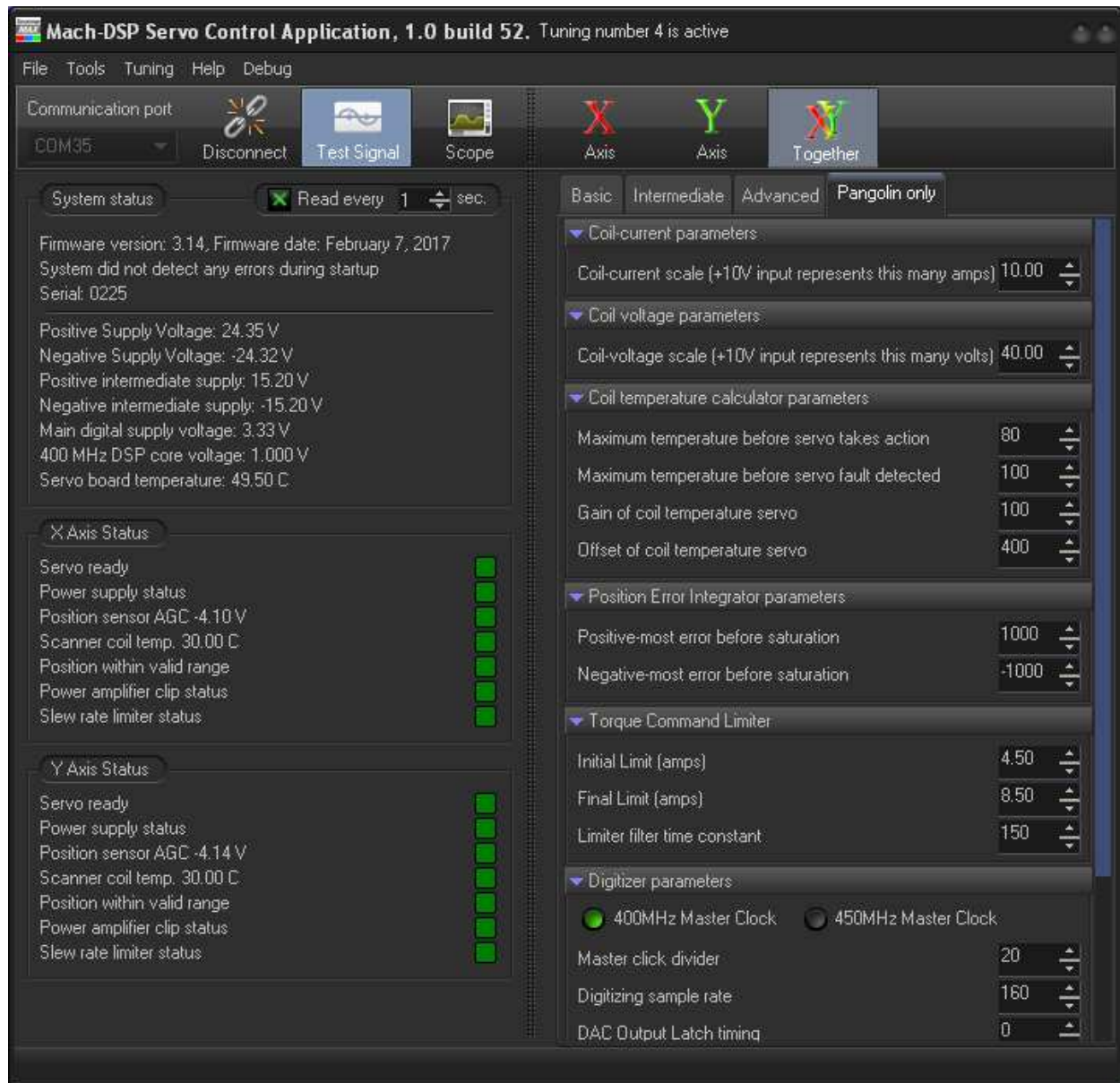
For these reasons and more, you should not rely on the TTL Outputs from the Mach-DSP as the sole means of ensuring laser safety.

Indeed, Pangolin makes a separate product called **PASS**, which monitors the power supply, scanner position signals, the actual measured laser power, and other laser projector health-related phenomenon, and does so using circuits implemented in a redundant fashion so that even if one or more circuits fail (either external or internal to PASS), the PASS system will ensure that the overall projection system fails safe.

If you are interested in ensuring the greatest degree of laser safety in your product, you should take a look at PASS. Overall information about it, including links to the PASS manual can be found here: <http://pangolin.com/PASS/>

7.7 Pangolin-only (calibration) parameters

The controls that are found on the “Pangolin only” tab (only some of which are shown below, and which may change from program version to version) are used for fine-tuning and calibrating the Mach-DSP servo, and are generally not recommended to be adjusted by users. It is recommended that no changes be made to these controls without the input and advice of Pangolin.

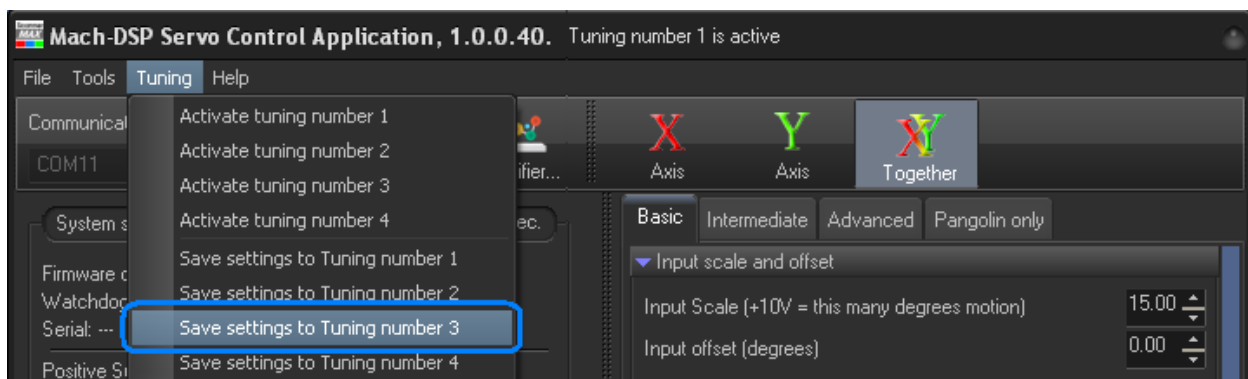


7.8 Saving and recalling scanner tunings from memory and files

All of the settings in the Mach-DSP servo driver described above can be saved to memory as well as a file on disk, for instant recall at power-up or at some point in the future. The settings are collectively referred to as a “tuning”.

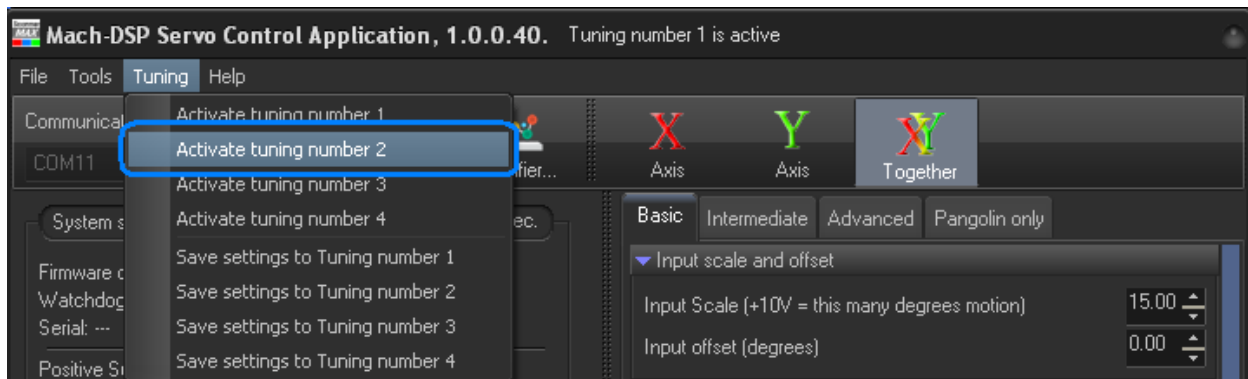
Saving a tuning to memory

At any point in time, you can save all of the settings found on the Basic, Intermediate, Advanced, and Pangolin-only tabs, as well as the settings of the Test Signal Generator, Oscilloscope and Analog Outputs. These settings are all saved to flash memory on the Mach-DSP amplifier using the Tuning menu, as shown below.



Recalling (and activating) a tuning from memory

Once a tuning is saved in memory, it can be recalled later using the “Activate tuning number” item on the Tuning menu. **In addition to loading all of the settings from memory, this is also used to specify which tuning should be used on power-up!**

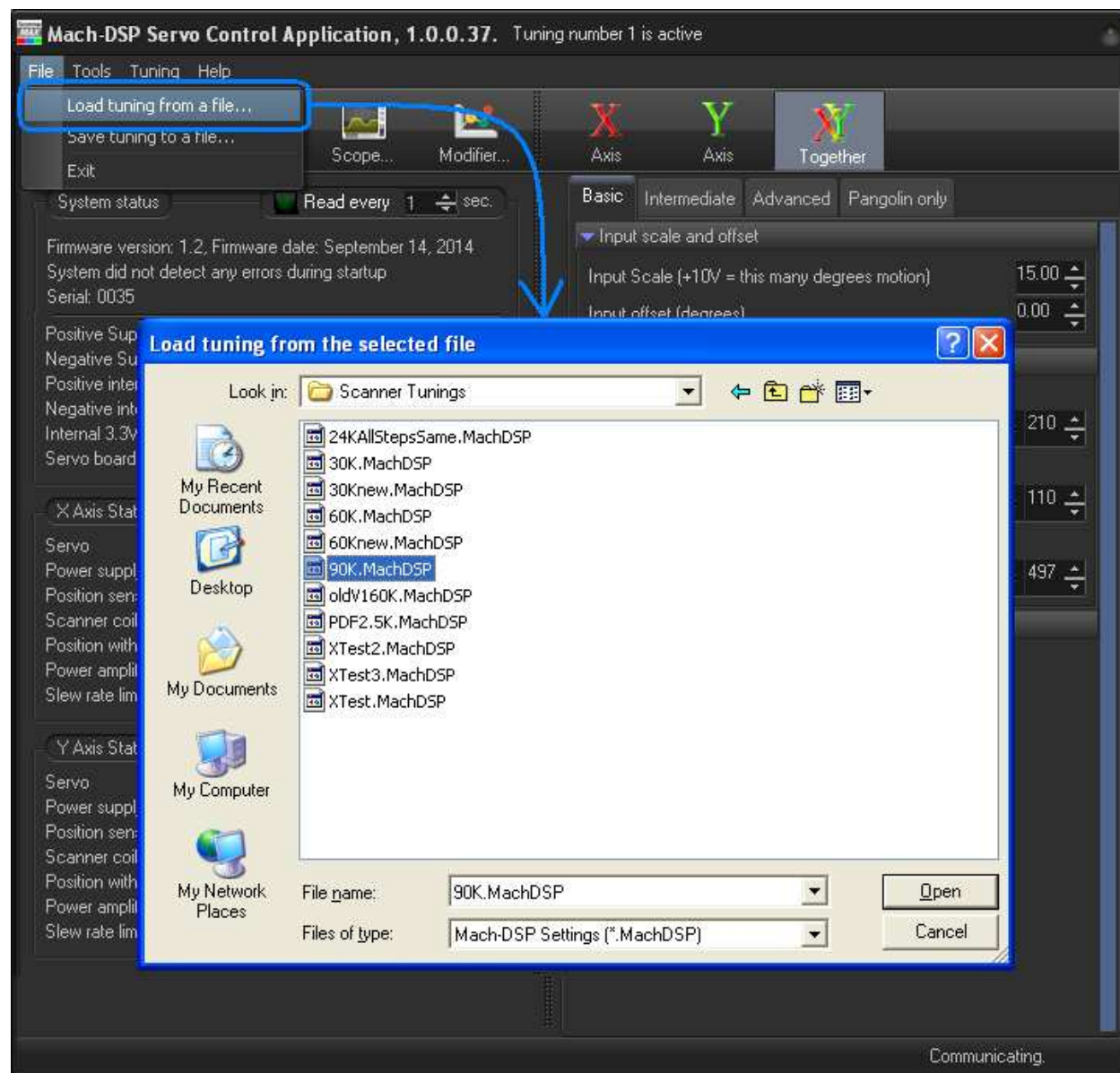


Note that the “Activate tuning number” menu can be used at any time. For example, if you currently have “Tuning 1” activated, and have changed some of the tuning settings, and want to undo your changes, just click on “Activate tuning memory 1”, and it will recall all of the original settings for “Tuning 1”. This is a convenient way to undo any unintentional changes.

Saving and recalling tunings from a file on disk

In addition to being able to save up to four separate tunings in memory, all of the settings that make up a tuning can also be saved to a file on disk. This allows you to have a virtually infinite number of tunings, instantly accessible any time you want them.

Saving and loading of tunings is accessed using the File menu.

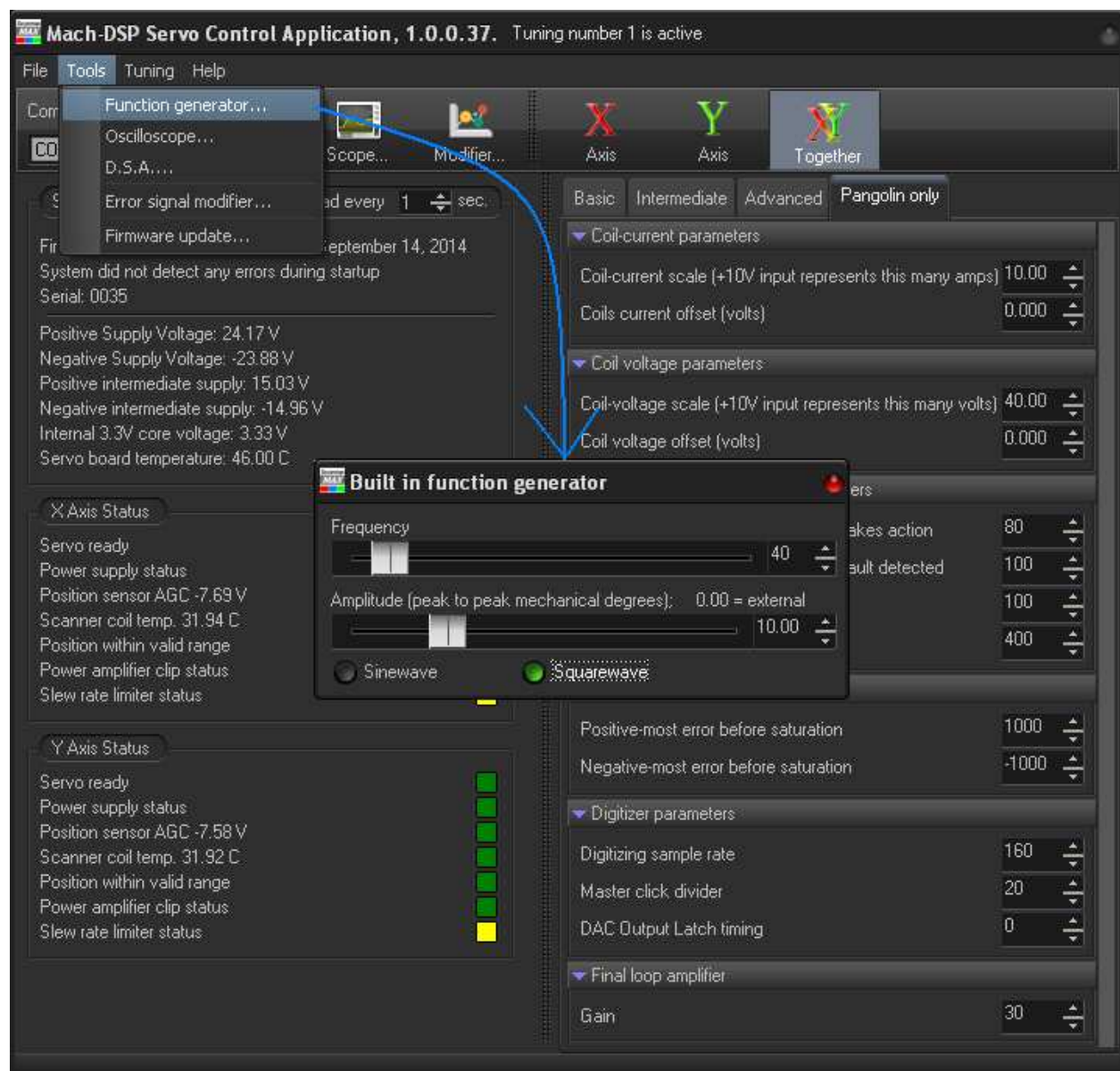


8.0 Built-in Tools accessed using the program

The Mach-DSP servo includes a variety of tools that are built in, which help to characterize and optimize performance. These tools can be found in the Tools menu in the Mach-DSP program. The tools are described below. Each tool occupies its own window. Multiple tool windows can be opened, and these windows can be moved around on the screen, and may overlap in any way desired.

8.1 Test signal (function) generator

The Mach-DSP includes a Test Signal Generator, which may be used as a signal source during scanner tuning as well as other purposes. The Test Signal Generator is accessed using the Tools menu as shown below.



The Test Signal Generator can generate sine-waves or square-waves (quadrature and in-phase) having a frequency from 1Hz to 500Hz. The amplitude of the Test Signal Generator is specified in hundredths of a degree, up to 40 degrees mechanical peak-to-peak (up to 80 degrees optical).

When the amplitude is set to 0.00, the external Command Input is used to drive the servo. When the amplitude is set greater than 0.00, the Test Signal Generator drives the servo.

Test Signal Generator Settings are saved as part of the Scanner Tuning

Note that the Test Signal Generator settings are stored with the scanner tuning, so if you do not want the signal generator to drive the servo when a particular tuning is selected, make sure that the Test Signal Generator Amplitude is set to 0.00.

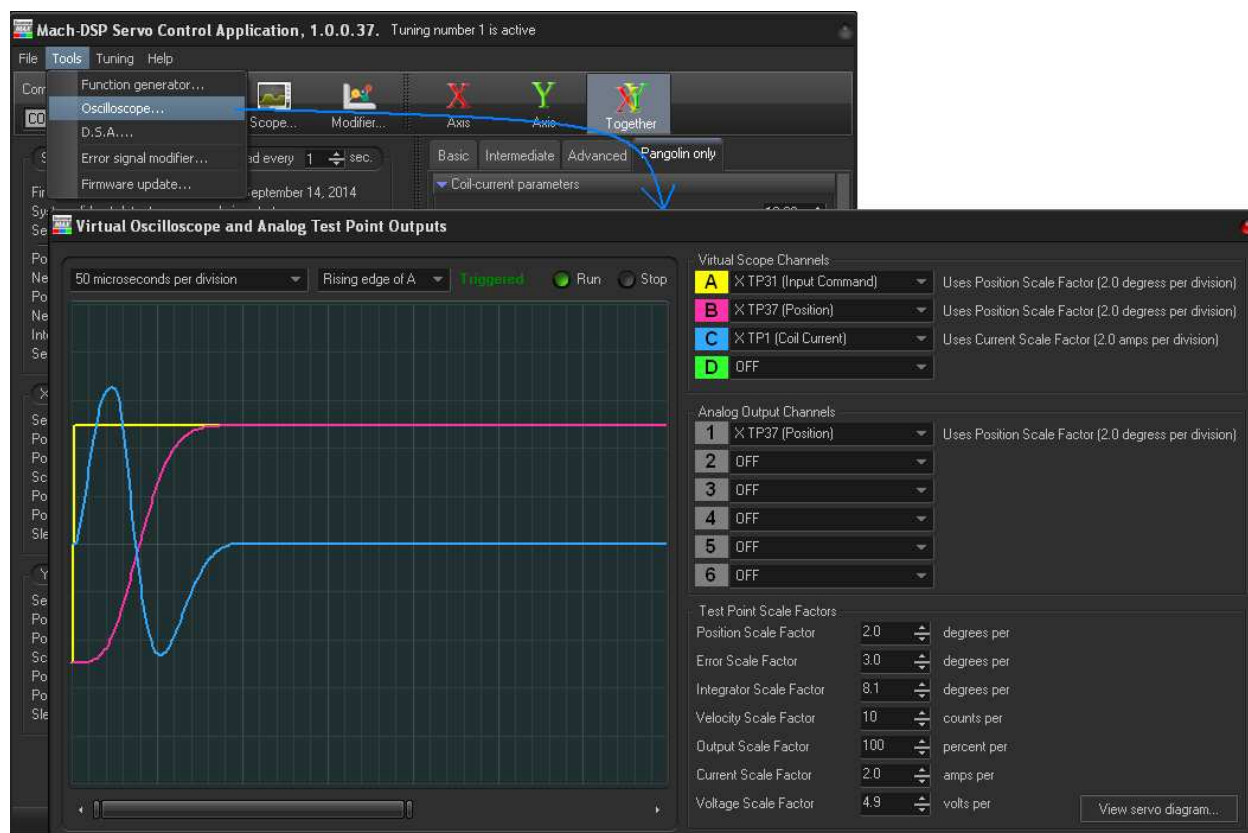
(Note that the frequency and amplitude limitations noted above are believed to be reasonable limits for the intended purpose, but they are purely artificial limits built into the software. If you have an application that requires alternative limits, please contact Pangolin to discuss a software update.)

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8.2 Oscilloscope and Analog Output controls

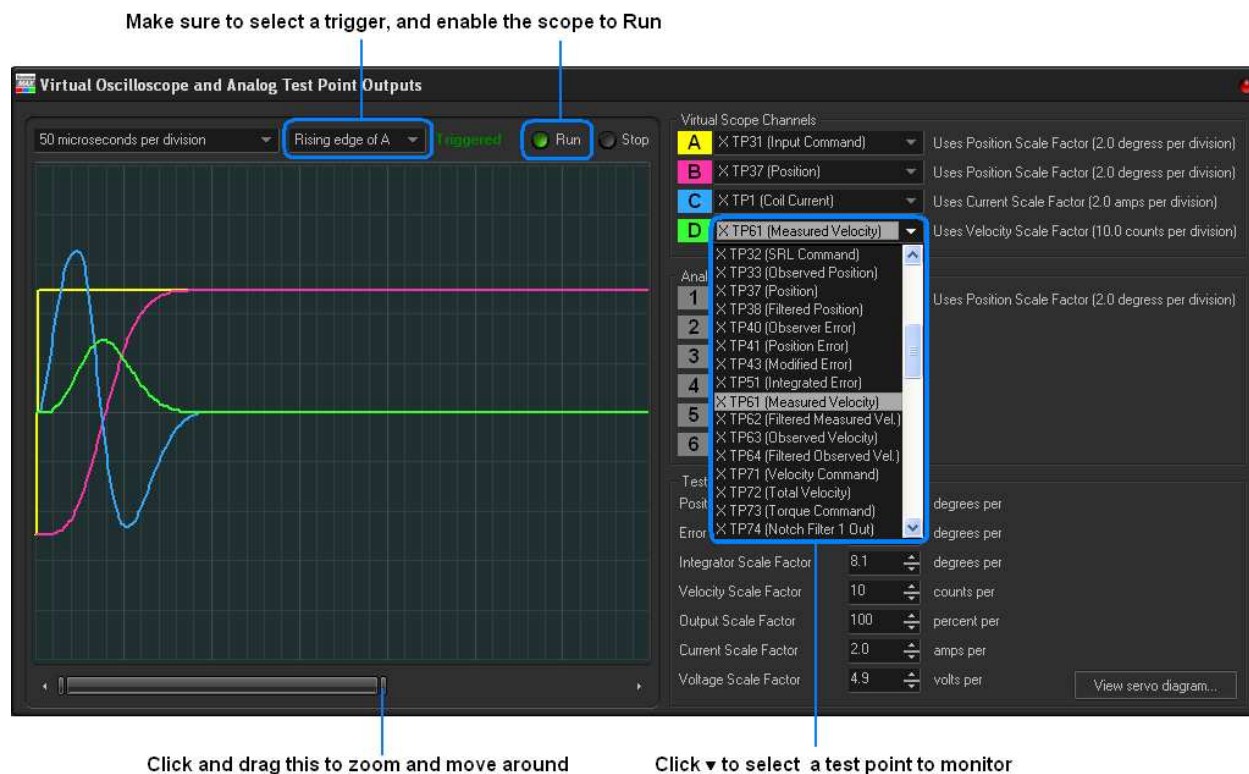
The Mach-DSP includes a four-channel digital Oscilloscope that can be used during scanner tunings or at any other time when you'd like to monitor the behavior inside and outside the Mach-DSP servo loop. The window used to access the Oscilloscope is also used to direct signals to the user-defined analog outputs described in Chapter 3 of this manual.

The Oscilloscope is accessed using the Tools menu as shown below. The Oscilloscope can also be accessed by pressing the “Scope” button on the toolbar.



Configuring the Oscilloscope

The Oscilloscope works like most modern digital oscilloscopes work today. The individual features are described below.



Time-base

The Oscilloscope features a time-base that can be used to view as little as 10 microseconds or as long as 100 milliseconds. The amount of time to be viewed can be selected using the drop-down list box found in the top-left of the Oscilloscope window (showing 50 microseconds per division in the picture above). In addition to being able to specify the time per division, the actual number of divisions can be selected using the scrollbar and zoom-bar found at the bottom of the window.

Trigger source

The Oscilloscope can be triggered on the rising-edge or falling-edge of any of the waveforms being displayed (as well as the X or Y Input Command signals). The trigger source can also be set to “Free-running” in which case it will acquire a new waveform as often as it can.

Run/Stop

When the Oscilloscope window is first opened, the Oscilloscope will be in STOP mode. No new waveforms will be captured unless it is placed into RUN mode.

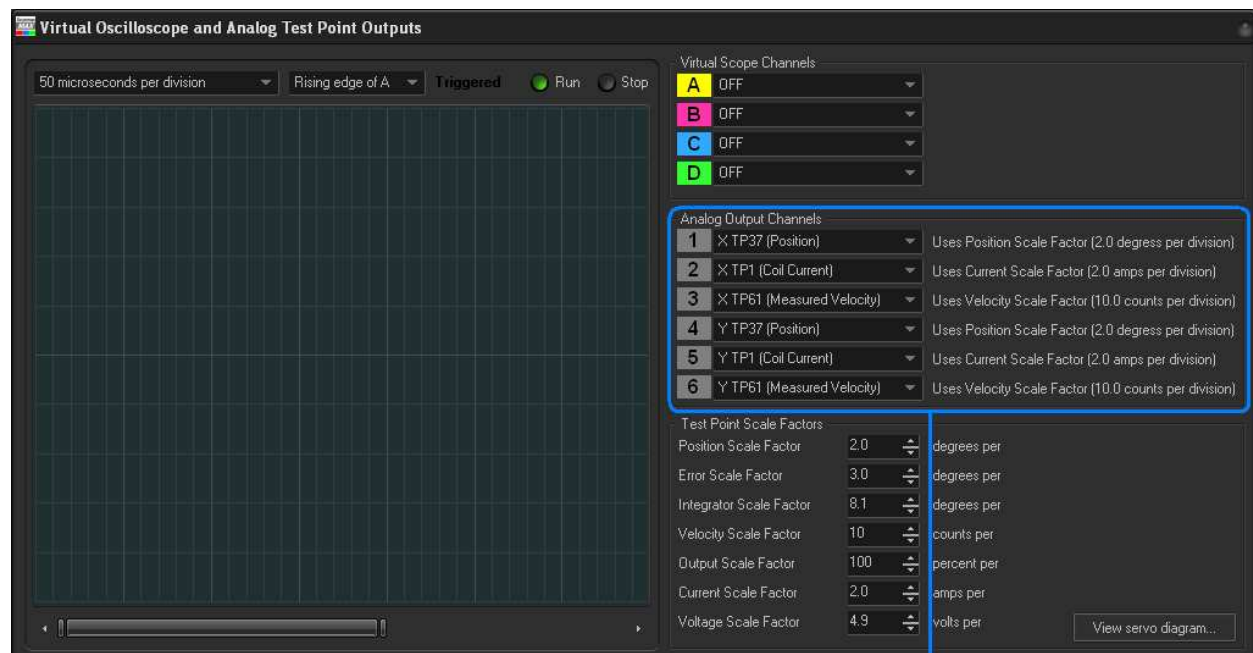
Four-channel display; selecting waveforms

Up to four channels can be displayed at the same time, each having its own color. The channels are called Channel A, Channel B, Channel C, and Channel D. Waveforms for a particular channel are selected using the drop-down list. In the list you will find test point numbers as well as a description of the selected signal. Press the button labeled "View servo diagram" to see a full list of the test point numbers, and their meaning.

On normal oscilloscopes, each channel has its own vertical sensitivity control. One channel might be showing 1 volt per division while another channel is showing 20 volts per division. The Oscilloscope found in the Mach-DSP does not offer a separate vertical sensitivity for each channel. Instead, signals of like-type are grouped together, and a single sensitivity is offered for all signals in a particular group. For example, the Command Input and Position signals share the same group, and thus have a single scale factor. This makes sense, since you often want to see the position signal in relation to the command signal, to check for tracking errors. The scale factor for each group of signals is adjusted using the spinners found on the bottom/right side of the Oscilloscope window.

Analog Output channels

In a similar way in which oscilloscope channels are selected, individual signals within the servo loop can be routed to user-defined analog outputs on the same window. (Details about the Analog Outputs can be found in Section 3.5 of this manual.)



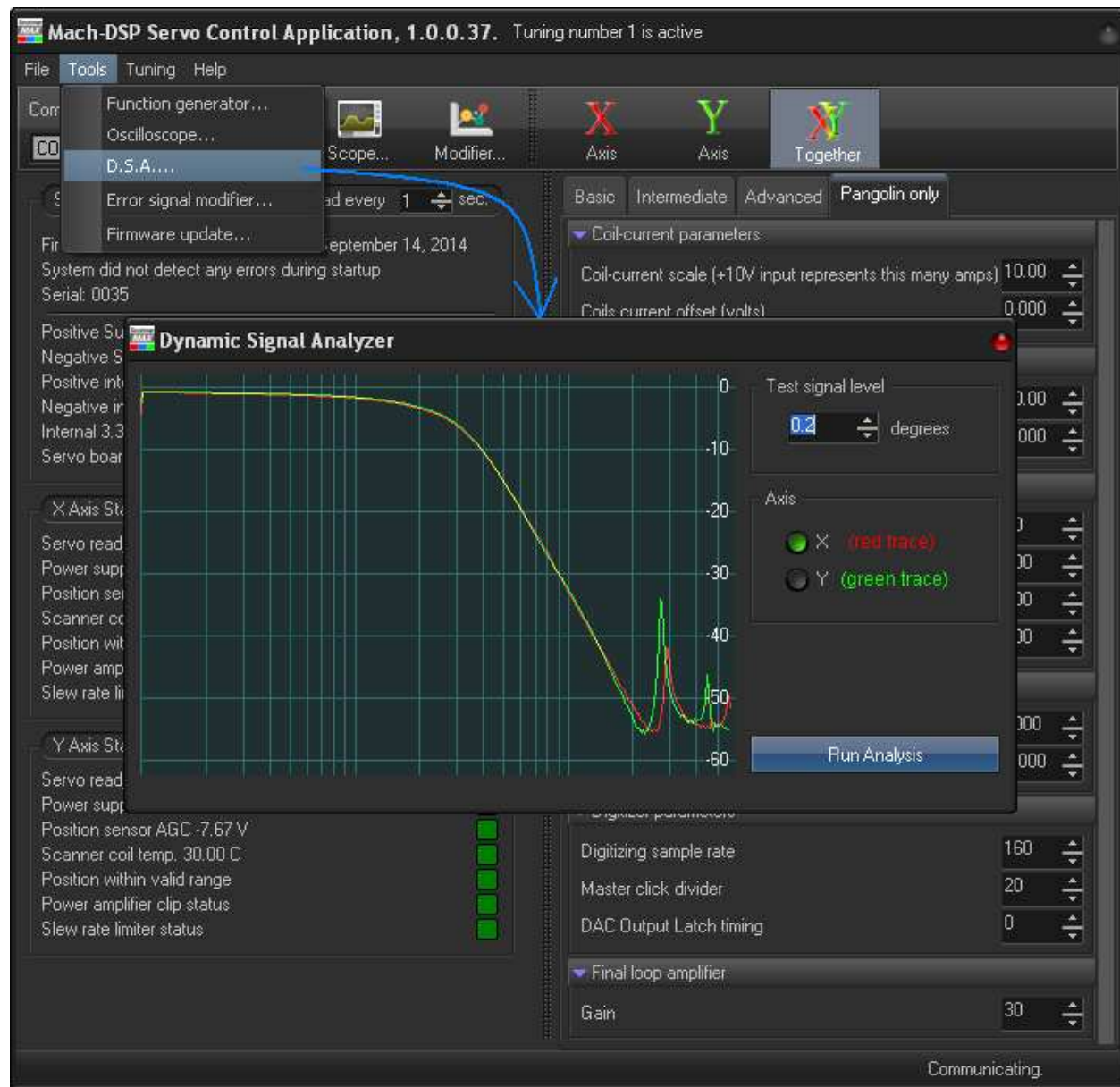
Select the signal to be output by the Analog Output Channels

The scale factor of each output is specified as it is with scope channels

IMPORTANT! All Oscilloscope and Analog Output selections are stored as a part of the tuning! It is important to select (or deselect) the channels you want before saving.

8.3 Dynamic Signal Analyzer

The Mach-DSP includes a Dynamic Signal Analyzer, which can be used to evaluate the spectral flatness and rolloff of a particular scanner tuning, as well as to locate the frequency and severity of torsional resonances. The Dynamic Signal Analyzer is accessed using the Tools menu as shown below.



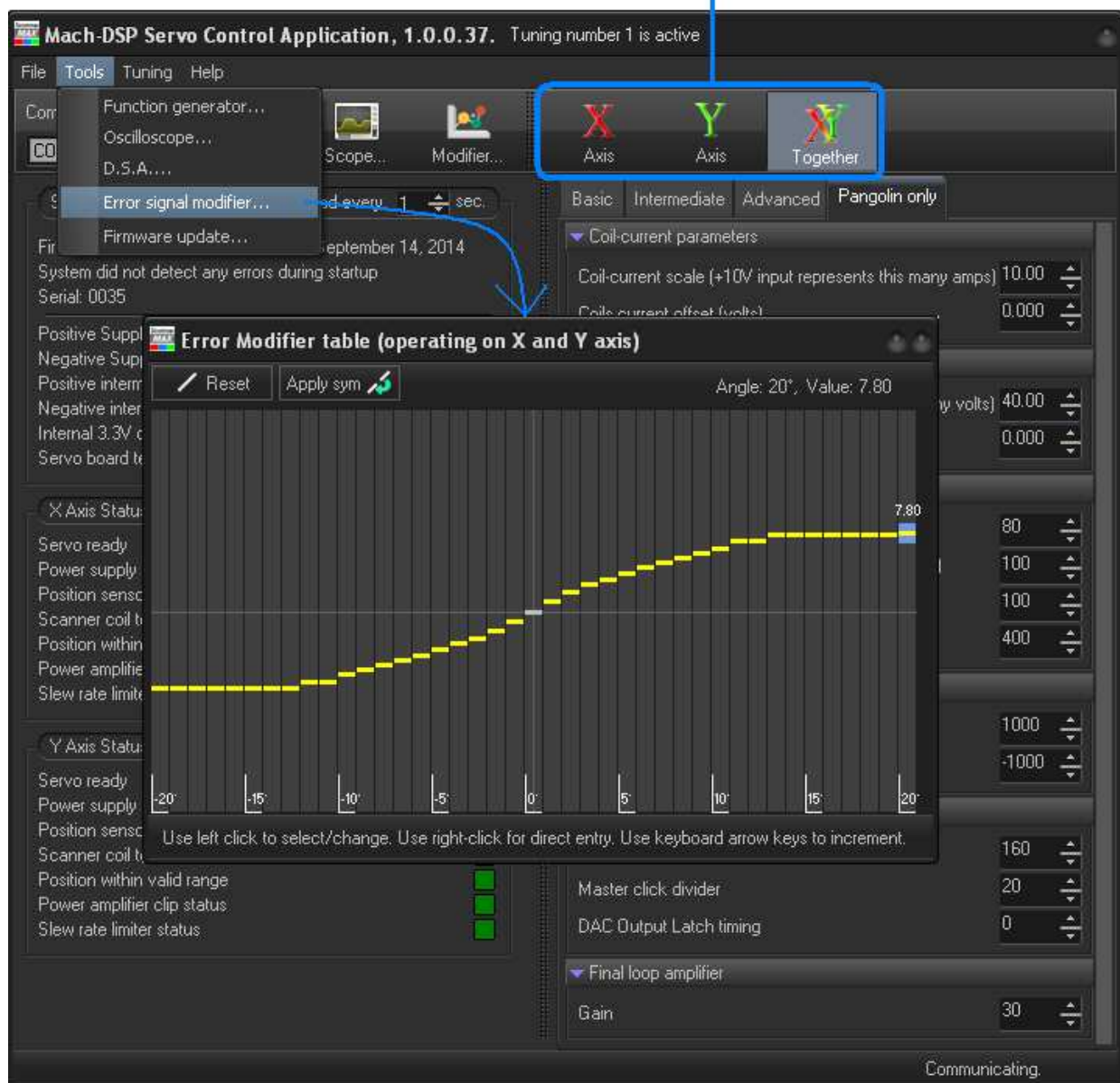
To use the Dynamic Signal Analyzer, select an axis and test signal level and press Run Analysis. The Dynamic Signal Analyzer will sweep a test signal from 100Hz to 60kHz while monitoring the amplitude of the position signal in comparison to the test signal. Once the analysis is run, you can move your mouse in the window and check the level (in db) and frequency (in Hz). Peaks shown in the response represent torsional resonances. You can use the information gathered in this window to set the notch filter.

8.4 Error Modifier (and other nonlinear correction tables)

The Mach-DSP includes an Error Modifier, which can be used to progressively limit the amplitude of the Position Error signal, before it is fed to the Summing node. This helps to eliminate overshoot when squarewaves or unstructured commands are used as an input. The net result is similar to a Slew Rate Limiter, but the Error Modifier can do this progressively, thus helping to achieve better overall performance with a wide variety of step sizes. The Error Modifier is accessed on the Tools menu as shown below.

(The latest version of the software calls this “Nonlinear correction” and the window now provides access to Torque-vs-position rolloff and Magnetic Spring Return as well.)

Use the X, Y and XY buttons to select the axis affected



9.0 Tuning Instructions

As described in section 7.7 of this manual, the Mach-DSP servo actually allows instant access to up to four separate scanner tunings, accessible from a menu in the Mach-DSP Servo Control Application.

When a complete system is purchased (scanners, mirrors, mount, servo driver, and cables) the Mach-DSP should arrive already tuned at the Pangolin factory. Often times, there will be several tunings already stored in memory, with the first, second, or third tuning activated on power-up.

In the first part of this chapter will cover PD and PID tuning. The second part covers PDF tuning. In any event it should be understood that, this manual is only meant to familiarize the reader with the some of the overall concepts of scanner tuning. Certain topics are not covered at all, such as how to properly tune the Low Frequency Damping Filter and High Frequency Damping Filter, Notch Filters or any nonlinear correction tables. To obtain a complete understanding of scanner tuning, you should contact Pangolin and arrange a full training session. You may also consult the book "LASER SCANNERS: Technologies and Applications found at www.LaserScanningBook.com.

If you are unfamiliar with the process of tuning galvanometers, it is recommended that you only access tunings created and stored by Pangolin in memory.

DO NOT ATTEMPT TO CHANGE THE ADJUSTMENTS ON THE MACH-DSP UNLESS YOU ARE THOROUGHLY FAMILIAR WITH SERVO TUNING CONCEPTS AS WELL AS THE TUNING INSTRUCTIONS FOUND IN THIS CHAPTER OF THE MANUAL.

9.1 *Equipment needed*

The following equipment is required to properly tune the Mach-DSP servo driver:

- Power Supply (see "Mach-DSP Specifications" for current and voltage ratings)
- Mach-DSP Servo Control Application for the Windows-based PC
- Test Signal Generator (external or built into Mach-DSP program)
- Oscilloscope (external or built into Mach-DSP program)
- Projection surface – preferably with optical scale or ruler
- Visible Laser
- Scanner Mount

9.2 *Initial "PD" Tuning*

The term "Initial PD tuning" refers to a tune that uses Proportional and Derivative servo terms, and which may or may not achieve a desired level of performance, but is adequate to set the most important servo parameters including *position scale*, *position offset*, *input gain*, *input offset* and possibly *notch filter*. After this initial tuning is accomplished, further tuning can be done to fully achieve the desired performance objective.

- A. Mount each scanner using an appropriate fixture, or X-Y mounting bracket. Make sure the mirror is securely fastened to the galvo shaft. Direct a laser beam to the scanner. If the ScannerMAX scanners were delivered with external mirror bumpers, find the mechanical center by rotating the shaft from one stop to the other, marking the center of the full excursion. Then ensure that the reflected laser beam is projected in the direction of a calibrated optical target, as shown in figure 9.2

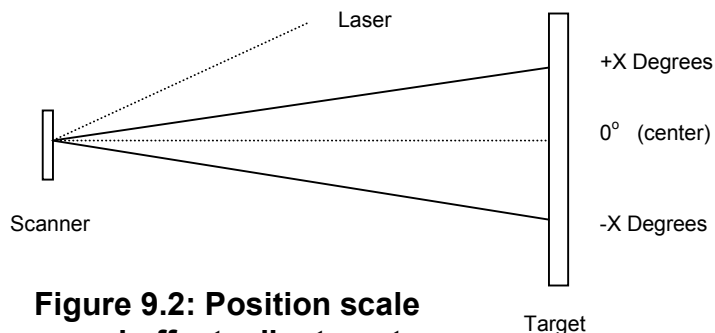
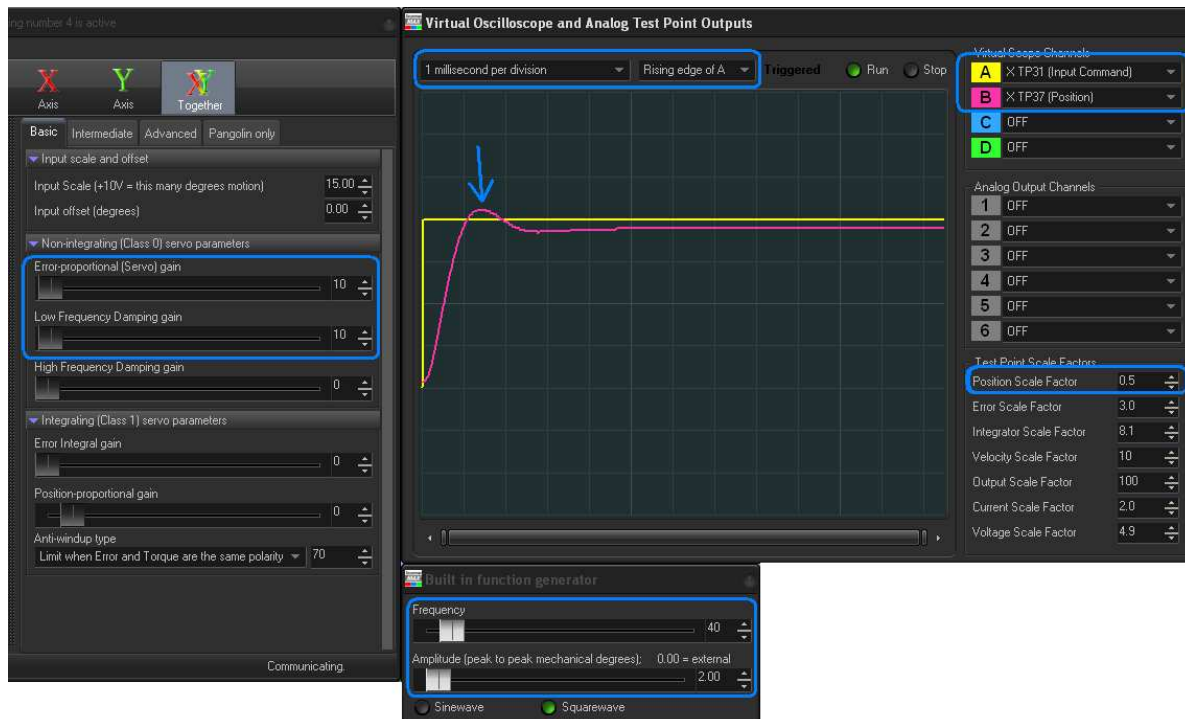


Figure 9.2: Position scale and offset adjustment

- B. Connect the *power supply* and *command input signal* to the Mach-DSP as described in Chapter 3 (Connections). Also connect the special serial cable to a Windows-based PC and the Mach-DSP. (Do not connect any scanners to the Mach-DSP and do not apply power.)
- C. Launch the Mach-DSP application program on the PC, select the proper serial port and press Connect. After that, apply power to the Mach-DSP servo driver. The Mach-DSP program should show that it is connected to the Mach-DSP, and indicate that there is a problem with the Position Sensor AGC of each scanner. (This is because no scanners are currently connected...)
- D. On the Basic tab of the Mach-DSP program, set the *Servo gain*, *Integrator gain*, *Position-Proportional gain*, *Low Frequency Damping* and *High Frequency Damping* all to 0. Set the *Input Scale* to a value that is appropriate for your input signal. On the Advanced tab, set the *Position fault detector* a little bit greater than your maximum projection angle. For example, if you intend to project at 40 degrees optical-peak-to-peak, you should set the *Positive-most position* to +11 and *Negative-most position* to -11. (Remember, the Mach-DSP program uses mechanical degrees.)
- E. Plug the scanners into the Mach-DSP servo driver. The Mach-DSP will go through a startup sequence, during which time the mirrors should not move much. After around one second, the Mach-DSP program should show that the Position Sensor AGC voltage is within a valid range.
- F. Using the Tools menu on the Mach-DSP program, open the Test Signal Generator and set it for 40Hz, and 2 mechanical degrees peak-to-peak.

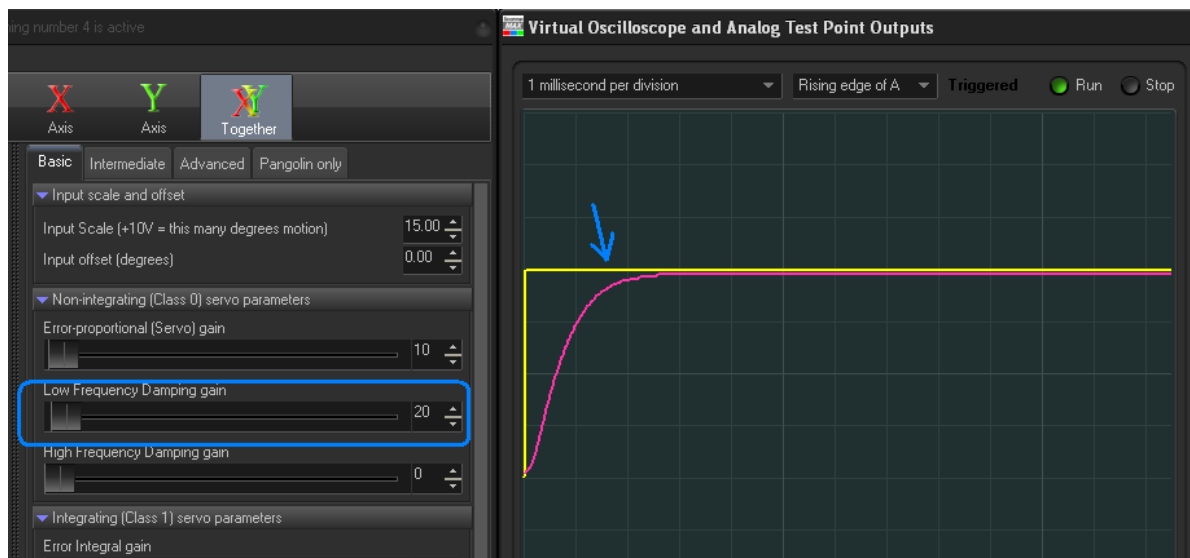
- G. Open the Oscilloscope and set the time-base to 1 millisecond per division and to trigger on the rising edge of Channel A. Select the Input Command signal for Channel A, and the Position signal for Channel B. Finally, set the Oscilloscope Position Scale Factor to 0.5 degrees per division.
- H. Arrange the Test Signal Generator, Oscilloscope, and Mach-DSP program windows so that they can all be accessed, as shown below.



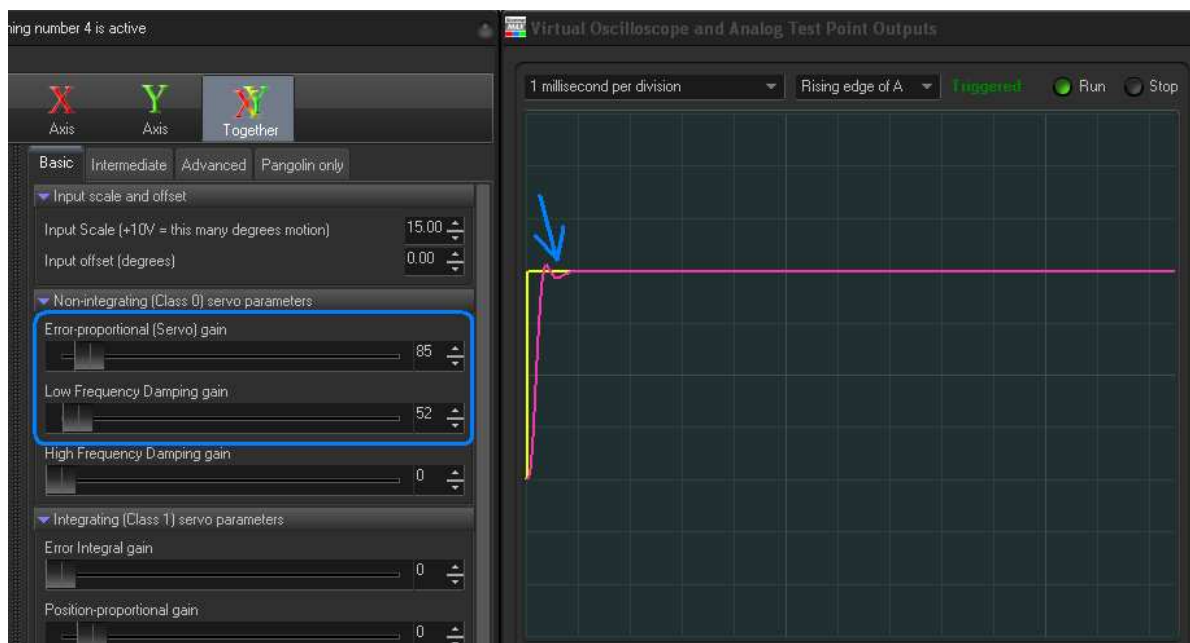
- I. On the Basic tab, set Low Frequency Damping to 10. Then slowly increase the Servo Gain up to 10. You should see something very similar to the screen shot above, including the overshoot denoted by the blue arrow above. If you do not see the overshoot, continue to increase Servo Gain until you have a slight overshoot.

(Note that the toolbar button “XY Together” button is depressed. This means that the settings that you are changing will be applied to both axes. Since ScannerMAX scanners are manufactured with a high degree of similarity between scanners, and since ScannerMAX mirror sets are designed to have the same inertia for both X and Y axis, adjusting both X and Y axis simultaneously is probably the best way to tune the system quickly. Fine-tuning of X and Y axis can be done separately, by pressing the X or Y button as needed.)

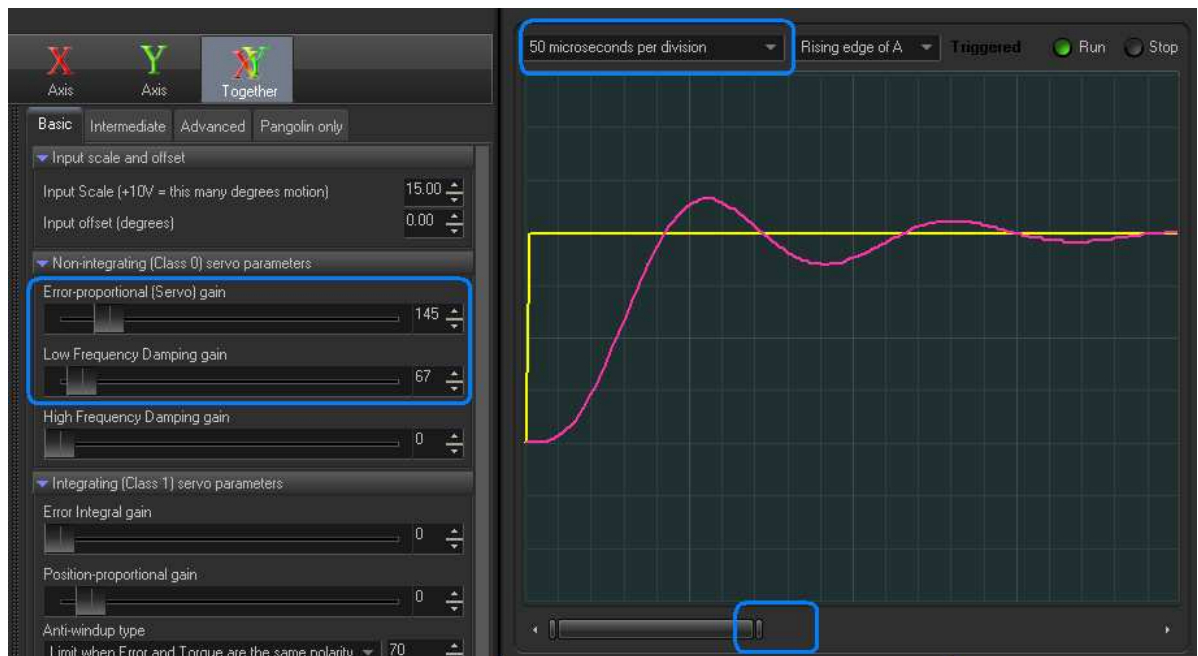
- J. Increase the Low Frequency Damping control to eliminate the overshoot.



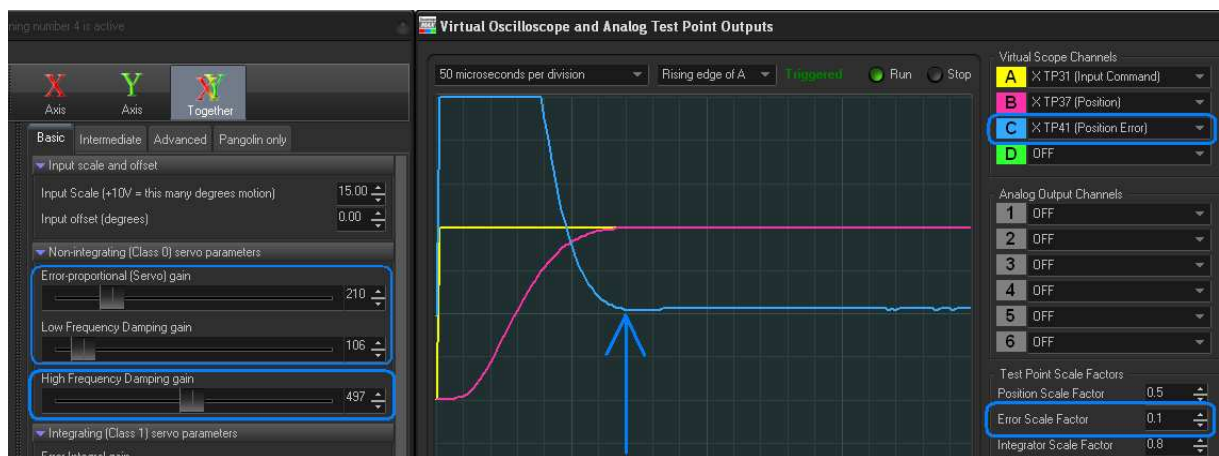
- K. At this point, the scanners should be scanning and you may adjust them in their mount, such that they are scanning toward the center of the projection surface.
- L. Continue to increase the Servo Gain and Low Frequency Damping little by little, in a manner that you achieve a bit of overshoot with Servo Gain, then eliminate the overshoot using Low Frequency Damping. Eventually you will reach a point where the squarewave no longer looks square after the rise, or that it is not possible to completely eliminate the overshoot using Low Frequency Damping. This is illustrated below.



M. (You can get a better view by changing the time-base on the Oscilloscope to 50 microseconds per division and then zooming as shown below.)



N. On the Oscilloscope, Select the Position Error signal for Channel C, and set the Error Scale Factor for 0.1 degrees per division. The Error signal will be used to help you fine-tune the controls to eliminate overshoots, and also identify the step time that is being achieved by the system. This is illustrated in the picture below.

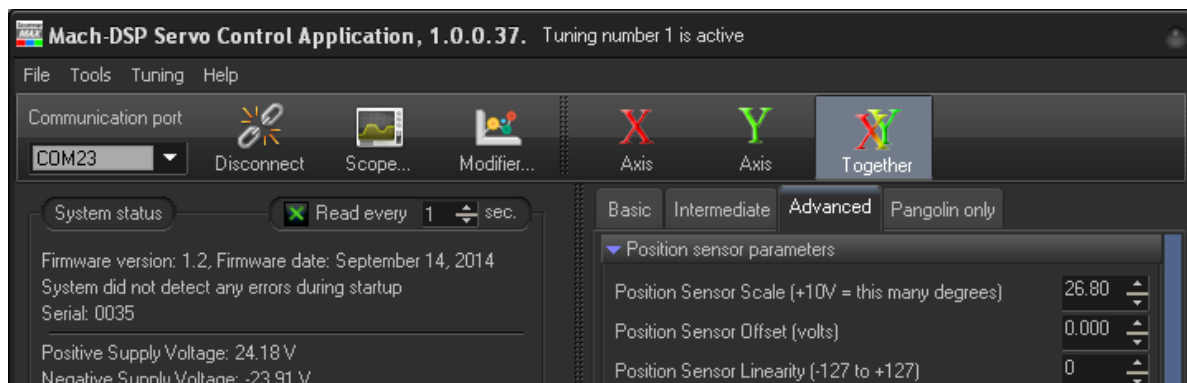


O. Increase the High Frequency Damping control to help eliminate the overshoot that could not be eliminated using Low Frequency Damping alone, then increase Low Frequency Damping as well. Basically you should adjust Low Frequency Damping and High Frequency Damping to levels that will completely eliminate overshoot.

- P. Continue to increase Servo Gain, Low Frequency Damping and High Frequency Damping, each one a little bit at a time, while keeping overshoot to a minimum and also while watching the Error signal (Oscilloscope Blue Trace C). The point at which the Error signal goes to zero (i.e. meets the middle of the vertical display) indicates the step response time of the system. Increase Servo Gain if you want to decrease the step time of the system; then increase the damping controls to eliminate overshoot. This is an iterative process.

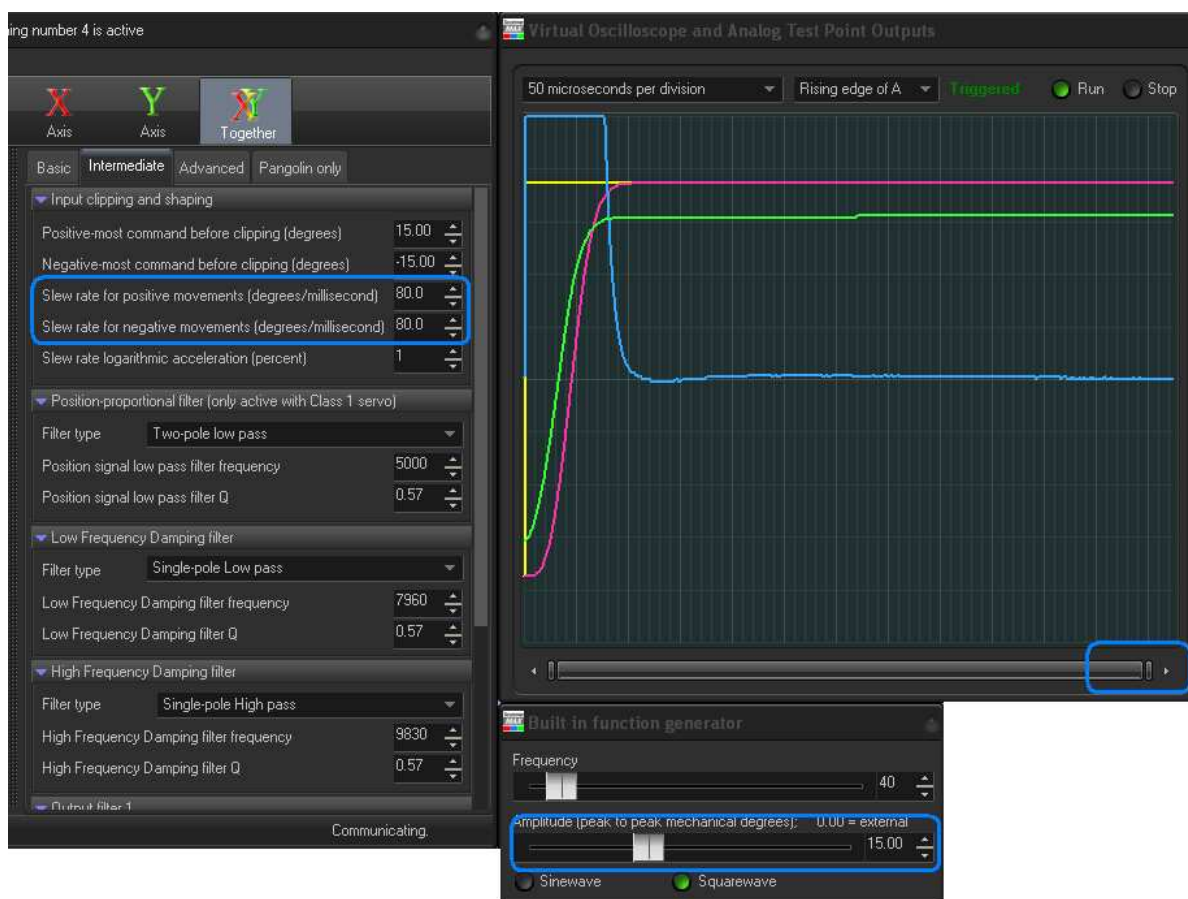
9.3 *Position Offset and Position Scale*

- Q. Set the Test Signal Generator to generate a sine-wave instead of a squarewave. This will change the projected image to a circle. Then change the amplitude of the Test Signal Generator to 0.01 degrees. This will produce an incredibly small scan, while still eliminating the Command Input signal.
- R. Position the scanners in the X-Y mount such that they are projecting as closely as possible to the center of the projection surface. (It may be impossible to achieve a true center with simple mechanical adjustments of the scanner. Fine-tuning will be done in the next step.)
- S. Click on the Advanced tab, then click on the X or Y button. This selects an individual axis to be adjusted instead of adjusting both axes together. Adjust the Position Offset control on the Advanced tab to center the projection on both the X and Y axis.



- T. Set the amplitude of the Test Signal Generator to produce the desired maximum-sized projection. For example, if you are trying to ultimately accomplish a 40-degree-optical projection angle, set the Test Signal Generator amplitude to 20 degrees. (Remember, the Test Signal Generator and all other angles specified in the Mach-DSP program use mechanical degrees, and the optical angle is twice the mechanical angle.)
- U. Adjust the Position Sensor Scale on the Advanced tab, to increase or decrease the size of the projected circle, as needed to accomplish the desired projection angle, according to the scale on the projection surface.

- V. Set the amplitude on the Test Signal Generator back to 2.00 degrees mechanical, and then set the waveform back to squarewave. Check the appearance of the squarewave and step time shown on the Oscilloscope. Adjust the Servo Gain, Low Frequency Damping and High Frequency Damping as needed.
- W. Gradually increase the amplitude on the Test Signal Generator toward your largest intended projection angle. (Note that this time, you are using a squarewave instead of a sine-wave). Carefully watch for overshoots in the projected image and also on the Oscilloscope. (You will need to increase the Position Scale Factor setting in the Oscilloscope.) If you see any overshoot, you should stop increasing the amplitude of the Test Signal Generator and adjust the Slew Rate Limiter. To do this, click on the Intermediate tab, then decrease the *Slew rate for positive movements* and the *Slew rate for negative movements* settings to eliminate the overshoot. Then continue to increase the amplitude on the Test Signal Generator until you have finally gotten to your intended maximum.



- X. Set the amplitude on the Test Signal Generator to 0, to allow external Command Input signals to control the Mach-DSP.

9.4 Going beyond PD – adding integration to accomplish PID tuning

A system that uses only Proportional servo terms to position the mirror will inevitably leave a small difference between the position commanded by the input and the position actually achieved by the mirror. This small difference is referred to as the “Position Error”. The Position Error is amplified by the servo loop (the amplification amount being controlled by the Servo Gain control) and applied to the motor in the form of current. Nevertheless, as long as there are mechanical imperfections in the scanner (and there always are) including bearing friction and magnetic hysteresis, some small amount of position error will always be present in the system. In many cases, this error is sufficiently small that it will not impact the user's application, especially since removing this small error can come with its own complications and may hinder performance.

This section describes how the Position Error can be eliminated by adding an Integration term to the servo loop.

See the figure below, which illustrates the Position Error signal during a squarewave command input. On the left side of the figure, you can see that the Position Error signal actually never goes all the way to zero volts, which indicates that there is always some error (difference) between the commanded position and actual position. The solution is to integrate (i.e. accumulate) this error over time, and include this integrated error in the final current that drives the motor. The right side of the figure shows the error signal when integration is added.

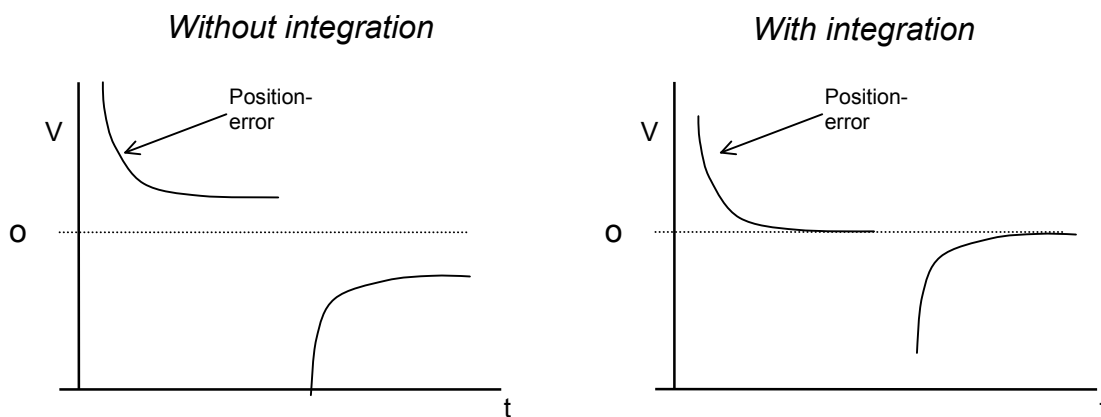
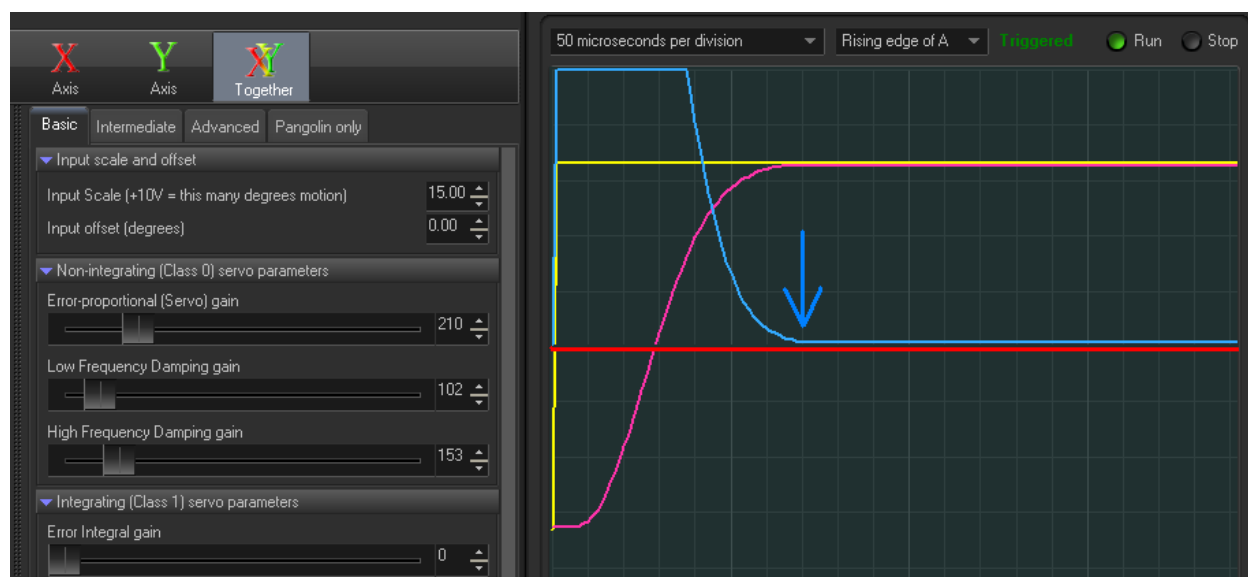


Figure 10.4: Without and with integration

Above we have presented a figure that is intended to graphically represent Position Error signal, but this can also be seen using the Oscilloscope built-into the Mach-DSP program.

Below you see a screen-shot from the Mach-DSP program. This screen shot was made after example rough PD tuning discussed in section 10.2. In this screen shot, the scanner is tuned for approximately 350 microsecond small steps (as can be seen with the blue arrow). In the example rough tuning above, a step of 2.0 degrees was input, and the blue trace shows Position Error, having a scale factor of 0.1 degrees per division.

In this screen shot, we have placed a red line on the zero axis, to highlight how the blue trace does not quite go to zero. Since this particular view shows 0.1 degrees per division, and since the blue line is approximately 1/10 the way upward on a division, this indicates that an error remains of approximately 0.01 degrees, or 175 microradians of error.

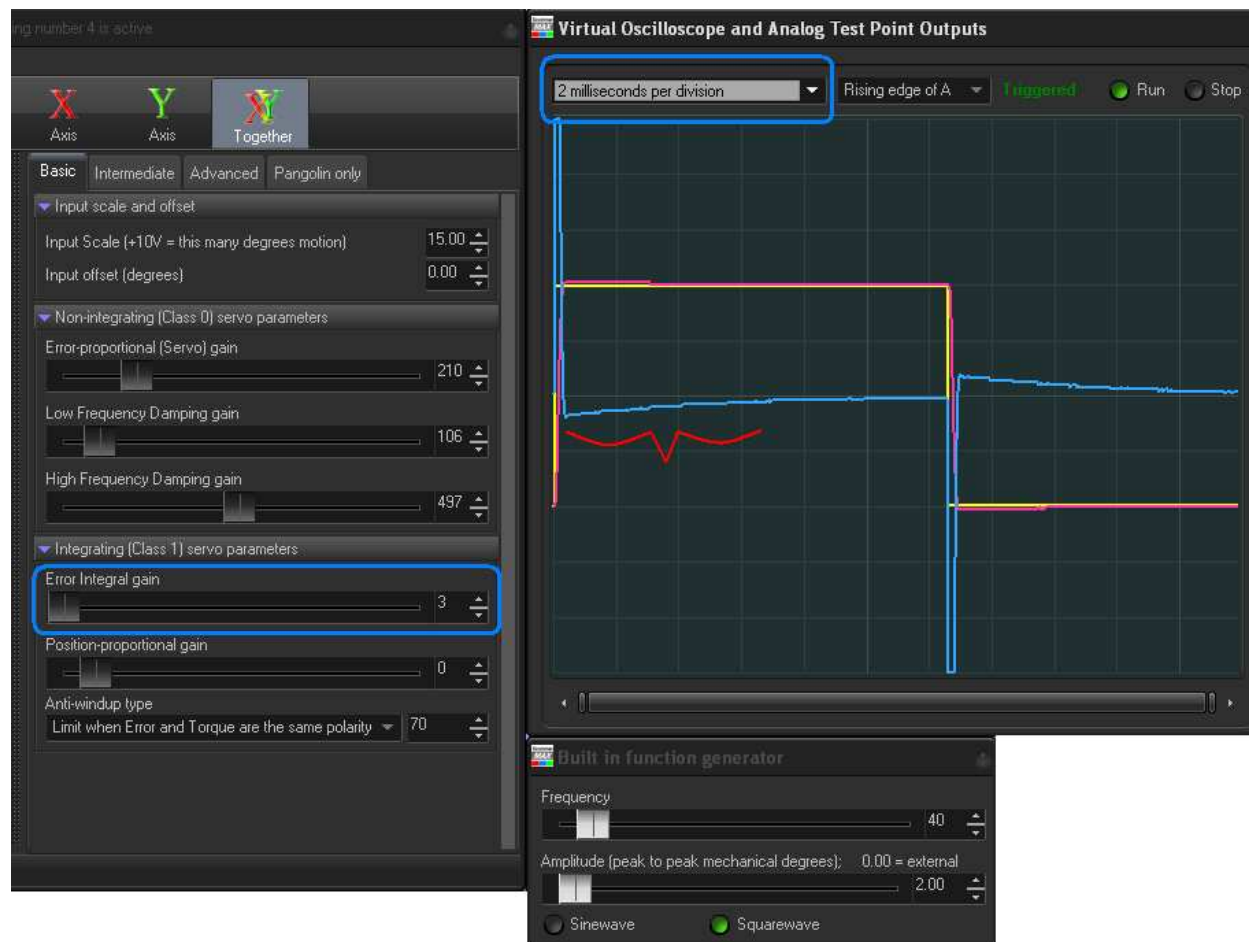


This error may be reduced by further increasing Error-proportional (Servo) gain, along with appropriate amounts of Low Frequency Damping and High Frequency Damping. Indeed, the particular scanner we were using while making all of these screen shots is capable of achieving step times of 75 microseconds, and so by tuning to 350 microseconds, there is a lot of performance remaining, and a lot of room remaining on the sliders for further tuning increases.

However, increasing Servo gain also increases servo bandwidth (along with noise), and if the particular application did not need any greater bandwidth, then perhaps this would not be a very good solution.

Therefore, to maintain the current servo bandwidth and eliminate the position error, the Error Integral gain can be increased. This is illustrated in the next screen shot. Note that we have increased the time-base to 2 milliseconds per division, and increased Error Integral gain to only 3.

Indeed, by integrating position error over time, and amplifying that and having it drive the motor, the position error will go to zero eventually. However, adding even this small amount of integration to the servo loop has caused the mirror to actually overshoot the intended command position, and this overshoot remains for more than 6 milliseconds!

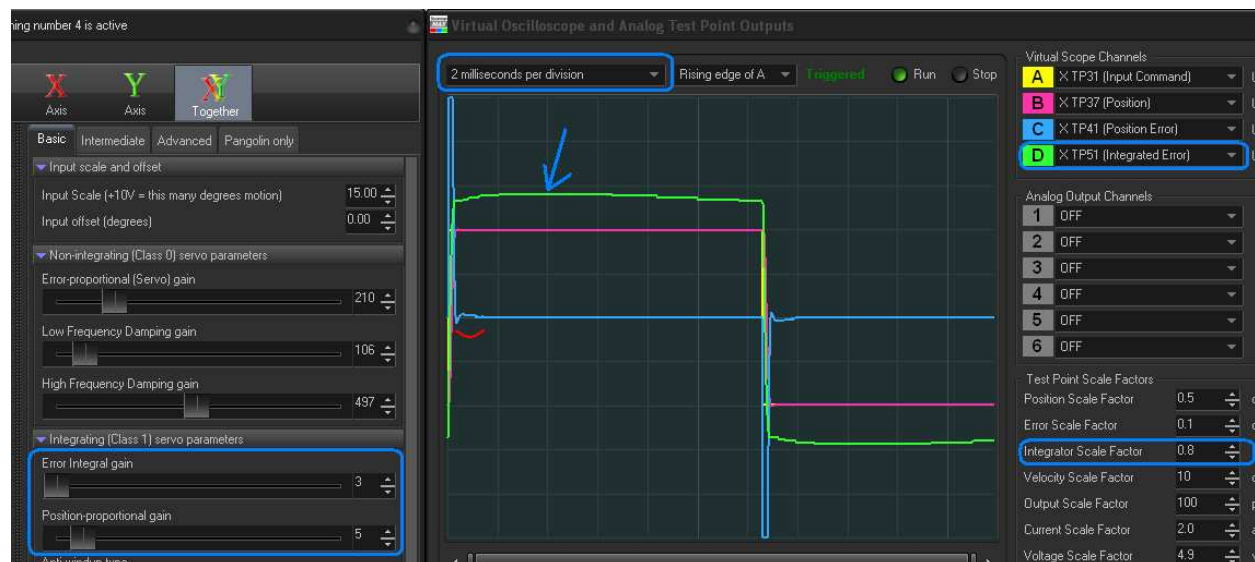


This happens because for approximately 350 microseconds, there was a large position error (4 degree error in the beginning of the step). This large error caused a large amount of accumulation by the integrator. This large accumulated error becomes amplified by the servo, ultimately causing an overshoot.

However, this problem can be largely solved by adding an additional servo term. To prepare to adjust that servo term, use the Oscilloscope in the Mach-DSP program, and set Channel D to show the Integrated Error, and set the Integrated Error scale factor to 0.8

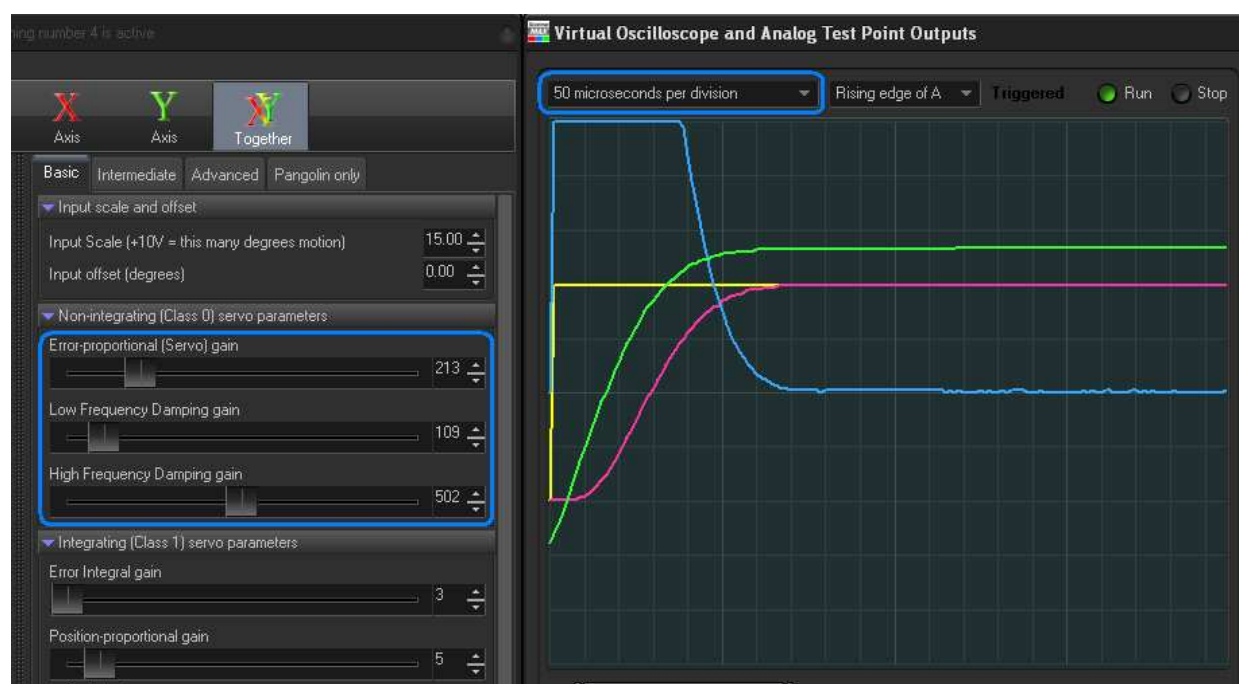
Once the Oscilloscope is setup as described above, adjust the Position-proportional gain to 5. You will observe that the Position Error is no longer overshooting the intended target. However, you will also notice that a small amount of overshoot and ringing has crept into the position (and error) signal – as if you had increased the Servo Gain control. This occurs because Error Integral and Position-proportional gains are very

similar to Servo Gain, and thus increasing any of these must be met with some increase of Low-Frequency Damping and High-Frequency Damping.



Also note the Integrated Error trace shown above in green. For a squarewave input, ideally this should also be a squarewave – essentially having flat tops. If this is slanting upward or downward, it shows that integration must be increasing or decreasing over time to try to correct the mirror position.

By changing the Oscilloscope to 50 microseconds per division, and then further tweaking Servo gain, Low-Frequency Damping and High-Frequency Damping, perfect results can be obtained.

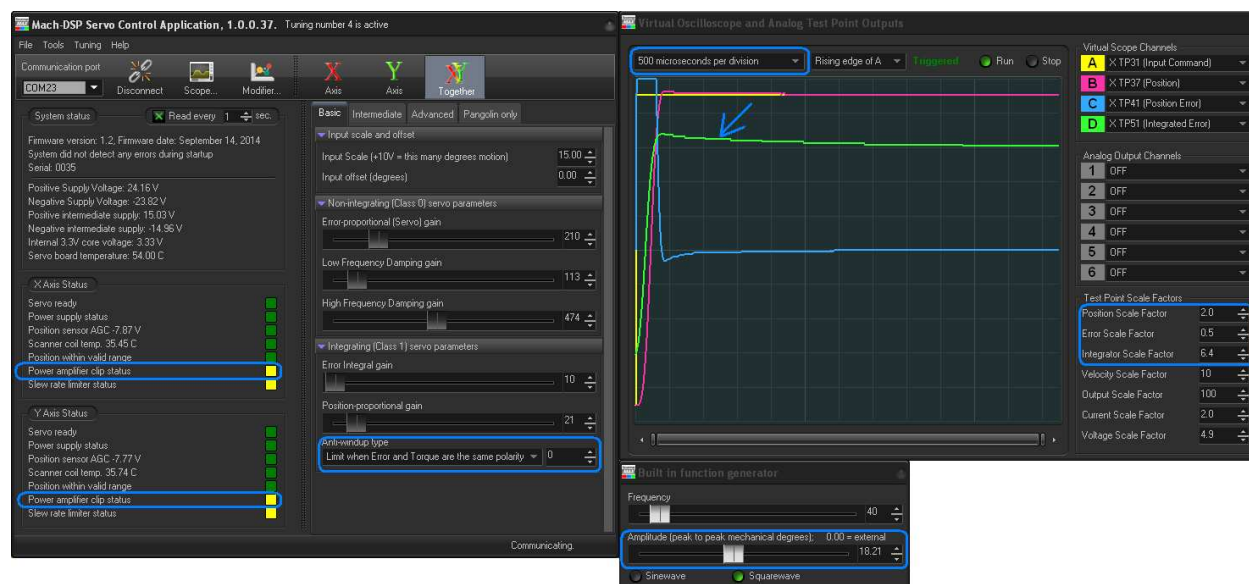


As was done in Step W above, you should re-check the large-signal performance after tuning for small signals. In the screen shot below, you will see that we have set the time-base for 500 microseconds per division, and set the Position Scale Factor, Error Scale Factor, and Integration Scale Factor as necessary to view a much larger waveform. We have also set the Test Signal Generator to produce waves greater than 18 degrees.

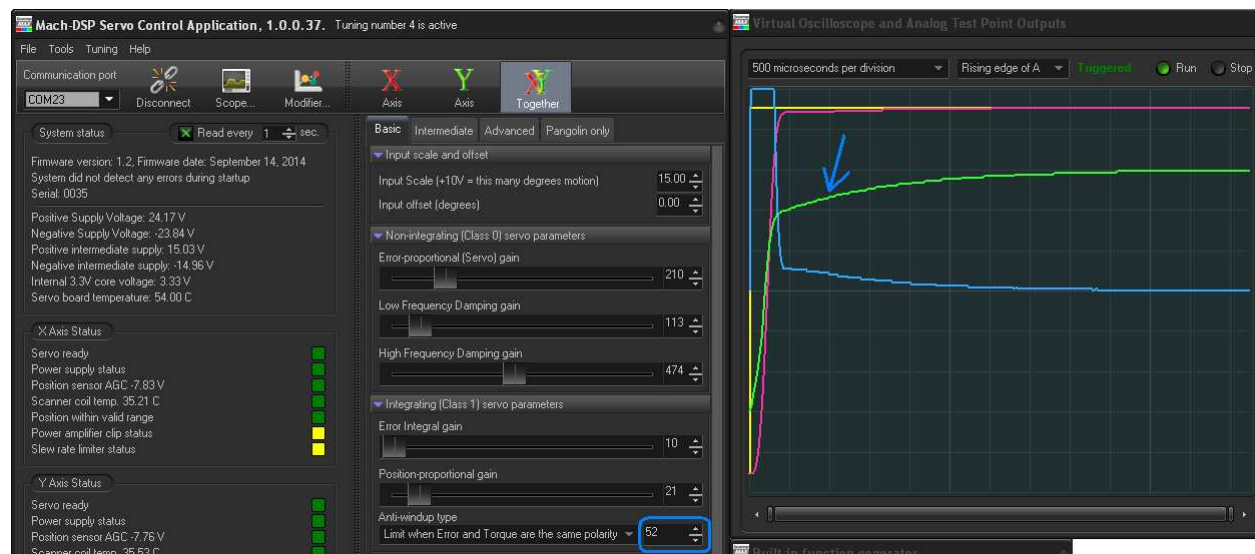
With this large squarewave input, there is overshoot present. This can be seen not only in the Position Error signal (blue trace) but also in the Integrated Error signal (green trace). This overshoot is caused by the fact that the power amplifier has become saturated. This is indicated by the yellow blocks that are illuminated in the status area.

This overshoot can be eliminated by adjusting the Slew-rate limiter, as described in Step W. But before doing that, it will be useful to set the Anti-Windup amount.

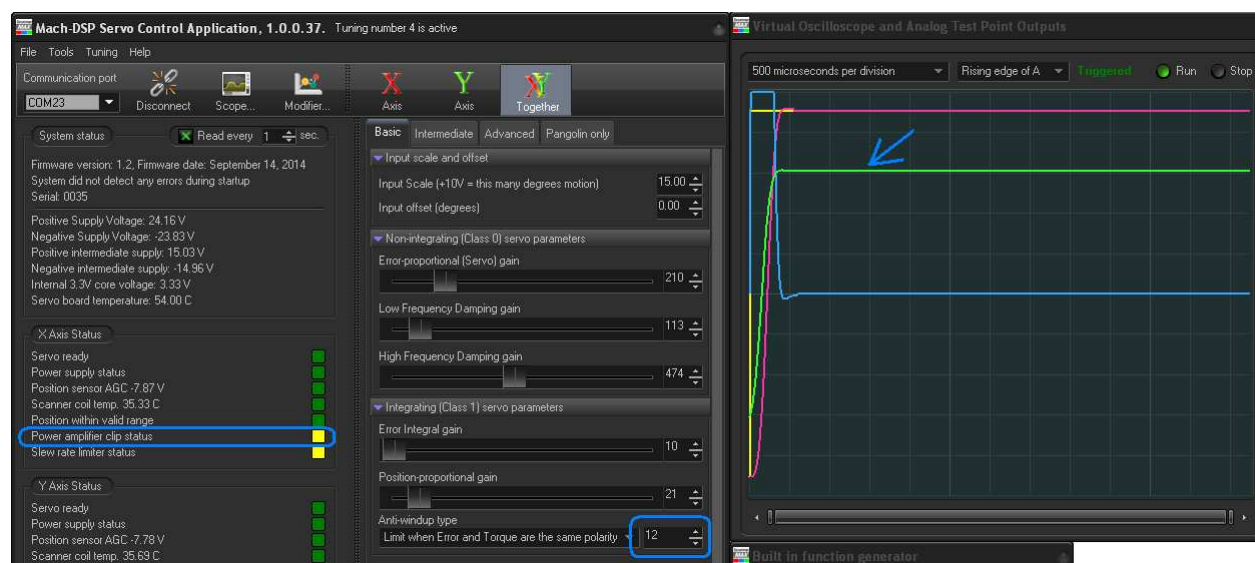
In the screen shot below, you will see that we have set the Anti-Windup gain to 0.



Increasing the Anti-windup gain to a value that is too high will cause undershoot of the position, and long settling time.



By carefully adjusting the anti-windup gain, the green trace can be made into a squarewave, which is desirable. Notice that there is still a small amount of overshoot present, as indicated by the Position Error signal. However, also notice that the power amplifier is still being saturated, as illustrated by the yellow blocks in the status area. At this point, the overshoot can be eliminated by adjusting the Slew-rate limiter, as discussed in Step W.



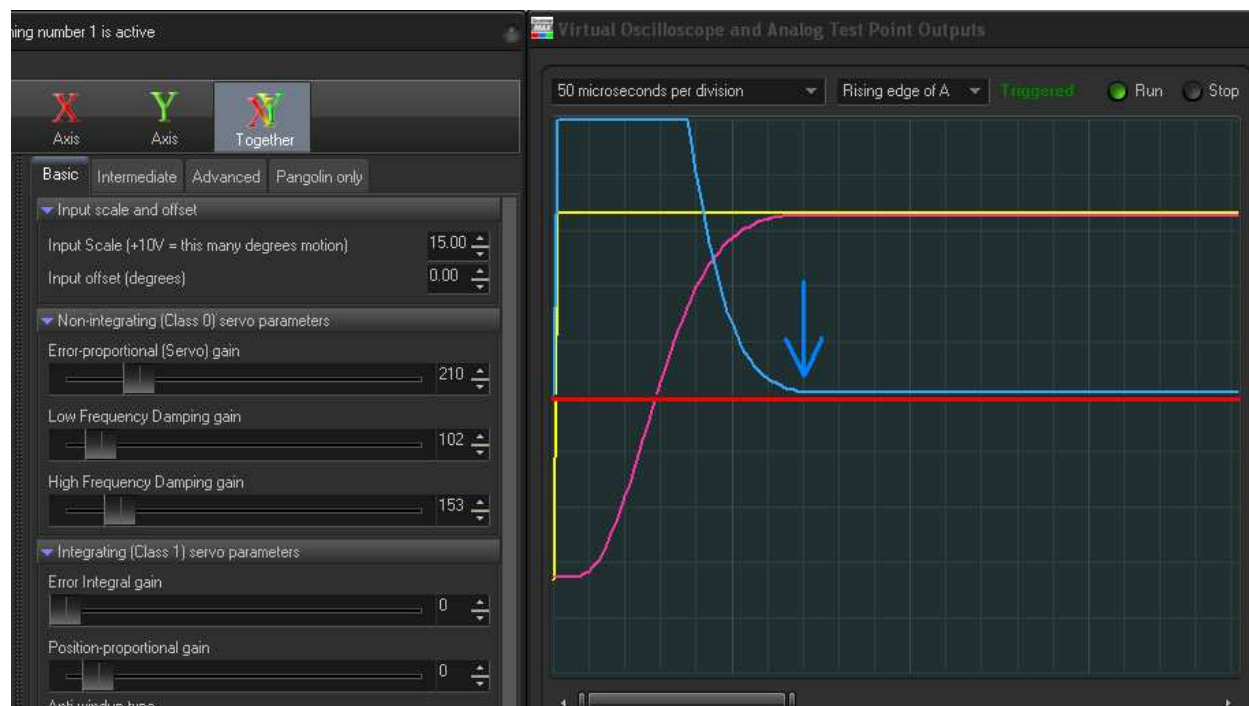
9.5 Careful tuning leads to optimal performance

Within this section we will present three separate scanner tunings. All three scanner tunings use exactly the same Servo gain setting, and achieve critical damping (no overshoot). Two of the three tunings achieve the same step time (approximately 350 microseconds). However, one of the tunings is more optimal – achieving 40% faster step-times. The difference between the scanner tunings is how the Damping setting is used.

PD tuning

The screen shot below shows an example of PD tuning. Here we can see that the step time is approximately 350 microseconds (as highlighted by the blue arrow). This is exactly the same screen shot used in 10.4 above.

There's certainly nothing wrong with this tuning, although this particular scanner can achieve much higher performance if desired.

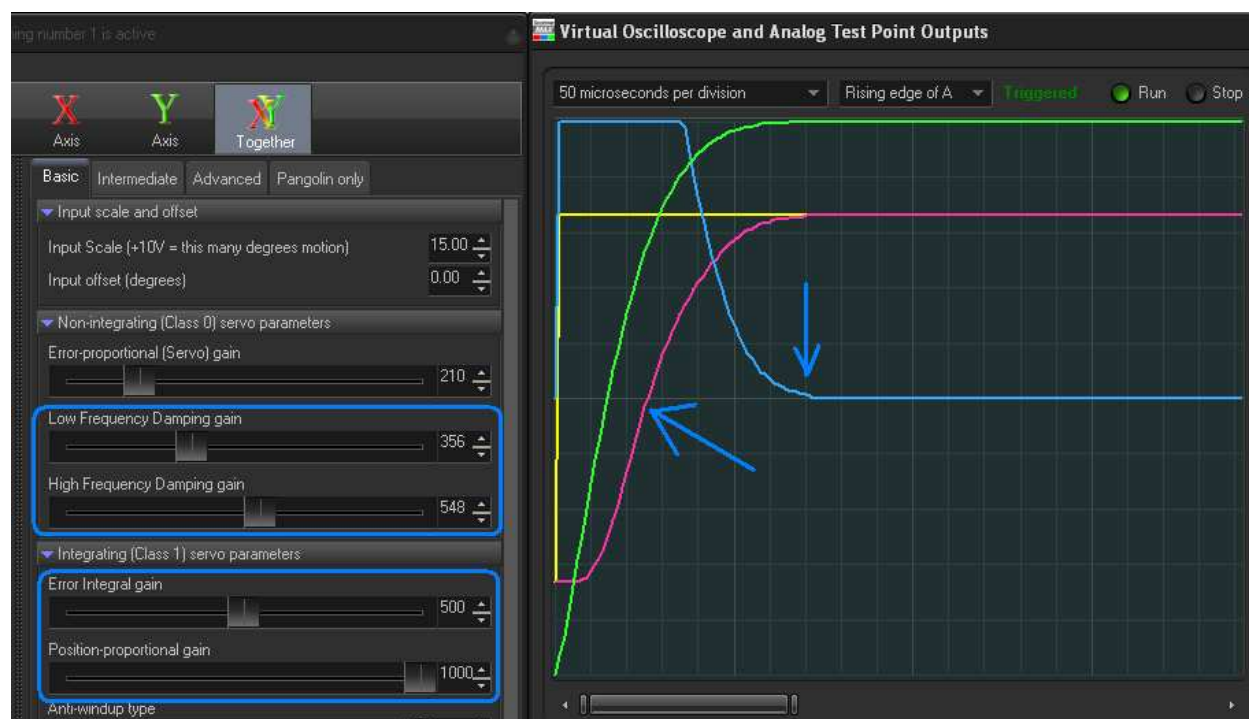


Adding a high amount of Integral and Position Proportional

The screen shot below shows how we've taken the PD tuning from above, and added a tremendously high Error Integrator gain. To counterbalance the integrator and keep the servo loop stable, we've also added a tremendously high Position-proportional gain. To achieve critical damping, Low-Frequency Damping and High Frequency Damping are also increased.

Notice that despite the Error Integral and Position Proportional gains being increased tremendously (both of which contribute to acceleration in the same way as Servo Gain), we still have a 350 microsecond step time.

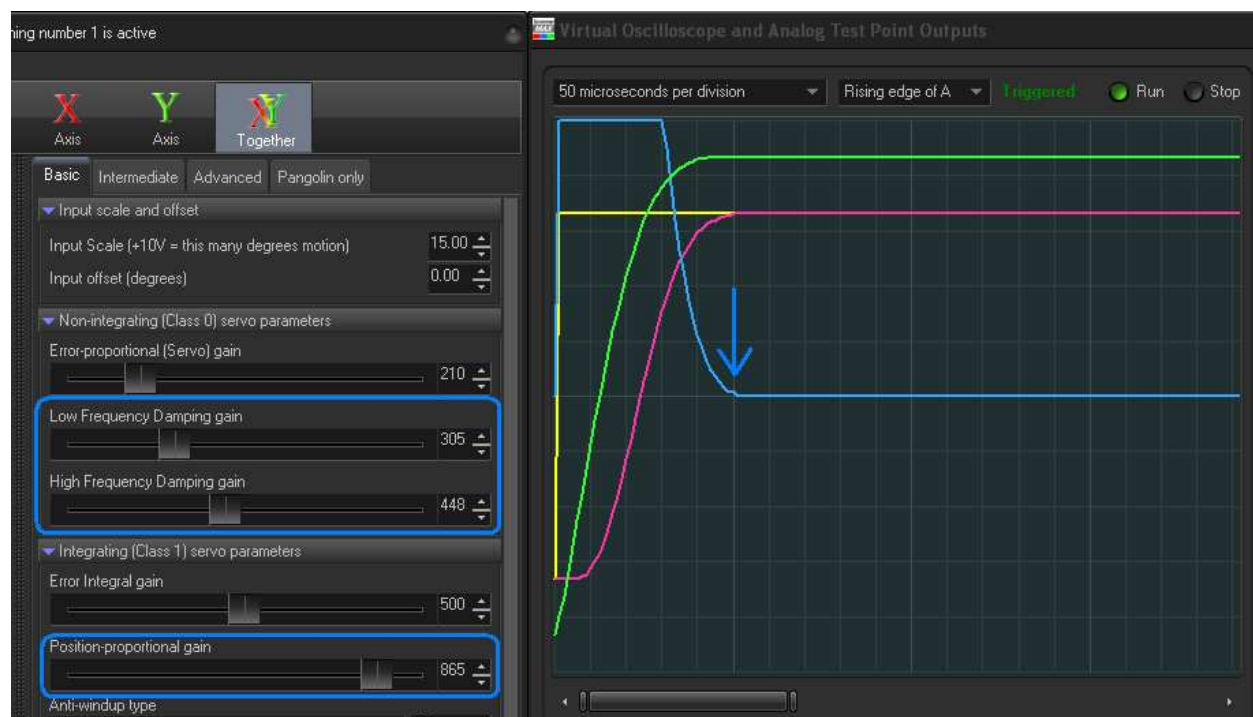
Also note that the position waveform appears to be asymmetrical in terms of acceleration and deceleration. The blue arrow that points to the pink trace shows that the position signal reached the half-way mark at around 125 microseconds. After that, the remaining 200 microseconds are spent slowing down and coming to a stop. When the servo is adjusted optimally, ideally the same amount of time is spent accelerating and decelerating.



Revisiting Damping and Position-Proportional gain improves performance

The screen shot below is almost identical to the screen shot above. It uses exactly the same Servo gain and Error Integral gain. However, here we see that we were able to achieve critical damping with far less Low Frequency Damping, High Frequency Damping, and Position-proportional gain. Here we see that we have achieved a step time of only 250 microseconds, which is a 40% improvement over the step times achieved in the previous two screen shots.

Also note that the position waveform now appears perfectly symmetrical in terms of time needed to accelerate and decelerate. Comparing this to the screen shot above, the pink trace shows that the position signal reached the half-way mark at around 125 microseconds, which is half of the 250 microseconds needed to achieve the full step.



The main lesson is that just because a step is critically damped does not mean that the servo is optimally tuned. Indeed, it is possible to achieve critical damping with High Frequency Damping and Low Frequency Damping adjusted to levels far greater than are necessary.

Tuning must be done carefully to achieve the optimal performance possible with ScannerMAX scanners and the Mach-DSP servo driver.

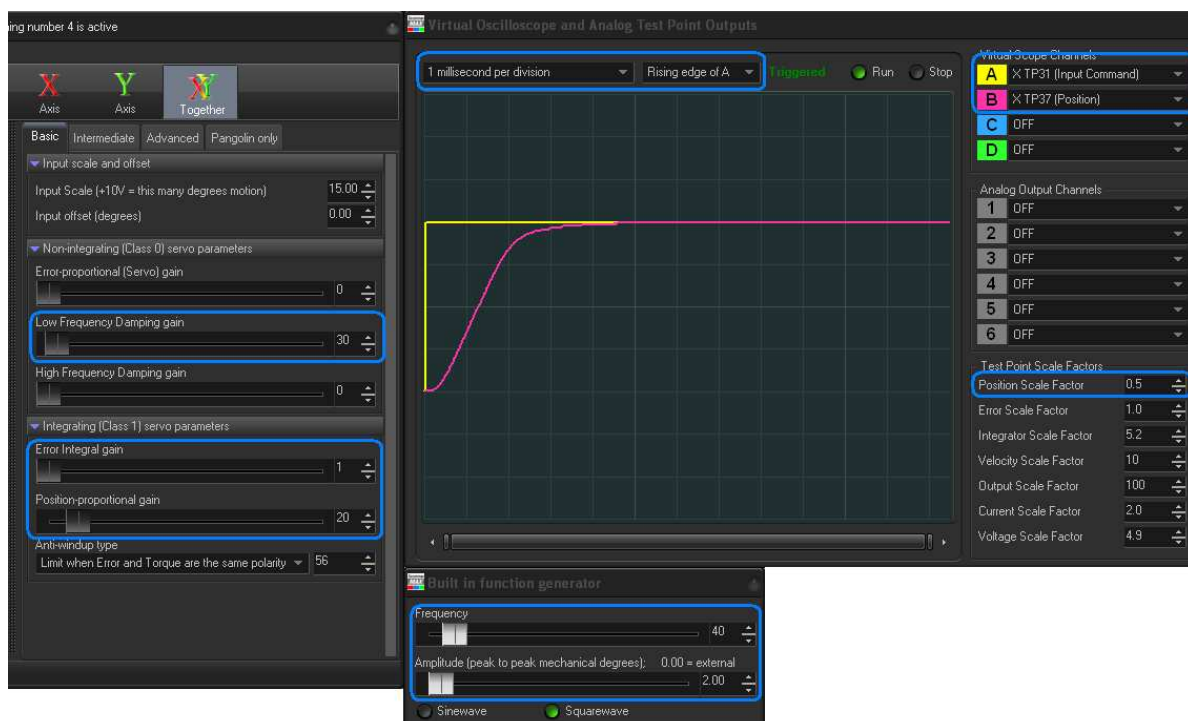
9.6 PDF configuration and tuning

With the PID tuning described above, the primary servo term responsible for accelerating the motor is the Proportional term – i.e. a term that is proportional to the error between the commanded position and actual position. The Integral term in PID tuning is only included to try to minimize the Position Error over time. However, due to the fact that only small amounts of Error Integral are used (low integrator gain), the effect of the integral is only applied after a relatively long period of time – typically several milliseconds. This means that while PID has the possibility of minimizing position error at very low frequencies, position errors may still remain at higher frequencies.

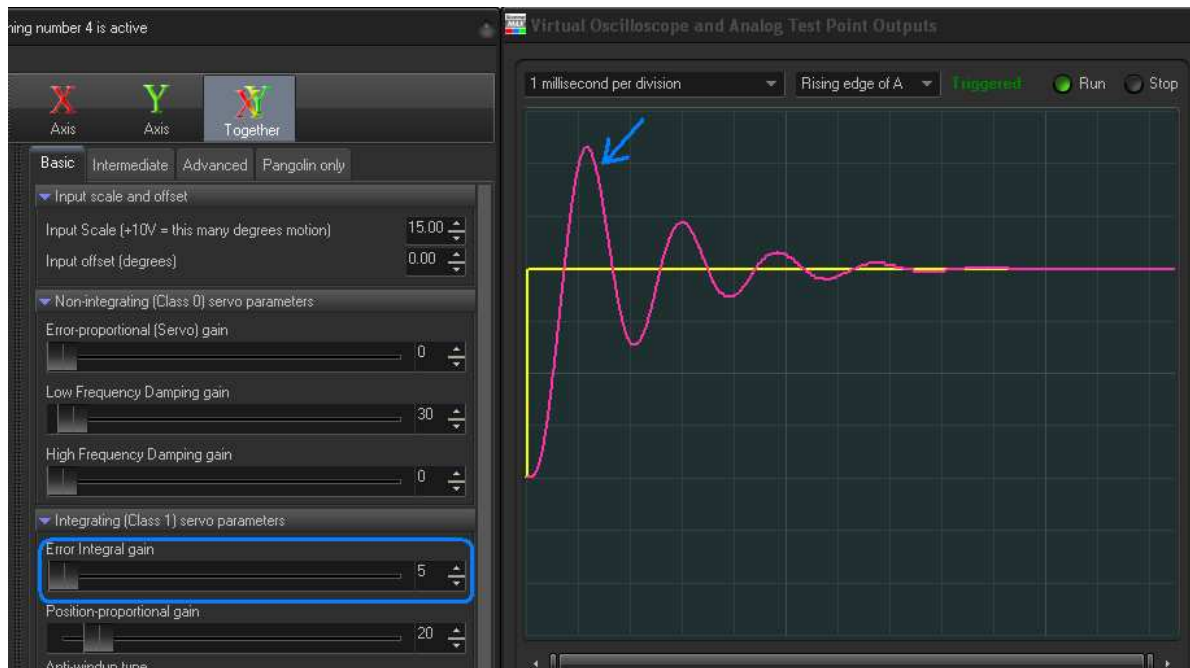
PDF (pseudo derivative feedback) is an alternative to PID tuning. Unlike PID where the Position Error is used to directly accelerate the mirror (in the form of Servo gain), PDF does not use Position Error at all (Servo gain is left at 0). Instead mirror acceleration is achieved purely with Error Integration servo term. Ordinarily, large amounts of error integration would make the servo loop unstable, and so a high amount of Position-proportional gain is used to counterbalance the high integrator gain. The high integrator gain ultimately means that the position error is constantly being minimized, as opposed to only being minimized at very low frequencies. PDF is sometimes referred to as a “third-order tune”.

To prepare for PDF tuning, complete steps A through H in Section 10.2 above.

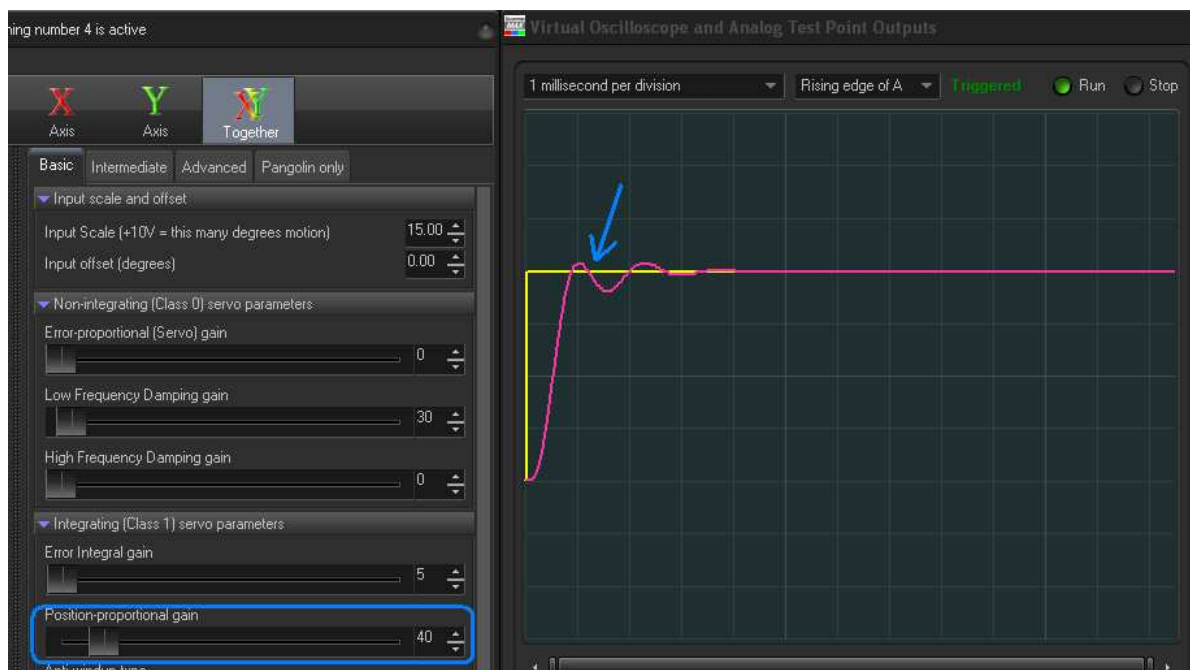
- I. On the Basic tab, set Low Frequency Damping to 30 and set Position-proportional gain to 20. Then set Error Integral gain to 1. You should see something very similar to the screen shot below, which may or may not include a bit of overshoot.



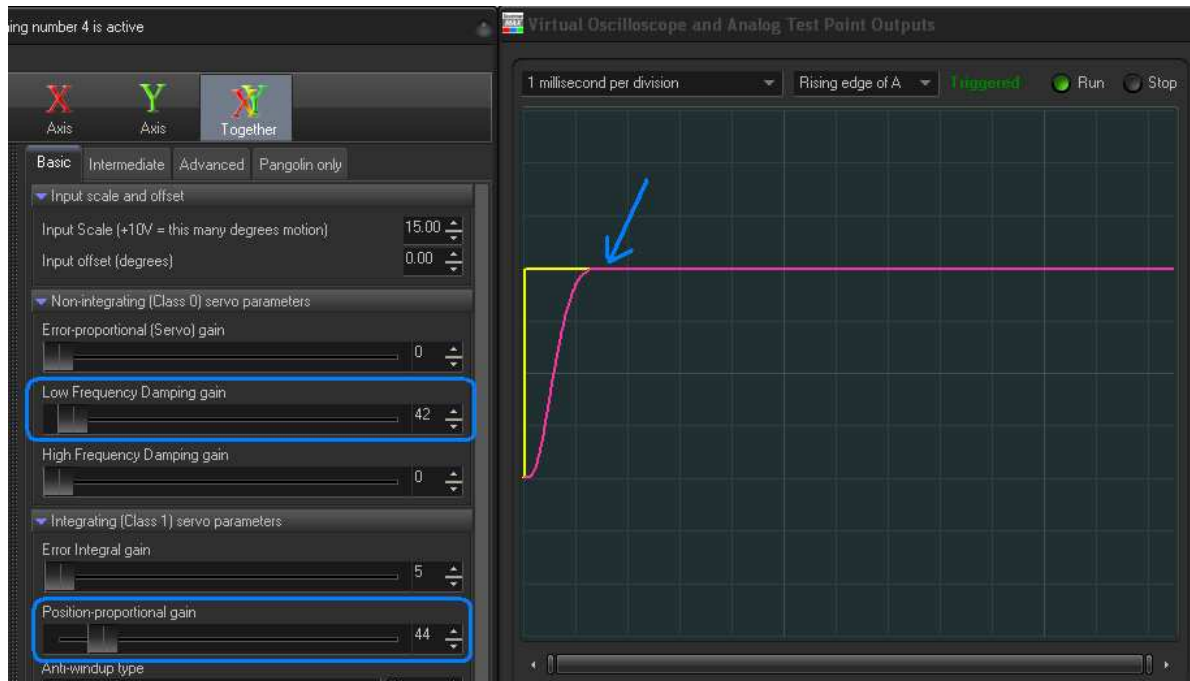
- J. Continue to increase the Error Integral gain very slowly, until pronounced overshoot is seen. In this case we have increased Error Integral gain to only 5.



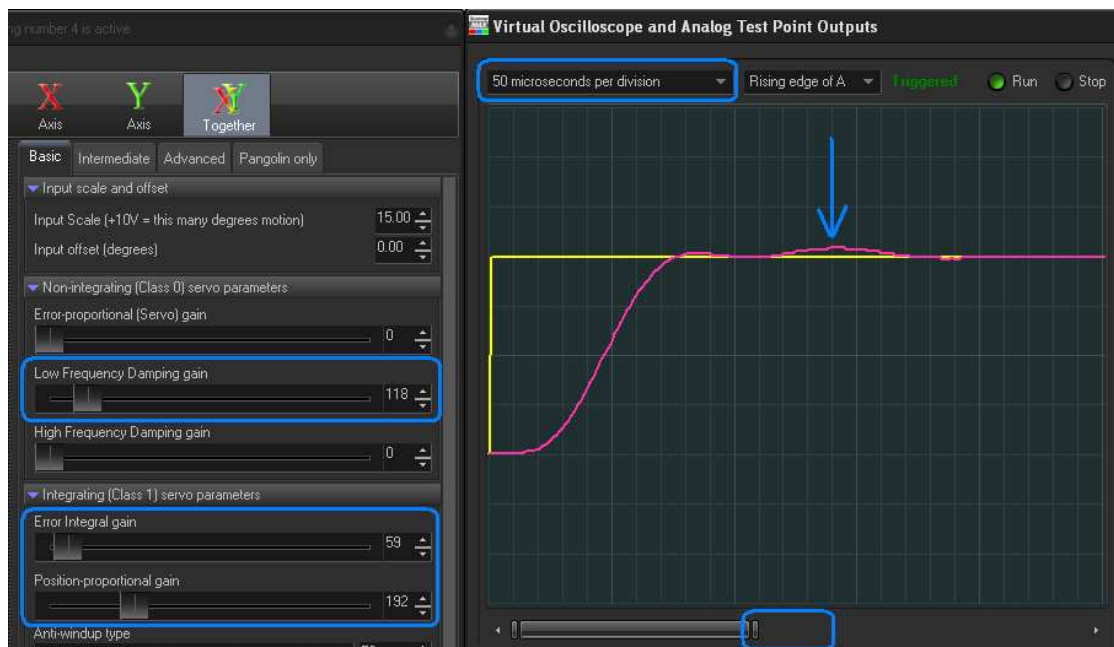
- K. Increase Position-proportional gain (instead of Low-Frequency Damping) to largely eliminate the pronounced overshoot seen above. With PDF tuning, you will find that the controls work in non-intuitive ways.



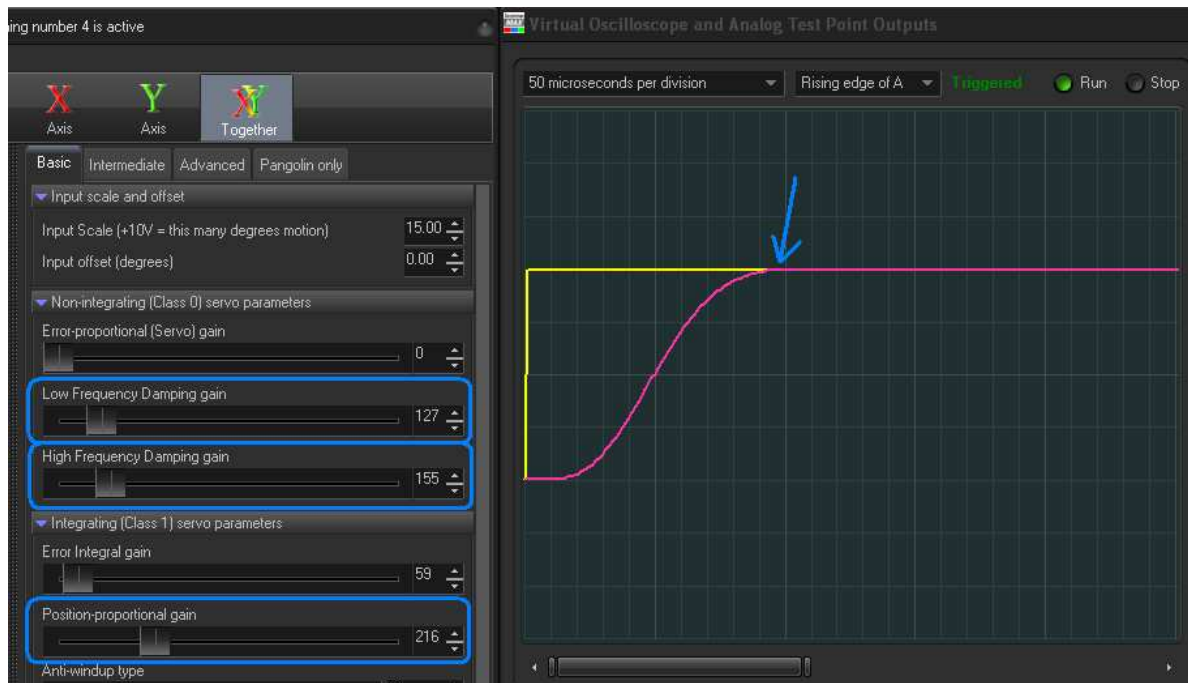
- L. Increase Low-Frequency Damping, and also Position-proportional gain to completely eliminate the overshoot.



- M. Continue increasing Error Integral gain, Low Frequency Damping, and Position-proportional gain to increase servo bandwidth and decrease step time. As was the case in step L of section 10.2 above, eventually you will reach a point where the squarewave no longer looks square after the rise, or that it is not possible to completely eliminate the overshoot using Low Frequency Damping and Position-proportional gain. This is illustrated below. (Set the time-base to 50 microseconds.)



- N. Increase the High Frequency Damping control to help eliminate the overshoot that could not be eliminated using Low Frequency Damping and Position-proportional gain alone. To decrease the step time (increase servo bandwidth), increase Error Integral gain, then use Position-proportional gain, Low-Frequency Damping and High-Frequency Damping to eliminate overshoots, as shown on the Oscilloscope.



PDF tuning requires a great deal of patience and skill, and you will find that the controls work in non-intuitive ways. You will find that increasing Position-proportional gain is useful in controlling the first overshoot that occurs after the step. You will also find that increasing Low-Frequency Damping without a sufficient amount of Position-proportional gain will actually make overshoots worse.

As was stated at the beginning of Paragraph 10, this manual is not meant to be a complete guide to scanner tuning – only to familiarize you with some of the controls and what they do. This section does not cover concepts that may be important, including setting of one or more Notch filters, found on the Advanced tab.

10.0 RoHS & REACH Declaration of Compliance

Restriction of the use of certain Hazardous Substances

Pangolin Laser Systems, Inc. is committed to fully support our customers regarding environmental and green production requirements. This statement declares the compliance with EU Directive 2011/65/EU and its amendment 2015/863/EU (EU Directive 2002/95/EC was recast by 2011/65/EU) on the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (the **RoHS** Directive), which restricts the use of the hazardous substances listed below. Based on information provided by our suppliers, Pangolin Laser Systems, Inc. designates the products listed below as **RoHS** Compliant for orders placed on or after the date of this certificate.

Confirmation of compliance status by our suppliers is either because the products do not contain any of the restricted substances referred to in the **RoHS** Directive at concentrations in excess of those permitted under the RoHS Directive, or because removal of the restricted substances is not technically possible and their existence in the products at levels in excess of these concentrations is allowed as one of the particular applications listed in the Annex to the RoHS Directive.

For these purposes, the maximum concentration values of the restricted substances by weight in homogenous materials are:

Lead	0.1%
Mercury	0.1%
Hexavalent Chromium	0.1%
Polybrominated Biphenyls (PBBs)	0.1%
Polybrominated Diphenyl Ethers (PBDE)	0.1%
Cadmium	0.01%
Bis (2-ethylhexyl) phthalate (DEHP)	0.1%
Dibutyl phthalate (DBP)	0.1%
Benzyl butyl phthalate (BBP)	0.1%
Diisobutyl phthalate (DIBP)	0.1%

Pangolin Laser Systems, Inc. also declares that all of our articles (i.e. materials, parts or products) comply with the legal obligations regarding Article 33 of the **REACH** regulation (Regulation (EC) No. 1907/2006 on Registration, Evaluation, Authorisation and Restriction of Chemicals). We confirm that all of articles do not contain any of the substances specified in the current Candidate List of Substances of Very High Concern (SVHC) in a concentration of more than 0.1% w/w.

Description
Manufacturer/Brand Name
Manufacturer Part No.
Date

Mach-DSP Servo Driver **RoHS and REACH Compliant: Yes**
ScannerMAX division of Pangolin Laser Systems, Inc.
Mach-DSP
February 12, 2019

William R. Benner, Jr.



President and CTO
Orlando, FL – USA



10.1 EU Declaration of Conformity

1. Product model: Mach-DSP

2. Name and address of the manufacturer or authorized representative:

Manufacturer:

Pangolin Laser Systems, Inc.
9501 Satellite Boulevard, Suite 109
Orlando, Florida 32837 USA
Phone: +1-407-299-2088
E-mail: contact@pangolin.com

3. This declaration of conformity is issued under the sole responsibility of the manufacturer.

4. Object of the declaration:

Brand name: ScannerMAX
Model/type: Mach-DSP

5. The object of the declaration described above is in conformity with the relevant Union harmonization legislation:

Electromagnetic Compatibility Directive (EMC) 2014/30/EU,
Restriction of Hazardous Substances (RoHS) Directive 2011/65/EU.

6. References to the relevant harmonised standards used or references to the other technical specifications in relation to which conformity is declared:

EMC: EN 55103-1:2009 + A1:2012
EN 55103-2:2009
RoHS: EN 50581:2012

7. Signed for and on behalf of:

Orlando, February 12, 2019

Manufacturer:
Pangolin Laser Systems, Inc.



William R. Benner, President and CTO

11.0 More Information

More information about ScannerMAX scanners and servo drivers, including additional application hints and tips can be found at www.ScannerMAX.com.

LASER SCANNING BOOK AVAILABLE

Detailed information about galvanometer scanners, servo driver techniques, and scanner applications can be found in the #1 best-selling book *LASER SCANNERS: Technologies and Applications*, written by Pangolin's William R. Benner, Jr. www.LaserScanningBook.com.

PATENT AND TRADEMARK INFORMATION

ScannerMAX products are covered by one or more of the following patents:

US Utility Patent Number: 7,092,135
US Utility Patent Number: 7,688,432
US Utility Patent Number: 7,940,380
US Utility Patent Number: 8,254,045
US Utility Patent Number: 8,508,726
US Utility Patent Number: 8,963,396
US Utility Patent Number: 9,077,219
US Utility Patent Number: 9,195,061
US Utility Patent Number: 9,244,273
US Utility Patent Number: 9,270,144
US Utility Patent Number: 9,366,860
US Utility Patent Number: 9,530,559
US Utility Patent Number: 9,991,773
US Utility Patent Number: 10,284,038
US Utility Patent Number: 10,305,358
US Utility Patent Number: 10,539,433
US Utility Patent Number: 10,720,824
German Patent (Utility Model) Number: 20 2012 009 275.8
German Patent (Utility Model) Number: 20 2013 000 369.3
German Patent (Utility Model) Number: 20 2013 003 263.4
German Patent (Utility Model) Number: 20 2014 000 846.9
German Patent (Utility Model) Number: 20 2014 002 094.9
German Patent (Utility Model) Number: 20 2016 000 737.9
German Patent (Utility Model) Number: 20 2019 002 282.1
German Patent (Utility Model) Number: 20 2020 000 007
German Patent (Utility Model) Number: 20 2020 000 420
Chinese Patent No. ZL201110066043.6
Chinese Patent No. ZL201210363949.9
Chinese Patent No. ZL201210363955.4
Chinese Patent No. ZL201310151544.3
Chinese Patent No. ZL201920775937.4
Chinese Application for Invention No. 201310128586.5
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Mach-DSP and *ScannerMAX* are trademarks of Pangolin Laser Systems, Inc.

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