Tech Note #4:
**Tuning a Servo Axis For Closed Loop Position Control**

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Abstract:

In this Tech Note a procedure for tuning a servo axis for closed loop position control through an I^{2}T Momentum motion module using the I^{2}T Motion Controller Setup Software will be presented. This document provides information on basic closed loop control, a description of tuning tools for quantifying performance, and a tuning procedure. In addition, a discussion on when to use feedforward tuning commands and what affect they have on the performance of the system will be presented.

What is closed loop control?

Closed loop control is the act of producing a control signal that will reduce the difference between some desired outcome and the current outcome as derived from a measurement.
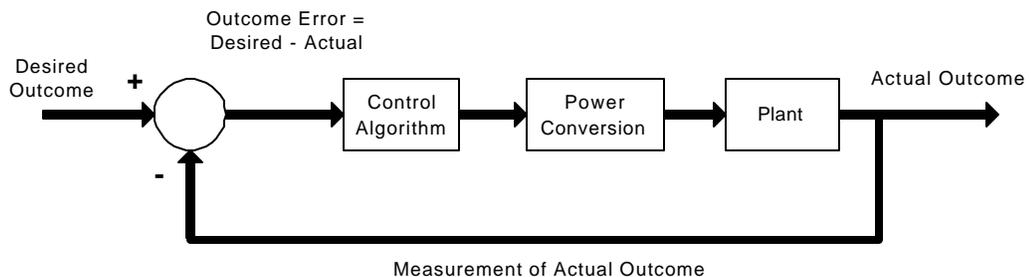
Defining the components in a closed loop servo axis
Control Variables:
For a servo system there are two outcomes, namely axis position and velocity.

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Feedback:

The measurement of position comes from the incremental change in the axis's encoder from some defined starting point.

The velocity measurement comes from the difference of the current position and previous position divided by the sample time of the control loop.

Control Signal:

The produced control signal is an analog signal that is proportional to the required torque to reduce the difference in the control variables at a rate a defined by the axis tuning.
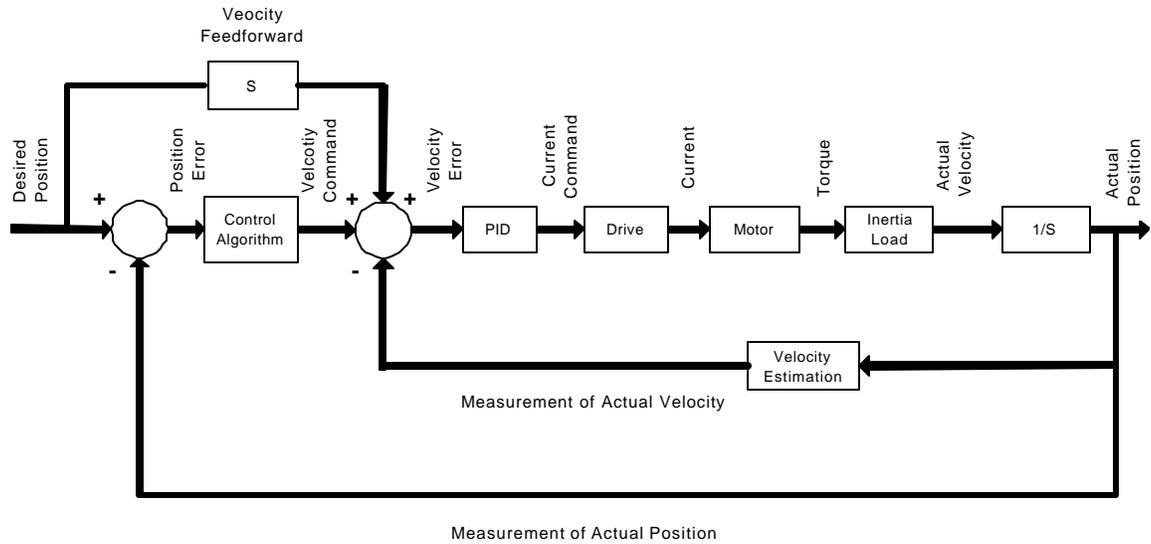
What is cascaded control?

For a servo axis the controller will close two loops with one wrapped around another. The inside loop regulates the velocity of the axis while the outside loop regulates the position of the axis. This configuration is referred to as cascaded control.

Measurement of Actual Position
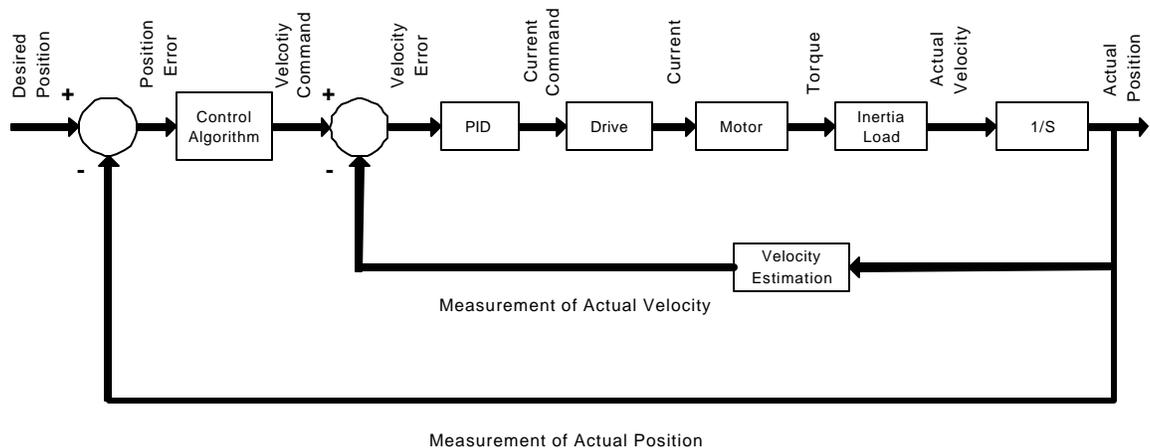
What is Feedforward Control?

Feedforward control is one of the advantages of having both the position and velocity control contained in the same digital controller. In the control loop shown above; the commanded velocity to the axis is produced from a position following error, so a velocity command, and consequently a torque command, is only produced after the axis has already fallen behind is desired position. Using velocity feedforward the required velocity to achieve the desired position profile is calculated and injected directly into the velocity loop resulting in an increase in system response and a decrease in following error. The loop diagram with velocity feedforward is presented below.

Diagram labels: Veocity Feedforward, S, Desired Position, Position Error, Velcotiy Command, Velocity Error, Current Command, Current, Torque, Actual Velocity, Actual Position, Control Algorithm, PID, Drive, Motor, Inertia Load, 1/S, Velocity Estimation, Measurement of Actual Velocity, Measurement of Actual Position

When should I use Velocity Feedforward?

Using velocity feedforward allows the system to track the commanded velocity better since the command signal is produced directly from the commanded position rather than waiting for a position error to develop. Using this gain requires lowering the position loop's proportional gain, and consequently a reduction in system stiffness. Using feedforward requires a trade-off between the system's stiffness and the magnitude of following error during a move.

Use this gain if following error during a move needs to be minimized. This requires that the position loop proportional gain be lowered resulting in a decrease in system stiffness.

Do not use this gain if system stiffness and response to disturbances is more important than following error during a move. After disabling this gain the position loop proportional gain can be increased resulting in an increase in system stiffness

Velocity Loop Controller

A description of the three gains present in the velocity loop controller is presented to aid in understanding the affects that changing the different gains will have on the performance of the system. The dominant gains in a motion control system for achieving high bandwidth performance are the velocity loop gains.

The velocity loop PID controller has the following form:
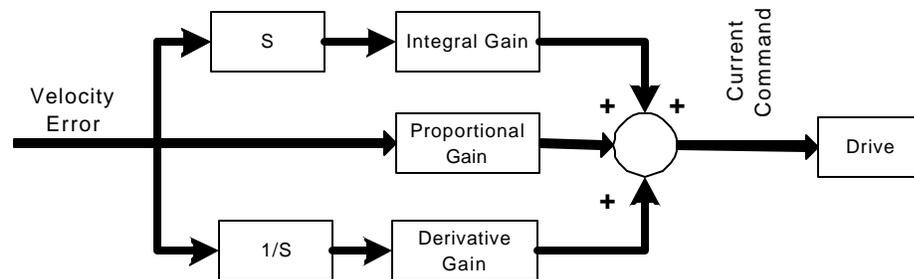
Proportional Gain

The proportional gain is multiplied with the current error between the commanded and actual velocity. This is the primary gain for achieving a system that responds quickly.

Integral Gain

The integral gain is multiplied with the **sum** of all previous errors between the commanded and actual velocity. This gain acts slowly to close the steady-state velocity error that would be present with a proportional gain only.

Derivative Gain

The derivative gain is multiplied with the difference between the current and previous errors between the commanded and actual velocity. This gain works to reduce the magnitude of change in velocity and as such will reduce the system's overshoot to a commanded velocity and consequently allows the proportional gain to be raised improving system performance. This gain usually allows the system to respond faster to a command, however it has several shortcomings. This gain operates at high frequencies so it can cause a high frequency buzzing that while providing only limited performance increases makes the system less stable. This gain increases the complexity of tuning a system and should only be used in the event that the desired performance could not be achieved through the proportional and integral gains at the velocity loop. This gain adds a phase lag to the system response from the position loop

Tuning tools

The Step function

When tuning a system setting the acceleration rates to the highest level that is expected during the application usually will suffice. However, when aggressive tuning is desired then the ideal acceleration time is 0 seconds resulting in an infinite commanded acceleration or a step input. The benefit of this step input is that it will magnify the system performance allowing it to be more accurately defined. Before applying a step input it should be verified that the mechanics are capable of handling the full torque output of the motor.

Quantifying performance

Useful terminologies for defining the response of a servo system are percent overshoot, peak time, settling time, rise time, and bandwidth. These variables provide some metrics for defining the desired performance of the system and a basis for discussion when tuning issues are present.

?? **Peak Time**, The time required to reach the first, or maximum, peak
?? **Percent overshoot**, The percentage that the system exceeds the steady-state, or final, value at the peak time
?? **Settling Time**, The amount of time required for the system to maintain oscillations to within +/- 2% of its steady-state, or final, value.
?? **Rise Time**, The time is takes the system to move from .1 to .9 of the steady-state, or final, value.
?? **Bandwidth,** The frequency at which the magnitude response curve is 3 dB down from its value at zero frequency. Usually referred to in Hertz, but can be referenced in Rad/sec which is Hertz / 2 Pi. Bandwidth = 4 / (Settling Time * 2 * Pi).

Using these values it is possible to calculate the closed loop systems' natural frequency and dampening factors if the system can be approximated as a second order system, which most servos systems can.

Although it is not necessary to quantify these variables when tuning they are useful when determining if the system performance is adequate for the application. It is a common mistake to tune a servo system more aggressively than the application requires resulting in unnecessary wear on the system components.

Clamping torque for tuning

If there is some concern about the system's ability to handle the full torque ability of the motor then the allowed torque production can

be clamped using the *analog output setup dialogue box* in the I^{2}T Motion Controller Setup Software.

Torque production in a motor is a linear function of the applied current. Therefore, clamping the allowed torque output for a system, when tuning, does not affect its performance, as defined using the tools above to quantify performance, as long as the clamped torque level is not reached. This condition, defined as torque saturation, can be monitored using the data collection screen provided on the I^{2}T Motion Controller Setup Software for the Momentum controllers. If during the acceleration the torque quickly moves up to the clamp level and then flat lines at that level then the system is considered saturated and any performance results from the move cannot clearly be defined. In this case, either decrease the acceleration rate, increase the torque clamp, or in the event that a step input is being used lower the magnitude of the input, i.e. lower the velocity.

Graphical tools for tuning

In the I^{2}T Motion Controller Setup Software a tool for axis tuning is provided under the **Tools** menu label titled Data collection. This tool provides a graph of all dynamic axis information for every update of the servo loop allowing system performance to be easily quantified.

Using the data collection tool with the *Move Immediate Dialogue Box,* and the *Tune Dialogue Box* all the tools necessary to tune a high performance servo system are provided. Checking the box next to *Trigger Chart on Move* on the *Move Immediate Dialogue Box* will result in all of the dynamic axis information for the next move being sampled and uploaded from the controller to the graphic data collection tool. From the data collection tool the commanded velocity/position and actual velocity/position can be viewed as well as the error between these signals and the resulting torque output.

Loop tuning from the inside loop out

High bandwidth to low bandwidth

When tuning any cascaded control system it is best to start tuning from the fastest loops to the slowest loops. In a servo system there are 3 closed loop systems with the fastest to slowest being the drive's current loop, the axis's velocity loop, and the axis's position loop.

The drive's current loop usually cannot be adjusted and is most likely performing at a high enough frequency that it can be ignored. The drive in a servo system closes the loop around the motor's electrical current and the desired current setting received from the motion controller. For many drives the bandwidth of this loop is around 800 Hertz, which is well beyond the bandwidth of a servo system. The affect on the servo system from the drive's closed loop performance can be modeled, or thought of, as a low pass filter with its break frequency at 800 Hertz.

The velocity loop controller regulates the performance that the system will respond to a velocity command. Closed loop performance of 100 Hertz is considered aggressive for this loop as this will result in the system settling to within 2% of a stepped velocity command in approximately 6 milliseconds. The majority of servo system's never reach this type of performance because of the system's mechanics or motor torque compared to the load inertia.

The position loop controls the performance that the system will respond to a position command given the constraints of the velocity loop's performance. Motion controls close the position loop even during a constant velocity move as the velocity command is produced from the error between the desired position and actual position of the system. This assures that even if the system's actual velocity is temporary disrupted, the average velocity over time, at consequently the distance traveled over time, will always be exactly what is desired.

Tuning the Servo System
Tuning the velocity loop

The velocity loop PID controller has the following form:
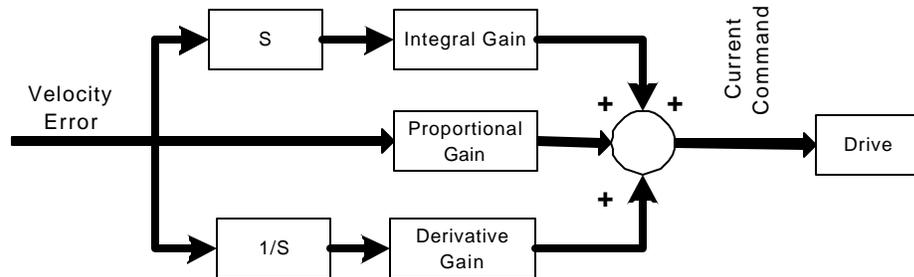
From the Main Menu select **Tools** followed by **Tune**. The following dialog box appears. The velocity loop gains in this dialogue box are the Proportional, Integral, and Derivative gains.

To tune the velocity loop perform the following task:
- ⌨ Zero the **Position** Proportional Loop Gain
- ⌨ Activate the velocity feedforward gain by checking the box next to it.
- ⌨ Zero the Velocity Loop Integral Gain
- ⌨ Zero the Velocity Loop Derivative Gain
- ⌨ Set the velocity loops Proportional Gain to a low level, I.e. 10

This configuration results in the velocity command being passed directly to the velocity loop through the velocity feedforward gain with no affect to this command from the position loop. Basically, the velocity loop has been isolated so that it can be tuned and its performance properly quantified.

-*Warning*-
When tuning a system the potential for damage to mechanical components is possible so patience should be exercised when increasing the gains. Gains should be increased at a percentage of their current setting. Be sure to have the ability to remove power from the system in the event that the system begins producing a high frequency buzz, a raspy noise, or other unpleasant noises. This may indicate that the system tuning has excited a mechanical resonance and indicates the upper limits to the gains. A high frequency Buzz usually can be removed using the available Low-pass filter as outlined in another tech note.   A raspy noise may indicate a low frequency natural frequency which can cause system damage if continued.

-*Tip*-
During the initial phases for tuning a system the analog output clamp can be used to limit the available motor torque. This will allow some confidence to be built in the gains while reducing the potential for system damage. However, the resulting torque output should be monitored to assure that saturation does not occur. Lowering the clamp and raising the proportional gains allows any mechanical resonance to be found with limited input power available.

Set the move command
> Set the acceleration and deceleration times to the lowest level allowed by the mechanics. A high acceleration rate will aid in magnifying the system response simplifying the tuning process. However, saturation of the resulting torque output needs to be avoided by reducing the speed command. These settings are made on the Move Immediate dialogues back. From the Main

Menu select the **Move** Pull-down Menu followed by selecting **Move Immediate**. The following dialog box appears:


Using the data collection dialogue box monitor the performance of the system to the commanded move. Raise the Proportional gain until little or no velocity overshoot is present. About 5% overshoot is usually acceptable. Listen for a high frequency buzzing or raspy noise from the motor while increasing the proportional gain. If the motor begins making one of these noises then lower the gain until it goes away. Once this is complete the integral gain can be raised until 10 to 15% overshoot is present. The integral gain will not have much impact on the high frequency response of the system, but will slowly close the running velocity error that occurs after the system has accelerated. If the system is very responsive then even a maximum setting of 32767 to the Integral gain may not produce any noticeable affect to the overshoot.

Screen shoot below shows the affect on torque from saturation.
The torque hits a peak flat line. This results in Integer Windup and
unreliable tuning. Lower the speed set point to reduce the required
torque.
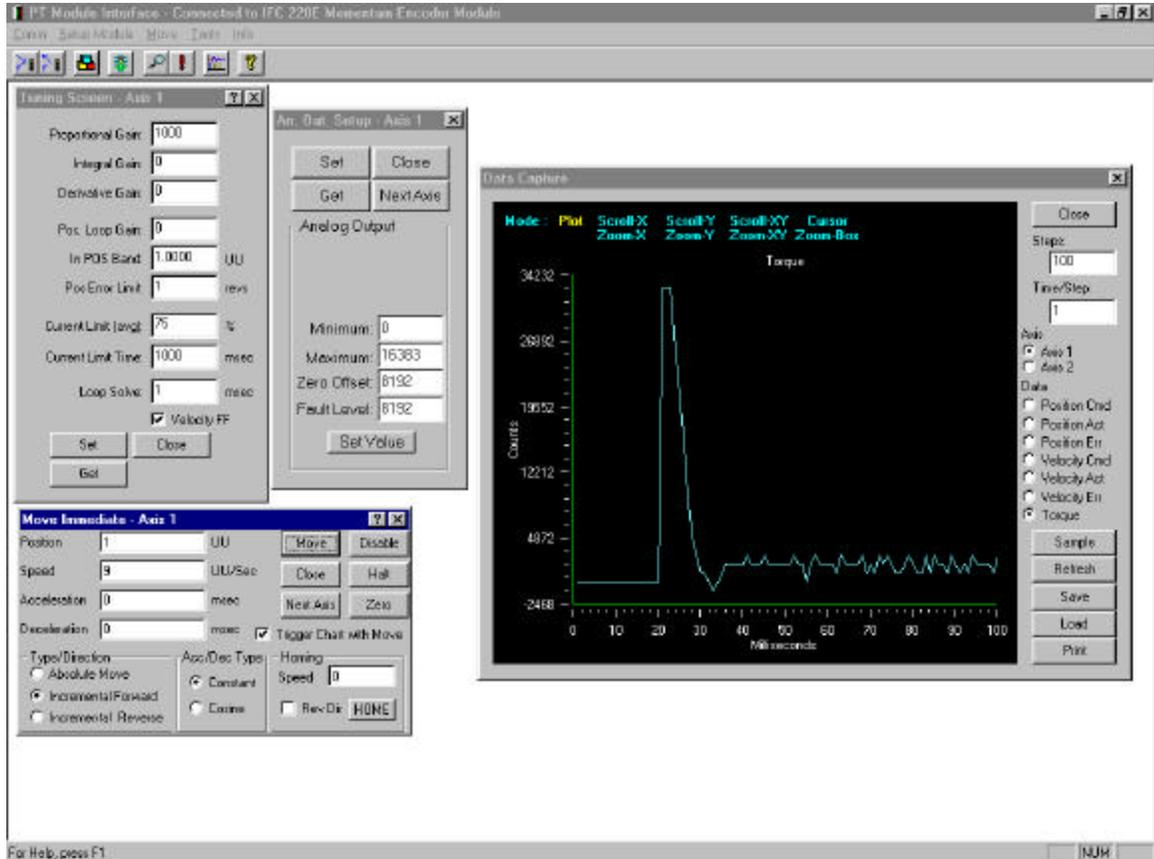
This plot shows the actual velocity feedback from the move command with little to no overshoot. The peak time in this plot is 12 msec with the settling time around 13 msec. This translates to a system frequency of 50 Hertz.
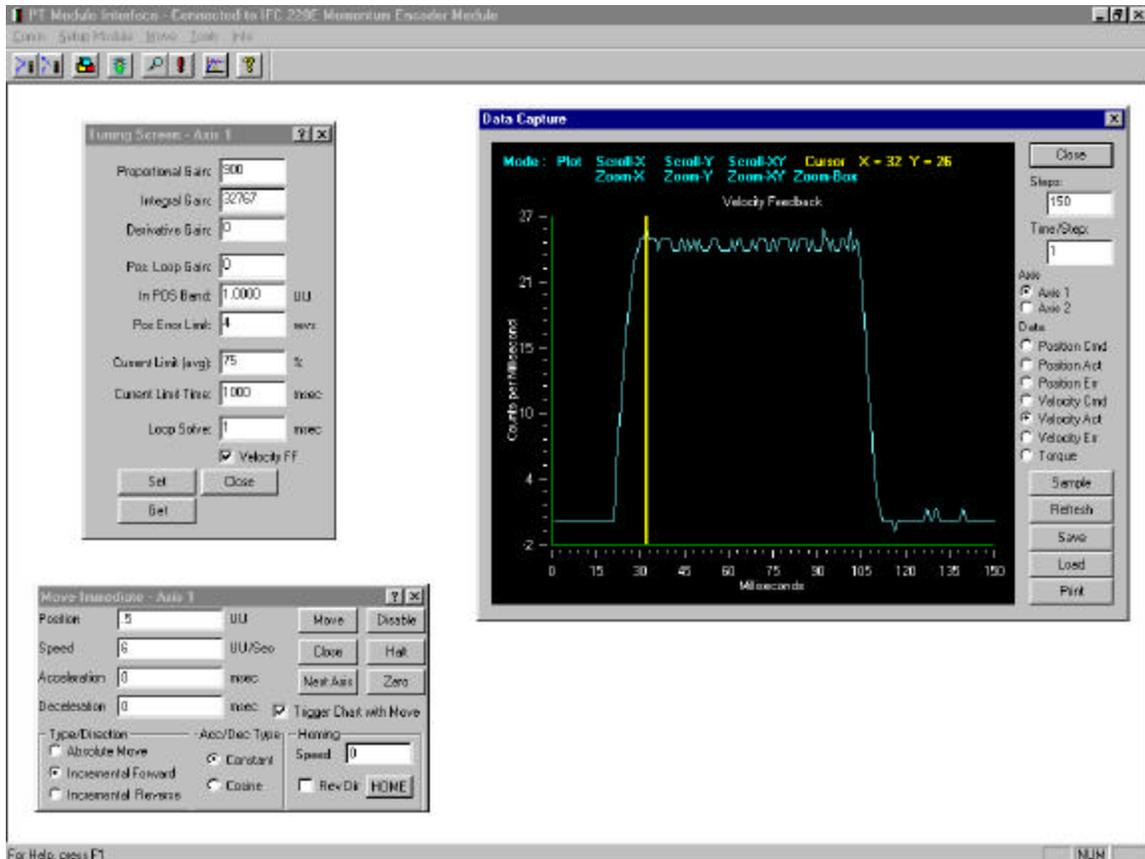

Tune the position loop

> With the velocity loop tuned we are now ready to close the position loop. Start by setting the position proportional gain to a low level and disabling the velocity feedforward gain. Apply a trapezoidal velocity command using the maximum acceleration and deceleration required by the application. Raise the position proportional gain to a level just below what will cause overshoot.

> **Pos Loop Gain**
> This sets the proportional gain in the axis's position loop. This proportional gain is multiplied with the current error between the commanded and actual position of the axis. The resulting output of this gain is a velocity command to the axis's velocity loop. This gain proportionally increases the stiffness of the system. During commissioning of a machine this gain should be raised slowly as excessive gain can cause oscillation possibly resulting in damage or injury.

The plot below shows the results from tuning the position loop. These gains produced an actual velocity curve that only minimally overshoots on an acceleration time of 50 milliseconds.
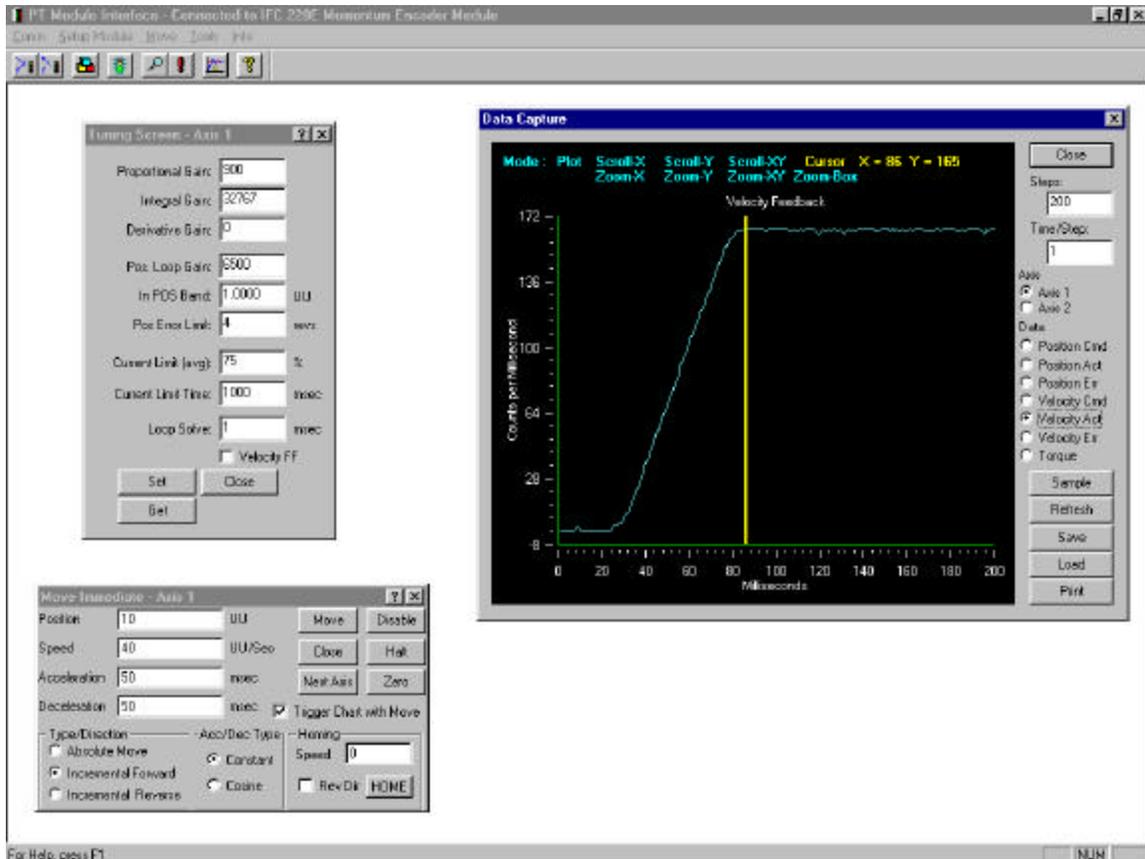
This should provide a system with enough bandwidth for most applications. In some high performance applications additional steps or iterations may be required to optimize the control. If the desired level of control performance cannot be reached through adjustment of the servo loop gains then several areas of the system can be examined to determine what is limiting the total system performance, such as mechanical couplings, gear ratio, motor size, Inertia ratio between motor and reflected load inertia, and system dampening.