

1 Introduction

Welcome to the ECP line of educational control systems. These systems are designed to provide insight to control system principles through hands-on demonstration and experimentation. Each consists of an electromechanical plant and a full complement of control hardware and software. The user interface to the system is via a user-friendly, PC window environment which supports a broad range of controller specification, trajectory generation, data acquisition, and plotting features. The systems are designed to accompany introductory through advanced level controls courses and support either high level usage (i.e. direct controller specification and execution) or detailed user-written algorithms.

The electromechanical apparatus may be transformed into a variety of dynamic configurations which represent important classes of "real life" systems. The Model 220 apparatus represents many such physical plants including rigid bodies; flexibility in drive shafts, gearing and belts; and coupled discrete vibration with actuator at the drive input and sensor collocated or at flexibly coupled output (noncollocated). Several other important non-ideal properties are readily introduced and removed including backlash, drive friction, and disturbances. This allows them to be characterized in a controlled manner and facilitates study of control approaches to mitigate their effects.

1.1 System Overview

-

The experimental control system is comprised of the three subsystems shown in Figure 1.1-1. The first of these is the electromechanical plant which consists of the emulator mechanism, its actuator and sensors. The design features brushless DC servo motors for both drive and disturbance generation, high resolution encoders, adjustable inertias and changeable gear ratios. It also has features to introduce coulomb and viscous friction, drive train flexibility, and backlash.

The next subsystem is the real-time controller unit which contains the digital signal processor (DSP) based real-time controller^[1], servo/actuator interfaces, servo amplifiers, and auxiliary power supplies. The DSP is capable of executing control laws at high sampling rates allowing the implementation to be modeled as continuous or discrete time. The controller also interprets trajectory commands and supports such functions as data acquisition, trajectory generation, and system health and safety checks. A logic gate array performs motor commutation and encoder pulse decoding. Two optional auxiliary digital-to-analog converters (DAC's) provide for real-time analog signal measurement. This controller is representative of modern industrial control implementation.

Figure 1.1-1. The Experimental Control System

The third subsystem is the executive program which runs on a PC under the DOS or Windows™ operating system. This menu-driven program is the user's interface to the system and supports controller specification, trajectory definition, data acquisition, plotting, system execution commands, and more. Controllers may assume a broad range of selectable block diagram topologies and dynamic order. The interface supports an assortment of features which provide a friendly yet powerful experimental environment.

1.2 Manual Overview

The next chapter, Chapter 2, describes the system and gives instructions for its operation. Section 2.3 contains important information regarding safety and is mandatory reading for all users prior to operating this equipment. Chapter 3 is a self-guided demonstration in which the user is quickly walked through the salient system operations before reading all of the details in Chapter 2. A description of the system's real-time control implementation as well as a discussion of generic implementation issues is given in Chapter 4. Chapter 5 presents dynamic equations useful for control modeling. Chapter 6 gives detailed experiments including system identification and a study of important implementation issues and practical control approaches.

2 System Description & Operating Instructions

This chapter contains descriptions and operating instructions for the executive software and the mechanism. The safety instructions given in Section 2.3 must be read and understood by any user prior to operating this equipment.

2.1 ECP Executive Software

The ECP Executive program is the user's interface to the system. It is a menu driven / window environment that the user will find is intuitively familiar and quickly learned - see Figure 2.1-1. This software runs on an IBM PC or compatible computer and communicates with ECP's digital signal processor (DSP) based real-time controller. Its primary functions are supporting the downloading of various control algorithm parameters (gains), specifying command trajectories, selecting data to be acquired, and specifying how data should be plotted. In addition, various utility functions ranging from saving the current configuration of the Executive to specifying analog outputs on the auxiliary DAC's are included as menu items.

2.1.1 The DOS Version of the Executive Program

2.1.1.1 PC System Requirements

For the ECP Executive (DOS version), you will need at least 2 megabyte of RAM and a hard disk drive with at least 4 megabytes of space. All DOS versions of the Executive program run under any of DOS versions 3.x, 4.x, 5.x, and 6.x. The Executive requires a VGA monitor with a VGA graphics card installed on the PC.

The Executive Program runs best on a 386, 486, or Pentium® based PC with 4 megabytes or more of memory under DOS 5.0 or higher with HIGHMEM.SYS driver included in your CONFIG.SYS file.^[2] Also, if the software does not "see" at least 2 megabytes of free RAM, you may find the program executing somewhat slowly since it will use the hard disk as virtual memory.

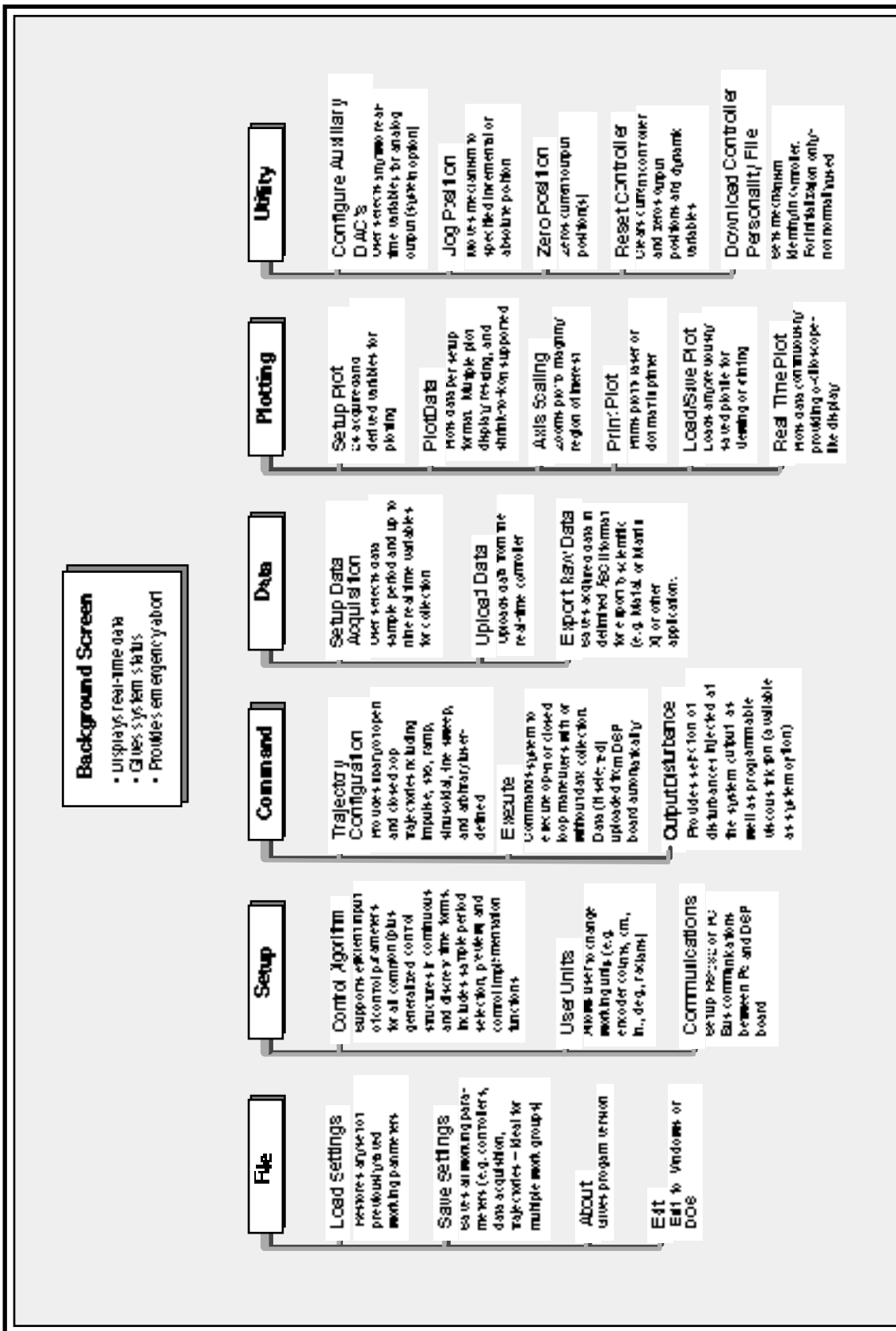


Figure 2.1-1. Structure and Key Features of Executive Program

2.1.1.2 Installation Procedure For The DOS Version

The ECP Executive Program consists of several files on a 3.25" 1.44 megabyte distribution diskette in a compressed form. The key files on the distribution diskette are:

```
ECPDYN.EXE
ECP.DAT
ECPBMP.DAT
*.CFG
*.PLT
*.PMC
```

The "ECP*. *" files are needed to run the Executive Program. The "*.CFG" and "*.PLT" files are some driving function configuration and plotting files that are included for the initial self-guided demonstration. The "*.PMC" file is the controller Personality File and should only be used in the case of a non curable system fault (see Utility Menu below).

To install the Executive program, it is recommended that you make a dedicated sub directory on the hard disk and enter this sub directory. For example type:

```
>MD ECP
>CD ECP
```

Next insert the distribution diskette in either "A:" or "B:" drive, as appropriate. Copy all files in the distribution diskette to the hard disk under the "ECP" sub directory. For example if the "B:" drive is used:

```
>COPY B:*. * C:
```

Next execute INSTALL.EXE by typing:

```
>INSTALL
```

You will notice some file decompression activities. This completes the installation procedure. You may run the ECP Dynamics Executive by typing:

```
>ECPDYN
```

The Executive program is window based with pull-down menus and dialog boxes. You may either use the cursor keys on the keyboard or a mouse to make selections from the pull-down menus. Vertical movement within these menus is accomplished by the up and down arrow keys, respectively. To make a selection with the keyboard, simply highlight the desired choice and press <ENTER>. Menu choices with highlighted letters may also be selected by pressing the corresponding function key. (The indicated key for menus; "alt" plus the indicated key within dialog boxes).

Within dialog boxes, movement from one object to the next is accomplished by using the <TAB> and the <SHIFT-TAB> keys. Here, "objects" includes input lines, check boxes, and "radio buttons". As you move from one object to the next, the selected object is highlighted. Pressing <ENTER> will effect the function of the highlighted button (e.g. termination of the dialog box will result if the Cancel button is highlighted).

2.1.2 The Windows Version of the Executive Program

2.1.2.1 PC System Requirements

The ECP Executive 16-bit code runs on any PC compatible computer under Windows 3.1x and/or Windows 95. You will need at least 8 megabyte of RAM and a hard disk drive with at least 12 megabytes of space. The 16-bit Windows version of the Executive Program runs best with Pentium® based PC having 16 megabytes or more of memory.

2.1.2.2 Installation Procedure For The Windows Version

The ECP Executive Program consists of several files on two 3.25" 1.44 megabyte distribution diskettes in a compressed form. The key files on the distribution diskettes are:

ECPDYN.EXE

ECP.DAT

ECPBMP.DAT

*.CFG

*.PLT

*.PMC

The "ECP*. *" files are needed to run the Executive Program. The "*.CFG" and "*.PLT" files are some driving function configuration and plotting files that are included for the initial self-guided demonstration. The "*.PMC" file is the controller Personality File and should only be used in the case of a non curable system fault (see "Utility Menu" below).

To install the Executive program enter the Windows operating system. Then go to the "Run" menu, and simply run the SETUP.EXE file from diskette labeled 1. Follow the interactive dialog boxes of the installation program until completion.

2.1.3 Background Screen

The *Background Screen*, shown in Figure 2.1.-1, remains in the background during system operation including times when other menus and dialog boxes are active. It contains the main menu and a display of real-time data, system status, and an *Abort Control* button to immediately discontinue control effort in the case of an emergency.

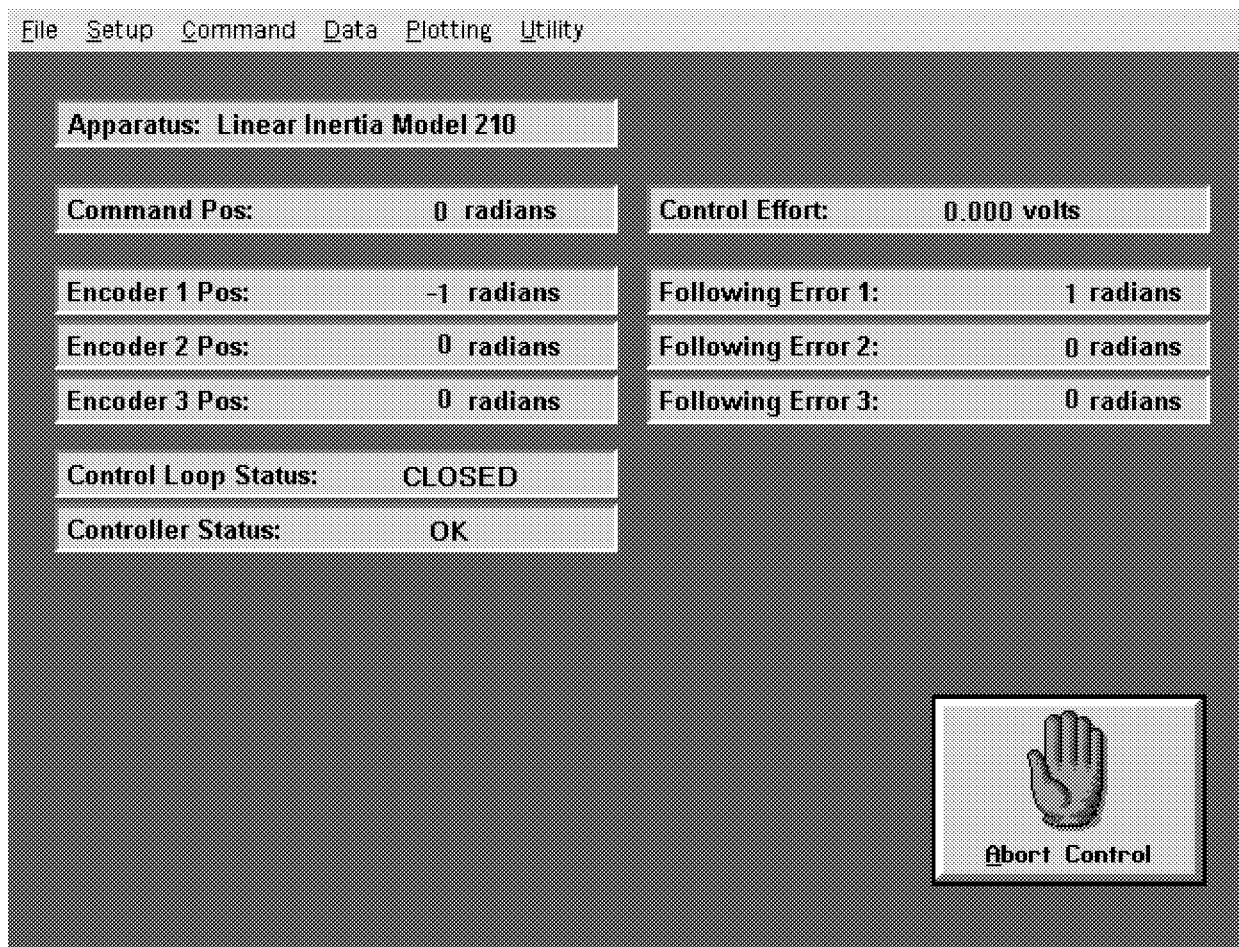


Figure 2.1-1. The Background Screen

2.1.3.1 Real-Time Data Display

In the *Data Display* fields, the instantaneous commanded position, the encoder positions, the following errors (instantaneous differences between the commanded position and the actual encoder positions), and the control effort in volts (on the DAC) are shown.

2.1.3.2 System Status Display

The Control Loop Status ("Open" or "Closed"), indicates "Closed" unless an open loop trajectory is being executed or a "Limit Exceeded" condition has occurred. In either of these cases the Control Loop Status will indicate "Open". The Controller Status will indicate "Active" unless a motor overspeed, a shaft over-deflection, or motor/amplifier over-temperature condition has occurred (see Section 2.3 for more details). In any of these cases the Controller Status will indicate "Limit Exceeded". The Limit Exceeded indicator will reoccur unless the user takes one of the two following actions depending on the nature of the over-limit cause. Either a stable controller (one that does not cause limiting conditions) must be implemented via the Control Algorithm box under the Setup menu or an acceptable trajectory must be executed under the Command menu. An "acceptable" trajectory is one that does not overspeed the motor, over-deflect the flexible shaft or result in sustained high current to the motor. The controller must be "reimplemented" in order to clear the Limit Exceeded condition – see Section 2.1.5.1.1.

The Disturbance Status will indicate "Active" when the viscous friction disturbance is invoked and/or when a profile disturbance torque is selected during a trajectory execution. It will otherwise indicate "Not Active" unless, due to disturbance motor amplifier over-current or load shaft over-speed, a "Limit Exceeded" condition develops. In this situation the "Limit Exceeded" indication will continue to appear until a new disturbance torque is implemented which does not cause a limit exceeding condition.

2.1.3.3 Abort Control Button

Also included on the Background Screen is the Abort Control button. Clicking the mouse on this button simply opens the control loop. This is a very useful feature in various situations including one in which a marginally stable or a noisy closed loop system is detected by the user and he/she wishes to discontinue control action immediately. Note also that control action may always be discontinued immediately by pressing the red "OFF" button on the control box. The latter method should be used in case of an emergency.

2.1.3.4 Main Menu Options

The *Main menu* is displayed at the top of the screen and has the following choices:

- File
- Setup
- Command
- Data
- Plotting
- Utility

2.1.4 File Menu

The File menu contains the following pull-down options:

- Load Settings
- Save Settings
- About
- Exit

2.1.4.1 The Load Settings dialog box allows the user to load a previously saved configuration file into the Executive. A configuration file is any file with a ".cfg" extension which has been previously saved by the user using Save Settings. Any "*.cfg" file can be loaded at any time. The latest loaded "*.cfg" file will overwrite the previous configuration settings in the ECP Executive *but* changes to an existing controller residing in the DSP real-time control card will not take place until the new controller is "implemented" – see Section 2.1.5.1. The configuration files include information on the control algorithm, trajectories, data gathering, and plotting items previously saved. To load a "*.cfg" file simply select the Load Settings command and when the dialog box opens, select the appropriate file from the directory.^[3] Note that every time the Executive program is entered, a particular configuration file called "default.cfg" (which the user may customize - see below) is loaded. This file must exist in the same directory as the Executive Program in order for it to be automatically loaded.

2.1.4.2 The Save Settings option allows the user to save the current control algorithm, trajectory, data gathering and plotting parameters for future retrieval via the Load Settings option. To save a "*.cfg" file, select the Save Settings option and save under an appropriately named file (e.g. "pid1disk.cfg"). By saving the configuration under a file named "default.cfg" the user creates a default configuration file which will be automatically loaded on reentry into the Executive program. You may tailor "default.cfg" to best fit your usage.

2.1.4.3 Selecting About brings up a dialog box with the current version number of the Executive program.

2.1.4.4 The Exit option brings up a verification message. Upon confirming the user's intention, the Executive is exited.

2.1.5 Setup Menu

The Setup menu contains the following pull-down options:

- Control Algorithm
- User Units
- Communications

2.1.5.1 Setup Control Algorithm allows the entry of various control structures and control parameter values to the real-time controller – see Figure 2.1-2. In addition to feedforward which will be described later, the currently available feedback options are:

- PID
- PI With Velocity Feedback
- PID+Notch

Dynamic Forward Path
Dynamic Prefilter/Return Path
State Feedback
General Form

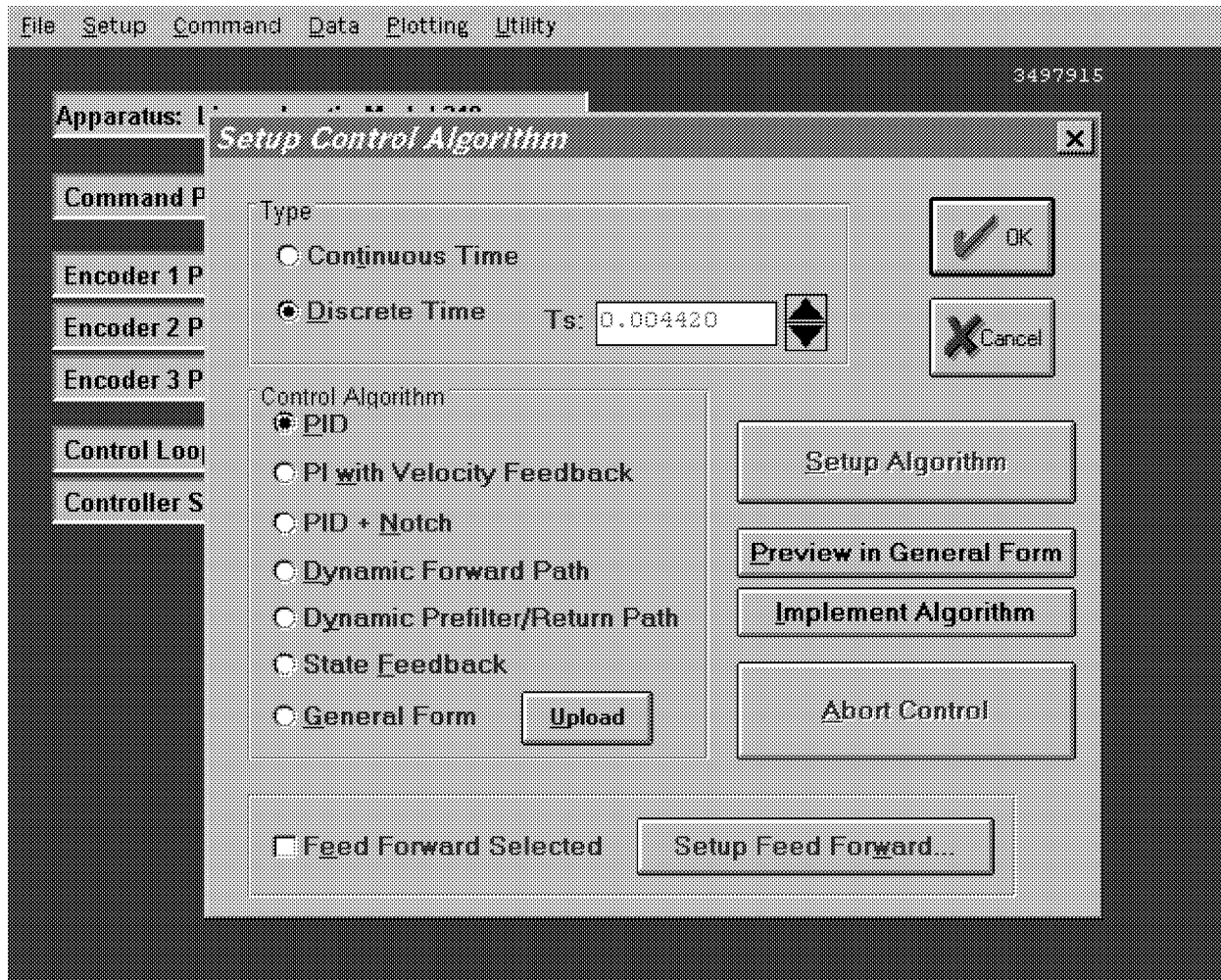


Figure 2.1-2. Setup Control Algorithm Dialog Box

2.1.5.1.1 Discrete Time Control Specification

The user chooses the desired option by selecting the appropriate "radio button" and then clicking on Setup Algorithm. The user must also select the sampling period which is always in multiples of 0.000884 seconds (1.1 KHz is the maximum sampling frequency).^[4] To run the selected choice on the real-time controller click on the Implement Algorithm button. The control action will begin immediately. To stop control action and open the loop with zero control effort click on the Abort button. To upload the current controller select General Form then click on the Upload Algorithm button followed by Setup Algorithm. Here you will find the current controller in the form that is actually executed in real-time – see Figure 2.1-3.

Configure Generalized Form Control Algorithm (discrete time)

Block Diagram: $T(z^{-1})$ → \oplus (Loop 1: $S(z^{-1})$) → $\frac{1}{R(z^{-1})}$ → \oplus (Loop 2: $I(z^{-1})$) → $\frac{1}{J(z^{-1})}$ → $E(z^{-1})$ → \oplus (Loop 3: $F(z^{-1})$) → $\frac{1}{G(z^{-1})}$ → \oplus

T0: 0.9340000	S0: 10.21790	R1: 0.000000000	H0: 1.000000000
T1: 0.000000000	S1: -9.40400	R2: 0.000000000	H1: 0.000000000
T2: 0.000000000	S2: 0.000000000	R3: 0.000000000	I0: 0.000000000
T3: 0.000000000	S3: 0.000000000	R4: 0.000000000	I1: 0.000000000
T4: 0.000000000	S4: 0.000000000	R5: 0.000000000	J1: 0.000000000
T5: 0.000000000	S5: 0.000000000	R6: 0.000000000	E0: 1.000000000
T6: 0.000000000	S6: 0.000000000	R7: 0.000000000	E1: 0.000000000
T7: 0.000000000	S7: 0.000000000		F0: 18.95650000
			F1: -18.8360000
			G1: 0.000000000

Buttons: OK, Cancel, Import

Encoder Selection:

Loop 1	Loop 2	Loop 3
<input checked="" type="radio"/> Encoder 1	<input type="radio"/> Encoder 1	<input checked="" type="radio"/> Encoder 1
<input type="radio"/> Encoder 2	<input type="radio"/> Encoder 2	<input type="radio"/> Encoder 2
<input type="radio"/> Encoder 3	<input checked="" type="radio"/> Encoder 3	<input type="radio"/> Encoder 3

Figure 2.1-3. Dialog Box For Generalized Control Algorithm Input

A typical sequence of events is as follows: Select the desired servo loop closure sampling time T_s in multiples of 0.000884 seconds; then select the control structure you wish to implement (e.g. radio buttons for PID, PID+Notch etc.). Select Setup Algorithm to input the gain parameters (coefficients). You must also select the desired feedback channel by choosing the correct encoder(s) used for your particular control design. Exit Setup by selecting OK. Now you should be back in the Setup Control Algorithm dialog box with a selected set of gains for a specified control structure. To download this set of control parameters to the real-time controller click on Implement Algorithm. This action results in an immediate running of your selected control structure on the real-time controller. If you notice unacceptable behavior (instability and/or excessive ringing or noise) simply click on Abort Control which opens up the control loop with zero control effort commanded to the actuator.

To inspect the form by which your particular control structure is actually implemented on the real-time controller, simply click on Preview In General Form. You may edit the algorithm in the General Form box,

however when you exit, you must select General Form prior to "implementing" if you want the changes to become effective. (i.e. the radio button will still indicate the box you were in prior to previewing and this one will be downloaded unless General Form is selected).

The Setup Feed Forward option allows the user to add feedforward action to any of the above feedback structures. By clicking on this button a dialog box appears which allows the feedforward control parameters (coefficients) to be entered. To augment the feedforward action to the feedback algorithm the user must then check the Feedforward Selected check-box. Any subsequent downloading (via the Implement Algorithm button) combines the feedforward control algorithm with the selected feedback control algorithm

Important Note: Every time a set of control coefficients are downloaded via Implement Algorithm button, the commanded position as well as all of the encoder positions are reset to zero. This action is taken in order to prevent any instantaneous unwanted transient behavior from the controller. The control action then begins immediately.

Important Note: For high order control laws (those using more than 2 or 3 terms of either the R, S, T, K, or L polynomials), it is often important that the coefficients be entered with relatively high precision– say at least 5 to 6 points after the decimal. The real-time controller works with 96-bit real number arithmetic (48-bit integer plus 48-bit fraction). Although the Executive displays the coefficients with nine points after the decimal, it accepts higher precision numbers and downloads them correctly.

2.1.5.1.2 Continuous Time Control Specification

Depending on your course of study, It may be desirable to specify the control algorithm in continuous time form.^[5] The method for inputting control parameters is identical to that described for the discrete time case. Again you may preview your controller in the continuous General Form prior to implementing. Upon selecting either Implement Algorithm or Preview in General Form, the algorithm also gets mapped into the discrete General Form where it may be viewed either before (following "Preview") or after (following "Implement") downloading to the real time controller.^[6]

Again it is the discrete time general form that is actually executed in real time. The input coefficients are transformed to discrete time using one of the two following substitutions. For polynomials: $n(s)$, $d(s)$ in PID + Notch; $s(s)$, $t(s)$, and $r(s)$ in Dynamic Forward Path, Dynamic Prefilter / Return Path, and the General Form; and $k(s)$, $l(s)$ in Feed Forward, the Tustin (bilinear) transform

$$s = \frac{2}{T_s} \frac{1-z^{-1}}{1+z^{-1}}$$

is used. All other cases (first order) use the Backwards Difference method:

$$s = \frac{1-z^{-1}}{T_s}$$

Blocks using the Tustin transform must be proper in s while those using backwards difference may be improper – e.g. a differentiator.^[7]

2.1.5.1.3 Importing Controller Specifications From Other Applications

You may import controllers designed using other applications such as Matlab® and Matrix X®.^[8] Within each controller specification dialog box is an Import button by which the user download the control gains or coefficients previously saved as an ASCII text file with a extension “*.par”. The format for the file is as shown in Table 2.1-1.

Table 2.1-1 File Format For Importing Controller Coefficients

Continuous Time Controller Specification				Discrete Time Controller Specification			
Control Algorithm	File Format	Control Algorithm	File Format	Control Algorithm	File Format	Control Algorithm	File Format
PID	[PID_C] kp=n.n kd=n.n ki=n.n	Dynamic Prefilter/ Return Path	[DYNPR_C] t0=n.n : : t7=n.n s0=n.n : : s7=n.n r0=n.n : : r7=n.n	PID	[PID_D] Kp=n.n Kd=n.n Ki=n.n	Dynamic Prefilter/ Return Path	[DYNPR_D] T0=n.n : : T7=n.n S0=n.n : : S7=n.n R1=n.n : : R7=n.n
PID w/ Velocity Feedback	[PID_C] kp=n.n kd=n.n ki=n.n	State Feedback	[STATEF_C] kpf=n.n k1=n.n k2=n.n k3=n.n k4=n.n k5=n.n k6=n.n	PID w/ Velocity Feedback	[PID_D] Kp=n.n Kd=n.n Ki=n.n	State Feedback	[STATEF_D] Kpf=n.n K1=n.n K2=n.n K3=n.n K4=n.n K5=n.n K6=n.n
PID	[PIDNOTCH_C]	General Form	[GENERAL_C]	PID	[PIDNOTCH_D]	General Form	[GENERAL_D]

+ Notch kp=n.n kd=n.n ki=n.n n0=n.n n1=n.n n2=n.n d1=n.n : d4=n.n	t0=n.n : : t7=n.n s0=n.n : : s7=n.n r0=n.n : : r7=n.n h0=n.n h1=n.n i0=n.n i1=n.n j0=n.n j1=n.n e0=n.n e1=n.n f0=n.n f1=n.n g0=n.n g1=n.n	+ Notch Kp=n.n Kd=n.n Ki=n.n N0=n.n : : N4=n.n D1=n.n : : D4=n.n	T0=n.n : : T7=n.n S0=n.n : : S7=n.n R1=n.n : : R7=n.n H0=n.n H1=n.n I0=n.n I1=n.n J1=n.n E0=n.n E1=n.n F0=n.n F1=n.n G1=n.n
Dynamic Forward Path [DYNFWD_C] s0=n.n : : s7=n.n r0=n.n : : r7=n.n	Feed Forward [FF_C] k0=n.n : : k6=n.n l0=n.n : : l7=n.n	Dynamic Forward Path [DYNFWD_D] S0=n.n : : S7=n.n R1=n.n : : R7=n.n	Feed Forward [FF_D] K0=n.n : : K6=n.n L1=n.n : : L7=n.n

2.1.5.2 The User Units dialog box provides the user with various choices of angular or linear units. For Model 220 the choices are *counts*, *degrees* and *radians*. There are 16000 counts, 360 degrees and 2π radians per revolution of both the load and drive inertia disks. By clicking on the desired radio button the units are changed automatically for trajectory inputs as well as the Background Screen displays, plotting and jogging activities. Units of *counts* are used exclusively for the examples in this manual.

2.1.5.3 The Communications dialog box is usually used only at the time of installation of the real-time controller. The choices are serial communication (RS232 mode) or PC-bus mode – see Figure 2.1-4. If your system was ordered for PC-bus mode of communication, you do not usually need to enter this dialog box unless the default address at 528 on the ISA bus is conflicting with your PC hardware. In such a case consult the factory for changing the appropriate jumpers on the controller. If your system was ordered for serial communication the default baud rate is set at 34800 bits/sec. To change the baud rate consult factory for changing the appropriate jumpers on the controller. You may use the Test Communication button to check data exchange between the PC and the real-time controller. This should be done after the correct choice of Communication Port has been made. The Timeout should be set as follows:

ECP Executive For Windows with Pentium Computer:	Timeout \geq 50,000
ECP Executive For Windows with 486 Computer:	Timeout \geq 20,000
ECP Executive For DOS with Pentium Computer:	Timeout \geq 150
ECP Executive For Windows with 486 or lower Computer:	Timeout \geq 80

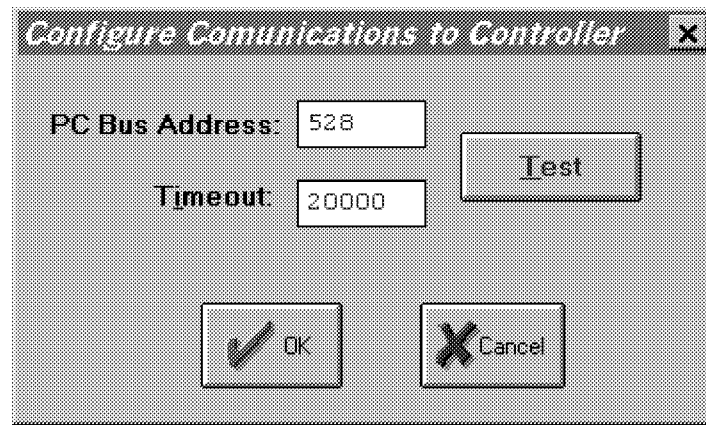


Figure 2.1-4. The Communications Dialog Box

2.1.6 Command Menu

The Command menu contains the following pull-down options

- Trajectory . . .
- Disturbance . . .
- Execute . . .

2.1.6.1 The Trajectory Configuration dialog box (see Figure 2.1.-5) provides a selection of trajectories through which the apparatus can be maneuvered. These are:

- Impulse
- Step
- Ramp
- Parabolic
- Cubic
- Sinusoidal
- Sine Sweep
- User Defined

A mathematical description of these is given later in Section 4.1.

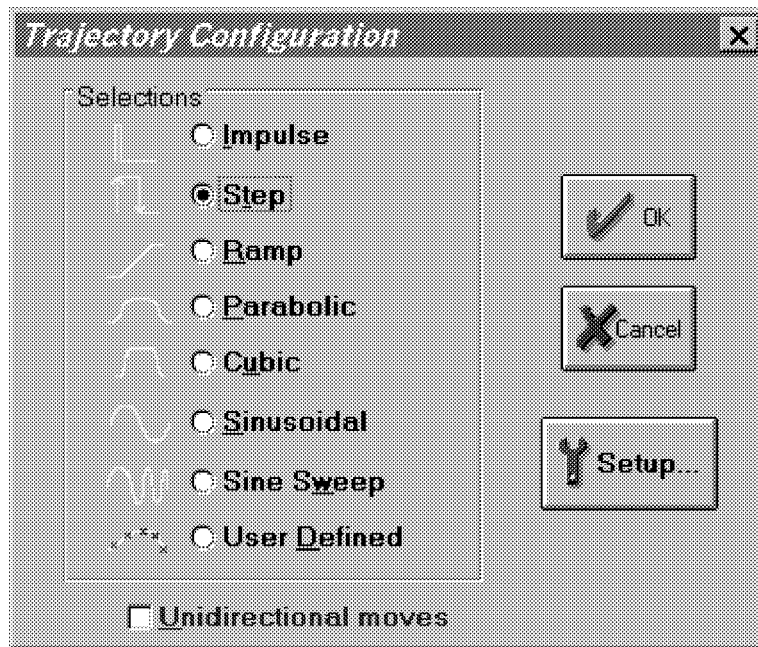


Figure 2.1-5. The Trajectory Configuration Dialog Box

All *geometric* input shapes – Impulse through Cubic – may be specified as Unidirectional or Bi-directional. Examples of these shape types are shown in Figure 2.1-6. The bi-directional option should normally be selected whenever the system is configured to have a rigid body mode (one that rotates freely) and the system is operating open loop. This is to avoid excessive speed or displacement of the system.

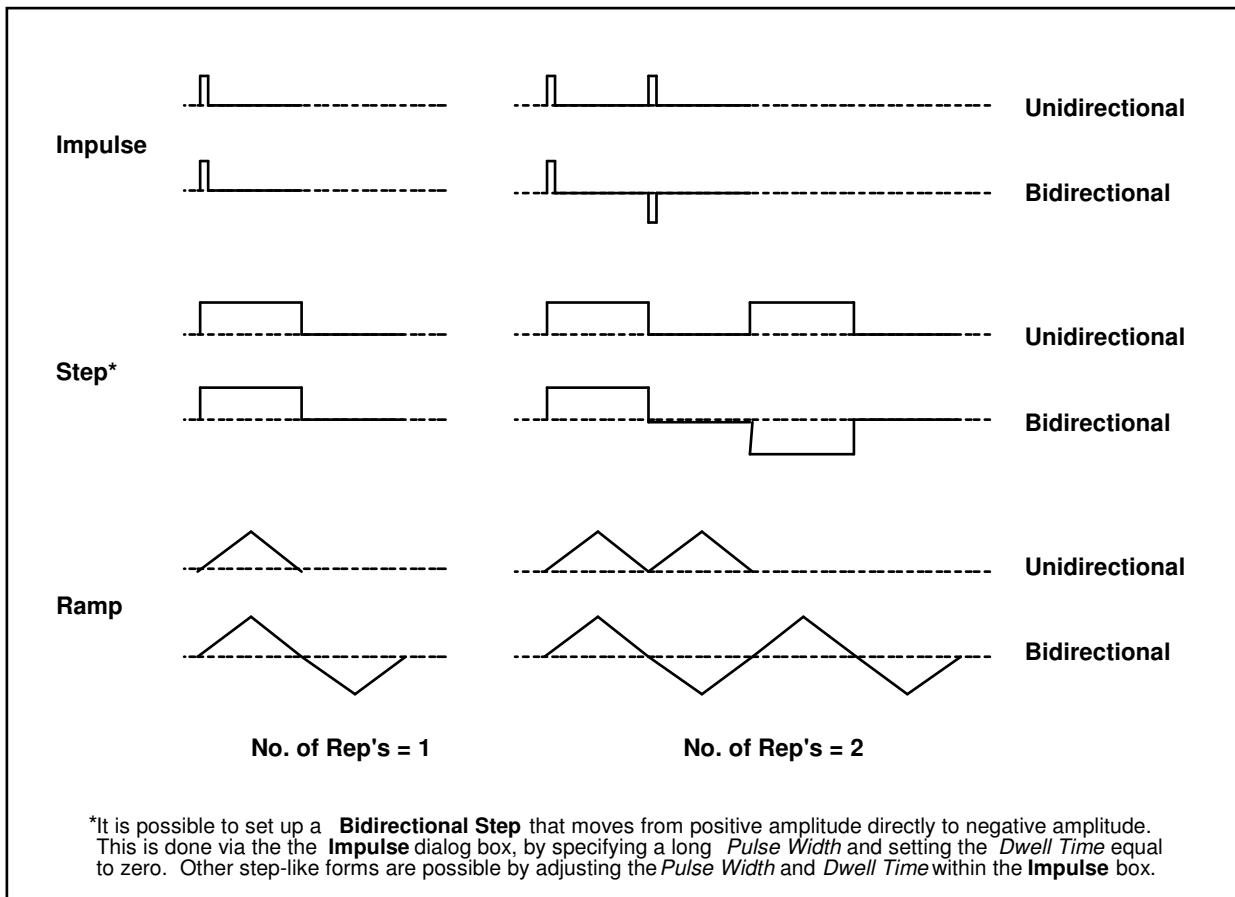


Figure 2.1-6. Example Geometric Trajectories

By selecting the desired shape followed by Setup, one enters a dialog box for the corresponding trajectory. Examples of these boxes are shown in Figure 2.1-7. The amplitude is specified in units consistent with the selected User Units (Setup menu) under closed loop operation and in units of DAC volts (0-5 VDC) under open loop. The closed loop units will change automatically to be consistent with the selected User Units. Amplitudes are always incremental from the value that exists at the beginning of the maneuver (see Execute, Section 2.1.6.3). The characteristic durations of the various shapes are specified in units of milliseconds.

The Impulse, Step, Sinusoidal, Sine Sweep, and User-defined trajectories may be specified as open or closed loop. The remaining shapes are closed loop only.

Important Note: It is possible to specify amplitudes and/or abruptly changing shapes that exceed the linear range of the motor and drive electronics or cause large excursions of the mechanism due to system dynamic response. These may result in inaccurate test results and could lead to a hazardous operating condition or overstressing of the apparatus^[9]. If in doubt as to whether the drive linear range has been exceeded, you may view Control Effort (either by real-time plotting or via data acquisition/plotting^[10]). When specifying an unfamiliar shape the user should generally begin with small amplitudes, velocities, accelerations, and RMS power levels and gradually increase them to suitable safe values. Similarly, when specifying driving function parameters, one should begin with conservatively low values; then gradually increase them. See Section 2.3 on safety.

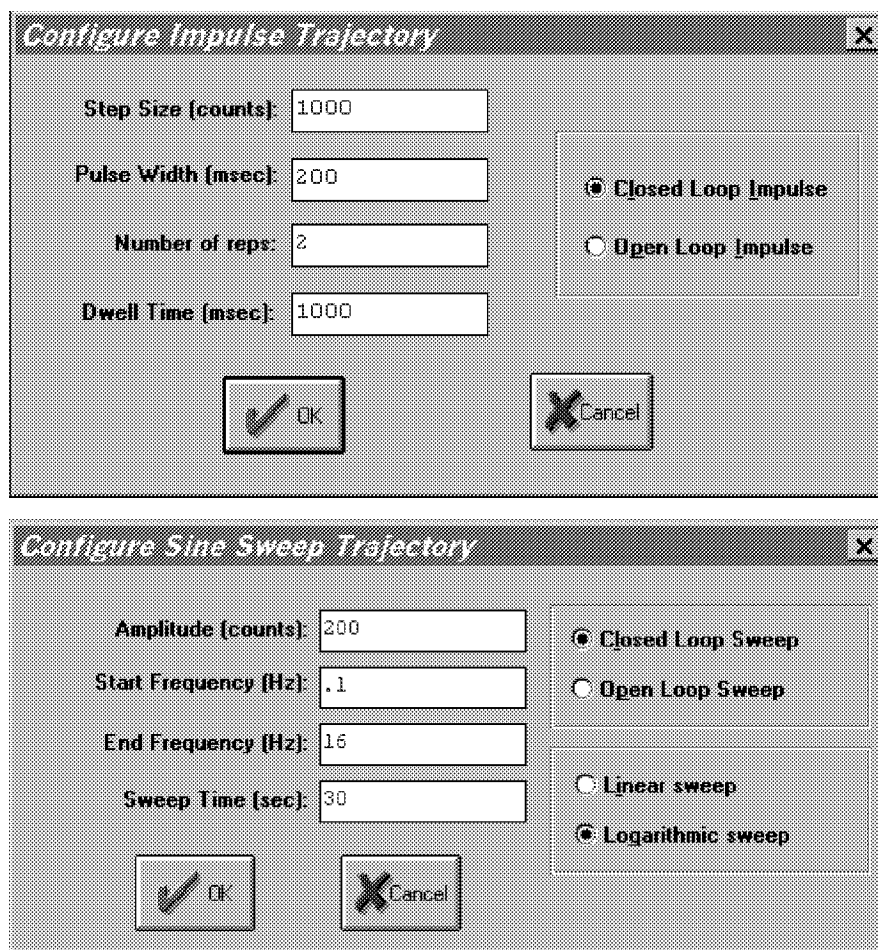


Figure 2.1-7. Example "Setup Trajectory" Dialog Boxes

The Impulse dialog box provides for specification of amplitude, impulse duration, dwell duration, and number of repetitions.^[11] The Step box supports specification of step amplitude, duration, and number of repetitions with the dwell duration being equal to the step duration. The Ramp shape is specified by the peak amplitude,

ramp slope (units of amplitude per second), dwell time at amplitude peaks, and number of repetitions. The Parabolic shape is specified by the peak amplitude, ramp slope (units of ampl./s), acceleration time, dwell time at amplitude peaks, and number of repetitions. In this case, the acceleration (units of ampl./s²) results from meeting the specified amplitude, slope, and acceleration period. The Cubic shape is specified by the peak amplitude, ramp slope (units of ampl./s), acceleration time, dwell time at amplitude peaks, and number of repetitions. In this case, the "jerk" (units of ampl./s³) results from meeting the specified amplitude, slope, and acceleration period where the acceleration increases linearly in time until the specified velocity is reached.

Note that the only difference between a parabolic input and a cubic one is that during the acceleration/deceleration times, a constant acceleration is commanded in a parabolic input and a constant jerk is commanded in the cubic input. Of course, in a ramp input the commanded acceleration/deceleration is infinite at the ends of a commanded displacement stroke and zero at all other times during the motion. For safety, there is an apparatus-specific limit beyond which the Executive program will not accept the amplitude inputs for each geometric shape.

The Sinusoidal dialog box provides for specification of input amplitude, frequency and number of repetitions.

The Sine Sweep dialog box accepts inputs of amplitude, start and end frequencies (units of Hz), and sweep duration. Both linear and logarithmic frequency sweeps are available. The linear sweep frequency increase is linear in time. For example a sweep from 0 Hz to 10 Hz in 10 seconds results in a one Hertz per second frequency increase. The logarithmic sweep increases frequency logarithmically so that the time taken in sweeping from 1 to 2 Hz for example, is the same as that for 10 to 20 Hz when a single test run includes these frequencies. There is an apparatus-specific amplitude limit beyond which the Executive will not accept the inputs.

Important Note: A large open loop amplitude combined with a low frequency may result in an over-speed condition which will be detected by the real-time controller and will cause the system to shut down. In closed loop operations, high frequency, large amplitude tests may result in a shut down condition. For both the open and closed loop cases, even modest commanded amplitude near or at a resonance frequency can cause an excessive shaft deflection. ^[12] Any of these conditions will cause the test to be aborted and the System Status display in the Background Screen to indicate Limit Exceeded. To run the test again you should reduce the input shape amplitude and then Reset Controller (Utility menu), and re-Implement a stabilizing controller (Command menu). In general, all trajectories which generate either too high a speed, too large a deflection, or excessive motor power will cause this condition – see the safety section 2.3. For a further margin of safety, there is an apparatus-specific amplitude limit beyond which the Executive program will not accept the inputs.

The User Defined shape dialog box provides an interface for the specification of any input shape created by the user. In order to make use of this feature the user must first create an ASCII text file with an extension ".trj" (e.g. "random.trj"). This file may be accessed from any directory or disk drive using the usual file path designators in the filename field or via the Browse button. If the file exists in the same directory as the Executive program, then only the file name should be entered. The content of this file should be as follows:

The first line should provide the number of points specified. The maximum number of points is 923. This line should not contain any other information. The subsequent lines (up to 923) should contain the consecutive set points. For example to input twenty points equally spaced in distance one can create a file called "example.trj" using any text editor as follows

20

5

10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100

The segment time which is a time between each consecutive point can be changed in the dialog box. For example if a 100 milliseconds segment time is selected, the above trajectory shape would take 2 seconds to complete ($100 \times 20 = 2000$ ms). The minimum segment time is restricted to five milliseconds by the real-time controller. When Open Loop is selected, the units of the trajectory are assumed to be DAC bits ($+16383 = 4.88$ V, $+16383 = -4.88$ V). In Closed Loop mode, the units are assumed to be the position displacement units specified under User Units (Setup menu). The shape may be treated by the system as a discrete function exactly as specified, or may be smoothed by checking the Treat Data As Splined box. In the latter case the shapes are cubic spline fitted between consecutive points by the real-time controller. Obviously a user-defined shape may also cause over-speed or over-deflection of the mechanism if the segment time is too long or the distance between the consecutive points is too great.

2.1.6.2 The Disturbance Configuration dialog box (see Figure 2.1.-5a) provides a selection of disturbance torque profiles for the disturbance motor. These are:

- Viscous Friction
- Step
- Sinusoidal (time)
- Sinusoidal (theta)
- User Defined

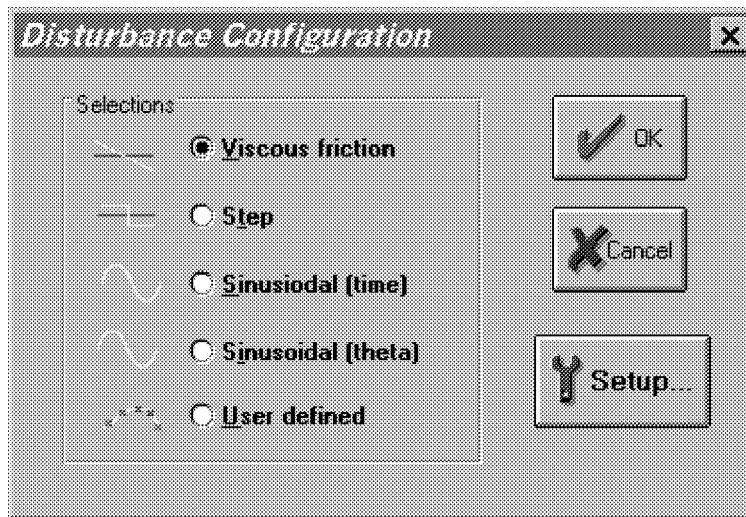


Figure 2.1-6. The Disturbance Configuration Dialog Box

By clicking on the desired radio button followed by Setup, one enters a dialog box for the disturbance profile selected.

The Viscous Friction window allows the user to input a disturbance signal proportional to the angular speed of the load shaft as sensed by the load encoder (encoder #2). The Amplitude entry is the magnitude of the viscous coefficient in units of volts/radian/second. Once the disturbance motor is calibrated this entry translates to a certain number of N-m/rad./sec. The user has a choice of implementing the viscous disturbance either directly through this dialog box or later prior to running a trajectory in the Execute dialog box. The maximum amplitude of viscous disturbance is limited to 10 volts/radian/second.

The Step disturbance dialog box allows the user to input the parameters for a square wave torque disturbance. The entries in this dialog box are identical to the Open Loop Step trajectory discussed above.

The Sinusoidal (time) option allows the user to input a torque disturbance to the load shaft via the disturbance motor in the form of a sinusoidal function of time. The entries in this dialog box are identical to the Open Loop Sinusoidal trajectory discussed above.

The Sinusoidal (theta) specifies a sinusoidal torque as a function of load disk position. This allows the simulation of spatially dependent disturbances such as motor cogging torque. The amplitude of the disturbance torque is entered in terms of volts. The user must enter the number of torque cycles per revolution of the load shaft (maximum number is limited to 100). In addition the period of time for which this disturbance is active must be specified.

The User Defined disturbance box provides the interface for the input of any form of disturbance trajectory created by the user. In order to make use of this feature the user must first create an ASCII text file with an extension `.trj` (e.g. `random.trj`). The format is identical to the User Defined trajectories discussed in the previous section. Note that the maximum number of points are still 100 and the first entry must be the number of points in a particular file. The units of inputs are in DAC bits ($+16383 = 4.88$ V, $+16383 = -4.88$ V). After the calibration of the disturbance motor, the exact ratio between a DAC bit and the actual disturbance torque on the load shaft may be determined.

During the active period of any of the above disturbance profiles the Disturbance Status would indicate "Active". It is, however, possible that the disturbance motor enters the "Limit Exceeded" condition either as a result of over current or over speed. To return to the "Active" condition, the user must modify the disturbance parameters and implement the disturbance torque again via the Execute dialog box (note that the Viscous friction disturbance may also be implemented within its own dialog box).

The following rules govern disturbance implementation:

1. You must have selected a disturbance (and verified its parameters) under the Disturbance Configuration dialog box and checked "Include XXX Disturbance" when Executing a trajectory.
2. The disturbance will only be active while the trajectory is executing. If the trajectory terminated before the specified disturbance duration, the disturbance will also terminate.
3. The only exception to rules 1 and 2 is viscous damping which may be invoked either via its own dialog box (under Disturbance Configuration) or when a trajectory is executed (by checking Include Viscous Friction before Executing). Viscous friction may run simultaneously with other disturbances. Note that Viscous Friction, if implemented, will remain in effect until either it is removed in its own dialog box, or a new trajectory is run without checking Include Viscous Friction.
4. Disturbance control effort is limited to $\pm 4.88V$.

2.1.6.3 The Execute dialog box (see Figure 2.1-7) is entered after a trajectory is selected. Here the user has a choice of including viscous friction and another additional disturbance with a set of parameters previously selected within the appropriate dialog box. The user may select either Normal or Extended Data Sampling. Normal Data Sampling acquires data for the duration of the executed input shape maneuver. Extended Data Sampling acquires data for an additional 5 seconds beyond the end of the maneuver. Both the Normal and Extended boxes must be checked to allow extended data sampling. (For the details of data gathering see Section 2.1.7.1 Setup Data Acquisition).

Once the choice is made as to whether to sample data, the user normally selects Run. The specified trajectory will start to be executed by the real-time Controller. Once finished, and provided the Sample Data box was checked, the data will be uploaded back into the Executive for plotting, saving and exporting. At any time during the execution of the trajectory or during the uploading of data the process may be terminated by clicking on the Abort button. Finally, if the disturbance torque profile has a time period longer than the selected trajectory period, it will be terminated at the end of the trajectory profile.

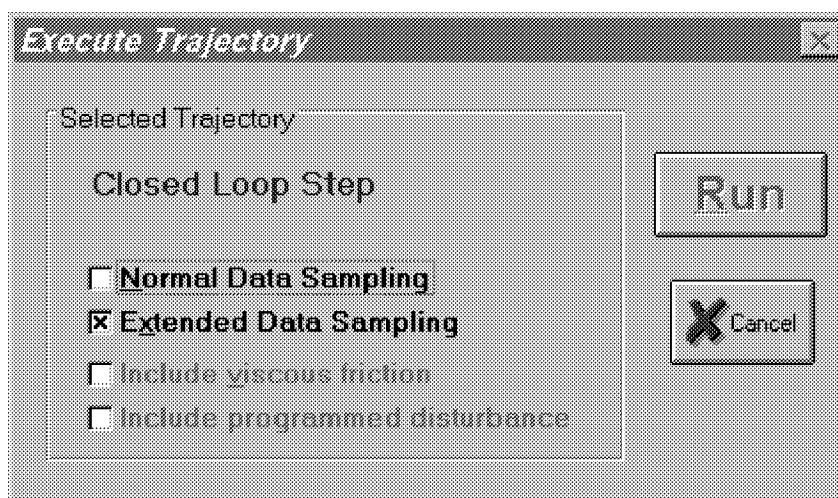


Figure 2.1-7. The Execute Dialog Box

2.1.7 Data Menu

The Data menu contains the following pull-down options

Setup Data Acquisition

Upload Data

Export Raw Data

2.1.7.1 Setup Data Acquisition allows the user to select one or more of the following data items to be collected at a chosen multiple of the servo loop closure sampling period while running any of the trajectories mentioned above – see Figures 2.1-8 and 4.1-1:

Commanded Position

Encoder 1 Position

Encoder 2 Position

Encoder 3 Position

Control Effort (output to the servo loop or the open loop command)

Disturbance Effort (disturbance motor command)

Node A (input to the H polynomial in the Generalized Control Algorithm)

Node B (input to the E polynomial in the Generalized Control Algorithm)

Node C (output of the 1/G polynomial in the Generalized Control Algorithm)

Node D (output of the feedforward controller which is added to the node C value to form the combined regulatory and tracking controller).

In this dialog box the user adds or deletes any of the above items by first selecting the item, then clicking on the Add Item or Delete Item button. The user must also select the data gather sampling period in multiples of the servo period. For example, if the sample time (T_s in the Setup Control Algorithm) is 0.00442 seconds and you choose 5 for your gather period here, then the selected data will be gathered once every fifth sample or once every 0.0221 seconds. Usually for trajectories with high frequency content (e.g. Step, or high frequency Sine Sweep), one should choose a low data gather period. On the other hand, one should avoid gathering more often (or more data types) than needed since the upload and plotting routines become slower as the data size increases.

2.1.7.2 Selecting Upload Data allows any previously gathered data to be uploaded into the Executive. This feature is useful when one wishes to switch and compare between plotting previously saved raw data and the currently gathered data. Remember that the data is automatically uploaded into the executive whenever a trajectory is executed and data acquisition is enabled. However, once a previously saved raw data file is loaded into the Executive, the currently gathered data is overwritten. The Upload Data feature allows the user to bring the overwritten data back from the real-time controller into the Executive.

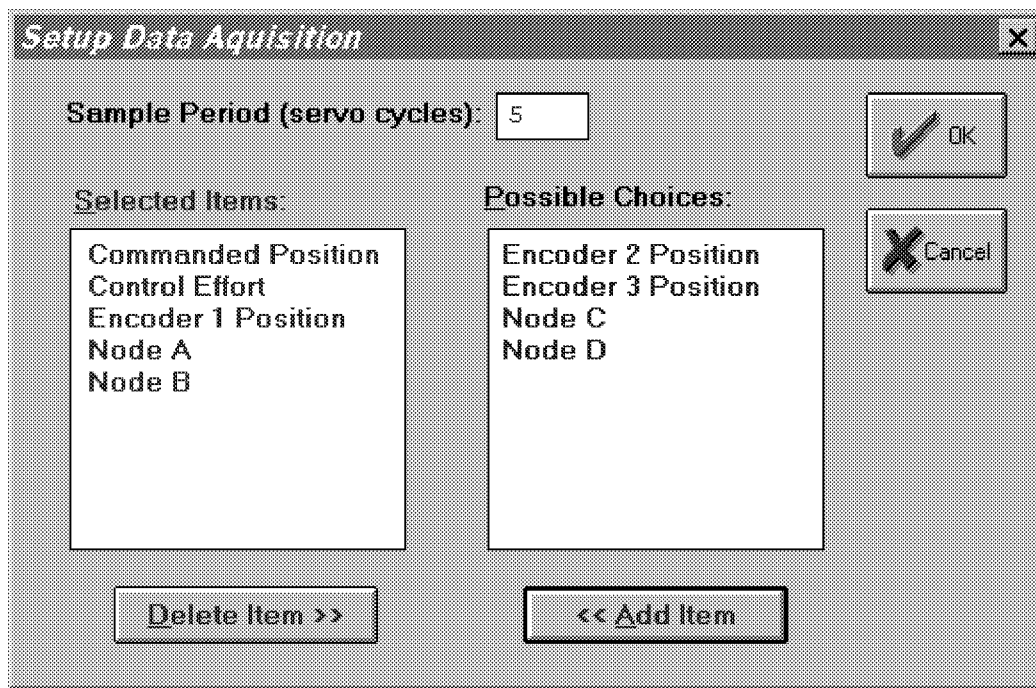


Figure 2.1-8. The Setup Data Acquisition Dialog Box

2.1.7.3 The Export Raw Data function allows the user to save the currently acquired data in a text file in a format suitable for reviewing, editing, or exporting to other engineering/scientific packages such as Matlab[®].^[13] The first line is a text header labeling the columns followed by bracketed rows of data items gathered. The user may choose the file name with a default extension of ".txt" (e.g. lqrstep.txt). The first column in the file is sample number, the next is time, and the remaining ones are the acquired variable values. Any text editor may be used to view and/or edit this file.

2.1.8 Plotting Menu

The Plotting menu contains the following pull-down options

- Setup Plot
- Plot Data
- Axis Scaling
- Print Plot
- Load Plot Data
- Save Plot Data
- Real Time Plotting
- Close Window

2.1.8.1 The Setup Plot dialog box (see Figure 2.1-9) allows up to four acquired data items to be plotted simultaneously – two items using the left vertical axis and two using the right vertical axis units. In addition to the acquired raw data, you will see in the box plotting selections of velocity and acceleration for the position and input variables acquired. These are automatically generated by numerical differentiation of the data during the plotting process. Simply click on the item you wish to add to the left or the right axis and then click on the Add to Left Axis or Add to Right Axis buttons. You must select at least one item for the left axis before plotting is allowed – e.g. if only one item is plotted, it must be on the left axis. You may also change the plot title from the default one in this dialog box.

Items for comparison should appear on the same axis (e.g. commanded vs. encoder position) to ensure the same axis scaling and bias. Items of dissimilar scaling or bias (e.g. control effort in volts and position in counts) should be placed on different axes.

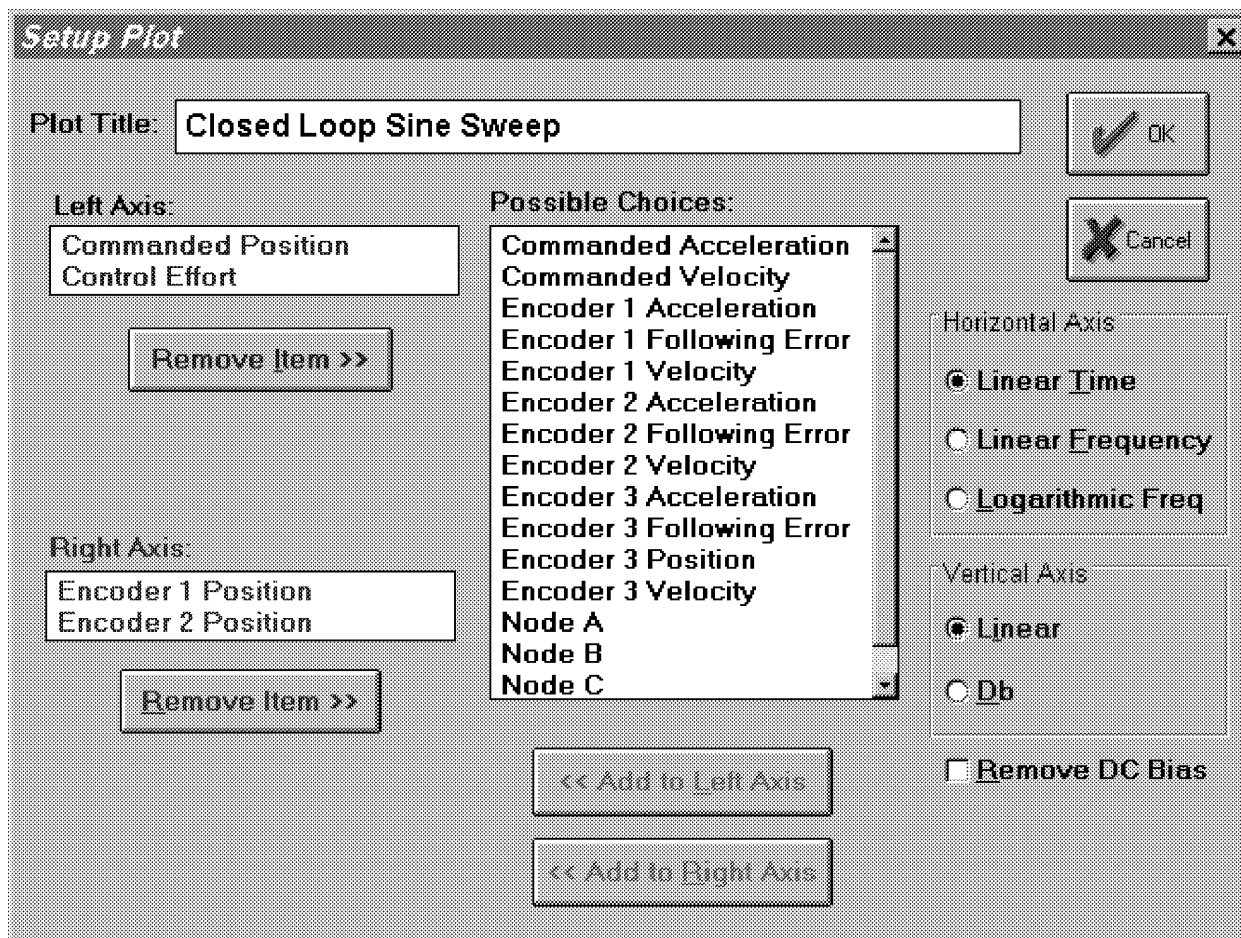


Figure 2.1-9 The Setup Plot Dialog Box (Shows case where data was gathered for encoders 1 & 2 and commanded input. Up to 20 variables may be made available for plotting)

When the current data (either from the last test run or from a previously saved and loaded plot file) is from a Sine Sweep input, several data scaling/transformation options appear in the Setup Plot box. These include the presentation of data with horizontal coordinates of time, linear frequency (i.e. the frequency of the input) or logarithmic frequency. The vertical axis may be plotted in linear or Db (i.e. $20 \cdot \log_{10}(\text{data})$) scaling. In addition, the Remove DC Bias option subtracts the average of the final 50 data points from the data set of each acquired variable. This generally gives a more representative view of the frequency response of the system, particularly when plotting low amplitude data in Db. Sine Sweep must be selected in the Trajectory Configuration dialog box in order for these options to be available in Setup Plot. Examples of sine sweep (frequency response) data plotted using two of these options is given later in Figures 3.2-3, -4TBD.

2.1.8.2 Plot Data generates a plot of the selected items. By clicking on the upper blue border of the plots, they may be dragged across the screen. The view size may be maximized by clicking on the up arrow of the upper right hand corner. It can also be shrunk to an icon by clicking on the down arrow of the upper left hand corner. It can be expanded back to the full size at any time by double-clicking on the icon. Also more than one plot may be tiled on the Background Screen. This function is very useful for comparing several graphs. By clicking on any point within the area of a desired plot it will appear over the others. Plots may be arbitrarily shaped by using the cursor to "drag" the edges of the plot. The corners allow you to resize height and width simultaneously (position cursor at corner and begin "dragging" when cursor becomes a double arrow). Finally

by double clicking on the top left hand corner of a plot screen one can close the plot window. A typical plot as seen on screen is shown in Figure 2.1-10.

2.1.8.3 Axis Scaling provides for scaling or “zooming” of the horizontal and vertical axes for closer data inspection – both visually and for printing. This box also provides for selection or deselection of grid lines and data point labels. When Real-time Plotting is used (see Section 2.1.8.7), the data sweep / refresh speed and amplitudes may be adjusted via the Axis Scaling box.

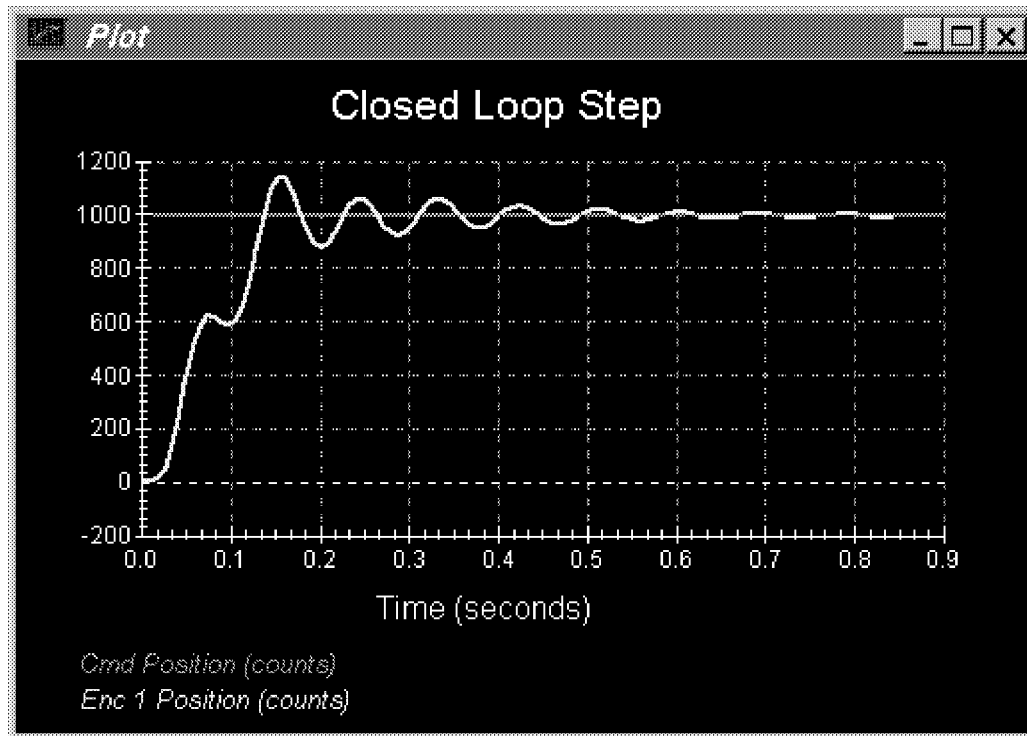


Figure 2.1-10. A Typical Plot Window

2.1.8.4 The Print Data option provides for printing a hard copy of the selected plot on the current PC system printer. The plots may be resized prior to printing to achieve the desired print format

2.1.8.5 The Load Plot Data dialog box enables the user to bring into the Executive previously saved ".plt" plot files. Note that such files are not stored in a format suitable for use by other programs. The ".plt" plot files contain the sampling period of the previously saved data. As a result, after plotting any previously saved plot files and before running a trajectory, you should check the servo loop sampling period T_s in the Setup Control Algorithm dialog box. If this number has been changed, then correct it. Also, check the data gathering sampling period in the Data Acquisition dialog box, this too may be different and need correction.

2.1.8.6 The Save Plot Data dialog box enables the user to save the data gathered by the controller for later plotting via Load Plot Data. The default extension is ".plt" under the current directory. Note that ".plt" files are not saved in a format suitable for use by other programs. For this purpose the user should use the Export Raw Data option of the Data menu.

2.1.8.7 The Setup Real Time Plotting dialog box enables the user to view data in real time as it is being generated by the system. Thus the data is seen in an oscilloscope-like fashion. Unlike normal (off-line) plotting, real-time plotting occurs continuously whether or not a particular maneuver (via Execute, Command

Menu) is being executed^[14]. The setup for real-time plotting is essentially identical to that for normal plotting (see Section 2.1.8.1). Because the expected data amplitude is not known to the plotting routine, the plot will first appear with the vertical axes scaled to full scale values of 1000 of the selected variable units. These should be rescaled to appropriate values via Axis Scaling. The sweep or data refresh rate may also be changed via Axis Scaling when real-time plotting is underway. A slow sweep rate is suitable for slow system motion or when a long data record is to be viewed in a single sweep. The converse generally holds for a fast sweep rate.

The data update rate is approximately 50 ms and is limited by the PC/DSP board communication rate. Therefore, frequency content above about 5 Hz is not accurately displayed due to numerical aliasing. The real-time display however is very useful in visually correlating physical system motion with the plotted data and is valid for most practical system frequencies. The data acquired via the data acquisition hardware (for normal plotting) may be sampled at much higher rates (up to 1.1 KHz) and hence should be used when quantitative high speed measurements are desired.

2.1.8.8 The Close Window option allows the currently marked plot window to close. This can also be done by double clicking on the top left hand corner of the plot window.

2.1.9 Utility Menu

The Utility menu contains the following pull-down options:

- Configure Auxiliary DACs
- Jog Position
- Zero Position
- Reset Controller
- Rephase Motor
- Down Load Controller Personality File

2.1.9.1 The Configure Auxiliary DACs dialog box (see Figure 2.1-11) enables the user to select various items for analog output on the two optional analog channels in front of the ECP Control Box. Using equipment such as an oscilloscope, plotter, or spectrum analyzer the user may inspect the following items continuously in real time:

- Commanded Position
- Encoder 1 Position
- Encoder 2 Position
- Encoder 3 Position
- Control Effort
- Node A
- Node B
- Node C
- Node E

The scale factor which divides the item can be less than 1 (one). The DACs analog output is in the range of +/- 10 volts corresponding to +32767 to -32768 counts. For example to output the commanded position for a sine sweep of amplitude 2000 counts you should choose the scale factor to be 0.061 ($2000/32767=0.061$) This gives close to full +/- 10 volt reading on the analog outputs. In contrast, if the numerical value of an item is greater than +/- 32767 counts, for full scale reading, you must choose a scale factor of greater than one. Note that the

above items are always in counts (not degrees or radians) within the real time controller and since the DAC's are 16-bit wide, + 32767 counts corresponds to +9.999 volts, and -32768 counts corresponds to -10 volts.

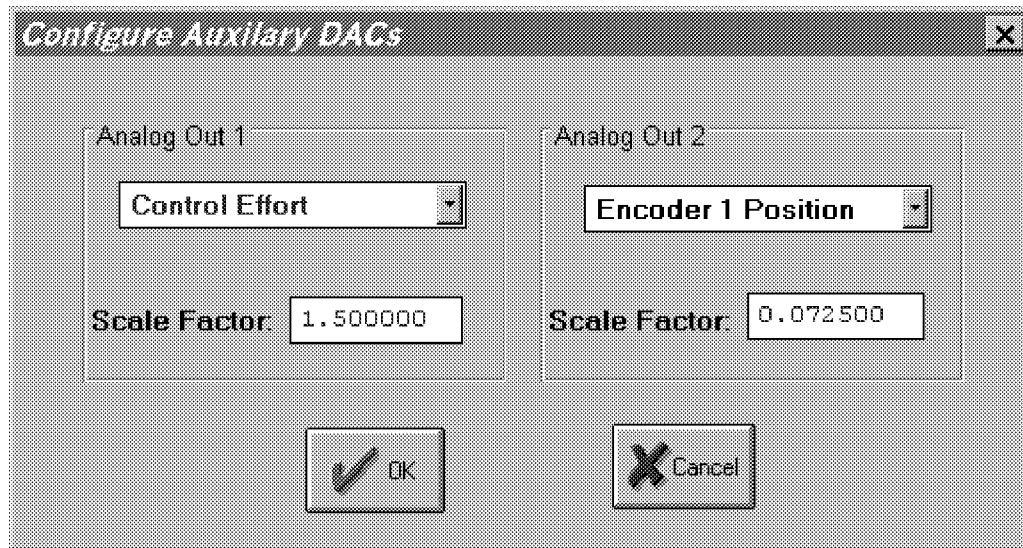


Figure 2.1-11. The Configure Auxiliary DACs Dialog Box

2.1.9.2 The Jog Position option enables the user to move the mechanism to a different commanded position. In contrast to displacements executed under the Trajectory dialog box, during a Jog command no data is acquired for plotting purposes. Since this motion is effected via the current controller, one can only jog under closed loop control with a stable controller. By selecting the appropriate radio button either incremental and absolute displacements may be carried out. The jogging feature allows the user to return to a known position after the execution of the various forms of open and closed loop trajectories.

2.1.9.3 The Zero Position option enables the user to reinitialize the current position as the zero position. Note that if following errors exists, then the actual positions may be other than zero even though the commanded position is at zero (since the action is similar to commanding an instantaneous zero set point, a sudden small jerk in position may occur).

2.1.9.4 The Reset Controller option allows the user to reset the real-time controller. Upon Power up and after a reset activity, the loop is closed with zero gains and there it behaves in the same way as in the open loop state with zero control effort. Thus the user should be aware that even though the Control Loop Status indicates "closed loop", all of the gains are zeroed after a Reset. In order to implement (or re implement) a controller you must go to the Setup Control Algorithm box.

2.1.9.5 The Rephase Motor option enables a user to simply rephase a brushless motor's commutation phase angle. This feature is not used by the Model 220 system since its motors use absolute sensors for commutation.

2.1.9.6 The Download Controller Personality File is an option which should not be used by most users. In a case where the real-time controller irrecoverably malfunctions, and after consulting ECP, a user may download the personality file if a ".pmc" file exists. In the case of Model 220, this file is named "m220xxx.pmc". Note that this downloading process takes a few seconds.

2.2 Electromechanical Plant

2.2.1 Design Description

The plant, shown in Figure 2.2-1 is designed to emulate a broad range of typical servo control applications. The Model 220 apparatus consists of a *drive motor* (servo actuator) which is coupled via a timing belt to a *drive disk* with variable inertia. Another timing belt connects the drive disk to the *speed reduction (SR)* assembly while a third belt completes the drive train to the *load disk*. The load and drive disks have variable inertia which may be adjusted by moving (or removing) brass weights. Speed reduction is adjusted by interchangeable belt pulleys in the SR assembly. Backlash may be introduced through a mechanism incorporated in the SR assembly, and flexibility may be introduced by an elastic belt^[15] between the SR assembly and the drive disk. The drive disk moves one-for-one with the drive motor so that its inertia may be thought of as being *collocated* with the motor. The load inertia however will rotate at a different speed than the drive motor due to the speed reduction. Also, drive flexibility and/or backlash may exist between it and the drive motor and hence its inertia is considered to be *noncollocated* with the motors.

A disturbance motor connects to the load disk via a 4:1 speed reduction and is used to emulate viscous friction and disturbances at the plant output. A brake below the load disk may be used to introduce Coulomb friction. Thus friction, disturbances, backlash, and flexibility may all be introduced in a controlled manner. These effects represent non-ideal conditions that are present to some degree in virtually all physically realizable electromechanical systems.

All rotating shafts of the mechanism are supported by precision ball bearings. Needle bearings in the SR assembly provide low friction backlash motion (when backlash is desired).

High resolution incremental encoders^[16] couple directly to the drive (θ_1) and load (θ_2) disks providing position (and derived rate) feedback. The drive and disturbance motors are electrically driven by servo amplifiers and power supplies in the Controller Box. The encoders are routed through the Controller box to interface directly with the DSP board via a gate array that converts their pulse signals to numerical values^[17].

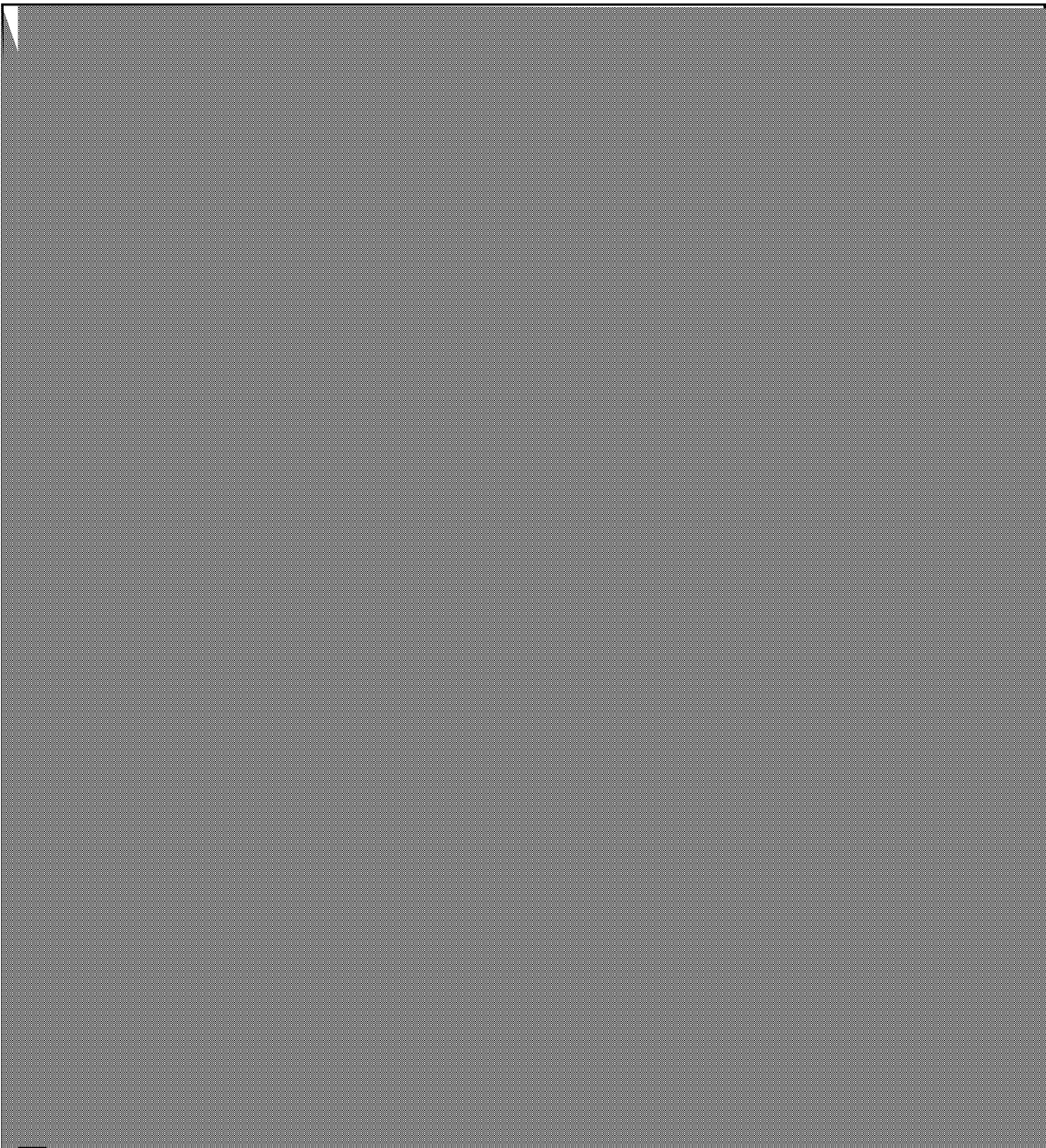


Figure 2.2-1. Emulator Apparatus

2.2.2 Instructions for Changing Configurations

Important notices:

- 1. Disconnect power to the electrical Controller Box prior to performing any procedure in this section.**
- 2. Replace and secure the plexiglass safety cover immediately after completing all procedures.**

2.2.2.1 Changing Pulleys & Gear Ratio^[18] (Refer to Figure 2.2-2)

Gear ratios are changed via selection of the sizes of the upper and lower pulleys in the SR assembly. Fixed pulleys at the drive and inertia disks have 12 and 72 teeth respectively so that in combination with the interchangeable pulleys, end-to-end gear ratios ranging from 1.5:1 to 24:1 are achieved. Table 2.2-1 gives the pulley combinations to establish a desired ratio and identifies the recommended timing belts for each combination. Once the user becomes familiar with the system, the proper belt lengths may generally be seen by inspection and gear ratios (end-to-end) resulting from the SR gear selection become obvious.

1. Remove the existing pulleys by first loosening the belt tension clamp screw to allow the belts to become slack. Loosen the clamp screw and the backlash adjustment screw. Lift the SR assembly off the idler shaft and unscrew the upper and lower pulley attach screws to free the existing pulleys.
2. Replace the new pulleys in reverse order of step 1. Be sure that the bearing contact boss is facing downward in the lower pulley and upward in the upper pulley and that the backlash contact boss on the lower backlash member is facing upward (away from the lower pulley). Also be sure that the backlash adjustment screw is tightened (only light torque is necessary – do not over tighten) unless backlash effects are desired.

2.2.2.2 Changing & Tightening Belts

1. Refer to Table 2.2-1 for proper belt selection. If the lower pulley is unchanged then the existing lower belt should be the correct one.
2. Fit the lower then upper belts over their respective pulleys. Simultaneously tighten both belts by applying 5-10 pounds (25-50 N.) of force in the direction shown in Figure 5.2-2. You may need to apply the force in an off-center direction to adequately tension both belts^[19]. Tighten the belt tension clamp screw while applying the force.
3. Manually rotate the disks for several rotations of the load disk and observe the belts. They should be just taught enough so that their nominally straight lengths do not further visibly straighten (they should already be straight) when the load and drive disks are manually counter-rotated. Belts that are too slack add flexibility and belts that are too tight add excess friction – both generally unwanted.

2.2.2.3 Changing Brass Weights

Instructions for changing or relocating the brass weights for the drive and load inertia disks are given in Figure 2.2-3.

2.2.2.4 Installing Flexible Drive Belt

It is recommended that the flexible drive belts be used with the 36 tooth pulley only (I.e. the 36 tooth pulley in the upper position in the SR assembly.) The flexible belt should be in place only for the duration of active testing. Prolonged periods (more than several hours) may permanently stretch the belts.

1. With the upper belt (from the SR assembly to the load disk) removed tighten the lower belt – see "Changing & Tightening Belts" above. Since the upper belt is removed, the SR assembly is free to move for a limited

range along a circular arc about the drive disk. It is usually preferred to position the SR assembly as close as possible to the load disk.^[20]

- 2 Stretch the flexible belt to fit it past the load disk and around the load disk pulley. Stretch the belt and begin to fit it about the 36 tooth pulley. By rotating the pulley with one section of the belt on the pulley edge, the belt is easily fed into place. The result should be as shown in Figure 2.2-4.

2.2.2.5 Adjusting Backlash

Backlash is adjusted (0 to 20 deg @ the SR) via the backlash adjustment screw (see Figure 2.2-2). You may measure the amount of backlash by temporarily tightening the friction clamp below the load disk and manually rotating the drive disk back and forth while noting the encoder readings at each extreme.^[21] You must have the "feedback connector connected to the control box and the ECP executive program operating. Drive power to the apparatus however must be disconnected. Be certain that you loosen the friction clamp before proceeding

















2.2.2.6 Adjusting Friction Brake

Coulomb friction is adjusted via the tightening screw in the friction brake. The brake should not be set greater than 1 N-m to avoid excessive friction^[22] and hence excessive drive current^[23] (under subsequent closed loop control) which can lead to amplifier burn-out.

Note:

1. Always move the drive disk manually prior to operation to verify that excessive brake torque does not exist.
2. Always loosen tightening screw on friction brake immediately after performing any needed tests. The brake should be used infrequently.

Table 2.2-1. Pulley and Belt Configurations For Various Gear Ratios

Bottom Pulley (No. of Teeth)	Top Pulley (No. of Teeth)	Gear Ratio (End-to-end)	Bottom Belt* (Drive to SAassy)	Top Belt* (SAassy to load)
 18	 24	4.5:1	140	250
	 36	3:1	140	260
	 72	1.5:1	140	300
 24	 18	8:1	140	250
	 36	4:1	140	260
	 72	2:1	140	300
 36	 18	12:1	150	250
	 24	9:1	150	250
	 72	3:1	150	300
 72	 18	24:1	200	250
	 24	18:1	200	250
	 36	12:1	200	260

* Numbers given are twice the number of belt teeth and are equal to the inner length of the flattened belt divided by 0.050 inches. These numbers appear on the belts (among other markings). E.g. a marking "250XLO37" corresponds to "250" in this table.

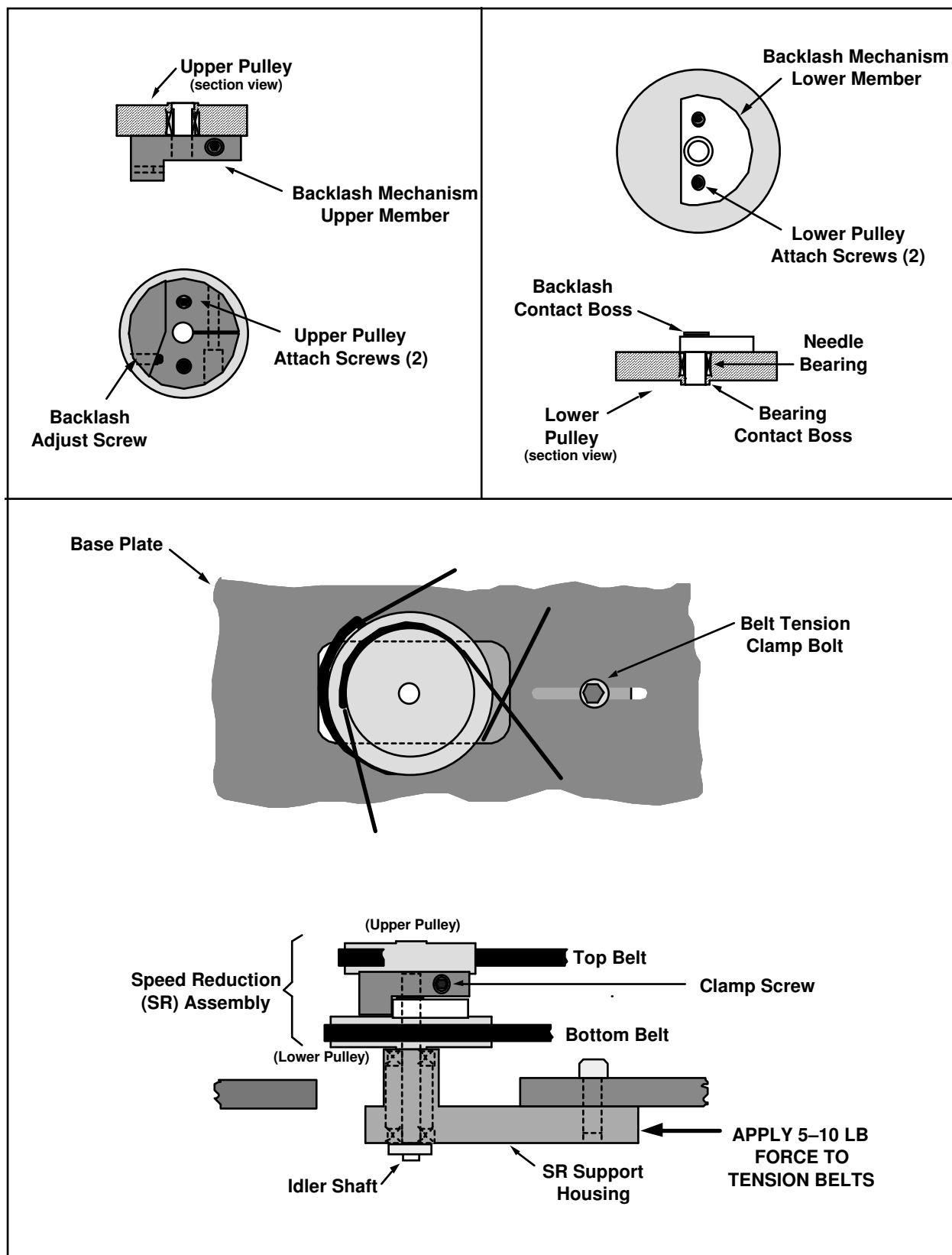


Figure 2.2-2.

Components Used In Changing Gear Ratio & Adjusting Backlash

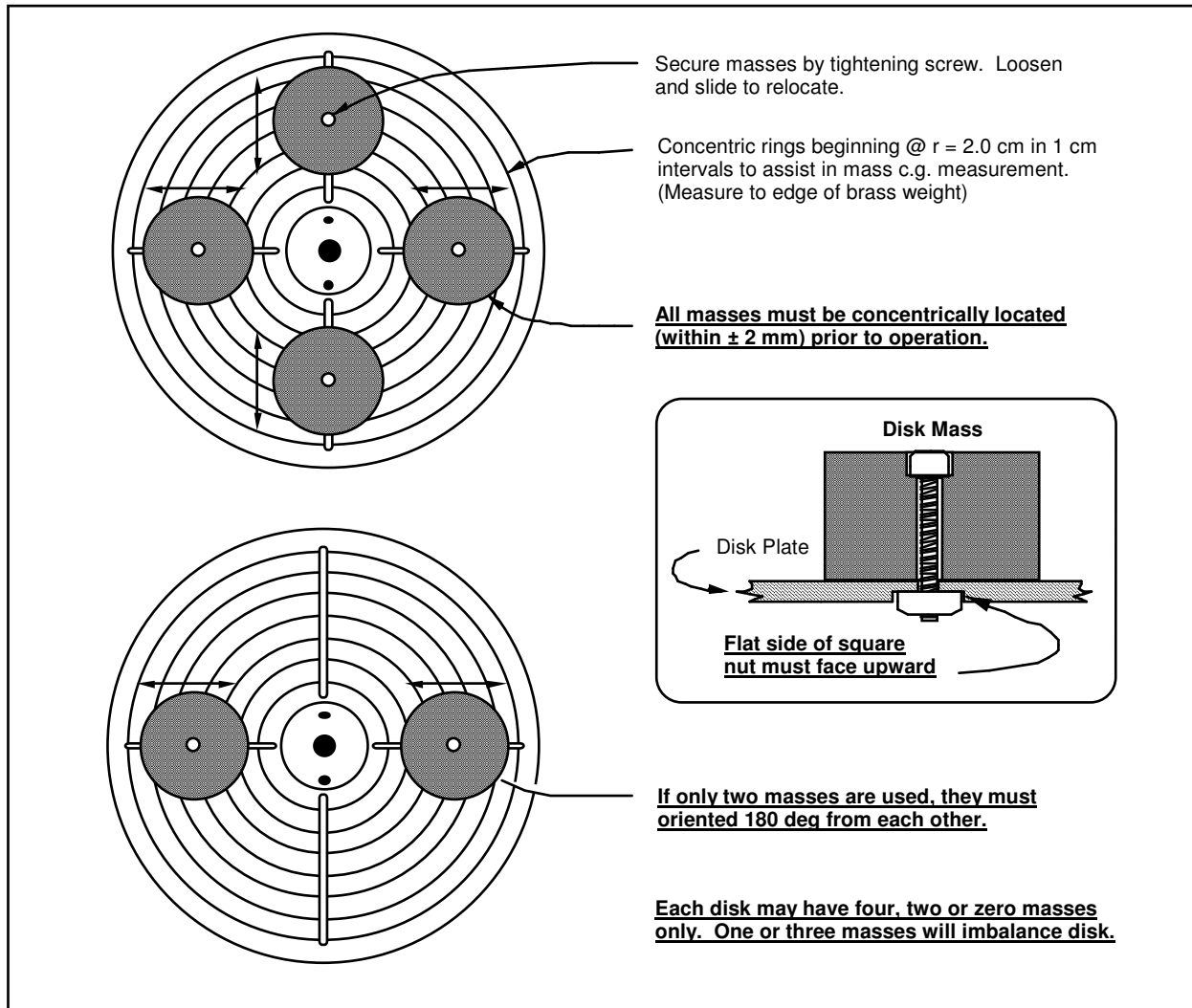


Figure 2.2-3.

Guidelines For Changing Or Adjusting Disk Masses

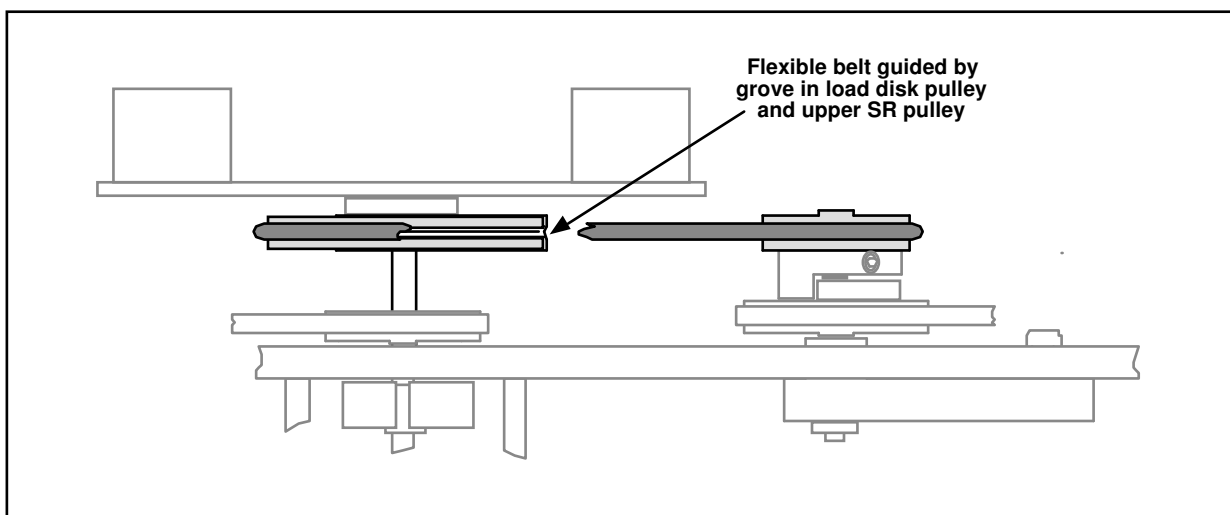


Figure 2.2-4. Installing Flexible Drive Belt

2.3 Safety

The following are safety features of the system and cautions regarding its operation. This section must be read and understood by all users prior to operating the system. If any material in this section is not clear to the reader, contact ECP for clarification before operating the system.

Important Notice: In the event of an emergency, control effort should be immediately discontinued by pressing the red "OFF" button on front of the control box.

2.3.1 Hardware

A relay circuit is installed within the Control Box which automatically turns off power to the Box whenever the real-time Controller (within the PC) is turned on or off. Thus for the PC bus version^[24] of the real-time Controller the user should turn on the computer prior to pressing on the black ON switch. This feature is implemented to prevent uncontrolled motor response during the transient power on/off periods. The power to the Control Box may be turned off at any time by pressing the red OFF switch.

Although not recommended, it will not damage the hardware to apply power to the Control-Box even when the PC is turned off. However, doing so does not result in motor activation as the motor current amplifier will be disabled. The *amplifier enable* signal input to the Control Box is connected to the real-time Controller via the 60-pin flat ribbon cable. This input operates in a normally closed mode. When power to the real-time Controller is off, this input becomes open which in turn disables the motor amplifier.

The recommended procedure for **start up** is as follows:

First : Turn on the PC with the real-time Controller installed in it.

Second: Turn on the power to Control Box (press on the black switch).

The recommended **shut down** procedure is:

First: Turn off the power to the Control Box.

Second: Turn off the PC..

FUSES: There are two 3.0A 120V slow blow fuses within the Control Box. One of them is housed at the back of the Control Box next to the power cord plug. The second one is inside the box next to the large blue colored capacitor.

2.3.2 Software

The Limit Exceeded indicator of the Controller Status display indicates either one or more of the following conditions have occurred:

Over speed of the motor.

Excessive drive motor power

The real-time Controller continuously monitors the above limiting conditions in its background routine (intervals of time in-between higher priority tasks). When one if these conditions occurs, the real-time

Controller opens up the control loop with a zero torque command sent to the actuator. The Limit Exceeded indicator stays on until a new set of (stabilizing) control gains are downloaded to the real-time Controller via the Implement Algorithm button of the Setup Control Algorithm dialog box, or a new trajectory is executed via the Command menu. Obviously the new trajectory must have parameters that do not cause the Limit Exceeded condition.

The Limit Exceeded indicator of the Disturbance Motor Status display indicates either one or both of the following conditions have occurred:

- Over speed of the disturbance motor.
- Excessive disturbance motor power

Also included is a *watch-dog timer*. This subsystem provides a fail-safe shutdown to guard against software malfunction and under-voltage conditions. The use of the watch-dog timer is transparent to the user. This shutdown condition turns on the red LED on the real-time Controller card, and will cause the control box to power down automatically. You may need to cycle the power to the PC in order to reinitialize the real-time Controller should a watch-dog timer shutdown occur.

2.3.3 Safety Checking The Controller

While it should generally be avoided, in some cases it is instructive or useful to manually contact the mechanism when a controller is active. This should always be done with caution and never in such a way that clothing or hair may be caught in the apparatus. By staying clear of the mechanism when it is moving or when a trajectory has been commanded, the risk of injury is greatly reduced. Being motionless, however, is not sufficient to assure the system is safe to contact. In some cases an unstable controller may have been implemented but the system may remain motionless until perturbed – then it could react violently.

In order to eliminate the risk of injury in such an event, you should always safety check the controller prior to physically contacting the system. This is done by lightly grasping a slender, light object with no sharp edges (e.g. a ruler without sharp edges or an unsharpened pencil) and using it to slowly move either the load or drive disk from side to side. Keep hands clear of the mechanism while doing this and apply only light force to the disk. If the disk does not spin up or oscillate then it may be manually contacted – but with caution. This procedure must be repeated whenever any user interaction with the system occurs (either via the Executive Program or the Controller Box) if the mechanism is to be physically contacted again.

2.3.4 Warnings

WARNING #1: Stay clear of and do not touch any part of the mechanism while it is moving, while a trajectory has been commanded (via Execute, Command menu), or before the active controller has been safety checked – see Section 2.3.3.

WARNING #2: The following apply at all times except when motor drive power is disconnected (consult ECP if uncertain as to how to disconnect drive power):

- a) Stay clear of the mechanism while wearing loose clothing (e.g. ties, scarves and loose sleeves) and when hair is not kept close to the head.
- b) Keep head and face well clear of the mechanism.

WARNING #3: Verify that the masses and inertia disks are secured per section 2.2 of this manual

prior to powering up the Control Box or transporting the mechanism.

WARNING #4: Do not take the cover off or physically touch the interior of the Control Box unless its power cord is unplugged (first press the "Off" button on the front panel) and the PC is unpowered or disconnected.

WARNING #5: The power cord must be removed from the Control box prior to the replacement of any fuses.

3. Start-up & Self-guided Demonstration

This chapter provides an orientation "tour" of the system for the first time user. In Section 3.1 certain hardware verification steps are carried out. In Section 3.2 a self-guided demonstration is provided to quickly orient the user with key system operations and Executive program functions. Finally, in Section 3.3, certain system behaviors which may be nonintuitive to a first time user are pointed out .

All users must read and understand Section 2.3, Safety, Before performing any procedures described in this chapter.

3.1 Hardware Setup Verification

At this stage it is assumed that

- a) The ECP Executive program has been successfully installed on the PC's hard disk (see Section 2.1.2).
- b) The actual printed circuit board (the real-time Controller) has been correctly inserted into an empty slot of the PC's extension (ISA) bus (this applies to the PC bus version only).
- c) The supplied 60-pin flat cable is connected between the J11 connector (the 60-pin connector) of the real-time Controller and the JMACH connector of the Control Box^[25].
- d) The other two supplied cables are connected between the Control Box and the Emulator apparatus;
- e) The apparatus has the two disks securely installed with no weights fastened to any disks and all clamps removed. (i.e. the plant should be set up as shown in Figure 2.2-1 except with no masses on the disks. This is the configuration the mechanism is shipped in.)
- f) You have read the safety Section 2.3. All users must read and understand that section before proceeding.

Please check the cables again for proper connections.

3.1.1 Hardware Verification (For PC-bus Installation)

Step 1: Switch off power to both the PC and the Control Box.

Step 2: With power still switched off to the Control Box, switch the PC power on. Enter the ECP program by double clicking on its icon (or type ">ECP" in the appropriate directory under DOS). You should see the Background Screen (see Section 2.1.3). Gently rotate the drive or load disk by hand. You should observe some following errors and changes in encoder counts. The Control Loop Status should indicate "CLOSED" and the Controller Status should indicate "ACTIVE". If this is the case skip Step 3 and go to Step 4.

Step 3: If the ECP program cannot find the real-time Controller (a pop-up message will notify you if this is the case), try the Communication dialog box under the Setup menu. Select PC-bus at address 528, and click on the test button. If the real-time Controller is still not found, try increasing the time-out in 20 ms increments up to a maximum of 300 ms. If this doesn't correct the problem, switch off power to your PC and then take its cover off. With the cover removed check again for the proper insertion of the Controller card. Switch the power on again and observe the two LED lights on the Controller card. If the green LED comes on all is well; if the red LED is illuminated, you should contact ECP for further instructions. If the green LED comes on, turn off power to your PC, replace the cover and turn the power back on again. Now go back to the ECP program and you should see the positions change as you gently rotate the disks.

Step 4: Make sure that you can rotate disks freely. Now connect the power cord to the Control Box and press the black "ON" button to turn on the power to the Control Box. You should notice the green power indicator LED lit, but the motor should remain in a disabled state. Do not touch the disks whenever power is applied to the Control Box since there is a potential for uncontrolled motion of the disks (see the warnings in Section 2.3) unless the controller has been safety checked.

This completes the hardware verification procedure. Please refer again to Section 2.3 for future start up and shut down procedures.

3.2 Demonstration of ECP Executive Program

This section walks the user through the salient functions of the system. By following the instructions below you will actually implement a controller, maneuver the system through various trajectories, and acquire and plot data. The procedures given in this section are specific to the Model 220 system.

Step 1: Loading A Configuration File. With the power to the Control box turned off, enter the ECP Executive program. You should see the Background Display. Turn on power to the Control Box (press on the black button). Now enter the File menu, choose Load Settings and select the file `default.cfg`. This configuration file is supplied on the distribution diskette and should have been copied under the ECP directory by now. Note that this file would have been loaded into the Executive automatically (see section 2.1.4.1). This particular `default.cfg` file contains the controller gain parameters and other trajectory, data gathering and plotting parameters specifically saved for the activities within this section.

Note that the plant type for which this file has been created has a 4:1 mechanical advantage (speed reduction) between the Load Disk and the Drive Disk with no brass weights on either disks. This is the standard set up for the Model 220 when shipped from factory.

Step 2: Implementing The Controller. Now enter the Setup menu and choose Setup Control Algorithm. You should see the sampling time $T_s = 0.00442$ seconds, and the PI + Velocity Feedback "radio button" selected. Now click on the Setup Algorithm button and you should see the following gains: $k_p = 0.20$, $k_d = 0.010$, $k_i = 0$. These are *continuous time* gains designed for a closed loop natural frequency of approximately 4 Hz and a damping ratio of 1 (critical damping). Note that the feedback loop is closed around Encoder #1. Exit this box and then click on Implement algorithm. The control law is now down-loaded to the real-time Controller. If you do not notice any motor power, click again until you notice the servo loop closed.

Now select Discrete Time and click on Upload Algorithm then on General Form and again select Setup Algorithm. You should see the general form algorithm with some non zero coefficients. These coefficients correspond to PID gains mapped to the general form algorithm structure. Notice that the general form algorithm is the only structure that actually runs in real-time. All other structures (e.g. dynamic filters, State Feedback etc.) are translated to the general form by the Executive prior to the implementation. Prior to leaving the Setup Control Algorithm dialog box select the Continuous Time radio button again.

Step 3: Setting Up Data Acquisition. Enter the Data menu and select Setup Data Acquisition. In this box make sure that the following five items are selected: Commanded Position, Encoder 1, Encoder 2, Control effort and Disturbance Effort. *Data sample period* should be 3 which means that the data will be collected every second servo cycle (in this case every $3 * 0.00442 = 0.0133$ seconds).

Step 4: Executing A Trajectory & Plotting. Enter the Command menu and select Trajectory. In this box select Step and then Setup. You should see *step size = 4000*, *dwel time = 1000* ms, and *no. of repetitions = 1*. If not, change the values to this parameter set. Exit this box and go to the Command menu. Select Execute and, with *only* the Sample Data box checked, run the trajectory and wait for the data to be uploaded from the real-time Controller. You should have noticed a step move of 4000

counts (1/4 of revolution of the smaller Disk, a dwell of 1 second and a return step move. Now enter the Plotting menu and choose Setup Plot. Select Commanded Position and Encoder 1 Position for plotting (both on left axis) and click on Plot Data. You should see a plot similar to the one shown in Figure 3.2-1. This is the step response of a critically damped system with an (underdamped) natural frequency of approximately 6 Hz.

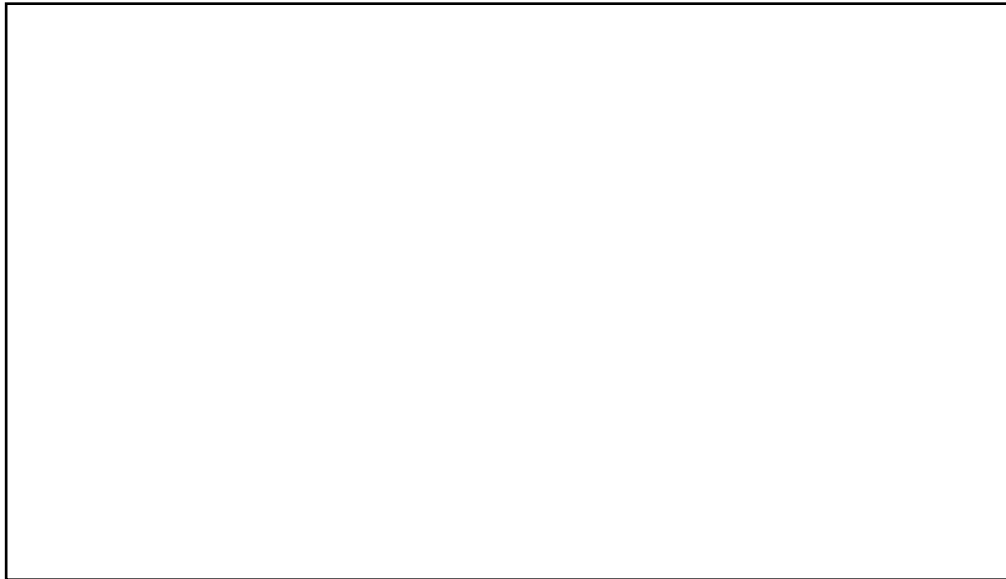


Figure 3.2-1 Critically Damped Step Response at Encoder 1

Note that all plot screens may be repositioned by dragging the plot frame bar using the mouse. A plot screen may be minimized or "shrunk" by clicking on the left most button on the top right hand corner. By double clicking on a minimized plot screen it may be expanded again. In general, to limit the program memory usage, one should avoid minimizing more than 8 to 10 plot screens on the Background screen. It is best to close unwanted plot screens rather than minimize them. You can re-size the plots using the cursor to "drag" any edge of the plot frame (position cursor at corner and begin "dragging" when cursor becomes double arrow).

Step 5: Underdamped Step Response. Now enter the Setup menu again and choose Setup Control Algorithm. You should again see $T_s = 0.00442$ s., PI + Velocity Feedback, and Continuous Time selected. Now click on Setup Algorithm and you should see the following gains: $k_p = 0.20$, $k_d = 0.010$, $k_i = 0$. Change the derivative gain to $k_d = 0.002$ leaving the values for the other two gains unchanged. You have just reduced the velocity feedback gain. By reducing the amount of derived velocity feedback a critically damped second order system becomes under damped. To demonstrate this, implement the algorithm in the Setup Control Algorithm box. Repeat Step 4 above with the new set of gains and plot the response of the Encoder #1 position to the same commanded step input. The response should look like the graph shown in Figure 3.2-2 which exhibits characteristics of an under damped system. Now change the derivative gain back to 0.010 for critical damping, implement the new gains via the Setup Control Algorithm dialog box.

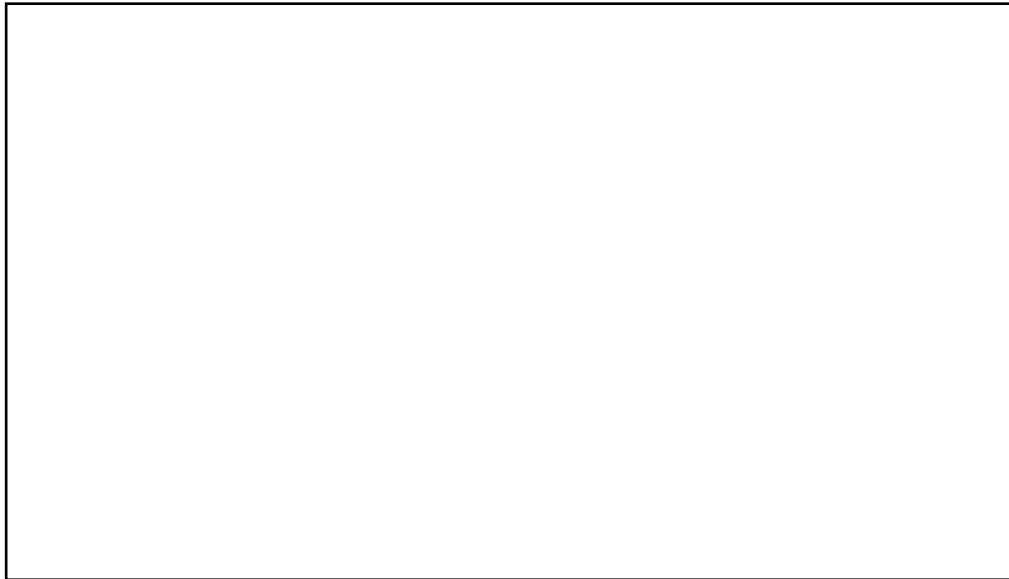


Figure 3.2-2 Underdamped Step Response

Step 6: Tracking Response. Enter the Command menu and select Trajectory. Choose Ramp and Setup to enter the *Ramp* dialog box. You should see *distance = 10000* counts, *velocity = 10000* counts/s, *dwell time = 100* ms, and *no. of repetitions = 1*. If not, change the values to this set. Exit this dialog box and go to the Command menu. Now select Execute and with only Sample Data checked, run the trajectory and wait for the data to be uploaded. You should have noticed a ramp (constant velocity) move of 10,000 counts (5/8 of a revolution of the small disk) followed by an 100 ms dwell and then the return motion. Now enter the Plotting menu and choose Setup Plot. Select Commanded position and Encoder 1 Position and then plot the data. You should see a plot similar to the one shown in Figure 3.2-3. Repeat the last step but this time add the Commanded Velocity and Encoder 1 Velocity for plotting on the right axis. Note that you may save the plot data under *anyname.plt* using the Save Plot Data option. Any plot data thus saved may be reloaded from the disk using the Load Plot Data option for future inspection, plotting or printing. To print simply choose the Print Data menu option and select the appropriate printer before the printing command. You may also save the data in an ASCII format suitable for entry to other software packages via the Export Data option under the Data menu. The file extension for ASCII data is **.txt*. Now close all plot windows.

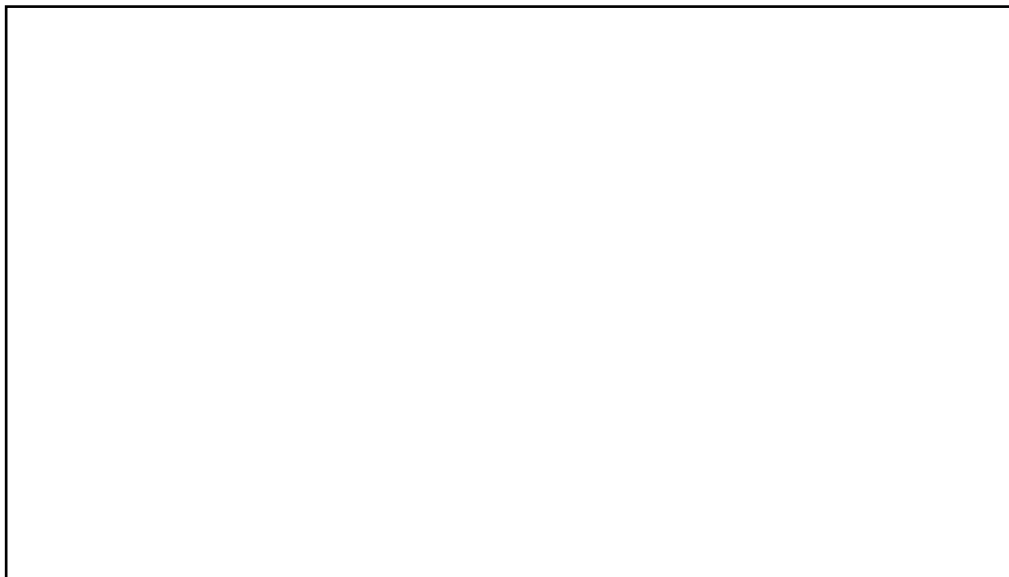


Figure 3.2-3 Ramp Tracking With PD Control

Step 7: Frequency Response. Again enter Trajectory and select Sine Sweep then Setup. You should see: Amplitude = 500 counts, min. freq. = 0.1 Hz, max. freq.= 12 Hz and sweep time = 30 seconds. Exit this box and go to Command menu and Execute. With only Sample Data checked, run the trajectory and wait for the data to be uploaded. You should notice a sinusoidal motion with increasing frequency and reducing amplitude for about 30 seconds. After the data has been uploaded at the end, go to the Plotting menu and choose Setup Plot. Remove the velocities from the right axis and Command Position from the left axis, then plot the Encoder 1 Position. The plot should look like the one shown in Figure 3.2-4. This is a typical response associated with a damped second order system when excited sinusoidally with an increasing frequency (frequency response).

Now as done previously, change to $k_d = 0.002$ (underdamped) and Implement. Exit and the repeat the same sine sweep trajectory maneuver. The response should now indicate the characteristic peak associated with the frequency response of an under damped second order system (resonance at approximately 6 Hz in this case) as shown in Figure 3.2-5.

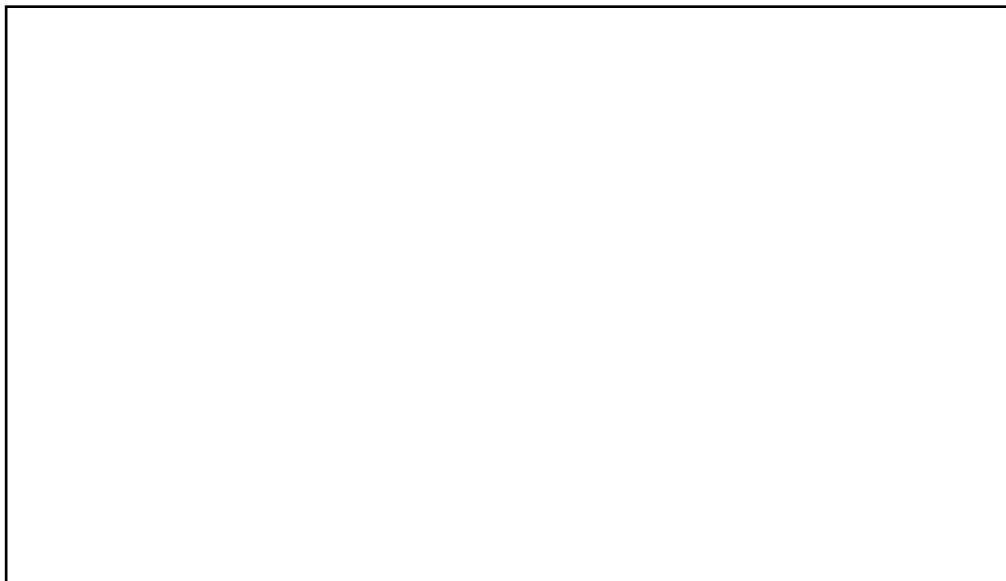


Figure 3.2-4 Sine Sweep Response of Critically Damped System



Figure 3.2-5 Sine Sweep Response of Underdamped System

Step 8: Adding Viscous Damping. Enter the Disturbance dialog box under the Command menu. Select

Viscous Friction and then Setup. Using this menu you may enter the parameters for the viscous friction coefficient in units of volts/radian/second. It should be set to 1.0 volts/radian/second. Exit this dialog box and go to the Execute dialog box. This time check both Sample Data and Include viscous friction prior to running the previously used Step trajectory. The response observed should look similar to the one shown in Figure 3.2-6. Relative to Figure 3.2-2, this response shows that the effect of viscous friction is to add damping which is the same as the effect of derivative feedback. Note that the viscous friction torque, if implemented, will remain in effect until either it is *removed* in its own dialog box, or a new trajectory is run without checking the Include viscous friction check box. For the Model 220 system, viscous friction is effected via the disturbance motor coupled to the Load Disk.

Return to Setup Control Algorithm menu and return the derivative gain to $k_d = 0.010$ for critical damping. Implement the new gain and then exit the dialog box. Set up a 0 (zero) count step for 7500 ms duration and 1 repetition via Step under Trajectory in the Command menu. This prepares the system for regulation and data collection.

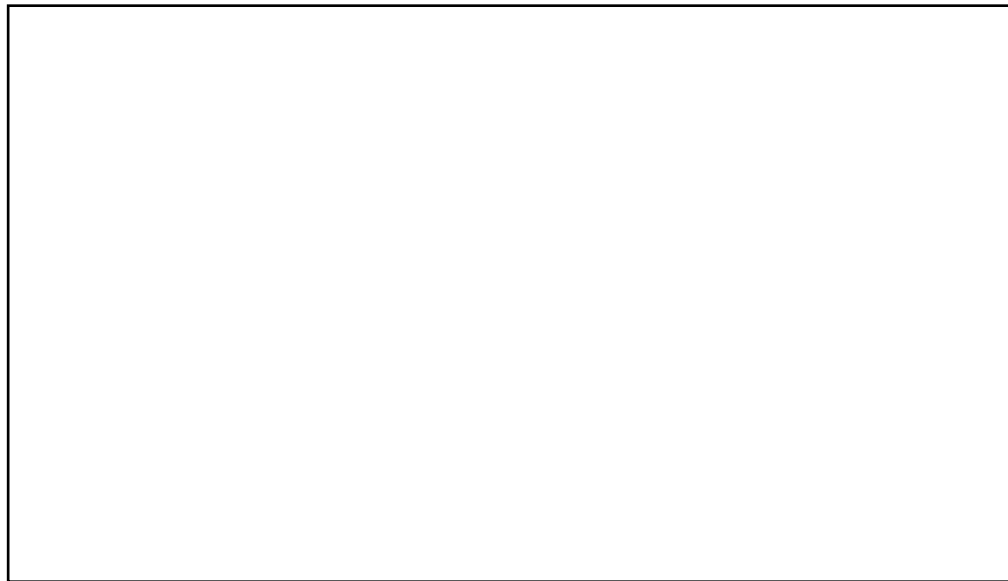


Figure 3.2-6 Damping Of Underdamped System Via Viscous Friction

Step 8: Disturbance Regulation & Integral Control. Enter the Disturbance dialog box under the Command menu. Select Step and then Setup. Using this menu you may enter the parameters for a step torque disturbance (all disturbance torque profiles are physically activated from the motor connected to the larger "load" disk via the 4:1 pulley below the disk). The parameters should be: *Step Size* = 0.5 volts, *Dwell time* = 2500 ms and *no. of repetitions* = 2. Exit and Execute the (zero amplitude) Step trajectory making sure to check both Sample Data and Include Step Disturbance prior to running. The response observed after plotting Encoder 1 position should look similar to the one shown in Figure 3.2-7 (You may want to plot Disturbance Effort as well to see the overall regulation effect). Notice the increased size of the steady state error due to the step disturbance. After plotting this data, shrink it for later comparison.

Now re-enter Setup Control Algorithm and the PI + velocity Feedback window and add integral gain by setting $k_i = 1.0$ leaving the other two gains unchanged. Exit and Implement. Repeat the above procedure and plot the response. You should notice that the response overshoots but the steady state errors due to the step torque disturbance are eliminated by the addition of the integral action. A plot similar to the one shown in Figure 3.2-8 should have been obtained. All disturbance torque profiles (except viscous friction) are synchronized to start of any selected trajectory maneuver. If a disturbance profile's selected duration is longer than the selected duration for a particular trajectory,

the disturbance effort is brought to zero at the end of the trajectory maneuver. This means that the disturbance torque profiles may be cut short if the end of trajectory motion is reached first. Also the scaling for the disturbance effort between volts and Newton meters of torque is discussed in the chapter 6.

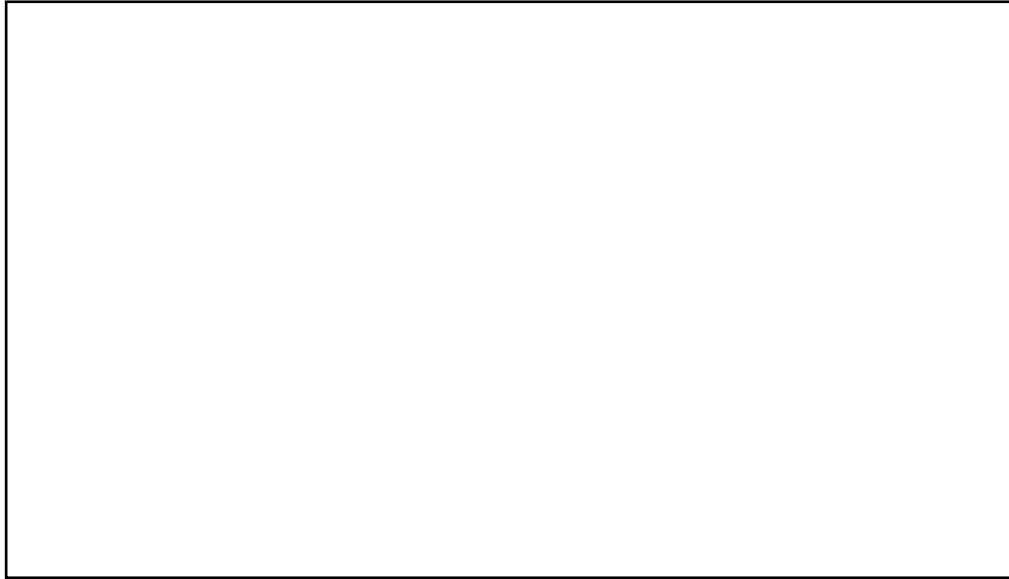


Figure 3.2-7 Response Of PD controlled System To Step Disturbance Torque

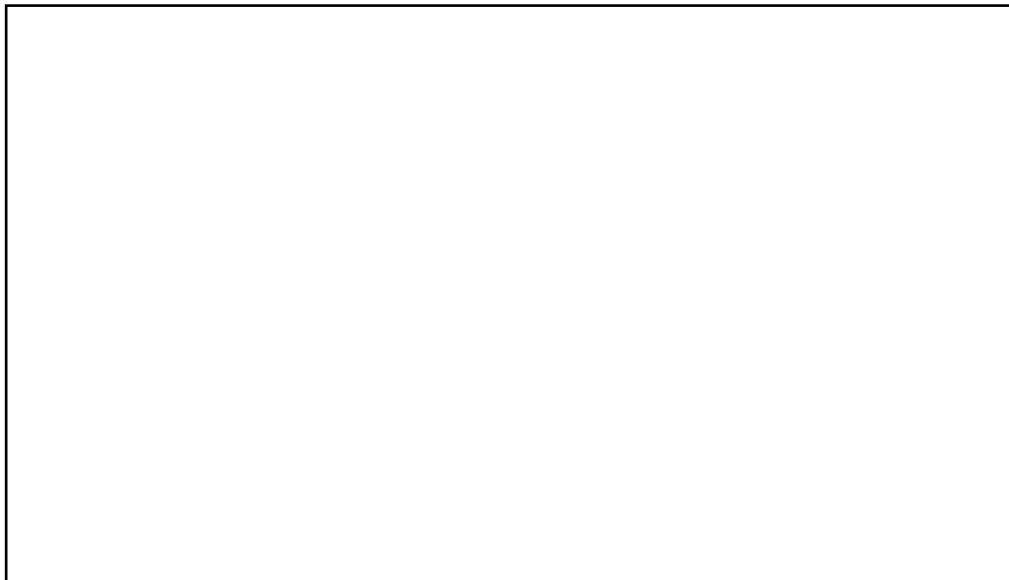


Figure 3.2-6 Elimination Of Steady State Error Via Integral Action

This completes the self-guided tour. It is strongly advised that the user read all material in Chapters 2 and 3 before further operation of the system.

3.3 Nonintuitive System Behavior

An explanation of system functionality which may be nonintuitive to first time (or first few time) users is given below.

- Point 1:** Upon PC power up, the control loop is closed but all gains are cleared to zero. As a result, even though the status display indicates CLOSED LOOP, the control effort is zero indicating that there is no torque command to the actuator. With zero gains, the closed loop system behaves like an open loop one. This initialization of the gains to zero also takes place every time the real-time controller is Reset under the Utility menu.
- Point 2:** Even though the parameters for a particular control algorithm may exist within the Executive, the real-time Controller does not carry them until the Implement Algorithm button of the Setup Control Algorithm dialog box is activated. Then control is implemented immediately
- Point 3:** The **Limit Exceeded** message comes on as a result of either motor over-speed, shaft over-deflection or drive over-current. In any case the message does not clear until a stable set of control gains are downloaded and if necessary a less abrupt trajectory is requested (see Section 2.1.3). This condition may also occur when the following takes place. With the control loop closed, the power to the Control Box is turned off and the disks are rotated manually and then the power is turned back on again. In this case the sudden motions of the disks may cause the limiting conditions.

4. Real-Time Control Implementation

This chapter is a description of the real-time controller functionality and a tutorial on related implementation issues. A functional overview of the control system is shown in Figure 4.0-1. This system is comprised of three subsystems: The user/system (“Executive”) interface software, the mechanism including motor and sensors, and the controller including the drive electronics. At the heart of the control implementation is the real-time controller.

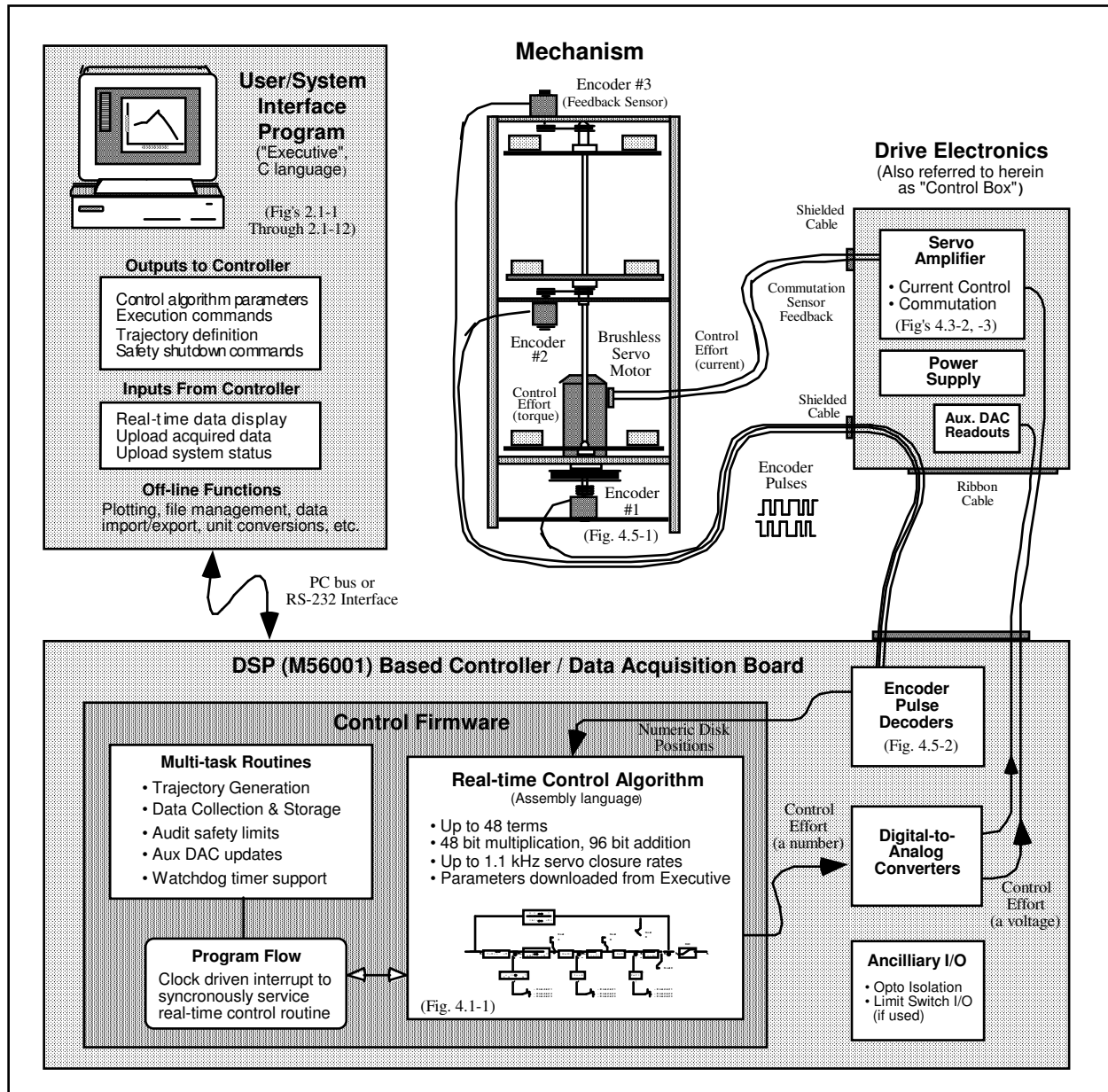


Figure 4.0-1. Overview of Real-time Control System.

This architecture is consistent with modern industrial control implementation.

The ECP real-time Controller is a Digital Signal Processor (DSP) based single board computer which executes the following real-time tasks:

- Servo loop closure
- Command generation

Sensor Interface

In addition, in the background (while not executing the above tasks) it carries out the following:

User Interface via PC and/or RS232 Bus

Limits and Safety Activities

4.1 Servo Loop Closure

Servo loop closure involves computing the control algorithm at the sampling time. The real-time Controller executes the General Form equation of the control law at each sample period T_s . This period can be as short as 0.000884 seconds (approx. 1.1 KHz) or any multiple of this number. The Executive program's Setup Control Algorithm dialog box allows the user to alter the sampling period. All forms of control laws are automatically translated by the Executive program to the General Form prior to downloading ("implementing") to the Controller. The General Form uses 96-bit real number (48-bit integer and 48-bit fractional) arithmetic for computation of the control effort. The control effort is saturated in software at +/- 16384 to represent +/- 5 volts on the 16-bit DACs whose range is +/- 10 volts. The +/-5 volt limitation is due to the actuator 's amplifier input voltage scaling.

Referring to Figure 4.1-1, the control equations are as follows:

$$R(q^{-1})\text{nodeA}(k) = T(q^{-1}) * c_p(k) - S(q^{-1}) * f_{b1}(k)$$

Here T, S, and R are seventh order polynomials of the unit time shift operator q, and the letter k represents the k^{th} sampling period for $k=0, 1, 2, \dots$. The variable nodeA is an intermediate value

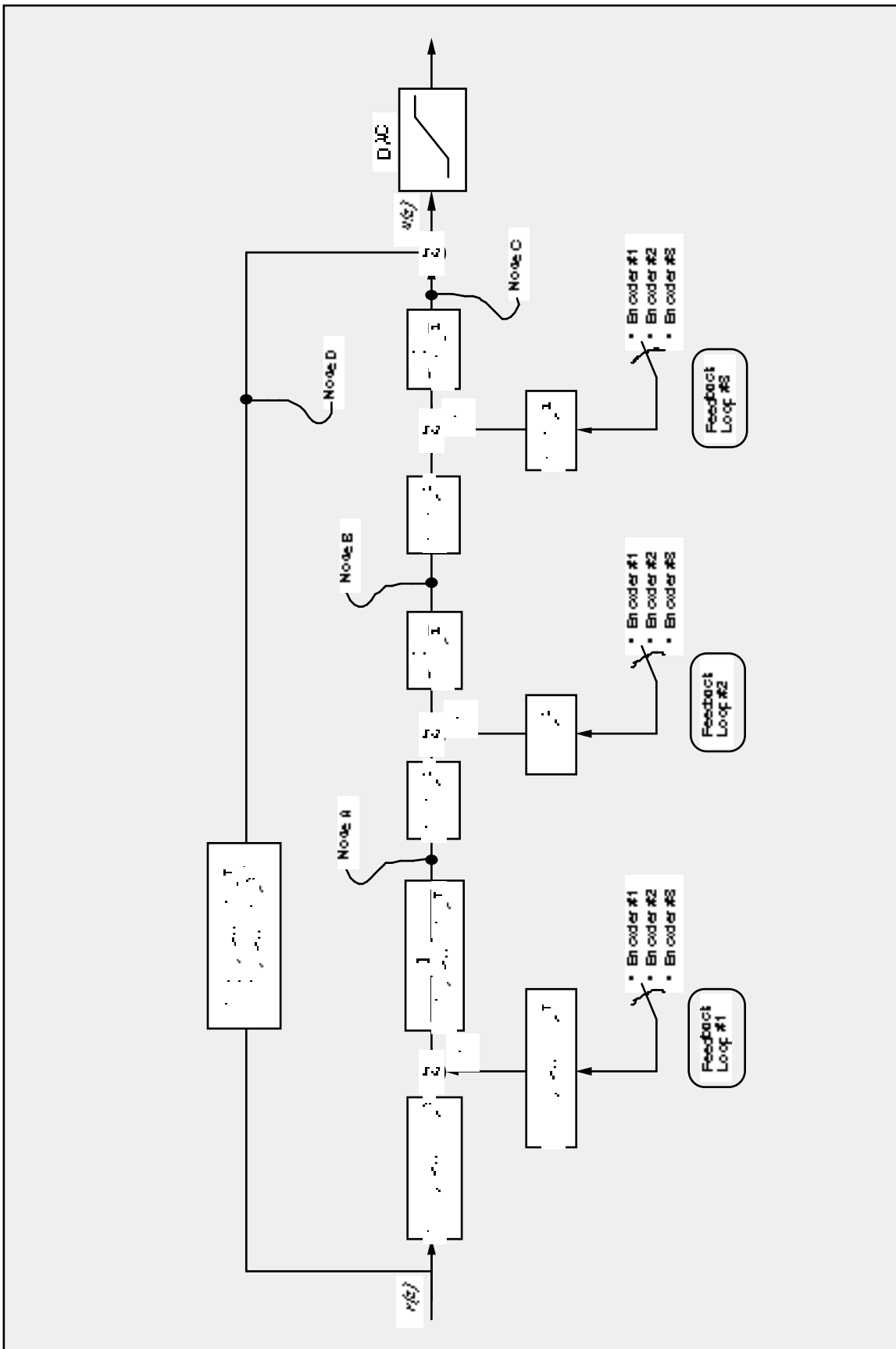


Figure 4.1-1. General Form Of The ECP Control Algorithm

of the overall control law equation which is stored in the memory and may be acquired by the user through the Data Acquisition feature of the Executive program. The variable $c_p(k)$ is the commanded position which is generated by the real-time Controller as described in the next section. The variable $f_{b1}(k)$ may be from any of the three possible feedback sensors depending on the state of software loop switch 1.

Next the intermediate loop is computed as follows

$$J(q^{-1}) * \text{nodeB}(k) = H(q^{-1}) * \text{nodeA}(k) - I(q^{-1}) * f_{b_2}(k)$$

Here again nodeB is an intermediate value stored in the memory and f_{b_2} is the sensor feedback selected via loop switch 2. J, H, and I are second order polynomials. For the inner loop we have

$$G(q^{-1}) * \text{nodeC}(k) = E(q^{-1}) * \text{nodeB}(k) - F(q^{-1}) * f_{b_3}(k)$$

NodeC is the contribution to the value of the control effort generated by the overall regulator and f_{b_3} is the sensor feedback selected via loop switch 3. G, E, and F are second order polynomials. For the feedforward loop we have

$$L(q^{-1}) * \text{nodeD}(k) = K(q^{-1}) * c_p(k)$$

In this case nodeD is the contribution to the value of the control effort generated by the feedforward terms, L and K are sixth order polynomials.

The combined regulatory and tracking controller generates the control effort as:

$$\text{control effort}(k) = \text{nodeC}(k) + \text{nodeD}(k)$$

The general control structure described above supports the implementation of a broad range of specific control forms.

4.2 Command Generation

Command generation is the real-time generation of motion trajectories specified by the user. The parameters of these trajectories are downloaded to the real-time Controller through the Executive program via the Trajectory Configuration dialog box. This section describes the trajectories generated in the current control version.

4.2.1 Step Move

Figure 4.2-1a shows a step move demand. The desired trajectory for such a move can be described by

$$\begin{aligned} c_p(t) &= c_p(0) + C && \text{for } t > 0 \\ c_v(t) &= 0 && \text{for } t > 0 \\ c_v(0) &= \infty \end{aligned}$$

Where $c_p(t)$ and $c_v(t)$ represent commanded position and velocity at time t respectively and C is the constant step amplitude. Such a move demand generates a strong impulsive torque from the control actuator. The response of a mechanical system connected to the actuator would depend on the dynamic characteristics of the controller and the system itself. However, in a step move, the instantaneous velocity and its derivatives are not directly controllable. Usually step moves are used only for test purposes; more gentle trajectories are nearly

always used for practical maneuvers.

4.2.2 Ramp Move

A ramp demand is seen in Figure 4.2-1b. The trajectory can be described by

$$\begin{aligned}c_p(t) &= c_p(0) + V * t && \text{for } t > 0 \\c_v(t) &= V && \text{for } t > 0 \\c_a(0) &= \infty\end{aligned}$$

where $c_a(0)$ represents commanded acceleration at time zero and V is a constant velocity. Relative to a step demand, a ramp demand is more gentle, however the acceleration is still impulsive. The commanded velocity is a known constant during the maneuver.

4.2.3 Parabolic Move

Figure 4.2-1c shows a parabolic move demand. Its trajectory can be expressed as:

$$\begin{aligned}c_p(t) &= c_p(0) + c_v(0) * t + 1/2 A * t^2 && \text{for } t > 0 < 1/2 t_f \\c_v(t) &= c_v(0) + A * t && \text{for } t > 0 < 1/2 t_f \\c_a(t) &= A && \text{for } t > 0 < 1/2 t_f \\c_j(0) &= \infty\end{aligned}$$

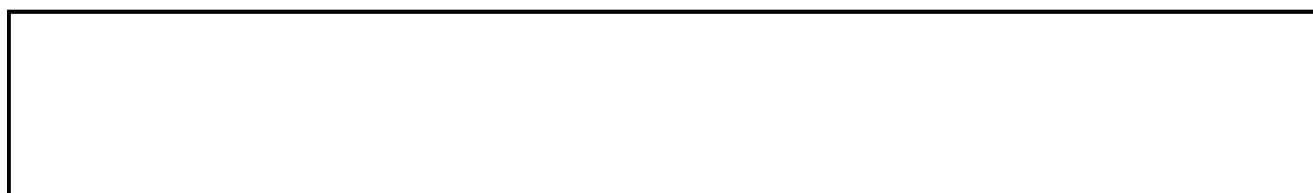
where $c_j(t)$ represents commanded jerk at time t and A is a constant acceleration, and t_f is the final destination time. Relative to a ramp demand, a parabolic demand is more gentle, however the rate of change of acceleration (jerk) is still impulsive. Note that the commanded acceleration is a known constant during the maneuver. The second half of a parabolic demand uses $-A$ for deceleration.

4.2.4 Cubic Move

Figure 4.2-1d shows a cubic demand which can be described by

$$\begin{aligned}c_p(t) &= c_p(0) + c_v(0) * t + 1/2 c_a(0) * t^2 + 1/6 J * t^3 && \text{for } t > 0 < 1/4 t_f \\c_v(t) &= c_v(0) + c_a(0) * t + 1/2 J * t^2 && \text{for } t > 0 < 1/4 t_f \\c_a(t) &= c_a(0) + J * t && \text{for } t > 0 < 1/4 t_f \\c_j(0) &= J\end{aligned}$$

where J represents a constant jerk. Relative to all the above demands, a cubic demand is more gentle. The commanded acceleration is linearly changing during the three sections of the maneuver. The second half of a cubic demand uses $-J$ and the third part uses J again for the jerk input.



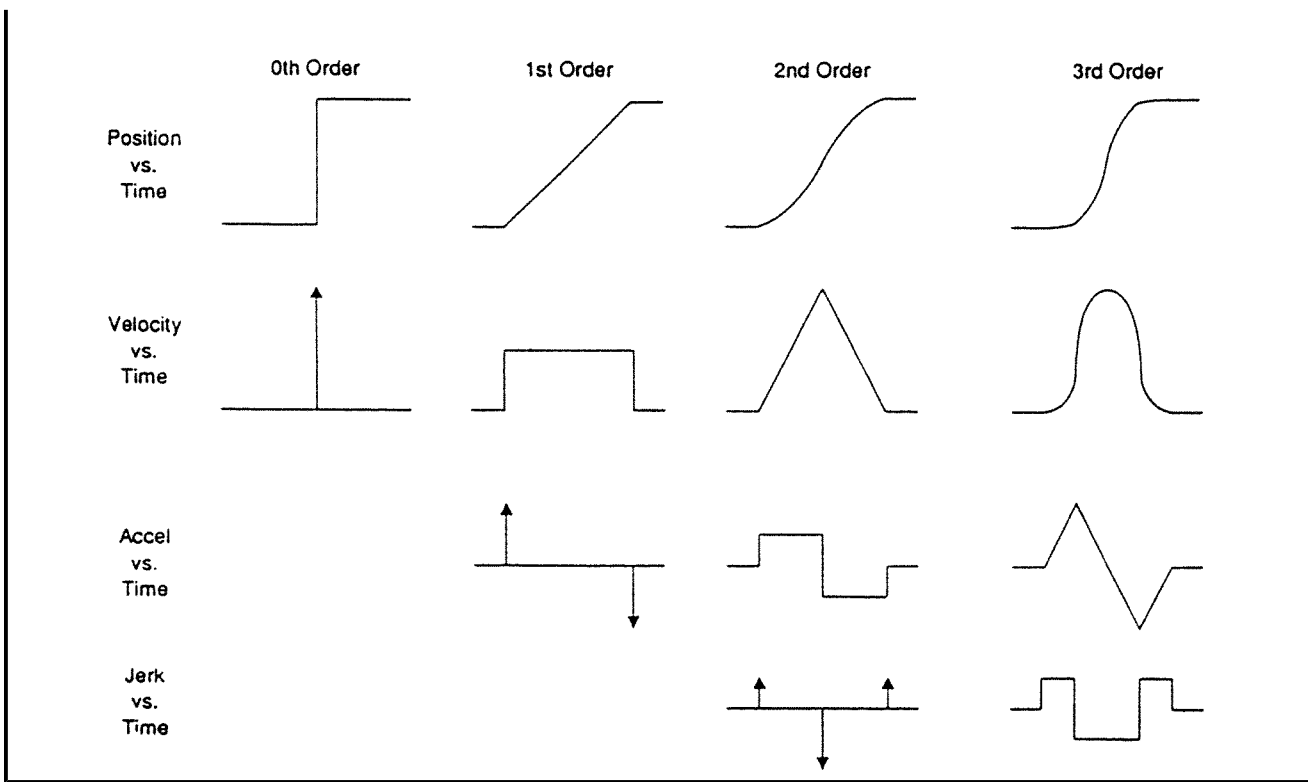


Figure 4.2-1. Geometric Command Trajectories Of Increasing Order

4.2.5 The Blended Move

Any time a ramp, a parabolic or a cubic trajectory move is demanded the real-time Controller executes a general blended move to produce the desired reference input to the control algorithm. The move is broken into five segments as shown in the velocity profile of Figure 4.2-2. For each section a cubic (in position) trajectory is planned. Five distinct cubic equations can describe the forward motion. After the dwell time, the reverse motion can be described by five more cubic trajectories. Each cubic has the form:

$$c_{p_i}(t) = c_{p_i}(0) + V_i * t + 1/2 A_i * t^2 + 1/6 J_i * t^3 \quad i = 1, \dots, 5$$

Using a known set of trajectory data (i.e. the requested total travel distance, acceleration time t_{acc} , and the maximum speed v_{max} , for each move), the constant coefficients V_i , A_i , and J_i are determined for each segment of the move by the real-time Controller. This function is known as the "motion planning" task. Note that for a parabolic profile $J_i=0$, and for a ramp profile A_i is also zero which further simplifies the task. Having determined the coefficients for each section, the real-time Controller uses these values at the servo loop sampling periods to update the commanded position (reference input). For example if the segment is a cubic ($J \neq 0$):

$$c_a(k) = c_a(k-1) + J * T_s$$

$$c_v(k) = c_v(k-1) + c_a(k) * T_s$$

$$c_p(k) = c_p(k-1) + c_v(k) * T_s$$

where T_s is the sampling period and $c_a(k)$, $c_v(k)$, $c_p(k)$ represent commanded acceleration, velocity and position at the k^{th} sampling period.

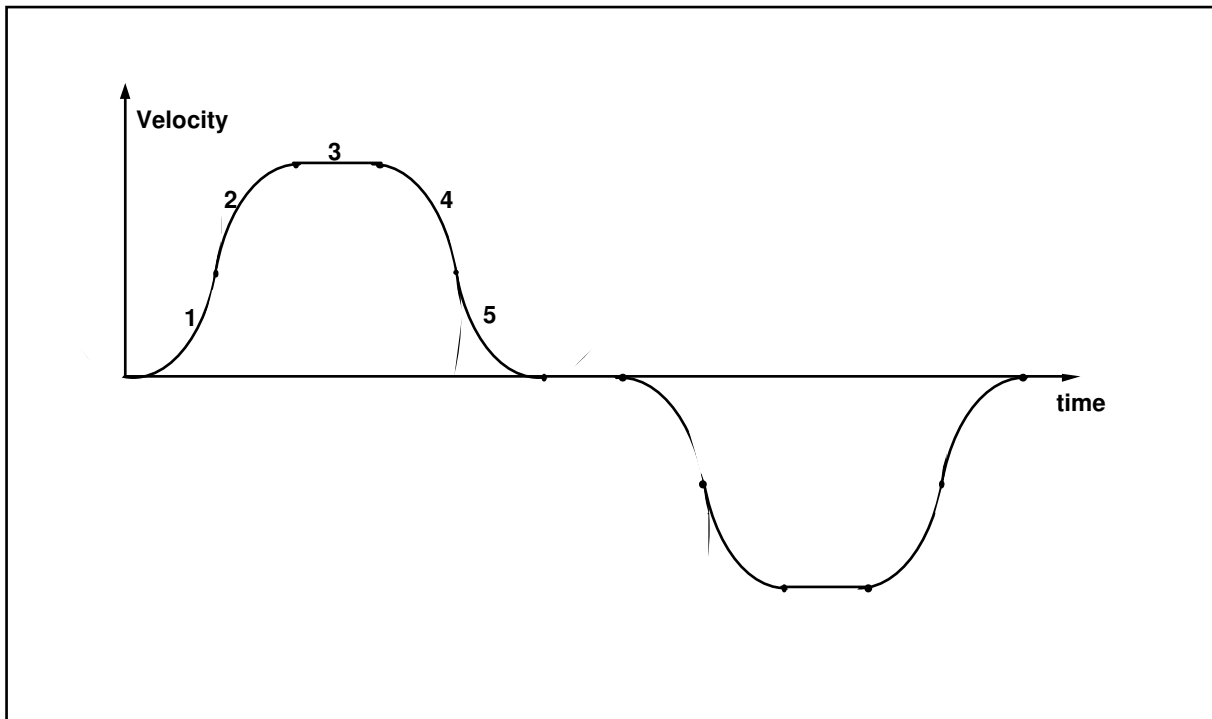


Figure 4.2-2 Velocity Profile for General Blended Move

4.2.6 Sinusoidal Move

The sinusoidal move is generated using the following equation:

$$c_p(k) = R * \sin(\theta(k))$$

where R is the amplitude, $\theta(k) = \omega * k * T_p$ for $k=0,1,\dots$, and ω is the commanded frequency in Hz. T_p is set to five milliseconds (i.e. k is incremented every 5 ms.). To further smooth out the trajectory, a cubic spline is fitted between the points as follows:

$$c_p'(k) = (c_p(k-1) + 4 * c_p(k) + c_p(k+1)) / 6$$

For the linear sine sweep, $\omega(k) = \alpha * T_p$, where α is a constant determined by the difference between the maximum and the minimum frequency divided by the sweep time

$$\alpha = (\omega_{\max} - \omega_{\min}) / \text{sweep time}$$

For the logarithmic sweep

$$\omega = \omega_{\min} * 10^{(B-A) * (k * T_p) / \text{sweep time}}$$

where A and B are defined according to

$$A \triangleq \log_{10}(\omega_{\min}), B \triangleq \log_{10}(\omega_{\max})$$

4.3 Brushless Motor Commutation and Torque Control

The main advantage of a DC brushless motor (otherwise known as a *permanent magnet synchronous* motor) over the conventional DC brush motor is the elimination of both brush friction associated wear.

Figure 4.3-1 shows a cross sectional view of a typical DC brushless motor. In contrast to the conventional DC brush motor, the permanent magnets are fixed to the rotor. The phase windings (typically 3 phases) are distributed in slots of the stator. This arrangement also provides for greater heat dissipation (i^2R), which in turn leads to improved life and typically greater volume-to-power ratios for brushless motors than for brush motors.

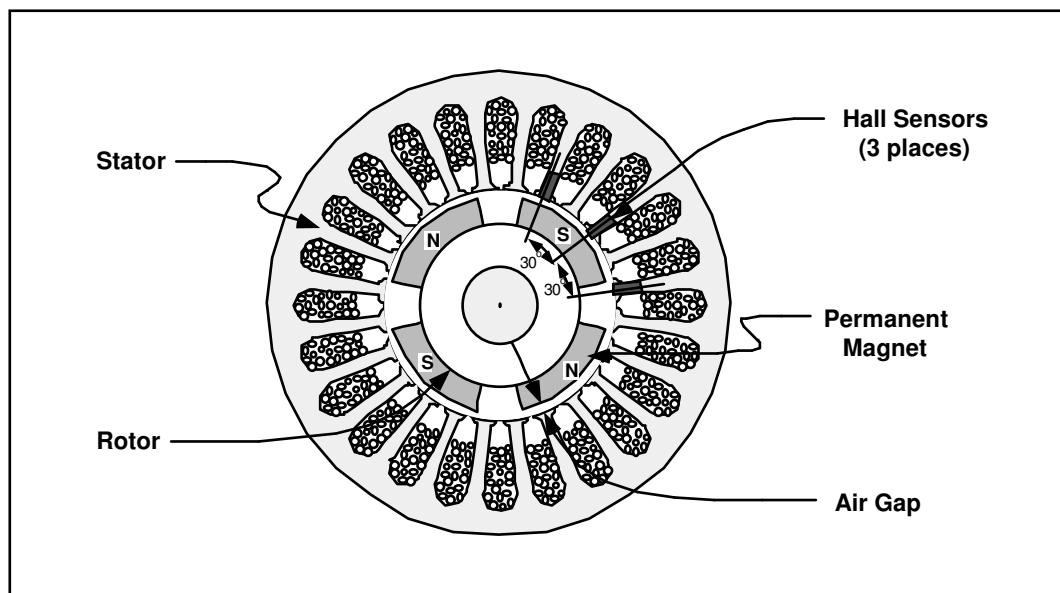


Figure 4.3-1. Cross-section of a Typical DC Brushless Motor. (Four pole type shown)

In any continuously rotating motor, to provide continuous torque the current must be successively altered or switched depending on the absolute position of the rotor. In a DC brush motor, this switching is implemented mechanically by the commutator. In a DC brushless motor, a rotor positioning sensor is used and the commutation procedure is done electronically. We will consider two different types of commutation procedures for DC permanent magnet brushless motors: rectangular and sinusoidal.

4.3.1 Rectangular (Hall-Effect) Commutation

Figure 4.3-2 shows a simplified schematic of the drive system(s) used in this mechanism. This is a typical drive scheme for a 4-pole 3-phase star-wound brushless motor with Hall-effect (rectangular) commutation. The three Hall-effect sensors are positioned on the stator. The sensed magnetic field switches between the adjacent north/south poles as the rotor rotates. This switching sequence is then used to direct the commanded motor current to individual winding phases (Figure 4.3-3). A simple electronic logic circuit is used for the generation of the switching steps (six steps per electrical cycle or 12 steps per mechanical cycle for a 4-pole motor). Analog high bandwidth *proportional plus integral* (PI) current feedback loops are then used on two of the three phases to assure almost instantaneous response of the actual winding current following any commanded current changes. The third phase does not require a current feedback loop because (as per Kirchoff's law) the current in the third phase is the negative of the sum of the current in the other two phases.

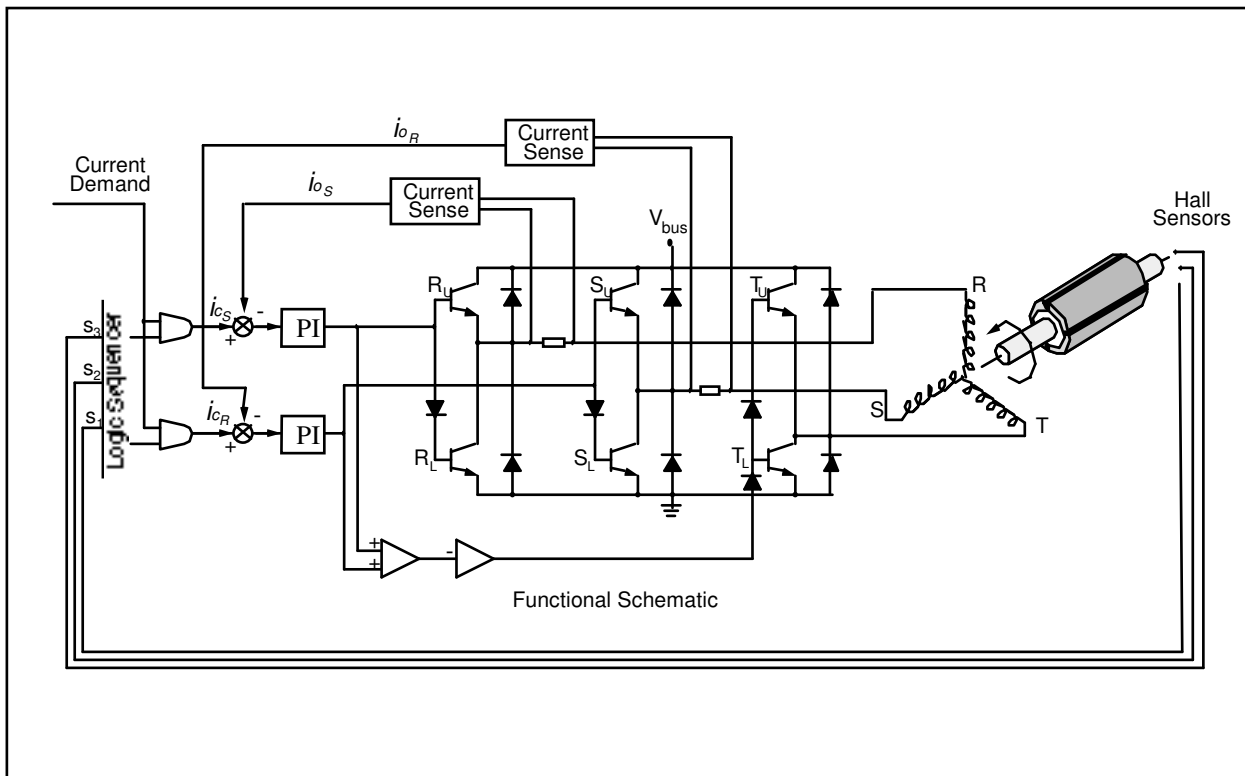


Figure 4.3-2 Simplified Schematic of Hall-effect Commutated DC Brushless Motor Drive System

We assume that, due to the relatively high bandwidth of the current loops, nearly instantaneous matching of the commanded current (torque) and the actual current occurs.^[26] With the rectangular drive scheme shown in Figure 4.3-3b, at any position only two of the three phases are operational so that the current in the third phase is zero. Consider a 60 electrical degree interval $0 \leq \theta \leq 60$. The torque input from phase R is

$$T_R = K_t I_R \sin\theta \quad (4.3-1)$$

and

$$I_R = -I_T \text{ with } I_S = 0$$

where $K_t = Z \cdot B_p \cdot r \cdot l$ is the torque constant per phase in N-m. Z is the number of turns per winding, r is the inside radius of the stator in meters, and l is the active length of conductors in meters. B_p is the peak air gap flux density in Teslas.

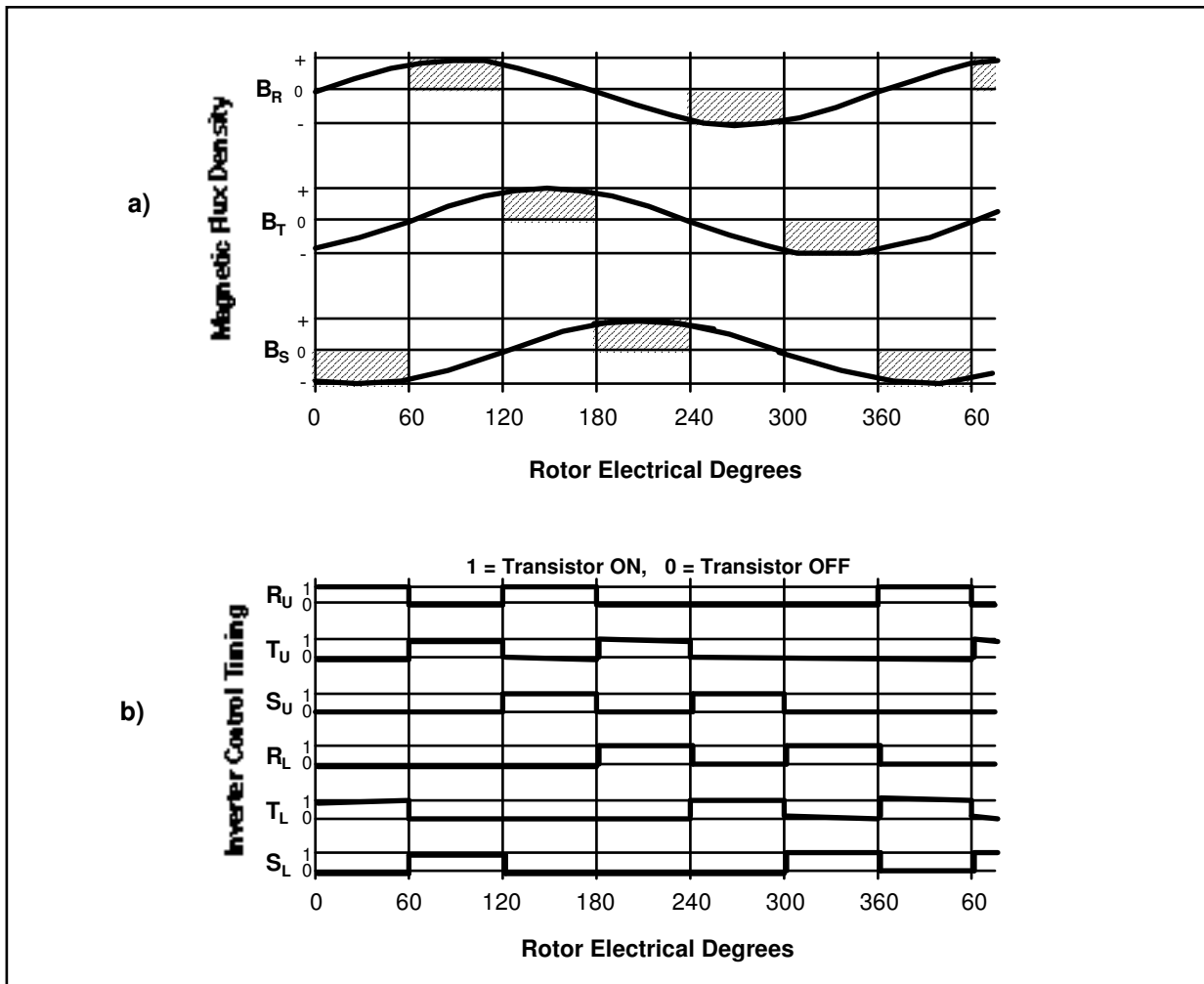


Figure 4.3-3 Hall-effect Commutation Timing Diagram

To produce positive torque, the flux density must be negative for phase T. This is the case for a sinusoidally wound motor (see Figure 4.3-3a):

$$\begin{aligned} T_T &= K_t I_R \sin(\theta+240) \\ &= K_t I_R (0.5\sin\theta+0.886\cos\theta) \quad \text{for } 0 \leq \theta \leq 60 \end{aligned} \quad (4.3-2)$$

The total torque is given by the addition of T_T and T_R over the interval $0 \leq \theta \leq 60$:

$$T = T_R + T_T = K_t (1.5\sin\theta + 0.886\cos\theta) \cdot I_R \quad (4.3-3)$$

Equation 4.3-3 shows that the effective torque constant, $K_t(1.5\sin\theta+0.886\cos\theta)$, changes as a function of rotor angle producing a torque ripple as much as 13% for rectangular commutation. This torque ripple can be treated

as a disturbance which, in most practical applications, is reduced by closing outer velocity and position loops around the current loop.

4.3.2 Sinusoidal Commutation

For a motor with sinusoidally wound stator coils the air gap flux densities are:

$$\begin{aligned} B_R &= B_p \sin \theta \\ B_S &= B_p \sin(\theta+120) \\ B_T &= B_p \sin(\theta+240) \end{aligned} \quad (4.3-4)$$

Where B_R , B_S , and B_T are the per phase flux densities for the motor phases R, S, and T respectively and B_p is the peak value in Tesla. If we assume that the PI controllers around the current loop maintain the phase currents in phase with the air gap flux densities, then the current in each phase in terms of the peak current I_p are given by

$$\begin{aligned} I_R &= I_p \sin \theta \\ I_S &= I_p \sin(\theta+120) \\ I_T &= I_p \sin(\theta+240) \end{aligned} \quad (4.3-5)$$

From equation 4.3-4 and 4.3-5, the instantaneous torque being produced in each phase is

$$\begin{aligned} T_R &= K_t I_p \sin^2 \theta \\ T_S &= K_t I_p \sin^2(\theta+120) \\ T_T &= K_t I_p \sin^2(\theta+240) \end{aligned} \quad (4.3-6)$$

The total torque is the sum of the above torque components, which is given by

$$\begin{aligned} T &= T_R + T_S + T_T \\ &= K_t I_p (\sin^2 \theta + \sin^2(\theta+120) + \sin^2(\theta+240)) \\ &= 3/2 K_t I_p^2 \end{aligned} \quad (4.3-7)$$

Equation 4.3-7 shows that "perfect" sinusoidal commutation of a "perfectly" sinusoidally wound motor provides for a ripple free torque constant. In practice, however, a small amount of torque ripple may exist due to imperfections in the windings and the current loop elements and misalignment of the rotor position sensor. Note that for this method of commutation, a high resolution absolute position sensor is required.

4.3.3 Proportional Plus Integral (PI) Current Loop

Each phase of the motor winding coil is characterized by its resistance R and its inductance L . If we assume that the per-phase back emf of motor is negligible in the high torque / low speed region of operation, then the block diagram shown in Figure 4.3-4 represents the per-phase PI loop for two of the three phases. (There is no need for PI loop on the third phase, as the sum of the total current must be zero in a star winding circuit).

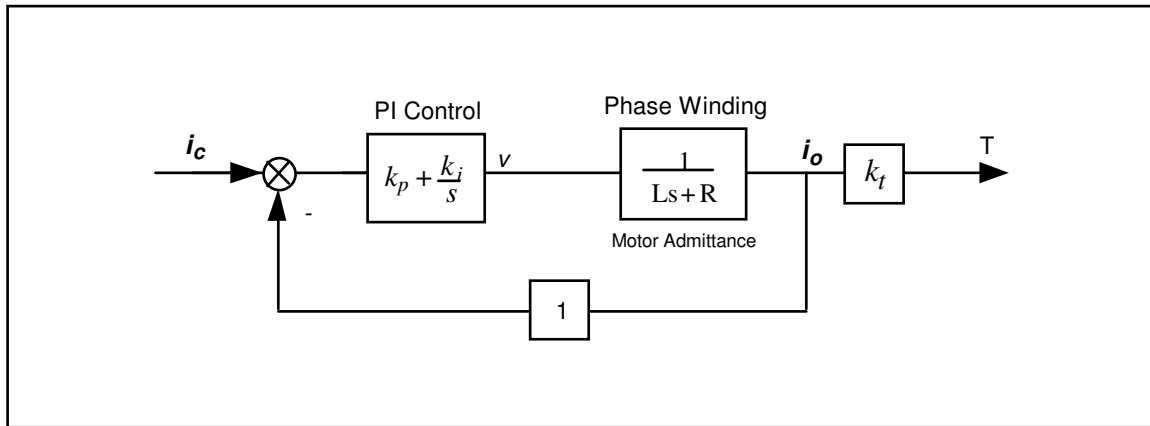


Figure 4.3-4 Simplified Block Diagram of Analog PI Controller (applies to each motor winding phase)

This is a second order system with the transfer function

$$\frac{i_o(s)}{i_c(s)} = \frac{(k_p/L)s + k_i/L}{s^2 + (R + k_p/L)s + k_i/L} \quad (4.3-8)$$

having natural frequency

$$\omega_n = \sqrt{\frac{k_i}{L}} \quad (4.3-9)$$

and damping ratio

$$\zeta = \frac{k_p + R}{2\sqrt{k_i L}} \quad (4.3-8)$$

By choosing the appropriate values for k_i and k_p , very high bandwidths for closed loop current (torque) response may be achieved (>500 Hz). In comparison to the achievable bandwidths for the outer velocity and/or position loops, the bandwidth of the current loop is generally about two orders of magnitude greater. This means that the current (torque) response is essentially instantaneous and therefore its dynamics may usually be ignored. Note also that the addition of the integrator has made this closed loop system a type one system. This, in turn, results in zero steady state error and a unity DC gain.

4.4 Multi-Tasking Environment

Digital control implementation is intimately coupled with the hardware and software that supports it. Nowhere is this more apparent than in the architecture and timing used to support the various data processing routines. A well prioritized time multi-tasking scheme is essential to maximizing the performance attainable from the processing resources.

The priority scheme for the ECP real-time Controller's multi-tasking environment is tabulated in Table 4.4-1. The highest priority task is the trajectory update and servo loop closure computation which takes place at the maximum rate of 1.131 KHz (minimum sampling period is 0.000884 seconds). In this case, the user may reduce the sampling rate through the Executive Program via changes to T_s in the Setup Control Algorithm dialog box.

The trajectory planning task has the third highest priority and is serviced at a maximum rate of 377 Hz. Here the parameters for a new trajectory need not be calculated every time this task is serviced by the real-time Controller. Whenever a new trajectory is required (i.e. the current trajectory is near its completion) this task is executed. The lower priority tasks are system house keeping routines including safety checks, interface and auxiliary analog output.

Table 4.4-1 The Multi-Tasking Priority Scheme of the Real-Time Controller

Priority	Task Description	Service Frequency
1	Servo Loop Closure & Command Update	1.1 KHz
2	Trajectory Planning	377 Hz
3	Background Tasks including User Interface, Auxiliary DAC Update, Limit checks etc.	Background (In time between other tasks)

The higher priority tasks always prevail over lower ones in obtaining the computational power of the DSP. This multi-tasking scheme is realized by a real-time clock which generates processor interrupts.

4.5 Sensors

There are two incremental rotary shaft encoders used in the Model 220. Each has a resolution of 4000 pulses per revolution. These encoders measure the incremental displacement of the motor and the load shaft.

The encoders are an optical type whose principle of operation is depicted in Figure 4.5-1. A low power light source is used to generate two 90 degrees out of phase sinusoidal signals on the detectors as the moving plate rotates with respect to the stationary plate. These signals are then squared up and amplified in order to generate quadrate logic level signals suitable for input to the programmable gate array on the real-time Controller. The gate array uses the A and B channel phasing to decode direction and detects the rising and falling edge of each to generate 4x resolution – see Figure 4.5-2.^[27] The pulses are accumulated continuously within 24-bit counters (hardware registers). The contents of the counters are read by the DSP once every servo (or commutation) cycle time and extended to 48-bit word length for high precision numerical processing. Thus the accumulation of encoder pulses provides an angular position measurement (signal) for the servo routines.

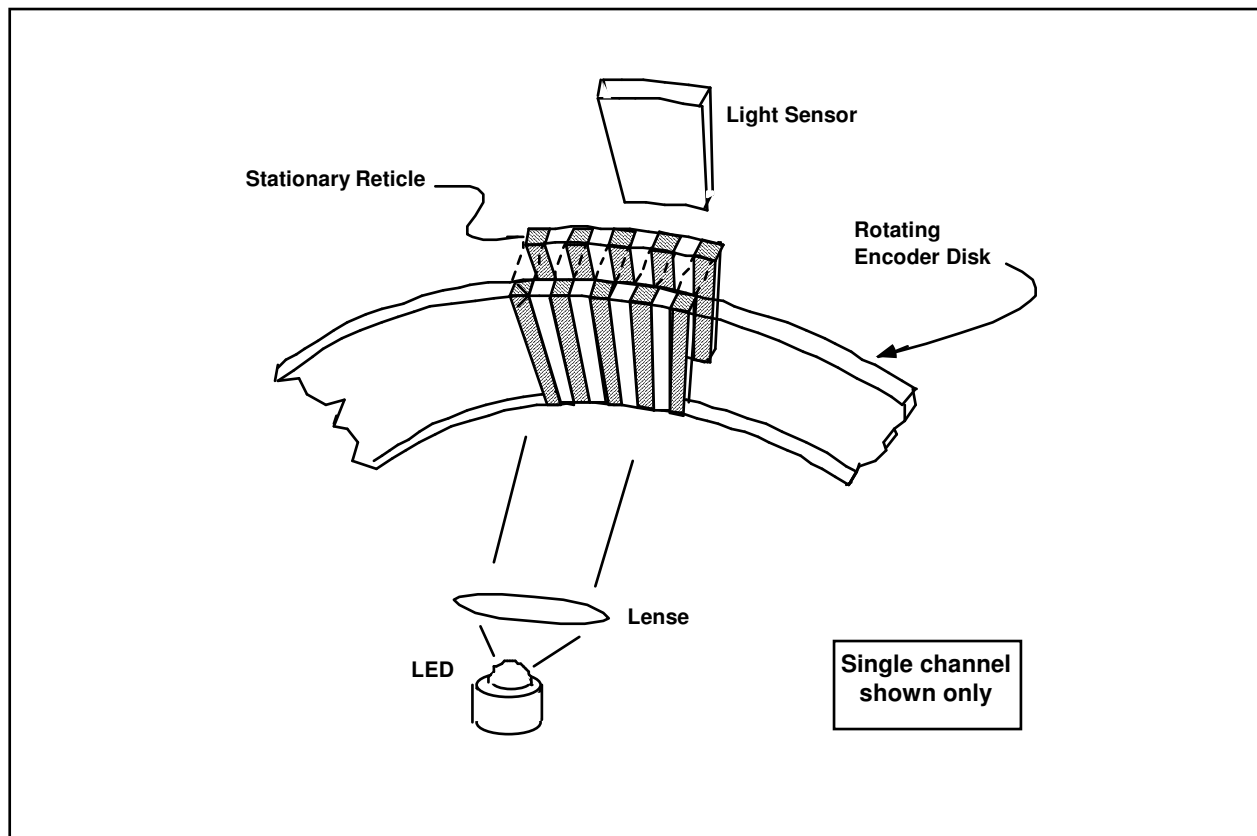


Figure 4.5-1 The Operation Principle of Optical Incremental Encoders

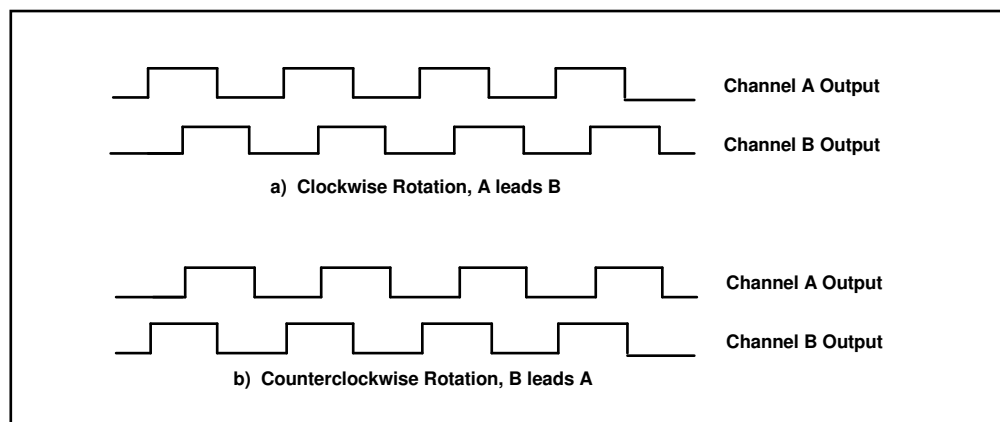


Figure 4.5-2. Optical Encoder Output

4.6 Auxiliary Analog Output (System Option)

A system option provides two analog output channels in the Control Box which are connected to two 16-bit DACs which physically reside on the real-time Controller. Each analog output has the range of ± 10 volts (-32768 to $+32767$ counts) with respect to the analog ground. The outputs on these DACs are updated by the real-time Controller as a low priority task. However, for virtually all trajectories (e.g. for sine sweep up to approx. 25 Hz) the update rate is sufficiently fast for an oscilloscope or other analog equipment to inspect the various internal Controller signals. See the section on the Executive Program's Utility menu for the available signals to output on these DACs.

5. Plant Dynamic Models

This Chapter provides time and Laplace domain expressions which are useful for linear control implementation and are used in the experiments described later in this manual.

5.1 Rigid Body Plant

5.1.1 Basic Speed Ratio Effects

By inspection of Figure 5.1-1, the overall drive train gear ratio, gr , is such that $\theta_1 = gr\theta_2$, i.e.:^[28]

$$gr = \frac{r_p r_{p1}}{r_d r_2} \quad (5.1-1)$$

We shall refer to the partial gear ratio between the idler pulley assembly and the drive disk gr' , i.e.:

$$gr' = r_{p1}/r_d \quad (5.1-2)$$

so that $\theta_1 = gr'\theta_p$.

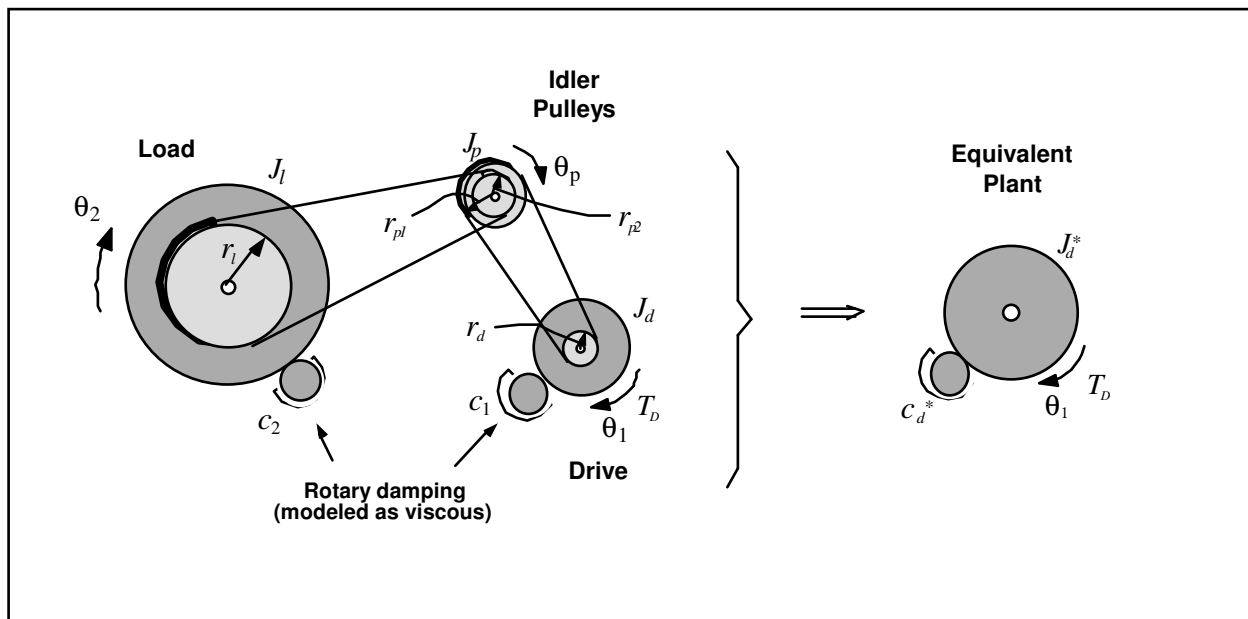


Figure 5.1-1. Rigid Body Plant Model

If we call the torque acting on the load T_l , and equate this to the portion of the drive torque acting on the load, T_{Dl} , we have:

$$T_l = gr T_{Dl} \quad (5.1-3)$$

so that from

$$T_l = J_l \ddot{\theta}_l \quad (5.1-4)$$

we have

$$gr T_{Dl} = J_l \ddot{\theta}_l = J_l gr^2 \ddot{\theta}_d \rightarrow T_{Dl} = J_{lr} \ddot{\theta}_d \quad (5.1-5)$$

where

$$J_{lr} = J_l gr^2 \quad (5.1-6)$$

is the load inertia *reflected* to the drive or input.

The same squared scaling of inertia with speed ratio between elements holds in general. The drive inertia reflected to the load location, for example, is $J_{dr} = J_d gr^2$. We may then express for Figure 5.1-1:

$$J_d^* = J_d + J_p gr^2 + J_l gr^2 \quad (5.1-7)$$

and

$$J_l^* = J_d gr^2 + J_p (gr/gr)^2 + J_l \quad (5.1-8)$$

where J_d^* and J_l^* are the total inertias reflected to the drive and load respectively.

Similarly for the friction coefficients it may be shown that^[29]

$$c_d^* = c_1 + c_2 gr^2 \quad (5.1-9)$$

and

$$c_l^* = c_1 gr^2 + c_2 \quad (5.1-10)$$

where c_d^* and c_l^* are the total reflected friction constants at the drive and load.

5.1.2 Rigid Body Dynamics

For many applications involving servo drives, non-ideal effects such as drive flexibility, backlash, static and kinetic friction, and other nonlinearities are sufficiently small that the plant may be modeled as a simple rigid body obeying Newton's second law. That is, modeling friction effects as being viscous, from Figure 5.1-1 we may express:

$$J_d^* \ddot{\theta}_1 + c_d^* \dot{\theta}_1 = T_D \quad (5.1-11)$$

or:

$$J_l^* \ddot{\theta}_2 + c_l^* \dot{\theta}_2 = grT_D \quad (5.1-12)$$

which have the Laplace transforms:

$$\frac{\theta_1(s)}{T_D(s)} = \frac{1}{s(J_d^* s + c_d^*)} \quad (5.1-13)$$

$$\frac{\theta_2(s)}{T_D(s)} = \frac{gr}{s(J_l^* s + c_l^*)} \quad (5.1-14)$$

When friction may be neglected these reduce further to

$$J_d^* \ddot{\theta}_1 = T_D \quad (5.1-15)$$

$$J_l^* \ddot{\theta}_2 = grT_D \quad (5.1-16)$$

$$\frac{\theta_1(s)}{T_D(s)} = \frac{1}{J_d^* s^2} \quad (5.1-17)$$

$$\frac{\theta_2(s)}{T_D(s)} = \frac{gr}{J_l^* s^2} \quad (5.1-18)$$

5.2 Flexible Drive Dynamics

5.2.1 Equations Of Motion

An approximation of the emulator plant with flexibility in the drive train is shown in Figure A-1a . Using the free body diagram of Figure 5.2-1b and summing torques acting on J_l we have via Newton's second law (in its rotational form)^[30]

$$(F_1 - F_2)r_l - c_2 \dot{\theta}_2 = J_l \ddot{\theta}_2 \tag{5.2-1}$$

or

$$J_l \ddot{\theta}_2 + c_2 \dot{\theta}_2 + 2k_L(r_l \theta_2 - r_{p2} \theta_p)r_l = 0 \tag{5.2-2}$$

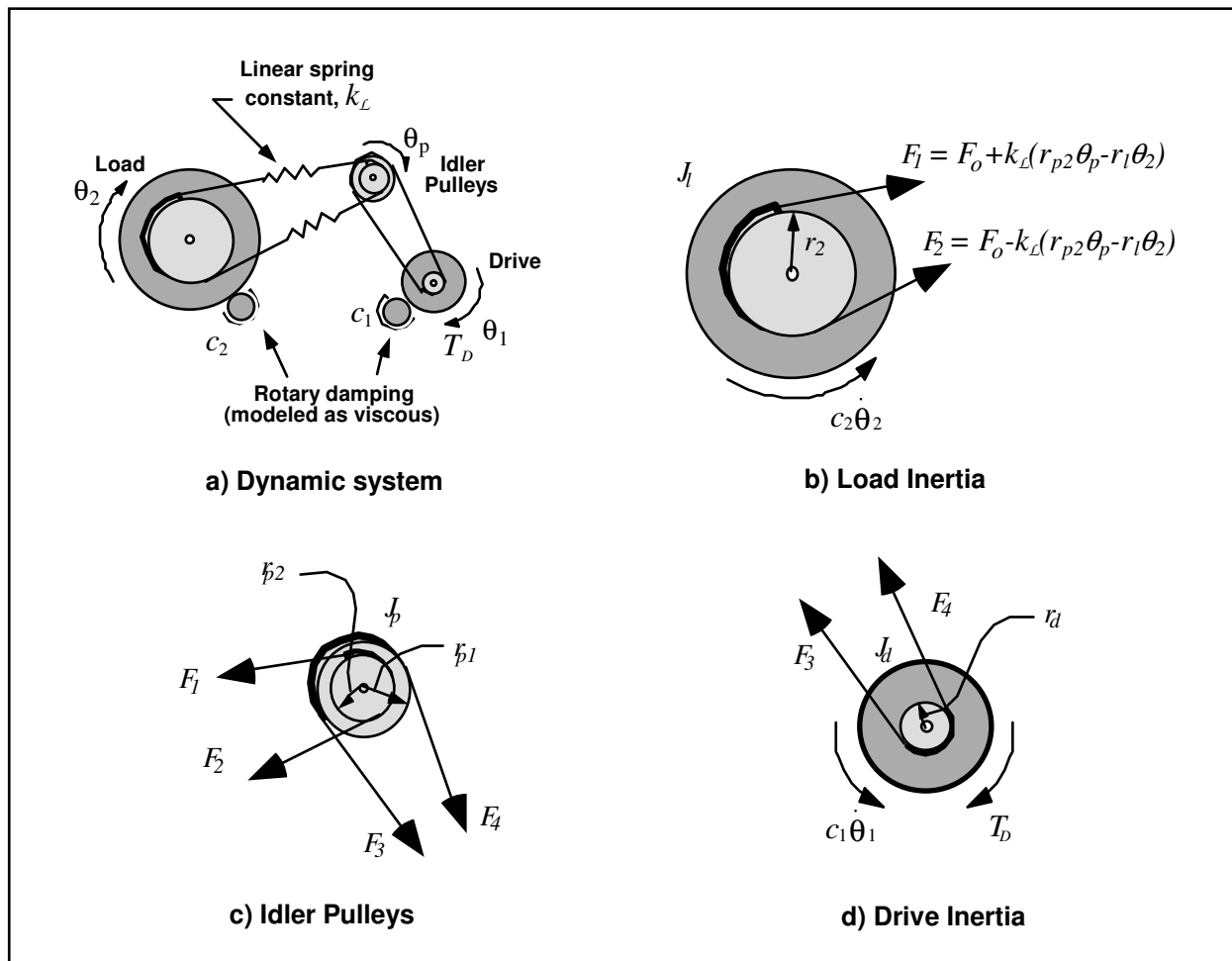


Figure 5.2-1.

Plant Description And Free Body Diagrams For Dynamics Modeling

By defining a torsional (or rotary) spring constant

$$k \triangleq 2k_L r_l^2 \tag{5.2-3}$$

Eq.(5.2-2) becomes:

$$J_l \ddot{\theta}_2 + c_2 \dot{\theta}_2 + k(\theta_2 - r_{p2}/r_l \theta_p) = 0 \tag{5.2-4}$$

For the idler (Fig. 5.2-1c) we have:

$$(F_2-F_1)r_{p2} + (F_4-F_3)r_{p1} = J_p \ddot{\theta}_p \quad (5.2-5)$$

or:

$$\begin{aligned} (F_4-F_3)r_{p1} &= J_p \ddot{\theta}_p + 2k_L(F_1-F_2)r_{p2} \\ &= J_p \ddot{\theta}_p + 2k_L(r_{p2}\theta_p - r_l\theta_2)r_{p2} \end{aligned} \quad (5.2-6)$$

For the drive inertia:

$$T_D + (F_3-F_4)r_d - c_1 \dot{\theta}_1 = J_d \ddot{\theta}_1 \quad (5.2-7)$$

which combines with (5.2-6) as:

$$T_D - \frac{r_d}{r_{p1}} \left(J_p \ddot{\theta}_p + 2k_L(r_{p2}\theta_p - r_l\theta_2)r_{p2} \right) - c_1 \dot{\theta}_1 = J_d \ddot{\theta}_1 \quad (5.2-8)$$

Using (5.1-2 and 5.2-3) we have

$$(J_d + gr^2 J_p) \ddot{\theta}_1 + c_1 \dot{\theta}_1 + k(r_{p2}\theta_p - r_l\theta_2) \frac{r_d r_{p2}}{r_{p1} r_l^2} = T_D \quad (5.2-9)$$

Finally, by defining

$$J_d^* \triangleq J_d + gr^2 J_p \quad (5.2-10)$$

equations (5.2-9, -4) yield, with obvious substitution, the desired equations of motion in two coordinates:

$$J_d^* \ddot{\theta}_1 + c_1 \dot{\theta}_1 + k(gr^2 \theta_1 - gr^1 \theta_2) = T_D \quad (5.2-11)$$

$$J_l \ddot{\theta}_2 + c_2 \dot{\theta}_2 + k(\theta_2 - gr^{-1} \theta_1) = 0 \quad (5.2-12)$$

In matrix notation we may express:

$$\mathbf{J} \ddot{\boldsymbol{\theta}} + \mathbf{c} \dot{\boldsymbol{\theta}} + \mathbf{k} \boldsymbol{\theta} = \mathbf{T} \quad (5.2-13)$$

where

$$\begin{aligned} \boldsymbol{\theta} &= \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}, \quad \mathbf{J} = \begin{bmatrix} J_d^* & 0 \\ 0 & J_l \end{bmatrix}, \quad \mathbf{c} = \begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix}, \\ \mathbf{k} &= k \begin{bmatrix} gr^2 & gr^1 \\ gr^1 & 1 \end{bmatrix}, \quad \mathbf{T} = \begin{bmatrix} T_D \\ 0 \end{bmatrix} \end{aligned} \quad (5.2-14)$$

5.2.2 State Space Realization

A state space realization which is useful in several control approaches to this system follows directly from Eq 5.2-13. i.e.:

$$\begin{aligned} \dot{x} &= Ax + BT(t) \\ Y &= Cx \end{aligned} \quad (5.2-15)$$

where:

$$\mathbf{X} = \begin{bmatrix} \theta_1 \\ \dot{\theta}_1 \\ \theta_2 \\ \dot{\theta}_2 \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -kgr^2/J_d^* & -c_1/J_d^* & kgr^1/J_d^* & 0 \\ 0 & 0 & 0 & 1 \\ kgr^1/J_l & 0 & -k/J_l & -c_2/J_l \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ 1/J_d^* \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} C_1 & 0 & 0 & 0 \\ 0 & C_2 & 0 & 0 \\ 0 & 0 & C_3 & 0 \\ 0 & 0 & 0 & C_4 \end{bmatrix}$$

and $C_i = 1$ ($i=1,2,3,4$) when X_i is an output and equals 0 otherwise.

5.2.3 Transfer Functions

From the Laplace transform of Eq's(A.2-8,9) we have:

$$\frac{\theta_1(s)}{T_D(s)} = \frac{J_l s^2 + c_2 s + k}{D(s)} \quad (5.2-16)$$

$$\frac{\theta_2(s)}{T_D(s)} = \frac{k/gr}{D(s)} \quad (5.2-17)$$

where:

$$D(s) = J_d^* J_l s^4 + (J_d^* c_2 + J_l c_1) s^3 + (J_d^* k + J_l gr^2 k + c_1 c_2) s^2 + (c_1 k + c_2 gr^2 k) s \quad (5.2-18)$$

The above models are useful when the plant parameters J_x , k_x & c_x are known or are measurable explicitly. In many cases, the plant is identified via its natural frequencies, damping ratios, and gains. The above transfer function types may also be expressed in the form:

$$\frac{\theta_1(s)}{T(s)} = \frac{K_1 (s^2 + 2\zeta_z \omega_z s + \omega_z^2)}{s(s+c^*) (s^2 + 2\zeta_p \omega_p s + \omega_p^2)} \quad (5.2-19)$$

$$\frac{\theta_2(s)}{T(s)} = \frac{K_2}{s(s+c^*) (s^2 + 2\zeta_p \omega_p s + \omega_p^2)} \quad (5.2-20)$$

where the gains K_1 & K_2 , are nominally equal to $1/J_d^*$ and $k/(grJ_d^* J_l)$ respectively (but may be measured more

directly in some cases). The coefficient c^* is nominally equal to $c/(J_d^* + J_l)$ where c is the damping (modeled as viscous) associated with the scaled rigid body mode (i.e. the mode where the rotating members move uniformly without oscillatory motion).

Measurement of parameters to establish the explicit plant transfer functions for the Model 220 plant is covered in Section 6.1 of this manual.

5.2.4 Damping In Flexible Drive

In systems where the flexible element contains a significant fraction of the plant damping, it may be useful to include this damping in the plant model. An example of where such damping may arise is when the flexible element is a drive belt^[31] such as the one in the Model 220 apparatus employed specifically to impart drive flexibility. Figure 5.2-1 depicts the approximation used to derive the dynamic model.

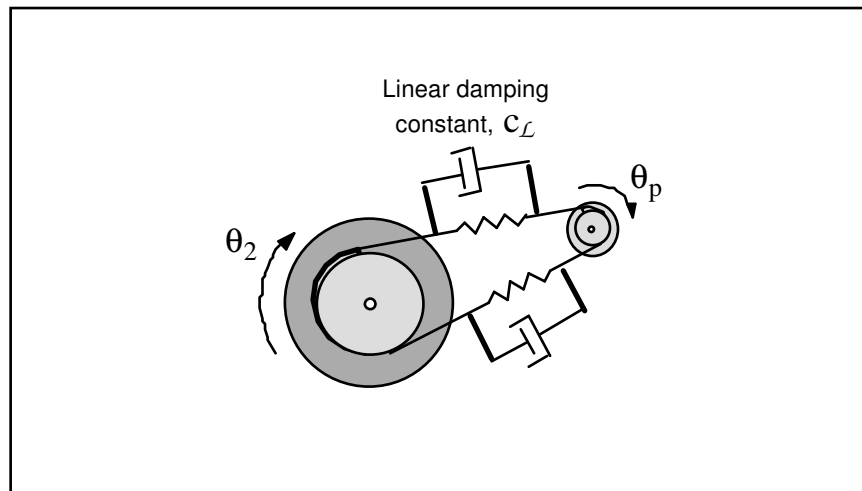


Figure 5.2-1. Model of Flexible Drive Damping

By performing the dynamic analysis according to the steps in Section 5.2.1 and defining

$$c_{12} \triangleq 2c_L r_l^2 \quad (5.2-21)$$

The following equations of motion are obtained.

$$J_d^* \ddot{\theta}_1 + (c_1 + gr^2 c_{12}) \dot{\theta}_1 - gr^{-1} c_{12} \dot{\theta}_2 + k (gr^2 \theta_1 - gr^{-1} \theta_2) = T_D \quad (5.2-22)$$

$$J_l \ddot{\theta}_2 + (c_2 + c_{12}) \dot{\theta}_2 - gr^{-1} c_{12} \dot{\theta}_1 + k (\theta_2 - gr^{-1} \theta_1) = 0 \quad (5.2-23)$$

Which have the state space realization form of Eq.(5.2-15) with

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -kg r^2 / J_d^* & -(c_1 + c_{12} g r^2) / J_d^* & kg r^1 / J_d^* & c_{12} g r^1 / J_d^* \\ 0 & 0 & 0 & 1 \\ kg r^1 / J_l & c_{12} g r^1 / J_l & -k / J_l & -(c_2 + c_{12}) / J_l \end{bmatrix} \quad (5.2-24)$$

and all else unchanged.

The transfer functions become.

$$\frac{\theta_1(s)}{T_D(s)} = \frac{J_1 s^2 + (c_2 + c_{12})s + k}{D(s)} \quad (5.2-25)$$

$$\frac{\theta_2(s)}{T_D(s)} = \frac{(k + c_{12})/gr}{D(s)} \quad (5.2-26)$$

where

$$D(s) = J_d^* J_1 s^4 + (J_d^* (c_2 + c_{12}) + J_1 (c_1 + c_{12} gr^2)) s^3 + (J_d^* k + J_1 gr^2 k + c_1 c_2 + c_1 c_{12} + c_{12} c_2 gr^2) s^2 + (c_1 k + c_2 gr^2 k) s \quad (5.2-27)$$

The inclusion of the coupled friction c_{12} , is not necessary in many practical applications. It does render better agreement between simulation and system test results however when it is included in the dynamic model of the Model 220 apparatus.

-
- [1] The system is also available in a PC bus installation form in which the DSP based real-time controller resides in the PC and all other control unit hardware remains in a separate box. This form has faster PC/controller communication rates. (Controller speed is unaffected.)
- [2] A faster computer, such as a ≥ 66 Mhz 486 with the real-time controller on the PC bus provides a much more expeditious working environment than a 386 or 286 and/or RS232 controller/PC communication. Real-time control speed, however, is unaffected.
- [3] Its fastest to simply double-click on the desired file.
- [4] For many designs, the value $T_s = .00442$ sec is a good midpoint between the spatial quantization induced noise associated with rate derivation over small sample periods and the phase lag associated with large ones.
- [5] An often used rule of thumb is that the continuous time approximation of sampled data systems is acceptably accurate if the sampling frequency is at least 10 times the system bandwidth. (This rule is not always conservative however, see Section 6.3.5 & 6.3.5i). Since the attainable closed loop bandwidths for the system are generally less than 10 Hz, sampling rates above 100 Hz usually provide results that are indistinguishable between equivalent continuous and discrete controller designs. I.e. for sampling rates above 100 Hz, the user may generally design and specify the controller in continuous time with no measurable difference in system behavior than if the controller were designed in discrete time.
- [6] Note that in previewing the discrete generalized form of a continuous controller you should select Discrete Time , General Form, then Setup Algorithm. If instead the sequence Discrete Time, Preview In General Form, is used, then the selected discrete time algorithm (the one with the red dot next to it and which will not generally contain parameters that correspond to the continuous time design) will be previewed. Subsequent "Implementing" will then download the wrong design.
- [7] You may notice the term r_1 in the Continuous Time General Form has a default value 0.0000002 whenever PD, PID, PID+ Notch, or State Feedback are selected. (in this case you would enter the General Form via the Preview In General Form button). This adds a pole at very high frequency and is of no practical consequence to system stability or performance. It is necessary to make the S(s)/R(s) and T(s)/R(s) blocks proper when implementing the differentiator terms in the above mentioned control forms.
- [8] This format may be produced in Matlab® using the `fprintf` function.
- [9] The system contains safeguards to prevent unsafe operations in most cases. If a hardware or software limit is exceeded, the Controller Status display on the Background Screen will indicate Limit Exceeded. In this event, the user should Reset Controller (Utility menu), and re-Implement (Command menu) using an appropriate (safe) set of control coefficients.
- [10] The software is set to saturate control effort at ± 5 V. If this amplitude is exceeded, the input shape amplitudes or accelerations as appropriate should be reduced.
- [11] If the specified "impulse" duration becomes long enough, the resulting torque becomes more step-like than impulsive. Thus the Setup Impulse dialog box may also be used for Step input shapes where the dwell (zero excitation) period may be specified independently of the step duration.
- [12] Sweeping through resonances is very useful in visualizing the frequency response dynamics, but must be done at a sufficiently low input amplitude. When viewing open loop sine sweep results, it is often best to view velocity rather than position data to reduce position drift effects. By selecting a relatively long sweep period, the transient effects of frequency change are minimized and the true frequency response is best approximated.
- [13] The bracketed rows end in semicolons so that the entire file may be read as an array in Matlab by running it as a script once the header is stripped i.e. the script should be: `<array name>= [exported data file]`. Variable values over time are the columns of this array; the rows are the variable value set at successive sample numbers.
- [14] In some cases, you will need to "drag" the Executing Input Shape box out of the way to see the plot during the maneuver. This is practical for longer duration maneuvers.
- [15] Either a "rigid" or flexible belt may be used between the SR assembly and the load disk.
- [16] 4000 lines per revolution with 4X hardware interpolation provide 16,000 count per rev. resolution for control.
- [17] See Chapter 4 for a description of component functionality (e.g. actuators and sensors) and I/O processing (e.g. motor commutation and encoder pulse counting)
- [18] We apply the term "gear ratio" due to its common usage even though the speed reduction is effected by pulleys and belts.
- [19] Precise measurement of the force is not necessary.
- [20] If the flexible belt is found to slip during later testing, the SR assembly may be positioned further from the load disk to increase the flexible belt tension.
- [21] Note here that 1 disk revolution = 16,000 encoder counts.
- [22] This is approximately the torque produced by two 0.5 kg brass weights at a 10 cm radius under the force of gravity when the mechanism is placed in the disk-vertical position. The two weights should be horizontally oriented from the load disk axle.
- [23] While there are safety checks embedded in the control software, it is bad practice to leave the motor stalled or with significant steady state load such as that required to overcome high friction. ECP is not responsible for equipment failures resulting from excessive brake friction.
- [24] The majority of this section (2.3.1) pertains to the PC bus installation of the real-time controller. For the controller box/RS-232 version, the control box should generally be powered on before entering the executive software.
- [25] This applies to the PC-bus installation only. For the controller in the Control Box, the RS-232 cable must be connected between the Control Box and the PC.

^[26]We qualify the validity of this assumption later when we discuss the PI current loops.

^[27]I.e. the disk encoder resolution effectively becomes 16,000 counts per revolution.

^[28]Although the our mechanism does not use gears, we use the term "gear ratio" to refer to speed reduction because of its common usage in practice.

^[29]In this model we neglect the bearing friction at the speed reduction idler shaft.

^[30]The term F_o in Figure 5.2-1 is the static tension in the flexible belt. It is assumed that this value is never exceeded during dynamic motion (i.e. that no section of the belt becomes slack).

^[31]Metallic drive elements on the other hand typically have very low material damping and this added model complexity would be of no value.