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. Shown in Figure 1.1-1, each consists of an electromechanical plant and a full complement of control hardware and software. The user interface to the system is via a friendly, versatile, 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 210 spring/mass apparatus represents many such physical plants including rigid bodies; flexibility in linear drives, gearing and belts; and coupled discrete vibration with actuator at the drive input and sensor collocated or at flexibly coupled output (noncollocated). Thus the plant models may range from a simple double integrator to a fourth order[1] case with two lightly damped poles and either two or no zeros.

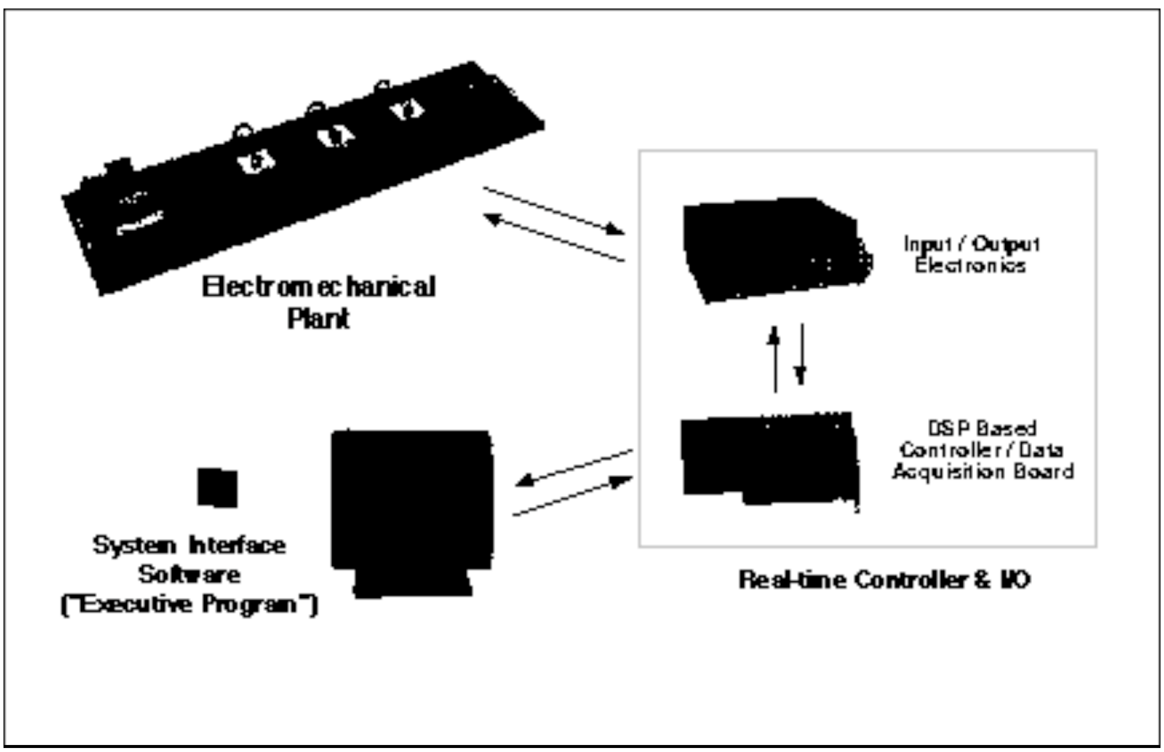

Figure 1.1-1. The Experimental Control System

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[1] For Model 210a the model order may be as high as six with either four, two, or no zeros.

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 spring/mass mechanism, its actuator and sensors. The design features a brushless DC servo motor, high resolution encoders, adjustable masses, and reconfigurable plant type.

Next is the real-time controller unit which contains the digital signal processor (DSP) based real-time controller[1], servo/actuator interfaces, servo amplifier, and auxiliary power supplies. The DSP is capable of executing control laws at high sampling rates allowing the implementation to be modeled as being continuous or discrete in 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.

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] 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.)

2.2 Electromechanical Plant

2.2.1 Design Description

The mechanism shown in Figure 2.2-1 is designed to emulate a broad range of real-world applications including 1 DOF rigid bodies, flexibility in linear drives, gearing and belts, and other coupled discrete oscillatory systems. The apparatus, shown in Figure 2.2-1, consists of two (Model 210) or three (Model 210a) mass carriages interconnected by bi-directional springs. The mass carriage suspension is an anti-friction ball bearing type with approximately ± 3 cm of available travel. The linear drive is comprised of a gear rack suspended on an anti-friction carriage and pinion (pitch dia. 7.62 cm (3.00 in)) coupled to the brushless servo motor shaft. Optical encoders measure the mass carriage positions – also via a rack and pinion with pinion pitch dia 3.18 cm (1.25 in)[1].

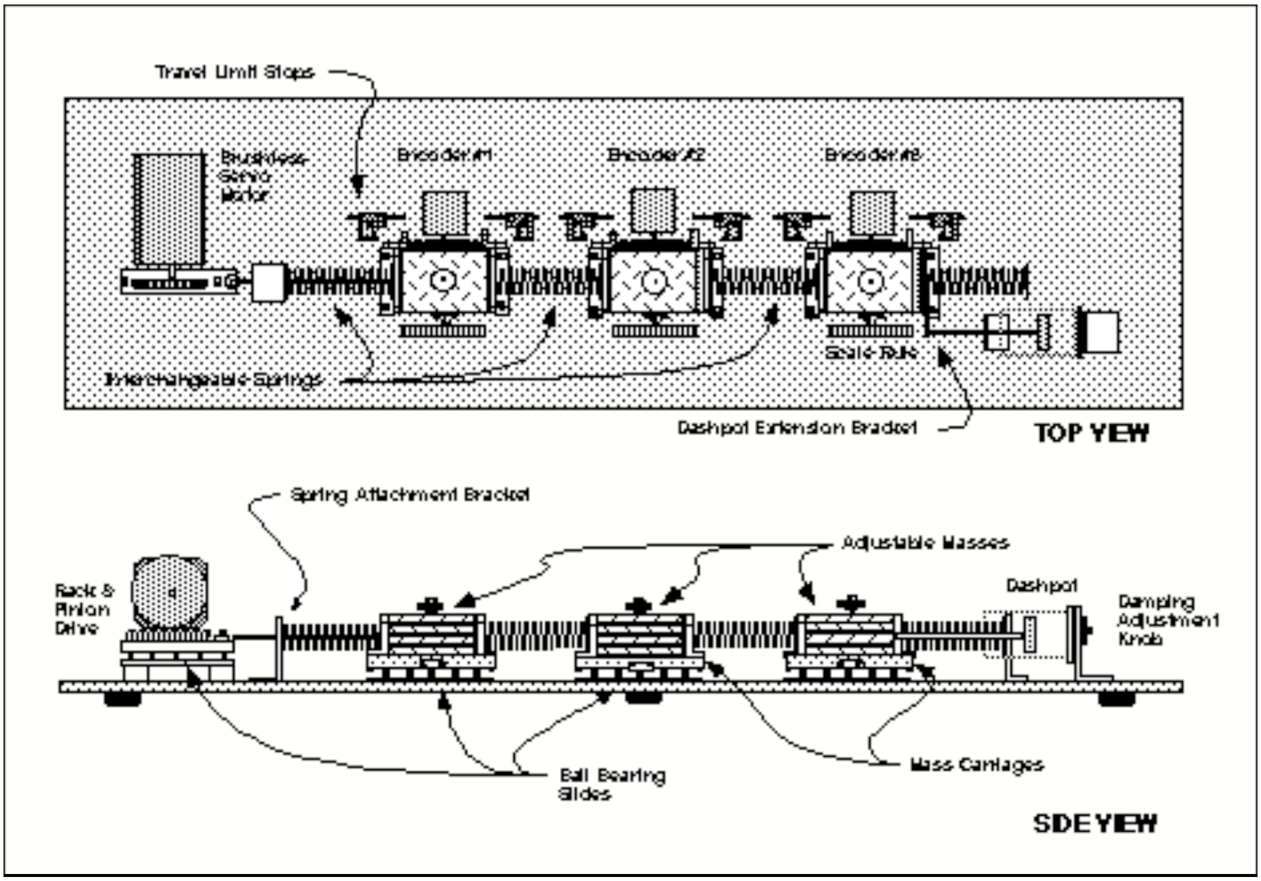


Figure 2.2-1. Rectilinear Apparatus

[1]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)

Springs of various stiffness may be attached between masses or between the masses and the base plate. A dashpot with adjustable damping may be coupled to any of the masses. Position measurement scales are provided to assist in certain experiments and system setup.

Figures 2.2-2a & b also show the variety of plant types that are supported by each model. Mathematical modeling and parameter identification of these plants are described in Chapters 5 and 6.

2.2.2 Changing Plant Configurations and Parameter Values

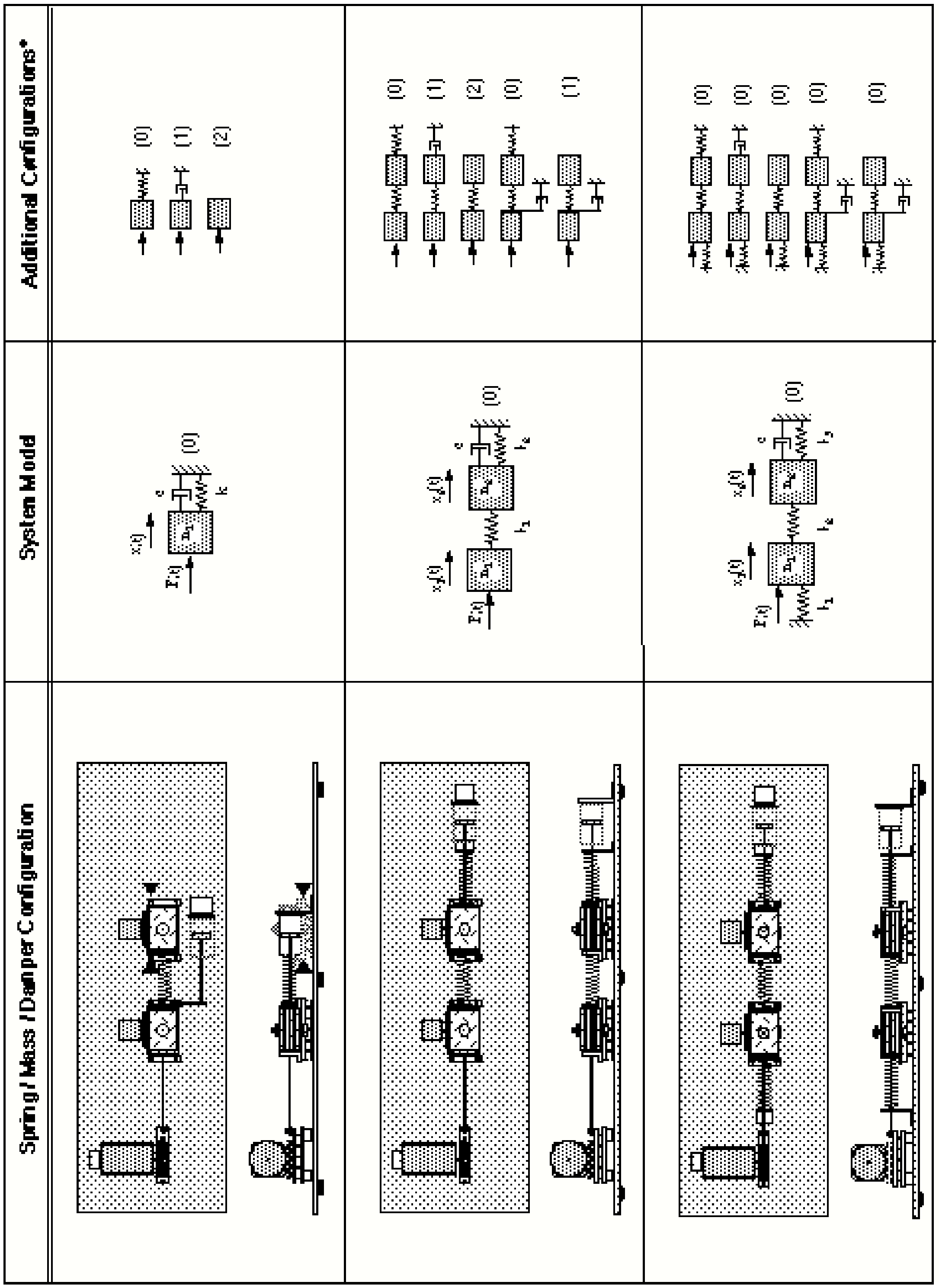
As shown in Figure 5.2.2-2, the plant may be placed in a variety of spring/mass/damper configurations with 1, 2, and 3 (Model 210a) degrees of freedom (DOF). Springs may be mounted interchangeably and are supplied in three nominal stiffnesses: 175 N/m (1.0 lb/in), 450 N/m (2.25 lb/in), and 800 N/m (4.5 lb/in).

The dashpot connects to any of the mass carriages either through direct attachment or via the extension bracket. The damping constant may be varied by adjusting the air flow valve on the rear of the dashpot. Coarse adjustments are made via the knurled knob and fine adjustments via the metal screw.

The user may change inertia values by changing the number of brass weights (500± 5g each). Make certain that the weights are firmly clamped by the thumb nut before operating or transporting the mechanism.

The travel limit stops must also be set before operating or transporting. Figure 2.2-3 gives instructions for adjusting the stop positions. The stop assemblies include a rubber "bumper" to physically stop the motion, and a limit microswitch[1] set to engage prior to the stop tab contacting the bumper. When a given mass carriage is intended to have free motion, the limits should generally be set to ± 3 cm. Whenever the stop positions are moved, the user should verify that they are securely fastened in their new position. It should also be checked that the limit switches engage ("click" sound) prior to contacting the bumper, and that they are contacted prior to interference between any other mechanical elements (e.g. that the encoder cable ends do not travel beyond their pulley). For some plant configurations, the second or third mass must be clamped. In this case a shim (e.g. a 1/4 in. threaded nut) must be placed between the bumper and the stop tab to ensure that the corresponding limit switch is not engaged – see Figure 2.2-3.

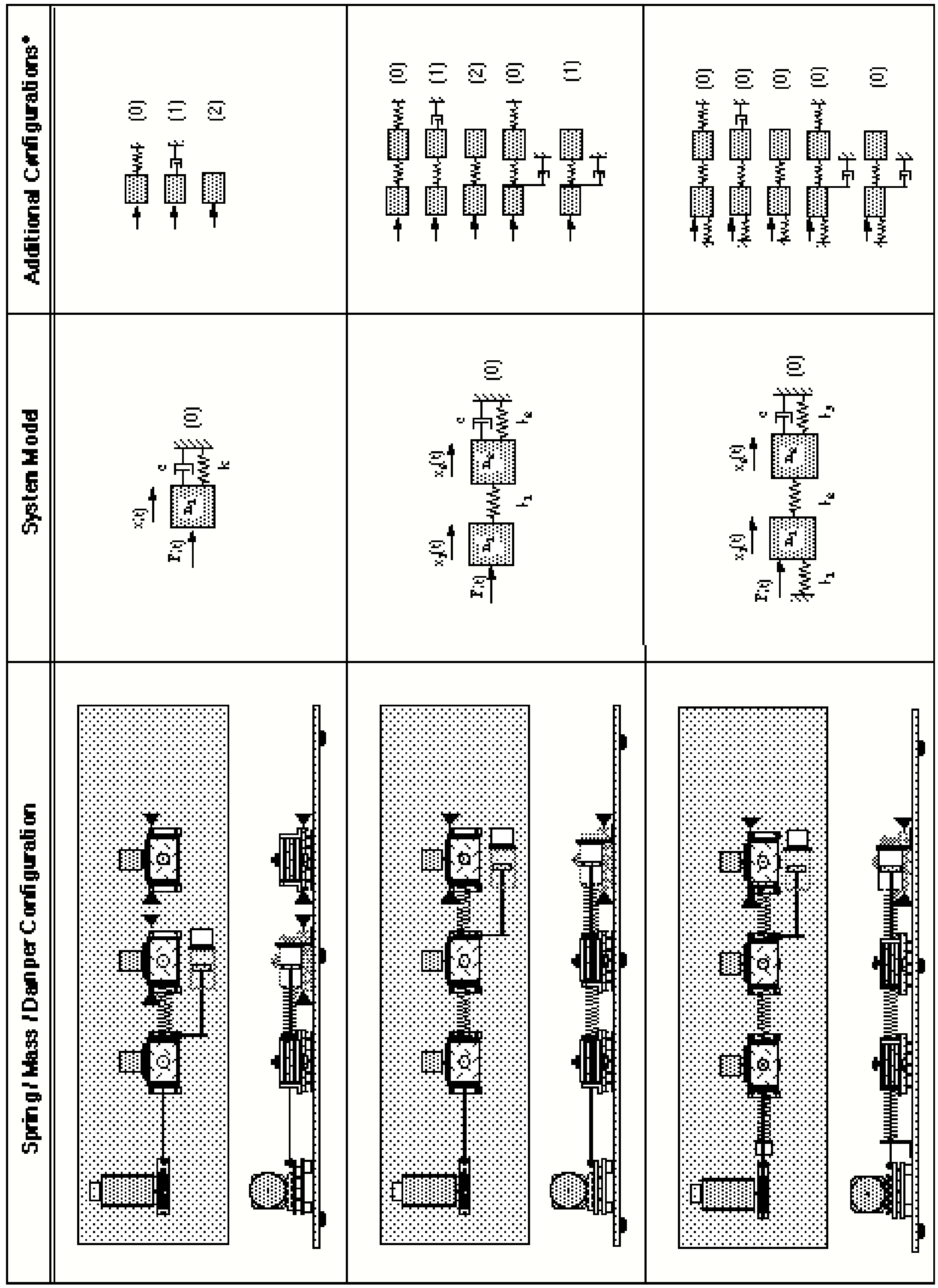
[1]This microswitch causes the controller to be disabled during control implementation.



- indicates mass carriage is immobilized by limit switch clamps.

* Numbers in parenthesis are the so-called "system type" or number of integrators in the plant.

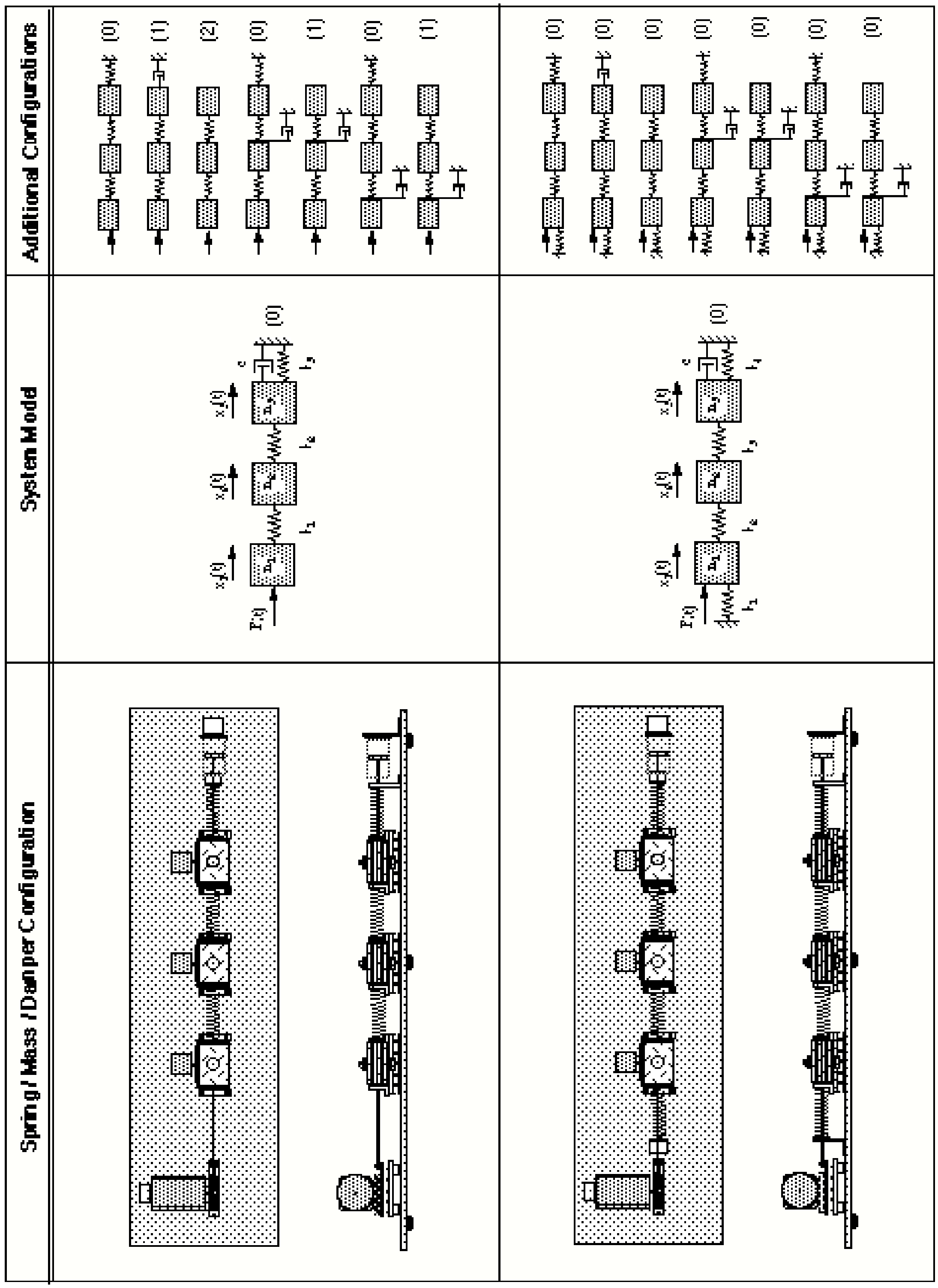
Figure 2.2-2a. Plant configurations for Model 210



◄▬► – indicates mass carriage is immobilized by limit switch clamps.

* Numbers in parenthesis are the so-called "system type" or number of integrators in the plant.

Figure 2.2-2b. Plant configurations for Model 210a.



– indicates mass carriage is immobilized by limit switch clamps.

* Numbers in parenthesis are the so-called "system type" or number of integrators in the plant.

Figure 2.2-2b. Plant configurations for Model 210a.

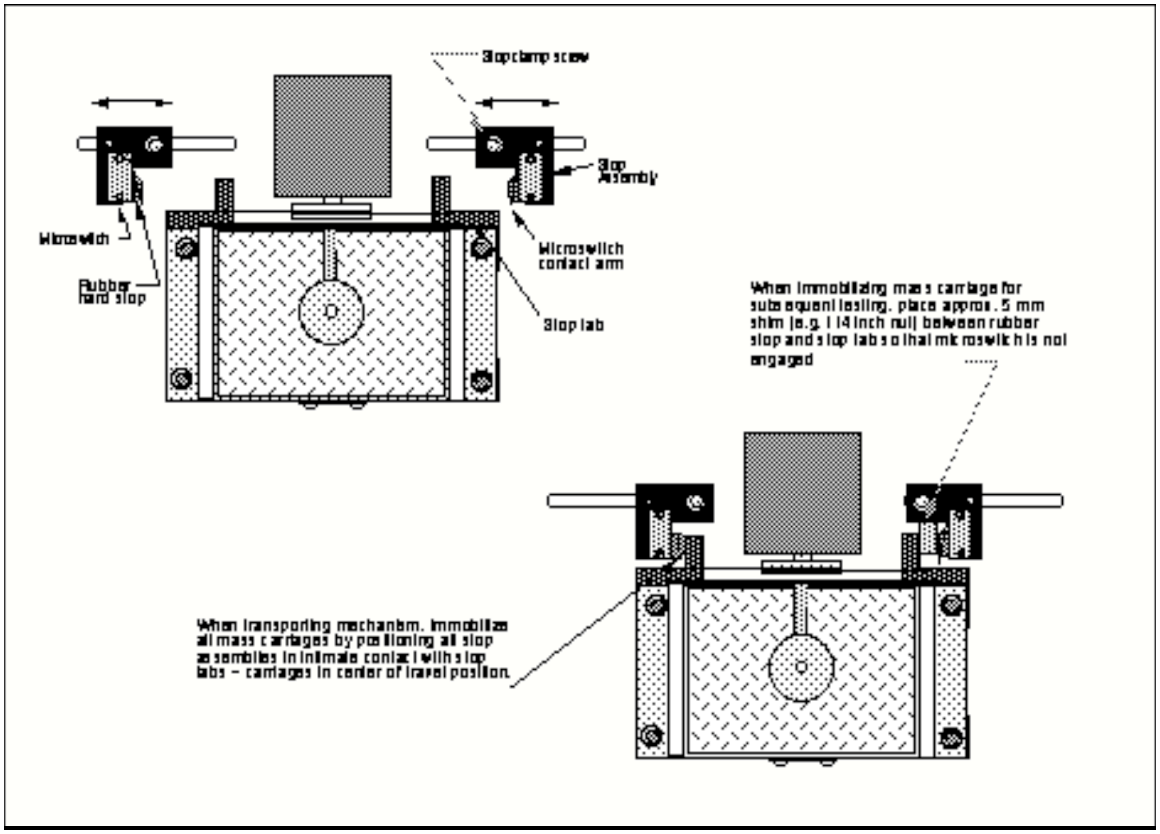


Figure 2.2-3. Guidelines For Setting Stop Positions

Important Notes

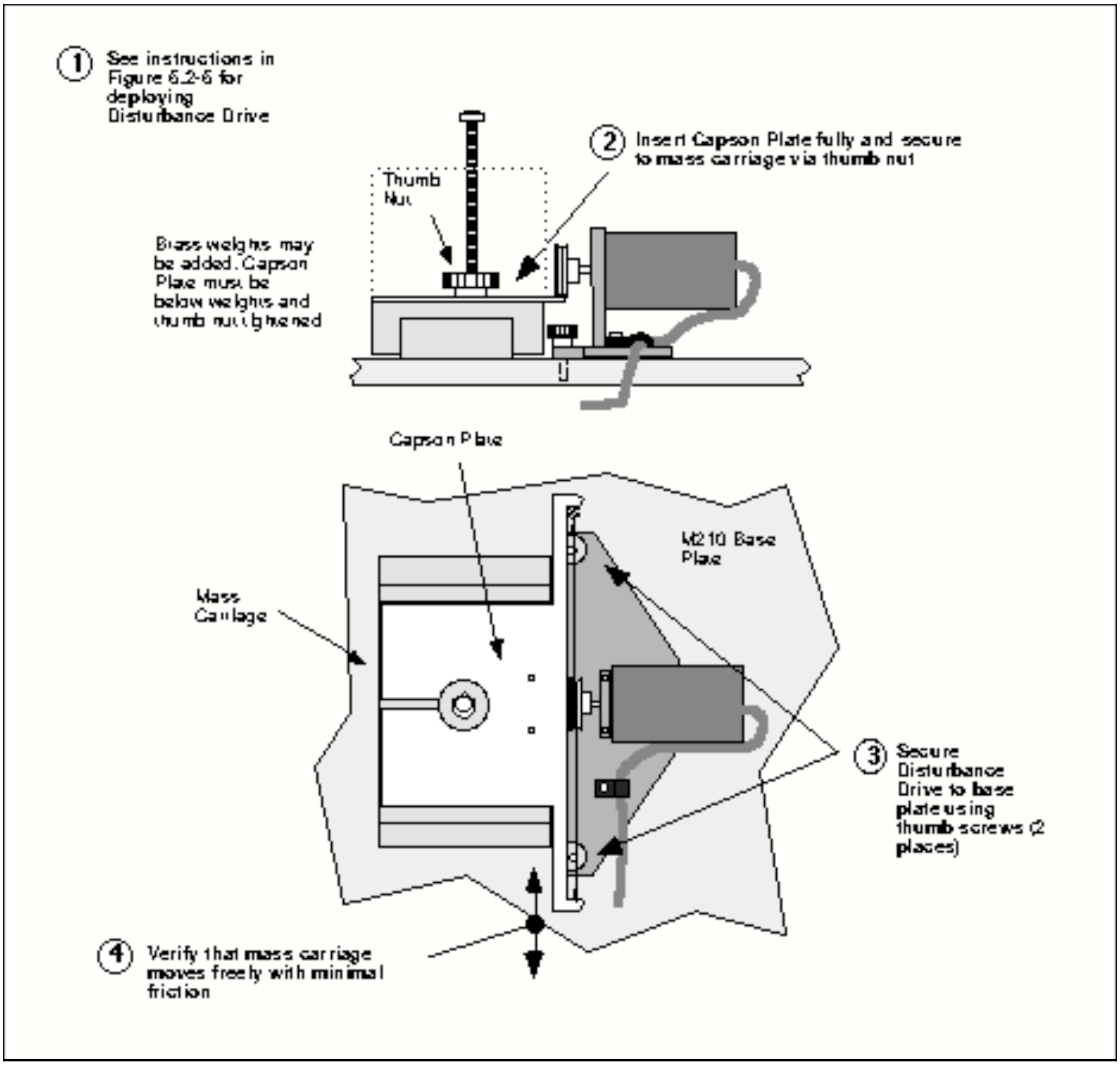
1. Prior to operation the user should verify that: a) the brass mass pieces are properly secured, b) the mass carriages travel freely, and c) the limit stop blocks are properly set and secured to limit motion of the mass carriages.
2. Prior to transporting the mechanism the user should verify that: a) all brass mass pieces are removed, b) the limit stop blocks are set to immobilize the mass carriages and are secured, and c) the disturbance drive and its carriage plate (if included as system option) are secured using the provided screws.

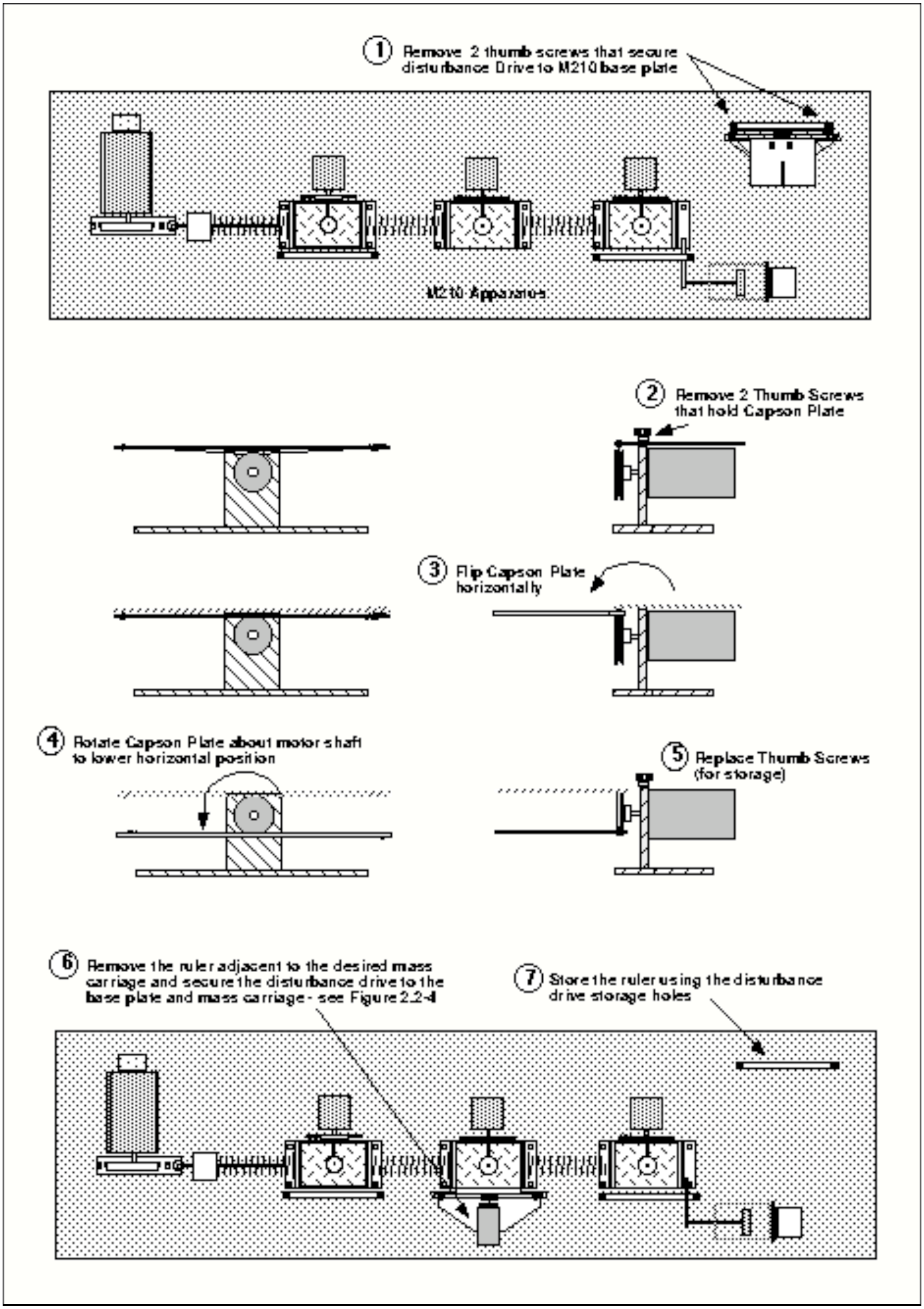
2.2.3 Damper Protective Cover

The damper is supplied with a protective black elastomeric cover. The user or using institution may chose to remove the cover to expose the dashpot's glass cylinder body and give a more illustrative view of its functionality. This is easily accomplished by parting the elastomer along its length with a sharp knife and peeling away. The user is warned however that the cover is provided to help protect against damage by objects striking the dashpot. ECP will not be responsible for damage resulting from the removal of the cover.

2.2.3 Optional Disturbance Drive

The optional disturbance drive consists of a high torque density DC motor and capstan drive - see Figure 5.2-4. It may be installed to apply a disturbance to any of the mass carriages using existing features on the Model 210 apparatus. Detailed instructions for installing the drive are given in Figure 5.2-5. The drive should be stowed when not in use according to the reverse procedure of Figure 5.2-5. It is important that the drive be properly secured and the mass carriage be shown to slide freely before operation of the system. The unused ruler and thumb screws should also be secured as per the figures to avoid their loss or damage. If the drive has been purchased as an "add-on" accessory (not purchased with the Model 210 system originally) the two storage holes shown in the upper right mechanism base plate (upper & lower Figure 2.5-5) may not be available.




1 Remove 2 thumb screws that secure disturbance Drive to M210 base plate
M210 Apparatus
2 Remove 2 Thumb Screws that hold Capson Plate
3 Flip Capson Plate horizontally
4 Rotate Capson Plate about motor shaft to lower horizontal position
5 Replace Thumb Screws (for storage)
6 Remove the ruler adjacent to the desired mass carriage and secure the disturbance drive to the base plate and mass carriage - see Figure 2.2-4
7 Store the ruler using the disturbance drive storage holes

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[1] 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 2.5A 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

[1]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.

box next to the large blue colored capacitor. See warnings in Section 2.3.4 regarding replacement of the fuses.

2.3.2 Software

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

Travel limits have been contacted.
Over speed of the motor.
Excessive motor drive 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 force 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. One should first Reset Controller (Utility menu) to be certain that no anomalous states exist in the controller due to the interruption caused by the Limit Exceeded condition, then Implement Algorithm (via the Setup Control Algorithm dialog box). Obviously the input trajectory must also have parameters that do not cause the Limit Exceeded condition.

The Limit Exceeded indicator of the optional 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 necessary 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 remains 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 the first mass (the one connected to the motor drive) from side to side. Keep hands clear of the mechanism while doing this and apply only light force to the mass. If the mass does not race away 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: Do not apply power to the mechanism while the clear cover about the drive rack and pinion is not securely in place.

WARNING #4: Verify that the masses and stops are secured per Section 2.2 of this manual prior to powering up or transporting the Control Box.

WARNING #5: 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 #6: The power cord must be removed from the box prior to the replacement of any fuses.

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 and 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.

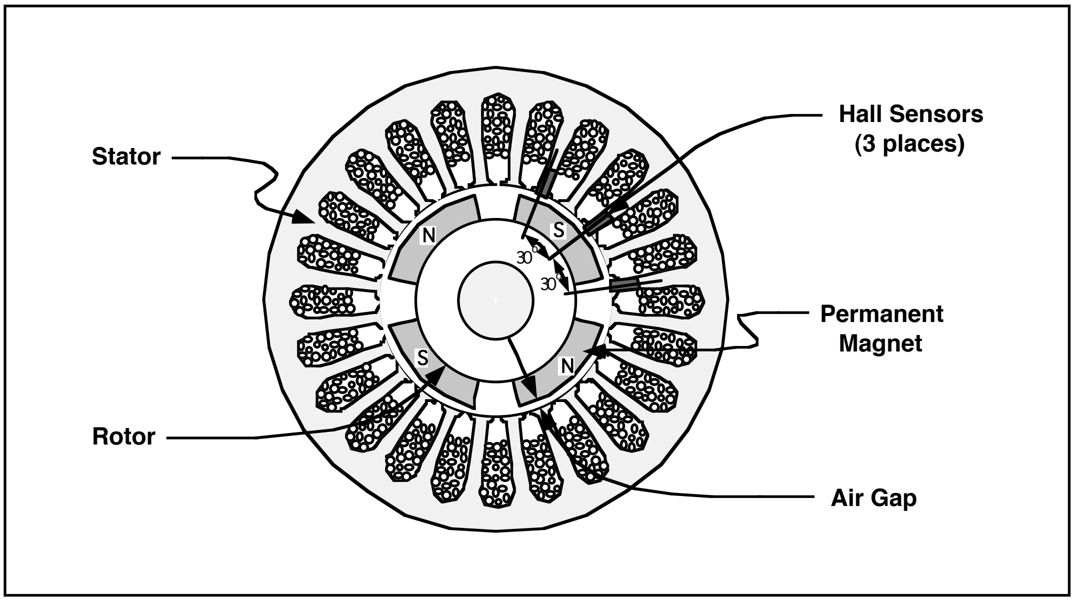


Figure 4.3-1. Cross-section of a Typical DC Brushless Motor. **(Four pole type shown)**

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 Kirchhoff's law) the current in the third phase is the negative of the sum of the current in the other two phases.

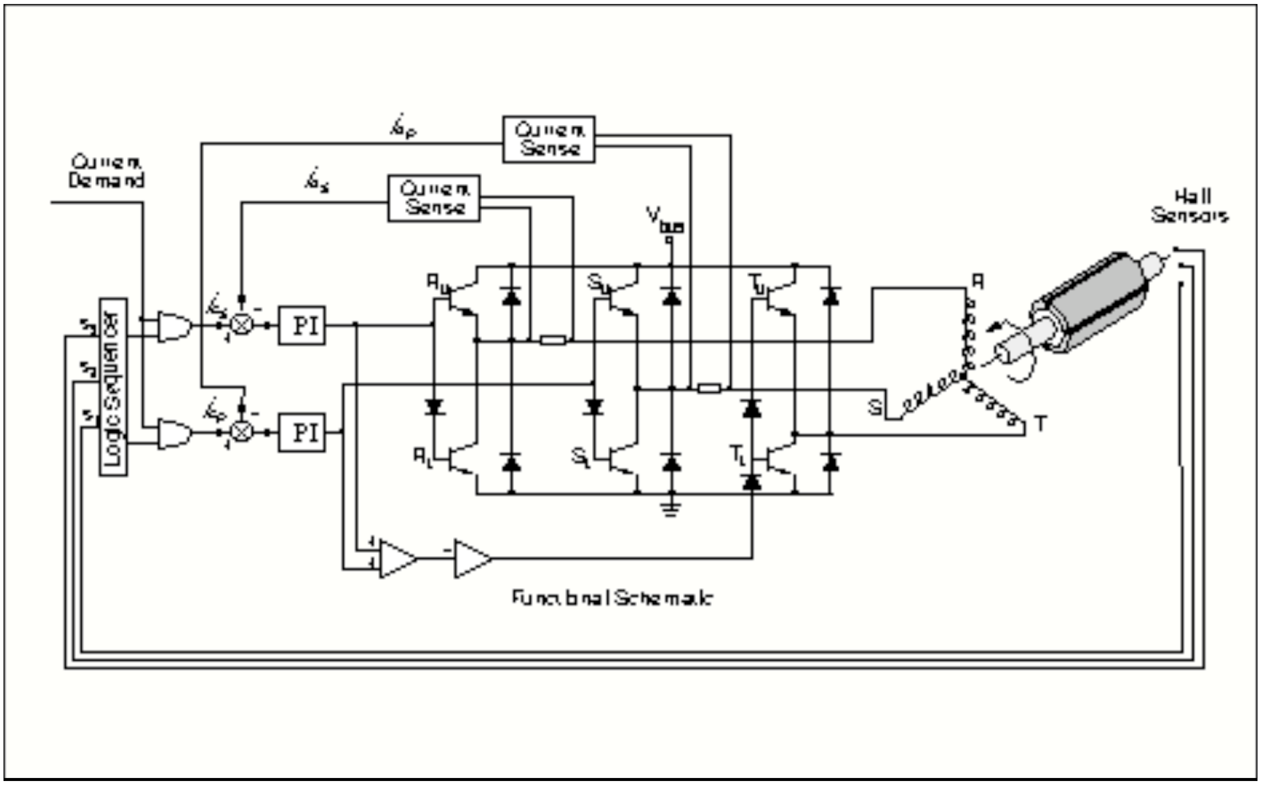


Figure 4.3-2 Simplified Schematic of Hall-effect Commutated DC Brushless Motor Drive System

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.[1] 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 $0 \le \theta \le 60$. The torque input from phase R is

$$T_R = K_t I_R \sin\theta \tag{4.3-1}$$

and

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

where $K_t = Z^*B_p^*r^*l$ 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.

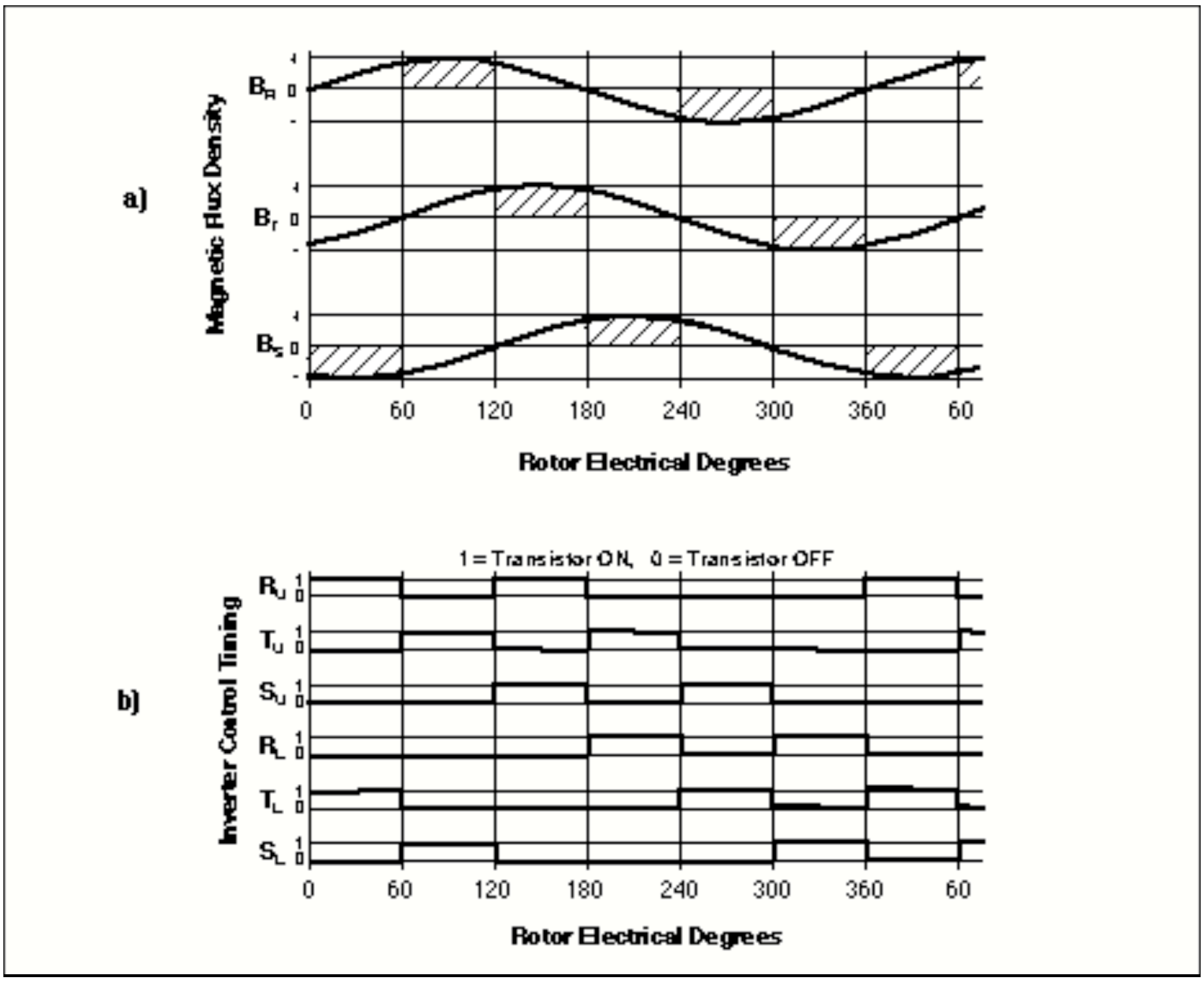


Figure 4.3-3 Hall-effect Commutation Timing Diagram

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

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):

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

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

$$T = T_R+T_T = K_t(1.5\sin\theta+0.886\cos\theta)*I_R \tag{4.3-3}$$

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:

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

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

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

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

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

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

$$T = T_R+T_S+T_T$$

$$= K_t\, I_p\, (\sin^2\theta+\sin^2(\theta+120)+\sin^2(\theta+240))$$
$$= 3/2\, K_t\, I_p \qquad (4.3\text{-}7)$$

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).

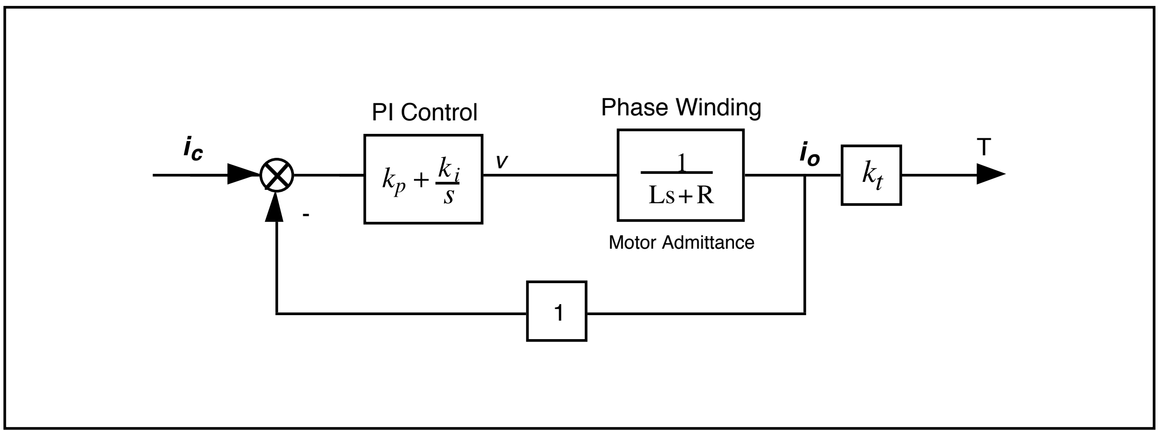


Figure 4.3-4 Simplified Block Diagram of Analog PI Controller (applies to each motor winding phase)

This is a second order system with the transfer function

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

having natural frequency

$$\omega_n = \sqrt{\frac{k_i}{L}} \tag{4.3-9}$$

and damping ratio

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

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 four incremental rotary shaft encoders used in the 3 mass version, Model 210a. (Three for Model 210). Three of these encoders are used to sense the position of the three masses. Each has a resolution of 4000 pulses per revolution. The fourth encoder is directly coupled to the brushless motor and is only used for commutation purposes. It has an output of 1000 pulses per revolution.

The encoders are all 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.[1] 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.

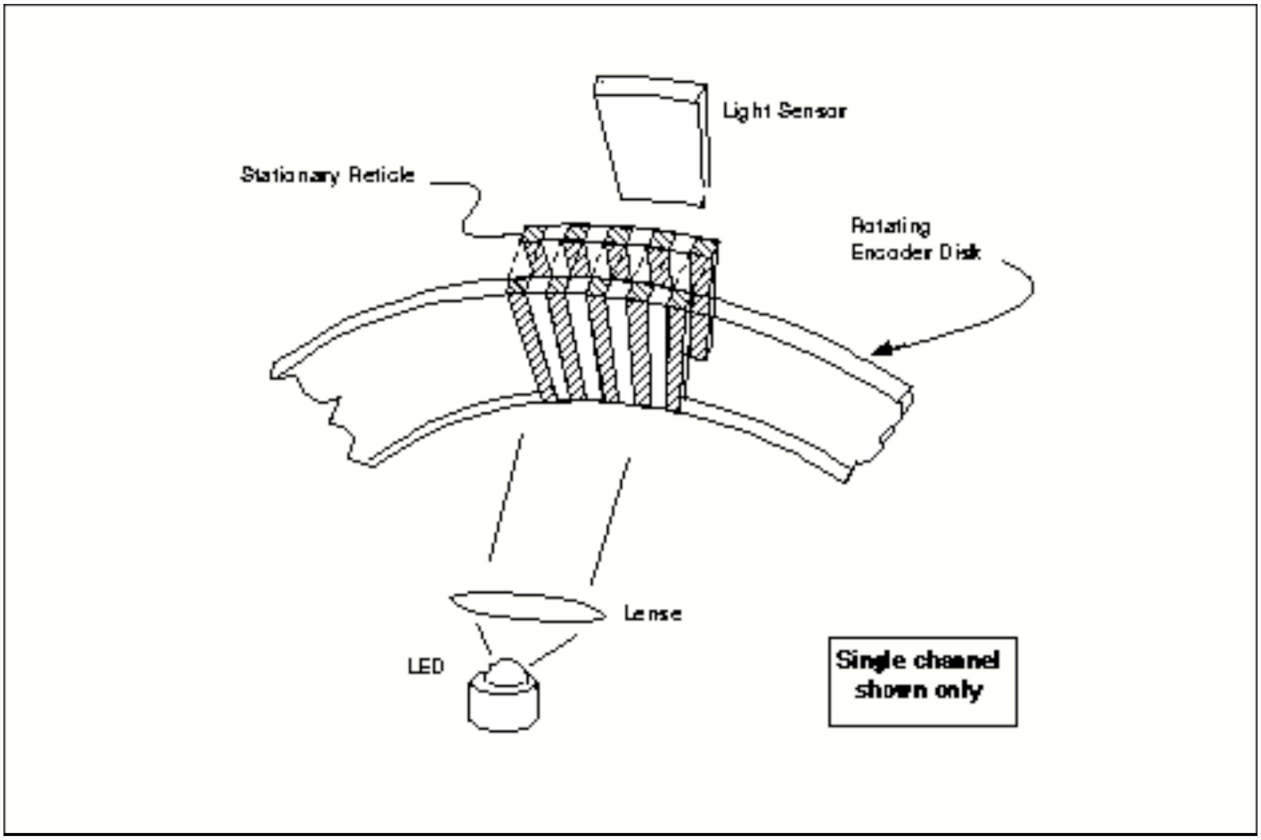


Figure 4.5-1 The Operation Principle of Optical Incremental Encoders

[1]That is the mass position encoder resolution effectively becomes 16,000 counts per revolution. The effective resolution is then 16,000 counts/($2\pi r_p$) where r_p is the encoder pinion pitch radius – i.e. resolution = 1604.1 counts/cm.

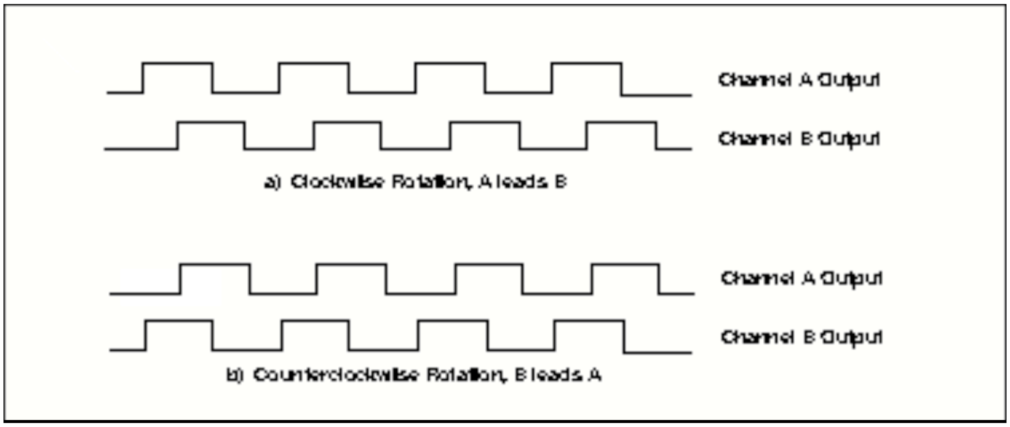


Figure 4.5-2. Optical Encoder Output