Motion Control Handbook

by

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MOTION CONTROL HANDBOOK

I. Why Should I Read This Handbook?

- This handbook is *your* resource guide to motion control technology, products, and applications.

- The *objective* of this handbook is to provide you with a friendly starting place in the world of motion control. It addresses some of the major questions first time users and experienced engineers alike want to know when they must specify an unfamiliar system.

- Above all, this handbook is a *compendium of practical information* about motion control. It is not an in-depth design manual, but rather an introduction to the technology and a guide to further resources compiled by leading vendors and developers of motion control technology.

Assumptions About You

- You're someone who is involved in the design, specification, construction, operation, service, or sale of industrial control products or systems.
- You've heard about motion control.
- You suspect that motion control technology might have some benefits for you.
- You wish you knew more about it.
- You're looking for a Ground Zero motion control introductory overview, not an exhaustive textbook.

How To Use This Handbook

- This handbook is divided into 7 chapters. The first 5 chapters, including this one, are Quick Read concept summaries of motion control fundamentals. Read them all, and you will have gained a good basic understanding of the subject of motion control.

- Chapter 6 is a reference guides to standards. Just glance over this chapter, then use it as your specific needs arise. Chapter 7 is a glossary of popular motion control terms and definitions.

What You'll Learn

After reading this booklet, you will be able to:

. . . understand the *uses* and *benefits* of programmable motion control technology (Chapter II).

. . . recognize and discuss motion control *applications* (Chapter III).

. . . recognize and discuss the major categories of motion control *systems* and *products* (Chapter IV).

. . . select in a preliminary manner the *appropriate type* of motion control system for your type of application (Chapter V).

. . . refer to the appropriate motion control *technical standards* (Chapter VI).

. . . locate any unfamiliar motion control *term* in the Glossary (Chapter VII).

II. What Is Programmable Motion Control?

The Early Days

In the early days of machine development, the control of position and velocity was accomplished by elaborate, expensive, and time consuming solutions such as a series of cams, gears, shuttles, and the like. Frequently, other devices such as hydraulic and pneumatic cylinders, electric solenoids, plungers, and grippers were added to these systems. Some examples of these solutions include early textile machinery, coil making, and wire winding equipment.

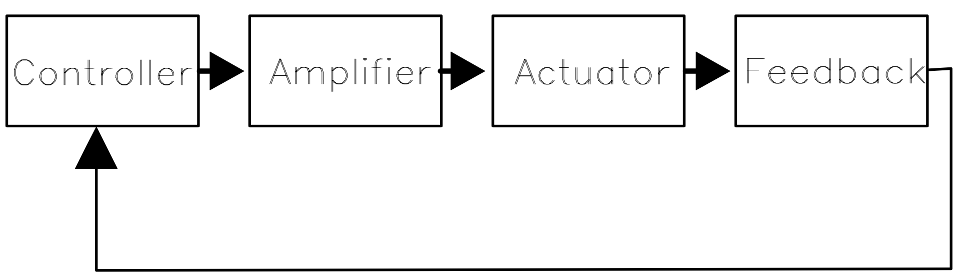
The automotive and machine tool industries were among those who saw the control of motion as a means of providing complex shapes and integrating complex operations. Being able to move heavy materials and process them in a repeatable and continuous manner added value and increased the productivity of their operations. While this was of great benefit in operations which were continually repeatable and injected no changes, this was not an optimum solution for operations which required short runs of parts for any degree of variety or customization. This was, of course, because early automated systems were highly dedicated and required laborious retooling and set-up when even marginally different products or processes were required.

With the emergence of computers and microprocessor technology, other options became possible. In electronically based systems one may choose a variety of different parameters by merely changing the software within the system. This translates into less set-up work and more throughput. For example, to change the speed of an operation, a mechanical system might require you to exchange an existing gear with a larger or smaller one. In the modern world of programmable motion control, this could be accomplished by entering a few lines of code or selecting a different velocity profile from the system's memory. This is what we refer to as programmable motion control.

PMC Defined

Programmable Motion Control (PMC) is defined as the application of programmable hardware and software (in conjunction with input sensory devices, actuators, and other feedback devices) for the control of one or more linear or rotary motions. Expanding on this definition in today's concepts for the equipment used to control motion, a programmable motion controller commonly takes the form of a microprocessor based system. The system will be comprised of the following basic elements: controller, amplifier, actuator, feedback. A simplified block diagram of a programmable motion control system appears below.

The controller will include a means of entering a set of instructions or code into its memory which are then translated into a series of electrical pulses or analog signals and output to an amplifier for controlling some type of actuator. The amplifier receives the signals from the controller and boosts or amplifies them to appropriate levels for the actuator.



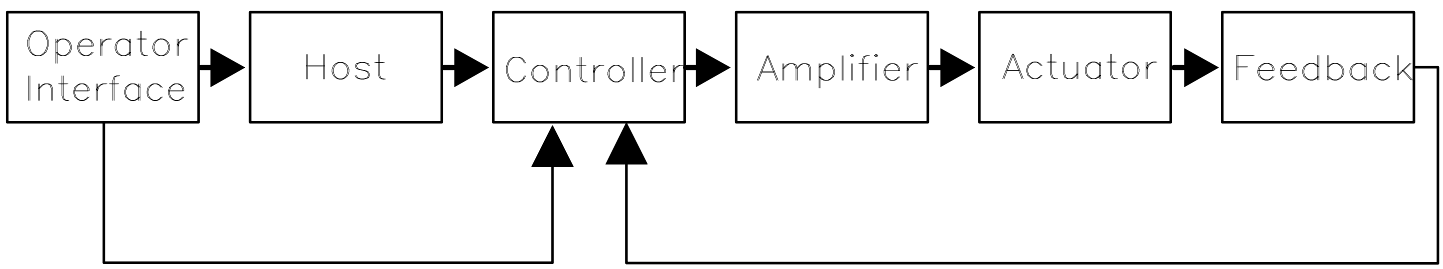
Motion Control Product Categories

The actuator provides the actual physical motion and will be closely coupled to the design characteristics of the amplifier. The amplifier/actuator set may be any one of several different design classifications. Typically, but by no means always, they will take the form of an electronic amplifier and an electric motor. Other common means of motion are pneumatic or hydraulic actuators.

The final element of our system is the feedback device. There are a wide variety of feedback devices that are commonly used in motion control systems today which provide information on linear or rotary motion. Generally, a motion control system will base and adjust its functions on the input of any one or combination of the following devices:

Optical encoders
Magnetic encoders
Resolvers

Many motion control systems are integrated into a larger system. Various computer-based devices, such as programmable controllers, PC's, stand-alone industrial computers, or remote mainframe computers serve to link and coordinate the motion control function with other functions. In addition, an operator interface is present to input control logic, change existing programs, or provide real time modifications, such as system shut down or schedule changes. Thus, a more integrated motion control system would appear as shown below.



The Purpose of Motion Control

The motion control system's purpose is to control any one, or combination, of the following parameters:

Position
Velocity
Acceleration
Torque

The types of feedback devices used in a motion control system will depend on both the control element (position, velocity, and/or torque), as well as the accuracy required. Another parameter used in the selection of a feedback device might be environmental considerations, such as temperature, sensitivity, and stiffness.

The machine manufacturer who wishes to electronically automate his product must select control equipment which will do many things, at the very least the following:

- Provide Process Control: To turn on and off and control any fluids, heaters, coolers, air pressure, and associated functions.
- Manage System Faults: To monitor and act upon information supplied to the control unit from interlock switches, jam-up sensors, process control limits, etc.
- Provide Motion Control: To command, control, and monitor the motion of those things in the machine for which the desired motion profile must sometimes be changed either during normal operation, at set-up, or under emergency conditions. Thus, the motion controller must be PROGRAMMABLE, so that it can be told in advance just what it must do following the receipt of specific input signals.

Motion System Classifications

The block diagram (Figure 1) on the next page gives a general overview of the various types of motion control systems commonly used today. Sometimes, the controller is very specialized and designed to accomplish very specific tasks. Examples of such controllers include the following:

Computerized Numerical Control
Industrial Robot
Transfer Line
Plastic Molding
Coordinate Measuring Machine
Laser Welding and Cutting
Plasma and Flame Cutting
Water Jet Cutting

Another type of unit which became popular in the 1990's is the general purpose stand-alone controller. This controller is typically more flexible than a dedicated unit and is adaptable to many different applications. It is used in higher volume generic applications such as X-Y positioning, palletizing, and other general motion activities which require adjustable activities or duty cycles. General purpose controllers are available as board level products which may be incorporated inside larger pieces of machinery; as enclosed units, in which the controller and its associated amplifier and power supply are contained in an enclosure with external connections and operator interface; and as bare cards which are designed to be fit into a larger logic device such as a computer or programmable controller. In cases such as the latter, the higher level logic or control unit is referred to as a host controller. The host generally is responsible for several more specialized or higher level control functions and may also provide ancillary functions such as statistical process control, high speed mathematical calculations, and intermachine communications and coordination.

Processors at the chip level are not generally useful to the end-user. Motion control chips are generally incorporated into a larger controller which then integrates their function (motion or actuator control) with other functions as a portion of a complete system (tracking of events, performing calculations, maintaining internal and external communications, etc.).

A popular motion control system for larger installations is the adjustable speed drive (ASD). Typically an integral horsepower configuration, the ASD consists of either an AC or DC motor and an amplifier or inverter which accommodates heavy industrial processes. ASDs are typically found in paper and steel mills and continuous process environments where very large loads must be transferred and acted upon at various rates of speed in the course of their processing.

III. Fundamentals of Applying Programmable Motion Control

Introduction

When applying programmable motion control, it is essential that the designer understand the motion parameters important to his or her application. This chapter covers issues pertinent to motion control to help designers qualify and quantify their requirements. This will help in the study and selection of motion components to meet an application.

The decision to apply programmable motion control to a motion system is fundamentally determined by the need to control a system or process beyond the capability of a single ungoverned device such as a line connected AC motor. The next step is to classify the parameters that are needed for control. This usually begins by considering the load and goes on to include process control, safety and fault management, and user interface to name a few.

Motion Considerations

As mentioned in the previous chapter, the purpose of a motion control system is to control one or more of the following: position, velocity, and torque. In addition, it is not uncommon for the system to switch between operating modes.

- Velocity Control: Velocity control or speed control needs to be quantified with respect to several issues. First, what is the speed required to do the application? Further, does this load vary with speed or is load constant? For example, a machine tool axis will require, in general, constant thrust (torque) over a fairly wide range of cutting speeds, plus have a high speed requirement at low load for rapid traversing. This would result in an overall speed range of hundreds or thousands to one. In contrast, a machine tool spindle driving a part in a lathe, or a tool for milling, will require a fairly constant power requirement over a speed range of perhaps 5 to 1 as supplied by the motor (transmissions are generally added to further extend the constant power range). Another consideration of velocity control is speed regulation. Speed regulation is generally expressed in percent of a set speed. Based on the application, the concern for speed regulation

Typical Programmable Motion Control Systems

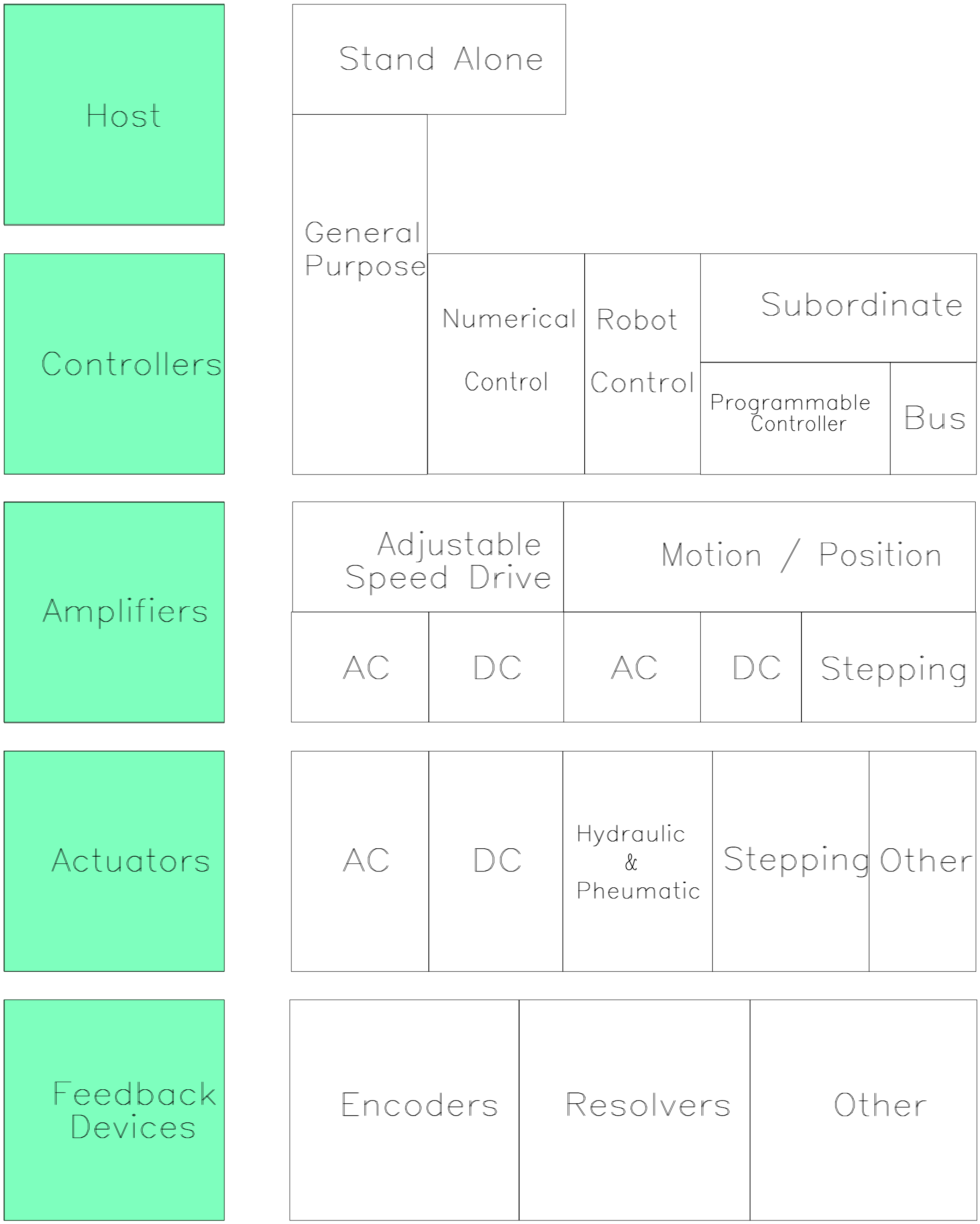


Figure 1

might be short-term or long-term. Short-term regulation would be the consideration for speed deviation due to some transient load of a known quantity. Long-term regulation would be the concern of speed control over seconds, minutes, or longer. In addition, speed ripple in a system, often the result of motor and driver design, may be a concern relative to certain frequencies for which the application is sensitive. Examples of this would be the effects of speed ripple on the surface finish of parts made by machine tools or consistency of coating in a web process.

- Torque Control: Torque control suggests the need to control the torque or force in a system independent of speed. An example would be a simple feed or take-up roll in a web application for which web tension is controlled. Maintaining constant tension on the web results in varying torque at the rolls as a function of roll diameter, resulting in a constant power requirement. A more complex tension control might require a changing or tapered tension as a function of roll diameter. As in the evaluation of a velocity controlled system, a torque controlled system needs to be quantified by a number of parameters. What is the required torque range? Over what speed range must the torque be provided? Is torque ripple of concern, and if so, what frequencies of ripple present a problem?

- Position Control: Position control entails the control of motion displacement which is the change of motion with respect to time. This includes command, control, and the monitoring of motion. This can be as simple as the change in velocity command by limit switches on a simple slide drive, or as complex as linear and circular interpolation among axes on a multi-axis machine. Within the discipline of position control, numerous issues need to be quantified or measured. The resolution of the position control, that being the smallest unit of displacement, needs to be defined. Along with the resolution, the accuracy and repeatability of the motion displacement needs to be determined. Resolution, accuracy, and repeatability are common quantities associated with position feedback devices like encoders and resolvers; but, the specification of a complete motion system must also take into account the mechanical system and position controller.

- Position control typically involves motion acceleration, or the change in velocity with respect to time. The acceleration rate will affect the forces in the system since torque is the product of inertia and acceleration rate. It is important to include the inertia of the actuator (typically a motor) in any torque calculation of this kind since its inertia may contribute considerably to the torque required. Chapters IV and V contain examples of application types and the calculation methods for determining inertial, acceleration torque, and other load related issues. The selection of acceleration or deceleration profiles will also affect system performance. Constant torque acceleration may result in the fastest acceleration rate, but a parabolic acceleration/deceleration profile will result in the least heating or root mean square (RMS) value of torque required. On the other hand, an S-type acceleration will produce the least mechanical stress or jerk in a system.

- Position control typically requires flexibility regarding the need to change certain parameters of the required motion. For example, the length of a move, or speed of the system may be changing based on variables in the process or parts being manufactured. For this reason, a programmable motion controller is needed along with specific application software. The application software can be canned or bundled software that might come with the system, or custom software requiring additional cost or effort. When considering flexibility in programming, it is also important to define the degree of operator interface for implementing changes. A simple operator interface could be a thumb wheel switch allowing selection of particular predetermined functions. A more complex and flexible interface might entail an alpha-numeric display and keypad.

Machine Control

In designing a complete system, subjects other than motion control need to be addressed. These include process control functions and system fault management. As mentioned in Chapter II, process control involves the turning on and off of associated functions to the main process such as pumps, coolers, heaters, air pressure, and so on. System fault management includes detection and response process limits, mechanical limits, jam sensors, and safety functions such as interlock switches. Always be sure to consult local and industry safety and installation standards, as some of these features may be required for your particular installation.

IV. Building Blocks of Programmable Motion Control Systems

This section is about programmable motion control from the perspective of the kinds of hardware and software that are involved in acting upon a command to execute a desired motion. Every programmable motion control system must have the foundation blocks: controller, amplifier, actuator, and feedback.

Motion/Position Drives / Controllers and Amplifiers

The terms controller and amplifier when used in a discussion about motion control can be interpreted to mean almost anything. A controller may consist of a simple on/off type of sensing device that might operate a small fan motor when fumes are detected under a vent hood. If the motor needs a transistor to provide drive current, the system could be said to have an amplifier. All of the basic building blocks of a motion control system are in place. These are the motor, the transistor (amplifier), the fan (load), and the fume detector (controller/feedback sensor).

Amplifiers are classified based on the characteristics of their output. Some of the more common types include:

- *DC Amplifier:* Linear amplifier which is capable of outputting a bi-directional DC voltage for powering a brush-type DC motor.

- *Brushless DC:* Linear amplifier used in conjunction with a brushless servo motor. Commutation of motor is based on amplifier generated trapezoidal wave form which is compared to a pulse feedback from motor.

- *Brushless AC:* Linear amplifier used in conjunction with a brushless servo motor. Commutation of motor based on amplifier generated AC signal which is compared to a pulse feedback from motor.

- *Vector Control:* Linear amplifier which is capable of servo control of an AC induction type motor, the torque of which is controlled via vector analysis on motor current feedback.

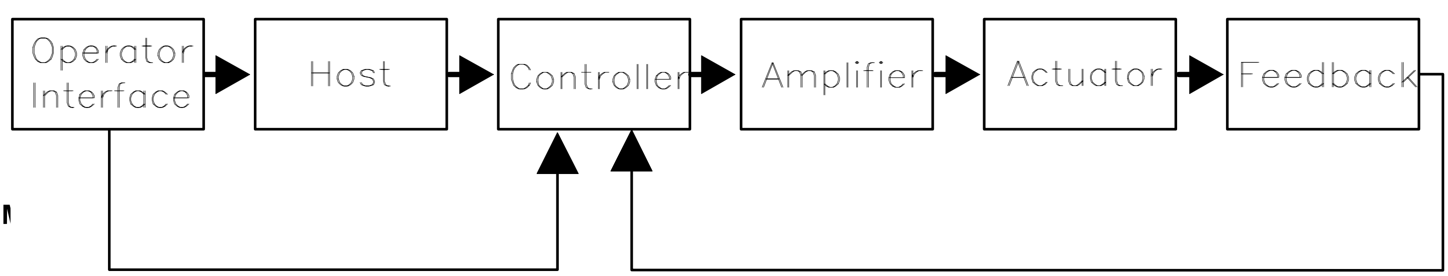
On the other hand, the motion system may be very complex and include many different types of motion components. An example of such a system might be a computer integrated manufacturing (CIM) system which receives as input a computer-aided design (CAD) data file, inspects and loads tools into a manufacturing cell, makes a part in accordance with the CAD information, provides real-time adjustment in the manufacturing process, and then collects, processes, and stores information for statistical process control (SPC) purposes.

There are many types of controls, amplifiers, motors, and applications. The combination of components required to perform a given application will vary and many considerations affect which type of system is optimal. Often there are several ways to accomplish the desired result. In these cases, secondary considerations such as cost, versatility, expansibility, or availability cast the deciding ballot for the type of system ultimately selected. An astute applications engineer should be able to give you a number of options depending on the cost, accuracy, lead time, and space constraints of your application.

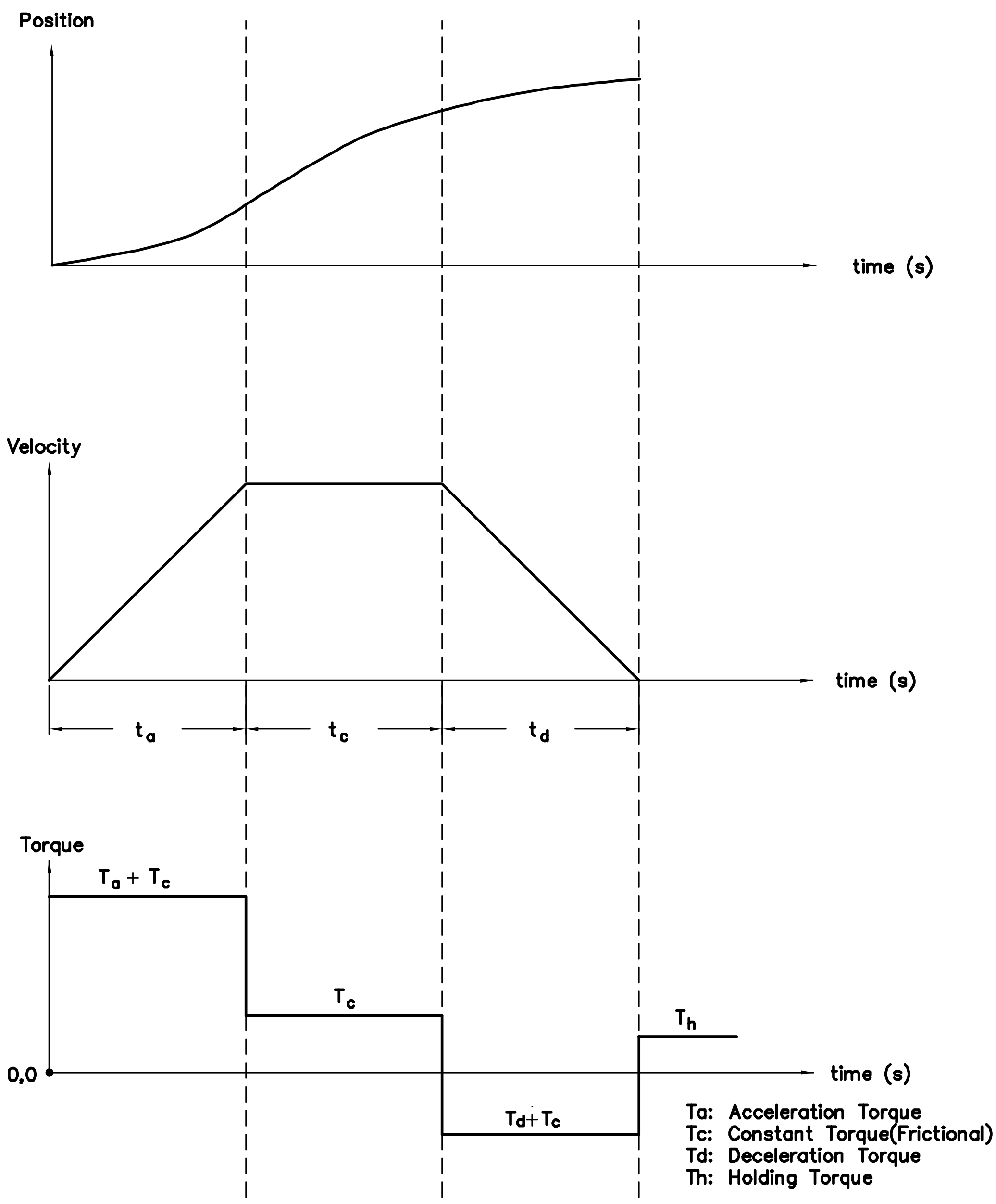
- *Motion Profile Generator:* At the top of this control hierarchy is the profile generator, which will typically contain many defined profiles. These profiles have been placed in memory by either your vendor or yourself utilizing a keyboard or by downloading this information from a computer. When you select a specific profile, the profile generator will feed its velocity and position commands to the next block, which is the real time control loop of the drive. An example appears in Figure 2.

- *Position Control Drive:* The drive module can include both velocity and torque control inner loops or not, depending on the control technique used. The output of this block is drive power to the motor, with feedback from the motor output providing position information (typically via encoders or resolvers) plus, sometimes, velocity information (via tachometers) for the drive loop.

These functions are packaged in a number of ways by different manufacturers. Elements included in your system will also vary according to the application. Some systems are contained in an all-in-one box. Others may consist of several boxes containing a driver or amplifier, a motion control board, and power supply, for example. The advantages and disadvantages of each approach relate to cost, availability, and whether the profile generator complexity requires that it be teamed with a host instead of existing as a free-standing drive unit. IT IS VERY IMPORTANT TO COMMUNICATE REQUIREMENTS AND CONSTRAINTS FULLY WITH AN EXPERIENCED APPLICATIONS ENGINEER BEFORE TRYING TO SELECT A SYSTEM.



Typical Profiles



Motors for your system can generally include any kind or make of motor known. The typical kinds, in order of general use, are noted below. The advantages of each type are application-specific, and must be weighed by you and the applications engineer who helps you specify your system:

- *Brush-type DC Motors:* This is the oldest type of technology used in industrial feedback servos, and is still the most widespread variety found in actual use. Among the advantages are wide availability, time proven technology and construction, and favorable initial cost. The main disadvantage is brush wear, although in many applications this is not a consideration.

- *Stepping Motors:* Stepping motors are sometimes used with feedback devices, such as encoders; but most of the time they are used “open loop.” Power ratings are typically 1 horsepower and below, with operation at high torque and low speed. Cost is a clear advantage of an open loop system. The disadvantage is that if your torque requirements are even momentarily exceeded, a position error is introduced which cannot be corrected.

- *Brushless Motors:* These motors are similar in operating features to brush-type DC motors; the key difference is that they do not require brushes to operate. Typically, lower rotor inertia and efficient thermal dissipation result in faster acceleration and better volumetric efficiency.

- *Induction Motors:* Until about 1980, induction motors were not used in servo systems due to the slow response caused by the inductance lag in the rotor circuit. Since the invention of “vector control” technology, however, improvements have been made in servo system response using these motors, typically in spindle applications due to their high speed and performance requirements and positioning capability.

Motion/Position Hydraulic/Pneumatic Actuators

Hydraulic or pneumatic actuation may be linear or rotary, depending on the application. Linear actuation may be accomplished using either actuators or variable volume, variable flow pumps and cylinders. Each device may be controlled by either proportional, electrically-operated servovalves or solenoid valves. Speed is dependent on fluid flow and pressure (as controlled by the selected valve), covering a broad range of speeds. Advantages are application specific, and must be weighed by you and the applications engineer who helps you configure the system. A general advantage is high power to size ratio with large horsepower output precisely controlled with small electrical signals. Disadvantages include increased machine maintenance, or lack of fluid cleanliness, and failures in high pressure lines. Following is a brief description of each device.

- *Linear Actuator:* This is one of the oldest types of servo elements used by system engineers. It consists of a pressure cylinder with a piston and either a single ended or dual rod. They incorporate integrally mounted, proportional servovalves to provide highest performance and accuracy. Linear actuators are direct acting devices, eliminating pulleys, guide tracks, ball screws, etc., and their associated mechanical losses. Linear actuators with reduced performance may be constructed by using hydraulic cylinders and external valves. A wide range of actuators are available with operating fluids and pressures, seal configurations, and feedback transducers selectable by the user.

- *Rotary Actuator:* This actuator is similar to an electric motor, including mounting and feedback devices and is available from a number of sources. Again, high performance is achieved when a servovalve is integrated into the actuator housing.

- *Variable Volume, Variable Pressure Pumps:* These are hydraulic pumps driven from a constant speed electric motor with internal components positioned to maintain the required system flow/pressure to operate a hydraulic cylinder, either rotary or linear. The advantage of this system is increased efficiency of the system. The disadvantage is that a separate pump is required for each axis of control.

Motion/Position Fluid Control

Two devices are used to control fluid for motion systems: servovalves and solenoid valves. Each are available in a variety of flow and pressure ranges. The advantages of each type are applications specific and must be weighed by you and the applications engineer who helps you specify your system. Generally, the valves are mounted to a manifold that is either an integral part of the actuator or pump or a separate fluid distribution assembly. Details of each device follow:

- *Servovalves:* These devices use an analog input signal, either voltage or current to control the output. Servovalves can be three-way devices that connect either end of the cylinder to pressure, the other to return. Four-way servovalves provide the highest performance. In a pneumatic system, the return is usually vented to atmosphere. Servovalves with a range of flow sizes and dynamic performance capabilities are readily available from a number of sources with associated application help to properly select the right valve.

- *Solenoid Valves:* These devices use a digital signal to open/close the control orifice. Proportional control can be achieved by Pulse Width Modulation of the command signal. Multiple solenoids and additional components are required to simulate operation of a servovalve. Fixed flow (speed) applications are optimum applications for these devices.

Motion/Position Feedback Devices

Feedback devices for position systems are most often mounted integrally with the motor, but sometimes they are mounted on another system component such as an output gear shaft or a leadscrew. Many varieties of feedback devices have been designed, but the most widely used are the following:

- *Optical Encoder:* There are two types of optical encoders: incremental and absolute. They combine high accuracy with low cost (incremental type), and are, therefore, in widest use for position feedback. They are available for integral mounting with the motor, or for mounting on another shaft. Optical encoders are also used in linear configurations for machine beds. Among their disadvantages, they are less robust than resolvers or magnetic encoders. If used to commutate a brushless DC motor, an optical encoder must also be enhanced with supplementary commutation tracks. The recent introduction of higher resolution magnetic encoders make this technology a viable feedback alternative.

- *Resolver:* The resolver is an absolute position sensing device. This feature, coupled with its robustness, are the reasons for its popularity in high-end applications. Integrated circuit packages are also available for converting the resolver output signal to digital position and velocity data, thereby making it easy to use in digital systems. Resolvers are most common for integral motor mounting, but also for mounting on separate shafts or in linear form for a machine bed.

- *Additional Feedback Devices:* In addition to resolvers and encoders, many applications require the use of additional feedback devices to support most integrated system operations. The feedback required by a given operation can have many forms and may provide a myriad of functions to be supported. Some examples include home initialization sensing, system safety and status monitoring, and user/process interfaces, as well as sensors for position, velocity, or other motion related attributes. See Table 1 for a summary of the most common feedback devices.

Table 1
Common Feedback Devices

DEVICE	OUTPUT	MOTION	CHARACTERISTICS
Encoder	Quadrature single ended differential	Rotary	Position Feedback Home to marker
Linear scale	Quadrature single ended differential	Linear	Position feedback Home to selectable marker
Linear scale with DCRM	Quadrature single ended differential	Linear	Position feedback multiple encoded markers
Absolute encoder	Parallel	Rotary	Position feedback Absolute device
Resolver	Analog- (amplitude or phase)	Rotary	Position feedback 1 rev absolute Rugged
Multiple resolver	Analog	Rotary	Position feedback Multiple rev absolute Rugged

Inductosyn	Analog	Linear or Rotary	Position feedback Single cycle absolute Rugged, Very accurate
Magnetostrictive	Analog Parallel Pulse	Linear or Rotary	Position feedback Absolute
Tachometer	Analog	Rotary	Velocity feedback
Pressure	Analog		Pressure feedback
Load cell	Analog		Force feedback

The use of feedback devices for system safety and status monitoring is very applications dependent. While an x-y stage system programmed to position specimens under a microscope probably wouldn't require the use of a light curtain, a robot programmed to perform a laser cutting operation might. Monitoring system operation for abnormal conditions provides opportunities for the implementation of many types of feedback devices.

User/Process interfaces can also benefit from the use of feedback devices by allowing more information to be available in real time. Imagine a conveyor loader programmed to load a product onto a variable speed conveyor where the line speed is controlled externally. Depending on the product spacing requirements, a scheme to accomplish the loading process could be developed using most types of feedback devices. A simple proximity sensor may be located to signal when the next product is to be loaded; or, the loader can monitor the conveyor speed and calculate the timing based on information downloaded from a host controller for this particular product's package configuration, and then changed later for a different package configuration.

Adjustable Speed Motors and Drives

Systems available for adjustable speed motion control are generally of two types:

- **AC Motors & Drives:** Sometimes known as "Volts per Hertz Drives," these are open loop induction motor drives with a variety of programmable features including as a minimum the following:

  Discrete speed selections.
  Acceleration and deceleration values.
  Boost
  Volts/Hertz Setting

There are many sources for this type of drive which is specified by those desiring a system for a wide power range utilizing standard induction motors.

- **DC Motors & Drives:** Typically, the lowest cost system is the DC drive. The use of brushes is its major limitation. Brushless DC motors overcome the brush wear problem, but typically at a greater initial purchase cost.

The process of selecting an adjustable speed AC or DC drive is one where load is of primary consideration. Motor loads are classified into three main groups depending on how their torque and horsepower varies with operating speed. The following paragraphs deal with the various DC and AC motor load types usually found in process, manufacturing, or machining applications.

A constant torque load is the one most frequently encountered. In this group, the torque demanded by the load is constant throughout the speed range. The load requires the same amount of torque at low speeds as at high speeds. Loads of this type are essentially friction loads. In other words, the constant torque characteristic is needed to overcome friction.

In a constant horsepower situation, the horsepower demanded by the load is constant within the speed range. The load requires high torque at low speeds. With the horsepower held constant, the torque will decrease as the speed increases. Put another way, the speed and torque are inversely proportional to each other.

With a variable torque load, the torque may be directly proportional to some mathematical power of speed, usually speed squared:

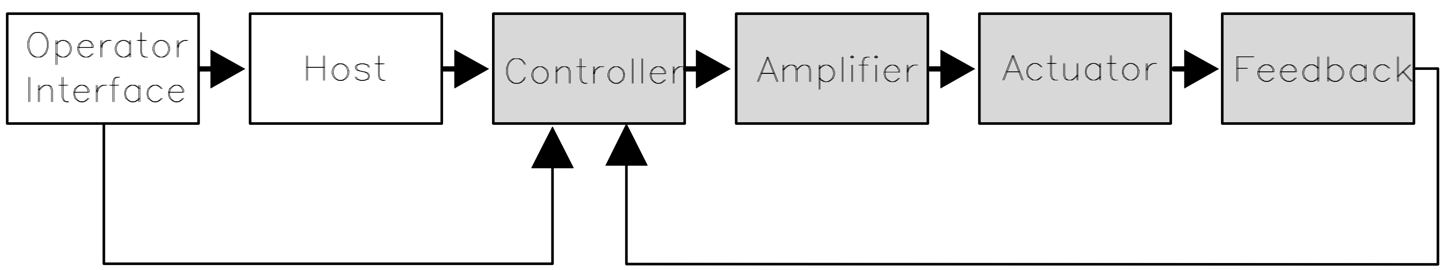
Torque = Constant x (Speed)^2

It is important to understand the speed and torque characteristics as well as horsepower requirements of the type to be considered. AC drive characteristics are somewhat different than DC drives. The demands and economics of a particular application should be matched to the drive capabilities. After this matching process is completed, the decision regarding the type of adjustable speed drive can be made.

When considering load characteristics, the following should be evaluated:

- What type of load is associated with the application?
- Does the load have a shock component?
- What is the size of the load?
- Are heavy inertial loads involved?
- What are the motor considerations?
- Over what speed range are heavy loads encountered?

V. How Do I Select A Programmable Motion Control System?



Classifying Your Application

The first step in determining the best solution for an application involving motion is to classify the application. Classifying the application will help determine what type of motion control is needed and what type of motion features may be required. The key question to ask is: **What type of process is the motion being applied to?** Identifying the process will help determine some of the key requirements that motion systems must address. Some typical classifications of applications and typical motion control requirements are shown below:

Classifying Your Application

- Web lines:
  - Tension control
  - Positioning or ratioing
  - Coordination of motion with external events (registration)
- Metal removal:
  - Multi-axis contouring
  - Complex interpolation (linear, circular, helical)
  - Adaptive control
  - Zero following error servo loop algorithms
- Robotics:
  - Multi-axis coordination
  - Coordinate transformations
  - Ratioing
  - Vision system interface
  - Absolute feedback
- Gantry:
  - Ratioing

    - Linear interpolation
    - Absolute feedback
- Packaging:
    - Ratioing
    - Coordination of motion with external events
    - Vision systems
- Transfer lines:
    - Multi-axis coordination
    - Adaptive feed rate control
    - Feed to hard stop
    - Moving to a gauge input
- Automated storage/retrieval systems (AS/RS):
    - Adaptive feed rate control
    - Jerk limiting acceleration profiles
    - Absolute feedback

Application Parameters

Once an application has been classified, the application parameters have to be defined. The key to a successful application solution is proper definition of the application requirements. This will help determine the machine, motion control, actuator, and feedback device requirements. Some questions which must be answered before a selection can be considered include: How fast? How accurate? How much? Other considerations that must be addressed are listed below:

- Motion parameters:
    - What is the required positioning accuracy?
    - What are the maximum and minimum speeds?
    - What are the maximum acceleration/deceleration rates?
    - What is the duty cycle?
- Continuous load requirements:
    - What is the measured thrust?
    - Is there counterbalance?
    - What is the measured friction?
- Machine characteristics:
    - What are the machine dynamics?
    - What is the reflected load inertia?
    - How is the load moved (e.g. via pneumatics, hydraulics, electric servo)?
    - What are the potential losses to overcome, such as inefficiencies and coeffi cients of friction?
- Communication characteristics:
    - What type (serial, discrete, backplane)?
    - What type & amount of information is to be sent?
    - What are the throughput requirements?
- Input/Output (I/O) requirements:
    - What type?
    - How many?
    - Are there throughput requirements?
- Feedback requirements:
    - What type?
    - What is the required accuracy?

What Are The Motion Requirements?

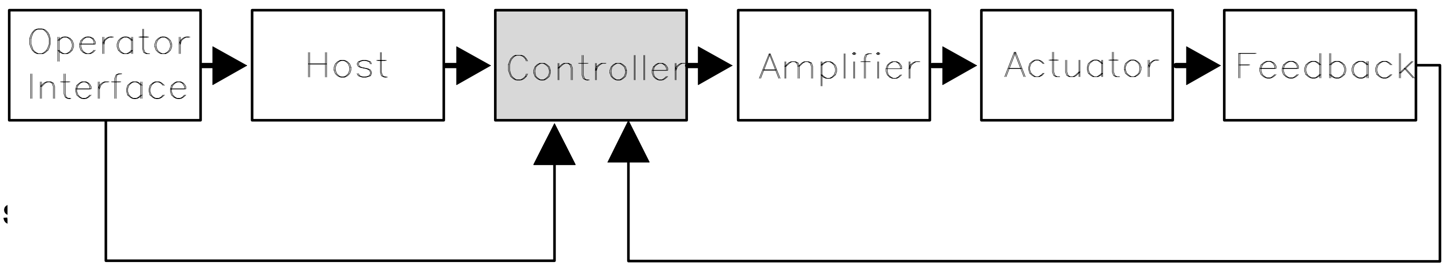
The next question you must ask is: What motion functions are needed? There are four categories of motion functions:

- Simple control of position or velocity of single or non-synchronized multiple axes. This is the simplest of motion requirements. Requirements of non-synchronized multiple axes can be handled by multiple motion modules without concern about tight synchronization of axes on different modules.

- Motion synchronized to external events. Motion often has to be synchronized to some external event. This may be a discrete event (such as limit switch closure), analog event (analog gauge input), or position event (a linear transducer event), and may trigger a change in speed, the start or end of a move, or a position correction. While many controls are capable of performing these functions, they may vary in their throughput capability (number of simultaneous events and reaction time).

- Synchronized multi-axis control. This involves tight coordination of independent axes. Most controls are capable of synchronizing axes within a given module, but may be limited in terms of how tightly they can couple axes on different modules.

- Complex motion algorithms. Typical examples of this motion requirement include ratioing (straight and caming), contouring with various types of interpolation (circular, linear, spline), and time-based cams.



The first issue you must address is the application classification. If the application were classified as machine tool control, robot control, or a transfer line application, an application specific control may be available. Application specific controls have features, performance, and packaging which are designed for specific applications and conform to standards for those applications. For example, CNC controls have a number of features which are required for machine tools. Examples of these features are an RS274 programming interface, multiple axes contouring, circular/linear/spherical/ mathematical interpolation, and operator interface support.

The general purpose controller is used for applications where the application specific control is not appropriate because of cost, packaging, or available features. Choosing the appropriate general purpose control involves answering three key questions:

- What is the control architecture of the application?
- What are the motion requirements?
- What type of feedback is required?

Control Architecture

Critical question to be answered in classifying the application is: What is the control architecture? This question deals with things like:

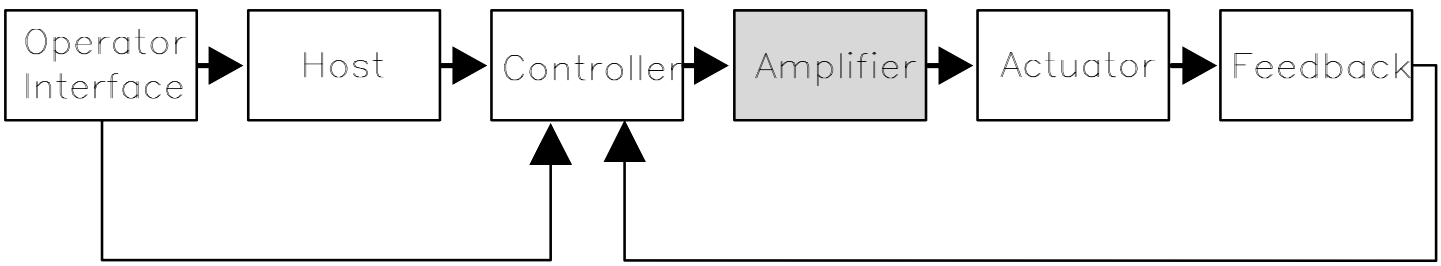
- Is there a host computer or control?
- Does motion drive the process; or is motion a small part of a larger process?
- Is a localized or distributed control architecture desired?

Answers to these questions will impact the type of motion controller used. For example, if motion is a small part of a larger process (as in the case of an assembly line), then the majority of the process may be sequence control with motion subsections. This type of application will typically use a programmable controller to control the process, with a motion control (programmable controller based, stand alone, or smart drive) acting as a slave. If the application is motion dominant (as in the case of machine tools), then the motion function is the major portion of the system and may control the process. There may or may not be a host controller.

In many applications there may already be a host computer or programmable controller that is used for control of the overall process. In these cases, it may be advantageous to use a programmable controller-based motion control that resides in the controller's rack. This type of configuration allows the motion controller access to all of the programmable controller's resources (i.e. power, analog I/O, discrete I/O, operator interface). This approach can also result in a compact, cost effective package. Programmable controller motion modules and associated control boards are generally packaged as 1 to 4 axes modules. Axes within a module can be tightly coupled, while multiple modules may be loosely coupled via discrete wiring between modules or through backplane integration.

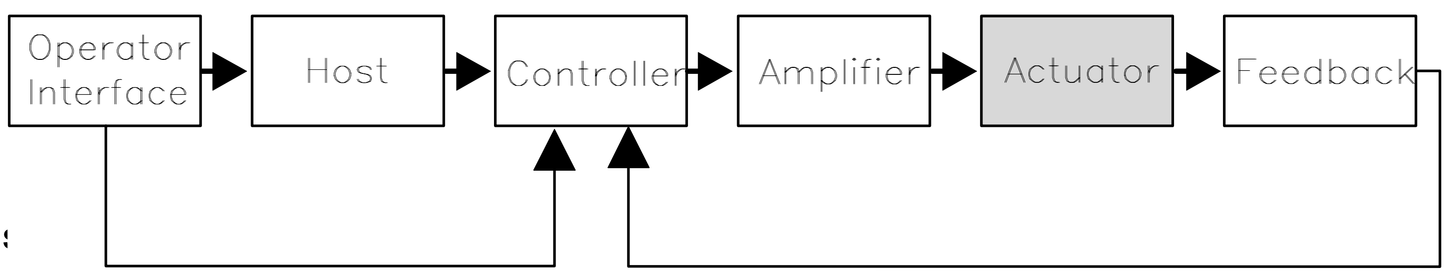
In cases where there is a non-programmable controller host, no host, or the motion section does not have to be tightly coupled, a stand alone controller may be more appropriate. Stand alone controllers are typically supplied in 1 to 8 axes configurations with some handling 32 axes or more. Communication with a host control or operator interface is achieved via discrete wiring (e.g. BCD), serial connection (e.g. RS-232, RS-422), or a multi-drop network (e.g. Ethernet, RS-485, DeviceNet).

If the host utilizes a bus interface, a bus-based motion controller can be used. Controllers are available for most types of buses. Bus-based controls offer a great deal of flexibility and high throughput communications, but may require a commensurate amount of engineering effort to integrate.



Generally, the type of motion amplifier required for a given application is dependent on the type of actuator to be driven. In some cases, actuator performance is defined and optimized with respect to a specific amplifier matched for its use. In many cases, however, there are choices that can be made. For example, if a DC servo motor is selected as the actuator, overall cost may dictate that a PWM amplifier, as opposed to a more costly linear amplifier, is in order. Output voltage relative to motor rating or maximum speed requirement needs to be determined. Continuous and peak current ratings are chosen according to torque requirements.

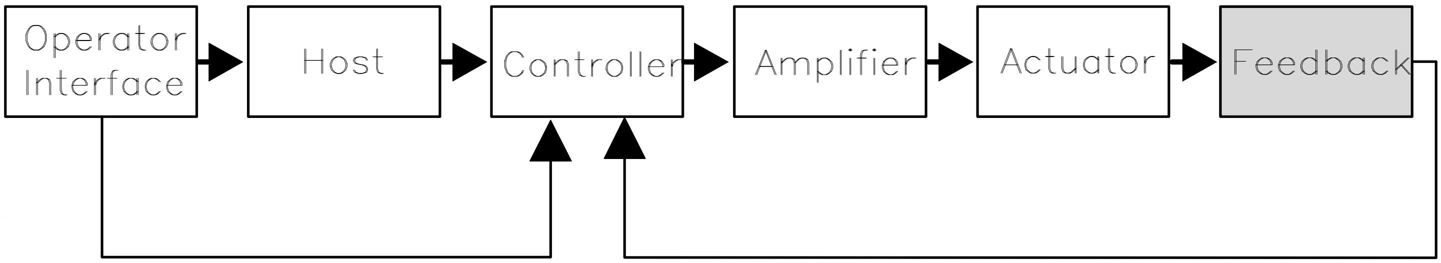
Special drive requirements can exist for all types of drives if extremely high resolution or wide speed range is required. Additionally, many applications require that radio and electromagnetic emissions be kept to a minimum.



Determining the type of motion actuator best suited to your application requires careful consideration. On the surface, it may seem as if any of several types of actuators may be acceptable. The first topic of consideration is usually load definition. Once a set of accurate load characteristics is developed, items such as actuator configuration, size, dynamic characteristics, reliability, and cost can be examined. Since many motion control applications may require the implementation of several types of actuators within the same system, the following questions are intended to help identify which actuator types are best suited to a given task:

- Are there any special system power limitations?
- What is the operational duty cycle?
- Will heat dissipation by the actuator have any adverse effect on the application?
- What is the operating temperature range?
- What type of feedback device is to be used?
- What range of mean time between failure MTBF is desired?
- What are the dynamic characteristics of the intended motion profile?

- What range of shaft velocities are required to achieve the desired feed rates?
- Will your system require direct drive or will a gearing system have to be accommodated?



There are many types of feedback devices as shown in Table 1 on page 13. Motion controls vary in terms of the devices they will support. Most support incremental encoders as standard, and some also support resolvers. If absolute feedback is required, there are controls which will support proprietary suppliers' devices, dual resolvers, or absolute encoders. Some motion controllers also support analog feedback. This feature can be used to interface to load cells, pressure and temperature transducers, and other types of analog feedback devices.

A feedback device will be needed if closed loop control is used, or if events (e.g. turn output on) are to be based on actual machine feedback.

There are a multitude of feedback transducers available which are capable of monitoring speed, position, pressure, tension, and other process variables. The questions which must be addressed in order to determine the best feedback device to use include the following:

- What is the process variable being controlled?
- If the variable is position, is rotary or linear displacement being controlled?
- Is incremental or absolute feedback required? What are the resolution, accuracy and repeatability requirements?
- What is the speed range?
- With what feedback device is the motion control unit compatible?

The most commonly specified position transducer is the encoder. The encoder provides incremental position information to the motion controller via a quadrature type output. If using an incremental encoder is not practical, resolvers or absolute encoders are capable of providing absolute position information. Either device is absolute within one revolution. Dual devices can be used to provide multiple revolution absolute position feedback.

The Physics of Motion

In order to discuss such system characteristics as inertia, mass, acceleration, and the like, it will be necessary for you to be able to quantify some of the properties of your particular application.

Moments of Inertia: Every moving body possesses inertia around its particular axis. If you were, for example, trying to calculate the moment of inertia for a bowling ball with a diameter of 25cm and a weight of 4 kg, the moment of inertia around an axis through its center would be solved as follows:

$$J = 2/5Mr^2$$
$$J = 2/5 \times 4kg \times (0.125m)^2$$
$$J = 0.025kg(m)^2$$

Just as mass is the inertial property in translational motion, moment of inertia is that property of matter which resists a change in rotational motion. In translational motion, force equals mass times acceleration (F=ma), but in rotational motion, Torque equals moment of inertia times angular acceleration (T=Ja).

Angular Momentum: The angular momentum of a rotational body (for example, a shaft or drum) is given by the relation angular momentum equals moment of inertia times angular velocity (P=Jw). Bodies or systems of bodies in rotational motion, unless acted upon by an external force, exhibit conservation of angular momentum; i.e., the product Jw is a constant.

Angular Acceleration: Rotating bodies may undergo changes in angular velocity just as bodies in translation undergo changes in their linear velocity. The basic expression for angular acceleration is:

$$\alpha = \frac{\omega_1 - \omega_2}{t}$$

There are a number of fine points involved in the calculation of these properties such as the differentiation between centripetal acceleration and tangential acceleration. Your applications engineer can help you complete these calculations appropriate to your particular system characteristics.

Torque: Torque is the cause of angular acceleration. Torque is defined as the rotary equivalent of force. It is equal to the product of the force perpendicular to the radius of motion and distance from the center of rotation to the point where the force is applied. As a formula, it is represented as:

$$T = F \times r$$

Power: Power is transmitted by rotating shafts by virtue of the fact that the torque applied produces an angular velocity. Therefore, power equals torque times angular velocity (P=Tw).

Coefficient of Friction: In order to calculate the power requirements for your applications, the applications engineer also addresses the forces involved to overcome friction. The frictional force between two surfaces equals the product of the force pressing the surfaces together times the coefficient of friction, represented as:

$$F_{fr} = WK$$

There are many of these values which can be referenced in most engineering and physical handbooks.

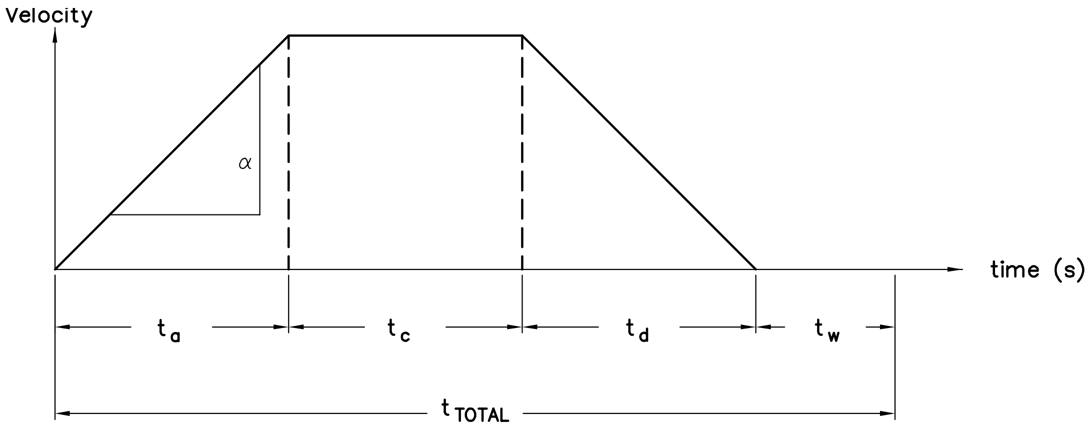
Typical Application Types

Following are five typical programmable motion control schemes which are used in the vast majority of the applications. See Appendix A for explanations of the symbols shown.

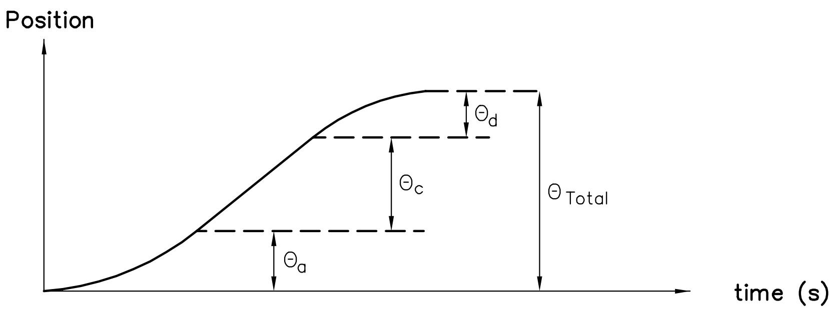
Putting It All Together

Based on the analysis contained in this chapter, the search for an optimum programmable motion control system can be

Figure 3
Profile Calculations



VELOCITY VS. TIME



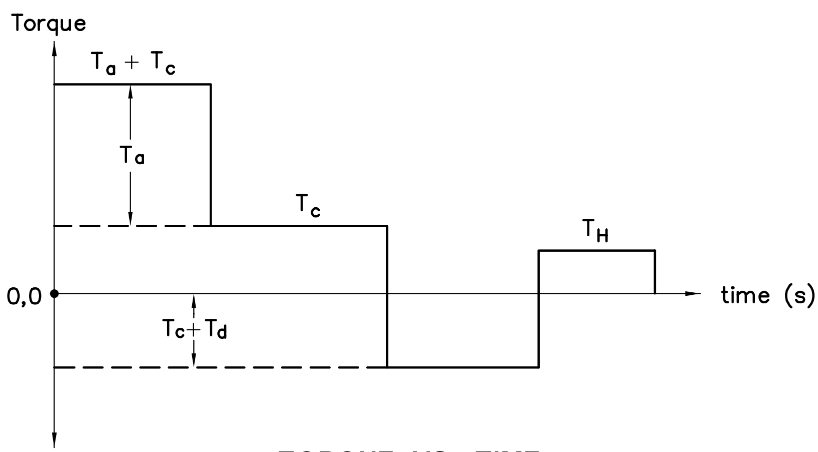
REVOLUTIONS VS. TIME

TRAPEZOIDAL

$$\Theta_{Total} = \Theta_a + \Theta_b + \Theta_d$$

$$= \omega max\left(\frac{t_a}{2} + t_c + \frac{t_d}{2}\right)$$

$$\omega max = \frac{\Theta_{Total}}{\left(\frac{t_a}{2} + t_c + \frac{t_d}{2}\right)}$$



TORQUE VS. TIME

TRIANGULAR

$$\Theta_{Total} = \Theta_a + \Theta_d$$

$$= \omega\, max\left(\frac{t_a}{2} + \frac{t_d}{2}\right)$$

$$\omega max = \frac{\Theta_{Total}}{\left(\frac{t_a}{2} + \frac{t_d}{2}\right)}$$

$$\alpha = \frac{\omega\, max}{t_a} * 2\pi$$

FUNDAMENTAL EQUATIONS FOR TORQUE CALCULATION

$T_{TOTAL} = T_a + T_C$: Total Torque (in–lb) = Acceleration Torque + Constant Torque

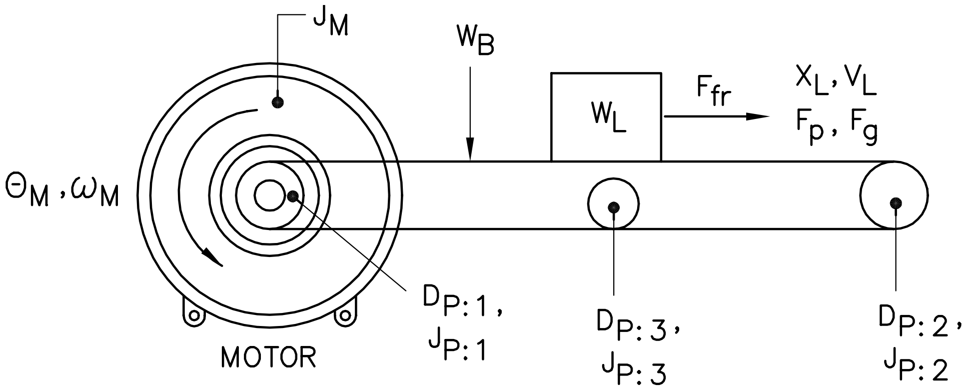
$T_a = J_{TOTAL} * \alpha$ Acceleration Torque (in–lb) = Mass Inertia (in–lb–sec^2) * angular acceleration

$\alpha = \frac{\omega_{max.}}{t_a} * 2\pi$: Angular Acceleration $\left(\frac{radians}{sec^2}\right) = \frac{\text{Maximum speed}}{\text{accel time}} \quad \left(\frac{rev/sec}{sec}\right)$

T_C = Torque due to all other "Constant" forces, such as friction, gravity, push–pull, preload

$T_{RMS.}$ = "Root Mean Squared" (average) Torque over entire cycle $= \sqrt{\frac{(T_a + T_c^2)\, t_a + T_c^2 t_c + (T_d + T_c)^2 t_d + T_H^2 t_w}{t_a + t_c + t_d + t_w}}$

Figure 4
Conveyor



$$C_{P:1} = \pi * D_{P:1} = \frac{N_t}{P_G} \quad \text{[in]}$$

$$\Theta_M = \frac{X_L}{C_{P:1}} \quad \text{[revs]}$$

$$\omega_M = \frac{V_L}{C_{P:1}} \quad \text{[revs/sec]}$$

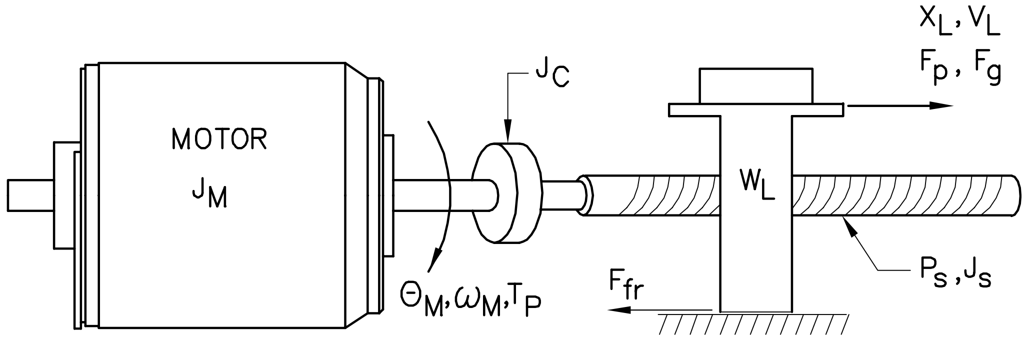
$$J_{TOTAL} = J_M + J_{P:1} + J_{P:2} * \left(\frac{D_{P:1}}{D_{P:2}}\right)^2 + J_{P:3} * \left(\frac{D_{P:1}}{D_{P:3}}\right)^2 + \frac{J_{L \rightarrow M}}{e} \quad \text{[in-lb-sec}^2\text{]}$$

These two terms are also influenced by the efficiency but it is not necessarily the same number as the overall efficiency of the mechanism.

$$J_{L \rightarrow M} = \left(\frac{W_L + W_B}{g}\right) * \left(\frac{D_{P:1}}{2}\right)^2 \quad \text{[in-lb-sec}^2\text{]}$$

$$T_{C \rightarrow M} = \frac{F_p + F_g + F_{fr}}{e} * \left(\frac{D_{P:1}}{2}\right)^2 \quad \text{[in-lb]}$$

Figure 5
Leadscrew



$$\Theta_M = P_S * X_L \quad \text{[revs]}$$

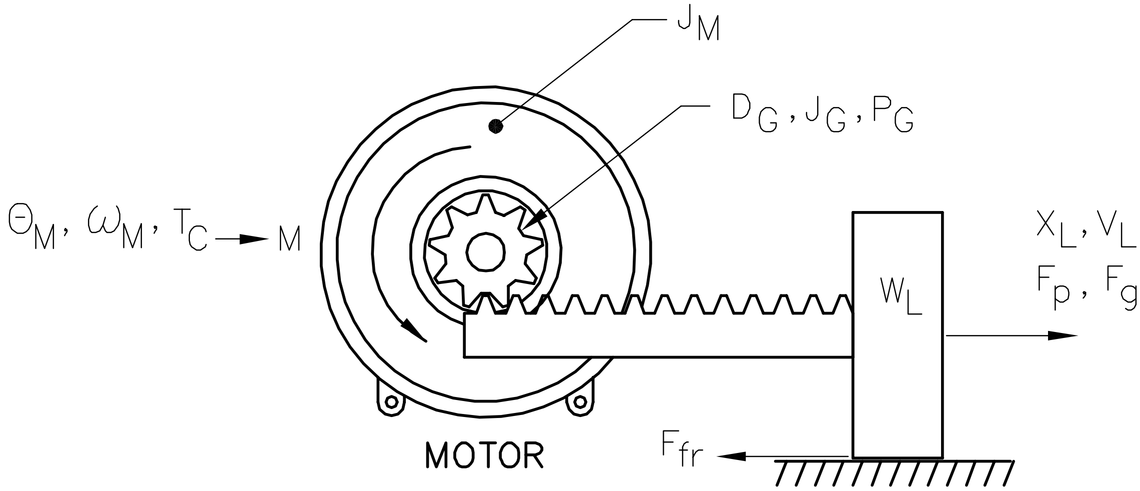
$$\omega_M = P_S * V_L \quad \text{[revs/sec]}$$

$$J_{TOTAL} = J_M + J_C + J_S + \frac{J_{L \rightarrow M}}{e} \quad [\text{in-lb-sec}^2]$$

$$J_{L \rightarrow M} = \left(\frac{W_L}{g}\right) * \left(\frac{1}{2\pi P_S}\right)^2 \quad [\text{in-lb-sec}^2]$$

$$T_{C \rightarrow M} = \frac{\left(F_p + F_g + F_{fr}\right) * P_S}{2\pi * e} + T_p \quad \text{[in-lb]}$$

Figure 6
Rack & Pinion



$$C_G = \pi * D_G = \frac{N_t}{P_G} \qquad [in]$$

$$\Theta_M = \frac{X_L}{C_G} \qquad [revs]$$

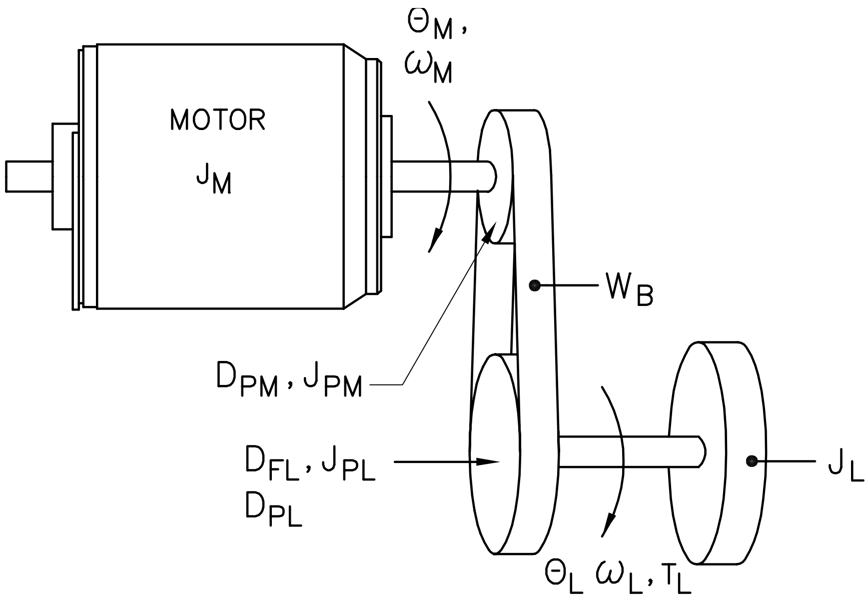
$$\omega_M = \frac{V_L}{C_G} \qquad [revs/sec]$$

$$J_{TOTAL} = J_M + J_G + \frac{J_{L \to M}}{e} \qquad [in-lb-sec^2]$$

$$J_{L \to M} = \left(\frac{W_L}{g}\right) * \left(\frac{D_G}{2}\right)^2 \qquad [in-lb-sec^2]$$

$$T_{C \to M} = \frac{F_p + F_g + F_{fr}}{e} * \left(\frac{D_G}{2}\right) \qquad [in-lb]$$

Figure 7
Timing Belt



$N_r = \frac{D_{PL}}{D_{PM}}$

$J_{L \to M} = \left(\frac{1}{N_r}\right)^2 * J_L\left(\frac{1}{e}\right)$ [in-lb-sec^2

$\Theta_M = N_r * \Theta_L$ [revs]

$J_{PL \to M} = \left(\frac{1}{N_r}\right)^2 * J_{PL}\left(\frac{1}{e}\right)$ [in-lb-sec^2]

$\omega_M = N_r * \omega_L$ [revs/sec]

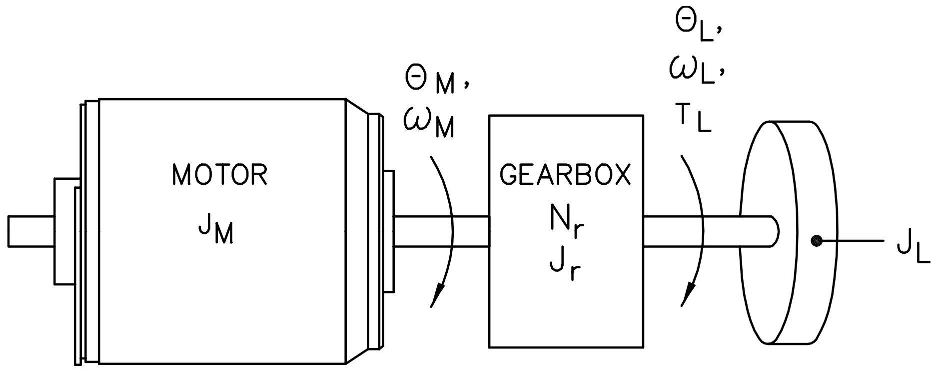
$T_{C \to M} = \frac{T_L}{N_r * e}$ [in-lb]

$J_{TOTAL} = J_M + J_{PM} + J_{B \to M} + J_{PL \to M} + J_{L \to M}$ [in-lb-sec^2]

$J_{B \to M} = \frac{W_B}{ge} * \left(\frac{D_{PM}}{2}\right)^2$ [in-lb-sec^2]

This "e" is not necessarily the same as the overall efficiency of the mechanism. It is probably higher.

Figure 8
Gearbox



$$N_r = \frac{\text{INPUT SPEED}}{\text{OUTPUT SPEED}}$$

$$\Theta_M = N_r * \Theta_L \quad \text{[revs]}$$

$$\omega_M = N_r * \omega_L \quad \text{[revs/sec]}$$

$$J_{TOTAL} = J_M + J_r + \frac{J_{L \rightarrow M}}{e} \quad [\text{in-lb-sec}^2]$$

$$J_{L \rightarrow M} = \left(\frac{1}{N_r}\right)^2 * J_L \quad [\text{in-lb-sec}^2]$$

$$T_{C \rightarrow M} = \frac{T_L}{N_r * e} \quad \text{[in-lb]}$$

narrowed greatly. One or more of the following general categories should meet your needs:

- Standalone Controllers:
    - Computerized Numerical Control
    - Robot Control
    - General Purpose Control

- Subordinate Controllers:
    - Programmable Controller
    - Bus-based Controller

- Drive Amplifiers:
    - Adjustable Speed
        - AC
        - DC
    - Motion/Position
        - AC
        - DC
    - Stepper

- Motion Actuators:
    - AC
    - DC
    - Stepping
    - Other (Hydraulic/Pneumatic)

- Feedback Transducers:
    - Linear
    - Rotary
    - Other

After preliminary analyses have been made, contact competent suppliers so your specific application can be reviewed in order to insure that the motion control components and system you select have the features necessary for your particular application.

VI. What About Technical Standards?

Background

The area of technical standards is, perhaps, one of the fastest moving and most confusing aspects of the motion control field. One of the reasons for this is that there is, as yet, no single, unified, complete set of standards for motion control technology anywhere in the world.

The 1990s are a time of vast and far reaching changes, from the dawning of EC 1992 to the opening of previously inaccessible markets and technologies. Accompanying these developments are various performance and applications standards which are likely to both help and confuse users and manufacturers alike in the years to come. Undoubtedly, many standards bodies never foresaw the interrelated and systems-oriented configurations that today's motion control applications demand.

NEMA acts as both an originator and an information source for standards for motion control products, motors, sensors, communications, controls, and related technologies in the United States. It is presently addressing the question of control standards in the Association's Programmable Motion Control Business Segment, Industrial Control and Systems Section, and Motor Generator Group. The PMC group, in fact, has already issued MG-7, the first comprehensive standard for motion and position control devices to be published anywhere. They continue, in concert with other industry and standards groups throughout the world, to work towards the goal of providing complete and practical standards information for motion control technology in the years to come.

The following standards compendium identifies some, although by no means all, programmable motion control standards along with a short description and information on what organization developed and distributes them. Before they are referenced in your applications specifications, the entire standard should be obtained and reviewed to ascertain whether or not it is appropriate for your specific situation. Note that some referenced items are still pending final review and release. To assist you in the procurement of these standards, addresses and phone numbers of the standards development organizations appear at the end of this chapter.

Product Standards

Title: Programmable Controllers
Designation: ANSI/ICS 3-304
Description: Provides information concerning the construction, programming, performance, test, installation, protection and safety of programmable controllers. The definitions and standards of Part ICS 3-100 and NEMA Standards Publication No. ICS 1 apply.
Developed by: NEMA (ANSI also distributes)

Title: Motion/Position Control Motors And Controls
Designation: NEMA/MG-7
Description: Provides technical information concerning performance, safety, tests, construction, and manufacture of servo and stepping motors, feedback devices, and related control systems.
Developed by: NEMA

Title: Human Engineering Design Criteria for Hand-held Robot Control Pendants
Designation: ANSI/RIA R15.02/1-1990
Description: Provides design and applications considerations for the production and incorporation of hand-held control devices designed to interface with robotic systems.
Developed by: RIA (ANSI also distributes)

Title: Automated Vision SystemsCPerformance TestCMeasurement of Relative Position of Target Features in Two-Dimensional Space
Designation: ANSI/AVA A15.05/1-1989
Description: Provides information for application of vision to automated equipment and methods to verify and measure the performance of same.
Developed by: AIA (ANSI also distributes)

Title: Safety Standard for Industrial Control Equipment
Designation: UL 508
Description: A general standard for safety covering such topics as enclosures, wiring and spacings, tests and rating, and precautions for motors and controls.
Developed by: UL

Title: Enclosures for Electrical Equipment
Designation: NEMA Standards Publication No. 250
Description: Includes definitions, descriptions, features, and test criteria for enclosures for equipment up to 1,000 volts maximum. Although enclosures for rotating equipment are not included, this publication is a basis for NEMA standards for motion control enclosures.
Developed by: NEMA

Title: Industrial Cell Controller Classification Concepts and Selection Guide
Designation: NEMA/IA 1-1990
Description: Provides a general description of cell controllers used in automated control systems configurations that supervise and coordinate plant floor operations.
Developed by: NEMA

Title: General Standards for Industrial Control Devices, Controllers, and Assemblies
Designation: NEMA/ICS 1-1983
Description: Provides practical general information concerning ratings, construction, testing, performance, and manufacture of industrial control and systems equipment.
Developed by: NEMA

Title: Safety Guidelines for the Application, Installation and Maintenance for Solid State Control
Designation: NEMA/ICS 1.1-1984
Description: Provides general guidelines for the application, installation, and maintenance of solid state control in the form of individual devices or packaged assemblies incorporating solid state components.
Developed by: NEMA

Title: Preventive Maintenance of Industrial Control and Systems Equipment
Designation: NEMA/ICS 1.3-1986
Description: Covers fundamental principles, safety precautions, and common guidelines for preventive maintenance of most industrial control and systems equipment.
Developed by: NEMA

Title: Industrial Control Devices, Controllers and Assemblies
Designation: NEMA/ICS 2-1988
Description: Provides practical information concerning ratings, construction, testing, performance, and manufacture of industrial control devices.
Developed by: NEMA

Title: Industrial Systems
Designation: NEMA/ ICS 3-1988
Description: Provides practical information concerning ratings, construction, testing, performance, and manufacture of industrial systems equipment.
Developed by: NEMA

Title: Safety Standards for Construction and Guide for Selection, Installation, and Operation of Adjustable-speed Drive Systems
Designation: NEMA/ICS 3.1-1983
Description: These standards apply to all industrial equipment, electrical components and wiring that are part of the electrical drive system, commencing at the point of input power.
Developed by: NEMA

Title: Industrial Robots and Robot SystemsCCommon Identification Methods for Signal and Power Carrying Conductors
Designation: ANSI/RIA R15.01-1-1990
Description: A standard for the electrical interfacing of industrial robots and robotic systems.
Developed by: RIA (ANSI also distributes)

In surveys conducted by both NEMA and other industry groups, the pervasive lack of programming language and interface standards for control products is, along with the lack of software standards in general, the most frequently mentioned problem confronting the motion control industry today. This problem is confounded by the fact that while Europe appears to favor fiber optic systems, the United States leans towards the copper cable approach. Nevertheless, some standards do exist which can be useful for a motion system user or specifier to know. The following include communication and interface standards which are widely, but not universally, accepted as de facto standards for much commercial and industrial equipment.

Interface Standards

Title: Interface Between Data Terminal Equipment and Data Circuit-Terminating Equipment Employing Serial Binary Data Interchange
Designation: ANSI/EIA 232-D
Description: This standard for the popularly known RS-232/232-C serial interface is applicable for the interconnection of data terminal equipment and data circuit-terminating equipment employing serial binary data interchange. It defines signal characteristics of interchange circuits, functional description of interchange circuits, and standard interfaces for selected communication system configurations. Included are 13 specific interface configurations intended to meet the needs of 15 defined system applications. Additionally, Industrial Industry Bulletin No. 9, Application Notes for EIA- 232-D is a recommended companion document.
Developed by: EIA (ANSI also distributes)

Title: Axis and Motion Nomenclature for Numerically Controlled Machines
Designation: ANSI/EIA-267-B
Description: This standard is the basis for innumerable post processors and for existing as well as likely machine control units.

Developed by: EIA (ANSI also distributes)
Title: Interchangeable Variable Block Data Contouring, Format for Positioning and Contouring/Positioning Numerically Controlled Machines
Designation: ANSI/EIA-274-D
Description: This standard applies whenever a variable block format is used on perforated tape to control contouring or contouring/positioning numerically controlled machines.
Developed by: EIA (ANSI also distributes)

DeviceNet: DeviceNet is a low-level network that provides connections between simple industrial devices (senors, actuators) and higher-level devices (controllers).

Title: Electrical Characteristics of Balanced Voltage Digital Interface Circuits
Designation: EIA-422-A
Description: This standard for the RS-422 interface specifies the electrical characteristics of the balanced voltage digital interface circuit normally implemented in integrated circuit technology. EIA standard EIA-449 provides the mechanical characteristics for these systems.
Developed by: EIA

Title: Electrical Characteristics of Unbalanced Voltage Digital Interface Circuits
Designation: EIA-423-A
Description: This standard specifies the electrical characteristics of the unbalanced voltage digital interface circuit normally implemented in integrated circuit technology. EIA standard EIA-449 provides the mechanical characteristics for these systems.
Developed by: EIA

Title: Manufacturing Automation Protocol
Designation: MAP Specification
Description: This specification references a series of standards and documents related to production machinery control and communications. No longer used in USA; survives in modified form in Japan.

Developed by: MAP/TOP User Group, through SME and COS

Title: Subset of ANS Code for Information Interchange for Numerical Machine Control Perforated Tape
Designation: ANSI/EIA-358-B
Description: Describes use of ANSI X3.4 for numerically controlled machines and associated perforated tape preparation equipment.
Developed by: EIA (ANSI also distributes)

Title: 32 Bit Binary CL Exchange (BCL) Input Format for Numerically Controlled Machines
Designation: EIA-494
Description: Provides standard input format to enhance portability of part programs among numerically controlled machines.
Developed by: EIA

Title: Interface Between a Numerical Control Unit and Peripheral Equipment
Designation: EIA-491
Description: Defines common interfaces and connector contacts to enable user to connect numerical control equipment to a plurality of peripheral devices.
Developed by: EIA
Title: Manufacturing Message Specification (MMS)
Designation: ISO/IEC 9506
Description: This standard addresses communication methods between production machinery and equipment. Networking considerations are addressed as are protocol concerns for different classes of programmable devices on the factory floor.
Developed by: ISO/TC184/SC5/WG2

Title: Coded Character SetC7-Bit American National Standard for Information Exchange
Designation: ANSI X3.4
Description: This standard contains the ASCII code value of Decimal/Hexadecimal values. It is used for intermachine communication and for control commands. The counterpart for CNC equipment is the EIA standard for RS-358B.
Developed by: CBEMA (only ANSI distributes).

Title: Punched Codes
Designation: EIA RS-244B
Description: Standard for character and tape punched input used for numerical machine code, which is different from ASCII code.
Developed by: EIA
Title: Character Code for Numerical Machine Control Perforated Tape
Designation: EIA-244-B
Description: A hardware standard which defines a method for transmitting high speed serial data over very long distances using a balanced, twisted pair transmission line.
Developed by: EIA

Title: Portable Operating System Interface
Designation: POSIX 1003
Description: This set of standards defines a standard interface between a real-time application and the operating system. Designed to provide the benefits of UNIX and open systems without having to use actual UNIX code.
Developed by: IEEE

Title: Portable Operating System Interface for Computer Environments
Designation: 1003.1
Description: This set of standards defines a standard interface between a real-time application and the operating system. Designed to provide the benefits of UNIX and open systems without having to use actual UNIX code.
Developed by: IEEE

Title: Profibus
Designation: EN 50 170 (European Fieldbus Standard)
Description: Profibus is a vendor-independent, open fieldbus standard for a wide range of applications in manufacturing, process and building automation.
Developed by: Profibus International

Title: SYSTEM Interface (SERCOS) C Serial Data Link for Real-Time Communications Between Controls and Drives
Designation: Proposed IEC (International Electrotechnical Commission) Standard
Description: A fiber-optics-based standard for interface of digitally controlled drives to general machine controls, including NC controls. It defines the interface for exchange of command values and additional functions. It contains specifications for transmission medium, topology, connector technology, signal level, procedures, message (telegram) content, data format, and scaling.
Developed by: The SERCOS Interface Promotion Association. The IEC will assume the final control of the finished standard.

Title: Safety Standard for Industrial Robots & Robotic Equipment
Designation: UL 1740 (Proposed)
Description: Safety standards and tests applicable to many automated installations
Developed by: UL

Both standards and motion control products are organic entities. They are constantly changing, adapting, and growing to meet environmental and process-specific requirements. We anticipate that NEMA's Programmable Motion Business Segment will begin to establish a firm foundation for future motion control standards. These standards will reflect the uses, the technology, and innovations used to accomplish both routine and complex motion control tasks.

While not addressed specifically in this handbook, we also envision that the world of motion control will grow even more complex than it is at the moment. Increasing integration and even more demanding performance requirements will challenge motion control systems to provide ever greater component and system interconnectability; software and hardware transportability; greater computing, processing, and reporting power; and such ancillary integrations as vision capability, tactile feedback, and neural programming enhancement capabilities.

Standards Sources

You may want to contact one or more of the following organizations for additional information on standards activities and the previously referenced standards themselves.

AIA (Automated Imaging Association)
900 Victors Way

P.O. Box 3724
Ann Arbor, MI 48106
(734)994-6088 Web Site: www.automated-imaging.org

ANSI (American National Standards Institute)
11 West 42nd Street
New York, NY 10036
(212) 642-4900 Web Site: www.ansi.org

EIA (Electronic Industries Association)
2500 Wilson Blvd
Arlington, VA 22201
703-907-7500 Web Site: www.eia.org

IEEE (Institute of Electrical & Electronics Engineers)
PO Box 1331
Piscataway, NJ 08855-1331
(908) 562-3803 Web Site: www.standards.ieee.org

NEMA (National Electrical Manufacturers Association)
1300 North 17th Street
Suite 1847
Rosslyn, VA 22209
703-841-3201 Web Site: www.nema.org

NIST (National Institute of Standards & Technology)
Building 221/A323
Gaithersburg, MD 20899-0001
(301) 975-2208 Web Site: www.nist.gov

RIA (Robotic Industries Association)
P.O. Box 3724
Ann Arbor, MI 48106
(734) 994-6088 Web site: www.robotic.org

SME (Society of Manufacturing Engineers)
One SME Drive
Post Office Box 930
Dearborn, MI 48121
(313) 271-1500 Web Site: www.sme.org

UL (Underwriters Laboratories)
333 Pfingsten Road
Northbrook, Il 60062
(708) 272-8800 Web Site: www.ul.com

VII. What Do All These Buzzwords Really Mean?

Motion Control Terminology

This chapter contains a description of many of the terms used in the design and application of motion control products and programmable devices. Although other reference books and definitions exist, these should serve as a ready reference for most needs.

Absolute Position: Position referenced to a fixed zero position.
Absolute Positioning: Refers to a motion control system employing position feedback devices (absolute encoders) to maintain a given mechanical location.
Absolute Programming: A positioning coordinate reference wherein all positions are specified relative to some reference, or

“home” position. This is different from incremental programming, where distances are specified relative to the current position.
AC Adjustable-Speed Drive: All equipment required to adjust the speed or torque of AC electric motor(s) by controlling both frequency and voltage applied to the motor(s).
AC Servo Drive: A servo drive used to control either or both synchronous or induction AC motors.
Acceleration: The change in velocity as a function of time. Acceleration usually refers to increasing velocity and deceleration describes decreasing velocity.
Accuracy: The difference between the expected value of a parameter and its actual value.
Actuator: A device which creates mechanical motion by converting various forms of energy to mechanical energy.
Adaptive Control: A technique to allow the control to automatically compensate for changes in system parameters such as load variations.
Ambient Temperature: The temperature of the cooling medium, usually air, immediately surrounding the motor or another device.
Amplifier: Electronics which convert low level command signals to high power voltages and currents to operate a servomotor.
ASCII (American Standard Code for Information Interchange)*:* This code assigns a number to each numeral and letter of the alphabet. In this manner, information can be transmitted between machines as a series of binary numbers.
Bandwidth: The frequency range in which the magnitude of the system gain expressed in dB is greater than -3 dB.
Back EMF: The voltage generated when a permanent magnet motor is rotated. This voltage is proportional to motor speed and is present regardless of whether the motor winding(s) are energized or un-energized.
Baud Rate: The number of binary bits transmitted per second on a serial communications link (such as RS-232).
Bit (Binary Digit): A unit of information equal to 1 binary decision or having only a value 0 or 1.
Block Diagram: A simplified representation of a system, with each component represented by a block, and each block positioned in order of signal flow through the system.
Bode Plot: A plot of the magnitude of system gain in dB and the phase of system gain in degrees versus the sinusoidal input signal frequency in logarithmic scale.
Brush: Conducting material which passes current from the DC motor terminals to the rotating commutator.
Brushless Servo Drive: A servo drive used to control a permanent magnet synchronous AC motor. May also be referred to as an AC Servo Drive.
Bus: A group of parallel connections carrying pre-assigned digital signals. Buses usually consist of address and data information and miscellaneous control signals for the interconnection of microprocessors, memories, and other computing elements.
CAM Profile: A technique used to perform nonlinear motion electronically similar to that achieved with mechanical cams.
Characteristic Equation: 1+ GH = 0, where G is the transfer function of the forward signal path and H is the transfer function of the feedback signal path.
Circular Coordinated Move: A coordinated move where the path between endpoints is the arc of a circle.
Class B Insulation: A NEMA insulation specification. Class B insulation is rated to an operating temperature of 130 degrees centigrade.
Class H Insulation: A NEMA insulation specification. Class H insulation is rated to an operating temperature of 180 degrees centigrade.
Closed Loop: A broadly applied term relating to any system where the output is measured and compared to the input. The output is then adjusted to reach the desired condition. In motion control the term is used to describe a system wherein a velocity or position (or both) transducer is used to generate correction signals by comparison to desired parameters.
Cogging: A term used to describe non-uniform angular velocity. Cogging appears as a jerkiness especially at low speeds.
Command Position: The desired angular or linear position of an actuator.
Commutation: A term which refers to the action of steering currents or voltage to the proper motor phases so as to produce optimum motor torque. In brush type motors, commutation is done electromechanically via the brushes and commutator. In brushless motors, commutation is done by the switching electronics using rotor position information typically obtained by hall sensors, a tachsyn, a resolver or an encoder.
Commutator: A mechanical cylinder consisting of alternating segments of conductive and insulating material. This cylinder used in DC motors passes currents from the brushes into the rotor windings and performs motor commutation as the motor rotates.
Compensation: The corrective or control action in a feedback loop system which is used to improve system performance characteristics such as accuracy and response time.
Compensation, Feedforward: A control action which depends on the command only and not the error to improve system response time.
Compensation, Integral: A control action which is proportional to the integral or accumulative time error value product of the feedback loop error signal. It is usually used to reduce static error.
Compensation, Lag: A control action which causes the lag at low frequencies and tends to increase the delay between the input and output of a system while decreasing static error.
Compensation, Lead: A control action which causes the phase to lead at high frequencies and tends to decrease the delay between the input and output of a system.
Compensation, Lead Lag: A control action which combines the characteristics of lead and lag compensations.

Compensation, Proportional: A control action which is directly proportional to the error signal of a feedback loop. It is used to improve system accuracy and response time.
Compliance: The amount of displacement per unit of applied force.
Computer Numerical Control: A computer-based motion control device programmable in a numerical word address format. A computer numerical control (CNC) product typically includes a CPU section, operator interface devices, input/output signal and data devices, software and related peripheral apparatus.
Control Systems or Automatic Control Systems: An engineering or scientific field that deals with controlling or determining the performance of dynamic systems such as servo systems.
Coordinated Motion: Multi-axis motion where the position of each axis is dependent on the other axis such that the path and velocity of a move can be accurately controlled. (Requires coordination between axes.)
Coupling Ratio: The ratio of motor velocity to load velocity for a load coupled to motor through a gear or similar mechanical device.
Critical Damping: A system is critically damped when the response to a step change in desired velocity or position is achieved in the minimum possible time with little or no overshoot.
Daisy Chain: A term used to describe the linking of several RS232C devices in sequence such that a single data stream flows through one device and on to the next. Daisy-chained devices usually are distinguished by device addresses which serve to indicate the desired destination for data in the stream.
Damping: An indication of the rate of decay of a signal to its steady state value. Related to setting time.
Damping Ratio: Ratio of actual damping to critical damping. Less than one is an underdamped system and greater than one is an overdamped system.
DC Adjustable-Speed Drive: All equipment required to adjust the speed or torque of DC motor(s) by controlling the voltages applied to the armature and/or field of the motors.
DC Drive: An electronic control unit for running DC motors. The DC drive converts AC line current to a variable DC current to control a DC motor. The DC drive has a signal input that controls the torque and speed of the motor.
Dead Band: A range of input signals for which there is no system response.
Decibel (dB): A logarithmic measurement of gain. If G is a systems gain (ratio of output to input) then 20 log G = gain in decibels (dB).
Demag Current: The current level at which the motor magnets will be demagnetized. This is an irreversible effect which will alter the motor characteristics and degrade performance.
Detent Torque: The maximum torque that can be applied to an un-energized stepping motor without causing continuous rotating motion.
Dielectric Test: A high voltage breakdown test of insulation's ability to withstand an AC voltage. Test criterion limits the leakage current to a specified magnitude and frequency, applied between the specified test points.
Differential: An electrical input or output signal which uses two lines of opposite polarity referenced to the local signal ground.
Distributed Processing: A technique to gain increased performance and modularity in control systems utilizing multiple computers or processors.
DNC, Direct Numerical Control: Technique of transferring part program data to a numerical control system via direct electrical connection in place of paper tapes.
Drive, Analog: Usually referring to any type of motor drive in which the input is an analog signal.
Drive, Digital: Usually referring to any type of motor drive in which the tuning or compensation is done digitally. Input may be an analog or digital signal.
Drive, Linear: A motor drive in which the output is directly proportional to either a voltage or current input. Normally both inputs and outputs are analog signals. This is a relatively inefficient drive type.
Drive, PWM: A motor drive utilizing Pulse-Width Modulation techniques to control power to the motor. Typically a high efficiency drive that can be used for high response applications.
Drive, SCR: A DC motor drive which utilizes internal silicon controlled rectifiers as the power control elements. Usually used for low bandwidths, high power applications.
Drive, Servo: A motor drive which utilizes internal feedback loops for accurate control of motor current and/or velocity.
Drive, Stepper: Electronics which convert step and direction inputs to high power currents and voltages to drive a stepping motor. The stepping motor driver is analogous to the servo motor amplifier.
Duty Cycle: For a repetitive cycle, the ratio of on time to total cycle time.
Dynamic Braking: A passive technique for stopping a permanent magnet brush or brushless motor. The motor windings are shorted together through a resistor which results in motor braking with an exponential decrease in speed.
Efficiency: The ratio of output power to input power.
Electrical Time Constant: The ratio of armature inductance to armature resistance.
Electronic Gearing: A technique used to electrically simulate mechanical gearing. Causes one closed loop axis to be slaved to another open or closed loop axis with a variable ratio.
EMI: Electro-Magnetic Interference: EMI is noise which, when coupled into sensitive electronic circuits, may cause problems.
Encoder: A type of feedback device which converts mechanical motion into electrical signals to indicate actuator position.

Typical encoders are designed with a printed disc and a light source. As the disc turns with the actuator shaft, the light source shines through the printed pattern onto a sensor. The light transmission is interrupted by the patterns on the disc. These interruptions are sensed and converted to electrical pulses. By counting these pulses, actuator shaft position is determined.
Encoder, Absolute: A digital position transducer in which the output is representative of the absolute position of the input shaft within one (or more) revolutions. Output is usually a parallel digital word.
Encoder, Incremental: A position encoding device in which the output represents incremental changes in position.
Encoder, Linear: A digital position transducer which directly measures linear position.
Encoder Marker: A once-per-revolution signal provided by some incremental encoders to specify a reference point within that revolution. Also known as Zero Reference signal or index pulse.
Encoder Resolution: A measure of the smallest positional change which can be detected by the encoder.
Explosion-proof: A motor classification that indicates a motor is capable of withstanding internal explosions without bursting or allowing ignition to reach beyond the confines of the motor frame.
Fall Time: The time for the amplitude of system response to decay to 37% of its steady-state value after the removal of a steady-state step input signal.
Feedback: A signal which is transferred from the output back to the input for use in a closed loop system.
Feed Forward: A technique used to pre-compensate control a loop for known errors due to motor, drive, or lead characteristics. Provides improved response.
Field Weakening: A method of increasing the speed of a wound field DC motor; reducing stator magnetic field instantly by reducing magnet winding current.
Filter (Control Systems): A transfer function used to modify the frequency or time response of a control system.
Flutter: Flutter is an error of the basic cycle of an encoder per one revolution.
Following Error: The positional error during motion resulting from use of a position control loop with proportional gain only.
Form Factor: The ratio of RMS current to average current. This number is a measure of the current ripple in a PWM or other switch mode type of controller. Since motor heating is a function of RMS current while motor torque is a function of average current, a form factor greater than 1.00 means some fraction of motor current is producing heat but not torque.
Four Quadrant: Refers to a motion system which can operate in all four quadrants i.e. velocity in either direction and torque in either direction. This means that the motor can accelerate, run, and decelerate in either direction.
Friction: A resistance to motion caused by surfaces rubbing together. Friction can be constant with varying speed (coulomb friction) or proportional to speed (viscous friction) or present at rest (static friction).
Full Load Current: The armature current of a motor operated at its full load torque and speed with rated voltage applied.
Full Load Speed: The speed of a motor operated with rated voltage and full load torque.
Gain: The ratio of system output signal to system input signal. The control loop parameter that determines system performance characteristics.
Hall Sensors: A feedback device which is used in a brushless servo system to provide information for the amplifier to electronically commutate the motor. The device uses a magnetized wheel and hall-effect sensors to generate the commutation signals.
Holding Torque: Sometimes called static torque, it specifies the maximum external force or torque that can be applied to a stopped, energized motor without causing the rotor to rotate continuously.
Home Position: A reference position for all absolute positioning movements. Usually defined by a home limit switch and/or encoder marker. Normally set at power up and retained for as long as the control system is operational.
HP: Horsepower. One horsepower is equal to 746 watts. Since Power = Torque <F128M>‘<F255D> Speed, horsepower is a measure of a motor’s torque and speed capability (e.g. a 1 HP motor will produce 35 lb-in. at 1800 rpm).
Host Computer: An auxiliary computer system which is connected to a controller or controllers. The host computer in distributed control systems is frequently involved with controlling many remote and distributed motion control devices. It may also be used for off-line tasks such as program preparation, storage, and supervisory control and evaluation.
Hunting: The oscillation of the system response about a theoretical steady-state value.
Hybrid Stepping Motor: A motor designed to move in discrete increments or steps. The motor has a permanent magnet rotor and wound stator. These motors are brushless and phase currents are commutated as a function of time to produce motion.
Hysteresis: For a system with an analog input and digital output, the output value is dependent on both the input value and output state such that there is an input range over which the output can be high or low.
I/O: Input/Output. The reception and transmission of information between control devices. In modern control systems, I/O has two distinct forms: switches, relays, etc., which are in either an on or off state, or analog signals that are continuous in nature such as speed, temperature, flow, etc.
Idle Current Reduction: A stepping motor driver feature that reduces the phase current to the motor when no motor motion (idle) is commanded for a specified period of time. This reduces motor heating and allows high machine throughput to be obtained from a given motor.
Incremental Motion: A motion control term that is used to describe a device that produces one step of motion for each step command (usually a pulse) received.
Indexer: Electronics which convert high level motion commands from a host computer, programmable controller, or operator

panel into step and direction pulse streams for use by the stepping motor driver.
Inertia: The property of an object to resist changes in velocity unless acted upon by an outside force. Higher inertia objects require larger torques to accelerate and decelerate. Inertia is dependent upon the mass and shape of the object.
Inertial Match: An inertial match between motor and load is obtained by selecting the coupling ratio such that the load moment of inertia referred to the motor shaft is equal to the motor moment of inertia.
Inrush Current: The current surge generated when a piece of equipment such as a servo amplifier is connected to an AC line. This surge is typically due to the impulse charging of a large capacitor located in the equipment.
Instability: Undesirable motion of an actuator that is different from the command motion. Instability can take the form of irregular speed or hunting of the final rest position.
Lead Screw: A device for translating rotary motion into linear motion, consisting of an externally threaded screw and an internally threaded carriage (nut).
Lead Ball Screw: A lead screw which has its threads formed as a ball bearing race; the carriage contains a circulating supply of balls for increased efficiency.
Least Significant Bit: The bit in a binary number that is the least important, or having the least weight.
Limits: Motion control systems may have sensors called limits that alert the control electronics that the physical end of travel is being approached and that motion should stop.
Linear Coordinated Move: A coordinated move where the path between endpoints is a line.
Linearity: For a speed control system it is the maximum deviation between actual and set speed expressed as a percentage of set speed.
Logic Ground: An electrical potential to which all control signals in a particular system are referenced.
Loop, Feedback Control: A control method that compares the input from a measurement device, such as an encoder or tachometer, to a desired parameter, such as a position or velocity and causes action to correct any detected error. Several types of loops can be used in combination (i.e. velocity and position together) for high performance requirements.
Loop Gain, Open: The product of the forward path and feedback path gains.
Loop, PID: Proportional, Integral, and Derivative Loop: Specialized very high performance control loop which gives superior response.
Loop, Position: A feedback control loop in which the controlled parameter is motor position.
Loop, Velocity: A feedback control loop in which the controlled parameter is mechanical velocity.
Master Slave Motion Control: A type of coordinated motion control where the master axis position is used to generate one or more slave axis position commands.
Mechanical Time Constant: The time for an unloaded motor to reach 63.2% of its final velocity after the application of a DC armature voltage.
Microstepping: An electronic control technique that proportions the current in a step motor's windings to provide additional intermediate positions between poles. Produces smooth rotation over a wide speed range and high positional resolution
Mid-Range Instability: A phenomenon in which a stepping motor can fall out of synchronism due to loss of torque at mid-range speeds. The loss of torque is due to interaction between the motor's electrical characteristics and the driver electronics. Some drivers have circuitry to eliminate or reduce this phenomenon.
Most Significant Bit: The bit in a binary number that is the most important or that has the most weight.
Motor, AC: A device that converts electrical alternating current into mechanical energy. Requires no commutation devices such as brushes. Normally operated off commercial AC power. Can be single or multiple phase.
Motor, AC Asynchronous or Induction: An AC motor in which speed is proportional to the frequency of the applied AC. Requires no magnets or field coil. Usually used for non-precise constant speed applications.
Motor, AC Synchronous: Another term for brushless DC motor.
Motor Constant: The ratio of the motor torque to motor input power.
Motor, DC: A device that converts electrical direct current into mechanical energy. It requires a commutating device, either brushes or electronic. Usually requires a source of DC power.
Motor, DC Brushless: A type of direct current motor that utilizes electronic commutation rather than brushes to transfer current.
Motor, DC Permanent Magnet: A motor utilizing permanent magnets to produce a magnetic field. Has linear torque speed characteristics.
Motor, DC Wound Field: A direct current motor utilizing a coil to produce a magnetic field. Usually used in high power applications where constant horsepower operation is desired.
Motor, Stepping: A specialized AC motor that allows discrete positioning without feedback. Normally used for non-critical, low power applications, since positional information is easily lost if acceleration or velocity limits are exceeded. Load variations can also cause loss of position. If encoders are used, these limitations can be overcome.
NC, Numerical Control: Usually refers to any type of automated equipment or process used for contouring or positioning.
Negative Feedback: The type of feedbacks used in a closed loop system where the output value is inverted and combined with the input to be used to stabilize or improve system characteristics.
No Load Speed: Motor speed with no external load.
Open Collector: A term used to describe a signal output that is performed with a transistor. An open collector output acts like

a switch closure with one end of the switch at ground potential and the other end of the switch accessible.
Open-Loop System: A system where the command signal results in actuator movement but, because the movement is not sensed, there is no way to correct for error. Open loop means no feedback.
Operator Interface: A device that allows the operator to communicate with a machine. This device typically has a keyboard or thumbwheel to enter instructions into the machine. It also has a display device that allows the machine to display messages.
Optically Isolated: A system or circuit that transmits signals with no direct electrical connection. Used to protectively isolate electrically noisy machine signals from low level control logic.
Oscillation: An effect that varies periodically between two values.
Overshoot: The amount that the parameter being controlled exceeds the desired value for a step input.
Phase-Locked Servo System: A hybrid control system in which the output of an optical tachometer is compared to a reference square wave signal to generate a system error signal proportional to both shaft velocity and position errors.
Phase Margin: The difference between 180 degrees and the phase angle of a system at the frequency where the open loop gain is unity.
PID: Proportional-Integral-Derivative. An acronym that describes the compensation structure that can be used in a closed-loop system.
PLC: Programmable Logic Controller. Also known as a programmable controller, these devices are used for machine control and sequencing.
PMDC Motor: A motor consisting of a permanent magnet stator and a wound iron-core rotor. These are brush type motors and are operated by application of DC current.
Point to Point Move: A multi-axis move from one point to another where each axis is controlled independently. (No coordination between axes is required.)
Pole: A frequency at which the transfer function of a system goes to infinity.
Pole Pair, Electromechanical: The number of cycles of magnetic flux distribution in the air gap of a rotary electromechanical device.
Position Error: The difference between the present actuator (feedback) value and the desired position command for a position loop.
Position Feedback: Present actuator position as measured by a position transducer.
Power: The rate at which work is done. In motion control, Power = Torque<F128M> '<F255D> Speed.
Process Control: A term used to describe the control of machine or manufacturing processes, especially in continuous production environments.
Pull-In Torque: The maximum torque at which an energized stepping motor or synchronous motor will start and run in synchronism.
Pull-Out Torque: The maximum torque that can be applied to a stepping motor or synchronous motor running at constant speed without causing a loss of synchronism.
PWM: Pulse width modulation. An acronym which describes a switch-mode control technique used in amplifiers and drivers to control motor voltage and current. This control technique is used in contrast to linear control and offers the advantages of greatly improved efficiency.
Pulse Rate: The frequency of the step pulses applied to a stepper motor driver. The pulse rate divided by the resolution of the motor/drive combination (in steps per revolution) yields the rotational speed in revolutions per second.
Quadrature: Refers to signal characteristics of interfaces to positioning devices such as encoders or resolvers. Specifically, that property of position transducers that allows them to detect direction of motion using the phase relationship of two signal channels.
Ramping: The acceleration and deceleration of a motor. May also refer to the change in frequency of the applied step pulse train.
Rated Torque: The torque producing capacity of a motor at a given speed. This is the maximum continuous torque the motor can deliver to a load and is usually specified with a torque/speed curve.
Regeneration: The action during motor braking, in which the motor acts as a generator and takes kinetic energy from the load, converts it to electrical energy, and returns it to the amplifier.
Repeatability: The degree to which the positioning accuracy for a given move performed repetitively can be duplicated.
Resolution: The smallest positioning increment that can be achieved. Frequently defined as the number of steps or feedback units required for a motor's shaft to rotate one complete revolution.
Resolver: A position transducer utilizing magnetic coupling to measure absolute shaft position over one revolution.
Resonance: The effect of a periodic driving force that causes large amplitude increases at a particular frequency. (Resonance frequency.)
RFI: Radio frequency interference.
Ringing: Oscillation of a system following sudden change in state.
Rise Time: The time required for a signal to rise from 10% of its final value to 90% of its final value.
RMS Current: Root mean square current. In an intermittent duty cycle application, the RMS current is equal to the value of steady state current which would produce the equivalent resistive heating over a long period of time.
RMS Torque: Root mean square torque. For an intermittent duty cycle application, the RMS torque is equal to the steady

state torque which would produce the same amount of motor heating over long periods of time.
Robot: A reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.
Robot Control: A computer-based motion control device to control the servo-axis motion of a robot.
Rotor: The rotating part of a magnetic structure. In a motor, the rotor is connected to the motor shaft.
Serial Port: A digital data communications port configured with a minimum number of signal lines. This is achieved by passing binary information signals as a time series of A1's and A0's on a single line.
Servo Amplifier/Servo Drive: An electronic device which produces the winding current for a servo motor. The amplifier converts a low level control signal into high voltage and current levels to produce torque in the motor.
Servo System: An automatic feedback control system for mechanical motion in which the controlled or output quantity is position, velocity, or acceleration. Servo systems are closed loop systems.
Settling Time: The time required for a step response of a system parameter to stop oscillating or ringing and reach its final value.
Shunt Resistor: A device located in a servo amplifier for controlling regenerative energy generated when braking a motor. This device dissipates or "dumps" the kinetic energy as heat.
Single Point Ground: The common connection point for signal grounds in a control wiring environment.
Slew: In motion control, the portion of a move made at a constant non-zero velocity.
Slew Speed: The maximum velocity at which an encoder will be required to perform.
SPS: Steps-per-second. A measure of velocity used with stepping motors.
Speed Regulation: For a speed control system, speed regulation is the variation in actual speed expressed as a percentage of set speed.
Stall Torque: The torque available from a motor at stall or zero rpm.
Stator: The non-rotating part of a magnetic structure. In a motor the stator usually contains the mounting surface, bearings, and non-rotating windings or permanent magnets.
Stiffness: Ratio of an applied force or torque to change in position for a mechanical system.
Synchronism: A motor rotating at a speed correctly corresponding to the applied step pulse frequency is said to be in synchronism. Load torques in excess of the motor's capacity (rated torque) will cause a loss of synchronism.
Tachometer: An electromagnetic feedback transducer which produces an analog voltage signal proportional to rotational velocity. Tachometers can be either brush or brushless.
Tachsyn: A brushless, electromagnetic feedback transducer which produces an analog velocity feedback signal and commutation signals for a brushless servo motor. The tachsyn is functionally equivalent to hall sensors and a tachometer.
Torque: The rotary equivalent to force. Equal to the product of the force perpendicular to the radius of motion and distance from the center of rotation to the point where the force is applied.
Torque Constant: A number representing the relationship between motor input current and motor output torque. Typically expressed in units of torque/amp.
Torque Ripple: The cyclical variation of generated torque given by the product of motor angular velocity and number of commutator segments.
Torque-to-Inertia Ratio: Defined as a motor's torque divided by the inertia of its rotor, the higher the ratio the higher the acceleration will be.
Transducer: Any device that translates a physical parameter into an electrical parameter. Tachometers and encoders are examples of transducers.
Transfer Function: The ratio of the Laplace transforms of system output signal and system input signal.
Trapezoidal Profile: A motion profile in which the velocity vs. time profile resembles a trapezoid. Characterized by constant acceleration, constant velocity, and constant deceleration.
TTL: Transistor-transistor Logic.
Variable Frequency Drives: An electronic device used to control the speed of a standard AC induction motor. The device controls the speed by varying the frequency of the winding current used to drive the motor.
Vector Control: A method of obtaining servo type performance from an AC motor by controlling two components of motor current.
Velocity: The change in position as a function of time. Velocity has both a magnitude and a direction.
Voltage Constant (or Back EMF Constant): A number representing the relationship between Back EMF voltage and angular velocity. Typically expressed as V/krpm.

Appendix A

SYMBOL LEGEND

SYMBOL	DESCRIPTION	UNITS
C_G	circumference of gear	in
$C_{P:1,2,3}$	circumference of pulleys 1,2, or 3	in
D	diameter of cylinder	in
D_G	pitch diameter of gear	in
D_{PL}	pitch diameter of pulley on load	in
D_{PM}	pitch diameter of pulley on motor	in
$D_{P:1,2,3}$	pitch diameter of pulleys 1,2, or 3	in
e	efficiency of mechanism	%
F	force due to	lb
F_{fr}	friction =	lb
F_g	gravity	lb
F_P	push of pull forces	lb
a or d	linear acceleration or deceleration	in/sec^2
g	gravity constant	$386\ in/sec^2$
J	mass moment of inertia of	$in\text{-}lb\text{-}sec^2$
J_{B-M}	belt reflected to motor	$in\text{-}lb\text{-}sec^2$
J_C	coupling	$in\text{-}lb\text{-}sec^2$
J_G	gear	$in\text{-}lb\text{-}sec^2$
J_L	load	$in\text{-}lb\text{-}sec^2$
J_{L-M}	load reflected to motor	$in\text{-}lb\text{-}sec^2$
J_M	motor	$in\text{-}lb\text{-}sec^2$
J_{PL}	pulley on the load	$in\text{-}lb\text{-}sec^2$
J_{PM}	pulley on the motor	$in\text{-}lb\text{-}sec^2$
J_{PL-M}	pulley on the load reflected to motor	$in\text{-}lb\text{-}sec^2$
$J_{P:1,2,3}$	pulley or sprocket 1,2 or 3	$in\text{-}lb\text{-}sec^2$
J_r	reducer (or gearbox)	$in\text{-}lb\text{-}sec^2$
J_{Total}	total of all inertias	$in\text{-}lb\text{-}sec^2$
J_S	lead screw	$in\text{-}lb\text{-}sec^2$
N_r	ratio of reducer or gearbox	
N_t	number of teeth on gear, sprocket, pulley	
P_G	pitch of gear, sprocket, pulley	teeth/in.
P_S	pitch of leadscrew	teeth/in.

SYMBOL	DESCRIPTION	UNITS
t	time	sec
t_a, t_d	for acceleration of deceleration	sec
t_c	at constant speed	sec
t_m	for move	sec
t_{Total}	for total cycle	sec
t_w	for wait (dwell)	sec
T	torque	in-lb
T_a, T_d	during acceleration or deceleration	in-lb
T_C	while at constant speed	in-lb
T_{C-L}	constant, external at load	in-lb
T_{C-m}	constant, reflected to motor	in-lb
T_H	holding, while motor stopped	in-lb
T_L	@ load not yet reflected to motor	in-lb
T_P	due to preload on screw nut	in-lb
T_{RMS}	root mean square avg. over the entire cycle	in-lb
T_{Total}	total from all accel and constant forces	in-lb
V_L	linear velocity of load	in/sec
W_L	weight of load	lb
W_B	weight of belt	lb
X_L	length or distance travelled by load	in
α	angular acceleration	$radians/sec^2$
π	"pi"	
2π	rotational unit conversion	radians/rev
Θ	rotation	revs
Θ_a, Θ_d	distance during accel or decel	revs
Θ_C	distance during constant speed	revs
Θ_L	of load	revs
Θ_M	of motor	revs
Θ_{Total}	total rotation of motor during move	revs
ω_L	angular velocity of load	revs/sec
ω_M	angular velocity of motor	revs/sec
ω_{max}	maximum angular velocity of motor	revs/sec
μ	coefficient of friction	