MOTION CONTROL

MADE SIMPLE

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by

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DISCLAIMER & ACKNOWLEDGEMENTS

This manual is designed to assist users in understanding Electro-Mechanical Motion Control and by no means serves to replace factory published manuals. It should be used in conjunction with all other factory supplied documentation. Considering the multitude of applications and technologies, this guide should by no means serve as a definitive guide.

A debt of gratitude is owed to a few people who played a large role in the creation of this manual. Dr. Jacob Tal from the Galil Corporation provided his technical expertise and encouragement. Warren Osak from Electromate volunteered his considerable editing skills. Finally, Karmjit Kaur Gill was tolerant of my many rewrites and displayed creativity in layout and production.

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INTRODUCTION

The inspiration for this handbook came from a frustrating hunt for practical help on choosing electronic and mechanical motion control products. Despite a plethora of manuals and textbooks that deal with the theory of motion control, there are few sources of current information that serve as a topical, "single source" selection guide to the world of motion control. As it turned out, this quest had been shared by hundreds of electrical and mechanical engineers, managers, academics and programmers alike.

The culmination of this information search is this manual. The insights are based on our firm's 10 year success in specifying electronic and mechanical motion control equipment. My objective was to create a user-friendly reference guide for the selection and application of servo, stepper and mechanical motion control products and not to explain the theory behind the technologies; there are many excellent sources available for this information. As examples, there are chapters that deal with choosing the right system, comparative technologies and appendices with handy engineering formulae. This primer is intended for the design engineer and presupposes little experience with the concept of motion control. However, it is by no means, an all-encompassing reference tool. The guide does not address all available products, applications and technologies. What we hope to accomplish is a sharing of our expertise, and the experience of successful (and unsuccessful) motion control solutions with the reader.

In order to maximize the value of this guide, I suggest the readers familiarize themselves with the first two chapters that deal with the basics of motion control and common sense design before proceeding to more detailed product discussions later on.

WHY CHOOSE MOTION CONTROL FOR YOUR APPLICATION?

Programmable Control. Multi-Tasking. JIT. Cell Manufacturing. These manufacturing innovations make up the latest revolution in factory automation. The common denominator is that they all incorporate motion control products in their designs.

This chapter introduces the technology of Motion Control (MC) and places it within the universe of automation technologies. At the chapter's conclusion, you will: a) understand the basic principles of MC; b) know the advantages and disadvantages of various MC systems and; c) determine whether MC is the appropriate solution for the application. For the purpose of simplicity, we will limit our examination to servo (brush & brushless) and stepper products plus the popular mechanical components and assemblies used with these systems.

What is Motion Control? Loosely defined, it is the use of a programmable computer controlled system to control a process involving mechanical motion. Whereas primitive motion systems have existed for hundreds of years, MC represents a new era in industrial automation, offering performance benefits previously unattainable. The core principles and technologies of MC are relatively new, having only come into prominence in industrial markets during the past 10-15 years. Two recent developments have fostered the growth of MC.

Firstly, the rapid decrease in cost and improvements in microprocessor-based technologies have improved the tools available to the design engineer to address a myriad of applications relatively inexpensively and easily. Secondly, the increasing demands from industry for improved product quality, increased throughput, and just-in-time (JIT) delivery have mandated continuous improvement in manufacturing techniques and quality control. As a result, MC penetration has grown significantly over the past 10 years in a variety of industries. Typical MC applications include: material handling, dispensing, machine tools, inspection stations, robotics, packaging and injection molding.

Many analysts believe that less than 15% of cost-justifiable manufacturing applications (discrete and process) are currently employing motion control.

Motion control solves many of the problems associated with traditional mechanical systems due to its programmable nature, smaller size, high processing power and open architecture. For example, individual programs can be stored in the controller shortening product changeover and limiting maintenance associated with changing cams and linkages. As well, motors can direct-drive the load reducing system backlash, complexity, and mechanical wear while eliminating the need for gearing.

Since motion control systems often have multi-tasking and I/O capabilities, they can provide flexibility and cost-effective machine control while increasing throughput, quality and factory integration.

Among automation solutions, MC represents the leading edge solution versus more mature products like pneumatics and hydraulics. As the following matrix indicates, a variety of technologies are available, each offering different performance, cost and flexibility values:

COMPARATIVE TECHNOLOGIES

Technology	***Cost***	***Performance***	***Flexibility***
Brush Servos	moderate	high	high
Brushless Servos	high	very high	high
Steppers	low	moderate	moderate
AC/DC Motors	low	low-moderate	low
Pneumatics	moderate	moderate	low
Hydraulics (open loop)	low	low	low

Cost = Purchase Cost, Installation Time, Maintenance
Performance = System Precision, Throughput, Quality, Fast Changeovers
Flexibility = Concurrent Control Capabilities, System Reconfiguration

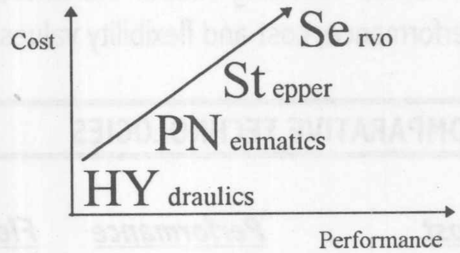
In general, electro-mechanical MC offers the following benefits to an application:

a) Improved precision resulting in fewer defects and lower material costs;
b) Quicker changeovers for higher flexibility and easier product customization;
c) Increased throughput for higher efficiency and capacity utilization;
d) Simpler design for easier installation, programming and training;
e) Less downtime and lower maintenance costs for reduced overall costs.

Be cautious of claims and specmanship by pseudo Motion Control systems (i.e servo-pneumatics) that claim similar performance to MC products at lower cost.

Although MC addresses many of a system designer's needs, it should not be viewed as a panacea for all applications. The optimal application of these products will depend on the level of engineering expertise and available resources within the firm. Furthermore, since electro-mechanical MC systems are often not the lowest cost option, their cost/benefit ratio should always be evaluated in terms of other technologies, as the following diagram indicates:

Motion Control vs. Other Technologies

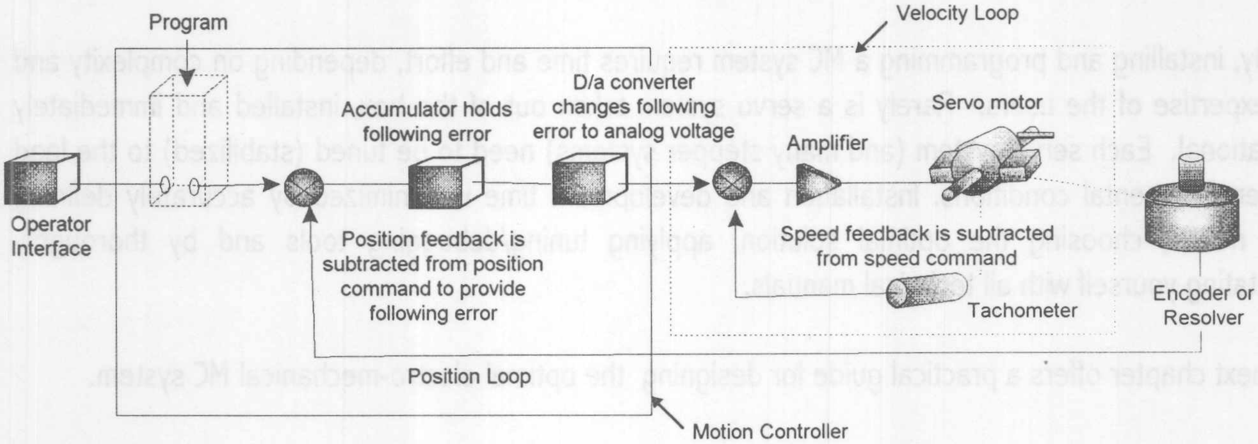


The following section will introduce the basic concepts of motion control.

THE BASICS

The most basic electro-mechanical MC system incorporates the following components, all of which will be discussed in greater detail in later chapters.

The Classic Servo Loop



In broad terms, a motion controller receives a set of operator instructions from a host or operator interface and outputs a corresponding command signal to an amplifier in order to control a motor driving a load. An optional feedback device can be utilized to provide "position" and/or "velocity" feedback of the load. It is the use of feedback devices that primarily differentiates MC into two basic forms: Open & Closed Loop Systems.

Closed Loop systems utilize programmable controllers, amplifiers and **servo** motors (occasionally stepper motors) with a feedback device (usually encoder, resolver or tachometer) to close the position and/or velocity loop. The closed loop system ensures precise and dynamic motor positioning is achieved. The position of the load during motion is determined by the controller sampling the feedback signal on a continuous basis and issuing corrective position/velocity commands. As a result, a high degree of repeatability and responsiveness is obtained. Closed loop systems are also effective where load conditions are non-linear or subject to external disturbances.

Conversely, a typical **Open Loop** system utilizes programmable indexers or pulse generators, drivers and **stepper** motors. The open loop system does not utilize a feedback device, since it controls load position and velocity on the basis of a predetermined step sequence (number of pulses and pulse direction) sent to the driver from the indexer. Since load position is not sampled from a feedback device, system precision, responsiveness and flexibility are usually lower. As a result, positional (step) errors become cumulative over time. Open loop systems excel in simple motion, low speed and high friction applications where there is a high degree of application and load predictability.

In general, certain principles govern all dynamic motor applications:

1) Higher torque applications are typically slower speed systems;
2) Higher precision applications are typically slow speed systems;
3) High duty cycle and high speed applications result in greater maintenance requirements;
4) The more complex the application, the greater the cost and expertise needed.

Finally, installing and programming a MC system requires time and effort, depending on complexity and the expertise of the users. Rarely is a servo system taken out of the box, installed and immediately operational. Each servo system (and many stepper systems) need to be tuned (stabilized) to the load and environmental conditions. Installation and development time is minimized by accurately defining your needs, choosing the optimal solution, applying tuning/debugging tools and by thoroughly orientating yourself with all technical manuals.

The next chapter offers a practical guide for designing the optimal electro-mechanical MC system.

CHOOSING THE RIGHT SYSTEM

At the conclusion of this chapter, you will be able to establish the criteria by which you can select the optimal MC system.

Solve the problem, then worry about the design!

This is easier said than done, but not if you apply a disciplined, time-tested framework. First, you must clearly understand the problem and the local environment. Failure to do this often results in a sub-optimal solution, or at worst, total failure. Secondly, the designer should evaluate the application in light of existing, **proven** solutions. As well, the engineer must take stock of their skills and the expertise of the firm in order to effectively choose the right option and to accurately anticipate development time and resources.

Before choosing any products, the design engineer needs a set of principles to guide his or her selection. Long term experience and common sense has taught us 7 important, but often overlooked, principles. These key learnings have been encapsulated in a simple notion known as the **SHAIRED** paradigm:

- **S**implicity of design to reduce problem-causing complexity and cost;
- **HO**mework: calculate the required torque, inertia, duty cycle etc. Don't guess the critical parameters;
- **A**nalysis of application and alternatives must be thorough;
- **I**ntegration of the system into existing factory automation;
- **R**edundancy built in to system to exceed performance expectations and deal with unexpected changes in load and operating parameters;
- **E**conomical solution for the short and long term;
- **D**evelopment time must be accurately estimated;

Using the above guidelines during system design, evaluation of alternatives and final product selection will help increase the odds of application success.

Choosing the right vendor is as important as picking the appropriate system. Your local vendor should provide timely technical support, have a strong MC product focus and carry sufficient product inventory for emergencies.

After defining your problem and establishing design principles, it is time to choose the components of your system. Whether you require a closed or open loop system, six key variables must be addressed:

1) **Torque** - What is the required torque? Is the torque requirement dynamic or static in nature? Over what speed range must the torque be provided? Is torque ripple a concern?
2) **Velocity** - What maximum, minimum speeds are required?
3) **Acceleration** - What acceleration, deceleration rates are needed?
4) **Precision** - What accuracy, repeatability and resolution is desired?
5) **Motion Profile** - How many axes of motion is needed? What type of motion profile will satisfy the application?
6) **Load Analysis** - Define the dynamic versus static load requirement? What are the moment and overhang loads? What is the inertia and duty cycle?

Other important selection criteria include:

1)	environmental conditions	4)	maintenance requirements
2)	ease of use	5)	budget (purchase & development)
3)	fit/form factor	6)	programming and installation time

After identifying your operating parameters, you will be ready to consider various solutions. During this stage, the following questions are typically raised. Each choice has a significant impact on the cost, development time and effectiveness of your solution:

Custom vs. Standard Product? - For the vast majority of applications, purchasing an "off-the-shelf" standard product is clearly preferable to a custom solution in terms of lower cost, simpler design, ease of installation plus shorter delivery. Spare part availability is likely to be better with a standard product than a custom one. However, if you purchase standard products, know the market! Build your solution around components that are readily available and popular. If your needs can not be met by the vendor or you need to build your own solution, incorporate as many standard components as possible in the initial design and phase in the custom items at a cautious rate. Always use proven, quality components.

Turnkey vs. Mix n' Match Components? This choice is not clear cut and is application and product specific. In the past, purchasing a turnkey system from one manufacturer would help ensure that the system would work effectively. The downside was that the cost would typically be higher than assembling a similar system from multiple vendors. Furthermore, it usually reduced overall system flexibility through proprietary designs and limited interface capability. However, with the growth of the MC market and the creation of industry standards, it is now much easier to match compatible "off-the-shelf" products from a variety of vendors in a cost effective manner. Working with an experienced distributor is the best way to guarantee you are purchasing a cost effective and high performance system.

Make vs. Buy? In theory, it may be less expensive to build your own solution rather than purchase one already designed, particularly if time and resources are plentiful. In reality, this is not likely the case, since a lack of technical expertise, servicing issues, time delays, and unanticipated hidden development costs reduce the overall cost-effectiveness of in-house production. Moreover, few firms have the resources to develop new and field-support exisiting products as inexpensively as a manufacturer. A good rule of thumb is that producing a standard product should never be attempted unless: 1) high quantities warrant significant cost-savings or; 2) the application is so unique that there is no readily available market source.

Motion Controller vs. PLC? When advanced level motion control-high speeds, multi-axis capability math functions and multi-tasking-is priorized, the motion controller is the logical choice. Furthermore, motion controllers can interface easily with PLCs as part of a larger machine design or even undertake complete machine control of small systems (less than 100 bits of I/O). However, since motion controllers can handle only a limited amount of I/O, they are not well suited for overall machine control of large, complex systems. This is a result of the motion controller's ability to provide background PLC control only and secondary priority to I/O handling. When the application requires simple motion, traditional ladder logic programming or involves large I/O scanning, the PLC is the right choice. However, be wary of PLC systems that oversell their motion control capabilities; they are hampered by cumbersome ladder logic, slower processing speeds and slow servo loop update rates.

Many PLCs offer motion control capabilities as options. In many cases, this feature is really an interface to a separate module providing secondary motion control. An important rule is called for: motion control should be left to motion controllers. When the choice between PLCs and motion controllers is difficult, choose the control device which best performs the critical task of the application. Usually, this ends up being the motion controller because of its superior math processing and multi-axis capabilities.

Lastly, consideration of the operating environment is important. Evaluating and pre-empting potentially disruptive environmental effects plays a major role in ensuring system reliability, life and performance. These effects should be thoroughly analyzed in the planning phase, and not after purchase.

Environmental conditions to safeguard include:

1)	extreme temperature/humidity	6)	radioactivity/vacuums
2)	vibration/shock	7)	combustible conditions (i.e paint, fuel)
3)	washdown/immersion	8)	corrosive materials
4)	EMI/RFI noise	9)	dust/contaminants/fungus
5)	spikes/surges/brown-outs	10)	ground loops

In general, **design the mechanical system to exceed the performance of the control and drive electronics.** This will ensure that the mechanical system will not fail should the application require the maximum capabilities of the control and drive or the system "runs away". Unfortunately, too often an engineer will design the system with the mechanical/electronics relationship backwards, resulting in reduced life and/or premature system failure.

Where possible, use easy and inexpensive hardware solutions to replace time-consuming and expensive software development (i.e. system tuning with programmable Smart Drives).

The effective use of MC does not end with choosing the right products or ensuring the optimal system design. Notwithstanding the importance of careful planning, installation errors can derail project success for days or even weeks. For example, poor and careless wiring, sloppy parameter calculations, having incorrect assumptions, ignoring electro-mechanical interface needs and the environment all can contribute to needless delays, overspending or, at worst, failure. In the majority of cases, these problems are the responsibility of the system designer and/or installer. While it may be convenient to blame product failure on the manufacturer or vendor, the worst case defect rates of mature products do not often exceed 10% and are typically below 3%. Thus, common sense remains the byword: purchase proven products from reputable manufacturers and distributors who are technically competent; keep the design simple and easy to access; check and double-check all calculations and; consider all operational parameters.

Thus, what may be the most important lesson in this text is:

Poor installation ruins good design!

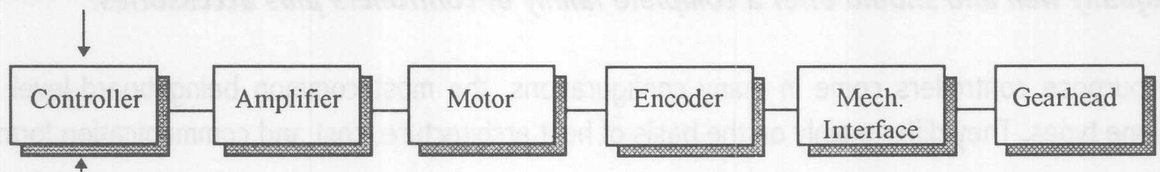
The following chapters describe the most common electro-mechanical MC components beginning with servo products.

ELECTRONIC PRODUCTS

SERVO SYSTEMS

A servo is not so much a device but a function. It is the basic premise by which programmable closed loop positioning is achieved. This section provides an overview of servo products with particular emphasis on controllers, amplifiers, DC motors and feedback devices. The first and most important component in the servo system is the motion controller.

MOTION CONTROLLERS

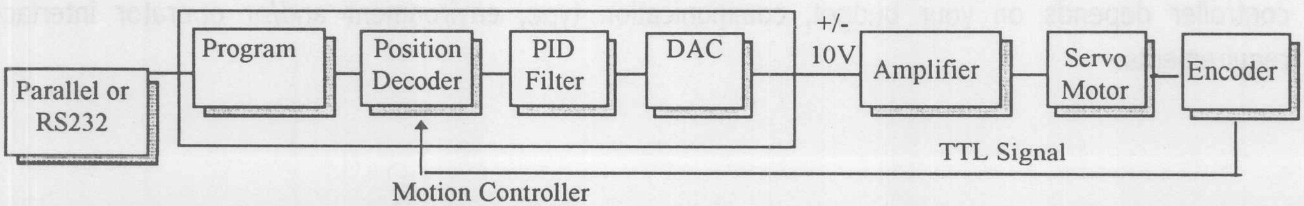


Often considered the "brains" of the servo system, the motion controller is the most important element in a MC system. Next to choosing the proper motor, the selection of a motion controller will be the designer's most important decision.

Simply put, a controller processes and compares two signals: the command signal from the microprocessor and the position feedback signal from an encoder, resolver or tachometer. The position feedback signal is subtracted from the position command to provide a following error which is converted by a digital-to-analog converter (DAC) to analog voltage for the servo amplifier. The purpose of the controller is to reduce the value of this position error to a minimum without causing system instability.

A motion controller shifts the priorities of the designer towards stabilizing and programming the system. Before numerical control, the designer focused on getting the mechanical system to work. Now with programmable motion controllers, the emphasis is on achieving precision and system stability using the controller's math processing and filtering to stabilize a wide variety of electro-mechanical systems.

The following diagram illustrates the typical control loop:



Motion Controllers fall into two broad categories: application specific controllers and general purpose controllers. Application specific controllers are usually higher cost and possess features, performance and packaging specific to certain types of applications (i.e CNC). Though they are well suited for specific applications and feature application-oriented programming, they are not usually the best choice for most general-purpose tasks.

On the other hand, general purpose controllers offer lower cost, a variety of communication interfaces and flexible programming to satisfy the vast majority of simple and complex applications effectively.

Evaluate the total package when choosing a controller. Look for a market leader with a large installation base who specializes in motion control. The controller should serve OEMs and end users equally well and should offer a complete family of controllers plus accessories.

General purpose controllers come in many configurations, the most common being board-level and stand-alone types. They differ mainly on the basis of host architecture, cost and communication form.

Board-level controllers include a microprocessor containing the logic embedded in a PC/ISA, VME or STD BUS. The PC/ISA BUS is the most popular platform. Programming is accomplished via fast and simple parallel processing, with program storage on memory chips, high-capacity disk or hard drives. Program execution occurs when the program is downloaded to a non-volatile EEPROM memory chip residing on the controller, and then executed. Board-level controllers also benefit from the sophistication of software interfaces (DLL, VisualBASIC, Pascal, C, etc.) and available functionality found in the host. Low cost, standard host architectures and rapid programming make board-level controllers MC's most popular control solution.

However, because board-level controllers require a separate host interface, they are often ill-suited for environmentally-demanding or remote location applications. The stand-alone controller solves this problem by combining the host and controller in one packaged unit. Programs are typically downloaded from a PC via an RS 232, 422 or 485 serial communication link to an EEPROM or battery-backed RAM (preferably non-volatile) on the controller. Since communication takes place in serial mode, execution is usually slower versus the faster parallel communication. Moreover, program size is limited to on-board memory capacity versus the hard and floppy drives found in board-level controller hosts. Furthermore, separate operator interfaces (joysticks, keypads, thumbwheels, displays) are required to improve functionality, although these may be desirable in their own right. In summary, the choice of controller depends on your budget, communication type, environment and/or operator interface requirements.

As noted earlier, the advantage of MC is its ability to accomplish a wide variety of jobs with speed and precision. This is accomplished through the use of high-level ASCII-based or compiled programming languages plus powerful microprocessors, counters etc. in the hardware. Although some controllers can control up to 32 axes of motion, most applications require 4 axes or less. Motion controllers are used to control a variety of different components: DC brush & brushless motors, stepper motors, linear motors, induction motors, pneumatic/hydraulic servos and proportional servo valves. In addition, multi-tasking, PLC interfacing and analog & digital I/O control is provided to control solenoids, relays, switches etc. for complete machine control.

Choosing the right controller is about: specifiying the type of motor control; defining the motion profiles; choosing the right configuration; establishing the operational needs; choosing the features; understanding the communications link; considering the I/O requirements and; picking the right operator interface.

There are three basic types of motor control in any application: Position, Velocity and Torque. Position (or current) control is found in servo (and some stepper) applications and utilizes feedback devices to close the position loop and make the system repeatable and dynamically responsive (i.e part insertion). As motor loading increases and the motor speed falls, the controller senses the speed decrease via the feedback device. The controller then issues a new command voltage to maintain the original motor speed. Velocity control specifies the load velocity for a prescribed time interval. It is not concerned with load position but rather with ensuring the stopping point is within the range of the system's deceleration profile (i.e spindles). Velocity control uses either the feedback of the motor's Back EMF signal or a tachometer as a regulating signal, often as part of an inner velocity loop tied into the amplifier. Torque control's emphasis is on delivering constant torque regardless of load position or velocity (i.e clamping). As the load increases, the motor will slow and approach a stall condition. At a stall condition, there is a constant torque applied to the load but no speed. Torque control is not self-compensating as compared to position control.

In all servo applications, the two most common motion profiles are:

Point-to-Point - Constant and repeatable movements from one point to another (i.e. pick and place, drilling, scanning).

Coordinated Motion - Tight synchronization of independent axes along a path (i.e. CNC, web lines, contouring, grinding).

Coordinated motion applications require that the actual load position follow the commanded position in a very predictable (stable) manner with a high degree of stiffness (loop gain) in order to reject external torque disturbances (i.e. changes in load, inertia). On the other hand, point-to-point profiles typically are not concerned with precise path motion but rather with settling times, move times and velocity profiles.

Filtering is the method used by a controller to stabilize the system and reduce the following error to essentially zero (i.e making the system repeatable). A motion controller with a sophisticated PID filter will be able to achieve a high level of dynamic response, higher accuracy, minimum settling time and reduced instability not to mention ease of system tuning.

Other complex forms of motion profiling include: electronic gearing and cams, master/slave synchronization, linear and circular interpolation, contouring, cubic splines, parabolic profiling, spline interpolation, helical interpolation, S-Curve acceleration and acceleration feed-forward.

Given that the motion controller choice plays a large role in the success of the system, a number of important configuration questions need to be addressed at the design stage.

Centralized vs. Remote Control - This choice is highly dependent on the application. Centralized control via board level controllers is recommended where the motion profiles must be tightly coupled, rapid communication is needed, programming & PC flexibility is required and a host programmable computer or other BUS is readily available at low cost. Remote control via a stand alone motion controller should be used where there is not a programmable host available, the motion does not have to be tightly coupled and the surrounding environment is harsh adversely affecting the life of the BUS.

PC vs. Other Hosts - For low cost, ease of use and reliability proven by a large installation base, the standard PC/ISA BUS is recommended. However, the emerging PCI BUS will soon challenge the ISA dominance by providing significantly better performance at reasonable cost. Use the VME BUS for it's ruggedness in harsh environments, low noise, high speed capability (multi-tasking & real-time operations) and open-ended hardware flexibility. The VME bus is also well suited for computers where CPUs work independently but must communicate over the same backplane. The compact STD BUS is utilized where space is at a premium and high vibration & temperatures are concerns. The PC/104 BUS is attempting to penetrate embedded markets based on its compact size.

First popularized in the office environment, the PCI and new Compact PCI BUS provides extremely fast processing speeds (up to 64-bit data transfers) and networking capabilities for LANs, video, disk and other high-speed peripherals. Moreover, advanced features (i.e jumperless, on-chip DMA) are standard offerings. The PCI BUS is ideal for real-time, computational and graphics-intensive applications.

Proprietary vs. Standardized Software - The choice is highly dependent on user programming expertise, software development commitment as well as application type. By utilizing simple ASCII or

BASIC-like commands, most proprietary software delivers ease of use for beginners yet allows for flexible and complex motion profiles. The use of standardized languages like C, Pascal and VisualBASIC, provide a recognized programming infrastructure but requires specific programming expertise and the additional use of compilers and/or post-processor subroutines for program execution. For specific applications (i.e. machine tools), G and M code and/or HPGL code software is still widely used but increasingly in conjunction with motion controller software translation tools.

Increasingly, MC systems are being used as the back end of a CAD/CAM system. In particular, some software programs act as file translators between the CAD system and the motor, allowing the motion controller to execute a 2 or 3-dimensional path from a CAD or plotter-produced DXF and HPGL file.

Since software requirements encompass 3 key levels: the operating system, application-level programming and the user interface, it is unlikely that a common standardized software solution is optimal or even likely, except perhaps in application-level programming.

Having decided on your system configuration, you must define your operational needs in order to choose the appropriate controller:

1) Axes of Control - How many axes are to be controlled? What kind of motors are to be used? What type of feedback is required?
2) Motion Parameters - What is the required position accuracy/repeatability? What are the maximum/minimum speeds and acceleration/deceleration rates?
3) Machine/Load Characteristics - What is the needed duty cycle? What is the reflected load inertia? What are the potential friction, hysteresis losses?
4) Current Processes - What is the existing level of automation? What resources are available to achieve success? What maintenance level is desired?

Specmanship and "feature-loading" can contribute to overspending and unwanted complexity. The following controller features offer enough performance to satisfy most applications:

1) Minimum 16-bit processor (32-bit preferred) for multi-tasking and high-speed math processing;
2) Minimum 16 bits of digital uncommitted I/O for flexibility;
3) Minimum 7 analog inputs for joysticks, load cells, etc;
4) Servo loop update rates of 250 μsec for high bandwidth and speeds;
5) Full PID filtering and 14-bit DAC for improved system stability and resolution;
6) Large on-board program storage capacity;
7) Minimum 4 axis control capability per board to minimize BUS slots;
8) Variety of feedback devices accomodated (i.e. encoders, resolvers, transducers, tachometers);

9) Encoder feedback of 8 MHz for high speed capability;
10) High level motion profiles to satisfy a wide range of applications .

When choosing a motion controller, the designer should ensure the unit can handle the maximum encoder frequency response (often at 100 KHz), particularly if the application involves high motor speeds and encoder resolutions. Otherwise, the controller could be saturated with excessive encoder counts causing the application to suffer from: lower repeatability due to missed encoder pulses, high speed "jitter" on the load, poor high speed performance and programming & tuning problems.

If high processing speeds are critical, the following controller features are needed: 1) a 32-bit microprocessor with a sub-micron gate array 2) 8 MHz encoder feedback 3) 125 µsec sample rate per axis and 4) RS-232/422 communications with up to 38.4K baud transmission rates.

If sub-micron precision is desired, the controller will need: 1) an 18-bit motor command output DAC 2) a 2nd order PID (proportional, integral, derivative) filter with velocity and acceleration feedforward and 3) dual encoder feedback for backlash compensation.

Some hardware features are essential for machine and load protection. In particular, a drive enable/abort connection to the amplifier should be available to protect the system from unexpected motion during system start-up & shutdown and whenever the controller detects a fault. Home and limit switch inputs are needed for mechanical and load protection during motor runaway. Another critical feature is the watchdog circuit which shuts down the machine should the controller fail. Finally, a non-volatile program memory and motor-off feature is needed to protect the program should the controller crash.

For many applications and environments, choosing the right communication link is very important for fast and reliable data transfer, particularly where electrical noise is a concern. There are two types of communications: serial and parallel. **Serial** communication transmits data one bit of a time over a single data line. Serial links can be as simple as three connections: ground, receive and transit. As a result, it is the least expensive communication scheme.

The two most common serial interfaces are:

RS-232C - This is the most common serial link. Maximum cable length should not exceed 50 ft. with a data rate of 20 KB/s. Up to 38.4K baud communication is possible.

RS-485/422A - This is used for long distance communications or in electrically noisy environments. Maximum cable length should not exceed 40 ft. for 10 MB/s, 400 ft. for 1 MB/s, and 4000 ft. for 100 KB/s. Up to 38.4K baud communication is possible.

Where faster communications are needed, **Parallel** communication is used. Parallel links require handshaking and transmit data quickly, a byte (8 bits) at a time. Parallel communications usually require more communication lines, and as a result, are more expensive than serial links. Examples of Parallel BUS structure include: ISA/PC, PCI, VME, STD and MULTIBUS. The European standard BUS, IEEE-488, should be configured as follows:

IEEE-488 - Maximum length between any two devices should not exceed 6.5 ft. Total number of devices should not exceed 14. Total cable length of all devices should not exceed 66 ft.

New digital communication links have recently emerged, the most noteworthy being SERCOS (Serial Real-time Communications Systems). SERCOS is a standardized fiber optic interface specification providing an open, digital alternative to a ±10 V analog and other proprietary digital interfaces found between amplifiers and controls. The SERCOS interface is gaining global acceptance as a result of its superiority versus conventional analog designs in: 1) lower RFI and improved noise immunities 2) 32-bit precision 3) improved error checking capabilities 4) lower cost and space savings of replacing hard wiring with plastic wiring and 5) improved ruggedness against cable breakage.

Insufficient attention is often paid to I/O needs. Often the designer will specify a controller before considering what type of sensor is needed and how it will interface to the controller. Dedicated I/O (i.e. home and limit switches) are essential for machine and load protection. Uncommitted I/O are used to monitor and control external devices and allows the user to link internal programs with external events in order to provide background PLC functionality. Some high-performance controllers can control up to 100 bits of uncommitted I/O, including: switches, relays, contactors, solenoids, valves and indicators. Controller's possessing an on-board analog-to-digital converter (ADC) are able to monitor analog I/O including: temperature & pressure sensors, load cells, gauges, potentiometers and thermocouples.

When wiring encoders, switches and uncommitted I/O, the designer should resist the temptation to reduce cost by hard wiring rather than using interconnect boards and connectors. The system will inevitably require de-bugging, repair and maintenance which is extremely time-consuming and difficult in a hard-wired system. The interconnect boards should be opto-isolated for noise protection.

Before choosing your uncommitted I/O, consider the following criteria to ensure they are compatible with the motion controller:

1) accuracy/repeatability
2) environmental constraints
3) sensor type
4) sensor power requirement
5) timing requirements
6) voltage and state of sensor signal (NPN or PNP)
7) Number of digital & analog I/O

Finally, a major consideration is the operator interface. Operator interfaces can be used with both board-level or stand-alone motion controllers depending on the needs of the application. For many board-level controller applications the host PC is sufficient for editing data, programming or performing tuning diagnostics. The addition of optional software interfaces or VisualBASIC can turn the host PC into a flexible operator display. Increasingly, more applications are calling for other peripherals like keyboards, colour CRTs, programmable flat panel displays, membrane switches and thumbwheels. Often used in conjuction with packaged controllers, these devices are intended to provide full function display & diagnostics and to serve as data input or programming pods. Advanced models enable the user to program locally when a host PC is not always available or suitable.

Operator terminals vary according to functionality and programmability. In general, hand-held pendants are well suited for simple data entry and operator training only. Panel-mount interfaces provide better functionality and programmability in a more robust enclosure. Nevertheless, they should be simple to use, controller-compatible and ruggedized for industrial environments (preferably NEMA 4).

When choosing an operator interface, the designer should confirm with the vendor that the software communication protocols are present to ensure controller-operator interface compatibility.

Increasingly, designers are seeking to integrate MC systems within a total factory environment which includes: industrial CPU's, PLCs, data acquisition boards, remote I/O racks and operator interfaces to name but a few. Driving this trend are JIT and Total Quality Management (TQM) programs that attempt to link manufacturing process data to a central location for statistical process 'concurrent' control via networks (ARCNET, Ethernet etc.) and dynamic data exchange (DDE) communication links. Unfortunately, this multi-process integration has proven difficult to achieve due to interface complexity, the lack of a standardized communication language, and different vendor's technology requiring separate hardware needs.

The PC-based revolution has opened the door to open-architecture and easy communication connectivity allowing MC systems and other components to finally be integrated. The innovative Pro-Log Corporation has made great strides in providing total process integration through hardware and software connectivity via strategic alliances with major control manufacturers (i.e. Allen-Bradley, GE, Modicon). The result is that motion controllers, MC sub-systems and industrial computers are linked via specialized hardware devices and software to PLCs, industrial PC's, I/O networks and/or other BUS/Node boxes for central processing and system management.

Like the PC market, the trend over the past few years has been for controller hardware improvements to outpace the majority of the demands placed on them by users. In addition, the growth in the number of controller vendors combined with falling prices and the rapid diffusion of hardware features into many brands, has led to a reduction in product differentiation. From a hardware and cost perspective, there are now many "copy cat" products.

The engineer's attention has increasingly turned to other benefits such as ease-of-use, flexibility, reputation, installation base and software power as key purchase determinants. It is here that controllers vary the most and "where the wheat is separated from the chaff." Since the bulk of total system cost rests in implementation, the engineer's comfort level with the software and support will have a big impact on hardware selection, developmental cost, system performance and long term reliability.

The sophistication, versatility and value of a controller is only as good as the power of its software tools. Good software should be easy to use, have comprehensive documentation, a rich library of application examples and should have available accompanying tutorials, common software drivers, motor/drive tuning utilities and translation tools for application-specific (ie. CAD, G & M Code, HPGL Code) programs..

A final note of system tuning: no discussion of motion controllers is complete without making reference to servo tuning. Tuning can have a significant impact on performance, development cost and time. Specifically, all servo systems require a certain amount of system tuning, compensation and debugging in order to stabilize the system to the load and to reduce oscillation. Rarely is a system tuned out of the box. This is achieved by manipulating the proportional, integral and derivative (PID) values to achieve stability and precision under varying loads, speeds and resolutions. Servo tuning will vary in time and difficulty depending on system configuration, motion profile, system inertias and mechanical compliance. It will involve all electro-mechanical elements of a MC system. For multi-axis systems, each axis has to be tuned independently. Once the load, operating parameters or even ambient temperature changes, the system needs to be retuned.

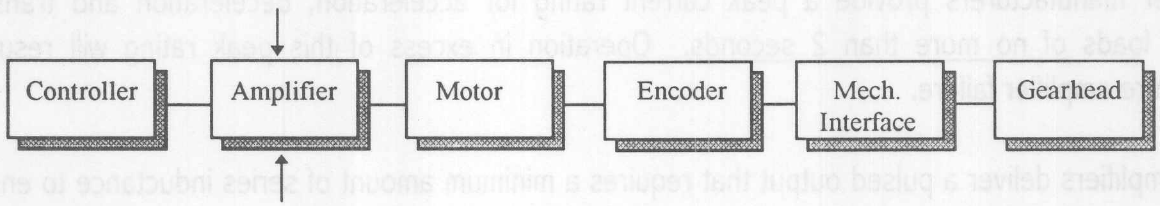
One particular mechanical condition, backlash, creates many problems for servo tuning and precision. Backlash creates a mechanical "dead band" which induces system oscillation and reduces system repeatability. It is observable between the motor-mounted encoder and the load through the gearing, couplings and drive screw. Designers will minimize tuning time and increase precision if they can reduce overall system backlash. There are three ways to accomplish this. The easiest solution is to use a minimum number of mechanical interfaces and to ensure these are low-backlash components. The next best alternative is to close the velocity loop with a tachometer to dampen the system oscillation.

Where absolutely no backlash can be tolerated, dual-loop encoder feedback should be utilized. Specifically, the designer mounts two encoders: one on the motor (for system stability) and one on the load (for position error). The controller compares the two encoder signals and compensates for the backlash and oscillations.

Recent studies suggest that the purchase price of a product is only 1/3 the cost of solving of a MC problem. The other 2/3 includes: installation, programming, training and maintenance.

On the receiving end of the motion controller's command signal is the servo amplifier.

SERVO AMPLIFIERS & POWER SUPPLIES



The servo amplifier converts a low level analog or digital command signal to high power voltage and current necessary to drive servo motors. Since an amplifier can produce acceleration and deceleration torque in either direction of rotation, it is often referred to as a four-quadrant drive. Servo amplifiers fall into two main categories: **Switching amplifiers** utilize pulse width modulation (PWM) to minimize heat dissipation in order to provide variable current for the DC servo brush and brushless motors. These amplifiers are the most popular generating the least amount of heat. They are suitable for all but the lowest power and most noise-sensitive applications. They are available in ±10 V analog or digital versions. On the other hand, **Linear amplifiers** have the benefit of low cost and no radiated electrical noise (EMI/RFI) making them suitable for noise-sensitive applications (i.e medical equipment, instrumentation). Unfortunately, due to high dissipation of output transistors, linear amplifiers run very hot usually requiring forced-air cooling and large transistors/heat sinks. As well, they produce less power per watt displacement, translating into lower efficiency.

The following chart summarizes the benefits and drawbacks of each type of amplifier:

PWM vs. Linear Amplifiers

Criterion	PWM	Linear
Efficiency	High-up to 98%	Low-typically less than 60%
Electrical Noise	Noise in MW and VHF range. Requires filters	Virtually none
Minimum Load Inductance	Necessary, requires chokes	Not necessary, good for resistive loads
Power Loss	Low	High
Output	Up to 50A cont., 320 VDC	Low, usually around 3A cont., 24 VDC
Size	Compact	Bulky
Cost	Low-Medium	Low

The selection of an appropriate amplifier depends on the type, power and inductance rating of the motor, electromagnetic emission requirement as well as mode of operation. Servo amplifiers are rated in terms of peak & continuous output (Amps), maximum & minimum voltage (VDC), minimum load inductance (uH), switching frequency & bandwidth (KHz). Care must be taken to **size the amplifier against the continuous current and maximum voltage rating of the servo motor** since most amplifier manufacturers provide a peak current rating for acceleration, deceleration and transient (peak) loads of no more than 2 seconds. Operation in excess of this peak rating will result in premature amplifier failure.

PWM amplifiers deliver a pulsed output that requires a minimum amount of series inductance to ensure the servo motor is properly filtered. This amount of inductance varies according to each amplifier. If the amplifier is operated below the rated maximum voltage, then the minimum load inductance may be reduced. Most brush type servo motors contain enough inductance due to their iron core design. However,

"Pancake", "basket wound", and "moving coil" servo motors have inherently low inductance (typically <25 uH) usually requiring external inductors in order to reduce overheating, maintain torque output and to meet amplifier inductance requirements.

In order to properly choose an amplifier, the current and voltage of the amplifier must be matched to the motor winding parameters, including: continuous torque (oz-in), maximum motor voltage and current, load speed (RPM), voltage constant-KE (V/KRPM), torque sensitivity-KT (oz-in/amp) and inductance (uH).

To ensure long life and reliability, select amplifiers with a current and voltage safety margin of at least 33% higher than what is needed in the application.

It is relatively easy to size amplifiers to servo motors. See Appendix 3k pages 123-124 for the details. The peak current rating of the amplifier should always be higher than the maximum rating of the motor. In addition, the amplifier's voltage rating should be at least 20% higher than the maximum power supply voltage to allow for regenerative operation and power supply variations. Great care must be taken in matching an amplifier with a brushless motor because of the differences in brushless amplifiers and motor commutation. **Unless the designer has considerable experience with brushless products, it is recommended that they purchase the brushless amplifier and motor from the same manufacturer.**

Since the amplifier functions as part of a high performance closed loop servo system, a number of other attributes will be important. In addition to the critical role played by the motion controller's PID filter, the bandwidth and gain values of the PWM amplifier play an important role in ensuring suitable dynamic response. Both the gain and bandwidth provide the "dynamic stiffness" necessary for successful servo systems under operation. Dynamic stiffness is defined by how well a servo system maintains position in response to an impulse load or disturbance. A minimum amplifier bandwidth of 2.5 KHz and high gain values will ensure the load is responsive to the command signal and the system responds well to load changes plus the forces associated with performing the task (i.e cutting, drilling).

The PWM frequency of the amplifier should be a minimum 20 KHz to provide a high gain current loop control that will minimize current ripple and audible noise. The amplifier should operate at a minimum 95% switching efficiency for reduced heat generation, greater compactness and lower audible noise. In order to achieve this performance, power MOSFETS and surface mount technology are indispensable to the design. Finally, for machine protection TTL signal fault protection is helpful. The amplifier signals the controller when an over-current, over-voltage, over-temperature condition or cable break has occurred.

Most servo amplifiers are used in systems where the position loop is closed by a position feedback device like an encoder. In this case, the amplifier generates a current output proportional to the ±10 V command signal received from a motion controller. The amplifer is configured for <u>Current mode</u> in this design. This mode is also known as <u>Torque mode</u> or flat gain response.

Servo amplifiers could also be used as stand-alone devices (with or without motion controllers) to close the velocity loop in speed-sensitive applications such as coil winding. In this configuration, the amplifier operates in <u>Tach mode</u> as a speed regulator. The velocity loop is closed via an analog (usually tachometer) input voltage from the motor. The tachometer produces a voltage proportional to rotor speed which is compared to the incoming velocity control signal. The result of this comparison is a torque demand or current change to the motor.

Where no tachometer signal is present, <u>Back EMF mode</u> is selected whereby the servo amplifier regulates motor speed by the simple adjustment of potentiometers found on the amplifier. However, this mode is less stable and precise in controlling motor speed than tach mode but is useful in certain low speed applications. Typical speed regulation is less than 5% of commanded motor speed in Back EMF mode.

Where crude speed control can be tolerated, <u>IR Compensation</u> is used. An external circuit raises motor voltage and current to maintain a set speed in response to a change in load. The compensation must be matched percisely to the DC resistance of the motor and is dependent on load and ambient temperature.

In summary, a servo amplifier should offer four operating modes for flexibility:

a) **Current (Torque) Mode** - The most common operating mode; used with a position controller whereby the amplifier produces a torque output proportional to the reference voltage (command) input.

b) **Voltage-Voltage (Back EMF) Mode** - Recommended for velocity control when tach feedback is unavailable; input voltage commands a proportional motor voltage regardless of power supply voltage. The motor's natural KE characteristic provides the necessary feedback.

c) **Voltage-to-Speed (Tach Feedback) Mode** - Used when a tachometer signal is provided. The amplifier compares the tach feedback with the command signal and adjusts the voltage and current output accordingly.

d) **IR Compensation** - Used for simple speed control within 5% of required speed. An external circuit commands a DC voltage in response to changes in load at the motor.

In addition to simple speed control, the velocity loop could be closed to stabilize the load as part of a highly responsive MC system. In this case, an inner tachometer feedback loop is closed in the amplifier providing additional stability while the encoder signal closes the outer position loop in the motion controller. Velocity loops should be employed where the application: 1) requires a high degree of speed stability (motor speeds less than 25 RPM or better than 1% of speed regulation) 2) needs to be stabilized for system backlash and 3) involves load inertia exceeding the motor inertia by a minimum 5 times (creating an inertia mismatch). In this case, the velocity loop will continue to operate even if the position loop becomes saturated, ensuring the system remains stable. The drawback of closing the velocity loop within a position loop is that it adds system complexity (extra wiring) and requires a tachometer at extra cost. Moreover, should the tachometer be added later, it may be difficult to integrate into the existing design.

Electrical noise is a major consideration with PWM amplifiers. Electrical noise is generated from motor outputs and are introduced into digital encoder signal wires, especially if they are routed in the same cable harness without shielding. **Edge & low pass filters, capacitors plus filter cards between the motor outputs and the amplifier should be used to reduce electrical noise.** See Appendix 1, pages 90-92, for further information on electrical noise and countermeasures.

Features to look for when choosing a PWM amplifier are:

1) Packaged units for ruggedness, noise immunity board level types for embedded applications;
2) Extensive protection features: over/under voltage & current, over-temperature, short circuits;
3) High switching frequencies (30+ KHz) and bandwidth (2+ KHz) for high responsiveness and noise immunity;
4) Adjustable potentiometers, dip switches, connectors for easy configuration;
5) Variety of operating modes for flexibility;
6) Efficient MOSFETs and surface mount technology for small size, high performance;
7) High PWM switching of 95% or better for reduced heat generation and audible noise.

For motors drawing over 15 A continuous current, dissipated energy (Back EMF) caused by reversing direction or dynamic braking can damage the amplifier by overloading power supply capacitors. This occurs because the motor operates as a generator during operation. These applications typically involve high inertial loads /motor speeds/duty cycles featuring rapid start and stops.

In applications drawing over 15 A continuous current, ensure that a shunt regulator is installed in the system to prevent rapid dynamic braking from damaging the amplifier during Back EMF discharge.

Analog technology has traditionally been the most common interface to brush and brushless servo amplifiers. In this design, the amplifier receives a ±10 V analog command signal from the controller and outputs the desired voltage and current to the servo motor. Without special utility software, servo tuning is accomplished with analog circuitry via adjustable potentiometers and switches. The benefits of this approach have been relatively low cost, good performance and widespread understanding. However, this process can prove a difficult and time-consuming method of tuning a servo system, particularly in noisy and unstable environments.

Recently, the introduction of digital amplifiers (i.e Smart Drives) have simplifed servo tuning and configuration via enhanced digital electronics and set-up software. The command reference and tuning are sent digitally via a pulse format or through a RS-232/422/485 serial link. The benefits of digital drives are: ease of use, greater noise immunity and simpler load compensation for inertia, friction and compliant factors. In addition, fault diagnostics are more comprehensive and are often maintained even after power loss. Some designs features include automatic self tuning where the load parameters are unknown and dynamic tuning where the load inertia changes during operation. Eventually, most servo amplifiers will adopt digital technology.

Power Supplies

Once the amplifier and motor are specified, the power supply must be chosen and sized. **Unregulated Power Supplies** are recommended for both servo and stepper systems in order to provide isolation and deliver DC power to the amplifier. In most cases, the power supply should contain an isolation transformer, bridge rectifier, fuse diode assembly, and resistance-capacitor filter arrangement. Built-in soft-start circuitry protects power supply components and eliminates nuisance tripping of breakers or fuse blowing due to large in-rush currents. The transformer should also provide a voltage matching function where the standard AC input is not suitable. The power supply could be conveniently built-in to the amplifier or external, in which case, certain selection criteria must be considered.

A suitable power supply should furnish the equivalent or greater average voltage and current for the chosen amplifier(s) plus a healthy safety margin. Assuming amplifier and motor losses, KW of input power (1∅ or 3∅) is needed for every 750 Watts (approximately 1HP) of output power (see power supply sizing in Appendix 3I, page 125).

If the application requires the motor to generate peak torque values, then the power supply must be sized to accomodate the peak current draw since the transformer cannot generate peak current outputs (like motors and amplifiers). It is recommended that the designer averages the current draw between the continuous and peak current requirements for intermittent operation. Under this scenario, extra current is dissipated as heat during continuous operation.

Special attention should be paid to the peak value of the no load voltage and the power supply ripple under load. The peak value of the operating voltage should not exceed the maximum value required by the system. Excessive ripple reduces instantaneous power supply voltage and may reduce the DC supply voltage available for acceleration, curtailing servo responsiveness. In addition, ripple may drive VDC momentarily below the motor's minimum rating. Ripple increases with rising load, but when this occurs, the minimum voltage discharged falls. As a result, ripple should not exceed 500 mV peak to peak or exceed 10% between 12 and 90 VDC in order to maintain system integrity. Finally, three-phase DC power supplies will produce lower ripple than single-phase supplies.

Ripple is countered by changing the transformer tap, raising the DC output voltage or increasing the capacitance of the power supply's filter capacitor.

To minimize EMI coupling to the power line, the transformer should incorporate an electrostatic shield while a power supply to line filter may also be used. As a result of AC line fluctuations, the PWM amplifier voltage rating should be at least 20% higher than the rated power supply voltage.

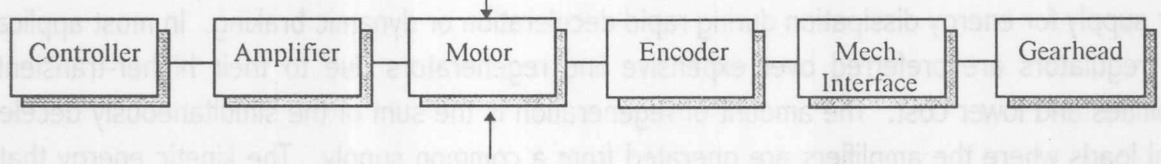
Since autotransformers generate excessive electrical noise, they are not recommended for MC systems.

In high power applications with sizable load inertias, a shunt regulator should be installed with the power supply for energy dissipation during rapid deceleration or dynamic braking. In most applications, shunt regulators are preferred over expensive line regenerators due to their higher-transient load capabilities and lower cost. The amount of regeneration is the sum of the simultaneously decelerating inertial loads where the amplifiers are operated from a common supply. The kinetic energy that must be dissipated is based on the system inertia (load plus motor inertia), maximum speed and deceleration time. Typically, the shunt regulator is connected to the DC bus to monitor the voltage. When a preset trip voltage is reached, a power resisitor is connected across the DC bus by the shunt regulator circuit to absorb the energy surge.

Line regeneration is recommended for very high-power applications but is very expensive and complicated.

The choice of amplifier and power supply is highly dependent on the motor type and size. The next chapter examines servo motors.

SERVO MOTORS



After the motion controller, the most important component in a closed loop system is the servo motor. The choice and size of the servo motor will have the biggest impact on system success.

Servo motors, by and large, utilize DC voltage for power and always include a feedback device. Servo brush and brushless motors have numerous advantages over AC and Permanent Magnet DC motors. They are:

1) Availability of broad range of supply voltages regardless of AC line voltage;
2) Higher speed capability;
3) Wider speed range;
4) Linear torque versus speed curve simplifies system design;
5) Intermittent peak torque capability.
6) Better torque-to-volume ratio;
7) Broader dynamic response;
8) Less drift and no AC current ripple effects.

Furthermore, AC motors suffer from line voltage and frequency variances between geographic regions and facillities.

A DC servo motor is a device that converts direct electrical current into mechanical energy via electronic or brush commutation. Servo motors are ideal for MC applications due to their low inertias, powerful magnets, compact size and rapid responsiveness. They excel in rapid start & stop, high speed and high precision applications. A key advantage of the servo motor is that sudden changes in load will not cause adverse consequences in motor operation (assuming the load is within the peak torque range). The servo motor will draw increased current and voltage (increased torque) to compensate for the increase in load. Conversly, a decrease in load will result in the motor drawing less current and voltage. Furthermore, the torque versus speed relationship is much flatter for servo motors than other motors such as steppers. Finally, the servo motor is energy efficient with a wider useable speed range.

There are two major categories of servo motors: brush and brushless. How commutation is achieved is one of the key features that differentiates the two: **Brush** servo motors utilize brushes and mechanical means to achieve commutation while **Brushless** servo motors accomplish commutation electronically. **Linear** motors include brush, brushless and stepper varieties and feature a unique, high performance design for the most demaning linear applications. Servo motors are rated in terms of continuous and peak torques (oz-in), inductance (uH), current (A), and different KT (oz-in/A) and KE (V/KRPM) values depending on the winding.

In addition to a feedback device, servo motors often require accessories to achieve their high performance and ruggedness. Common options include: fail-safe brakes, special sealings & shafts, custom cabling, gearheads, NEMA or metric flanges and MS mating connectors.

Before the type of servo motor is specified, it is necessary to define the operating parameters. They are:

1) What continuous and peak torque ratings are needed to accelerate and decelerate the load?
2) What motor speed do you need to achieve the desired feed and acceleration rates?
3) What is the operational duty cycle?
4) What level of maintenance is specified?
5) What kind of feedback device will be used?
6) Are there any environmental considerations?
7) Is dynamic and static load inertia a consideration?
8) Is physical size an issue?
9) Will the motor be operated in a horizontal or vertical plane?
10) What mechanical time constant is required for responsiveness?

The designer should also consider all frictional, viscuous and gravitational forces present in calculating the torque needed as well the forces inherent in executing the desired task.

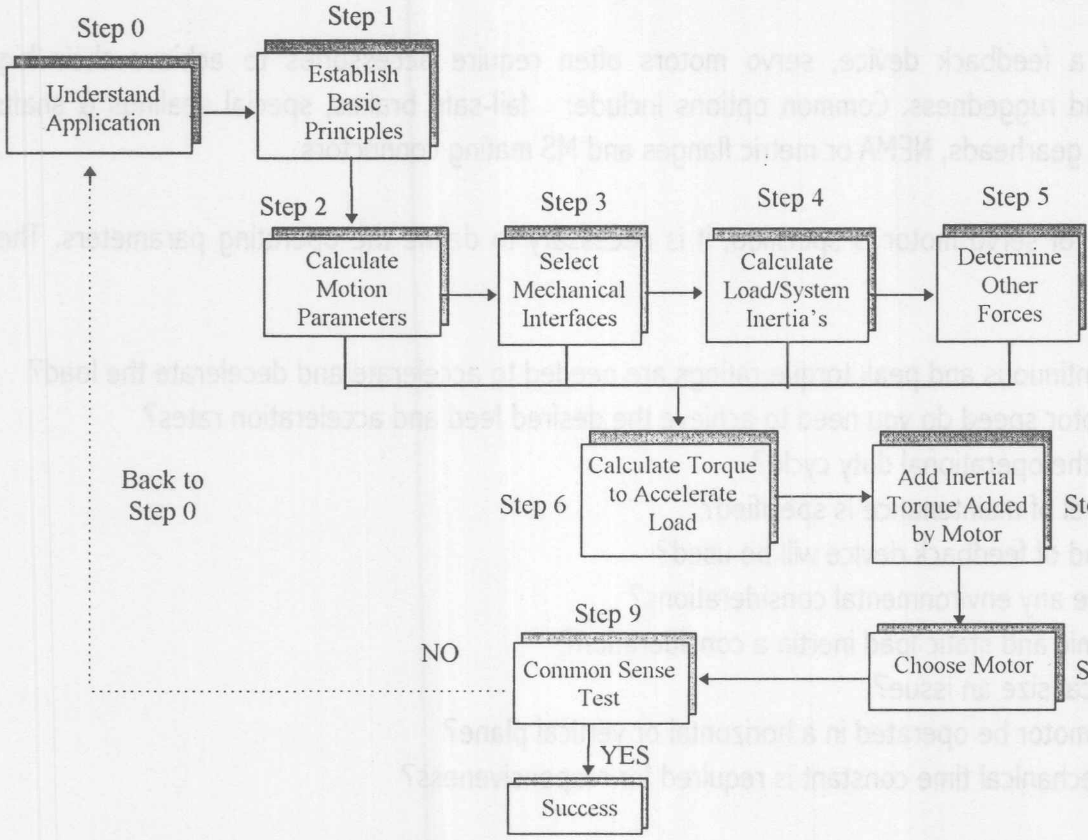
Frictional forces include: 1) dynamic or static motor losses 2) bearing surface drag and 3)bearing preload losses. Where possible, the engineer should minimize, but not eliminate, frictional forces for optimal motor sizing. Some friction in the system (usually a preload) is desired to reduce settling times and improve performance.

Some of the forces required to accomplish the task include: 1) viscuous forces (temperature dependent) 2) gravitational forces 3) acceleration forces including system inertia and 4) thrust or cutting forces.

Determining a servo motor's torque requirement is often difficult because of the large number of parameters to consider. **Whatever the motion objective, the designer should address the worst case, <u>continuous duty</u> scenario in regards to maximum torque and speed .**

The following flow chart illustrates a 9 step procedure for sizing the optimal motor.

Motor Sizing



Step 0 <u>Understanding the Application.</u>

Step 1 <u>Basic Principles</u>: motion profile, environment, budget, time, resources available, expertise.

Step 2 <u>Motion Parameters</u>: calculate maximum and minimum speeds, continuous and peak torques, duty cycle, resolution, maximum acceleration and deceleration rates over time. Type of motion ie: trapezoidal, triangular or parabolic. Precision.

Step 3 <u>Mechanical Interfaces</u>: effect of couplings (mechanical losses, wind-up), type of drive system (screw pitch, efficiencies)and gearheads (efficiency, reduction ratio) on torque and speed.

Step 4 <u>System Inertia</u>: calculate all reflected inertias to the motor (i.e load, couplings, gears, bearings) excluding the motor inertia.

Step 5 <u>Other Forces</u>: include all frictional and task specific forces.

Step 6 Calculate to Determine Acceleration Torque: adding steps 1-5 including gearing effects.

Step 7 Include Inertial Torque Added by the Motor plus Safety Torque Margin.

Step 8 Motor Selection: Select sufficiently torqued motor. Confirm with motor's torque versus speed curve, if available. Ensure proper inertia relationship between motor and load.

Step 9 Common Sense Test: Does the motor choice make sense for the application, budget or environment? Is the worst case scenario accommodated by the continuous motor torque rating? If not, go back to step 0 and repeat the procedure. Double-check calculations, challenge assumptions. Rethink the mechanical design.

Many of the above steps will be dealt with in greater detail in the following chapters.

The inclusion of a torque safety margin in motor sizing is crucial because of the impact of external disturbances and load changes plus the possibility of incorrect calculations. Since duty cyles are often difficult to predict, size the servo motor first against the continuous duty torque rating. Use the peak torque ratings for intermittent operation only. Unforeseen long term factors which would necessitate an additional torque margin include: lubrication hardening, mechanical & bearing wear and extra loads.

Because it is sometimes difficult to estimate the required torque, always choose a servo motor with a 33 to 75% safety margin over your estimated continuous torque requirement. Never size a servo motor only against its peak rating.

A cautionary note on motor ratings is needed. Most manufacturers lab test their motors at a typical 25° C ambient temperature. Ambient temperature is the temperature of the cooling medium, usually air, surrounding the motor. However, actual ambient temperatures are often higher than the 25°C used in the lab test.

Under higher than normal ambient temperatures, continuous and peak torque ratings plus the duty cycle must be derated as a result of motor heating unless special measures (i.e. fan cooling) are taken.

Where higher than ambient temperatures are expected, increase the torque rating of the motor.

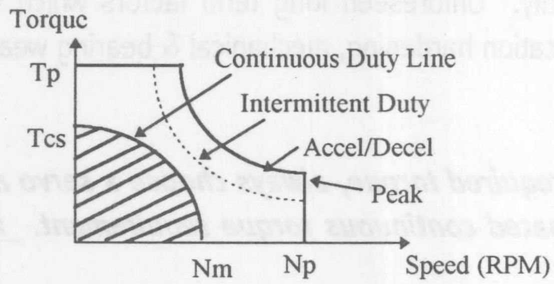
Brush Motors

Brush-type servo motors are the most popular choice in MC applications due to their low relative cost, good torque and speed performance, feedback capability, high installation base and relatively easy system integration.

With a brush servo motor, the physical location of the brushes is such that the current vector is maintained perpendicular to the fixed magnetic field at any rotor speed. This results in torque generation proportional to armature current and motor speed proportional to armature voltage.

A typical Brush type motor exhibits the following torque versus speed relationship:

Brush Motor Performance



Nm = Maximum speed, continuous operation
Np = Peak speed, acceleration/deceleration and intermittent duty
Tcs = Continuous stall torque
Tp = Peak torque

The first step in choosing the right brush servo motor is to decide on the type of motor needed. There are three major types of brush servo motors, differentiated primarily according to performance, design and size:

Iron Core - These are the most common type of brush motor due to their low cost, large selection and good performance. Iron core motors feature a rotating armature of wound coil around an iron core within a housing containing magnets. Typically, Iron Core motors are found in the 2.3" to 7.0" diameter frame sizes including NEMA 23, 34, 42 and 56 sizes. Depending on the motor winding, continuous torques range from 20 oz-in to 3850 oz-in with typical operating speeds from 50 to 4000 RPM. Unfortunately, these motor suffer from iron losses, brush arcing (electrical noise), high rotor inertia and a limited speed range versus other types of servo motors.

Do not operate Iron Core brush-type motors at speeds below 50 RPM as they tend to cog, reducing smoothness. For applications requiring less than 50 RPM, add gearing, a tachometer or consider switching to brushless motors.

Moving Coil - This type of motor type has a higher cost and performance profile over the Iron Core motor. The armature is not wound around the iron stator but is wound independently, orientated between the magnets and stator. Since there is no moving core, these motors have reduced brush arcing, lower inertias and do not suffer iron losses. The result is higher attainable speeds (up to 10000 RPM), faster and smoother acceleration/deceleration and less brush maintenance. Moving Coil motors tend to be less than 2.3" in diameter and 100 oz-in continuous torque, and therefore, are limited to low power applications. However, they are well suited for designs where space is limited (i.e medical products, robotics, instrumentation, testing stations) and where EMI/RFI noise must be minimized.

Disc-Armature - Also known as **"Pancake"** motors, they feature a unique design with an ironless flat disc armature as opposed to a conventional iron-core cylindrical design. These motors offer the same advantages of the moving coil motor but include greater space efficiencies due to their smaller size/lower profile and lower inductance values due to a lack of iron in the armature. In addition, these motors possess low mechanical and electrical time constants, providing excellent acceleration/deceleration capability. Disc-Armature motors are well suited for applications requiring compact size, low speeds & cogging and low rotor inertia. Since the armature contains no iron, inductance is low resulting in EMI/RFI effects being minimized. Brush and brushless types are available.

Where available, the designer should reference the manufacturer's torque versus speed curves in order to correctly choose the optimal size motor and winding. Since torque and motor speed are often inversely related, a performance trade-off may have to be made for a given frame size or winding.

Most iron core servo motors contain enough inductance to operate PWM servo amplifiers. Since Moving Coil and Disc Armature motors do not have a conventional iron core, they often do not contain the minimum amount of inductance needed to operate many PWM amplifiers. For optimal usage, the motor inductance must equal the minimum inductance of the amplifier. **Where there is insufficient inductance, an external inductor or choke is used such that the total motor plus inductor/choke inductance is at least equal to, or preferably up to 50% greater (including safety margin) than the amplifier inductance.** As well as targeting a maximum 50% safety margin, the current rating of the inductor/choke should not exceed the peak current rating of the amplifier. However, too much inductance should be avoided as it tends to dampen motor responsiveness.

Chokes and inductors are inexpensive devices rated in terms of inductance (uH) and current (A). They are used for both servo and stepper motors. In addition to inductance matching, inductors and chokes provide other important benefits: 1) minimizes current ripple arising from AC line spikes 2) reduced heat generation in the motor windings thereby increasing motor life and 3) current limit capability with the amplifier. Different inductance and current combinations are available depending on the model chosen. The designer can tailor the unit's performance according to their needs. As a result, a small upfront investment in inductors and chokes will pay large dividends by avoiding downtime, extending motor life and delivering improved system performance.

When selecting an iron core motor, specify a NEMA-standard frame size for easy replacement and common performance ratings.

Analyzing motor and system inertia is one of the most important, yet often ignored, steps in selecting brush servo motors. It directly affects the amount of torque and current (power) required and impacts on motor acceleration/deceleration, speed, precision and motor life. Motor inertia is based on the design, mass and size of the motor's rotor and mechanical commutator. Due to their design, moving coil and pancake servo motors generally have the lowest inertias (and power ratings) among brush servos. Since the design of the iron core motor requires the commutator and armature to rotate, rotor inertia is higher. As brushless motors feature electronic commutation, they usually have lower overall inertia. System inertia is design-dependent and is significantly affected by the type of materials used and the size of the machine.

In addition to limiting start/stop capability, high motor inertia may complicate servo tuning due to the likelihood of motor instability. A system where the motor inertia is too small relative to the load may result in tuning problems, lower acceleration/deceleration and duty cycle rates. Furthermore, the motor is prone to overheating (resulting in early failure) and lower positional accuracy. If the motor inertia is too high relative to the load, then the motor plus drive package is probably over-sized for the application. In general, a minimum motor inertia of at least 50-70% of the load inertia will be sufficient to give the motor a chance at effectively driving the load. The motor versus load inertia should never exceed a 1:5 relationship.

Target for a 1:1 ratio between the motor and the reflected load inertia for optimal performance.

System designers with applications requiring rapid start/stop capability should also reference the motor's mechanical and electrical time constants. The mechanical time constant of a motor is the mechanical rate at which a motor will accelerate to its final speed. It is used in conjunction with the electrical time constant which measures the motor's ability to overcome inherent resistance/inductance and accelerate to final velocity. The lower the two time constants the faster will be the motor response time. Brushless servo motors provide the best ratings while moving coil and pancake brush servos provide the lowest values for brush servos. Most applications require electrical time constants in the range of 5 to 10 milliseconds.

Magnet, brush and commutator life will be dependent on many factors including: operating and ambient temperatures, axial & radial loads on the front shaft bearings, duty cycle, external vibrations, operating mode, electrical load & stray noise, maximum speed and the type of magnets used. In general, motor life will be significantly reduced if low power magnets are used and the above variables are demanding.

Brush servo motors possess a number of limitations tracing to internal heating and brush commutation breakdown. As a result, they do not convert all input power into mechanical power. This is caused by the electrical resistance of the armature and the losses associated with high speed and high current operation. As the torque output of the motor is increased, the winding losses become greater. In addition, as motor temperatures increase, winding resistance rises and magnetic forces decrease, resulting in reduced torque and performance. Motor losses arising from high speed operation include: eddy current losses, friction losses, brush contact losses, iron and hysteresis losses and short circuit currents. All these factors combine to create heat generation inside the motor. Excessive internal heating limits motor life since heat can only escape through the shaft, bearings or armature. As a result, thermal dissipation is limited resulting in demagnetization of the motor, wearing down of the mechanical commutator and armature burn out. Magnetic fields can also tend to reduce motor life due to demagnetization affects on the stator.

Operating a servo motor consistently at peak torque or regularly above the continuous torque and current rating (in the intermittent range) will result in the motor's normal duty cycle being exceeded. The result is excessive heating in the motor and amplifier, leading to demagnetization and the breakdown of the brushes and armature. Every additional 10° C increase (above the ambient rating of the motor) the windings see, the winding insulation life expectancy is reduced by approximately 50%. Moreover, overheated motors become a safety risk to those who touch them.

In order to prevent heating-induced motor breakdown, the following steps should be taken:

1) Reduce current and voltage to motor, if possible;
2) Fan cool the motor and amplifier;
3) Install a heatsink on the motor and drive; run the fins vertically for maximum thermal dissipation;
4) Use higher-power brushes;
5) Check amplifier/motor for inductance mismatch; if present, install filters and inductors;
6) Install chokes for current ripple suppression;
7) Switch to a higher power brush motor or a brushless type;
8) Upgrade motor with high current motor brushes.

Using longer-life rare earth magnets and precious metal or graphite brushes will improve thermal capability, duty cycle and responsiveness to a point but may not deliver the desired performance due to the limits of mechanical commutation. Silver graphite brushes are effective in applications requiring low voltage start-ups and running at slow speeds.

The inherent limitations of mechanical commutation reduces the brush servo's suitability for high power, rapid start/stop applications. Uner these conditions, the brushes and the commutator will wear out quickly requiring regular replacement. The minimal contact between the brush and commutator often limits top speeds to a maximum 5000 RPM and hinders low speed performance, often resulting in cogging and torque ripple below 50 RPM. Moreover, brush commutation limits overall performance through contact and friction losses, commutator bar oxidation and arcing. Consequently, brush motors are not well suited for clean room and explosive environments. Finally, brush commutation produces EMI, creating problems in noise-sensitive applications.

The simplest way to maintain load safcty is to ensure the motor is disconnected from the load during initial tuning. Otherwise, the motor may runaway resulting in damage to the load.

Motor brushes should be checked every 6 months. Replacing brushes is relatively simple and inexpensive.

Common assumption: Brush servos are problematic because their brushes wear out quickly. This may have been true 10 years ago but today's brush servos use high quality brushes (made of precious metals or graphite) with a rated life of 1-2 years under normal operating conditions.

If the motors are stored in a humid environment, turn the motor shaft once per month so that the motor bearings remain lubricated. Otherwise, bearing scoring could occur reducing overall performance. If possible, dry motors in an oven before using them. Do not use regular room temperature vulcanizing (RTV) compounds to seal motor leads as they need to breathe. Moreover, avoid spray-painting and wet conditions around motors as fluids often seep into the seals. Where motor shafts, bearings and encoders are being regularly damaged, the motor is most likely seeing higher than rated axial, radial and shock loads. Seek out the optimal shaft loading, utilize flexible couplings and ensure the motor has preloaded ball bearings and heavy-duty incremental shaft encoders.

Occasionally, electrical noise has a negative impact on bearing life, even under no-load conditions. For example, current can cross from the driveline, across the bearings, to ground. Where the bearings and race touch, etching could occur. As a result, bearing failure under load is quite possible. Before undertaking electrical work around the machine, uncouple or ground the motor shaft.

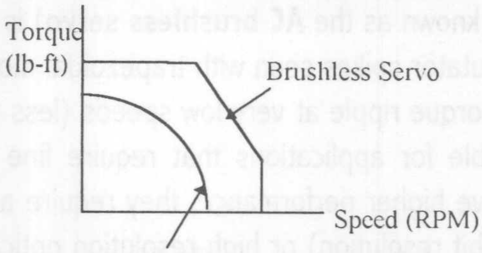
Brushless Motors

Brushless motors are a higher performing servo motor solution. They are referred to as either DC brushless or AC Servo types. The two are quite similar in construction and purpose. A brushless servo motor differs from a brush-type motor in three basic design features: 1) higher-power, longer-life rare earth magnets are used versus conventional ceramic/ferrite magnets found in brush servos; 2) stator windings are commutated electronically versus a mechanical commutator and; 3) the rotor becomes a permanent magnet while the stator becomes the wound iron core (the inverse of brush servo design). Typical applications for brushless motors are in the: automotive, aerospace, CNC, injection molding, robotics and material handling industries.

The brushless motor design provides many benefits. The rotor/stator scheme provides reduced rotor inertia and improved cooling efficiency since the thermal path is much shorter than a brush type motor. Therefore, with an integral heat sink, brushless motors are able to achieve significantly higher torques at higher speeds & duty cycles than a brush servo motor. In addition, their lower inertia and electronic commutation allows for better start/stop capabilities plus a wider useable speed range between 1 and 10,000 RPM. Typical acceleration/deceleration rates of a brushless motor are 2 to 4 times better than those of a brush servo motor. The use of high-performance samarium cobalt or neodymium iron bore magnets plus a superior design delivers a high torque versus size ratio making brushless motors ideal for small size/high torque applications. Moreover, brushless motors tend to provide greater dynamic stiffness and deflect less under load than brush motors due to their operation at higher amplifier gain values. Since they do not employ mechanical brushes (which generates sparking and bristle loss), brushless motors require less regular maintenance and are well-suited for remote, explosive, vacuum, medical, and clean room environments.

Compared to brush motors, brushless motors have the following torque vs. speed profile:

Brush vs. Brushless Motors



Despite their abundant benefits, brushless motors possess some drawbacks. Higher performance and reduced maintenance comes with a higher purchase price and longer delivery since they utilize more expensive magnets, an electronic commutator and more sophisticated drive electronics. Since they often require additional feedback devices (i.e resolvers, hall effect sensors) for commutation and gearing for inertia-matching, there is an increase in complexity and tuning time. Unlike brush servo or stepper motors, there is little dimensional standardization (particularly frame sizes) among brushless motor manufacturers creating potential design and replacement problems. Few brushless motors are available in NEMA-standard frame sizes and special mounting kits are required for gearhead mounting.

Because of the higher complexity and tuning requirements of a brushless motor/amplifier system, an inexperienced designer should purchase the motor and drive from the same vendor in order to ensure compatibility.

Brushless motors were developed to address the maintenance and performance shortcomings of brush-type motors. Although they are initially more costly and complex than brush-type motors, when downtime, energy consumption, and maintenance are considered, they are usually less expensive on a total cost basis.

Brushless motors and drives come in two varieties which vary according to their torque characteristic and commutation: trapezoidal (6-step or 12-step) and sinewave (sinusoidal).

As a result of the non-linearity of the torque output, trapezoidal motors emit a wave form torque ripple (5-17% on average). This results in some velocity instability of the load, particularly at slow speeds. In addition, they generally rely on difficult-to-tune hall effect sensors located in the motor or fragile encoders for commutation. Closing the velocity loop, manipulating the gain of the accompanying amplifier and utilizing high-resolution encoders will help minimize this effect, albeit with some effort. Notwithstanding this, trapezoidal motors do have their advantages. They are the most cost effective brushless motor solution and produce approximately 10% more torque by volume/size than brushless motors utilizing sinewave power.

Where a minimum torque ripple can be tolerated (1-2%) and very smooth performance and precision is needed, the sinewave motor (also known as the **AC brushless servo**) is preferred. A sinewave torque profile does not contain the commutator spikes seen with trapezoidal motors, and therefore, has much smoother performance and lower torque ripple at very low speeds (less than 20 RPM). Consequently, sinewave systems are indispensable for applications that require fine surface finishes like coating, grinding and machining. To achieve higher performance, they require a very precise feedback device like a resolver (typically 12 to 16-bit resolution) or high-resolution optical encoder (i.e. 2048 PPR) to control commutation and to provide for the smooth sine-cosine relationship. As a result, the sinewave motor package is generally more expensive and sophisticated than the trapezoidal system. Their superior performance and ease of use versus trapezoidal systems have made them the preferred brushless motor choice today.

Once a brushless motor design is specified, the most important decision becomes what, if any, gearing is required between the motor and the load. In order to achieve maximum start/stop capability and to simplify system tuning, pay close attention to the inertia relationship between the brushless motor and the load.

Problems occur where the inertia of the load is more than 5 times that of the motor. A 1:1 ratio is ideal.

In the case of a mismatch and where the load is fixed, the designer has three options: 1) increase the rotor inertia of the motor; 2) use a gearhead to reduce the mismatch or; 3) reduce the inertia of the load, although this is often not practical. Some manufacturers feature motors with internal flywheels that add inertia to minimize inertial mismatches. Note that with option 2) adding a gearhead will reduce the reflected load inertia by the inverse of the gear ratio squared. However, this will also provide torque multiplication, reduce maximum motor speed and increase cost and complexity. For further information on inertial loads, see the Gearheads section pages 74-77.

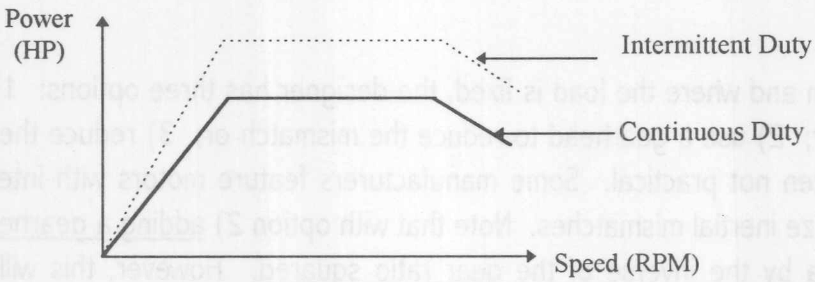
Applications concerned with precisely following motion paths (i.e CNC machines, plotters), achieving high cycle times (i.e packaging) or being resistant to external disturbances (i.e pick and place, injection molding) will rely greatly on the system bandwidth and dynamic stiffness. Bandwidth (KHz or Hz) measures the ability of the motor or actuator to react to a command. It is influenced by the controller, motor and amplifier. The higher the system bandwidth, the more commands per unit of time to which the motor will respond. As a result, high cycle times, precise paths and optimal speed control is achieved. However, too high bandwidth can cause system instability and controller problems. Dynamic stiffness impacts directly on the precision of the system and is affected by most of the system's electro-mechanical components. Simply put, it is the slope of the torque-displacement curve as it crosses the zero torque axis. Although it may be difficult to measure directly, dynamic stiffness should be 10% of the static stiffness for optimal performance.

AC Vector Motors

AC Vector motors and drives are beginning to replace spindle and standard brushless motors for certain high power tasks. They are ideal for applications with large load inertias that require closed loop servo control, such as: machine tools, injection molding, web converters, press feeders, textile/printing machines and rotary cutting. Up to 12000 RPM and 20 HP continuous duty torque is available with resolver-based feedback for rugged operation. Versus spindle motors, AC Vector systems provide many benefits including: better servo capabilities (via higher bandwidth), accurate positioning (via low vibration, smooth operation), good inertia matching for large loads, constant power range and higher acceleration/deceleration rates, as well as reduced noise and better energy efficiency (yielding improved cooling, reduced size).

Vector motors generate a trapezoidal torque versus speed curve:

AC Vector Motor Performance

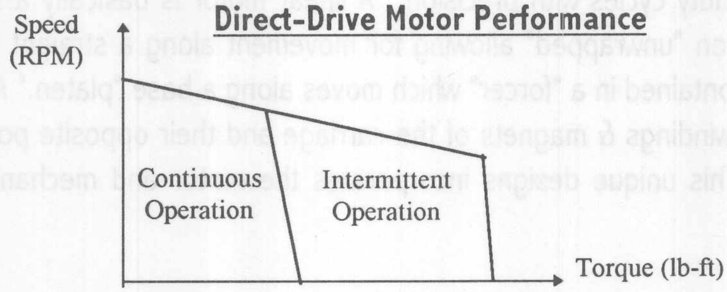


However, AC Vector systems have some shortcomings. Because of their design and accompanying electronics, they are more expensive and complicated than spindle and standard brushless systems. In addition, they can not provide full rated torque at zero or low speeds nor are they very effective at reversing direction. Moreover, servo capability will not be as good as a standard brushless motor. Because of high power generation, accompanying cooling fans and a separate power supply may be needed increasing total cost and complexity. Like other brushless systems, the motor and drive should be purchased as part of a matched system from the same vendor. Where size is critical and high speeds are needed, a Disc Armature brush or brushless motor should be used.

Direct Drive-Frameless Motors

For applications requiring maximum servo stiffness, the fastest settling times, minimum size, high torque at high speeds and zero backlash, a Direct Drive-Frameless servo motor is recommended. They are ideal for robotics, aerospace, medical equipment and packaging applications. These motors are available in brush and brushless (most common) versions and are mounted directly to the load ensuring maximum mechanical compliance and efficiency (power versus size ratio). There is no transmitted backlash, little cogging and low torque ripple. As they can be built directly into the load or drive with no shaft protrusion, they offer significant space savings, mechanical simplicity and compliance plus design flexibility. Direct Drive-Frameless motors typically operate at very high speeds and continuous torques, able to generate a maximum 35,000 RPM at 5 HP of continuous torque.

Their speed versus torque performance is generally flat reflecting their high speeds at constant torque, as the following curve illustrates:



Due to their design and high temperature operation, care must be taken with torque sizing, mechanical installation and in ensuring adequate thermal dissipation/cooling is available. As a result of their unique design and high power matching drives, Direct Drive-Frameless motors tend to be higher cost than other brushless systems.

The following chart illustrates the advantages and disadvantages of each type of servo motor:

COMPARING BRUSH & BRUSHLESS MOTORS

Parameter	***Brush***	***Brushless***
Acel/Decel. Capability	Good	Excellent
Power	Low-Moderate	Low-High
Rated Max/Min Speeds (RPM)	50-4,000	0-10,000
Maintenance Required	Moderate	Low
Thermal Design	Good	Excellent
Duty Cycle	Moderate	High
Harsh Environments	Poor	Excellent
Set-Up	Easy	Moderate
Purchase Cost	Low-Moderate	Moderate-High
Rotor/Armature Inertia	Higher	Lower
Torque-to-Weight Efficiency	Good	Excellent
Noise Generated	EMI	RFI

For the vast majority of applications, the housed brush and brushless servo motor are the ideal solution. However, some applications are best suited by the latest innovation in motor technology, Linear Motors.

Linear Motors

Linear motors are the preferred choice for applications requiring small load & mass objects to be moved at high speeds and duty cycles with precision. A linear motor is basically a servo, stepper or induction motor that has been "unwrapped" allowing for movement along a straight path. The motor windings and magnets are contained in a "forcer" which moves along a base "platen." A strong magnetic flux is created between the windings & magnets of the carriage and their opposite poles on the platen resulting in linear thrust. This unique designs incorporates the motor and mechanical drive system within a single envelope.

Linear motors have two unique characteristics that differentiate them from traditional mechanical drive systems. They transmit force using only two moving elements. Secondly, their force transmission is low (stepper) or zero contact (brushless servo) via a small air-gap. As the linear motor's moving parts are non-contact, they are well suited for low maintenance, high duty cycle applications. Since their design eliminates mechanical inertia, efficiency/mechanical losses and backlash, they are able to achieve high acceleration (3+ Gs), speeds (up to 270 inches per second-IPS), precision and very smooth performance at all speeds (as low as 0.001 IPS). Other benefits include: almost unlimited travel length (up to 50 ft. stroke), excellent dynamic stiffness, minimum settling time and backdrivability.

Linear motors are generally more expensive than a ball screw plus motor combination on an installation basis. Also, the need to achieve high speeds necessitates choosing a higher power amplifier or drive. However, the cost difference narrows when lower indirect costs (maintenance, complexity), higher reliability (high mean-time-between-failure ratings-MTBF) and performance advantages (higher throughput, speeds, precision) are considered. In addition, linear motors possess other unique advantages due to their design. They enjoy a smaller three-dimensional work envelope than a comparable mechanical system. Moreover, linear motors can have multiple forcers on the same platen without the need for overlapping trajectories.

Thus, linear motors are often used to replace the complete motor and mechanical drive system, thereby reducing system complexity. In general, the higher the speed required by the application the lower the attainable thrust. They have quickly become the major drive system in high performance applications such as: parts insertion, blow molding machines, optical scanning, materials handling, water jet cutters and machine tools.

Due to their open frame design, linear motors are susceptible to dirt and dust contaminats on the platen, reducing smoothness and speed. Bellows and forced air must be provided to protect the motors from contaminants. Furthermore, consider mounting the linear motor upside down or on its side to improve particulate runoff.

The following chart compares the performance of linear motors versus ball screws as drive mechanisms:

COMPARING BALL SCREWS & LINEAR MOTORS

Parameter	***Ball Screw***	***Linear Motor***
Maximum Speeds-IPS	20	270
Maximum Acceleration-G	3	10
Settling Time-msec	100	10
Dynamic Stiffness-N/mm	100,000-200,000	180,000-250,000
Maximum Length-in.	240	600
Minimum Backlash-in.	0.002-0.013	Zero

Linear motors are available in single or dual axis configurations using DC brush & brushless servo, induction or stepper motors. Although single axis configurations are most common, dual axis systems are ideal for laser trimming, inspection stations and flexible manufacturing workstations. Two axis systems may incorporate the traditional overlapping trajectory design of a positioning table or may contain multiple forcers on the same platen, reducing overall system height and length.

Brushless linear motors are the most common type of linear motors owing to their higher force, acceleration and feedback capabilities. They are dynamically balanced containing a small air gap between the forcer and platen. As a rule of thumb, brushless versions are recommended where the number of application cycles exceeds 500,000 per year. Like a rotary brushless motor, there is no need for regular maintenance or lubrication making them ideal for clean room, vacuum and food processing environments. The linear encoder is the most common feedback device used with linear motors. Other feedback options include inductsyns and laser interferometers for very high precision.

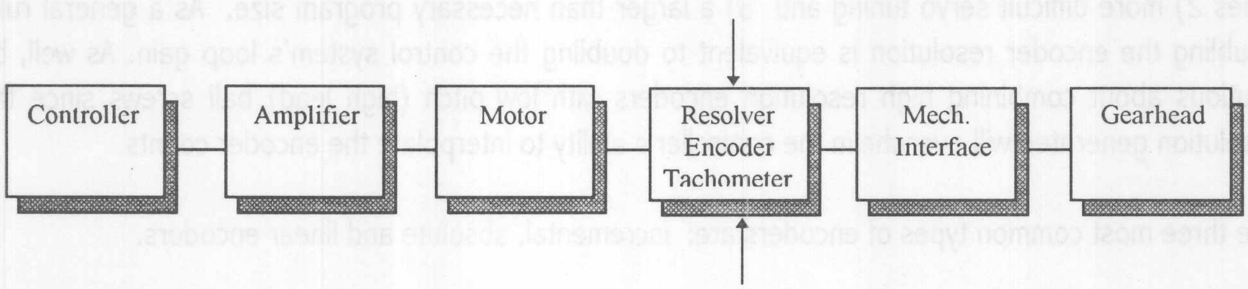
Where cost, simple construction and easy set up is important, a linear stepper motor is a cost effective solution that still provides open loop, unidirectional repeatability and accuracy to 1 micron with microstepping. However, there are some drawbacks to linear step motors. They are prone to the same inductance and repeatability problems as rotary stepper motors. Secondly, since there is contact between some components (usually bearings), some wearing of the mechanical parts will occurr. In spite of this, linear steppers still require less regular maintenance than a drive screw assembly. Finally, close attention should be paid to a linear stepper's velocity ripple since it is a more important consideration than with rotary step motors. With rotary steppers, the losses inherent in a mechancial system dampen these effects.

Because of the strong magnetic force existing between the forcer and platen, a strong preload can occur in the bearings making the system overly stiff. This could require the motor to be oversized larger than it normally should be. In extreme cases, a magnetically balanced brushless model which offers little or no preload and a frictionless bearing system (using cross roller, v-way or air bearings) should be selected.

In order to ensure long life expectancy for linear steppers, the wear of the platen to the surface of the mechanical bearings should be monitored. Care must be taken to ensure loads (dynamic, static, moment) do not exceed rated specifications. Furthermore, the designer should employ only the minimum required velocity of the application (versus the maximum rated velocity of the motor and drive). This ensures that the platen does not suffer eddy current losses or demagnetization.

All servo systems require a feedback device to close the position or velocity loop. Typically, an encoder, tachometer or resolver is specified.

FEEDBACK DEVICES



There are many different types of feedback devices associated with MC systems. Three of the most common are optical encoders, tachometers and resolvers.

Encoders

An encoder is an electro-optical device which measures the position and direction of a motor shaft or load by means of an optical sensor outputing a digital signal to a motion controller. The function of the encoder is to close the position loop. Simply put, photo-transistors read an LED shining through a glass, plastic or mylar disk containing etchings (number of pulses per 360 degree revolution), generating a pulse train each time a motor or load shaft rotates over an increment of motion. Due to its output form and a controller's math processing capabilities, the encoder can also provide satisfactory velocity feedback.

The accuracy of an encoder is determined by the resolution, known as counts per revolution (CPR) or pulses per revolution (PPR). Standard encoders have 500 or 1000 PPR, but some models are available from 1 to 5000 PPR direct read or 25,000 PPR with 5 times interpolation. The higher the encoder's resolution, the higher attainable accuracy. With quadrature decoding common in many controllers, the encoder's resolution is multiplied 4 times, easily and cheaply increasing system accuracy. For example, a 1000 line encoder will generate 4000 counts per revolution after quadrature decoding.

It is easier and more economical to achieve higher precision by relying on the controller's quadrature decoding than it is to increase the resolution of the encoder to achieve the same objective.

A 1000 PPR encoder has sufficient resolution for most applications. The designer should not recklessly increase encoder resolution over this value, particularly if the application involves high speeds, without consideration of system stability. Adding resolution provides increased accuracy and finer resolution but also increases oscillation as a result of excessive encoder input frequency to the controller. Other problems of too high resolution include: 1) lower precision due to motor "hunting" and higher settling times 2) more difficult servo tuning and 3) a larger than necessary program size. As a general rule, doubling the encoder resolution is equivalent to doubling the control system's loop gain. As well, be cautious about combining high resolution encoders with low pitch (high lead) ball screws since the resolution generated will overwhelm the controller's ability to interpolate the encoder counts.

The three most common types of encoders are: incremental, absolute and linear encoders.

An **incremental** encoder generates a digital pulse for a given increment of a shaft (often motor) rotation from a reference point. Because of its simplicity, good performance and relatively low cost, it is the most popular type of encoder. It can be mounted on the motor, the load or on both places in a typical MC system. Incremental encoders are available in two designs. Modular or kit encoders which fit directly over the rear motor shaft. These are the lowest cost and easiest to install. Rotary shaft encoders are installed on the rear motor shaft via a separate coupling and flange. They are higher in cost than incremental encoders and are usually found within a can assembly on the motor end bell. Rotary shaft encoders are more industrial since they absorb higher axial and radial shaft loads. Many rotary shaft encoders also feature MS mating connectors for ruggedness and easy disconnects. Both types of incremental encoders will lose home position on power down. However, because they are a counting device, incremental encoders often lose encoder counts resulting in position loss.

Absolute encoders, on the other hand, never lose position at power down because each shaft location has a unique location on the absolute disk. The output is Gray code versus Binary code for incremental encoders. Another advantage of absolute encoders is that only one bit changes at a time, creating a maximum error of only 0.5 bits. In addition, absolute encoders provide advantages over incremental models in applications requiring long distance data transfer (between 30 and 4,000 ft), where high speeds are required and noise immunity is important. Typical applications for Absolute encoders include: positioning satellite dishes, robotics, laser positioning and any application where the device is inactive for long periods or moves at very slow rates (i.e. flood gates, cranes, telescopes).

A number of important factors affect incremental encoder accuracy and reliability and should be considered. The encoder is often the weakest link of the MC system due to its susceptibility to electrical noise, ease of mis-wiring and temperamental mounting. In fact, a properly installed encoder can still suffer accuracy problems resulting from lost encoder counts. These could result from too high shaft speeds, electrical noise and low frequency responses. Specifically, the rated maximum encoder frequency (usually 100 KHz) and mechanical rating limits shaft rotation to usually no more than 5,000

RPM. Finally, lost encoder counts could also stem from: poor shaft eccentricity and perpendicularity, quantization error, incorrect encoder mounting, high shaft run out and axial and radial play.

A number of important yet inexpensive features go a long way to ensure system accuracy and performance. Choosing differential, rather than single-ended, encoder outputs will improve noise immunity, although it requires additional termination. A TTL line driver output will help maintain signal integrity and voltage stability along the cable, particularly at longer transmission lengths (up to 25 ft.). Using three channels (versus single or two channels) with complements will also improve noise immunity. A minimum 100 KHz frequency capability to accommodate high shaft speeds and high resolutions will prevent controller saturation. To pre-empt mounting errors that reduce accuracy, choose encoders with factory pre-aligned air gaps.

Before purchasing encoders, ensure your motion controller accepts differential encoder inputs.

Maximum speed, shaft loading and environmental ratings will have a significant impact on encoder reliability and life. Encoders should have a rated speed of at least 3,000 RPM in order to accommodate high-speed brush or brushless servo motors. As well, encoders should be factory-rated in terms of temperature, humidity, vibration and shock conditions as well as axial and radial shaft loading for industrial applications. Naturally, the designer should take great care in ensuring the wiring is correct, and motor mounting tolerances are maintained. Unfortunately, a surprising number of problems are still caused by poor wiring of the encoder.

The important selection parameters for encoders are:

1) Resolution-500 or 1000 PPR is standard;
2) Shaft bore size;
3) Output type (CMOS, TTL, Line Driver, Complementary);
4) Voltage (5V, 12V, 15V);
5) Ease of installation i.e. pre-set air gap;
6) Frequency (response time);
7) Number of Channels (1, 2 or 3);
8) Tolerances of mounting surfaces;
9) Current requirements (sinking-NPN versus sourcing-PNP);
10) Shaft loading;
11) Encoder location;
12) Cable or termination requirement.

Incremental encoders can be mounted in either of two positions: the motor or the load. The designer's decision will be based on a trade-off between system stability or precision and is generally application-specific.

Mounting the encoder on the motor will usually produce the most stable system (good for responsiveness, dynamic stiffness) but may result in reduced precision due to inherent backlash found in most couplings, ball nuts, gearheads etc. plus poor mechanical compliance. This could be overcome by using low backlash mechanical components throughout the mechanical design or using dual-loop encoder feedback.

On the other hand, installing the encoder on the load will provide superior precision but may result in stability problems due to added backlash in the control loop. In this case, stabilize the system by closing the velocity loop with a tachometer.

Mounting the encoder on the motor and load both stabilizes the system and provides high precision. However, this comes with higher cost and complexity including additional wiring. In general, mounting the encoder to the motor is recommended for most applications unless precision is critical.

Linear encoders are used in applications where there must be direct measurement of the load and high linear speed is needed. These encoders comprise a glass scale with a designated number of gradients per unit of measure plus a reading head. They operate on the principle of photoelectrically scanning very fine line gratings and outputing a digital signal to a motion controller.

There are two types of linear encoders; transmissive and reflective tape. Transmissive models are the most popular design utilizing a glass scale and reader head mounted in an aluminum housing. They have a large installation base, are rugged and are generally the least expensive type of linear encoder. Glass scales are thermally stable making transmissive linear encoders well suited for high accuracy and high speed applications. Reflective tape models utilize magnetic tape instead of glass scales. They are used in applications where minimal scale thickness and simple installation is needed. However, as they are exposed, they are vulnerable to environmental contamination.

Though they are more expensive than incremental encoders, linear encoders have three major advantages. They offer higher attainable accuracy, higher frequency/speed capability and zero backlash/hysterisis due to its non-contact operation. They are best suited for applications requiring high accuracy and long travel which include: optical scanning, machine tools, parts insertion and coordinate measuring systems. Linear encoders come in absolute and incremental types with lengths of up to 120 inches, maximum speeds to 1200 feet per minute and accuracies from 0.1 to 30 microns over the entire travel length, depending on interpolation.

Once the decision to use linear encoders is taken, four important, and often overlooked factors, should be considered: 1) reference mark location for machine homing; 2) surface tolerances and misalignments of mounting surface to insure mounting correctness, accuracy and reliability; 3) type of connector and cabling needed for environmental protection and; 4) the thermal expansion coefficient of the machine for precise feedback.

When mounting linear encoders, ensure no coupling and alignment errors are present that can cause position inaccuracies.

A few hardware features should be considered. Firstly, linear encoders all require separate reader electronics for interpolation etc. High performance encoders contain the electronics in the reading head for lower cost, greater convenience and protection. The reader electronics should be operable with light sources as low as 3% of ambient illumination for greater reliability under a variety of conditions. Finally, the reader head should utilize a bearing suspension to reduce backlash and compensate for wide mounting misalignments between the encoder and machine guideway.

Encoders are especially susceptible to EMI noise. For improved noise immunity, choose encoders with differential TTL Line Driver output with long (up to 25 ft.) shielded and twisted pair cable. Otherwise, you may lose encoder counts, and as a result, position accuracy.

Important selection factors for linear encoders include:

1) Physical size, type of linear encoder used;
2) Maximum mechanical travel ignoring all limit switches and mechanical stops;
3) Resolution before quadrature decoding - English or Metric terms;
4) Maximum velocity needed - Compatible with controller frequency input rate;
5) Operating environment -temperature, shock, dust, vibration, noise;
6) Accuracy and repeatability;
7) Connector and cables needed;
8) Ease of Installation;
9) Output type;
10) Frequency response - from 5X to 50X interpolation.

Since linear encoders are susceptible to environmental contaminants, built-in seals and air-purging should be used for protection.

An important note on linear and rotary encoder transmission cable. Encoder signals transmitted over long distances (3+ feet) are vulnerable to noise pickup and capacitive coupling within the cabling. Two cable schemes are most commonly used to solve these problems, twisted pair and shielded. Twisted-pair cables equally distribute capacitance along the length of the conductor, keeping capacitance to ground balanced. This reduces capacitive coupling and maintains a high common-mode rejection ratio. With balanced capacitance, noise is induced equally into the wires and is cancelled at the amplifier input.

Cable shielding reduces noise along the input lines by 60 dB or more and reduces capacitive coupling. Furthermore, shielded cable also absorbs magnetic fields and reflects external electric fields. Noise-resistant connectors should always be used, particularly where cable connections are needed. Finally, armour or specialty cables with MS mating connectors are needed for harsh, corrosive environments.

To summarize: **Shielding is best used in conjuction with twisted pair cabling for maximum protection.**

Where only the velocity loop needs to be closed or speed control is critical, a tachometer is used.

Tachometers

A tachometer is a feedback device used to sense motor velocity by outputing an analog signal to a motion controller or servo amplifier. Output voltage is proportional to the motor speed. Tachometers are rated in terms of ripple (1% or less is best) and a voltage constant (7 V/KRPM is typical). Voltage constants from 2V/KRPM to 55V/KRPM are most common. Tachometers come in many different varieties for both brush and brushless servo motors. Since tachometers produce analog signals, they must be used in conjuction with an Analog-to-Digital converter (ADC) to interface with a digital motion controller.

If you want to close the velocity loop through the controller, you must ensure your motion controller accepts analog inputs to read the tachometer feedback.

In applications where slow speed operation (less than 50 RPM), fast response to external disturbances and position feedback is required, the tachometer is used in conjunction with the encoder to provide system stability. Tachometers can be mounted to the motor (most common) or to the load (better stability). An effective means of increasing stability is to close the tachometer (velocity) loop in the amplifier and the encoder (position) loop in the motion controller. Or for simple speed control applications where position feedback is not required, a tachometer can easily be interfaced with most servo amplifiers (configurable in tach mode) to create a velocity loop.

Adding tachometer feedback to close the velocity loop brings additional system benefits including:

1) Added dampening to eliminate oscillations in systems with backlash;
2) Increased stability in systems with resonance between the motor and the encoder;
3) Increased stability in systems with oscillation under high inertial loads (>3-5 times higher than motor inertia).

Two key tachometer considerations is that the output voltage should be smooth over the operating range and stabilized against temperature variations and shock loads.

It is cheaper and easier to purchase a motor with a integral tachometer than it is to add one in the field.

Another popular means of providing feedback is the resolver.

Resolvers

A resolver is an electromagnetic device that provides position & velocity feedback and a commutation signal for brushless motors. Similar in construction to a motor, a resolver is essentially a rotating transformer with one primary and two secondary windings. By design, the primary winding is energized with a sinusoidal signal. In response, the two secondary windings produce signals of the same frequency, whose amplitudes are dependent on the angular position of the shaft. By processing the two output signals, the shaft position (digital) plus speed (analog) is decoded via a resolver-to-digital converter (RDC), found in the motion controller, drive or as a separate unit.

Resolvers offer a lot of advantages for MC systems. They can provide both position and velocity feedback similar to an encoder. Since they are similar in construction to a motor, they are very robust with high vibration, shock load and temperature ratings. Furthermore, the resolver is an absolute position feedback device within one revolution for initial start-up. Due to their rugged design, they are most commonly used with sinewave brushless motors in providing commutation and position/velocity feedback. In a brushless motor, resolvers are functionally equivalent to hall-effect sensors plus a tachometer and absolute encoder. As demanding servo applications are increasingly met by brushless motors, resolvers will play an increasingly prominent role, replacing complex hall-effect sensor commutation and fragile encoders.

Although they appear to be a superior alternative to the optical encoder, resolvers possess some weaknesses. They are: 1) more expensive and complex, especially with the accompanying RDC converter 2) less accurate (reduced accuracy via lower resolution) and 3) lower line count flexibility (only binary, decimal). Moreover, as resolution is increased for better precision, the maximum attainable motor speed is significantly reduced. For example, say a brushless motor can deliver 7,000 RPM with 12-bit resolver resolution. Increasing resolution to 16-bit will reduce maximum motor speed to 500 RPM. Other than its superior ruggedness versus the encoder, it offers less value as a feedback device for all motors except in demanding brushless applications.

The following chart compares the performance of encoders versus resolvers:

ENCODERS vs. RESOLVERS

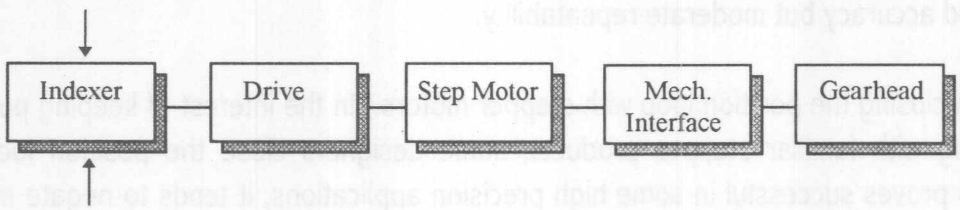
Parameter	***Encoder***	***Resolver***
Input	DC	High frequency AC (1or 2 phase)
Output	Digital (2 or 3 channel)	Analog
Cost	Low-Moderate	Moderate-High plus RDC
Typical Accuracy	2 arc-min. line-line	7 arc-min. absolute shaft angle
Speed Range	Excellent	Average
Maximum Speed - RPM	5000	10000
Maximum Resolution - PPR	25000	4096 for 12-bit RDC
Frequency	Up to 200 KHz	Limited
Shock Load Capability	Low	Medium-High
Temperature Range - °C	-10 to 100	-55 to 125

The previous chapters dealt exclusively with servo products. A discussion of stepper indexers, drives and motors follow.

STEPPER SYSTEMS

The previous section illustrated how servo systems are used to provide high performance, precision and flexibility. However, not all applications have the budget or require the sophistication of a servo system. For these applications, a stepper system is the most cost effective and simplest solution. As you will note, stepper components share many of the same functions as their servo counterparts but use a different nomenclature.

INDEXERS



Indexers are the equivalent of the digital motion controller for the stepper system. They share many of the same features of the servo motion controller-programmability, digital I/O, and network communications-albeit at lower performance and cost. Indexers execute a stored program that issues a command pulse train (step pulse and direction) to a step motor driver. By merely counting the number of pulses applied to the motor, the mechanical distance traversed is known. Point-to-point motion is the most common motion profile for indexers although some limited forms of linear and circular interpolation are possible.

Indexers come in packaged and board-level models. Packaged indexers are most common, usually possessing single axis control, RS-232 communications, limited uncommited I/O, optional built-in drive and a power supply. Programs are downloaded from a host PC or operator interface to a non-volatile memory in the stand-alone indexer via a serial or parallel communications link. Recent designs incorporate MOSFET technology and C programming software and now deliver microstepping performance, multi-axis control and closed-loop positioning via encoders. Increasing in popularity, board level indexers offer lower cost and increased flexibility through PC or STD-based architectures. Some indexers can now control up to 8 motor axes per board.

The lowest cost and performance stepper control are pulse generators which issue a pulse train and direction. Most pulse generators also include oscillators which allow the user to adjust slew speed, acceleration and deceleration rates. They are triggered from an external signal emanating from a PLC, computer parallel port or mechanical switches. Pulse generators can be embedded on the driver or can be mounted on a separate board.

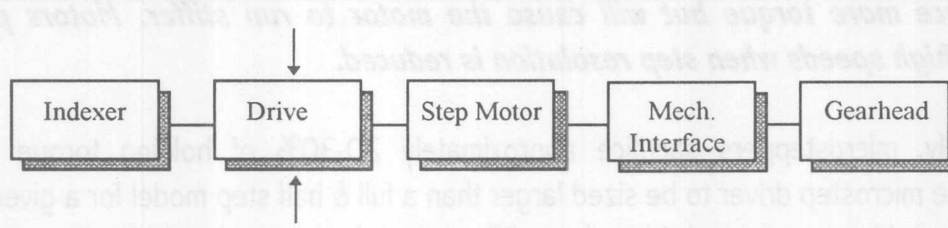
For the best performance, indexers should be used in microstepping mode.

The open loop nature of the stepper system is its primary drawback. While the indexer can precisely count the pulses to the motor (good for accuracy), it cannot guarantee that the motor moved the specified number of steps since there is no position feedback. Position error will result from: the motor missing steps, the load changing, unexpected external disturbances, significant environmental considerations (i.e high temperature) and mechanical inaccuracies inherent in the system. Additionally, since there is no position feedback, the step error will be cumulative over multiple cycles. Net, stepper systems provide good accuracy but moderate repeatability.

An important note on closing the position loop with stepper motors. In the interest of keeping purchase cost low and working with familiar stepper products, some designers close the position loop with encoders. While this proves successful in some high precision applications, it tends to negate many of the stepper systems advantages (cost, simplicity) while bringing out the step motor's limitations (poor speed control, resonance). Closing the position loop is useful where position verification is needed and to provide stall detection information to the indexer.

Providing the power to the step motor is the driver.

STEPPER DRIVES



The stepper motor driver provides current, voltage and step resolution to the motor in response to the pulse train from the indexer or pulse generator. Controlling the frequency of the pulse train applied to the motor provides speed control, torque and resolution.

There are two basic types of step motor drives, Chopper and Bi-level. Chopper drives are the most common type, utilizing PWM switching technology to maintain constant current levels. These drives employ a high voltage source to lower the current rise time in the motor windings. Their flexibility, good performance and low cost make them the most popular step motor drives. However, they suffer from excessive EMI noise, low maximum speeds and poor thermal efficiency. Bi-level drives provide improved performance versus Chopper drives through higher current & voltage generation, reduced noise and better thermal dissipation. However, they are generally more expensive than chopper drives.

In order to minimize EMI, the driver should have a switching frequency of at least 20 KHz..

Traditionally, the most common driver resolution is **Full & Half** step mode whereby the motor is operating in a detent-detent or halfway between detent position. A typical 200-step motor will rotate at 1.8 degrees per full step while the same motor would produce 400 half step at 0.9 degrees per step. Due to low cost and widespread popularity, these drives are suitable for the most basic applications but suffer from a lack of smoothness and accuracy in addition to their inherent resonance problems. In the last decade, **Microstepping** has grown in popularity whereby the motor receives anywhere from 1000 to 50,800 steps per revolution. This is accomplished by the driver electronically subdividing each full step into many smaller steps.

Ensure your driver has a "reduced current at standstill" jumper to reduce current to the motor at rest. This will ensure that the motor does not consistently operate at peak temperature, that there is less likelihood of positional loss and that energy efficiency is maximized.

Microstepping offers many advantages versus full & half step drives. It provides higher attainable motor resolution, reduced resonance, improved accuracy & smoothness and audibly quieter operation. Smoothness is important for overall machine reliability because it reduces machine wear and makes a machine run quieter. Finally, microstepping ensures the motor is stable and free from drift at rest.

Decreasing motor current by 10% will provide smoother operation. Increasing current by 10% will produce more torque but will cause the motor to run stiffer. Motors produce greater torque at high speeds when step resolution is reduced.

Unfortunately, microsteppers sacrifice approximately 20-30% of holding torque when energized requiring the microstep driver to be sized larger than a full & half step model for a given application. As well, when matching motors and drives from different vendors, occasional vibration and bias errors can create uneven driving torque resulting in a loss of steps. Finally, microstepping comes at a higher cost, reducing the price difference between stepper and comparable servo systems. In many applications, microstepping systems are almost at cost parity versus a servo system.

In order to maximize microstepping performance, consider the following points:

1) Ensure that the indexer or pulse generator is capable of producing step rates high enough to achieve the desired speed. Often at very high resolutions (25,000 or 50,800 steps), the indexer's pulse train is insufficient to deliver the speed needed.
2) Position errors will occur even with encoder feedback as a result of the existence of an electronic deadband in-between microsteps.
3) Increasing the step resolution decreases torque available per microstep. Torque available per microstep is calculated as follows and should be used to size the right microstep drive:

Torque/microstep = Motor holding toque X Sine (90 deg/Microsteps per step)

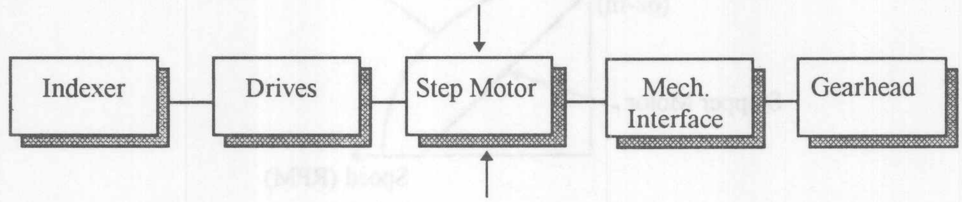
At high step rates, the application may require multiple microsteps in order to develop torque to drive the load. This condition is often referred to as "empty stepping". The proper selection of step resolution and motor size will overcome this effect.

The key drive selection parameters are:

1) Physical configuration-board level or packaged;
2) Current and voltage per phase;
3) Resolution (full, half or microstep);
4) Frequency;
5) Input voltage;
6) Thermal or short-circuit protection;
7) Automatic idle current reduction and stall detection.

STEP MOTORS

There are three basic types of step motors: variable reluctance, permanent magnet and hybrid. Hybrid step motors provide the best performance and will be discussed below.



A hybrid step motor is a simple, mature and low cost means of providing good motion performance. Step motors are electromechanical devices that work by dividing shaft rotation into discrete distances called steps. Basically, they are brushless motors which include permanent magnet variable reluctance and hybrid types. Most step motors in the MC universe are hybrids and feature 200 steps per revolution (1.8 degrees). The magnetic structure of the motor is designed to be incremental in nature i.e one pulse to the motor causes the armature to move one complete step. At power up, a hybrid step motor could rotate up to ±3.6 degrees in either direction due to the rotor having 200 natural detent positions.

The key difference between step and servo motors is commutation. When voltage is applied to a servo motor, it will develop both torque and rotation. On the other hand, when voltage is applied to a stepper motor, it will develop only torque. Therefore, the servo self-commutates while the stepper has no internal commutation. Until a stepper is externally commutated (phase switched), it will generate only static torque at energization.

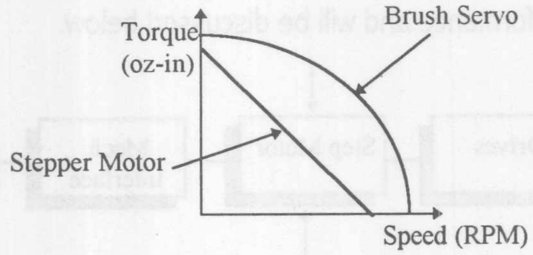
Steppers are available with four to eight leads, depending on the motor's ratings. The greater the number of leads, the more wiring is necessary, but also the greater the flexibility. For example, with an eight lead motor, the stepper can be run with a unipolar drive as a six-leaded motor or connected in either series or parallel with a bipolar drive.

Step motors are rated in terms of stall, peak, static or holding torque, current and voltage per phase, step angle and inductance. Unlike servo motors, steppers are only rated according to maximum torque generated. At zero speed, step motors produce their maximum torque. Torque decreases quickly as motor speed increases. Stall torques range from 8 oz-in to 3200 oz-in depending on design and magnets used.

When sizing a step motor to a driver, ensure the driver's current and voltage rating per phase exceed the motor's ratings.

The following is a typical torque versus speed curve of a step motor versus a brush servo motor:

Stepper vs. Brush Motors



A step motor provides many advantages for the designer. Due to their design and the fact they usually require no feedback device or complex controls, a stepper system is generally lower cost and easier to wire and install. At energization, full torque is achieved relatively quickly. Since maximum dynamic torque occurs at low speed and pulse rates, steppers can easily accelerate a load. When the desired position is reached, the step motor is generally left energized at the stop position. Thus, there is no need for clutches or brakes with small loads. For many applications, step motor's deliver more than adequate accuracy and repeatability ratings, easily better than AC or permanent magnet DC motors. Finally, as step motors have been in operation for over forty years, there is a large installation base, NEMA-standard frame sizes, and a widespread technical understanding.

Stepper motors operate best under consistent operating conditions (acceleration, deceleration, slew rate) with a close matching of the load and motor torque. However, changing the operating parameters beyond the motor's capabilities, in particular the load, will result in the motor stalling. On the other hand, where the motor torque is too large for the load, it will be oversized and may run at sub-optimal performance. Moreover, steppers are prone to losing steps in high speed applications. Up to ±3% of a full step (at no-load) or a ±0.054 degree angular error (for a 1.8 degree motor) may arise as a result of bias, phase, hysterisis and deadband errors. For some motors, the step error is even ±5% of a full step. Moreover, since step motors do not use feedback devices as part of a closed loop system, they are prone to inaccuracies as a result of slight changes in system mechanics. Temperature, inertial and friction forces can all make the actual stop position different from the desired position. Thus, the indexer would be issuing step commands to a motor that does not move, creating a motion deadband. In another situation, motor and system inertia may result in the motor missing steps due to the motor and drive falling in and out of synchronization. In this situation, the position of the system will not be true and motor stall becomes very likely.

In addition to the limitations of being an open loop system, stepper motors suffer from a variety of performance shortfalls due to their inherent design. Steppers are not well suited for high speed, high cycling operations. Due to inherent inductance, torque falls off very quickly as speed is increased (usually greater than 1000 RPM). Therefore, step motors are usually limited to a maximum speed of 2000 RPM and 1400 oz-in holding torque.

Since step motors are energized via pulses, resonance and velocity ripple can occur at low speeds causing loss of torque, synchronization and position. Velocity ripple is the mechanical oscillation between the stator and armature. In general, the larger the step size and current draw, the higher the level of velocity ripple.

Velocity ripple is minimized by reducing the step size with microstepping, mechanically dampening the system or reducing the current required to make the motor move.

Resonance is a special by-product of step motor operation. It is the inherent vibration from the motor shaft caused by energizing a motor at or close to its natural frequency, particularly at low resolutions. Resonance is observed as a heavy oscillation being felt or heard from the motor, typically in the 200-400 Hz band beginning at approximately 60 RPM. This oscillation minimizes effective motor torque, reduces motor smoothness and may result in loss of synchronization.

A number of electro-mechanical steps are available to reduce resonance, although it is inherent in every step motor.

1) Mechanically dampen the motor via a friction or viscous damper mounted to the motor. This will also improve settling times;
2) Switch to microstepping or half step mode;
3) Accelerate faster through resonance speed ranges;
4) Insure proper coupling compliance;
5) Minimize system inertia;
6) Reduce the current needed to make the move.

Stepper motors are thermally inefficient (most input energy is dissipated as heat) with typical operating temperatures between 50° and 90° C. As a result, they tend to run very hot, limiting high speed performance and posing safety hazards. Finally, steppers produce significant noise (i.e ringing) and EMI making them ill-suited for noise sensitive applications. Dampening will be needed to reduce or minimize these effects.

Be careful in choosing too large a stepper motor for a given application. If the motor's rotor inertia is too high, resonance may increase and acceleration rates may be reduced.

Like brushless DC servo motors, proper inertia matching is important. Look for the reflected inertia of the load not to exceed 5 times the inertia of the motor. Where there is an inertial mismatch, some form of gearing (i.e gearhead, belt and pulley) must be added. The reflected load inertia is reduced by the inverse of the square of the gear ratio while the speed is correspondingly reduced by a multiple of the gear ratio.

Motor inductance is another important factor with stepper motors. As the motor phases are switched on and off, and reversed in polarity, the inductance of the motor phases prevents the rapid transmission of current. Since motor torque is proportional to phase current, torque decreases with increased pulse rate or frequency. As a result, exploiting inductance is a trade-off. For a given supply voltage, higher inductance provides better low speed torque & increased cooling but limits top speeds.

Using a low inductance design, however, is no panacea. Reduced inductance provides the opposite effect of increasing maximum speed/high speed torque. However, it also increases motor heating and causes current ripple. In some cases, separate inductance chokes must be used in series to control this current ripple. Unfortunately, this defeats the speed advantage of a low inductance motor and adds cost plus complexity.

The choice of parallel, series, or center tap connection windings between the motor and drive is important for optimal performance. Windings connected in series maximize low speed torques (and lower motor heating) by increasing inductance by up to 4 times. However, higher speed performance is limited. Wiring with parallel or center tap connections deliver the best torque at higher speeds (and greater motor heating) through reduced inductance. However, lower speed torque is reduced.

The key selection criteria for selecting stepper motor systems are:

1) Torque, voltage and maximum speed needed in the system;
2) Desired motion profile;
3) Motor resolution needed to provide desired precision;
4) Axial and radial loads on the motor shaft;
5) Maximum acceleration (slew rate), deceleration and settling time;
6) Reflected load to motor inertia;
7) Electrical noise considerations;
8) Fit/form;
9) System friction;
10) Wiring/cabling needs.

As it is difficult to estimate the torque required and loads vary, always choose a stepper motor with a 50-75% safety margin over your estimated peak, holding or stall torque requirement.

CHOOSING BETWEEN SERVO & STEPPER MOTORS

The choice between a servo and stepper motor is an important decision in any system design. In general, the higher the performance requirement (high precision, variable load, high duty cycle, high torque vs. speed) the more likely a servo will be the choice. Where purchase cost is critical, performance is not crucial, and simple set-up is needed, a stepper solution is a cost-effective option.

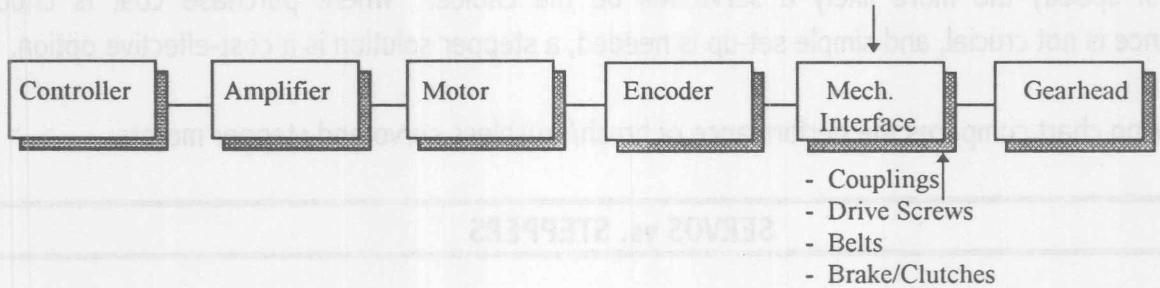
The following chart compares the performance of brush/brushless servo and stepper motors:

SERVOS vs. STEPPERS

Parameter	***Servo***	***Stepper***
Cost	Moderate	Low
Load	Can Vary	Constant Loads
Inertia Loads	Good	Poor
Speed	High	Low-Moderate
Motion Profiles	Complex	Simple
Axes of Control	Single/Multi	Primarily Single
Precision	Excellent	Good
Power	Fractional to 15 HP	< 1HP
Efficiency	Energy Efficient	Energy Inefficient
Maintenance Req'd	Low (Brushless)	Low
Moderate (Brush)		
Tuning Difficulty	Moderate-High	Low
Torque-Weight Ratio	High	Moderate

With stepper motors, closing the position loop via an encoder is not an effective means of providing increased precision. Whereas the encoder will provide position verification, the step motor is unable to "servo" to ensure high dynamic performance and repeatability. Adding an encoder and using a microstep driver makes the relative costs of servo and stepper systems roughly equivalent, yet the performance remains decidedly better with servos.

COMPONENTS



The following sections discusses common mechanical interfaces to servo and stepper motors and offers tips on integrating these components into a complete MC system. We will first examine mechanical components and later complete positioning systems.

The most common mechanical interface to the motor is the coupling.

COUPLINGS

Couplings connect a motor's rotor shaft to some kind of mechanical drive system, like a ball screw. Their role is to effectively translate power between the motor and another rotating shaft and to compensate for end movements and misalignments. As the demands of MC systems increase, the role of the coupling has become much more crititical.

Couplings introduce efficiency losses and inertias into a drive system. Their effects must be considered when sizing motors, gearheads etc.

The purpose of the coupling is to ensure maximum mechanical stiffness and compliance while minimizing lost motion. Misalignments (axial, radial, parallel and angular errors) are common in mechanical systems as a result of poor bearing support, bearing wear, improper component alignment, ambient temperature changes and deflection due to external loading. Lost motion occurs as a result of backlash, hysteresis and wind-up leading to reduced positional accuracy, repeatability and servo tuning problems.

Couplings are often the first mechanical component in the system to fail as a result of excessive misalignment, poor mounting or accidental shock load. Ensure you have at least one spare at all times.

There are many different types of couplings available but the two most common designs in mechanical systems are flexible shaft couplings and rigid couplings.

Flexible couplings are the preferred choice for applications needing to compensate for a moderate amount of shaft misalignment and end movement. However, they will not compensate for all mechanical play so caution and good design are the bywords. Excessive misalignment creates torsional forces and abnormal load imbalances which reduce the life of the drive assembly and hinders system performance. In general, **the lower the angular misalignment the longer the coupling life is**. High-performance flexible couplings feature zero backlash, minimum wind-up, 5 degree angular misalignment capability and low hysteresis. As well, they will also dampen vibration and reduce mechanical (RFI) noise. Low mass types are well suited for rapid acceleration/deceleration, high speed applications requiring no lubrication.

There are two major types of flexible couplings, bellows and helical couplings. Bellows couplings mechanically-press bellows forming a tube. They deliver zero backlash, excellent wind-up, hysteresis and longevity ratings while tolerating a moderate amount of misalignment. These couplings are generally higher in price than other flexible couplings. On the other hand, helical couplings feature a single beam approximately three revolutions long. They provide lower performance (higher wind-up, hysteresis and resonance ratings) than bellows couplings but better misalignment capability. As well, they tend to be lower in cost but higher in backlash.

Rigid couplings are used in applications where the rotating shafts are precisely aligned and where high duty cycles and large mass loads place an emphasis on safeguarding key components, particularly encoders and bearings. For example, at motor runaway, a flexible coupling will not effectively absorb the entire axial and radial shock load due to its poor "cushioning" qualities. As a result, much damage could occur to the motor, encoder or lead screw. Because of their design, rigid couplings have better shock resistance. Under severe shock, rigid couplings will break preventing damage to the more expensive drive screw assembly, motor and encoder. Rigid couplings are also used to connect equipment which maintain no shaft misalignments, have adequate bearing support and possess long, slender shafts that can absorb forces and moment loads. Furthermore, shaft support bearings should be located as close to the rigid coupling as possible. In high speed applications, the unsupported length of the shaft should be closely monitored for vibration and oscillation.

In summary, use flexible couplings where siginificant angular misalignment is present and low backlash/wind-up is required. Rigid couplings are preferred for shock load conditions.

For tuning purposes, it is important that the mechanical resonance frequency is at least twice the bandwidth of the servo system. This becomes very important for large inertial loads as they tend to have a low torsional resonance frequency.

The following parameters should be considered before choosing a coupling:

1) Maximum acceleration/deceleration torque the coupling will see. Include all motor/load inertias and gearing effects;
2) Maximum parallel and angular mislignment. Use worst case scenarios;
3) Maximum allowable windup. A shorter length or larger diameter may be required to achieve lower values;
4) Expected life expectancy;
5) Input/Output shaft bore sizes;
6) Peak or shock loads present;
7) Environmental conditions including vibration and temperature;
8) Maximum motor or shaft speed (RPM);
9) What method of attachment is required (i.e set screw or clamp).

There are a few guiding principles in using couplings. For example, If speed is reduced through a gearhead, the torque increases in proportion to the speed reduction. As a result, the designer should pay special attention to sizing a coupling larger than the maximum gearhead output torque, since couplings are generally rated as continuous torque devices. Also, for high-speed applications, the coupling should be dynamically balanced to reduce vibration and extend bearing life. In order to ensure proper torsional stiffness, the coupling should be clamped as close as possible to the motor flange. Key couplings do not provide as much torsional stiffness to the motor shaft and should be avoided in high performance applications.

Interfacing between the motor and coupling is the drive screw.

DRIVE SCREWS & BELTS

The three most common types of drive systems used in MC systems are drive screws (ball screws, acme screws) and drive belts. Their function is to convert the rotary motion of the motor into linear motion for the load.

Ball Screws are the preferred choice for most MC applications due to their high performance and long life. Ball screw assemblies utilize a machined screw with a single or double ball nut incorporating a recirculating track of ball bearings circulating between the screw and nut. Support bearings are included in the assembly for load support.

The typical ball screw application will require the following benefits:

1)	High load capacity	6)	Ease of maintenance
2)	High speeds/efficiency	7)	Smooth operation
3)	Long life	8)	Low heat generation
4)	High accuracy in positioning	9)	Simple & compact design
5)	Low backlash for repeatability	10)	Ease of installation

Additionally, ball screws are more than capable of operating under extreme temperatures from -65° F to 300° F.

However, since ball screws use high-quality materials and require additional annealing plus end machining, they are generally higher in cost. Furthermore, they cannot self-lock under load requiring a clutch or brake to prevent back driving. Since they make use of recirculating ball bearings during operation, ball screws tend to create mechanical noise (RFI).

Ball screws come in two general types, rolled thread and precision ground, that differ according to their lead accuracy, efficiency and smoothness. <u>Rolled thread</u> are the most common ball screw for applications requiring good accuracy and decent smoothness at moderate cost and good delivery. On the other hand, <u>precision ground</u> ball screws have superior lead accuracy and extreme smoothness but are more expensive with longer deliveries. They are used in applications like machine tools and coordinate measuring machines, needing extremely high precision. A general rule of thumb is that accuracies better than 0.003 in./ft. will require precision ground balls screws if linear encoders are not included in the design.

Ball screw assemblies generally employ steel or bronze drive nuts plus end bearings. At rated load, stroke is usually limited to a maximum 12 ft. length with speeds to 18 IPS due to the oscillation and vibration of the screw, commonly referred to as "whipping" or resonance. Careful attention must be paid to the lead screw's rated compression (extension) and tension (retraction) loads and critical speed curves to ensure long life and proper performance. In addition, proper mounting of the ball screw ends will help reduce oscillation and provide for high speed operation.

Lubrication is crucial to maintaining ball screw reliability and life. It is often difficult to determine when lubrication is necessary but most manufacturers recommend a schedule of at least once every 6 months of operation, assuming a normal duty cycle. For very high duty cycle, speed and load applications, more regular appplications must be made. A light-weight oil or lithium-based grease should be used. Synthetic, teflon-based greases have also shown to be very effective.

Regular lubrication of ball screws will extend ball screw life and provide smoother operation. If lubrication is not done regularly , you must derate the life of the ball screw a minimum 15%.

Ball screws are vulnerable to external contaminants (i.e. dirt and dust) which affect life and smooth operation. Integral ball nut wipers and seals are recommended. If the contamination is heavy or a precision ground screw is used, a protective cover or waycover should be installed. Furthermore, a highly humid operating environment leads to pitting of the screw and corrosion when waycovers or special finishes (i.e chrome) is not used.

Ball screws and ball nuts are machined parts. As such, it is very difficult to achieve the highest performance by "mix n' matching" components from different vendors since they have to maintain very tight tolerances. Smoothness and accuracy, in particular, can not be guaranteed. Furthermore, the nature of the ball nut makes it impractical to machine the nut while it is assembled to the ball screw.

High precision applications incorporating ball screws focus on low lead error, repeatability and straightness as critical measures. Often confused with repeatability, lead accuracy refers to the travel error of the nut when commanded to move to a desired position (usually 12 in.). This error could be cumulative or non-cumulative.

The following chart outlines the standard lead error of each screw type. Lead error is determined by the amount of machining and the quality of materials used. Precision ground screws have the best lead error and are typically rated by class:

Rolled Thread Screws:	Error:
Lowest Grade	0.018 in./ft.
Standard Grade (most common)	0.09 in./ft.
Precision Rolled Grade	0.003 in./ft.

Precison Ground Thread Screws	Error
Class 3	0.001 in./ft.
Class 5	0.0005 in./ft.
Class 7	0.0002 in./ft.

For most high-precision applications, repeatability is the most important measure. Repeatability is the ability to consistently move back and forth to the same position over a period of time. Backlash hinders repeatbility. If the mechanical system must repeat better than ±0.002 in/in., then an anti-backlash or zero backlash ball nut must be chosen. As well, highly repeatable systems will also require significant pre-load in the nut to ensure stiffness. However, this pre-load will reduce smoothness and will increase the amount of torque needed to drive the load (bearing drag).

The typical backlash range in a ball screw assembly with a standard single nut is as follows:

Screw Diameter (in.)	Maximum Backlash (in/in.)
0.375 0.75	0.007
0.75 - .25	0.009
1.50 - 2.00	0.013
2.00 - 2.50	0.015
3.00+	0.018

Lead screw straightness and concentricity impacts accuracy through the Total Indicator Runout (TIR) specification. TIR is a measurement of linear travel error of the nut across a centerline axis and could be applied to the assembly as a whole or merely the screw and nut. The calculation for TIR includes screw straightness plus the concentricity of all journals and other surfaces. Usually, off-the-shelf rolled ball screws have a TIR of 0.010 in. per foot. Machined precision lead screws have a better TIR of 0.005 in. per foot. For precise operation, the TIR should normally be twice the straightness plus a factor of 10 to 20%. For example, a ball screw with a 0.003 in./ft. straightness and a 0.002 in. concentricity of turned ends is expressed as a TIR of 0.008 in. along the entire length of the screw during rotation.

Achieving high accuracy, repeatability and smoothness entirely with ball screws is very costly. By using servo motion control, the designer has been able to achieve almost ground screw precision with rolled thread ball screws. In particular, linear encoder feedback has reduced the need to consider inherent lead accuracy in the screw. As well, dual-encoder feedback or electronic backlash compensation has eliminated mechanical deadband in the ball screw and nut assembly. Precision ground ball screws will always have their place in certain applications (machine tools, semiconductor insertion), but much of their advantage has been eclipsed electronically.

Acme screws are an effective means of providing linear motion for moderate performance, cost sensitive applications. Acme screws come in precision ground and rolled thread varieties. They consist of a plastic or bronze nut, without recirculating ball bearings, running on a machined screw. Plastic nuts (i.e. Turcite) are most common for light loads, low duty cycles and quiet running operations. Where high loads are needed (greater than 500 lbs thrust), a bronze nut is recommended.

They are usually lower cost with less maintenance than a ball screw. A wide variety of leads (pitchs), diameters and nut designs/materials are available for optimal usage and specific environments, often with better delivery than ball screws. Since their plastic nuts lack recirculating bearings, they often provide smoother motion and less mechanical noise than rolled ball screws. Importantly, acme screws generally do not backdrive under load particularly in vertical orientations. A typical rule of thumb is that acme screws with leads less than 1/3 the screw diameter will not backdrive in a vertical application. In addition, plastic nuts fit the lead screw very closely wiping the thread as they translate motion. Thus, acme screws usually do not need wiper kits. Because they are usually made of plastic, acme nuts are easily machined.

However, acme screws are not the recommended choice for high performance applications needing long life. They are less versatile than ball screws through reduced load capacities, slower speeds, lower duty cycle, poorer lead accuracy and shorter life. This is due to the acme screw's higher friction, lower efficiency and poorer quality of materials used. Since efficiencies are between 25% and 60%, a larger than necessary motor is needed for an acme screw (versus a ball screw) to translate the desired torque. Initially, backlash is low. However, it increases with wear and usage resulting in lower and inconsistent precision. As well, they suffer from positional errors due to screw thermal expansion, and are very susceptible to failure under adverse temperature conditions (below -40° F and above 160° F). It is often difficult to predict the operational life of acme screws and nuts due to variable thermal conditions and maintenance habits. As a result, greater attention to lubrication and monitoring is needed with acme screws. The same compression and extension load analysis used with ball screws should be employed in selecting the proper acme screw.

There are many parameters to consider when choosing a ball or acme screw:

1) Maximum dynamic, static and offset (moment) loads;
2) Maximum compression and extension loads;
3) Maximum speed without achieving resonance/vibration of the screw;
4) Screw length, travel length and diameter;
5) Vertical or horizontal orientation;
6) Operating environment;
7) Type of end bearings and supports needed;
8) Lead accuracy and TIR, indicated as inch per foot or inch per inch;
9) Duty Cycle;
10) Smoothness, backlash or mechanical noise tolerated;
11) Lead or pitch required plus direction of thread (right hand is standard);
12) Type of nut required: single, double, bronze, plastic, with or without a flange;
13) End machining of journals.

How are ball and acme screws affected by changes in parameters?

Increase in:	**Affects:**	**How:**
Screw Length	Critical Speed	Decreases
	Column Load	Decreases
Screw Diameter	Critical Speed	Increases
	Load Capacity	Increases
	Angular Velocity	Decreases
Load	Life	Decreases
Preload	Accuracy	Increases
	Drag Torque	Increases
Pitch	Critical Speed	Decreases
	Resolution	Increases
Lead	Critical Speed	Increases
	Resolution	Decreases
Mounting Rigidity	Critical Speed	Increases
	Column Load	Increases
Nut Length	Load Capacity	Increases
Angular Velocity	Critical Speed	Decreases
Number of Balls	Load Capacity	Increases

A general formula to calculate the torque needed to drive a ball or acme screw can be determined by:

$$T = PL/2\pi E$$

where
T=torque input (oz-in.)
P=operating load (lbs.)
L=screw lead (in./rev.)
E=drive screw efficiency (usually 90% for ball screws, 25-60% for acme screws)

The above calculation does not take into account bearing drag or inefficiencies due to mounting variations of drive components (i.e couplings) or nut preload which adds torque resistance.

Belt drives are often used in applications requiring extremely long strokes, low loads, high speeds and moderate precision. The three major parts are the belt, pulley and bearings. While they provide a good means of linear motion, they suffer slippage, maintenance and longevity problems due to the stretch and wear of belts. Furthermore, belt drives are vulnerable to breakdowns caused by hostile environments. Belts often must be replaced versus being repaired and typically use a more complex mechanical linkage than a drive screw.

The following are important design considerations to be considered when choosing belt drives:

1) Maximum dynamic, static and moment load;
2) Maximum allowable backlash;
3) Accuracy required;
4) Operating environment;
5) Maximum operating speed, acceleration and deceleration;
6) Horizontal or vertical orientation.

The following chart presents a comparison between ball& acme screws and belt drives:

BALL SCREWS vs. ACME SCREWS vs. BELT DRIVES

	Ball Screws	***Acme Screws***	***Belt Drives***
Accuracy	High	Moderate	Moderate
Backlash	Low	Low	Low
Max. Speed - IPS	18	10	120
Max. Acceleration G	3	1	5
Load	High	Moderate	Low
Smoothness	All speeds	Low speeds	All speeds
Duty Cycle	High	Low-Moderate	Moderate
Efficiency %	90	25-60	90
Maintenance	Lubrication	Lubrication/ Nut replacement	Retensioning/ Replacement
Life	Long	Moderate	Moderate
Max. Stroke - ft.	20	6	500
Backdriving	Yes	No	No
Audible Noise	Noisy	Quiet	Quiet
Cost	Moderate-High	Moderate	Low-Moderate

Where loads must be controlled under certain circumstances, electric brakes and clutches are recommended.

ELECTRIC BRAKES & CLUTCHES

Clutches and Brakes are designed to start and stop two independently-rotating inertial loads when a voltage is energized or de-energized. Although there are many different types of brakes and clutches, electro-magnetic types are the most prevalent in MC applications. Compared to simple mechanical clutches, electric types are used where remote actuation is required or special slip characteristics are needed. Typically, this is on a motor shaft or where a load must be coupled to a main line shaft of a machine. Most brakes and clutches are used in rapid start/stop motions or as a failsafe device for ball screws operating vertically. Typical applications include: packaging machinery, mobile power equipment, automated guided vehicles, medical & textile equipment and document feeders.

The advantages of electric clutch and brakes are many:

1) Easy integration;
2) Relatively low cost;
3) Exact speed matching for synchronizing line shaft applications;
4) Ability to control large loads with small control signals.

However, they are not without some drawbacks, as indicated below:

1) Uncontrolled acceleration and deceleration;
2) Poor positioning accuracy;
3) Subject to mechanical breakdown and loss of repeatability due to heat, friction, shock load.

Electric Clutches

These come in two basic types, friction and non-friction. Friction clutches utilize friction or tooth clutches engaged electrically and released by springs. These clutches respond more quickly, offer more control options and transmit higher torques than non-friction clutches. On the other hand, Non-friction clutches use electric methods to engage the independent shafts without direct mechanical connection. As they are non-contact, they dissipate heat better and offer longer life.

Electric clutches may not be ideal for hostile environments. They do not have high thermal capabilities for high temperature conditions. As well, they may possess inherent sparking, posing risks in explosive environments.

Electric Brakes

Brakes are basically a clutch with one member held stationary. The most commonly used electric brakes are electrically actuated but rely on mechanical friction for stopping action. When they are actuated, they bring the load to full stop. When released, they offer little or no drag. A typical application is to prevent load back driving with a ball screw in a vertical orientation. At power loss, the fail-safe electric brake engages, preventing the load from falling. Alternatively, electric brakes may be configured for engagement under power, with disengagement at power loss.

The clutch or brake should be mounted to the highest possible speed shaft in order to minimize the torque needed for braking.

Some simple applications use the on/off operation of clutches and brakes to vary load distances. While this set-up is easy to apply, low in cost and effective for speed matching, it is prone to premature wear, is non-repeatable and relatively inaccurate.

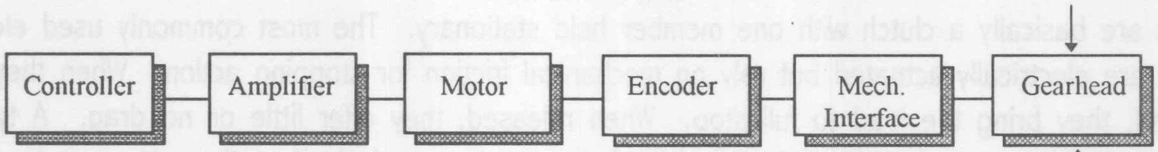
While effective at preventing motion at power-down, brakes are often not effective at bringing a motor or rotating shaft to a rapid halt, particularly if the amplifier is providing maximum current. In fact, the opposite effect may result with brake adding a greater load to the system. In particular, brakes can introduce friction when released and increase the amount of inertia in the system.

The following are selection considerations for clutches and brakes:

1) Torque required to stop the load;
2) Rotor and load inertia;
3) Acceleration or braking times;
4) Duty Cycle and life requirements;
5) Environmental considerations;
6) Maximum allowable speed/response time;
7) Bore diameter of shaft;
8) Required voltage and current.

The gearhead is MC's "Jack of all Trades" and is discussed next.

GEARHEADS



Approximately 75% of all applications require some form of gearing to provide optimal performance. Gearheads are the most popular choice among designers and serve many functions in MC applications. Their five primary roles are: 1) minimizing motor size by providing torque multiplication 2) motor speed reduction 3) reducing load/motor inertia mismatches to maximize acceleration 4) increasing motor resolution and 5) providing maximum torsional stiffness. Typical applications include: web processing, robotics, injection molding, medical equipment, packaging and printing machines.

The three most common gearheads are Spur, Planetary and Harmonic. **Spur** gearheads operate on the involute principle with the two meshed gears behaving as two disks rolling against each other. **Planetary** gearheads include a "planet" gear revolving about its own axis while its axis rotates around a "sun" gear. **Harmonic** gears use controlled deflection between a rotating wave generator and a non-rigid flexspline to generate torque. The wave generator (elliptoidal plug/ball bearing assembly) serves as a high-speed input member. The rigid circular spline (internal gear) is fixed while the non-rigid flexspline (external gear) drives the load at reduced speed.

For many applications, it is less expensive to choose a motor plus a gearhead than to use a larger motor only as part as a direct drive system.

The three types of gearheads vary significantly in performance and cost.

Spur and planetary gearheads are available as in-line or right-angle versions with reduction ratios from 1:1 to 100:1. Clamp-on pinions are used for motor mounting. Spur gearheads are the most popular gearhead due to low cost, ease of installation and decent performance. Typical backlash is 30 arc-min with low backlash designs to 15 arc-min. Spur gearheads feature integral NEMA flanges for simple mounting to NEMA standard motors. Stepper and brush servo motors are typically used with Spur gearheads.

Planetary gearheads cost more but feature greater compactness, lower backlash and higher available output torques and input speeds. Typical backlash is 10 arc-min. with 5 arc-min. available. Since planetary gearheads tend to be used with brushless servo motors without NEMA standard flanges, they usually require a custom mounting kit and pinion to fit the motor.

Right-angle spur and planetary gearheads are designed to minimize the overall footprint of the gear stage and to offer mounting flexibility. However, since right-angle gearheads suffer from efficiency losses due to their worm/bevel gear design, they may overheat in high power and high duty cycle applications. Ample air flow space or a cooling fan may be needed to ensure long life. Moreover, the worm/bevel gear design has different backdriving capabilities under different operating conditions versus an in-line type. As a result, the designer must consider axial and radial loads more closely than they would with in-line gearheads.

Vertical mounting poses special problems for in-line and right angle gearheads. Specifically, under high speed operation (greater than 2500 RPM), lubrication leakage could occur out of the housing seals. In addition, gravitational forces will cause grease or oil to collect at the bottom of the gearhead housing. This could create incremental frictional (viscuous) forces in some of the gears, thereby increasing breakaway torque.

Another potential concern with spur and planetary gearheads is low speed cogging. Specifically, under 5 RPM operation and when using brush servo motors, the gearhead may suffer cogging, reducing smoothness. In this case, the designer should use brushless motors with harmonic drive gearheads.

When choosing a Spur and Planetary gearhead, ensure the gearhead's mounting pinion matches the motor's output shaft diameter and that full mounting compliance is ensured.

Harmonic drive gears are the high performance gear choice. They are available in housed and non-housed configurations, offering the designer maximum compactness and the ability to incorporate the gear set directly into the design. For example, the harmonic gears have a concentric shaft arrangement, meaning the input and output are on the same centerline. In addition to saving space, mounting the gear directly into the design delivers maximum mechanical compliance and stiffness plus reduced wear. The gear's design supports very high input speeds and output torques as well as an excellent torque-to-weight and volume ratio. Reduction ratios from 50:1 to 320:1 are offered in the same footprint. Due to their design, harmonic gears feature zero backlash for superior positional accuracy, repeatability and servo stability. Positional accuracy is often one arc minute or less.

Despite its many advantages, installation is not as simple as with housed gearheads, as a housing often has to be provided for separately. In some applications, wind-up is a concern. Wind-up is the torsional deflection that occurs between the gear input and output as a torque load is applied to the output. It is defined by the torsional spring rate. Furthermore, in some servo applications, deflection of the flexspine results in a hysterisis curve (S-curve) and positional loss. Finally, due to their sophisticated design and high-quality materials, harmonic gears tend to be more expensive than other gearheads.

When sizing gearheads, ensure the gearhead can handle the maximum motor input speed and peak output torque. Otherwise, you will have to current limit the amplifier/controller.

Similar to choosing servo motors, gearheads must be sized according to their continuous and peak torque ratings plus maximum input speed. The gearhead should possess input speeds of at least 4,000 RPM in order to achieve high cycle times and to use higher speed brushless motors. Particular attention should also be paid to maximum axial and radial loads on the gear shafts. Exceeding these values will result in premature breakdown.

Like other mechanical products, gearheads requires periodic lubrication to ensure reliability. Lubrication frequency will depend on the duty cycle, motion profiles and torque/speed values.

High speed and rapid start/stop applications utilize gearheads to match the inertias between the load and motor. Inertia is a measure of a load's resistance to a change in velocity. The greater the mass, weight, material density and shape of an object the higher the inertia. The higher the inertia, the greater is the torque needed to accelerate it.

When the motor inertia is too small relative to the load (typical with brushless motors), oscillations (overshooting) and increased settling times will occur, resulting in loss of precision and problems with servo tuning, noise and instability. Where the motor inertia is too large relative to the load, the application's optimum cycle time will be limited and most of the power will be expended rotating the motor than accelerating the load. The gearhead will reduce the inertia mismatch and minimize the motor torque required to accelerate the load.

When estimating system inertia, include the inertias of couplings, pulleys and gears as these values are usually significant. As well, external forces such as load imbalances and gravity must be accounted for in the analysis. Changing the shape, density or weight of the load will produce different inertial values.

The reflected inertia seen by the motor is equal to the system inertia divided by the square of the gearhead ratio. The designer should aim for a load inertia no more than five times that of the motor plus gearhead inertia. The optimum gear ratio will yield a reflected inertia equal to the motor inertia.

The criteria to select gearheads are:

1) Maximum input speeds;
2) Continuous and peak output torque;
3) Motor type and size, particularly motor output shaft diameter and shaft length;
4) Maximum allowable backlash;
5) Axial, radial and overhang loads;
6) Size constraints;
7) Duty cycle;
8) Motion profile;
9) Motor and load inertias;
10) Expected life and maintenance needed;
11) Reduction ratio needed.

The following chart compares the performance of the three gearheads:

SPUR vs. PLANETARY vs. HARMONIC

Parameter	***Spur***	***Planetary***	***Harmonic***
Lost Motion- Backlash/Hysteresis	Moderate	Low	Zero
Positional Accuracy	Good	Good	Excellent
Output Torque	Moderate	High	Very High
Input Speed	Good	Very Good	Excellent
Audible Noise	Moderate	Moderate	Low
Stiffness	Good	Good	Excellent
Shock Load Capability	Moderate	Moderate	High
Min. Efficiency-% power	90	85	90
Back Drivable	Yes	Yes	Yes
Torque-to-Weight Ratio	Good	Very Good	Excellent
NEMA Flange Mounts	Yes	Yes	Yes
Max/Min Ratios	1/100:1	3/100:1	50/320:1
Installation Flexibility	Good	Good	Excellent
Cost	Low	Moderate	Moderate-High

The next chapter focuses on the common mechanical assemblies used in MC: positioning tables and linear actuators.

ASSEMBLIES

The previous section focused on the major electro-mechanical components in MC. This next section concentrates on products that combine mechanical components to form mechanical systems. They are mated to controls and electronics to form complete MC systems.

POSITIONING TABLES

Positioning tables are mechanical assemblies that convert a motor's rotary motion into linear motion. Also known as linear actuators and cartesian robots, they consist of three core components, the base, carriage and drive screw/nut assembly. Positioning tables satisfy a wide variety of motion applications including: welding & machining, inspection stations, drilling, pick & place and parts inspection. Tables are available in single and multi-axis versions (X to XYZ plus Rotary Table) as standard or custom configurations. They vary from commercial to industrial grades, with special clean room, washdown and vacuum-rated designs available. Product differentiation is based on the mechanical design, bearing system and linear drive (belt or drive screws) used, all of which impacts on the precision, speed, robustness and load capacity.

A positioning table with linear bearings, guide rails and ball screws is recommended for applications requiring high loads and high precision with a heavy duty cycle. Where performance is not critical and cost is a major consideration, a positioning system with acme screws and ball bushings/round shafting is suggested. Standard positioning tables accept NEMA standard motors or gearheads and optional hand cranks. Also, optional motor wrap packages allow the designer to minimize the overall table length by "wrapping" the motor parallel to the centerline axis.

The initial two selection parameters are the number of axes and stroke length of each axis. Systems requiring a combination of one (X) to three axes (XYZ) plus an optional rotary axis (φ) will typically use ball screw assemblies due to their high load capacities. The maximum stroke of a single axis ball screw table is usually limited to 72 inches due to performance limitations of the ball screw length (i.e oscillation, reduced speed). Strokes in excess of 72 inches length often require a belt drive table. The maximum stroke in a two or three axis configuration is usually limited to 24 inches for the Y and Z axis because of moment/overhang loads and deflection. A gantry table, with X axis passive and driven slides, is used for high loads and Y axis strokes in excess of 24 inches.

Other criteria to consider include: 1) payload 2) linear speed and acceleration 3) precision and 4) the operating environment. Each parameter will be considered independently.

Three kinds of **Payload** must be considered for its impact on table life, accuracy and operating speed: 1) maximum dynamic and 2) maximum static loads mounted to the centre of the table carriage plus 3) moment (offset) loads. Proper load analysis, conservative load mounting and designing within rated table specifications are crucial in ensuring that table life and reliability is maintained for at least 75 million inches of travel. In general, the higher the moment loads, the lower the table life, precision and attainable speed. However, different table designs and bearing/drive screw systems can be used to maintain desired performance. A vertical (Z) axis should always include a failsafe brake or non-backdrivable acme screw in order to prevent the the load from falling in the event of a power loss.

For most applications, a ball rail table provides good dynamic/static load capabilities at long travel lengths at a reasonable price. However, they have a small moment load capacity and maintain a large work envelope.

Where very high dynamic, static and moment loads must be positioned with smoothness and precision, a linear bearing/rail system is employed. These tables feature larger diameter ball screw assemblies and a recirculating bearing system which provides greater ball contact on the rail than ball rail tables. Furthermore, a smaller work envelope is provided along with protective waycovers and end-of-travel switches. Their key drawback is higher cost versus ball rail tables. All high payload tables should utilize low maintenance, long life rolled or precision ground ball screws. Belt drive tables are not recommended for high load, particularly moment load, applications unless accompanied by a linear bearing and rail system.

A safety margin of at least 33% should be maintained between the desired payload & speed and the rated table specification. Always plan for worst case scenarios (moment loads, minimum settling times) and specification changes.

A few design principles should be followed for multi-axis applications. Since vertical axes face incremental gravitational forces, the designer must include these forces when sizing the motor. Furthermore, the weight of the Y, Z and/or rotary axes must be considered when sizing a suitable motor for the X or Y axes. In order to reduce complexity, all axes should use the same frame size motor although continuous torque ratings of each motor may vary.

Virtually all positioning table manufacturers base their specifications on non-shock conditions. Depending on the operating conditions, the dynamic load may have to be derated according to a safety factor. Some of these applications include machining, drilling, material handling, parts insertion and contouring. In order to minimize the negative effects on the bearing and drive screw system, choose a table with high load capacity linear bearings and ball screws. Additionally, the load should be mounted as close to the center of the table carriage as possible to minimize moment loads while the table should be orientated horizontally, as opposed to sideways or upside down.

The designer should derate the table's dynamic load capacity by the appropriate safety factor in order to maintain rated life. The following chart applies a safety factor when dealing with adverse operating conditions:

$$\text{Safe Dynamic Operating Load} = \frac{\text{Rated Dynamic Load (from table specs)}}{\text{Safety Factor}}$$

Operating Conditions	Safety Factor
Smooth, shock-free	1
Gradual, varying loads	2
Heavy shocks, vibration	3

Where the payload and acceleration/deceleration rates are high, the designer should select a longer than required travel length in order to allow for controlled deceleration prior to tripping end-of-travel limit switches or overruning into mechanical shock blocks.

Since rotary tables utilize worm gears in their construction, they do not possess the same payload capacity as a linear positioning table, particularly with respect to moment loads. Close attention should be paid to the rotary table's vertical moment load rating if the load is mounted in a vertical fashion.

End-of-travel limit switches should always be used for load and table protection in the event of over travel or motor run away. These should come pre-assembled and pre-wired by the manufacturer. However, the customer should indicate whether they want them wired normally-open or normally closed in order to properly interface them to the controller.

Linear Speed is crucial where high throughput and duty cycles are needed. High speed (3-15 IPS) systems require efficient, low pitch/high lead ball screws (1-2 turns per inch or 0.5-1.0" per turn), low-friction linear bearing systems and high torque servo or stepper motors. In general, speeds greater than 18 IPS and acceleration rates higher than 3 Gs cannot be achieved by ball screw assemblies and would require the use of belt drive tables plus brushless servo motors or linear motors. Some belt drive tables are rated to a maximum 5 G acceleration and 120 IPS velocity, limited only by tensile belt strength and the rigidness of the mechanical components. Load deflection and oscillation will significantly affect linear speed and precision and should be considered in high speed, long stroke applications. Acme screws will suffice for moderate speeds and duty cycles applications. Where very low speeds or high resolution is needed, a high pitch/low lead ball or acme screw (5 or 10 turns per inch or 0.2-0.10" per turn) and a servo motor should be used.

Load and table inertia must be considered to insure sufficient acceleration (overcoming breakaway, frictional torque), deceleration, minimum settling times, accuracy and motor life. Where the load inertia is high, brushless motors and/or gearing may be needed to increase motor torque while reducing the reflected load inertia the motor sees. Typically, high-speed belt drive tables will need additional gearing to achieve the desired acceleration and motion profile. However, they still suffer from poor settling times and reduced life versus a ball screw-driven system.

Ensure the positioning table's limit switches are wired into the motion controller before tuning. Otherwise, motor runaway may cause table or load damage.

For rotary tables, maximum motor input speed and worm gear efficiency (typically around 50%) are constraints on allowable table speed. The higher the worm gear ratio, the lower the rotary table speed is. As well, a home switch is needed to ensure the table does not rotate more than 360 degrees and cause the motor and encoder cables to tangle.

Precision is defined by the accuracy, repeatability and resolution specifications. It is based on many factors including the type of mechanical components, table design, lead screw pitch error, motor selection, stroke length as well as ambient drive screw temperature and load orientation/weight. For most applications, bi-directional repeatability is the more important factor and is dependent on the presence and type of drive screw assembly, bearings, coupling, motion and system backlash. Backlash plays the largest role in compromising repeatability.

Accuracy, Repeatability and Resolution are three important and distinct measures. Do not confuse them as they are all fundamentally different aspects of mechanical precision. In very precise, long stroke or multi-axis applications, also consider runout errors (straightness, flatness), angular errors (pitch, roll, yaw) and orthogonality errors.

Backlash results in linear free play in drive systems, similar to a mechanical "dead band." As a result, system repeatability is easily compromised reducing system precision. Reflected backlash occurs in the drive screw/nut assembly, gearing and coupling during bi-directional motion. Importantly, drive train components and acme screws with zero-backlash nuts will begin generating backlash as they start wearing so acme screws are not recommended for continuous duty, high repeatability applications.

For rotary tables, runout inaccuracies and backlash are the important accuracy parameters.

To compensate for backlash, the designer has a variety of options:

1) Utilize a preloaded nut assembly;
2) Read position feedback from two encoders, on the motor shaft (for stability) and on the load (as a position corrector). Use the controller's dual loop control feature to read both signals and electronically compensate for the backlash;
3) Approach a stop position from the same direction;
4) Where possible, directly couple the motor to the lead screw eliminating all gearing, coupling;
5) Apply a constant linear force (always found on vertical axes due to gravity);
6) Utilize zero-backlash gearheads & flexible couplings and rigid end bearings.

Belt drive tables are not recommended for high accuracy and repeatable applications because of belt stretching and reduced life. Often, accuracy and repeatability specifications are not given for belt drive tables due to wide manufacturing tolerances for the individual belts & pulleys plus variances in belt tensile strength. Since belt drive tables are typically used in high-speed, point-to-point positioning, repeatability is the most important concern. When using belt drive tables, care should be taken not to exceed the maximum torque values at the listed speed since belts can "skip" over pulley teeth causing mis-positioning of the carriage.

While a closed loop servo system delivers superior repeatability, accuracy is best achieved through the use of highly-machined precision ground ball screws and sophisticated feedback devices. High accuracy systems will require precision ground ball screws, linear bearings/rails, servo motors, linear encoders or laser interferometers for feedback, and in some cases, a granite base to maintain flatness and squareness.

While steel or cast-iron bases offer sufficient stability for most applications, positioning systems requiring precision in the micron and submicron range should be mounted to a granite base due to its superior rigidity, flatness, non-magnetic properties, high thermal inertia and non-conductivity.

Importantly, most positioning tables rate their accuracy on a single axis plane due to lead screw error. As a result, multi-axis systems will have a cumulative position error, even with position feedback, which will vary according to the stroke and number of axes. Installing linear encoders and error-mapping with a motion controller will compensate for these inaccuracies. Since step motors generate cumulative error during multiple cycles, they should not be used in a multi-axis system because they multiply the cumulative error of each linear axis. Slow speed applications requiring accurate, smooth positioning should utilize rolled and precision ground ball screw assemblies, not acme screws.

Deflection is an important consideration in maintaining high precision in long stroke, multi-axis applications, particularly gantry systems. For example, with a gantry table, there are two X axes-a passive and driven type-plus a Y and Z axis. The cross Y axis and parallel X axes may exhibit some deflection depending on the load weight, orientation and distance between parallel axes (i.e load plus Z axis weight). The higher these values, the more likely deflection will be a problem. Deflection is compensated for by the use of steel supports on the Y axes and rigid cross-beams.

Resolution is increased through the use of high pitch (low lead) drive screws, microstepping step motor drivers or servo motors with encoders and high-reduction gearing. Typically, highly accurate and repeatable systems will also have high resolution. In general, the higher the resolution required, the lower the attainable linear speed will be.

The **Environment** plays a major role in determining table life, reliability and precision. Typical conditions of concern are high temperature & humidity, fluid splashing, vacuums and particulate contamination. A robust positioning table should have the capability for operating in temperatures between 0 and 200° F. Using the table above the maximum or below the minimum ratings may reduce table life and will require specialty drive screws and bearing systems. Waycovers (bellows) are recommended to protect drive screws, shafts and bearings from dirty or hazardous conditions. The chrome plating of drive screws, bearings and shafts will prevent corrosion in high humidity, washdown and vacuum-rated applications. Hall-effect limit switches (versus mechanical types) plus special lubricants (non-outgassing products) should be used in vacuum applications.

Hidden dangers also pose significant problems. In particular, innocuous laboratory humidifiers will attract moisture causing pitting of the ball screw. As well, electrical noise could etch the bearings.

Cabling should receive special consideration in multi-axis, long stroke or environmentally-harsh applications. To prolong their life, use quality gage cable, cable carriers and tie downs to reduce flex in the cable set. Moreover, specify cables with a high bend radii to maintain reliability.

Regular lubrication with high-grade, lithium-based bearing grease, light weight oil or a synthetic teflon-based compound is recommended. The higher the duty cycle, load and speed, the greater the lubrication frequency should be.

Typically, the greasing of the ball screw and linear bearing is recommended every 4 months of operation or 1000 hours of run operation or 600 miles of distance travelled, whichever occurs first. However, rapid start/stop operation or some environmental conditions (i.e. high humidity) will necessitate more frequent lubrication.

Some demanding applications like parts insertion, inspection stations, material handling and dispensing require performance that can not be achieved from a standard positioning table. For these applications, **SCARA** robots are used. They are multi-axis, 3 dimensional positioning systems utilizing brush or brushless servo-controlled articulated arms. SCARAs offer extremely high speeds and cycle times, human scale integration & flexibility, sophisticated profiling plus a work envelope of up to 220 degrees of freedom. However, dynamic and moment loads are much lower than a standard table while purchase cost, complexity and programming time is significantly higher. Since SCARAs often feature up to six driven axes per robot, achieving high precision could be costly due to inherent backlash and hysteresis.

Due to a SCARA robots complexity, controls and robots should be purchased from the same manufacturer.

LINEAR ACTUATORS

Linear actuators are self-contained lead screw assemblies that are driven by electric (AC or DC) motors. Also known as electric cylinders, their operation is simple. They convert rotary motion and torque into linear thrust and displacement. Four key components make up the design of an actuator. They are the drive screw, motor, translation tube and gearing. Actuators satisfy a myriad of applications for the industrial, instrumentation and commercial markets including: gate positioning, raising & lowering medical beds, valve actuaton, antenna extension and materials handling.

Linear actuators are increasingly replacing pneumatic and hydraulic drive systems in high performance applications. The advantages of linear actuators are higher precision, lower maintenance, easier installation and high power per displacement (efficiency). However, superior performance is accompanied by higher cost and potentially more difficult start-up when sophisticated servo controls and feedback devices are used.

The following chart compares the performance of linear actuators to pneumatic and hydraulic systems:

ELECTRIC ACTUATORS vs. PNEUMATICS vs. HYDRAULICS

Parameter	***Electric Actuator***	***Pneumatic***	***Hydraulic***
Maint. Req'd	Low	Moderate	High
Precision	High	Moderate	Low
Flexibility	High speed/thrust	High speed applications	High thrust applications
Speed	High	High	Moderate
Design Complexity	Low	High-hoses, plumbing, air	High-valving, fluids, pumps, plumbing
Cycle Life	Excellent	Good	Good
Environment	Flexible	Seals leak at extreme temperature	Seals leak at extreme temp
Control	Servo/Stepper	Complicated	Complicated/ Expensive
Purchase Cost	Moderate	Low	Low
Installation Cost	Low	High	High

Choosing the right actuator is based on consideration of the following selection factors: load or thrust, speed, duty cycle, precision required and operating environment.

The size and orientation of the dynamic **load** is a critical factor. A general rule of thumb is to choose an actuator that exceeds the desired dynamic and static load/thrust by at least 30% in order to account for load underestimation, frictional forces, vertical orientation and higher-than-expected duty cycles. In order to minimize purchase cost, the engineer should seek to maximize thrust ratings within a given actuator series. Increasing thrust is easily achieved by increasing the drive screw pitch, using higher ratio gearing or by using a higher-torque motor. However, these changes may affect the system's cost, speed and duty cycle.

Care must be taken to choose the proper actuator and drive screw (ball or acme) in order to safely accommodate compression (retraction) and tension (extension) loads and to ensure actuator life. Furthermore, load orientation and the mechanical mount should be chosen to minimize moment (offset) loads in order to maximize bearing and motor life. Actuators mounted vertically should utilize non-backdriving acme screws or fail-safe brakes with ball screws. Finally, limit switches are always recommended for over-travel protection of the load and actuator.

Actuator **speed** is affected by varying the voltage to the motor and by changing the pitch of the drive screw. For example, a 24 VDC actuator run at 20V will have 20/24 the speed at rated voltage. Speed versus thrust curves for each actuator at different voltages would be derated by a comparable fraction. Caution should be taken never to exceed maximum motor voltage ratings and rated actuator speed specifications. For higher speeds within an actuator series, utilize low pitch drive screws, direct drive (no gearing) and higher speed servo motors. However, increasing actuator speed by increasing the screw pitch usually results in the load rating being reduced if the motor size has not changed.

The designer should also pay close attention to maximum acceleration/deceleration rates plus settling times. The speed characteristics of each type of motor must be considered when analyzing the speed profile. Servo motors (particularly brushless types) offer better velocity profiles over a greater torque range than step motors. End-of-travel limit switches should always be used for actuator and load protection.

Work with your vendor to select matching drives and controls for your actuator.

The Duty Cycle has a major impact on actuator performance and life. The duty cycle is affected by motor on-time. For example, a short stroke actuator that cycles at the same frequency as a long stroke unit will be running a shorter amount of time. In addition, If the application requires a high duty cycle, a higher speed actuator would run a shorter period of time and have longer time to cool between cycles than a slower speed unit. Most applications call for intermittent operation (less than 60% on time) since the duty cycle often varies inversely with the load. For continuous duty (100% on time) applications, higher-efficiency ball screws, with brushless servo and step motors are recommended. Generally, the engineer would be better off to trade speed instead of payload to sustain actuator life.

Precision is defined by accuracy, repeatability and resolution. For uni-directional loads, accuracy is the key factor, and for bi-directional loads, repeatability is the most important. Accuracy is attained by using high-accuracy rolled ball screw assemblies plus servo motors or steppers with microstepping drives. Under bi-directional loads, axial end play (backlash) will introduce inaccuracies when the load changes position. This is minimized by using preloaded or anti-backlash nuts and gears plus servo motors. High repeatability is ensured by using servo motors with encoder feedback, a direct drive design and/or rolled ball screws with zero backlash nuts. High resolution is gained through the use of high-pitch ball or acme screws, additional gearing and microstepping motors.

Environmental factors often have a siginificant impact on actuator performance and life. Moreover, actuators are also affected by the specific environmental considerations of their accompanying motors, drives and encoders. Contaminants on the drive screw and nut will reduce reliability and life. Environmental sealing is recommended for overall protection of the actuator in dusty, wet, and humid conditions. In some cases, acme screws and nuts will offer better protection against dust and dirt due to their design. Under extreme temperatures, steel screws and nuts should be used since plastic nuts have a lower coefficient of thermal expansion and contraction.

Choose actuators that feature a modular design for simple field replacement of important components like drive screws, couplings, gears etc.

THE FUTURE OF MOTION CONTROL

The only sure thing in the MC industry is constant change. Today's applications and technologies are significantly different from what was present only five years ago. However, like other emerging industries, the MC world has begun exhibiting the characteristics of a maturing market, much like the PC industry did ten years ago. These include rapidly increasing usage, expanding competition, evolving standardization and, most importantly, falling prices.

On a systems level, the market will continue to evolve toward open, flexible PC architectures and application-level software and away from proprietary, close-ended systems. The hardware (PC/ISA BUS architecture) and software standards (DOS, Windows) developed for the office are now being widely used on the factory floor in a wide range of industries. Off-the-shelf PC's and standard programming languages like C and VisualBASIC have now become legitimate alternatives to PLCs for machine control. Furthermore, communication standards like Ethernet and ARCNET have spread to the plant floor making it possible for the first time to connect virtually every machine and workstation in an organisation. Consequently, design engineers will be able to build ever more powerful machines with the knowledge that common hardware platforms, operator interfaces, I/O networks and communication links are available.

From a product perspective, the near future will witness the arrival of servo over stepper technology as the dominant MC technology. Product improvements will focus on improved speed and communications, lower purchase and maintenance costs, greater compactness and easier integration within the machine.

Digital communications (perhaps SERCOS) via fiber optic networks will soon replace analog links like the ±10 V command signal due to its inherent performance advantages and superior noise immunity. New controller developments will include: parallel processing in applications like material handling, CNC and; embedded micro-controllers for the robotics market. The emergence of new data highways like Allen-Bradley's Device Net, SERCOS and Honeywell SDS will address total factory automation and dictate next generation hardware . Most control and drive systems will seek compatibility with one or more of these competing standards.

Finally, the PC computer market will continue setting the standards for software, networking and hardware architectures with the PCI BUS and Windows NT expected to establish new benchmarks.

Many controllers will soon be available with object-oriented programming for quick solutions to simple applications. Surface-mount design and more powerful microprocessors (soon 64-bit) will enable controllers to control more axes, accommodate more digital and analog I/O, and execute mathematical processing faster. New stand-alone designs will incorporate built-in operator interfaces and PWM amplifiers. Controllers, and increasingly amplifiers, will offer more advanced autotune and debugging features speeding up the tuning process.

The power device (i.e semiconductor) industry will distill new drive technologies (i.e. enhanced IGBT drives) into the amplifier and power supply market making them cheaper, more powerful and compact. More control and feedback capabilities will become distributed to amplifiers making them "smart drives." Thus, the balance may begin tipping to distributed versus central control, but complemented with real-time communications.

New motor designs on the horizon will combine the motor, amplifier and encoder in one compact package. Furthermore, linear motors will make significant inroads into the domain of the drive screw in positioning, scanning, CNC and materials handling markets. Finally, electric linear actuators will increasingly replace hydraulic and pneumatic systems.

Early evidence suggest eight likely developments over the next 3-5 years, in no order of likelihood, are:

1) The ascendancy of software over hardware as the key controller purchase determinator;
2) The shift from discrete MC cells to total factory, real-time integration (ie. more networking);
3) No software standardization. Continued battle between proprietary and standardized languages;
4) The emergence of the PCI architecture over the PC/ISA BUS;
5) Establishment of NEMA-like standard dimensions for Brush and Brushless servo motors;
6) Further blurring of the divisions between the functionality of PLCs and Motion Controllers;
7) Industry consolidation of manufactures and vendors into "super" organizations providing complete sales and support services;
8) Increasing use of fiber optic cabling due to its superior noise immunity, isolation and reduced size and weight.

APPENDICIES

CONTROLLING ELECTRICAL NOISE & GROUND LOOPS *Appendix 1*

Often overlooked, electrical noise has a significant impact on the reliability and accuracy of a MC system. In general, noise leads to a corruption in the normal function of the controller, causing the microprocessor to misinterpret or access the wrong data. Its effects can vary from minor positioning errors due to lost encoder counts to motor runaway causing load damage. Dealing with these problems is like following the old adage: "an ounce of prevention is better than a pound of cure."

Electrical noise could arise from a number of sources, the most common being: power line disturbances; externally conducted noise; transmitted noise and; ground loops. While the number of potential culprits is high, certain commonly-used electrical devices are known for generating electrical noise:

1) **Welders** - transmitted and power line noise.
2) **Motors and PWM Drives** - transmitted and power line noise due to high power switching equipment (AC/DC motors, contactor control HV switchgear).
3) **Coil-Driven Devices** - conducted and power line noise. Random occurences and specific times when the signal circuits are enabled. These generally show up as intermittent operating faults and are difficult to locate.
4) **SCR-fired Heaters** - transmitted and power line noise.
5) **Improper System Grounds** - connecting too many or grounds at the wrong points.

AC line fluctuations (also known as brown outs, transients and surges) are very common. Intermittent AC power fluctuations between 75-135 VAC are possible in most systems. Despite this, many designers overlook the likelihood of these disturbances occurring. Counter measures are simple and mostly inexpensive. Line filtering equipment should be used in every application, particularly if other equipment connected to the power line is switching large amounts of current at high frequencies. Where the environment is noisy or the equipment is being installed in poor electrically regulated regions (i.e. Third World countries), Isolation Transformers with filters should be used.

Where coiled equipment like relays, solenoids, clutches/brakes, motor starters are used, noise is likely to occur when the device is switched off. Surge suppressors and a series RC network-resistor/capacitor filters (resistance: 500 to 1000K, capacitance: 0.1 to 0.2 µF) are effective solutions. Ferrite beads are also helpful.

Externally conducted noise occurs in signal and ground wires connected to the controller. This noise corrupts the effective operation of the controller microprocessor by scrambling the stored program. A common example occurs when control equipment shares a common DC ground which often runs to other noisy devices (i.e power supply, relays, switches). To solve this, connect a diode backwards across the coil to clamp the induced voltage "kick" that the coil will produce. The diode should be rated at four times the coil voltage and ten times the coil current. Multiple devices on the same circuit should be earth grounded together at a single point. To prevent noisy devices grounded to earth from sending signals to the controller, it is recommended to have the controller signal ground or DC common floating with respect to Earth. Where this is not possible, the Earth ground should be made at only a signal point. In most cases, using solid state relays and opto-isolation will eliminate electrical contact between the controller and noisy devices.

Transmitted noise is picked up by external connections to the controller. Non-conductive Enclosures and packaged controllers help but in severe situations, noise can even affect a packaged controller through leaks in the front panel and connectors. To prevent this, the packaged controller should be grounded to Earth to minimize risk. Keep all noisy devices outside or away from protective enclosures. Another problem occurs when a burst of RFI noise is created when a current contact opens which is picked up by controller limit switch or other wiring (often encoder cabling). High current and voltage wires contain an electrical field surrounding them and may incite noise on signal wiring, particularly when tied in the same bundle or conduit. The solution to this problem is shielding or isolating signal cables and connectors. The shielding should be tied to Earth to drain induced voltages and should be used in conjunction with twisted pair cabling. The motor wiring should be kept as far as possible from the feedback device wiring or any other signal wiring. Finally, the motor must be properly grounded to reduce noise and to prevent shock hazard.

In certain noise-sensitive applications (i.e. ultra-sonic imaging, video cameras, magnetic or capacitive sensors), a major source of noise is high DV/DT of PWM amplifier's MOSFETS emitting noise into AC power lines or along motor cable/outputs into attached equipment. Unfiltered motor outputs can introduce noise in digital encoder signal wires if they are routed in the same cable harness without shielding. In these applications, an external filter card connected between the amplifier and motor with minimum 250 uH inductors and capacitors is recommended. For additional noise protection, use a common mode choke connecting the motor terminals to the controller. This choke will reduce the amplitude of the current pulses flowing in the motor ground wire. If all else fails, select Linear Amplifiers which produce pure DC output.

Ground loops occur as garbled transmission, system vibrations and intermittent operation within RS-232C communication. These systems often have multiple Earth ground connections, particularly when these connections are far apart. Ground loops also occur very often in applications requiring multiple axes. Any time there are two or more possible current paths to a ground, damage can occur or noise can be introduced into the system, regardless of the number of power supplies used. As a general rule, a shield should only be connected at one end to prevent ground loops while insulating the unconnected end to prevent accidental connection. Furthermore, the use of isolation techniques has shown to be very effective. In this case, the connections between two grounds are isolated while the desired signal is allowed to pass with little or no loss in accuracy.

The following steps should be taken in order of priority to prevent noise problems:

1) **Equipment** - Select equipment with a high tolerance to electrical noise (i.e opto-isolation).
2) **Motor Cabling** - Use twisted pairs shielding taken to a low impedence earth ground.
3) **Controller Cabling** - Shield vulnerable cables or areas within an electrical enclosure away from radiated noise; Keep leads short.
4) **Motor Drive Grounding** - Use single point earth ground, filter cards, chokes.
5) **I/O Shielding** - Use opto-isolation, line drivers on encoders. Shield logic lines of noise sensitive equipment. Install sensitive equipment far from motor, amplifier and in enclosures.
6) **AC Isolation & Line Filtering** - Provide separate isolated AC lines for amplifiers versus other noise sensitive equipment. Use isolation transformers, UPS systems and filters to provide drive power and isolate equipment from dirty power sources. Specify amplifiers with differential inputs.
7) **Routing Power/Signal Leads** - Separate AC input, signal and output power leads. Do not bundle or run in same conduit. Run separate power supply leads to each amplifier from the power supply filter capacitor.
8) **Routing Ground Leads** - Do not bundle ground lead with filter output lines, other signal lines, or run in the same conduit. Connect the filter ground by itself to the enclosure's single-point ground. Use as short a ground as practical. Never daisy-chain power or DC common connections; use "Star" connection.
9) **Serial Communications Line Filtering** - Use ferrites, RC filter networks, surge suppressors to eliminate noise on RS 232 lines.

Unfortunately low-frequency magnetic fields are not significantly reduced by metal enclosures. Typical sources of these fields include power transformers and low frequency current changes in the motor leads. The best countermeasure is to avoid large loop areas in power supply, signal and motor wires and use twisted pair cabling.

PWM current spikes generated by the power output are handled by the internal power supply capacitors as long as heavy-duty power leads are used and are kept short (less than 3 ft. from the amplifier). For power supply leads greater than 3 ft., the direct amplifier termination must be bypassed by a capacitor of 1000 uF minimum installed within 3 ft. of the amplifier. Twist the power leads for greater impedence.

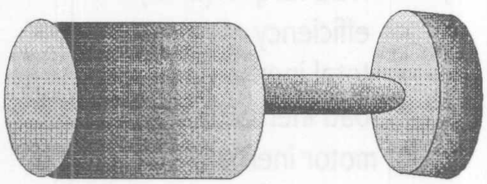
CALCULATING INERTIAS

DIRECT DRIVE

The simplest of designs is the direct drive. This would not require the load parameters to be reflected back, since there are no mechanical linkages involved.

The equations for the direct drive are presented below. Since the speed of the load is the same as the motor, the friction of the load is the friction which the motor must overcome, therefore the load inertia is directly what the motor would "see".

Direct Drive:



where
S_m = motor speed (RPM)
S_1 = load speed (RPM)
T_m = motor torque (lb-in)
T_1 = load torque (lb-in)
J_t = total inertia (lb-in-s^2)
J_1 = load inertia (lb-in-s^2)
J_m = motor inertia (lb-in-s^2)

speed (motor) = speed (load)

$$S_m = S_1$$

torque at motor = torque at load

$$T_m = T_1$$

total inertia = inertia (load) + inertia (motor)

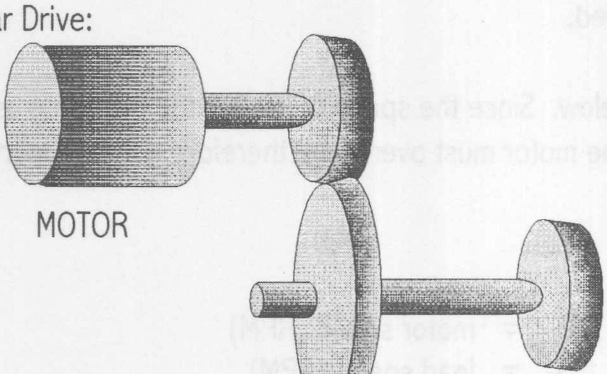
$$J_t = J_1 + J_m$$

GEAR DRIVE

Appendix 2b

In a gear application, since there are mechanical linkages between the load and motor, the load parameters must be reflected back to the motor shaft as follows:

Gear Drive:



where
S_M = motor speed (RPM)
S_1 = load speed (RPM)
N = gear ratio
N_1 = number of load gear teeth
N_m = number of motor gear teeth
T_m = motor torque (lb-in)
T_1 = load torque (lb-in)
e = efficiency
J_t = total inertia (lb-in-s^2)
J_1 = load inertia (lb-in s^2)
J_m = motor inertia (lb-in-s^2)

speed (motor) = speed (load) x gear ratio

$$S_m = S_1 \times N$$

or

$$S_m = S_1 \times N_1 \div N_m$$

torque at motor = torque at load ÷ gear ratio

$$T_m = \frac{T_1}{Ne}$$

total inertia = inertia (load) ÷ (gear ratio^2) + inertia (motor)

$$J_t = \frac{J_1}{N^2} + J_m$$

First, calculate the inertia for a solid cylinder:

$$J_{load} = \frac{1}{2} \times \frac{W R^2}{g}$$

Thus, reflecting this inertia through the gear ratio:

$$J_{ref} = \frac{J_{load}}{N^2}$$

The inertia of the gears should be included in the determination of total load inertia to be really accurate (this can be obtained from literature or calculated using the formulas for the inertia of a cylinder). Efficiencies of the gearing should also be considered when calculating torques.

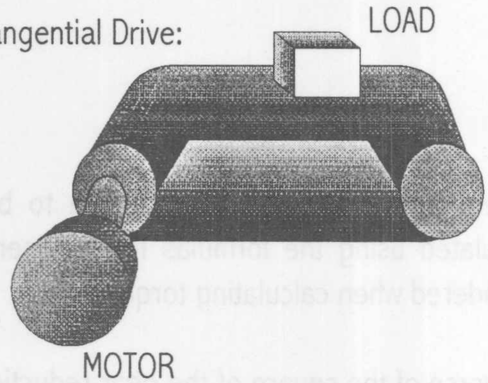
Load-to-motor inertia mismatches are reduced by the inverse of the square of the gear reduction ratio. Adding small increments of reduction can significantly reduce an inertia mismatch.

TANGENTIAL DRIVE

Appendix 2c

Another common mechanical drive design involves tangential drives. For this type of drive, the load parameters have to be reflected back to the motor shaft. A tangential drive can be a timing belt and pulley, chain and sprocket, or rack and pinion.

Tangential Drive:



where

S_m = motor speed (RPM)
V_1 = load speed (in/min)
R = radius (inches)
T_1 = torque reflected to motor (lb-in)
F_1 = load force (lb)
T_f = friction torque (lb-in)
F_f = friction force (lb)
J_t = total inertia (lb-in-s^2)
W = loadweight + belt weight (lb)
J_p = pulley inertia (lb-in-s^2)
J_m = motor inertia (lb-in-s^2)
g = gravitational constant (386 in/s^2)

$$\text{speed (motor)} = \frac{1}{2\pi} \times \frac{\textit{speed (load)}}{\textit{radius}}$$

$$S_m = \frac{1}{2\pi} \times \frac{V_1}{R}$$

load torque = load force x radius

$$T_1 = F_1 R$$

friction torque = frictional force x radius

$$T_1 = F_1 R$$

total inertia = (weight x radius^2) (gravity)
+ inertia (pulley #1) + inertia (pulley #2)
+ inertia (motor)

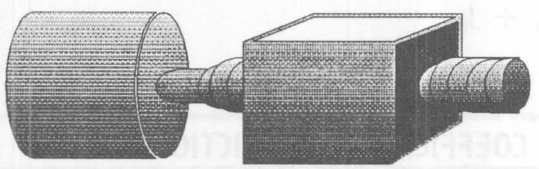
$$J_t = \frac{W R^2}{g} + J_{p1} + J_{p2} + J_m$$

The designer should also ensure inertia of the couplings, pulleys, sprockets, or pinion gears are included in the determination of total inertia.

LEADSCREW DRIVE *Appendix 2d*

The load parameters have to be reflected back to the motor shaft for this type of drive as well. The inertias which have to be considered include the leadscrew as well as the load. If the leadscrew inertia is not readily available, the formula for a cylinder may be used. The following formula is used to calculate reflected inertia:

Leadscrew Drive:



where
S_m = motor speed (RPM)
V_1 = load speed (in/min)
P = pitch (rev/inch)
T_1 = torque reflected to motor (lb-in)
F_1 = load force (lb)
F_{p1} = preload force (lb)
e = efficiency
T_f = friction torque (lb-in)
F_f = friction force (lb)
u = coefficient of friction
W = load weight (lb)
J_t = total inertia (lb-in-s^2)
J_{1s} = leadscrew inertia (lb-in-s^2)
J_m = motor inertia (lb-in-s^2)
g = gravitational constant (386 in/s^2)

speed (motor) = speed (load) x pitch

$$S_m = V_1 \times P$$

$$\text{load torque reflected to motor} = \frac{1}{2\pi} \times \frac{\textit{load force}}{\textit{pitch} \times \textit{eff}} + \frac{1}{2\pi} \times \frac{\textit{preload force}}{\textit{pitch}} \times 0.2$$

$$T_1 = \frac{1}{2\pi} \times \frac{F_1}{P\,e} + \frac{1}{2\pi} \times \frac{Fp_1}{P} \times 0.2$$

$$\text{friction torque} = \frac{1}{2\pi} \times \frac{\textit{frictional force}}{\textit{pitch} \times \textit{eff}}$$

$$T_f = \frac{1}{2\pi} \times \frac{F_f}{Pe}$$

where F_f = coefficient of friction x weight
= u x W

$$\text{total inertia} = \frac{load}{gravity}\left(\frac{1}{2\pi\, pitch}\right)^2 + \text{lead screw inertia} + \text{motor inertia}$$

$$J_t = \frac{W}{g}\left(\frac{1}{2\pi P}\right)^2 + J_{1s} + J_m$$

TYPICAL EFFICIENCIES	
Type	**Efficiency**
Ball-nut	90%
Acme (plastic nut)	65%
Acme (metal nut)	40%

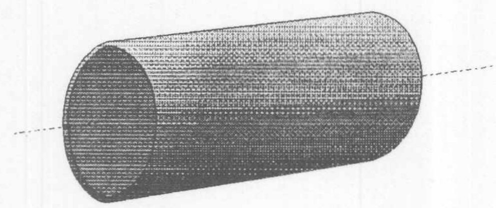
COEFFICIENTS OF FRICTION	
Steel on Steel	0.58
Steel on Steel (lubricated)	0.15
Teflon on Steel	0.04
Ball Bushing	0.003

For precision positioning applications, the leadscrew is sometimes preloaded to eliminate or reduce backlash. If preloading is used, the preload torque must be included since it can be significant. The leadscrew's efficiency must also be considered when finally determining torques.

SOLID & HOLLOW CYLINDERS *Appendix 2e*

This section illustrates the formulas for calculating the inertia of a cylinder. The inertia of a cylinder can be calculated if either the weight and radius are known, or the density, radius, and length are known. Inertia calculations for solid and hollow cylinders are presented below:

Solid Cylinder:

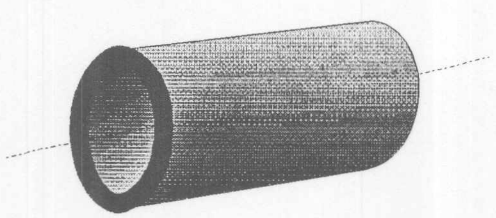


where J = inertia (lb-in-s^2)
W = weight (lb)
R = radius (inch)
g = gravitational constant (386 in/s^2)
L = length (inch)
P = density (lb/in^3)

For a known weight and radius: $$J = \frac{1}{2} \times \frac{W R^2}{g}$$

For a known density, radius, and length: $$J = \frac{1}{2} \times \frac{\pi L p R^4}{g}$$

Hollow Cylinder:



where J = inertia (lb-in-s^2)
W = weight (lb)
R_o = outer radius (inch)
R_i = inner radius (inch)
g = gravitational constant (386 in/s^2)
L = length (inch)
P = density (lb/in^3)

For a known weight and radius: $$J = \frac{1}{2} \times \frac{W}{g} (R_o^2 + R_i^2)$$

For a known density, radius, and length: $$J = \frac{1}{2} \times \frac{\pi L p}{g} (R_o^4 - R_i^4)$$

These equations are important since the inertia of mechanical components (i.e. shafts, gears, drive rollers, leadscrews, etc.) can be calculated by using them. Once the inertia is determined, it becomes just a matter of reflecting the load inertia and friction through the mechanical linkages to what the motor will "see".

Approximate Densities of Common Materials

Substance	Avg. Density (δ) lb/Ft³	Kg/m³
Aluminum	165	2643
Brass	534	8553
Bronze	509	8153
Copper	556	8906
Glass	162	2595
Iron, gray cast	442	7079
Iron, wrought	485	7658
Lead	710	11370
Nickel	537	8602
Paper	58	929
Polystyrene	68	1089
Rubber	94	1506
Steel, cold drawn	490	7841
Steel, machine	487	7800
Steel, tool	481	7703
Zinc	253	4052

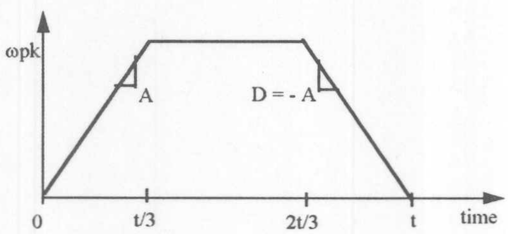
TORQUE ANALYSIS AND SIZING TECHNIQUES

The information presented here will serve as a guide for selecting stepping drive or servo drive elements of a motion control system. The motion profile and torque are examined first, since they must be considered in all applications. This is followed by separate procedures for sizing stepping and servo drives. Finally, specific types of loads, such as direct, leadscrew, gear, and tangential are examined.

Motion Profile

The most popular method (because it is optimal) of performing point-to-point moves is the "1/3" trapezoidal profile. In this profile, each part of the move (acceleration, slew, and deceleration) is of equal duration.

The governing equations are:



$$\alpha = \frac{4.5\theta}{t^2} \qquad \omega_{pk} = \frac{1.5\theta}{t} \qquad \text{(rad/sec}^2\text{)}$$

α = Acceleration (rad/sec^2)
ω_{pk} = Peak Velocity (rad/sec)
θ = Distance (rad)
t = Time (sec)

Torque Requirements

The total continuous torque needed in an application consists of several torques added together in worst-case fashion. For safety, the designer should size the motor according to continuous operation. Peak torque capability should only be considered for intermittent low duty cycle applications.

$$T_T = T_A + T_F + T_V + T_G \qquad \text{(oz-in)}$$

T_A = Torque necessary to accelerate (decelerate) all masses.
T_F = Torque necessary to overcome friction, viscuous forces and preloads. This torque is often ignored but could be significant.
T_V = Torque that is directly proportional to speed. This torque is often, but not always,negligible.
T_G = Torque necessary to overcome gravity in non-counter-balanced vertical applications.

Acceleration and gravitational torques are calculated using the following equations:

$$T_A = J_T\alpha \qquad \text{(oz-in)}$$

$$J_T = J_{motor} + J_{tachometer} + J_{load} \qquad \text{(oz-in-sec}^2\text{)}$$

$$T_G = \frac{2.55W}{Pe} \qquad \text{(oz-in)}$$

W = Weight of load (lbs)
P = Pitch of mechanical driving means (rev/inch)
e = Efficiency (dimensionless, <1)

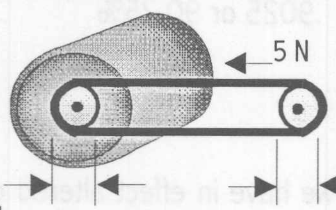
An optinal design should incorporate a 50% safety margin for torque sizing to improve motor life expectancy and safe guard against load changes.

TORQUE CALCULATIONS FOR BELT & PULLEY DRIVES *Appendix 3a*

Another very important equation necessary in motor sizing is the torque equation which is defined as follows:

Torque = Force x Distance where, Force is in Newtons or lbs
Distance is in meters or feet

Let's consider the following example of a Two Pulley system: to illustrate the formula:



.05 m .05 m

A force of 5 newtons (1.124 lbs) needs to be transmitted to the pulley-belt. What minimum torque rating must our motor have?

Answer: Torque = Force x Distance (Radius of Pulley)
= 5N (.025 m) = 1.124 lbs (.082 ft)
= .125 Nm or = .092 lb ft

This assumes a perfect system. Unfortunately any time energy is transferred, torque losses are eminent. This is caused by the system inefficiencies. In our pulley example, our energy transfer from the motor to the belt is not 100%. Losses such as heat and noise generation reduce the overall efficiency and increase the torque needed. For a belt-pulley system, efficiencies run approximately 95%. In our previous example, the torque rating of our motor would have to be increased to account for this.

Example: 2 pulley system with inefficiencies provided for:

$$\text{Torque} = \frac{Force \times Distance}{\eta}$$

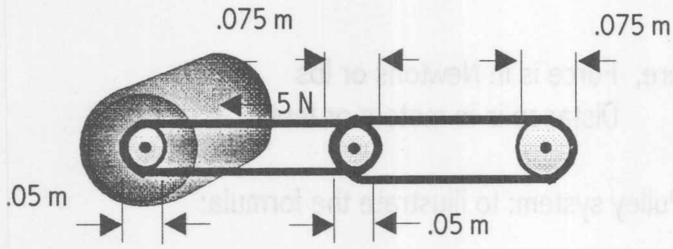
$$= \frac{5N(.025_{m})}{.95} = \frac{1.124\ lbs\,(.082\ ft)}{.95}$$

or

$$= .132\ \text{Nm} = .097\ \text{lb ft}$$

In a two stage system, e.g., 2 belts in series, the individual efficiencies of the energy transfer multiply.

Example: 2 BELT IN SERIES



Here we have 2 belt arrangements in series, and the combined efficiencies would be:

η total = η pulley 1 x η pulley 2
= .95 x .95
= .9025 or 90.25%

By using a larger diameter pulley on the second stage of our example, we have in effect altered our force and speed (distance/time) as seen by the second belt.

The ratio of change can be defined as:

$$\text{Ratio} = \frac{{}^{Dia}pulley2}{{}^{Dia}pulley1} \quad \text{where Dia = Diameter}$$

Using our example, determine the ratio

$$\text{Ratio} = \frac{.075m}{.05m} = \frac{.246\ ft}{.164\ ft}$$

or

$$= 1.5 \qquad = 1.5$$

Therefore, our torque as seen by the second pulley would be:

$$T_{pulley2} = \frac{F \times d}{\eta_1 \eta_2 n} \quad \text{where n = gear ratio}$$

$$= \frac{5N\,(.025)}{.95 \times .95 \times 1.5} = \frac{1.124\,lbs\,(.082\ ft)}{.95 \times .95 \times 1.5}$$

or

$$= .0923\ \text{Nm} \qquad = .068\ \text{lb ft}$$

The speed of the belt is also affected by the ratio in this example. Assume a motor speed of 2 RPM. What then is the speed of the second belt?

Answer: First we must convert to linear speed. This can be done by multiplying the motor speed by the circumference of the pulley.

$$^{V}belt\ 1 = {}^{N}motor \times 2\pi \times Radius$$

$$= 2\ RPM\ (2\pi .025\ m) \quad \text{or} \quad = 2\ RPM\ (2\pi\ .082\ ft)$$

$$= .314\ m/min \qquad = 1.03\ ft/min$$

The speed of belt 2 is:

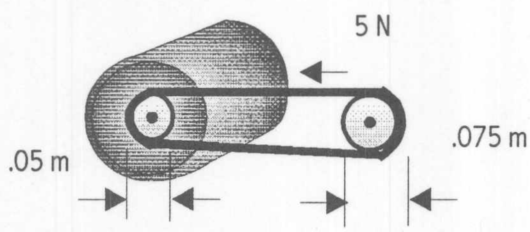
$$^{V}belt\ 2 = {}^{V}belt1 \times n \qquad \text{where } n = \text{ratio}$$

$$= .314\ m/min\ (1.5) \quad \text{or} \quad = 1.03\ ft/min\ (1.5)$$

$$= .471\ m/min \qquad = 1.545\ ft/min$$

The same result could have been achieved via a single belt using the different size pulleys.

EQUIVALENT DIAGRAM:



In this case, the losses due to efficiency would be less since only one belt/pulley arrangement is used.

In the same way as we use a belt and pulley, we can use other speed reducing/increasing methods. Most popular are rack & pinion (typically 90% efficient), gearbox (50% to 97% efficient), and lead or ballscrew (50% to 95% efficient). Each has specific advantages and disadvantages.

TORQUE CALCULATION FOR LEAD SCREWS & RACK + PINION DRIVES *Appendix 3b*

In using a lead screw or rack & pinion, use the following equation to determine required torque (if radius of leadscrew or pinion is not known):

$$T = \frac{F \times lead\ (Nm)}{2\pi\eta_s} \quad or \quad T = \frac{F \times lead\ (lb\ ft)}{24\pi\eta_s}$$

where F = Force (N or lbs)
lead (.../rev or in/rev)
η_s = efficiency

Derivation

T = F x d

lead = distance/revolution
= distance/rev

solving for distance
distance = lead x rev

distance is linear, we require radius
r = distance/2π
d = lead x rev/2π

substituting for d

$$T = \frac{F \times lead}{2\pi}$$

$$T = \frac{F \times lead}{2\pi\ \eta_s}$$ accounting for efficiency losses

Example: We have a lead screw with a lead of .0127 m/rev (.5 in/rev) using a motor with a continuous torque rating of 50 Nm (36.87 lb ft). What available force do we have assuming an efficiency of 90%?

Answer:

$$T = \frac{F \times lead\ (Nm)}{2\pi\eta_s} \quad or \quad T = \frac{F \times lead\ (lb\ ft)}{24\pi\eta_s}$$

solving for F.

$$F = \frac{T \times 2\pi\eta_s\ (Newtons)}{lead} \quad or \quad F = \frac{T \times 24\pi\eta_s\ (lbs)}{lead}$$

$$= \frac{50\ Nm\ (2\pi)\ (.9)}{.0127\ m / rev} \qquad = \frac{36.87\ lb\ ft\ (24\pi)\ (.9)}{.5\ in / rev}$$

= 22.3 K Newtons = 5000 lbs

MOTOR RESISTANCE *Appendix 3c*

High motor temperature is a primary cause of premature breakdown and reduced torque values. Due to the rise in temperature in an armature winding, the motor resistance value will change accordingly. It is standard to measure the winding resistance at 25°C. In order to calculate I^2R losses, etc., we must be able to calculate the resistance at actual winding temperature. This can be done as follows:

$$^{R}mhot = {}^{R}m25°C \; (1 + .00393 \; (Twinding - 25°C)) \text{ for copper}$$

where

$^{R}m25°C$ = Published Resistance value (at 25°C)

$^{R}mhot$ = Hot winding Resistance

$^{T}winding$ = Temperature of winding

POWER CALCULATIONS

Appendix 3d

Some designers and manufacturers (particularly brushless motor vendors) choose to specify torque in terms of power. Power can be defined by the equation:

$$P = \omega T \qquad HP = \frac{\omega T}{550}$$

where ω = angular velocity (rad/sec) $= \frac{2\pi N}{60}$

T = (Nm or lb ft)
N = RPM

substituting $\omega = \frac{2\pi N}{60}$

$$P = \frac{T \times N}{9.55}$$ (Watts, Nm, RPM)

$$HP = \frac{T \times N}{5252}$$ (HP, lb ft, RPM)

TORQUE REQUIRED TO ACCELERATE A LOAD *Appendix 3e*

Once the inertias of a system are defined, we are then able to calculate the acceleration and deceleration capabilities of a motor. The torque required to accelerate can be defined as follows:

$$T\alpha = \frac{J_T N\pi}{30t_a} + FT \quad (Nm\ or\ lb\ ft)$$

Assumes constant acceleration.

where J_T = total system inertia (Kgm^2 or $lb\ ft\ sec^2$)
N = motor speed (RPM)
t_a = allowed time to accelerate (sec)

Torque required to accelerate a load:

T = F x d — where: F = Force (N), d = distance (m)
substituting F = ma, where m = mass (Kg)

T = ma x d — a = acceleration (m/s^2)
T = ma x r — d = radius (r = meters)
J = mr^2, solving for m

$$m = \frac{J}{r^2}$$

substituting for m

$$T = \frac{j \times a \times r}{r^2}$$

$$a = \frac{V}{t_a}$$

where V = velocity
t_a = time to accelerate

V = N x circumference where N = RPM
= $N(2\pi r)$

requiring V in m/s we must multiply by 1 min/60 sec

$$V = \frac{N \times 2\pi r}{60}$$

$$a = \frac{N \times 2\pi r}{60t_a}$$

substituting for a

$$T = \frac{J \times N \times 2\pi r \times r}{r^2 \quad 60t_a}$$

$$T = \frac{J \times N\pi}{30t_a}$$

checking units

$$T = \frac{J \times N\pi}{30t_a}$$

= Kgm^2 rotation/sec   Note: rotations are unitless

= Kgm^2/s^2

which is equivalent to Nm, as N = Kgm/s^2

MINIMUM ACCELERATION TIME

Often it is necessary to calculate the time required to accelerate a load. We can easily come up with this value by solving the acceleration torque formula for time. The result is:

$$t\infty = \frac{J_T N \pi}{30\,({}^{T}available\ {}^{-FT})} \qquad \text{(seconds)}$$

where,
J_T = total system inertia (Kg m^2 or lb ft sec^2)
N = motor speed (RPM)
^{T}available = available torque (Nm or lb ft)

Occasionally, when working with high speed/torque applications (like robotics or injection molding) an acceleration rate in relation to a multiple of g (the acceleration due to gravity) is used. We can solve for the time to accelerate a load up to speed as follows:

$$t\infty = \frac{N \times Lead}{720a(32.174)} \qquad \text{(seconds)}$$

in English units where,
N = RPM
Lead = inches/rev
a = multiple of g (g = 32.174 ft/sec ^{2})

or

$$t\infty = \frac{N \times Lead}{60a(9.80665)} \qquad \text{(seconds)}$$

in Metric units where,
N = RPM
Lead = meters/rev
a = multiple of g (g = 9.80665 m/sec ^{2})

Proof :

Beginning with the definition of acceleration,

acceleration = distance/time^2

substituting distance = rotation speed x time x Lead

a = N x t x Lead/t^2

solving for t,

$$t = N \times Lead/a$$

requiring our answer in seconds,

$$t \propto = \frac{N \times Lead}{60a}$$

checking units:

$$t = \frac{N \times Lead}{60a}$$

$$= \frac{RPM \times m/rev}{sec/min \times m/sec^2}$$

$$= seconds$$

DUTY CYCLE CALCULATIONS

The required torque is dependent on the % duty cycle.

Here: $T_{RMS} = \sqrt{(T_{on})^2 \times \%\ Duty\ Cycle / 100}$

T_{RMS} = Ton $\sqrt{Duty\ Cycle}$

The effective torque can be determined simply when given a known duty cycle where % duty = t_{on} / (t_{on} + t_{off}).

Starting with the definition of the RMS Torque Equation:

$$T_{RMS} = \sqrt{\frac{(T_1)^2 \times t_1 + (T_2)^2 \times t_2}{t_1 + t_2}}$$

Note: We are only concerned with two time periods - that of time on (t_1) and time off (t_2)

$$T_{RMS} = \sqrt{\frac{(T_{on})^2 t_{on} + (T_{off})^2 t_{off}}{t_{on} + t_{off}}}$$

$$T_{RMS} = \sqrt{\frac{(T_{on})^2\ t_{on}}{t_{on} + t_{off}}}$$

Rewriting T_{off} = 0

$$T_{RMS} = \sqrt{\frac{(T_{on})^2 \times \%\ duty}{100}}$$

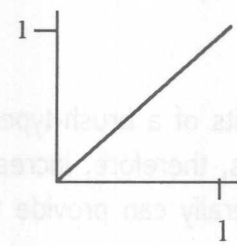
% duty = $\frac{t_{on}}{t_{on} + t_{off}}$ (100)

$$T_{RMS} = T_{on}\sqrt{duty\ cycle}$$

Motion controllers accurately control position, speed and acceleration/deceleration at each point in time during a move. The move profiles generated by the controller define how position changes with time. Three common move profiles are available: Linear Profile, Parabolic Profile and S-Curve Profile.

Choosing the best profile for the job will minimize the motor and amplifier's required peak and continuous ratings.

LINEAR PROFILE



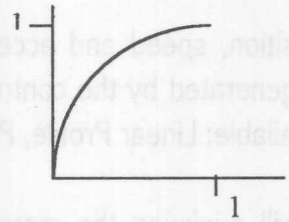
The linear move profile is the simplest mathematically. For this reason, it is the most common move profile used in simple positioners and point-to-point motion. The acceleration is constant during both acceleration and deceleration. This produces a linear velocity versus time plot. It is the basis for the trapezoidal move profile and is effective for all motors, particularly brushless types.

ADVANTAGES
* lowest peak torque
* lowest peak current
* easy application calculations
* effective at high inertial loads

DISADVANTAGE
* peak torque occurs at maximum speed (commutation limits of brush-type motors may limit the usable acceleration torque).

SUMMARY
The linear profile has the same peak torque and top speed as the S-Curve profile although its required peak torque is close to half that of the S-Curve's peak torque.

PARABOLIC PROFILE



The parabolic profile requires the least amount of energy and results in the lowest amount of motor heating. The acceleration is maximum at zero speed then decreases linearly to zero at maximum speed.

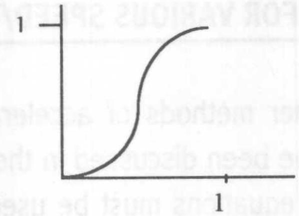
This profile fits well within the commutation limits of a brush-type servomotor and step motor. The highest current draw is required at low speeds, therefore, increasing brush life. Brushless motors benefit from the lower motor heating and generally can provide the highest number of indexes per second with this profile.

ADVANTAGES
* least required peak torque.
* least required maximum speed.
* least required continuous (RMS) torque.
* greatest brush life and energy efficient.

DISADVANTAGE
* high shock loading at the beginning and end of the index.
* slow acceleration particularly with high inertial loads.

SUMMARY
This is the profile of choice when the load ineritia is moderate , the load is directly coupled and structurally rigid. However, the desired cycle time and throughput may not be met.

S-CURVE PROFILE



The S-curve profile incorporates a soft start and finish for each index. The minimum shock load of this profile makes it compatible with real world mechanical systems. The acceleration reaches a maximum at about half speed and is zero at stall and maximum speed.

ADVANTAGES
* lowest shock load to mechanical systems.
* peak torque at half speed fits brush-type commutation limits.
* effective for step motors.

DISADVANTAGES
* highest required peak torque
* highest required RMS torque
* reduced brush life
* requires the largest amplifier

SUMMARY
A larger and more expensive motor and amplifier are required to execute this profile. However, in many mechanical systems, this is the only profile that avoids dynamic system problems (i.e oscillation).

A parabolic profile can be used to achieve smooth response at high velocities. It should also be considered with systems which include:
* mechanical backlash
* high accelerations
* reflected inertia greater than three times the motor inertia
* less structurally rigid loads or compliant loads

and in applications to:
* reduce audible noise, vibration and other dynamic system problems
* reduce settling times
* avoid system resonances
* reduce mechanical stress
* improve motor insulation life by controlling the current rate of rise

ACCELERATION TORQUE FOR VARIOUS SPEED/TORQUE PROFILES *Appendix 3i*

Besides constant torque acceleration, other methods of acceleration are used. Each has specific advantages and disadvantages. These have been discussed in the preceding appendix. If a parabolic or S-curve profile is required independent equations must be used for the torque requirements. The torque requirements can be defined as follows:

Parabolic:

$$T_{max} = \frac{J_T N \pi}{15 t_a} + FT \qquad \text{(Nm or lb ft)}$$

$$T_{EFF} = .5774\ T_{max}$$

Note: N is .75 times the value if constant torque was used; resultant T_{max} is 1.5 times that of constant torque value.

S-curve:

$$T_{max} = \frac{J_T N \pi}{30 t_a} + FT \qquad \text{(Nm or lb ft)}$$

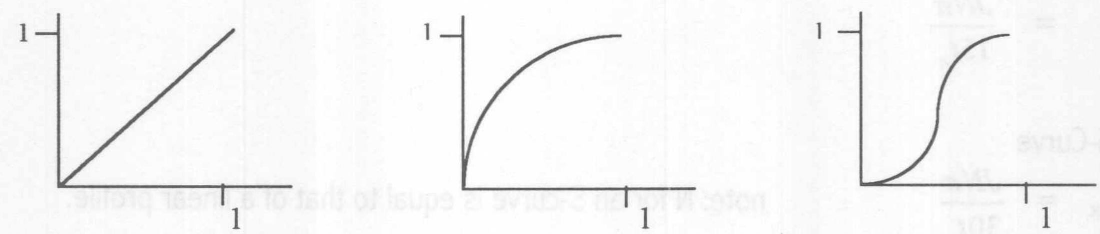
$$T_{EFF} = .5774\ T_{max}$$

Note: N is equal to that of constant torque value; resultant T_{max} is 2 times that of constant torque value.

Note: The max torque during an acceleration differs between the two methods, therefore, the effective value will also differ.

Proof:

Assume maximum velocity value for each profile is equivalent to 1 over a time frame of 1.



LINEAR ***PARABOLIC*** ***S-CURVE***

Assume:

The torque is reminiscent of the slope of these curves.

The slope at any given point (equal to the rate of acceleration) can be determined by taking the derivative of the velocity curve that point. Therefore:

LINEAR	PARABOLIC	S-CURVE
$N = N_{max}t$ $\frac{d\,t}{dt} = 1$ independent of location on curve (constant torque)	$N = N_{max}(1-(1-t)^2)$ $\frac{d\,(1-(1-t)^2)}{dt}$ $\frac{d\,(-t^2+2t)}{dt}$ @t = 0 (point of greatest slope) $-2t + \frac{2}{t} = 0$ $= 2$	$N = N_{max}t^2$, $(0<t<.5)\ (2-2t)^2, (.5<t<1)$ $\frac{d\,t^2}{dt}$ @t = .5 (point of greatest slope) $2t/t = .5$ $= 1$ or $\frac{d\,(1-(2t-2t^2))}{dt}$ @t = .5 $\frac{d\,(1-2t-2t^2)}{dt}$ $-2t + \frac{4}{t} = .5$ $= 1$

This gives us a weighting factor to use with the constant torque acceleration profile, previously proven.

So for parabolic,

$$T_{max} = 2\frac{JN\pi}{30t_a}$$

note: N for a parabolic profile is equal to 3/4 that of linear profile.

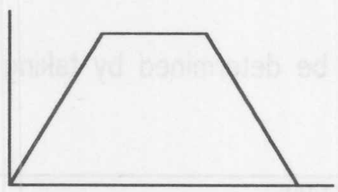
$$= \frac{JN\pi}{15t_a}$$

For an S-Curve

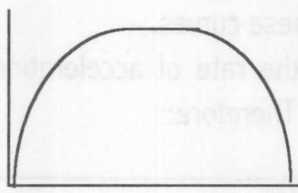
$$T_{max} = \frac{JN\pi}{30t_a}$$

note: N for an S-curve is equal to that of a linear profile.

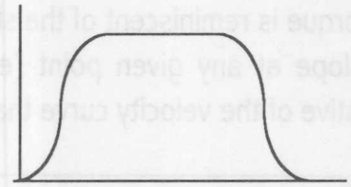
Complete move profiles (acceleration to speed, traverse, and deceleration to zero speed) illustrations are:



Linear



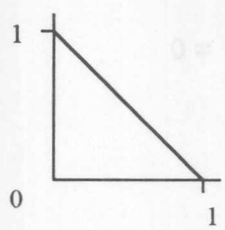
Parabolic



S-Curve

Note: The most efficient operation in terms of motor heating is a parabolic profile, or for practical purposes can be approximated when acceleration time, deceleration time, and traverse time are all equal.

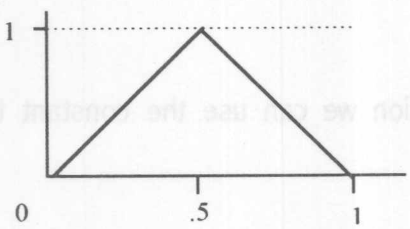
Proof:
Assume unitary values of max torque and time. This will give us a torque profile as follows:



The effective torque is the RMS (root mean square) of this profile. This can be done by taking the square root of the integral of $(1\text{-}t)^2$, the sum of the square of the equation of the line.

$$
\begin{aligned}
T_{RMS} &= T_{max}\,\alpha\sqrt{\int_0^1 (1-t)^2\,dt} \\
&= T_{max}\,\alpha\sqrt{\int_0^1 (1-2t+t^2)\,dt} \\
&= T_{max}\,\alpha\sqrt{(t-2t/2+t^3/3)\Big|_0^1} \\
&= T_{max}\,\alpha\sqrt{1/3} \\
&= .5774\ T_{max}\,\alpha
\end{aligned}
$$

In the same way, if we use a tight linear profile, our answer works out the same.



Assume this profile.

Working as before:

$$
\begin{aligned}
T_{RMS} &= T_{max}\,\alpha\sqrt{\int_0^{.5} (2t)^2\,dt + \int_{.5}^1 (2-2t)^2\,dt} \\
&= T_{max}\,\alpha\sqrt{\int_0^{.5} 4t^2\,dt \;+\; \int_{.5}^1 (4-8t+4t^2)\,dt} \\
&= T_{max}\,\alpha\sqrt{4t^3/3\Big|_0^{.5} + (4t-4t^2+4t^3/3)\Big|_{.5}^1} \\
&= T_{max}\,\alpha\sqrt{1/6+(4-4+4/3)-(2-1+1/6} \\
&= T_{max}\,\alpha\sqrt{1/3} \\
&= .5774\ T_{max}
\end{aligned}
$$

HORSEPOWER ACCELERATION

Typically, horsepower acceleration is used when trying to accelerate up to speed in the shortest possible time. By following the HP curve up to final speed we are using the maximum allowable torque the motor has available. Therefore the input signal used is a step input; resulting in the drive responding to the peak of its capabilities.

To calculate the time to accelerate we break the acceleration profile into two segments. That of constant torque up to the point of intersection of the constant HP curve, and then to follow that curve up to final speed. We can then calculate the time required for each step and then determine the sum for the total time for acceleration.

To determine the time required for constant torque acceleration we can use the constant torque formula and solve for time.

$$t_1 = \frac{J_T N_1 \pi}{30\,(T - FT)} \qquad \text{(seconds)}$$

where N_1 is the speed at where the constant torque intersects the constant HP curve.

The following equation can be used to determine the time to accelerate under constant HP conditions:

$$t_2 = \frac{J_T}{FT}\left[\frac{(N_1 - N_2)\pi}{30} + \frac{550HP}{FT}\; 1n\left[\frac{(5252HP/FT) - N_1}{(5252HP/FT) - N_{21}}\right]\right]$$

where N_1 is the same as described previously

N_2 is final motor speed

$t_{total} = t_1 + t_2$

AMPLIFIER SIZING *Appendix 3k*

Many performance curves show the matched amplifier. If a system performance curve is not available and the motor and drive is from different vendors, we can calculate the amplifier continuous current requirements according to the following formula:

Cont. Current = T_{load} / K_T
where T_{load} = load torque (Nm) or (lb ft)
K_T = motor torque sensitivity (Nm/Amp) or (lb ft/Amp)

Example: We have just chosen a servo motor. Our load requirement is 50 Nm (36.87 lb ft) @ 1350 RPM continuous. What is our continuous current requirement? Assume K_T = 2.39Nm/Amp or 1.763 Lb ft/Amp.

Answer:

I_c = 50 Nm / 2.39
= 20.9 Amps

or

I_c = 36.87 lb ft / 1.763
= 20.9 Amps

With this, we can now know an amplifier must at least be able to provide 20.9 amps of continuous current.

Assume we have an intermittent load (<1sec) requirement of 160 Nm (118 lb ft) @ 250 RPM. What peak amplifier rating would be required?

Solution:

I_c = 160 Nm/2.39

= 66.94 Amps For peak current requirement

The voltage required to power a system can be determined using the following equation for servo motors:

Brush Motors

$$V = I R_M Hot + \frac{N}{1000} K_B + BD$$

Brushless Motors

$$V = I\sqrt{3}\, R_M Hot + \frac{N}{1000} K_B$$

Where V = Volts (line to line for brushless)
I = Amps (brush type)
Amps/0 (brushless)
N = RPM
K_B = Back EMF (V/KRPM)
BD = Brush drop (V), usually 2V (brush type)

Many servo amplifiers perform as power converters. Therefore, when amplifier sizing is required, the power and not necessarily the current is the deciding factor. We can use an approximation of the output power versus input power of 750 watts to 1 Kwatt for AC Synchronous and DC motors and 600 watts to 1 Kwatt for AC Induction motors. This assumes a worst case efficiency of 75% & 60% respectively for these type motors/drives. These numbers can then be compared with the power ratings of available supplies and transformers to determine required sizing. Power supply and transformer power in watts can be determined by the following equation.

$$W = \text{Volts}_{L\text{-}L} \times (\text{Secondary Line Current}) \sqrt{X}$$

Where X = 1 for DC systems, and X = 3 for AC systems

If multiple motor-drive systems are to be powered off of a single supply and transformer, the individual drive requirements can be summed.

Example: We wish to power three servo motors at full rated power (4.1 Kwatts). What transformer and power supply requirements are needed? Assume $\text{Volts}_{L\text{-}L} = 208$.

Answer: 3(4100 watts)/.75 = 16.4 Kwatts

using $W = 208V_{L\text{-}L} \times I_{req}\sqrt{3}$, and solving for I

$$I_{req} = \frac{Watts}{208\sqrt{3}}$$

$$= \frac{16.4K}{208\sqrt{3}}$$

$$= 45.5 \text{ Amps}$$

Brush type motor drives operate in much the same way as brushless motor drives do. Here we must approximate power required per motor/drive by multiplying the RMS motor voltage by the RMS motor current. The total power requirement for multiple drives is the sum of the individual drive requirements. The same method is then valid as that used with the brushless type motor.

REGENERATIVE ENERGY *Appendix 3m*

Regenerative energy (Back EMG discharge) is transferred from the motor load through the amplifier to the power supply during deceleration. If this energy is not managed, it will boost the BUS voltage which may damage the driver.

Since the electrical energy stored within the motor is small, it usually can be neglected. However, the driver must be able to handle the motor and load mechanical energy:

($E=1/2J\,\omega^2$) less the energy dissipated by the cable and motor ($E_R = I^2Rt$).

$$E = \tfrac{1}{2} J\omega^2 \left(4.2 \times 10^{-5}\right) - I^2 Rt$$

where,

t	=	$\dfrac{J\omega}{K_T I}\left[\dfrac{2\pi}{60}\right]$	(seconds)
E	=	Amplifier regenerative energy capacity	(Joules)
J	=	Inertia of motor plus load	(oz-in-sec^2)
ω	=	Velocity	(RPM)
I	=	Current limit setting of driver	(Amps)
R	=	Resistance of cable and motor	(ohms)
t	=	Deceleration time	(sec)
K_T	=	Motor torque constant	(oz-in/Amp)

The energy handling capacity of the driver power supply must be at least the value calculated. Also, give consideration to simultaneous deceleration in multi-axis systems.

SIZING A GEARHEAD

Determining the proper gearhead is based on a number of factors including: desired torque and speed, duty cycle and type of move profile. The following steps should be taken.

1) Calculate the application torque ${}^{\tau}A$.
2) Calculate the application service factor SF.
3) Calculate the equivalent torque ${}^{\tau}E = {}^{\tau}A \times SF$
4) Base gearhead selection on a comparison of the equivalent torque and gearhead rated torque.

Service Factors

Hours/Day - Number of hours per day the machine is operating.
Motion Profile - Type of move being performed.
Maximum RPM - The highest motor speed.

Calculating Service Factor
${}^{\tau}A$ = Application Torque
SF = Service Factor
${}^{\tau}E$ = Equivalent Torque

$${}^{\tau}A \times SF = {}^{\tau}E$$

$$SF = A + B + C$$

HOURS/DAY	A
1-8	.3
8-16	.4
16-24	.5

MOTION PROFILE	B
Triangular	.8
Trapezoidal	.5
Continuous	.3

MAXIMUM RPM	C
0-3000	.4
3000-4000	.6
4000-4500	.8

IEC ENCLOSURE STANDARDS

The degree of motor protection is indicated by a symbol consisting of the two code letters IP, (International Protection) and two reference numbers indicating the degree of protection.

Example

IP 4 4

Code letters — IP

First reference number (see Table) — 4

Second reference number (see Table) — 4

An enclosure with this designation is protected against the penetration of solid objects of more than 1mm diameter and against splashed water.

First Number	Second Number
0 = no special protection.	0 = no special protection
1 = protected against solid objects greater than 50mm.	1 = protected against dripping water
2 = protected against solid objects greater than 12mm.	2 = protected from water falling at an angle up to 15 °.
3 = protected against solid objects greater than 2.5mm.	3 = protected from water falling at an angle of up to 60°.
4 = protected against solid objects greater than 1 mm.	4 = protected from splashed water from any direction.
5 = protected against harmful dust deposits, complete protection against contact.	5 = protected from water projected from a nozzle.
	6 = protected from heavy seas.
6 = dust-tight and complete protection against contact.	7 = protected from the effects of immersion.
	8 = protected from the effects of submersion.

Note:

This standard does not specify a degree of protection of electrical against mechanical damage, against the risk of explosion or against conditions such as moisture (produced for example by condensation, corrosive vapors, fungus or vermin).

HAZARDOUS SUBSTANCE RATINGS

The NFPA (National Fluid Power Association) has devloped a coding system for describing hazardous environments which consist of a Class and a Division.

Class:

I. Area where ignitable concentrations of flammable gases or liquid vapors are present.

II. Area where ignitable concentrations of combustible dusts are present.

Division:

1. Hazardous substances are present during normal operation.

2. Hazardous substances are present only during abnormal conditions.

Breakdown of Classes

Class I Groups

Group:

A. Acetylene
B. Hydrogen
C. Ethylene
D. Methane

Class II Groups

Group:

E. Conductive (metal) Dust
F. Carbonaceous (carbon or coal) Dust
G. Agricultural (flour or grain) Dust

NEMA ENCLOSURE RATINGS AND THEIR DEFINITIONS

The National Electrical Manufacturers Association (NEMA) has compiled a series of standards and test procedures for common type enclosures used by the electrical industry. An enclosure is a surrounding case constructed to provide a degree of protection to personnel against incidental contact with the enclosed equipment and to provide protection to the enclosed equipment against specific environmental conditions.

ENCLOSURES

Type 4

Type 4 enclosures are intended for indoor or outdoor use, preimarily to provide a degree of protection against windblown dust and rain, splashing water, and hose directed water. They meet hosedown, dust, external icing, and rust resistance design tests.

Type 4X

4X enclosures meet the same criteria as Type 4 except they are subjected to an extended (200 hour) corrosive test.

Type 12

Type 12 enclosures are intended for indoor use primarily to provide for a degree of protection against dust, falling dirt, and dripping non-corrosive liquids. They meet drip, dust and rust resistance tests.

Type 13

Type 13 enclosures are intended for indoor use, primarily to provide for a degree of protection against dust, spraying water, oil and non-corrosive coolants. They meet oil exclusion and rust-resitance design tests.

Typical Ratings Include:

NEMA:-

- **1:** General Purpose Indoor Use
- **2:** General Purpose Indoor Use with drip proof rating
- **3R:** General Purpose Outdoor Use Dust Tight, Rain Tight, Ice Resistant
- **4:** General Purpose Indoor/Outdoor Use, Water and Dust Tight.
- **4X:** General Purpose Indoor/Outdoor Use, Water and Dust Tight Corrosion Resistant
- **9:** Special Purpose Indoor, Hazardous Locations
- **12:** Industrial Indoor Use, Dust and Drip Tight
- **13:** Industrial Indoor Use, Oil and Dust Tight

	NEMA STANDARD ENCLOSURE									
ENVIRONMENTAL CONDITION	**1**	**2**	**3**	**3R**	**4**	**4X**	**5**	**11**	**12**	**13**
Incidental contact with enclosed equipment:	X	X	X	X	X	X	X	X	X	X
Outdoor use:			X	X	X	X				
Falling dirt:	X	X			X	X	X	X	X	X
Falling liquids and light splashing:		X			X	X	X	X	X	X
Dust, lint, fiber and flyings:					X	X	X		X	X
Hosedown and splashing water:					X	X				
Oil and coolant seepage:									X	X
Oil and coolant spraying and splashing:										X
Corrosive agents:						X				
Rain, snow and sleet:			X	X	X	X				
Windblown dust:			X		X	X				
Hosedown:					X	X				

Technical Reference Unit Conversions

Torque Conversions

Present Units	Convert To	Multiply By
Gram-centimeters	newton-meters	0.0000981
Gram-centimeters	ounce-inches	0.0138874
Gram-centimeters	pound-inches	0.000868
Gram-centimeters	pound-feet	0.0000723
Newton-meters	gram-centimeters	10,197.162
Newton-meters	ounce-inches	141.612
Newton-meters	pound-inches	8.85
Newton-meters	pound-feet	0.73756
Ounce-inches	gram-centimeters	72.0077
Ounce-inches	newton-meters	0.007062
Ounce-inches	pound-inches	0.0625
Ounce-inches	pound-feet	0.005208
Pound-inches	gram-centimeters	1,152.0
Pound-inches	newton-meters	0.11299
Pound-inches	ounce-inches	16.00
Pound-inches	pound-feet	0.08333
Pound-feet	gram-centimeters	13,825.5
Pound-feet	newton-meters	1.3558
Pound-feet	ounce-inches	192.0
Pound-feet	pound-inches	12.0

Distance Conversions

Present Units	Convert To	Multiply By
Arc-minutes	degrees	0.016666
Arc-seconds	degrees	0.000277
Centimeters	inches	0.3937
Centimeters	feet	0.03280
Centimeters	microns	10,000.0
Centimeters	millimeters	10.0
Degrees	arc-minutes	60.0
Degrees	arc-seconds	3,600.0
Degrees	radians	0.017453
Feet	centimeters	30.48
Feet	meters	0.3048
Inches	centimeters	2.54
Inches	meters	0.0254
Inches	microns	25,400.0
Inches	millimeters	25.4
Meters	feet	3.2808
Meters	inches	39.37
Meters	microns	1,000,000.0
Microns	centimeters	0.0001
Microns	meters	0.000001
Microns	inches	0.00003937
Microns	millimeters	0.001
Millimeters	centimeters	0.1
Millimeters	inches	0.03937
Millimeters	microns	1,000.0
Radians	degrees	57.295779

Reference: Handbook of Tables for Applied Engineering Science

Inertia Conversions

Present Units	Convert To	Multiply By
Gram-centimeters^2	ounce-inches^2	0.00546745
Gram-centimeters^2	ounce-inch-sec^2	0.000014161
Gram-centimeters^2	pound-inches^2	0.000341716
Gram-centimeters^2	pound-inch-sec^2	0.000000885
Gram-centimeters^2	pound-feet-sec^2	0.000000074
Ounce-inches^2	gram-centimeters^2	182.901
Ounce-inches^2	ounce-inch-sec^2	0.00259008
Ounce-inches^2	pound-inches^2	0.0625
Ounce-inches^2	pound-inch-sec^2	0.00016188
Ounce-inches^2	pound-feet-sec^2	0.00001349
Ounce-inch-sec^2	gram-centimeters^2	70,615.4
Ounce-inch-sec^2	ounce-inches^2	386.0
Ounce-inch-sec^2	pound-inches^2	24.13045
Ounce-inch-sec^2	pound-inch-sec^2	0.0625
Ounce-inch-sec^2	pound-feet-sec^2	0.00520833
Pound-inches^2	gram-centimeters^2	2,926.41
Pound-inches^2	ounce-inches^2	16.0
Pound-inches^2	ounce-inch-sec^2	0.0414413
Pound-inches^2	pound-inch-sec^2	0.00259008
Pound-inches^2	pound-feet-sec^2	0.00021584
Pound-inch-sec^2	gram-centimeters^2	1,129,850.0
Pound-inch-sec^2	ounce-inches^2	6,177.4
Pound-inch-sec^2	ounce-inch-sec^2	16.0
Pound-inch-sec^2	pound-inches^2	386.0
Pound-inch-sec^2	pound-feet-sec^2	0.0833333
Pound-feet-sec^2	gram-centimeters^2	13,558,200.0
Pound-feet-sec^2	ounce-inches^2	74,128.9
Pound-feet-sec^2	ounce-inch-sec^2	192.0
Pound-feet-sec^2	pound-inches^2	4,633.06
Pound-feet-sec^2	pound-inch-sec^2	12.0

Load Conversions

Present Units	Convert To	Multiply By
Grams	newtons	0.009806
Grams	ounces	0.03528
Grams	pounds	0.002204
Kilograms	pounds	2.2046
Newtons	grams	101.971
Newtons	ounces	3.59692
Newtons	pounds	0.224808
Ounces	grams	28.3495
Ounces	newtons	0.27802
Ounces	pounds	0.0625
Pounds	grams	453.592
Pounds	kilograms	0.45359
Pounds	newtons	4.44824
Pounds	ounces	16.0
Pounds	tons	0.0005
Tons	pounds	2,000.0

GLOSSARY

Absolute Position - An encoder which can maintain a given mechanical location by providing a unique binary identification for each position.

Acceleration/Deceleration - Changes in speed (velocity) as a function of designated time.

Accuracy - The difference between the target travel distance and the actual travel distance in linear motion. Dependent on the flatness & straightness of travel plus lead error of lead screw.

Ambient Temperature - The temperature of the cooling medium, typically air, surrounding a motor.

ASCII - American Standard Code for Information Interchange. A means of transmitting program code into binary data.

Axial Motion - The movement transmitted in the direction of the center of the shaft. Important measure for choosing couplings, ball screws etc.

Backdriving - An applied force, often gravity, causing a lead screw or nut to rotate back through the driving device.

Backlash - Lost motion arising from the axial play between a ball nut and screw during forward and reverse motion. Results in loss of repeatability.

Bandwidth - The frequency range that a controller and amplifier follows. Determines system responsiveness.

Baud - A unit of signalling speed equal to the number of code elements per second.

BCD - Binary Coded Decimal is an encoding technique used to transmit data between encoders and controls or counters.

Bilevel Drive - A step motor drive where two voltage levels are used to drive a motor. First high level voltage is applied to windings to quickly generate current. Drive then switches to lower voltage to maintain current in windings.

Breakaway Torque - The torque required to start positioning table motion assuming zero load weight. Affected by bearing drag and friction and lead screw assembly preload.

Bus - The power supply voltage available from a power supply. Also, a host computer architecture.

Chopper Drive - Type of step motor driver where an initial high voltage is applied to the winding until the current reaches a desired level. The voltage then switches off, the current drops off and the process repeats.

Cogging A term describing non-uniform angular velocity. It appears as jerkiness at low speeds (below 50 RPM) in motors.

Compensation - The adjustment of gain and frequency parameters in a servo system to achieve the desired dynamic response and stability.

Compression Load - The load applied to a lead screw that compresses the screw itself. Also referred to as column load.

Commutation - The action of applying current or voltage to motor phases to generate motor torque. Could be achieved via brushes or electronics.

Concentricity - A measure of rotational precision on a rotary table. The maximum deviation in inches between a true circle and the actual path.

Coordinated Motion - Motion controller profile that synchronizes the movement of two or more axes to create arcs, interpolation etc.

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.

Critical Speed - Maximum rotational speed of a lead screw or nut before resonant vibration occurs in the ball screw assembly.

Daisy-Chain - Connecting a number of RS 232 communicating devices in sequence so that a single data stream flows from one unit to another.

Damping Ratio - Key condition in servo system tuning comparing actual to critical damping. A 1:1 ratio is ideal; less than one results in an underdamped system; greater than one is an overdamped system.

Dead Band - A range of command inputs where there is no system response. Mechanical and electronic dead bands are possible.

Detent Torque - Maximum torque that can be applied to the shaft of a step motor without causing continuous rotation. Typically 1% of stall torque.

Duty Cycle - A ratio of "on" versus "off" time used to determine system requirements. Affects product life and reliability.

Eccentricity - Encoder error conditions affecting accuracy including amplifier and frequency modulation and inter-channel jitter. Caused by incorrect mounting, bearing play and shaft run out.

Efficiency - The ratio of power input to power output. Important in applications having space and heating constraints.

EMI - Electromagnetic interference. Potentially harmful noise generated by the operation of mechanical components and systems.

Flatness - An important measure of position accuracy in positioning stages. The deviation above or below a straight line when travelling in a straight line plane of travel. Specified as inch per inch rating.

Four Quadrant Drive - A drive which powers a motor in four quadrants: current and voltage in either direction.

Gain - A important parameter in servo system tuning. Measures ratio of system output to a command signal.

Hall Effect Sensors - A device that provides for commutation in a brushless motor system. Utilizes a magnetized wheel and hall effect sensors to generate the commutation signal.

Host - An auxillary computer that is connected to a controller. Often used in controlling off-line tasks i.e. program storage, editing, system evaluation.

Hysterisis - The difference in system response to an increased or decreased input signal. Typically describes lost motion or time lag between mechanical components.

Inductance - The property that exists between two current-carrying conductors or coils when magnetic lines of force form one link with those of the other.

Inertia - A property of an object to resist changes in velocity unless acted upon by an external force. Higher inertial forces require higher torque to accelerate of decelerate. Inertia is dependent on object's mass and shape.

Inertial Mismatch - When the inertia of the system is not equal to the motor's reflected load inertia. System is optimized when the load's inertia is equal to the rotor inertia of the motor.

Instability - Undesirable motion of a load that is different from the command motion. Typically includes irregular speed, oscillation, jerkiness or hunting of the final rest position.

Lead - Linear distance traveled by nut in one revolution of screw.

Lead Error - An important measure of positional error of a lead screw and nut assembly. The deviation between the desired and actual travel distance. Typically specified in terms of inch per inch and used in linear positioning applications.

Linearity - In a speed control system, it is the maximum deviation between the actual and set speed expressed as a percentage of set speed.

Line Driver - Low output impedance devices (usually encoders) used for driving signals over a long distance at high frequencies.

Logic Ground - An electrical potential to which all signals in a particular system are referenced.

Master/Slave Control - An advanced motion profile where a master axis position is used to synchronize one or more slave axis positions or velocities.

Mechanical Time Constant - The time for an energized motor to reach 63.2% of its set velocity after the application of a fixed voltage.

Mid-Range Instability - A condition in step motors where the motor falls out of synchronisation due to torque loss and oscillation at mid-range speeds. Often occurs in underdamped open loop systems.

Moment Load - Loads offset at a distance and angle from the center of gravity of a positioning table or ball screw. Also known as side load.

MTBF - Mean Time Between Failure. A measure of product reliability and life.

NEMA - National Electrical Manufacturer's Association that sets industry standards for motor and electrical products.

No-load Speed - Motor speed with no external load attached.

Non-Volatile Memory - A controller's memory system in which stored data and programs are retained when power is removed.

Open Collector - Describes a signal output that acts like a switch closure with one end of the switch at ground potential and the other end of the switch accessible.

Opto-isolated - A means of transmitting signals between equipment without the use of common grounds. Used to protect low voltage control logic from electrically noisy machines.

Orthogonality - The deviation from 90 degrees of a second axis when placed perpendicular to an existing linear axis. Common positioning table rating. Specified as a degree deviation of inch per inch deviation.

Oscillation - A vibration, jerkiness or ringing typical of an unstable condition in motion systems.

Overshoot - The amount that the parameter being controlled exceeds the desired value for a step input.

Parallel - A data communication format where many signals are used to communicate more than one piece of data at one time.

PID - Proportional, Integral, Derivative. Describes the compensation structure that is used in a closed loop servo system.

Pitch - The number of lead screw revolutions that will produce one inch of travel.

PLC - Programmable Logic Controller. Machines that control and sequence I/O i.e switches, relays, from a stored program (usually ladder logic).

Point-to-Point Motion - Common single or mulit-axis motion profile where each axis is controlled independently.

PPR - Pulses Per Revolution. A term used to describe the resolution of encoders over a 360 degree rotation. Also known as line count or counts per revolution.

Preload - The use of one group of ball grooves in oposition to another to increase stiffness and eliminate backlash in a ball screw asembly.

Pulse Rate - The frequency of pulses applied to a step motor driver. The pulse rate multiplied by resolution of the motor/drive combination yields the motor velocity.

PWM - Pulse Width Modulation. Describes an efficient switch-mode technique used by amplifiers to control current and voltage output.

Radial Play - The shaft displacement perpendicular to the shaft due to a side force applied to the shaft axis.

Ramping - The acceleration and deceleration rate of a motor. Also refers to the change in frequency of the applied step pulse train.

Rated Torque - The maximum continuous torque generated by a motor at a specific speed, usually derived from a torque versus speed curve.

Regeneration - During motor braking or free-wheel shutdown, the motor acts as a generator and drains kinetic energy from the load generating excessive power dissipation.

Registration Move - Controller function that changes a predefined move profile which is being executed to a different predefined move profile following receipt of an input or interrupt.

Repeatability - The ability of a system to consistently return to a known, previously travelled location. Important parameter in high precision applications, dependent on feedback devices, bearings, drive screws accuracy.

Resolution - The smallest positioning increment that can be achieved. Dependent on the type of electronic and mechanical components employed.

Resonance - Common problem with step motors whereby vibration occurs through the interaction of current pulses moving the motor and load. Results in loss of torque and accuracy plus mid-range instability.

Resonating Frequency - Length of time it takes for a shaft or coupling to stop its continuous reversing motion after a system has come to a stop.

RFI - Radio Frequency Interference. Harmful electrical noise generated by electronic products and systems.

Ringing Oscillation of a system following a sudden change in state. Usually generated by over-damped high frequency amplifier command signals.

Ripple - A variation or small change in an output signal leading to overshoot and positional errors.

RMS Torque - Similar to continuous torque ratings, it is the steady state torque which would produce consistent motor heating under continuous duty without premature motor breakdown.

RS-232 - A popular serial communications standard (less than 50 ft in length) that encodes a string of data on a single communication line in a sequential format.

RS-422/485 - Serial data communications standard similar to RS-232 but providing improved noise immunity and longer communications distances (up to 4000 ft). Also allows several devices to be placed on a single serial link in a multi-drop configuration.

Run Out - The maximum distance (in inches) any point on a rotary table will deviate above or below a perfectly flat plane, perpindicular to the axis of motion. Also known as wobble.

Service Factor - Derating of a mechanical system due to adverse operating conditions such as shock load or rapid start and stops.

Settling Time - The time required for a response of a system parameter to stop oscillating or ringing and reach its final value.

Shunt Regulator - A device located in a servo amplifier for controlling regenerative energy when motor braking occurs. The energy is dissipated as heat.

Slew - The portion of a move made at a constant non-zero velocity.

Spring Rate - A measure of stiffness equal to load per unit of deflection.

Stall or Static Torque - The maximum torque developed at zero speed.

Step Accuracy The worst case per step deviation from the theoretical position for any step taken as an unloaded motor is rotated through 360 degrees. Recorded as a percent, degree or minutes of arc.

Step Angle - The nominal angle through which the shaft of a step motor turns between adjacent step positions.

Stiffness - The ratio of applied force or torque to change in position for a mechanical system. Also known as the ability to resist movement induced by an applied torque.

Tension Load - Also known as pulling load, it is the load that stretches a lead screw.

Torque Constant - A variable denoting the relationship between motor input current and motor output torque. Typically expressed in terms of torque per amp.

Torque Ripple - The cyclical variation in generated torque as a product of motor angular velocity and commutator/magnetic poles.

TTL - Transistor-transitor logic. Common digital logic device found in encoders and controls characterized by two distinct states: low (<0.8 V) and high (2.5 to 5 V).

Unipolar Drive - Type of step motor drive. During excitation, torque generating current in each winding occurs in only one direction. The polarity of voltage to each winding is always the same.

Viscous Damping - A damping that provides a retarding torque during motion. The higher the velocity, the higher the torque. At zero velocity there is no retarding torque.

Voltage - A variable representing the relationship between Back EMF voltage and angular velocity. Typically expressed as volts per thousand rpm. Also known as the Back EMF constant.

Wind-up - An effect whereby a torque applied to the input end of a coupling or lead screw rotates it farther than the output end. A measure of lost motion common in high speed/torque applications. Also known as spring rate, torsional deflection and angular twist.

NOTES