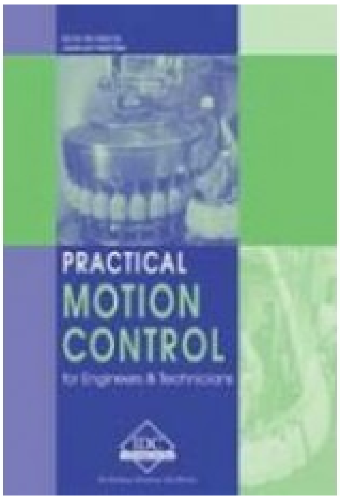
MC-E - Motion Control



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Short Description

This manual initially examines the basic building blocks and design tools to implement motion control systems. Fundamental concepts of load, inertia, force and real time are discussed. The various factors such as performance limitations and costs that impact the selection of electro hydraulic, pneumatic, electromechanical technologies are discussed. Servo basics are then examined in considerable detail giving you the practical tools in which to work with these systems.

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The electrical and mechanical characteristics important in tying together the drive and motor to the mechanical device are then reviewed. The basic motors used in motion control such as dc and ac motors, stepper and servo motors and their applications, are also examined. These motors range from small instrumentation motors to robust ac induction motors and to the stepper motors used in open loop control.

Table of Contents
Download Chapter List

Table of Contents

First Chapter
Chapter 1: Fundamentals of Motion Control

1

Fundamentals of motion control

1.1 Introduction

Motion control is the term used to describe a variety of techniques for orchestrating the movement of machinery and objects. Most often accomplished via electric motors and valves under computer control, it has rapidly become the mainstay of modern manufacturing. Robotics, CNC, and industrial automation are all examples of motion control.

Motion control is a process of computer-controlled kinetics, i.e. the foundation of robotics. **Computer numeric control** (CNC), is an antiquated term for this process, recalling an era when programmers entered the numeric commands and coordinates, for each machine movement. The ability to precisely control the path of a tool enables fabrication of objects that would not be possible or practical by hand held methods.

Example 1.1: Let us take an example of linear motion control in two dimensions—a pen plotter. The motion of a pen is broken up into two axes—X and Y, and controlled with the help of motors.

The above is an example of linear motion control in two dimensions, but the process can be expanded to three dimensions and generalized to other coordinate systems-- cylindrical, spherical, etc. The pen path information is stored as a list of consecutive x, y coordinates, and the pen up/down information, for the pen plotter. Such a format is the structure of all ‘plot-files,’ and readily available by drawing programs such as Adobe illustrator, CAD/CAM programs, CorelDraw, etc.

Over the period, motion control has evolved from total control of mechanical devices by mechanical means to mostly electrical and electronic means of control. More and more motion control systems are based on microprocessors and microcomputers. Motion control does not only involve controlling the movements of mechanical systems, but also coordinating the movements around the objects that might be fixed in their locations. Motion control involves much more than just turning the motor on or off in today’s world of high automation. Motion does not always involve an electrical motor; pneumatic, hydraulics and mechanical systems also play an important role.

For motion control, we need a motion controller that can be programmed or configured by simple means to control the desired motion. It is important to have a feedback unit, which gives the feedback about the motion and the environment. Another important device required for a motion control system is the motion actuator. During the design of a motion control system, a suitable motion actuator is selected in order to act as a final element for motion control. A motion actuator can be an electric motor, hydraulic/pneumatic control valve, etc.

1.2 Definition of motion control

The term motion is defined as an act, process, or an instance of changing position. Control is defined as the power or authority to guide or manage, coordinate or direct.

In motion control, we monitor a desired motion or movement and direct the motion based on a logical pattern, in order to achieve the desired result. A motion controller, whether a hardware or software control algorithm, helps us in coordinating, guiding, and managing the motion.

A block diagram of a typical motion control system is shown in Figure 1.1. The motion controller gets a motion set point or a reference position command from an operator or a host computer. The motion controller also gets the position feedback from the position sensor, and compares it with the desired position. The difference between the desired position and the actual feedback position is an error. Based on the error, the controller output is adjusted so that the error is minimized.

Figure 1.1

Block diagram of a typical motion control system

1.3 Fundamental concepts

As we will discuss motion control system in detail, it is important to go through the fundamental concepts of motion.

1.3.1 Motion

A body is said to be at rest, if it occupies the same position with respect to its surroundings, at all times. But, when a body changes its position with respect to its surroundings, it is said to be in motion.

For motion control, it is important to understand the motion we want to control. Dynamics is the part of mechanics that deals with the analysis of bodies in motion. The study of dynamics is divided in two branches known as **Kinematics and Kinetics**.

Kinematics is the study of relationships between displacement, velocity, acceleration, and time, of a given motion without considering the forces that cause the motion.

Kinetics is the study of relationships between the forces acting on a body, the mass and, the motion of the body. Kinetics can be used to predict the motion caused by the given forces or to determine the forces required, to produce a prescribed motion.

Since dynamics is based on the natural laws governing the motion of a particle, the concept of a particle is a convenient idealization, of a physical object that need not be small, in size. The mass of a body is assumed concentrated at a point and the motion of the body is considered as the motion of an entire unit neglecting any rotation about its own center of gravity. If rotation of a body about its center of gravity is not negligible, then the body cannot be considered as a particle.

1.3.2 Types of motion

When a particle moves in space, it describes a trajectory called a Path. The path can be straight or curved.

Rectilinear motion

When a particle moves along a path, in a straight line it is called Rectilinear motion.

Displacement

A particle in rectilinear motion, at any instant of time will occupy a certain position (P) on the straight line. Say, the particle was originally at point (O), the distance (x) of the particle at any point of time (t), is called the Displacement of the particle at that time. Displacement of a particle in rectilinear motion is represented on a straight line as shown in Figure 1.2 (a). The displacement is assumed positive in the rightward direction from the original position (O), and negative in the leftward direction.

Displacement-time diagram (x-t curve)

When the position of the particle is plotted as a function of time, we get the Displacement-time diagram as shown in Figure 1.3 (a). The slope of the x-t curve at any instant represents the velocity of the particle at that instant. In Figure 1.3 (a), the particle at different point of time t_1, t_2, t_3 has positive, zero, and negative velocity respectively.

Distance traveled

The distance traveled by a particle is different from its displacement from the origin. For example, in Figure 1.2 (a), if a particle moves from origin (O) to position P_1, and then to position P_2, its position is $-x_2$ from the origin, but the distance traveled by the particle is $2x_1 + x_2$.

Figure 1.2

Displacement and velocity of a particle

Figure 1.3

Graphical representation of displacement, velocity, and acceleration

Average velocity

Let the particle, at any point of time (t) occupy the position (P) at a distance (x) from the origin (O). At time (t + Dt), it occupies the position (P') at a distance (x + Dx) from the origin (O) as shown in Figure 1.2 (b).

The average velocity of the particle over the time interval Dt is given as:

$$v_{avg} = \frac{Dx}{Dt} \qquad \ldots 1.1$$

Instantaneous velocity

It is the velocity of a particle at a particular instant of time. It can be obtained from average velocity by choosing the time interval (Dt), and displacement (Dx) very small. The instantaneous velocity is defined as:

$$v = \text{limit} \ \frac{Dx}{} = \frac{dx}{} \qquad \ldots 1.2$$

$Dt \to 0 \quad Dt \quad dt$

The velocity-time diagram is obtained by plotting the velocity of the particle as a function of time as shown in Figure 1.3 (b).

Average acceleration

Let v be the velocity of the particle at any point of time (t). If at a later time (t + Dt), the velocity of the particle becomes (v + Dv), then the average acceleration of the particle is defined as:

$$a_{avg} = \frac{Dv}{Dt} \qquad \ldots 1.3$$

Instantaneous acceleration

It is the acceleration of a particle at a particular instant of time. It can be obtained by choosing the time interval (Dt), and velocity (Dv) very small. Instantaneous acceleration is defined as:

$$a = \lim_{Dt \to 0} \frac{Dv}{Dt} = \frac{dv}{dt} = v\frac{dv}{dx} \qquad \ldots 1.4$$

An acceleration-time diagram is obtained by plotting the acceleration as a function of time as shown in Figure 1.3 (c).

Uniform motion

A particle is said to have a uniform motion when its acceleration is zero, and its velocity is constant.

Uniformly accelerated motion

A particle moving with a constant acceleration is said to be in a uniformly accelerated motion.

Curvilinear motion

When a particle moves along a curved path, it is called Curvilinear motion. If the curved path lies in a plane, it is called Plane curvilinear motion. When the direction of the force acting on a particle varies, or when the particle has some initial motion in the direction that does not coincide with the direction of the force acting on the particle, the particle moves in a curved path.

The curvilinear motion of a particle is expressed in terms of rectangular components, in terms of components directed along the tangent, and the normal to the path of the particle.

1.3.3 Plane motion of rigid bodies

In the plane motion of a rigid body, all the particles of the body move in parallel planes. The motion of any one such parallel plane can represent the motion of a body.

Various types of plane motion of bodies are classified as:

Translation

A rigid body is said to have a translatory motion if an imaginary straight line drawn on the body remains parallel to its original position during the motion. As shown in Figure 1.4, all the particles of the body move along the parallel path in a translatory motion. If these paths are straight lines, the motion is said to be a rectilinear translation, and if these paths are curved, the motion is said to be curvilinear translation.

Figure 1.4

Translatory motion of a rigid body

Rotation

In a rotary motion, all the particles of a rigid body move in concentric circular paths. The common center of circles may be located in the body or outside as shown in Figure 1.5.

Figure 1.5

Concentric circular path in rotation of a rigid body

Let us consider a rigid body that rotates about a fixed axis, perpendicular to the plane of the slab, and intersecting it at point O. Let P be another point on the rigid body as shown in Figure 1.6. The position of the rigid body is defined by the angle (q), known as the Angular coordinate of the body.

The angular velocity (w), of the rigid body is given by:

$$w = \frac{dq}{dt} \qquad \text{…1.5}$$

The angular velocity is measured in radians/second. At times it is also measured in revolutions per minute (r.p.m) as follows:

$$w = \frac{2pN}{60} \qquad \text{…1.6}$$

where

N is the number of revolutions.

The angular acceleration (a) of the rigid body is given as:

$$a = \frac{d^2q}{dt^2} \qquad \ldots 1.7$$

Figure 1.6

Rotation of a rigid body

Uniform rotation

In uniform rotation, the angular acceleration of the body is zero, and it rotates with a constant angular velocity.

Uniformly accelerated rotation

The angular acceleration of the body is constant during the rotation.

Example 1.2: A grinding wheel is attached to the shaft of an electric motor with 1800 r.p.m., rated speed. On switching on the power, the grinder attains the speed in 5 seconds, and when the power is switched off, the grinder coasts to rest in 90 seconds.

Assume that the grinder wheel has uniformly accelerated motion. Determine the number of revolutions the grinder wheel has to turn before it attains the rated speed, when switched on and number of revolutions it turns to come to rest.

The rated speed of the motor (N) = 1800 r.p.m.

The angular velocity of the grinder wheel can be determined using equation 1.6 as follows:

$$w = \frac{2pN}{60}$$

or $w = \frac{2p\,(1800)}{60}$

or $w = 60\ p$

The grinder wheel thus attains the rated speed, and the following equations describe the angular motion of the grinder wheel:

$w = w_o + a\ t$

or $60\ p = 0 + a\ (5)$

or $5\ a = 60\ p$

or $a = 12\ p$ radians / sec^2

$w^2 = w_o^2 + 2\ aq$

or $(60p)^2 = 0 + 2\ (12p)\ q$

or $24p\ q = (60p)^2$

or $q = (60p)^2 / 24p$

or $q = (60p)^2 / 24p$

The number of revolutions the grinder wheel has to turn before attaining the rated speed is:

$= q\ / 2p$

$= (60p)^2 / (24p) (2p)$

$= (60p)^2 / (24p) (2p)$

$= 3600 / 48$

$= 75$

The angular motion of the grinder wheel rotating at the rated speed to come to rest, is determined by:

$w = w_o + a t$

or $0 = 60 p + a (90)$

or $90a = -60 p$

or $a = -60p / 90$ radians / sec^2

$w^2 = w_o^2 + 2 aq$

or $0 = (60p)^2 + 2 (-60p/90) q$

or $(4p /3)q = (60p)^2$

or $q = (60p)^2 / (4p /3)$

The number of revolutions the grinder wheel has to turn before coming to rest is:

$= q / 2p$

$= (60p)^2 / (4p /3) (2p)$

$= (60p)^2 / (8p^2 /3)$

$= 3 (60)^2 / 8$

$= 10800 / 8$

= 1350

General plane motion

Any plane motion that is neither translation nor rotation is known as a General plane motion. A general plane motion, however, has characteristics of a plane motion, that is, all the particles of the body move in parallel planes. A rolling cylinder without slipping is an example of a general plane motion, as shown in Figure 1.7. Another important aspect of a general plane motion of a rigid body is that it can always be considered as the sum of a plane translation, and rotation about an axis perpendicular to the plane motion.

Figure 1.7

General plane motion of a rigid body

1.3.4 Fundamental principles

Motion based on elementary mechanics rests on the following fundamental principles:

Newton's laws of motion

Newton's first law

Every body continues in a state of rest or of uniform motion in a straight line, unless it is compelled to change that state by a force imposed on the body.

Newton's second law

The acceleration of a given particle is proportional to the impressed force, and takes in the direction of the straight line in which the force is impressed.

$F = m a$

Newton's third law

To every action there is an equal and opposite reaction.

Newton's law of gravitation

Two particles are attracted towards each other along the line connecting them, with a force whose magnitude is proportional of their masses, and inversely proportional to the square of the distance between them.

$F = G (m_1 m_2) / d^2$

The parallelogram law

If two forces acting at a point are represented in magnitude and direction by the adjacent side of a parallelogram, then the diagonal of the parallelogram passing through their point off intersection represents the resultant, in both magnitude and direction.

Principle of transmissibility of a force

It states that, the condition of equilibrium or condition of motion of a rigid body remains unchanged, if the point of application of force, acting on the body is transmitted to act at any other point along its line of action.

1.4 Engineering practice and techniques

While designing a motion control system, there are several elements involved in the design, selection, and implementation of the control system. One has to design a control system with lowest cost, complexity, methods yielding high integrity and reliability, methods to ensure maximum throughput, lower power consumption, ease of use, and fulfill safety requirements. A control system with all these qualities can be designed only by adopting good engineering practices and techniques, while designing or implementation of the control system.

1.4.1 Applying motion control

To apply precise motion control and implement a motion control system successfully, one should follow the following steps:

- Clearly define the problem
- Specify detailed operating specifications
- Determine the load and machine requirements
- Prepare an operational time-diagram of mechanical operations to be controlled
- Identify the real-time needs of the operations, to arrive at hardware and software requirements
- Determine the amplifier / motor parameters to aid in the control of the system
- Ensure that the feedback device and resolution meets the system stability and precision requirements
- Select suitable input-output sensors for smooth reaction to various operating conditions
- Identify operator interface and motion control device
- View the complete system operation from the end-user point-of-view so that the system is easy to operate, repair, and troubleshoot

While defining the problem, know about the product, its requirements and limitations. Clear understanding about the product required will help you in producing precise motion. Consider the load variables; determine velocity, and acceleration limitations for the load. Load related information also indicates about the precision, and type of feedback device that is required to achieve precise control. It is important to understand the motion control application requirement first, and than select the hardware for the application.

It is important to determine the limitations of the mechanics and ensure that the mechanics designed to drive the load should not exceed the limitations. Machine design, gives the details of load weight, inertia, friction, and other parameters required for selecting motors. The motor and amplifier achieve the motion control objectives. Smooth and stable motion control also depends on the motor response, also known as Bandwidth. The motor response depends on the electrical time constant of the motor, and the mechanical time constant of the overall system. Proper selection of these two parameters helps in precise motion control. A feedback sensor helps in stabilizing the performance of the motion control system. While selecting motion control system components, selection of feedback sensor is most important followed by selection of motor and amplifier. As varieties of motors are available in the market, and several motors may meet the requirements of the particular application, the choice should be made based on availability, reliability and cost.

Next, to determine choice of control, make a flow chart of the operating software. A simple, control logic may require simple hardware, with an embedded controller whereas a complex, control logic may require a complete computer based system. The controller or the control system chosen should have easy understanding, and portable software language like Basic or C apart from non-portable motion command set.

1.4.2 Determining the limitations of the mechanics

The mechanics are designed to manipulate the product, and should not exceed those design requirements. This does not mean that the limitation of the machine is imposed by the product in all cases. The tools used to work the product might be the restricting influence. It might be the budget, size, or the strength problem such as the area in which the machine is to be placed. The machine design gives us a whole set of parameters— inertia, friction, weights, timing, etc., all of which are used to select a motor. The motor and amplifier help the motion controller to achieve its desired objectives. Smooth and stable slow motion is not just a control problem, neither is high speed indexing or a robot control. The motor adds a dimension of response, also referred as bandwidth. This is controlled by a combination of the motor's electrical time constant, and the overall systems mechanical time constant. If chosen properly, these two factors help the motion perform as desired. Irrespective of the mode of the motor amplifier, a tachometer feedback can help in stabilizing the system performance. The type of feedback sensor is the most important component in the selection of the entire control system, followed by the motor and its amplifier.

For a proper selection of a motor, it is recommended to consult the motor manufacturers and obtain detailed specification, application handbooks, product brochures, and manuals. The application requirement should be explained to them as it helps in proper selection.

1.4.3 Determining the control system hardware and software

After selecting the motor and amplifier, prepare a flow chart for the operating software. This helps in determining the choice of the control system. Simple logic requires simple hardware interfacing with an embedded controller. Complex logic, data storage and retrieval, operators interface, etc., requires a computer based control system.

Finally, the software language is also an important part of the selection criteria of any control system. An attempt to assemble the right motion control hardware into a functioning machine with several possible restrictions on, cycle time, product handling, serviceability, learning curve, schedule, budget, etc., is difficult enough. Selection of a motion control computer system primarily, based on its programming language instead of its functional capabilities, reliability and cost would not be a rational decision. At the same time, programming in any high level language can restrict system capability. It is easy to develop the programs using user-friendly high level programming language. Any pre-composed language reduces your programming efforts, but it rarely allows you the precise control over the control system.

How generic must be a programming language or a software package before it loses it effectiveness and user-friendliness? Let us assume that all the available motion control hardware has more or less same capabilities. The software required for the task can be taught from the base, from which the remaining software development effort can evolve. This includes—operator interface, data manipulation, memory storage, table construction, I/O handling, etc. Software development required to deal with a motion controller is a function of the value of the command set within the controller, and depending whether the controller is RS-xxx (e.g. RS-485) based, or Bus-based, or both. Command set and communication mode determines the efforts that will be required to solidify the overall system operations. Long update times from keystroke entry to display tend to hamper operator efficiency. Also long RS-xxx communication strings that have to be verified, and then decoded by the motion device reduce the high-speed real-time capability.

Any single computer device is limited in its capability to function in its hardware environment, or in real time by the operating software. For an adequate overall performance, you must maximize the computer’s capabilities. When you deal with control design, you must consider the real-time system response. If you require a real-time handling for successful operations, then it must be the primary criteria for the selection of control devices. To select the proper motion control device, you must always consider the system restrictions first. After knowing the requirements of the real-time system, you can choose the motion control devices that fit into the systems hardware requirements, and at this point, you can scrutinize the software for optimum handling and user-friendliness.

1.4.4 Techniques for designing control systems

The design of a control system is the most important function of every control engineer.

The following control engineering techniques are used for system analysis, which provide the necessary inputs required for design and implementation of a control system:

- Mathematical modeling of the physical system
    - Transfer functions
    - Block diagrams
    - Signal flow graphs
- Control system components and elements
    - Linear approximation of non-linear systems
    - Electrical systems
    - Pneumatic systems
    - Hydraulic systems
- Time response analysis
    - Standard test signals
    - Time response of first-order and second-order systems
    - Steady state errors and error constants
    - Performance indices
- Stability criteria
    - Concept and necessary conditions for stability
    - Routh stability criteria
    - Hurwitz stability criteria
    - Relative stability analysis
- Root locus technique
- Frequency response analysis
    - Correlation between time response and frequency response
    - Polar plots
    - Bode plots
    - All-pass and minimum phase systems
    - Log magnitude versus phase plots
- Stability in frequency domain
    - Nyquist stability criteria
    - Closed-loop frequency response

    - Sensitivity analysis of frequency domain
- Design considerations
    - Realization of basic compensators
    - Cascade compensation in time domain and frequency domain
    - Feedback compensation
    - Network compensation of AC systems
- Sampled data control systems
    - Spectrum analysis of sampling process
    - Signal reconstruction
    - Z-transfer function
    - Inverse z-transform and response of linear discrete systems
    - Z-domain and s-domain relation
    - Compensation techniques

During the design of a control system, while some of the direct design methods can be abstracted from analysis, in most situations the design proceeds on a trial and error basis, wherein the above-mentioned analysis techniques are repeatedly applied.