Unit-I
Introduction to Mechatronics

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Unit I: (7 Hrs)

- **Introduction**: Mechatronics key elements, design processes and issues,
- Modeling and simulation of physical system, Electrical system,
- Mechanical translation-rotation system,
- electromechanical coupling,
- Ball screws.
- Electronic cams,
- indexing mechanisms,

Introduction:
Mechatronics key elements

- **What is Mechatronics?**
- **Mechatronics is a methodology used for the optimal design of electromechanical products.**
- A *methodology* is a collection of practices, procedures, and rules used by those who work in a particular branch of knowledge or *discipline.*
- Familiar technological disciplines include thermodynamics, electrical engineering, computer science, and mechanical engineering, to name several.
- Instead of one, the mechatronic system is *multidisciplinary*, embodying four fundamental disciplines: *electrical, mechanical, computer science, and information technology.*

Introduction….

- The F-35, a U.S. Department of defense joint strike fighter plane developed by Lockheed Martin Corporation, is an example of mechatronic technology in action.
- The design metric emphasizes reliability, maintainability, performance, and cost.
- Multidisciplinary functions, including the on-board prognostics for zero downtime and cockpit technology, are being designed into the aircraft starting at the preliminary design stage.

What is Mechatronics ?

- Multidisciplinary systems are not new. They have been successfully designed and used for many years. One of the most common is the *electromechanical* system, which often uses a computer algorithm to modify the behavior of a mechanical system.
- Electronics are used to transduce information between the computer science and mechanical disciplines.

What is Mechatronics ?......

- The difference between a mechatronic system and a multidisciplinary system is not the constituents, but rather *the order in which they are designed.*
- Historically, multidisciplinary system design employed a sequential *design-by-discipline* approach.
- For example, the design of an electromechanical system is often accomplished in three steps, beginning with the mechanical design. When the mechanical design is complete, the power and microelectronics are designed, followed by the control algorithm design and implementation.

What is Mechatronics ?......

- The major drawback of the design-by-discipline approach is that, by fixing the design at various points in the sequence, new constraints are created and passed on to the next discipline.

- Many control system engineers are familiar with the quip:
- **Design and build the mechanical system, then bring in the painters to paint it and the control system engineers to install the controls.**

What is Mechatronics ?......

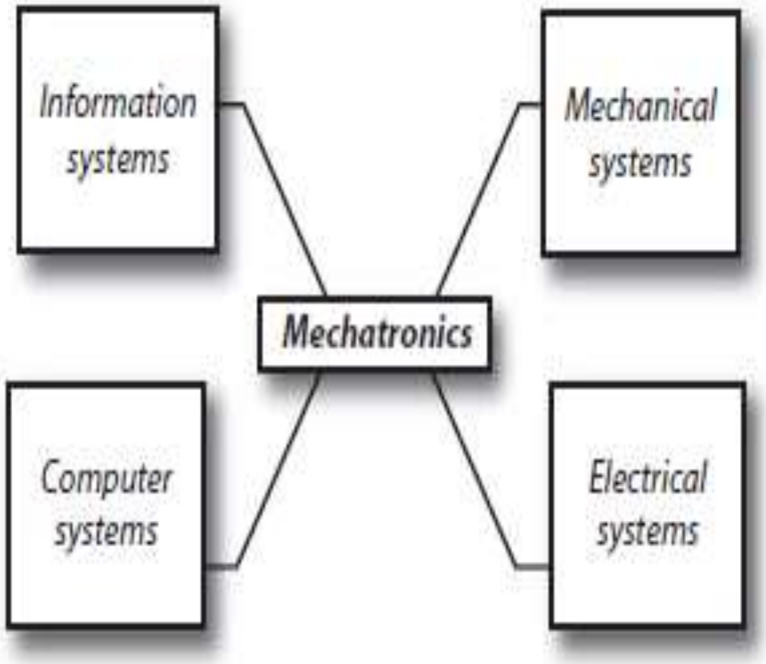
- Control designs often are not efficient because of these additional constraints. For example, cost reduction is a major factor in most systems.
- Trade offs made during the mechanical and electrical design stages often involve sensors and actuators. Lowering the sensor–actuator count, using less accurate sensors, or using less powerful actuators, are some of the standard methods for achieving cost savings.
- **The mechatronic design methodology is based on a concurrent (instead of sequential) approach to discipline design, resulting in products with more synergy.**

What is Mechatronics ?......

- The branch of engineering called *systems engineering* uses a concurrent approach for *preliminary design.*
- In a way, mechatronics is an extension of the system engineering approach, but it is *supplemented* with information systems to *guide* the design and is applied at *all* stages of design—not just the preliminary design step—making it more *comprehensive.*
- There is a synergy in the integration of mechanical, electrical, and computer systems with information systems for the design and manufacture of products and processes.

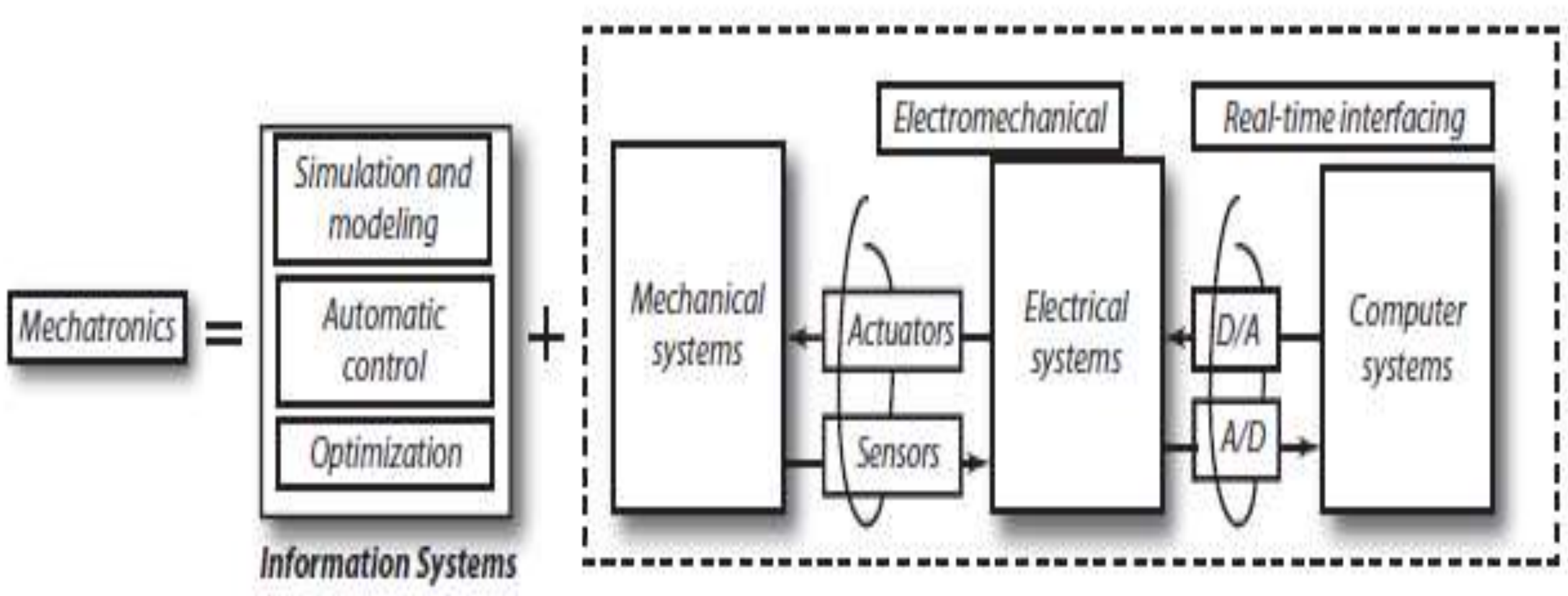
The key elements of the mechatronics approach are presented in Figure 1-1.

FIGURE 1-1 MECHATRONICS CONSTITUENTS



Even though the literature often adopts this concise representation, a clearer but more complex representation is shown in Figure 1-2.

FIGURE 1-2 MECHATRONICS KEY ELEMENTS



key elements of the mechatronics….

- Mechatronics is the result of applying information systems to physical systems. The physical system (the rightmost dotted block of Figure 1-2) consists of mechanical, electrical, and computer systems as well as actuators, sensors, and real-time interfacing.
- In some of the literature, this block is called an electromechanical system.
- **A mechatronic system is not an electromechanical system but is more than a control system.**

key elements of the mechatronics….

- Mechatronics is really nothing but good design practice.
- The basic idea is to apply new controls to extract new levels of performance from a mechanical device.
- Sensors and actuators are used to transduce energy from high power (usually the mechanical side) to low power (the electrical and computer side).

key elements of the mechatronics….

- The block labeled “*Mechanical systems*” frequently consists of more than just mechanical components and may include fluid, pneumatic, thermal, acoustic, chemical, and other disciplines as well.
- New developments in sensing technologies have emerged in response to the ever-increasing demand for solutions of specific monitoring applications.
- Microsensors are developed to sense the presence of physical, chemical, or biological quantities (such as temperature, pressure, sound, nuclear radiations, and chemical compositions).
- They are implemented in solid-state form so that several sensors can be integrated and their functions combined.

key elements of the mechatronics….

- Control is a general term and can occur in living beings as well as machines.
- The term *"Automatic control"* describes the situation in which a machine is controlled by another machine.
- Irrespective of the application (such as industrial control, manufacturing, testing, or military), new developments in sensing technology are constantly emerging.

key elements of the mechatronics….

- **Information Systems**
- **Mechanical Systems**
- **Electrical Systems**
- **Sensors and Actuators**
- **Real-Time Interfacing**

Information Systems

- Information systems include all aspects of information transmission—from signal processing to control systems to analysis techniques.
- An information system is a combination of four disciplines:

  communication systems, signal processing, control systems,

  and numerical methods.
- In mechatronics applications, we are most concerned with modeling, simulation, automatic control, and numerical methods for optimization.

Information Systems…..

- **Modeling and Simulation:**
- *Modeling* is the process of representing the behavior of a real system by a collection of mathematical equations and logic.
- The term *real system* is synonymous with *physical system*—that is, a system whose behavior is based on matter and energy.
- Models can be broadly categorized as either *static* or *dynamic.*
- In a static model, there is no energy transfer. Systems, which are static produce no motion, heat transfer, fluid flow, traveling waves, or any other changes.
- On the other hand, a dynamic model has energy transfer which results in power flow. Power, or rate of change of energy, causes motion, heat transfer, and other phenomena that change in time.
- Phenomena are observed as *signals,* and since time is often the independent variable, most signals are indexed with respect to time.

Information Systems: Modeling…..

- Models are cause-and-effect structures—they accept external information and process it with their logic and equations to produce one or more outputs.
- Exogenous, or externally produced, information supplied to the model either can be fixed in value or changing.
- An external fixed-value unit of information is called a *parameter*, while an external changing unit of information is called an *input signal.*
- Traditionally, all model output information is assumed to be changing and is therefore referred to as output *signals.*

Information Systems: Modeling…..

- Because models are collections of mathematical and logic expressions, they can be represented in text-based programming languages.
- Unfortunately, once in the programming language, one must be familiar with the specific language in order to understand the model.
- Because most practicing engineers are not familiar with most programming languages, text-based modeling proved to be a poor candidate for mechatronics.
- The ideal candidate would be picture or *visual* based instead of text-based and intuitive.

Information Systems: Modeling…..

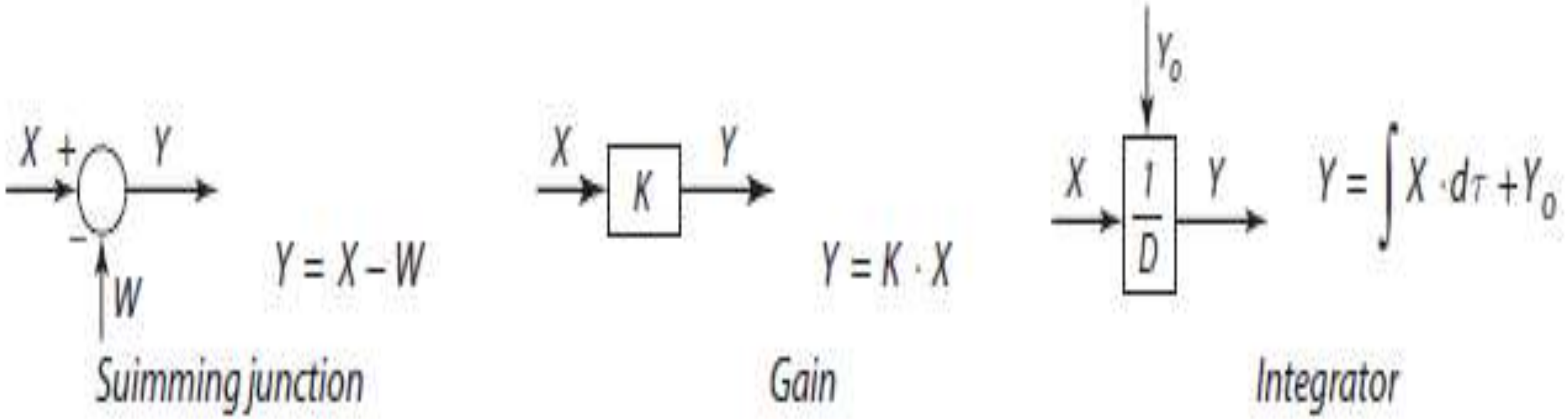
- All block diagram languages consist of two fundamental objects: signal wires and blocks.
- A signal wire transmits a signal or a value from its point of origination (usually a block) to its point of termination (usually another block).
- An arrowhead on the signal wire defines the direction in which the signal flows.
- Once the flow direction has been defined for a given signal wire, signals may only flow in the forward direction—not backwards.

Information Systems: Modeling…..

- A block is a processing element which operates on input signals and parameters (or constants) to produce output signals.
- Because block functions can be nonlinear as well as linear, the collection of special function blocks is practically unlimited and almost never the same between vendors.
- However, there is a three-block basis that all block diagram languages possess: summing junction, gain, and integrator blocks.
- These blocks and their associated functions are presented in Figure 1-3.

Information Systems: Modeling…..

FIGURE 1.3 BASIC BLOCKS



Information Systems: Simulation…..

- *Simulation* is the process of *solving* the model and is performed on a computer.
- Although simulations can be performed on analog computers, it is far more common to perform them on digital computers.
- The process of simulation can be divided into three sections:

    initialization, iteration, and termination.

- If the starting point is a block diagram-based model description, then in the initialization section, the equations for each of the blocks must be sorted according to the pattern in which the blocks have been connected.

Information Systems: Simulation…..

- The iteration section solves any differential equations present in the model using numerical integration and/or differentiation.
- An ordinary differential equation is (in general) a nonlinear equation which contains one or more derivative terms as a function of a single independent variable. For most simulations, this independent variable is time.
- The order of an ordinary differential equation equals the highest derivative term present.
- Most methods employed for the numerical solution of ordinary differential equations are based on the use of *approximating polynomials*, which fit a truncated Taylor series expansion of the ordinary differential equation. Three steps are required:

Information Systems: Simulation…..

- **Step 1.** Write a Taylor series expansion of the functional form of the ordinary differential equation solution about its initial condition(s). Since the independent variable considered is time, all derivative terms in the series will be taken with respect to time.
- **Step 2.** Truncate the Taylor series at one of the derivative terms, and the resulting truncated series becomes the approximating polynomial.
- **Step 3.** Compute all constant terms and each derivative term based on the initial condition values to complete the approximating polynomial.
- The display section of a simulation is used to present and post the output process. Output may be saved to a file, displayed as a digital reading, or graphically displayed as a chart, strip chart, meter readout, or even as an animation.

Information Systems: Optimization…..

- **Optimization:** Optimization solves the problem of distributing limited resources throughout a system so that pre specified aspects of its behavior are satisfied.
- In mechatronics, optimization is primarily used to establish the optimal system configuration. However, it may be applied to other issues as well, such as
- Identification of optimal trajectories
- Control system design
- Identification of model parameters

Information Systems: Optimization…..

- In engineering applications, certain conventions in terminology are used.
- Resources are referred to as *design variables*, aspects of system behavior as *objectives*, and system governing relationships (equations and logic) as *constraints.*

Mechanical Systems

- Mechanical systems are concerned with the behavior of matter under the action of forces. Such systems are categorized as rigid, deformable, or fluid in nature.
- A rigid-body system assumes all bodies and connections in the system to be perfectly rigid. In actual systems, this is not true, and some deformation always results as various loads are applied. Normally, the deformations are small and do not appreciably affect the motion of the rigid-body system;
- However, when one is concerned with material failures, the deformable-body system becomes important. Failure analysis and mechanics of materials are major fields based on deformable-body systems.
- The field of fluid mechanics consists of compressible and incompressible fluids.

Mechanical Systems….

- Newtonian mechanics provides the basis for most mechanical systems and consists of three independent and absolute concepts: space, time, and mass. A fourth concept, force, is also present
- but is not independent of the other three.

Electrical Systems

- Electrical systems are concerned with the behavior of three fundamental quantities: charge, current, and voltage (or potential).
- When a current exists, electrical energy usually is being transmitted from one point to another.
- Electrical systems consist of two categories: power systems and communication systems.
- Communication systems are designed to transmit information as low-energy electrical signals between points. Functions such as information storage, processing, and transmission are common parts of a communication system.
- Electrical systems are an integral part of a mechatronics application.

Electrical Systems...

- The following electrical components are frequently found in such applications.
- Motors and generators
- Sensors and actuators (transducers)
- Solid state devices including computers
- Circuits (signal conditioning and impedance matching, including amplifiers)
- Contact devices (relays, circuit breakers, switches, slip rings, mercury contacts, and fuses)

Sensors and Actuators

- *Sensors* are required to monitor the performance of machines and processes.
- Using a collection of sensors, one can monitor one or more variables in a process. Sensing systems also can be used to evaluate operations, machine health, inspect the work in progress, and identify part and tools.
- The monitoring devices are generally located near the manufacturing process measuring the surface quality, temperature, vibrations, and flow rate of cutting fluid.
- Sensors are needed to provide real time information that can assist controllers in identifying potential bottlenecks, breakdowns, and other problems with individual machines and within a total manufacturing environment.

Sensors and Actuators….

- *Actuators* are another important component of a mechatronic system.
- Actuation involves a physical action on the process, such as the ejection of a work piece from a conveyor system initiated by a sensor.
- Actuators are usually electrical, mechanical, fluid power or pneumatic based. They transform electrical inputs into mechanical outputs such as force, angle, and position.
- Actuators can be classified into three general groups.

1. Electromagnetic actuators, (e.g., AC and DC electrical motors, stepper motors, electromagnets)
2. Fluid power actuators, (e.g., hydraulics, pneumatics)
3. Unconventional actuators (e.g., piezoelectric, magnetostrictive, memory metal)

Real-Time Interfacing

- Simulation of a mathematical model is unrelated to real time—the time read from a wall clock.
- We often would like the model to *run* (or simulate) faster, but there is no harm if it does not.
- Consider a model which consists of several subsystems categorized as control algorithms, sensors, actuators, and the process (mechanical, thermal, fluid, etc.).
- The process of simulation requires that all cause-and effect equations in the model be ordered (or *sorted*) with inputs on the left and outputs on the right prior to simulation.
- During simulation, the sorted equations are solved, time is advanced, the equations are again solved, and the process continues.
- One passage through the equations is called a *loop.*

Real-Time Interfacing…

- In mechatronics, the main purpose of the real-time interface system is to provide data acquisition and control functions for the computer.
- The purpose of the acquisition function is to reconstruct a sensor waveform as a digital sequence and make it available to the computer software for processing.
- The control function produces an analog approximation as a series of small *steps*. The inherent step discontinuities produce new undesirable frequencies not present in the original signal and are often attenuated using an analog *smoothing* filter.
- Thus, for mechatronic applications, real-time interfacing includes analog to digital (A/D) and digital to analog (D/A) conversion, analog signal conditioning circuits, and sampling theory.

The Mechatronics Design Process

- The traditional electromechanical-system design approach attempted to inject more reliability and performance into the *mechanical* part of the system during the development stage.
- The control part of the system was then designed and added to provide additional performance or reliability and also to correct undetected errors in the design.
- Because the design steps occur sequentially, the traditional approach is a *sequential engineering* approach.

The Mechatronics Design Process….

A Standish Group survey of software dependent projects found.

- 31.1% cancellation rate for software development projects.
- 222% time overrun for completed projects.
- 16.2% of all software projects were completed on time and within budget.
- Maintenance costs exceeded 200% of initial development costs for delivered software.

The Mechatronics Design Process….

- The Boston-based technology think tank, Aberdeen Group, provided key information on the importance of incorporating the right design process for a mechatronic system design.
- Aberdeen researchers used five key product development performance criteria to distinguish "*best-in-class*" companies, as related to mechatronic design.
- The key criteria were revenue, product cost, product launch dates, quality, and development costs.

The Mechatronics Design Process....

- Best-in-class companies proved to be
- twice as likely as "*laggards* " (worst-in-class companies) to achieve revenue targets,
- twice as likely to hit product cost targets,
- three times as likely to hit product launch dates,
- twice as likely to attain quality objectives,
- and twice as likely to control their development costs.

The Mechatronics Design Process….

Aberdeen's research also revealed that best-in-class companies were.

- 2.8 times more likely than *laggards* to carefully communicate design changes across disciplines.
- 3.2 times more likely than *laggards* to allocate design requirements to specific systems, subsystems, and components.
- 7.2 times more likely than *laggards* to digitally validate system behavior with the simulation of integrated mechanical, electrical, and software components.

The Mechatronics Design Process

- The mechatronic design methodology is not only concerned with producing high-quality products but with maintaining them as well—an area referred to as *life cycle design*.

Life cycle design

- Several important life cycle factors are indicated.
- *Delivery:* Time, cost, and medium.
- *Reliability:* Failure rate, materials, and tolerances.
- *Maintainability:* Modular design.
- *Serviceability:* On board diagnostics, prognostics, and modular design.
- *Upgradeability:* Future compatibility with current designs.
- *Disposability:* Recycling and disposal of hazardous materials.

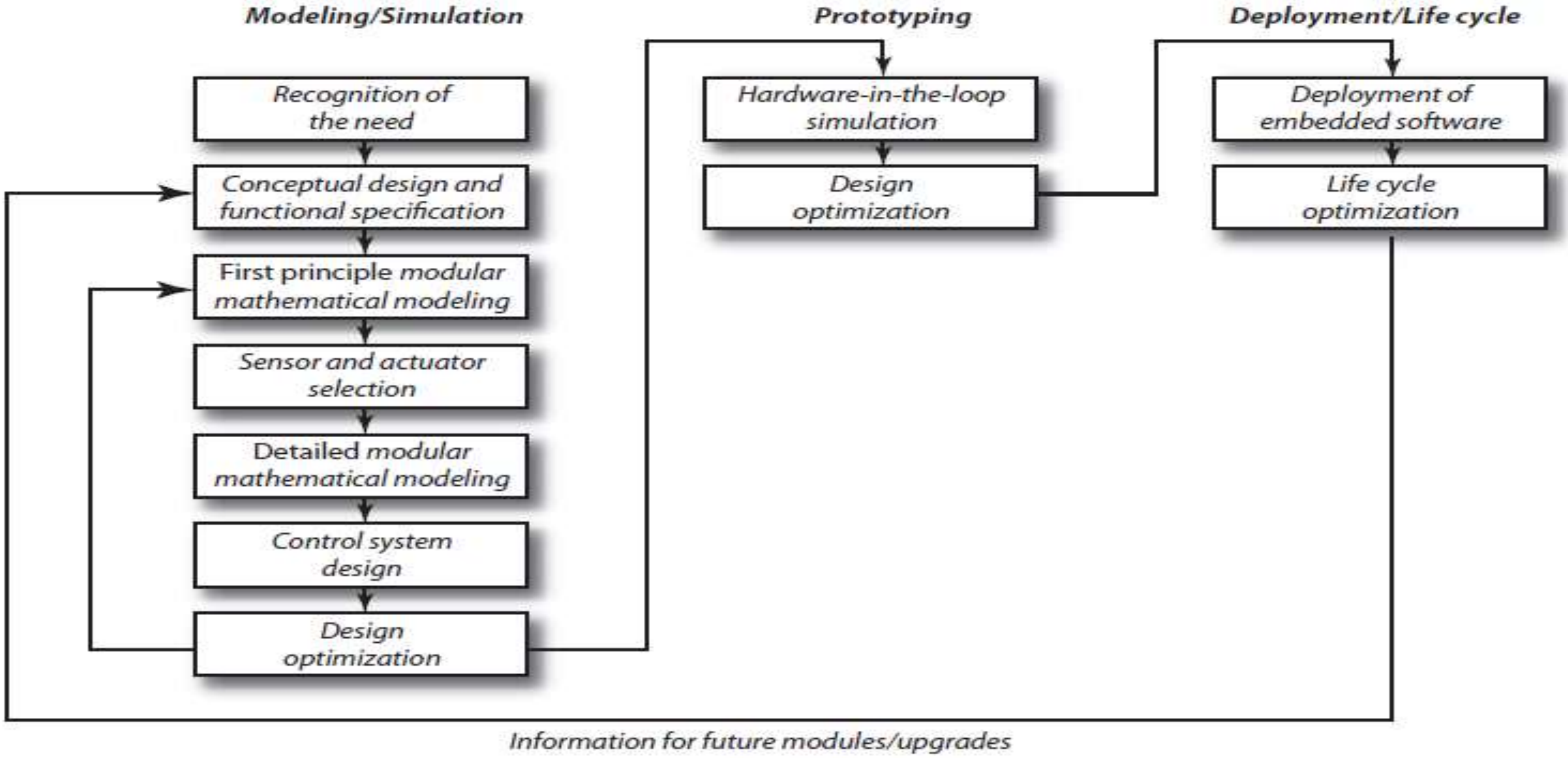
Life cycle design….

- *conventional design for life cycle* approach *begins* with a product *after* it has been designed and manufactured.

- In the mechatronic design approach, life cycle factors are *included* during the product design stages, resulting in products which are designed from *conception* to *retirement.*

The mechatronic design process is presented in Figure 1-4.

FIGURE 1-4 MECHATRONIC DESIGN PROCESS



The Mechatronics Design process….

- Because of their modularity, mechatronic systems are well suited for applications that require reconfiguration.
- Such products can be reconfigured either during the design stage by substituting various subsystem modules or during the life span of the product.
- Since many of the steps in the mechatronic design process rely on computer-based tasks (such as information fusion, management, and design testing),an efficient computer-aided prototyping environment is essential.

Important Features

- *Modeling*: Block diagram or visual interface for creating intuitively understandable behavioral models of physical or abstract phenomenon. The ability to encapsulate complexity and maintain several levels of subsystem complexity is useful.

- *Simulation*: Numerical methods for solving models containing differential, discrete, hybrid, partial, and implicit nonlinear (as well as linear) equations. Must have a *lock* for real-time operation and be capable of executing faster than real time.

- *Project Management*: Database for maintaining project information and subsystem models for eventual reuse.

Important Features…

- *Design*: Numerical methods for constrained optimization of performance functions based on model parameters and signals. Monte Carlo type of computation is also desirable.
- *Analysis*: Numerical methods for frequency-domain, time-domain, and complex-domain design.
- *Real-Time Interface*: A plug-in card is used to replace part of the model with actual hardware by interfacing to it with actuators and sensors. This is called *hardware in the loop* simulation or *rapid prototyping* and must be executed in real time.

Important Features…

- *Code Generator*: Produces efficient high-level source code from the block diagram or visual modeling interface. The control code will be compiled and used on the embedded processor. The language is usually C.

- *Embedded Processor Interface*: The embedded processor resides in the final product. This feature provides communication between the process and the computer-aided prototyping environment. This is called a *full system prototype.*

The Mechatronics Design Process..

- Because no single model can ever flawlessly reproduce reality, there always will be error between the behavior of a product model and the actual product.
- These errors, referred to as *unmodeled errors*, are the reason that so many *model-based designs* fail when deployed to the product

The Mechatronics Design Process…

- The mechatronic design approach also uses a model-based approach, relying heavily on modeling and simulation.
- However, *unmodeled errors are accounted for* in the *prototyping* step. Their effects are absorbed into the design, which significantly raises the probability of successful product deployment.

Components in a typical mechatronic system

- Figure 1.5 illustrates all the components in a typical mechatronic system.
- The actuators produce motion or cause some action;
- the sensors detect the state of the system parameters,
- inputs, and outputs; digital devices control the system;
- Conditioning and interfacing circuits provide connections between the control circuits and the input/output devices;
- and graphical displays provide visual feedback to users.

Components in a typical mechatronic system….

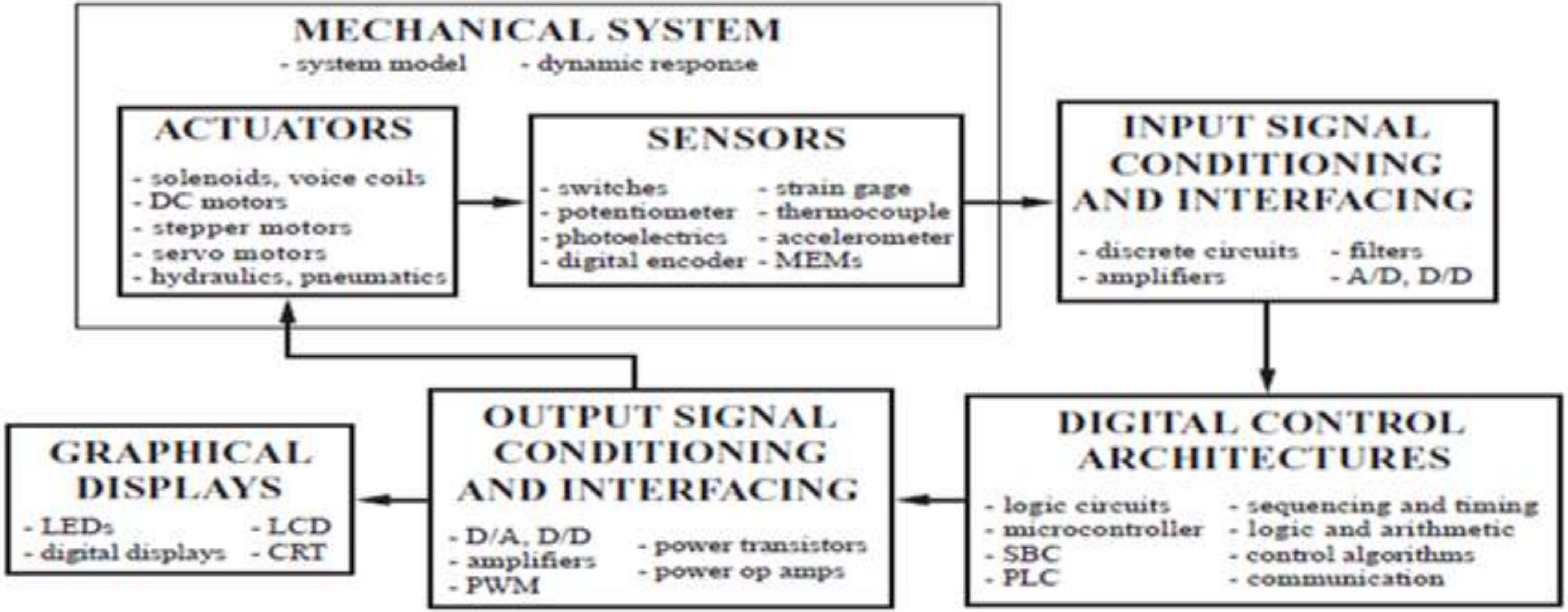


Figure 1.5 Mechatronic system components.

Mechatronics System-Copy machine (Xerox machine)

- An office copy machine is a good example of a contemporary mechatronic system.
- It includes analog and digital circuits, sensors, actuators, and microprocessors.
- The copying process works as follows: The user places an original in a loading bin and pushes a button to start the process; the original is transported to the platen glass; and a high intensity light source scans the original and transfers the corresponding image as a charge distribution to a drum.
- Next, a blank piece of paper is retrieved from a loading cartridge, and the image is transferred onto the paper with an electrostatic deposition of ink toner powder that is heated to bond to the paper.

Copy machine…

- A sorting mechanism then optionally delivers the copy to an appropriate bin.
- Analog circuits control the lamp, heater, and other power circuits in the machine.
- Digital circuits control the digital displays, indicator lights, buttons, and switches forming the user interface.
- Other digital circuits include logic circuits and microprocessors that coordinate all of the functions in the machine.

Copy machine…

- Optical sensors and micro switches detect the presence or absence of paper, its proper positioning, and whether or not doors and latches are in their correct positions.
- Other sensors include encoders used to track motor rotation.
- Actuators include servo and stepper motors that load and transport the paper, turn the drum, and index the sorter.

Modeling and simulation of physical system

- Component modeling, which is the derivation of mathematical equations suitable for computer simulation, plays a critical role during the design stages of a mechatronic system.
- For all but the simplest systems, the performance aspects of components (such as sensors, actuators, and mechanical geometry) and their effect on system performance can only be evaluated by simulation.
- Any modeling task requires the formulation of mathematical models suitable for computer simulation or solution—the terms are analogous.
- The analogy approach, can be used for such modeling tasks.
- It was developed by electrical engineers to model mechanical, thermal, and fluid systems for simulation on analog computers.

Modeling and simulation of physical system..

- Because the analog computer was used for the simulation environment, it was fitting that models were constructed using standard electrical elements, such as resistors, capacitors, and inductors.
- Analog computer simulation environments have two attractive features: precise integration and real-time operation,
- but they are limited in their ability to represent and solve complex nonlinear equations. For example, a nonlinear table function cannot be incorporated using the standard electrical elements, instead the function must be approximated by a truncated power series and represented as a polynomial.

Modeling and simulation of physical system..

- Being a sequence of multiplications and additions, the polynomial then can be represented using the standard electrical elements.
- If one table entry is modified, the approximating polynomial must be completely regenerated—a time consuming process.
- Today the digital computer is used extensively for simulation. Instead of using standard electrical elements and circuits, digital computer models are constructed using block elements and represented as block diagrams.
- Block diagrams are much more powerful, flexible, and intuitive than circuit models.

Modeling and simulation of physical system..

- In this chapter, we will present two approaches for developing block diagram models from system illustrations:

(1) the direct method and

(2) the analogy method with slight modifications.

Operator Notation and Transfer Functions

- For ease in writing linear lumped-parameter differential equations, the *D* operator is introduced.
- Any linear lumped differential equation can be converted to *operator form* by simply substituting the operation using differentiation or integration with the appropriate operator.
- Table 1-1 summarizes the operators for differentiation and integration and presents several examples.

Operator Notation and Transfer Functions..

TABLE 1-1 *D* OPERATOR FOR DIFFERENTIATION AND INTEGRATION

Type	Operation	Operator	Operator Form Examples
Continuous	Differentiation	$D \equiv \frac{d()}{dt}$	$\ddot{x}(t) - 3\dot{x}(t) + x(t) = \dot{r}(t) - 1$ $\Rightarrow D^2x(t) - 3Dx(t) + x(t) = Dr(t) - 1$
Continuous	Integration	$\frac{1}{D} \equiv \int_{t_0}^{t} ()d\tau$	$\dot{x}(t) + x(t) - \int x(\tau)d\tau + r(t) = 0$ $\Rightarrow Dx(t) + x(t) - \frac{1}{D}x(t) + r(t) = 0$

Operator Notation and Transfer Functions…

- The Laplace transform is used to represent a continuous time domain system, *f(t),* using a continuous sum of complex exponential functions of the form where *s* is a complex variable defined as $s = \sigma + j\omega.$
- The complex domain (or *s* plane as it's often called) is just a plane with a rectangular *x*–*y* coordinate system where σ is the real part and ω is the imaginary part.
- Applying the Laplace transform to a time-domain differentiation operation results in a frequency domain multiplication operation where ***s*** is the operator.

Operator Notation and Transfer Functions…

- The Laplace *s* operator is identical to the *D* operator previously introduced, except when a differential equation is written in *s*-operator or Laplace format, it is no longer in the time domain but rather in the frequency (complex variable) domain.
- The cause–effect relationship for many systems can be approximated by a linear ordinary differential equation.

Operator Notation and Transfer Functions….

For example, consider the following second-order dynamic system with one input, *r(t)* , and one output, *y(t)*.

$$\ddot{y}(t) - 2\dot{y}(t) + 7y(t) = \dot{r}(t) - 6r(t)$$

This type of system is called **a single input–single output or *SISO* system**. The transfer function is another way of writing a SISO system. The transfer function is *the ratio of the output variable over the input variable represented as the ratio of two polynomials in the D or s operator*.

Any linear ordinary differential equation can be converted to transfer function form using the following three step procedure.

Step 1. Rewrite the equation using operator notation

$$D^2y(t) - 2Dy(t) + 7y(t) = Dr(t) - 6r(t)$$

Step 2. Collect and factor all output terms on the left side and input terms on the right side:

$$y(t)\cdot(D^2 - 2D + 7) = r(t)\cdot(D - 6)$$

Step 3. Obtain the transfer function by solving for the ratio of the output over the input signal:

$$\frac{y(t)}{r(t)} = \frac{(D - 6)}{(D^2 - 2D + 7)} = \text{Transfer function}$$

- The transfer function consists of two polynomials in the *D* or *s* operator, a numerator polynomial, and a denominator polynomial.
- A *monic* polynomial has its highest *D or s*-power coefficient set to 1.
- To minimize the number of coefficients in a transfer function, the numerator and denominator polynomials are usually written in monic form with any gain factored out.

- For example, the following transfer function is converted to monic form by factoring 16 out of the numerator and 5 out of the denominator.

$$\frac{16D - 4}{5D^2 + 3D + 1} \xRightarrow{\text{Monic form}} \frac{16}{5} \cdot \left(\frac{D - \dfrac{4}{16}}{D^2 + \dfrac{3}{5}D + \dfrac{1}{5}} \right)$$

Block Diagrams, Manipulations, and Simulation

- *Simulation* is the process of *solving* a block diagram model on a computer. Generally, simulation is the process of solving *any* model, but since block diagram models are so widely used, we will use block diagrams for all modeling tasks.
- Block diagrams are usually part of a larger *visual programming environment*.
- Other parts of the environment may include numerical algorithms for integration, real-time interfacing, code generation, and hardware interfacing for high-speed applications.
- Visual programming environments are offered by many vendors and, depending on the supplier, will support different environment features.

Block Diagrams—Introduction

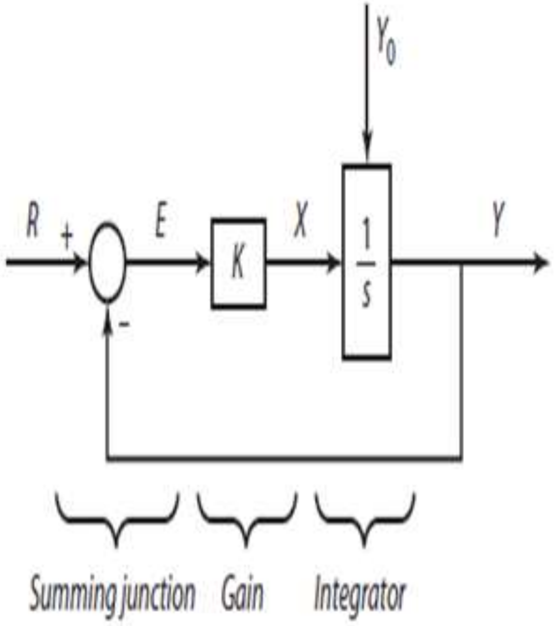
- Block diagram models consist of two fundamental objects: *signal wires* and *blocks*.
- The function of a signal wire is to transmit a signal or value from its origination point (usually a block) to its termination point (usually another block).
- The *flow* direction of the signal is defined by an arrowhead on the signal wire.

  A *block* is a processing element which operates on input signals and parameters to produce output signals.

There is, however, a fundamental set of three basic blocks that all block diagram languages possess. These blocks are the summing junction, the gain, and the integrator.

An example system using these three blocks is presented in Figure 1.6 below.

FIGURE 1.6 THREE BLOCK SYSTEM EXAMPLE

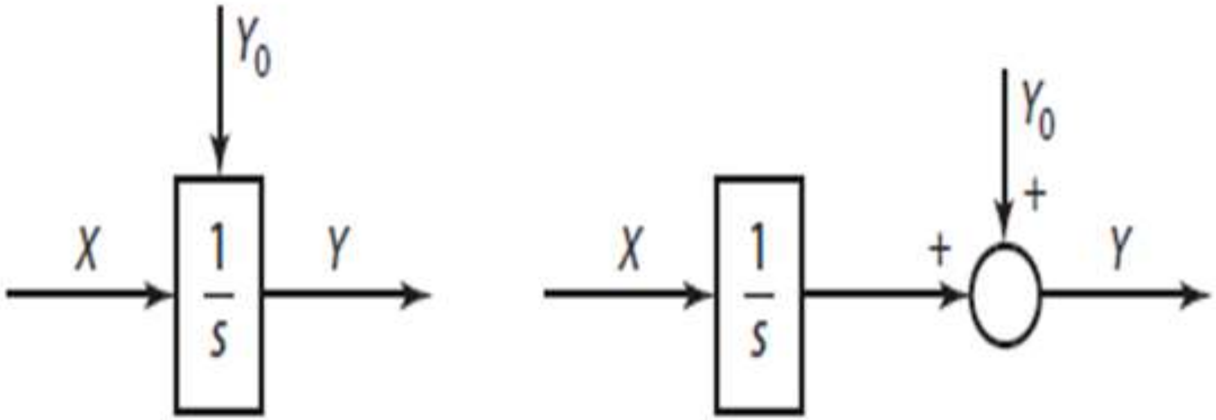


The vertical signal, Y_0, entering the integrator from the top represents the initial condition on the integrator.

When this signal is omitted, the initial condition is assumed to be 0.

The initial condition also could be represented as a summing junction downstream of the integrator,
as shown in Figure 1.7 below.

FIGURE 1.7 METHODS FOR REPRESENTATION OF INTEGRATOR INITIAL CONDITION IN A BLOCK DIAGRAM

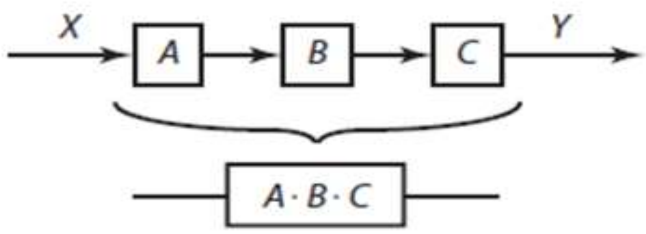


Block Diagrams—Manipulations

- Block diagrams are rarely constructed in a standard form, and it is often necessary to reduce them to more efficient or understandable forms.
- The ability to simplify a block diagram is often a critical step in understanding its function and behavior.
- See the basic rules which may be used to reduce a block diagram.

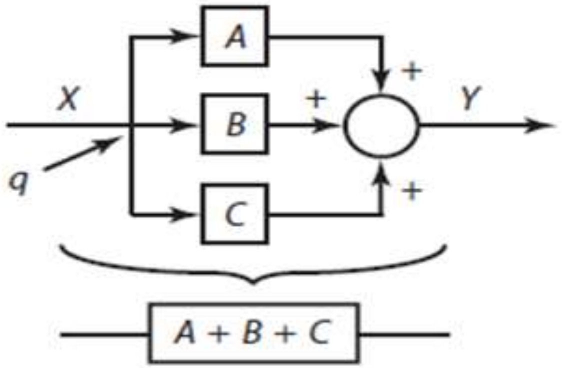
Series and Parallel Block Reduction see below

FIGURE 1.8 SERIES MANIPULATION—SERIES BLOCKS MULTIPLY



Parallel Block Reduction

FIGURE 1.9 PARALLEL MANIPULATION—PARALLEL BLOCKS ADD



- **Moving Pick-Off Points** Pick-off points are wire origination points located on a wire as opposed to a block output.
- When a signal is picked-off of a wire, both the signals and the picked-off signal are identical.
- It is often necessary to move pick-off points either downstream or upstream in order to create a parallel block configuration which can then be reduced using the parallel block reduction rule.

- **Downstream** When a pick-off point is shifted downstream over a block, the inverse of the block appears in the feedback path. Figure 1.10 illustrates this reduction.

- **Upstream** When a pick-off point is shifted upstream over a block, the block appears in the feedback path. Figure 1.11 illustrates this reduction.

FIGURE 1.10 PICK-OFF POINT SHIFTED DOWNSTREAM

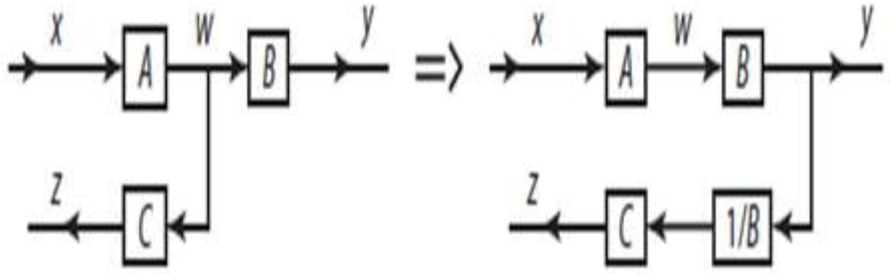
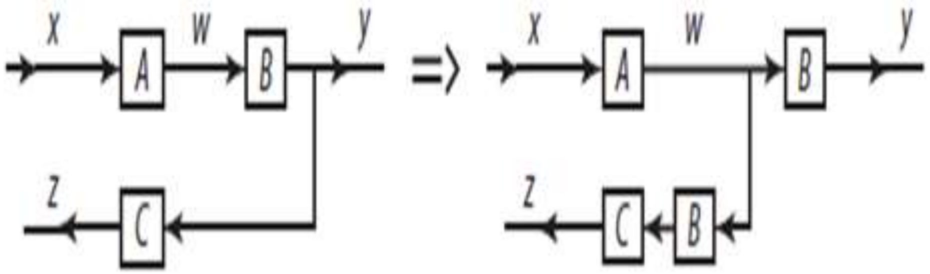


FIGURE 1.11 PICK-OFF POINT SHIFTED UPSTREAM



- **Moving Blocks Through Summing Junctions:**
- Moving blocks through summing junctions is based on the distributive property of the summation operation,

  $y=k(A+B)=kA+kB$.

Care must be taken to preserve the correct sign conventions.

Two situations are considered:

Moving a block through a summing junction in the **upstream** direction (See Figure 1.12)

and moving a block through a summing junction in the **downstream** direction (See Figure 1.13).

FIGURE 1.12 MOVING BLOCKS UPSTREAM THROUGH A SUMMING JUNCTION

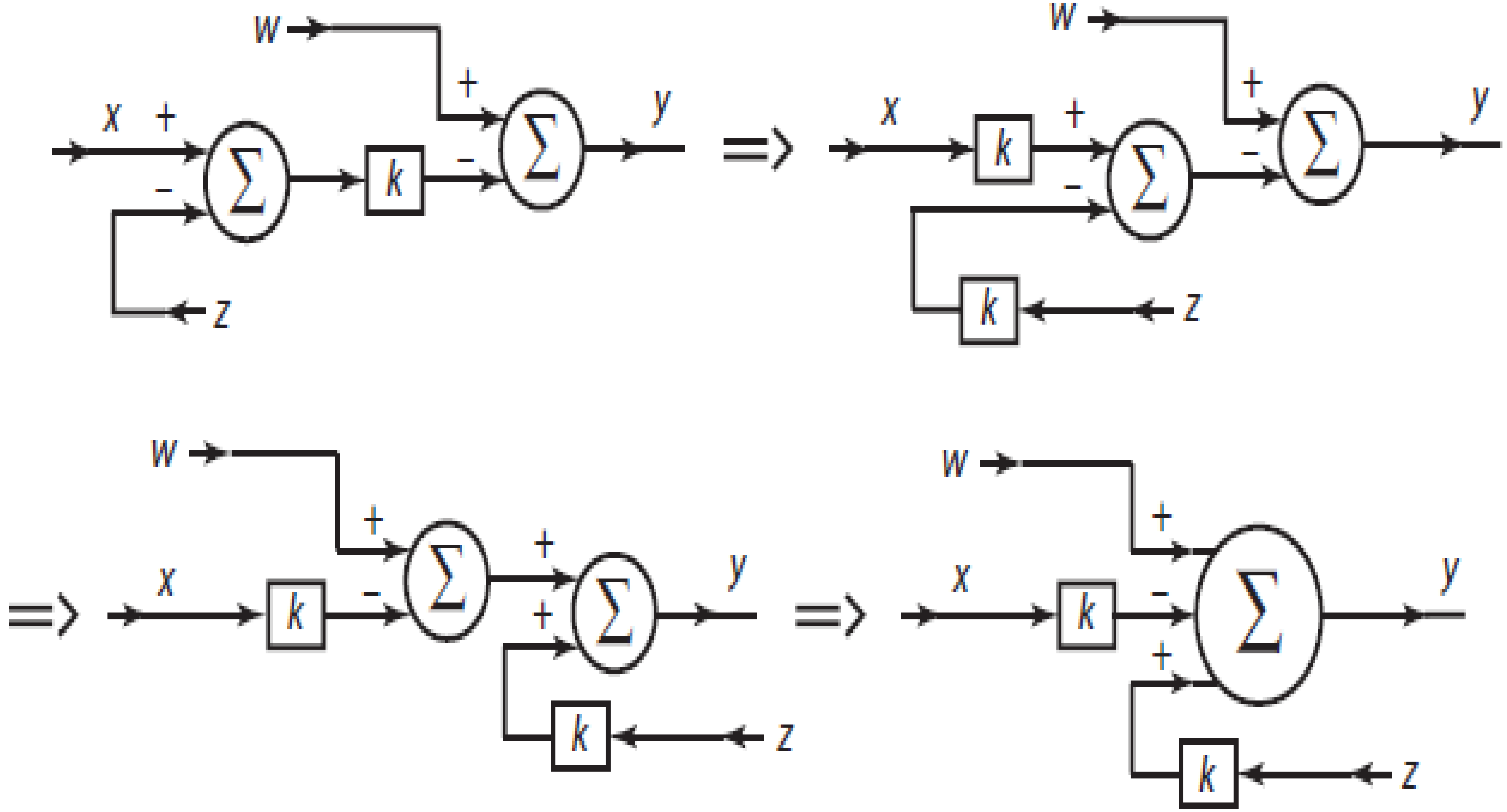
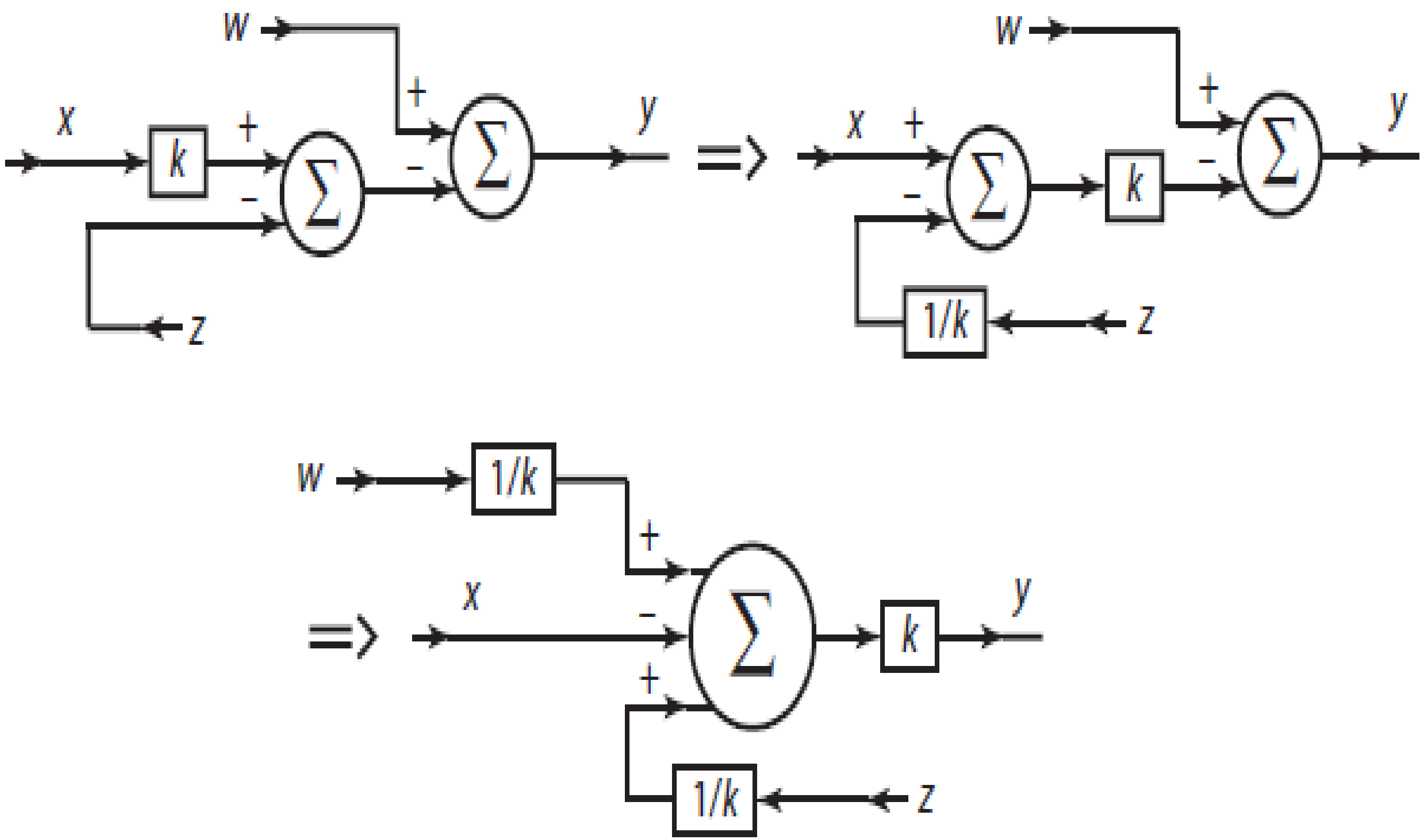


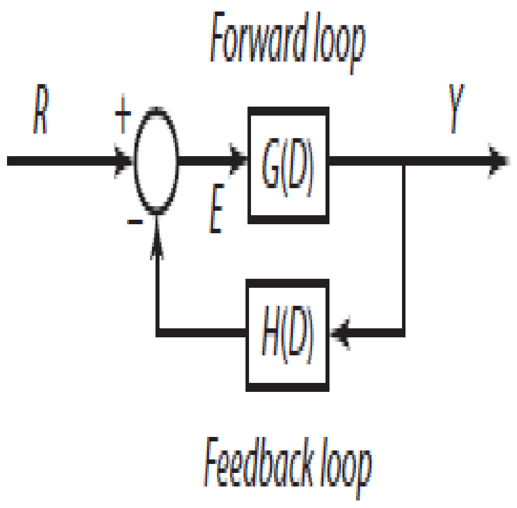
FIGURE 1.13 MOVING BLOCKS DOWNSTREAM THROUGH A SUMMING JUNCTION



Basic Feedback System Form

- One of the crucial ingredients of automatic control is *feedback*.
- It provides the mechanism for attenuating the effects of parameter variations and disturbances and enhancing dynamic tracking ability.
- The *basic feedback system* (BFS) shown in Figure 1.14 is the fundamental block diagram representing a feedback system.

FIGURE 1.14 BASIC FEEDBACK SYSTEM (BFS) BLOCK DIAGRAM



Basic Feedback System...

- The variable *R* is the input to the BFS, *E* is the control or error variable, and *Y* is the output.
- The closed-loop transfer function for the BFS is computed by writing two equations in three variables, *E*, and *Y*; then combining the equations to eliminate *E*; and solving for the ratio of *Y/R*.
- These steps are illustrated here.

Step 1. $E = R - H(D)\cdot Y$

Step 2. $Y = G(D)\cdot E$

Steps 1. → 2. $Y = G(D)\cdot(R - H(D)\cdot Y)$

$$Y + G(D)\cdot H(D)\cdot Y = G(D)\cdot R$$

$$Y\cdot(1 + G(D)\cdot H(D)) = G(D)\cdot R$$

$$\frac{Y}{R} = \frac{G(D)}{1 + G(D)\cdot H(D)}$$

Basic Feedback System…

- The function represents the transfer function around the loop of the feedback system and is called the *loop transfer function* (LTF). If a system is in BFS form, its *closed loop transfer function* (*CLTF* or *T*) can be written directly as

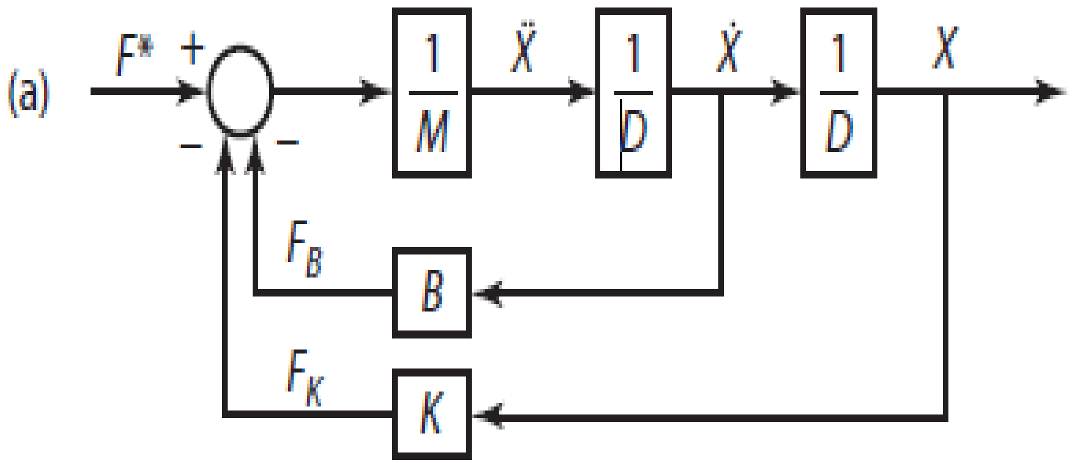
$$T(D) = \frac{\text{forward loop transfer function}}{1 + \text{loop transfer function}} = \frac{G(D)}{1 + G(D) \cdot H(D)}$$

The denominator of *T* is called the *return difference* and is defined as 1 + loop transfer function.

Simple Feedback Diagram Reduction

- Problem(1), the mass–spring–damper system model in Figure 1.15 has two feedback loops which represent the reaction forces exerted by the damper and the spring. Simplify the Block Diagram.

FIGURE 1.15 SIMPLIFYING A MASS-SPRING-DAMPER BLOCK DIAGRAM



Solution

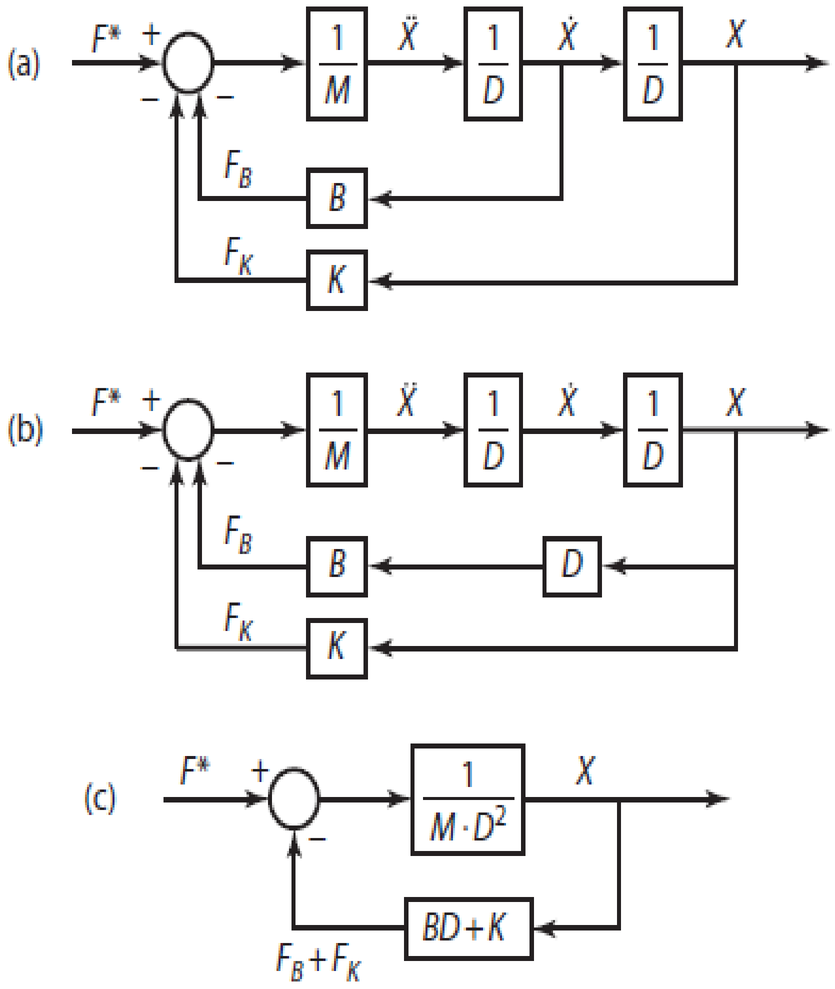
(a) Starting block diagram.

(b) The block diagram can be simplified by moving the $\dot{X}$ pick-off point to X and making the appropriate scaling change, a multiplication by 1/D , in the *FB* path.

(c) The two feedback loops now originate from the same pick-off point, X, and terminate at the same summing junction so they can be combined as a parallel combination.

- Similarly the entire forward loop can be reduced as a series combination.
- In this case, the price paid for the simplification is the loss of the $\ddot{X}$ and $\dot{X}$ signals. It is normal to expect the loss of some signal points, as a block diagram is simplified.

FIGURE 1.16 SIMPLIFYING A MASS–SPRING–DAMPER BLOCK DIAGRAM



Simulation

- Most visual simulation environments perform three basic functions.
- *Graphical Editing:* Used for the creation, editing, storage, and retrieval of models. Also used to create model inputs, orchestrate the simulation, and to present the model results.
- *Analysis:* Used to obtain transfer functions, compute frequency response, and evaluate sensitivity to disturbances.
- *Simulation:* Numerical solution of the block diagram model.
- All models in a visual simulation environment are block-diagram based, so a textual programming is not necessary; however, some environments supplement their block libraries with such a language for greater flexibility. Since block diagrams were introduced in the previous section, Let us see directly; the simulation process.

Simulation….

- **Simulation is the process through which the model equations are numerically solved.**
- The simulation process consists of three steps.

Step 1. Initialization

Step 2. Iteration

Step 3. Termination

Simulation….

- In the initialization step, the equations for each block in the system model are *sorted* according to the pattern in which the blocks are connected.
- For example, a model consisting of three blocks (A, B, and C) connected in series (input to A is exogenous, output of A to input of B, output of B to input of C) would have its equations sorted with the Block A equations first, followed by those in Block B, and then by those in Block C.
- The exogenous input to A would preceed the sorted list, as it is needed to process the A block.
- In the iteration step, differential equations present in the model are solved using numerical integration and/or differentiation, and the simulation time is advanced. Discrete equations are also solved in the iteration section.

Simulation....

- Results are presented in the termination step along with any other post-processed calculations. Output may be saved to a file, displayed as a digital reading, or graphically displayed as a chart, strip chart, meter readout, or even as an animation.

- All visual modeling environments include the simulation function. Some of the most commonly used environments are MATRIXX/System Build (National Instruments), MATLAB/ Simulink (Mathworks), LabVIEW (National Instruments), VisSim (Visual Solutions), and Easy5 (Boeing).

Electrical Systems

- Electrical circuits rely on two variables, voltage and current, to transport energy.
- Since current flows through an electrical circuit, it is natural to associate current with the flow variable and voltage with the potential variable.
- Using this convention, the impedances of six basic ideal circuit components are discussed: the resistor, capacitor, inductor, voltage source, current source, and transformer.
- The impedances of these components will provide the fundamental analogies for components in other disciplines.
- Of the six basic electrical components, only the resistor, capacitor, and inductor have impedance's which are not functions of the circuit to which they are attached. The resistor, capacitor, and inductor impedance characteristics are summarized in Table 1-2. The remaining three components have impedances which are functions of the circuit to which they are attached (Table 1.3)

TABLE 1.2 RESISTOR, CAPACITOR, AND INDUCTOR IMPEDANCES

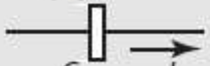
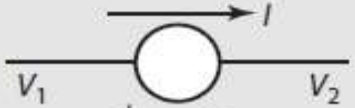
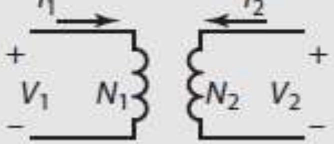
Analogy		Component		
$PV =$ Voltage, v	$FV =$ Current, i	Resistor: $+ V -$  R I $\Rightarrow Z_R = R$	Capacitor: $+ V -$  C I $\Rightarrow Z_C = \frac{1}{CD}$	Inductor: $+ V -$  L I $\Rightarrow Z_L = LD$

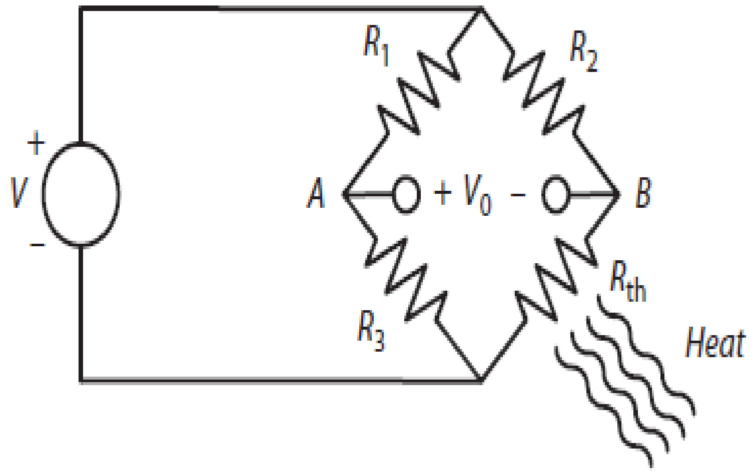
TABLE 1.3 VOLTAGE SOURCE, CURRENT SOURCE, AND TRANSFORMER IMPEDANCES

Component	Impedance Relationship
 I V_1 V_2 $+$ $-$ V Voltage source	Defining Equations: $V = V_1 - V_2$ $I = f_1$(Attached circuit) Impedance: $Z_{VS} = f_2$(Attached circuit)
 V_1 V_2 $+$ $-$ I Current Source	Defining Equation: $I =$ Specified current $V_1, V_2 = f_1$ (Attached circuit) Impedance: $Z_{CS} = f_2$ (Attached circuit)
 I_1 I_2 $+$ V_1 N_1 N_2 V_2 $+$ $-$ $-$ Primary Secondary Transformer	Defining Equations: $\frac{V_2}{V_1} = \frac{N_2}{N_1}$ and $\frac{I_1}{I_2} = \frac{N_2}{N_1}$ Impedance: $Z_T = f$(Attached circuit)

Bridge Circuit System

- A thermistor is a semiconductor device whose resistance changes with temperature. Temperature readings in terms of voltage can be obtained by installing the thermistor as one of the resistances in a bridge circuit. A typical configuration is shown in Figure 1.17.

FIGURE 1.17 BRIDGE CIRCUIT FOR TEMPERATURE MEASUREMENT



Bridge Circuit System…

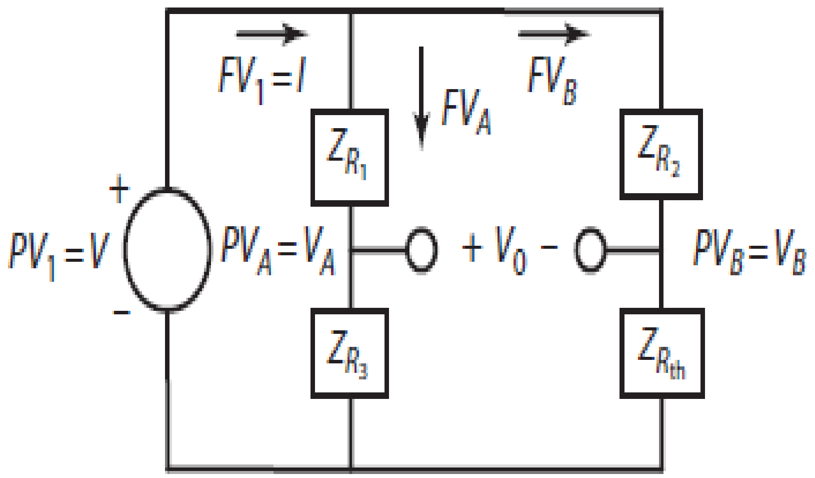
- When a constant voltage is applied to the circuit, *V*, heat source variations cause the thermistor resistance to change, thus creating a potential difference between points A and B, which is proportional to temperature.
- The objective of this example is to apply the analogy method to develop a block diagram model of the bridge circuit.
- **Solution**

Step 1. *Create/simplify the impedance diagram*.

- The first step of the procedure is the construction of the impedance diagram. This is relatively straightforward.
- All flow paths, potentials, and branches remain intact; the only difference is the replacement of each component with its associated impedance.

The impedance diagram is presented in Figure 1.18.

FIGURE 1.18 IMPEDANCE DIAGRAM FOR TEMPERATURE MEASUREMENT CIRCUIT



- **Step 2.** *Identify all independent nodes (FV and PV) in the impedance diagram and label all signals.*
- The impedance diagram has one *FV* node and two *PV* nodes. The node equations are given as

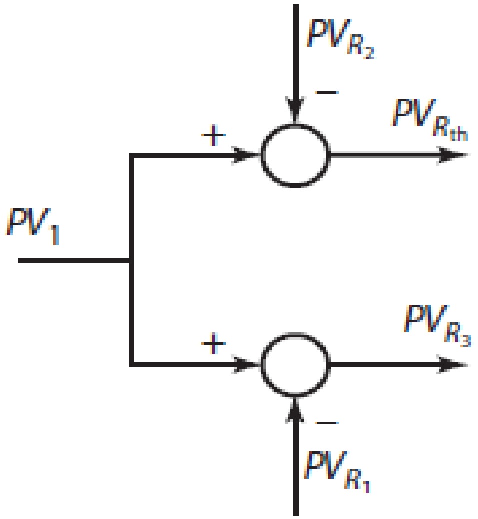
$$FV \text{ node equation: } FV_1 = FV_A + FV_B$$

$$PV \text{ node 1 equation: } PV_1 = PV_{R_1} + PV_{R_3} \text{ (note that } PV_A = PV_{R_3}\text{)}$$

$$PV \text{ node 2 equation: } PV_1 = PV_{R_2} + PV_{R_{th}} \text{ (note that } PV_B = PV_{R_{th}}\text{)}$$

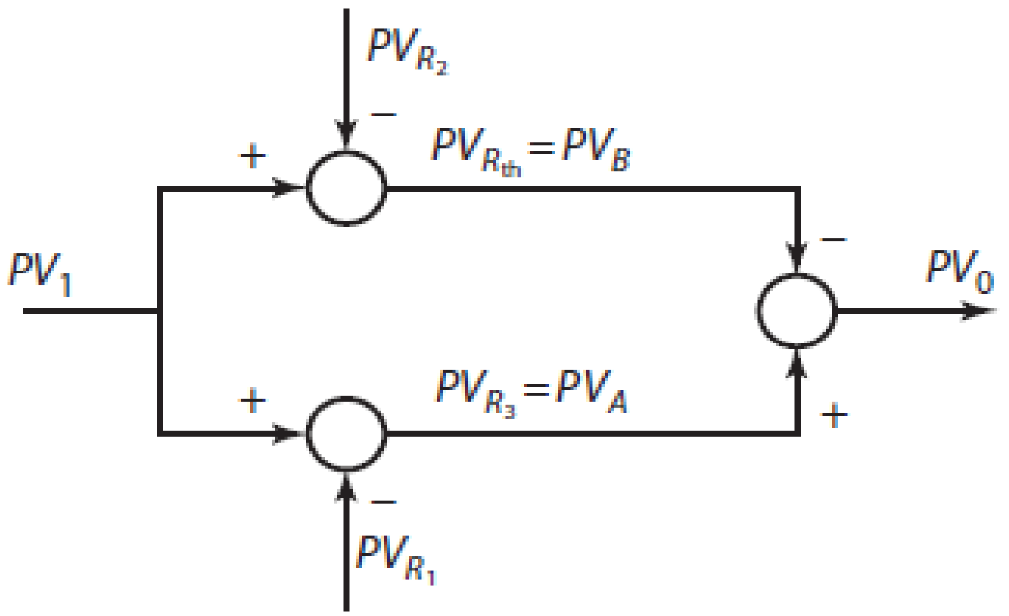
- **Step 3**. *Represent select nodes as a summing junction, and select the output of the summing junction such that (when it is connected to its associated impedance blocks) either gain or integral causality results.*
- The initial block diagram is constructed with two summing junctions to model the two *PV* nodes, Figure 1-19.

FIGURE 1.19 SUMMING JUNCTIONS FOR TEMPERATURE MEASUREMENT CIRCUIT BLOCK DIAGRAM



Next, the diagram is slightly modified to include the definitions $PV_A = PV_{R_3}$, $PV_B = PV_{R_{th}}$, and $V_0 = PV_0 = PV_A - PV_B$. These additions are presented in Figure 1.20

FIGURE 1.20 SUMMING JUNCTIONS FOR TEMPERATURE MEASUREMENT CIRCUIT BLOCK DIAGRAM WITH SLIGHT MODIFICATION



- **Step 4**. *Add the impedance blocks; connect and create all necessary intermediate and output signals to complete the block diagram.*

The FV node equation was not directly implemented using a summing junction; however, since Z_{R_1} and Z_{R_3} both have the same flow, FV_A, and since Z_{R_2} and $Z_{R_{th}}$ have FV_B flowing through them, the following two constraint relationships are written.

$$FV_A = \frac{PV_{R_1}}{Z_{R_1}} = \frac{PV_A}{Z_{R_3}} \Rightarrow PV_{R_1} = \frac{Z_{R_1}}{Z_{R_3}} \cdot PV_A$$

$$FV_B = \frac{PV_{R_2}}{Z_{R_2}} = \frac{PV_B}{Z_{R_{th}}} \Rightarrow PV_{R_2} = \frac{Z_{R_2}}{Z_{R_{th}}} \cdot PV_B$$

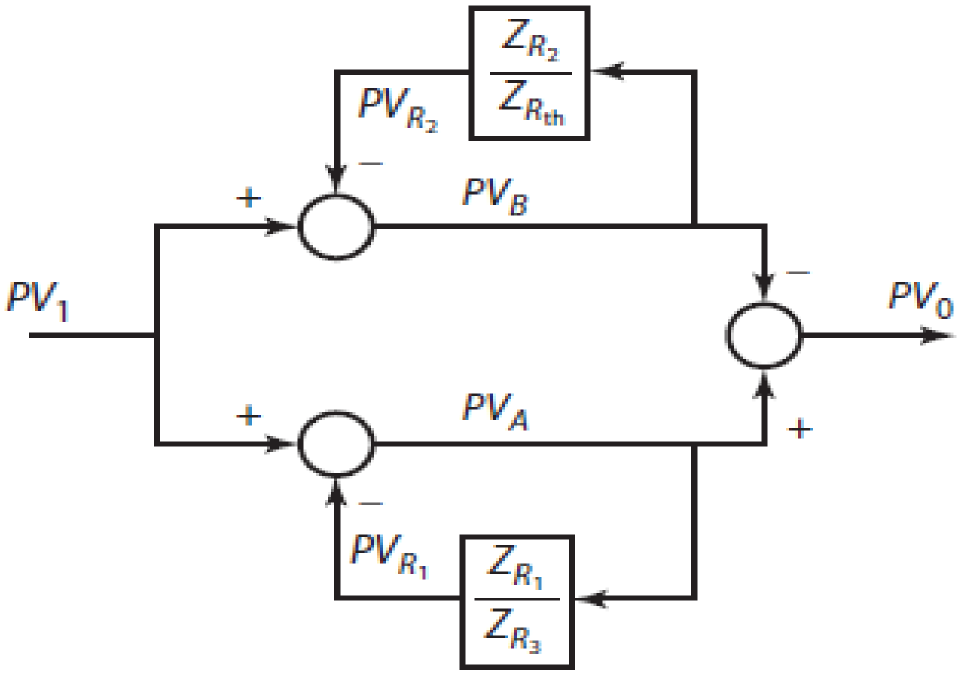
The final block diagram, Figure **1.21** is constructed by adding these two relationships to the block diagram to define the PV_{R_1} and PV_{R_2} signals. From the revised block diagram, the system equations may be derived after substituting the appropriate resistance values and noting that $V = PV_1$, $V_A = PV_A$, and $V_B = PV_B$, we have

$$V_A = \frac{R_3}{R_1 + R_3} V$$

$$V_B = \frac{R_{th}}{R_2 + R_{th}} V$$

$$\text{Potential difference A} - \text{B: } V_{AB} = V_0 = \left(\frac{R_3}{R_1 + R_3} - \frac{R_{th}}{R_2 + R_{th}} \right) V$$

FIGURE 1.21 BLOCK DIAGRAM FOR TEMPERATURE MEASUREMENT CIRCUIT



As written, the system equation represents the output voltage as a function of the thermistor resistance and the input voltage; $V_0 = V_0(R_{th}, V)$. With a constant input voltage, the output voltage becomes only a function of the thermistor resistance.

Mechanical Translational Systems

- Mechanical systems can be either translational or rotational.
- Although the fundamental relationships for both types are derived from Newton's law, they are different enough to warrant separate consideration.
- Mechanical translation system analysis is based on Newton's law, which states:
- **The vector sum of all forces applied to a body equals the product of the vector acceleration of the body times it's mass.**

Mechanical Translational Systems….

The equation for Newton's law is presented in Equation

$$F = Ma$$

where the units in the British system are

$$F = \text{total force, newtons, N}$$

$$M = \text{mass, kg}$$

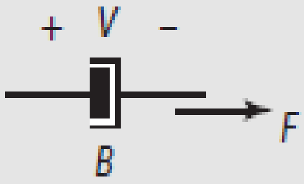
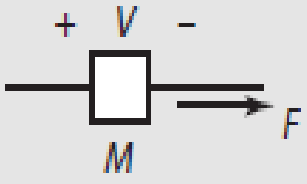
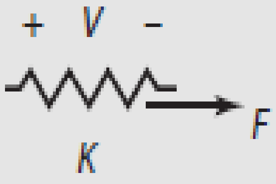
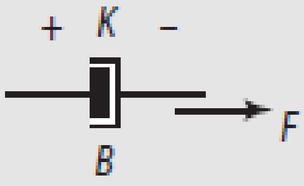
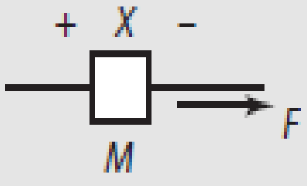
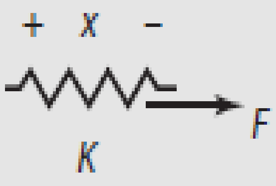
$$a = \text{total acceleration, } \frac{\text{m}}{\text{s}^2}$$

Mechanical Translational Systems….

- Two elements typically encountered in mechanical systems are the linear damper and the linear spring.
- The linear damper produces a force proportional to the applied velocity, and the linear spring produces a force proportional to the applied displacement.
- Depending on the system, either velocity or displacement may be used as the *PV*.
- Regardless of the choice of *PV*, force is used for the *FV*.
- Table 1-4 summarizes the impedance's of the three mechanical translation system components for both analogies.

Mechanical Translational Systems….

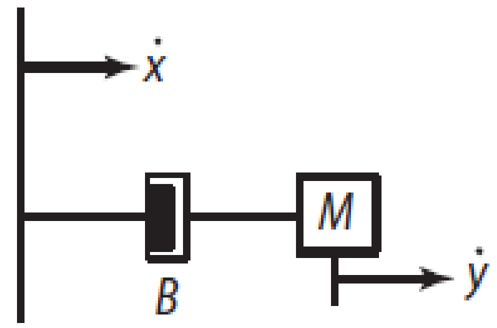
TABLE 1.4 MECHANICAL SYSTEM IMPEDANCE ANALOGIES

Analogy		Component		
PV = Velocity, v	FV = Force, F	Viscous damper:  $\Rightarrow Z_B = \frac{1}{B}$	Mass:  $\Rightarrow Z_M = \frac{1}{MD}$	Spring:  $\Rightarrow Z_K = \frac{D}{K}$
PV = Displacement, x	FV = Force, F	Viscous damper:  $\Rightarrow Z_B = \frac{1}{DB}$	Mass:  $\Rightarrow Z_M = \frac{1}{MD^2}$	Spring:  $\Rightarrow Z_K = \frac{1}{K}$

Mass–Damper System

- The basic mass–damper system is modeled in this example.
- Selection of logical *PV* and *FV* variables will create a causality problem which is also discussed.
- An illustration of the mass–damper system is shown in Figure 1-22. Since the input, $\dot{x}$, and output, $\dot{y}$, of the system are both velocities and no springs are involved, velocity is the logical choice for the potential variable.
- The flow variable is force.

FIGURE 1.22 MASS–DAMPER SYSTEM ILLUSTRATION



Solution

Step 1. *Create/simplify the impedance diagram.*

The impedance diagram for the mass–damper system is created by replacing each element of the circuit with its associated impedance.

Mass–Damper System..

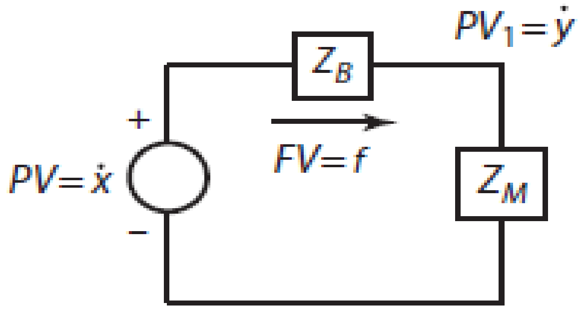
- The impedances are defined as

$$Z_B = \frac{1}{B}$$

$$Z_M = \frac{1}{MD}$$

The impedance diagram is presented in Figure 1.23.

FIGURE 1.23 MASS–DAMPER SYSTEM IMPEDANCE DIAGRAM



Step2: Identify all independent nodes (FV and PV) in the impedance diagram and label all signals.

- The impedance diagram consists of one *PV* node represented by the following equation.

$$PV - PV_{ZB} - PV_{ZM} = 0$$

The three auxiliary equations are also reaquired.

$$PV_{ZB} = Z_B \cdot FV$$

$$PV_{ZM} = Z_M \cdot FV$$

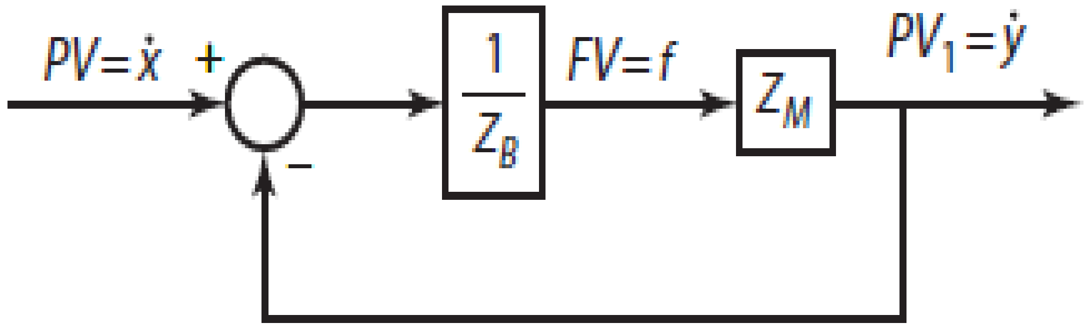
$$PV_{ZM} = PV_1$$

- **Step 3.** *Represent select nodes as a summing junction and select the output of the summing junction such that (when it is connected to its associated impedance blocks) either gain or integral causality results.*
- Integral causality for the Z_M element requires that *FV* be its input.
- Our strategy is to model the *PV* node equation such that PV_{ZB} is the output.
- The damper, which has no causality problems because the potential variable is velocity, is used to create the *FV* required as input to the Z_M block.
- Step 4. *Add the impedance blocks; connect and create all necessary intermediate and output signals to complete the block diagram.*

- The resulting block diagram is presented in Figure 1.24.
- The output velocity, $\dot{y}$, is computed by reducing the block diagram and substituting for the two impedances as

$$\dot{y} = \frac{Z_M}{Z_M + Z_B}\dot{x} = \frac{B}{MD + B}\dot{x}$$

FIGURE 1.24 MASS-DAMPER BLOCK DIAGRAM



- The force flowing through the system, *FV*, may also be computed from the block diagram as

$$f = \frac{\dot{x} - \dot{y}}{Z_B} = (\dot{x} - \dot{y})B$$

One also could solve this problem using displacement instead of velocity as the potential variable.

The input and output variables become *x* and *y*.

Since displacement is the integral of velocity and integration is represented in operator notation as 1/D , the impedances in the displacement–voltage analogy system are equivalent to the impedances of the velocity–voltage system multiplied by 1/D . These impedances become

$$Z_B = \frac{1}{BD} \text{ and } Z_M = \frac{1}{MD^2}$$

Because the system is linear, the transfer function relating $\dot{x}$ to $\dot{y}$ is

$$\dot{y} = \frac{B}{MD + B}\dot{x}$$

We can compute the transfer function from x to y by integrating both sides. This is analogous to division by the D operator. The resulting transfer function becomes

$$y = \frac{B}{MD + B}x$$

Mechanical Rotational Systems

- Mechanical rotational system analysis also is based on Newton's Law; however, the law is slightly modified to account for rotation instead of translation.
- The law states:
- **The vector sum of all moments applied to a body equals the product of the vector angular acceleration of the body times it's inertia.**

A rotational system obeys Equation

$$T = J\ddot{\theta}$$

- In the SI system, the units are defined as

T = total torque, N-m

J = body inertia about it’s center of mass, kg-m^2

$$\ddot{\theta} = \text{angular acceleration, } \frac{\text{rad}}{\text{s}^2}$$

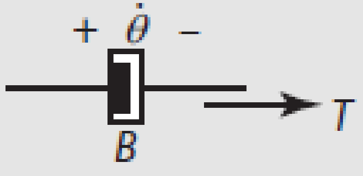
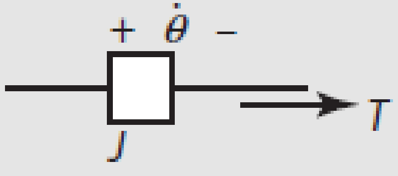
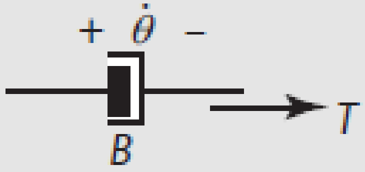
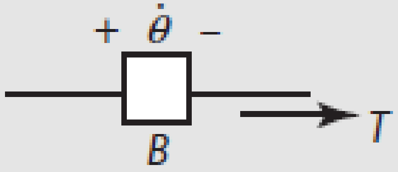
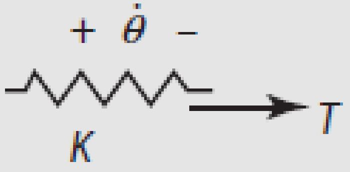
Two elements typically encountered in mechanical rotational systems are the linear torsional damper and the linear torsional spring.
The damper produces a torque proportional to the applied angular velocity,
and the spring produces a torque proportional to the applied angle.

An analogy similar to that used for translation systems exists for rotational systems—except angle replaces displacement, angular speed replaces velocity, and torque replaces force.

- Also, mass becomes inertia, the translational spring constant becomes a torsional spring constant, and translational damping becomes rotational damping.
- The impedance analogies are identical in form to those used in translational systems. The flow variable is defined as torque, and the potential variable is defined as either angular velocity or angle.

The analogies and impedances for rotational systems are summarized in Table 1-5.

TABLE 1-5 IMPEDANCE ANALOGIES FOR ROTATIONAL SYSTEMS

Analogy		Component		
PV = Velocity, $\dot{\theta}$	FV = Torque, T	Damper:  $\Rightarrow Z_B = \frac{1}{B}$	Inertia:  $\Rightarrow Z_M = \frac{1}{JD}$	Spring:  $\Rightarrow Z_K = \frac{D}{K}$
PV = Displacement, θ	FV = Torque, T	Damper:  $\Rightarrow Z_B = \frac{1}{DB}$	Mass:  $\Rightarrow Z_M = \frac{1}{MD^2}$	Spring:  $\Rightarrow Z_K = \frac{1}{K}$

The SI Units used for mechanical rotational systems are summarized in Table 1-6.

TABLE 1-6 ROTATIONAL SYSTEM UNITS

System	T	$\ddot{\theta}$	K	B	J
SI	nt − meter	$\frac{\text{rad}}{\text{sec}^2}$	$\frac{\text{kg} - \text{meter}^2}{\text{sec}^2}$	$\frac{\text{kg} - \text{meter}^2}{\text{sec}}$	kg − meter^2

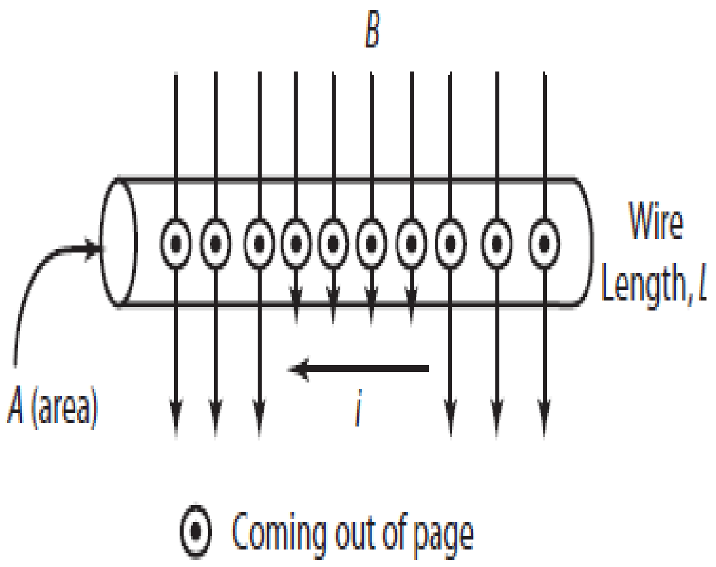
Electrical–Mechanical Coupling

- Motors, generators, and various sensors couple electrical systems with mechanical systems.
- The electromagnetic coupling is based on two laws: Lorentz's Law which describes electrical to mechanical coupling and
- Faraday's Law describing mechanical to electrical coupling.

Lorentz's Law—Electrical to Mechanical Coupling

- Lorentz's force law, Figure 1-25, is used to relate current traveling through a wire in a magnetic field to force exerted on the wire.

FIGURE 1-25 LORENTZ'S FORCE LAW



$$F = ilB \text{ (Lorentz's Law)}$$

where

F = force, newtons

i = current, amps = $\frac{\text{coulombs}}{\text{s}}$

l = length of wire, meters

B = magnetic field, Tesla = $\frac{\text{newtons}}{\text{Amp} \cdot \text{meter}}$

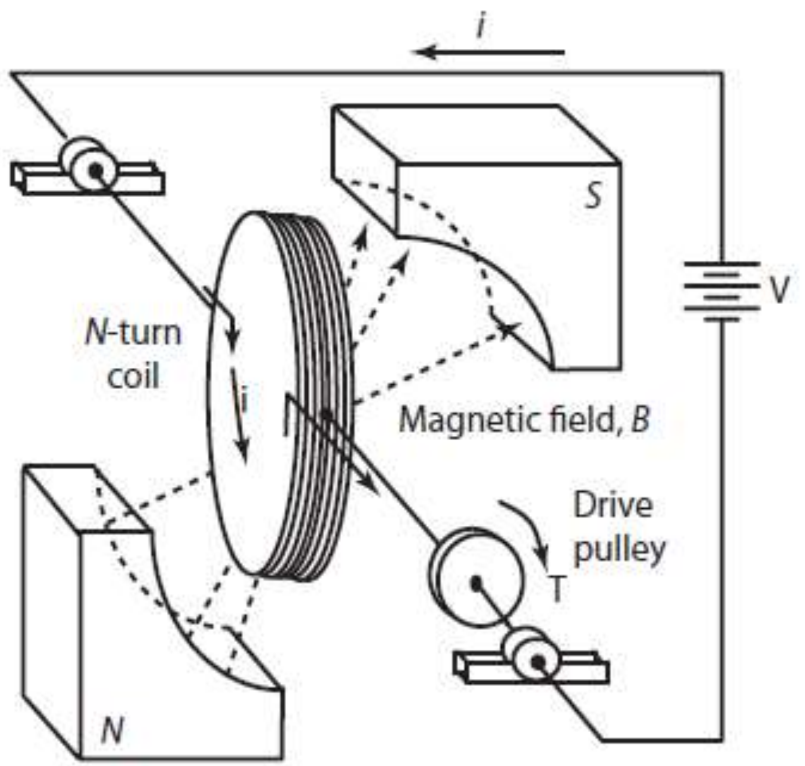
Lorentz’s Law….

- The force exerted on the wire is coming up out of the page, obeying the right-hand rule: pointer finger in the direction of the current, middle finger in the direction of the magnetic field, and thumb in the direction of the force.
- The magnetic field is oriented at right angles to the current traveling through the wire.
- In situations where an angle other than 90° exists, the force is $F = ilB \sin \varphi.$ using the orthogonal component of the magnetic field,
- Lorentz’s law relates current through a wire in a magnetic field to the mechanical translation force on the wire.

Lorentz's Law….

- A more useful form of the law, Figure 1-26, relates current in a coil to the mechanical torque exerted by the coil.

FIGURE 1-26 CURRENT–TORQUE RELATIONSHIP OF A COIL



Lorentz's Law....

Torque exerted by a current loop is the basic operating principal of many devices, including the electric motor and most electric meters.

$$T = NiAB \sin \varphi \text{ (Lorentz's law)}$$

where

T = torque, newton − meters

N = number of turns in the coil

i = current, amps

A = coil area, meters^2

B = magnetic field, Tesla $= \dfrac{\text{newtons}}{\text{amp} \cdot \text{meter}}$

φ = angle between B and current

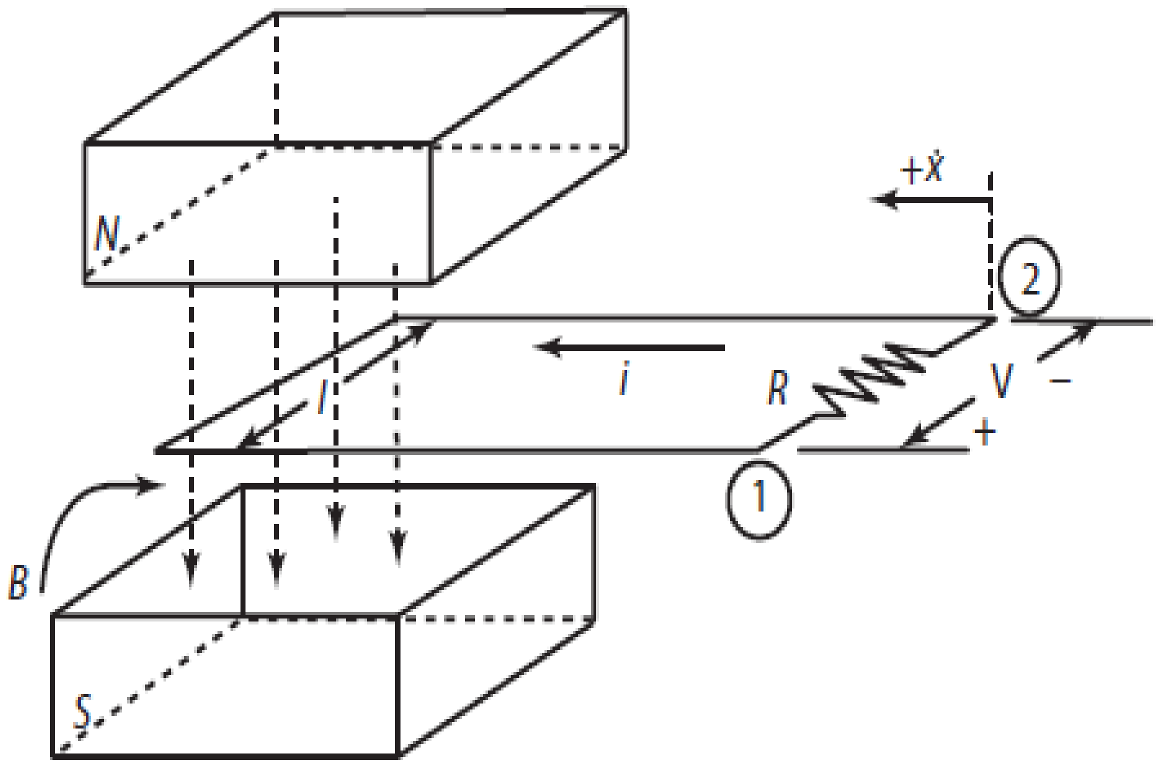
Lorentz's Law….

- An external voltage supply, V, is used to create the current flowing through the coil. The torque exerted by the coil, T, (accessible through the drive pulley) is in the clockwise direction obeying the right-hand rule: pointer finger in the direction of the current, middle finger in the direction of the magnetic field, and thumb in the direction of the force.
- The magnet is curved to follow the radius swept by the rotating coil for a fraction of the complete revolution.
- During that fraction, the angle between the current direction and the magnetic field, φ, is 90°; however, as the coil rotates further, only the orthogonal component of the magnetic field, $B\sin\varphi$, is used, hence the reason for the $\sin\varphi$ term.

Faraday's Law—Mechanical to Electrical Coupling

- Faraday's law of induction (Figure 1-27) relates the velocity of a wire loop as it is moved through a magnetic field to induce voltage (and current since the loop is closed) in the wire loop.

FIGURE 1-27 FARADAY'S INDUCTION LAW



Faraday's Law….

According to Faraday's law, current and voltage are induced in the closed loop only when motion exists $(\dot{x} \neq 0)$, ,otherwise the induced current and voltage are zero.

$$V = B\, l\, \dot{x} \text{ (Faradays law)}$$

$$i = \frac{V}{R} \text{ (Ohms law)}$$

where

$$V = \text{Induced voltage,volts}$$

$$B = \text{Magnetic field, Tesla} = \frac{\text{newton}}{\text{amp} \cdot \text{meter}}$$

$$l = \text{length of wire, meters}$$

$$\dot{x} = \text{horizontal velocity of loop, } \frac{\text{meters}}{\text{sec}}$$

$$i = \text{current, amps} = \frac{\text{coulombs}}{\text{s}}$$

$$R = \text{wire loop resistance, } \Omega$$

Ball Screws

- Ball screws are essential components in mechatronics systems, providing efficient and precise linear motion for various applications. They are mechanical devices used to convert rotary motion into linear motion or vice versa. The ball screw consists of three main parts: a screw shaft, a ball nut, and recirculating ball bearings.

- Ball screws are a type of linear actuator that is commonly used in mechatronic systems. They are characterized by their high efficiency, precision, and repeatability

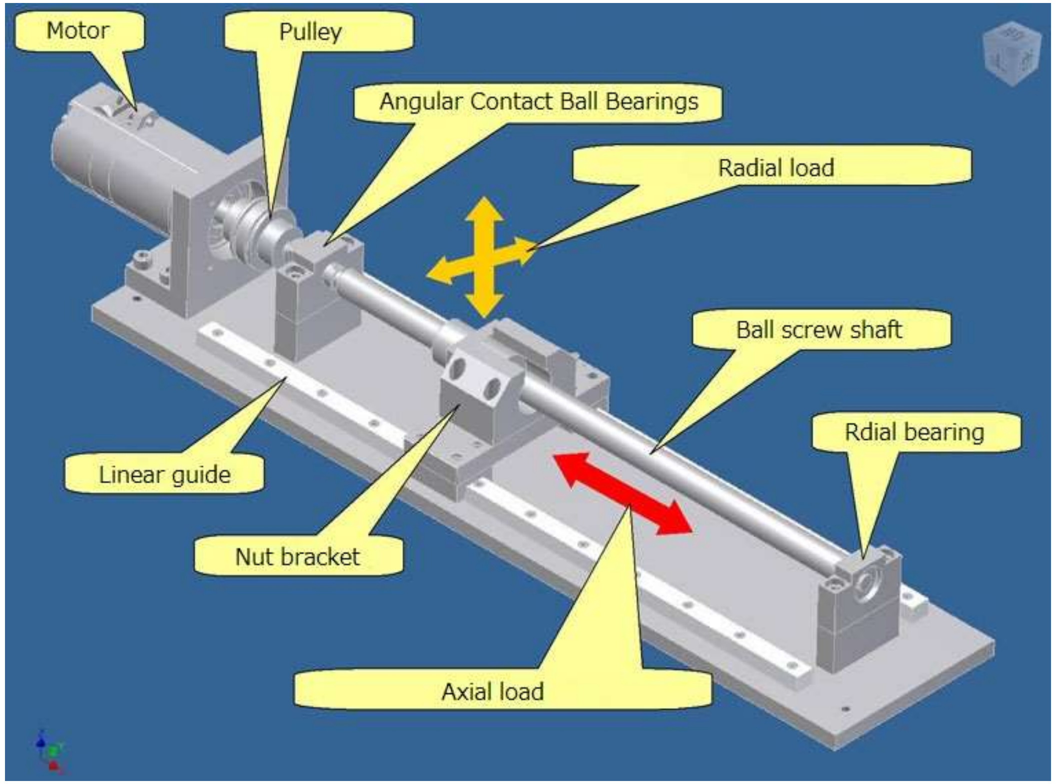
Parts Ball Screws…..

- Screw Shaft: The screw shaft is a threaded rod with precision-ground grooves, also known as helical raceways. The helical raceways form a track for the ball bearings to move along as the screw rotates. The screw shaft is typically made of high-quality steel to ensure durability and precision.

- Ball Nut: The ball nut is a housing that contains a set of ball bearings. These ball bearings are recirculating type, which means they continuously circulate through the ball nut as the screw rotates. The ball nut has internal grooves that match the screw shaft's helical raceways, allowing the ball bearings to move smoothly along the threads.

Ball Screws.....

- **Recirculating Ball Bearings**: The ball bearings are the crucial element of the ball screw. They are precision-machined small spheres that fit into the helical grooves of both the screw shaft and the ball nut. As the screw shaft rotates, the ball bearings roll between the two components, enabling smooth linear motion.



Stainless Steel Rust Proof Hiwin Ball Screw

Ball Screws…..

- Working Principle: When rotary motion is applied to the screw shaft (usually through a motor), the ball bearings inside the ball nut move along the helical raceways.
- This motion converts the rotational movement into linear motion, causing the ball nut to move along the length of the screw shaft. The direction of the linear motion depends on the rotation direction of the screw shaft.

Advantages of Ball Screws in Mechatronics:

- High Efficiency: Ball screws are known for their high efficiency in converting rotary motion to linear motion and vice versa. This efficiency is crucial in mechatronics systems, where precision and energy efficiency are essential.
- Precision and Repeatability: Ball screws offer excellent precision and repeatability, making them suitable for applications that require accurate positioning and motion control, such as CNC machines and robotics.

Advantages of Ball Screws in Mechatronics….

- Reduced Friction: The rolling contact between the ball bearings and the helical raceways results in lower friction compared to other types of linear motion systems, like lead screws. This reduces wear and extends the ball screw's lifespan.
- Backlash Compensation: Ball screws can be designed with low or even zero backlash, ensuring better control and eliminating errors caused by play in the system.
- High Load Capacity: Ball screws can handle significant axial loads, making them suitable for heavy-duty applications where large forces need to be transmitted.

Applications of Ball Screws in Mechatronics:

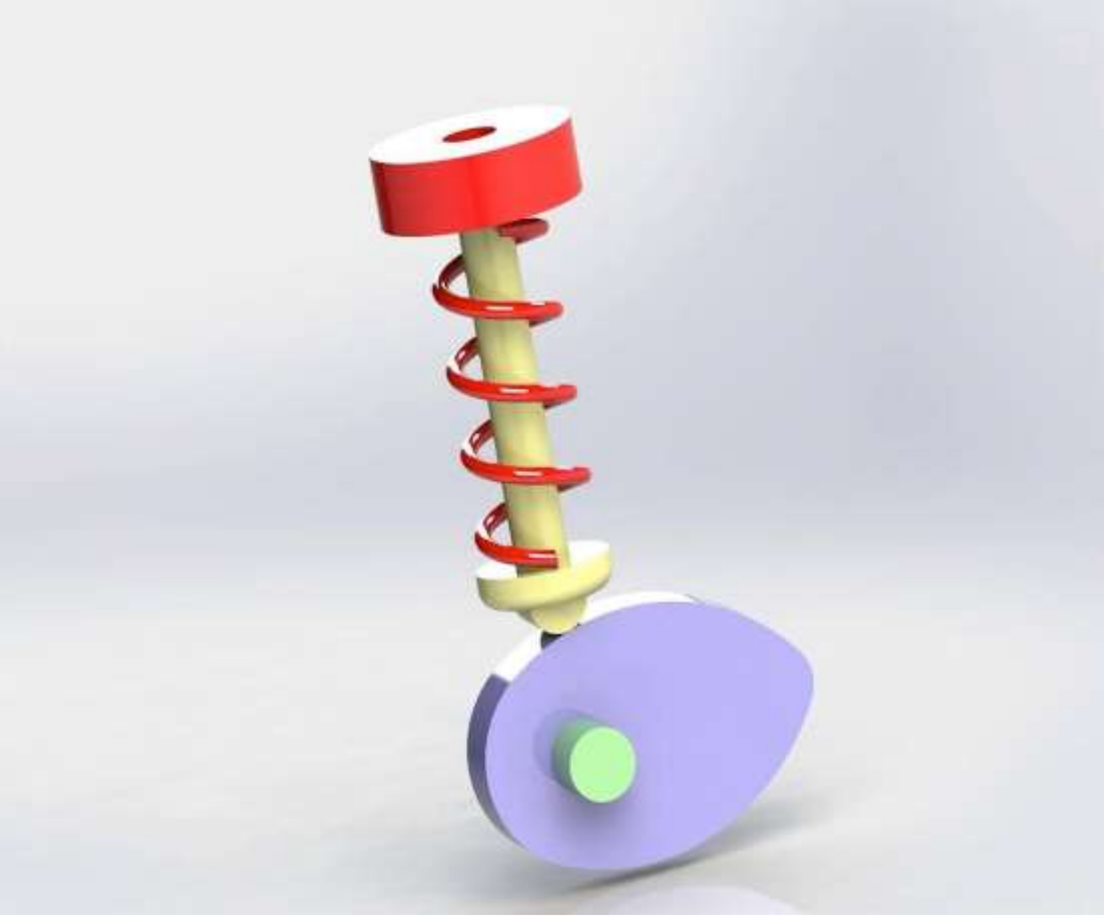
- CNC machines and 3D printers for precise positioning and motion control.
- Industrial robots and automation systems for accurate and repeatable movements.
- Aircraft control surfaces, where precise actuation is critical for flight control.
- Medical devices, such as surgical robots and imaging systems.
- Semiconductor manufacturing equipment for wafer handling and precision positioning.

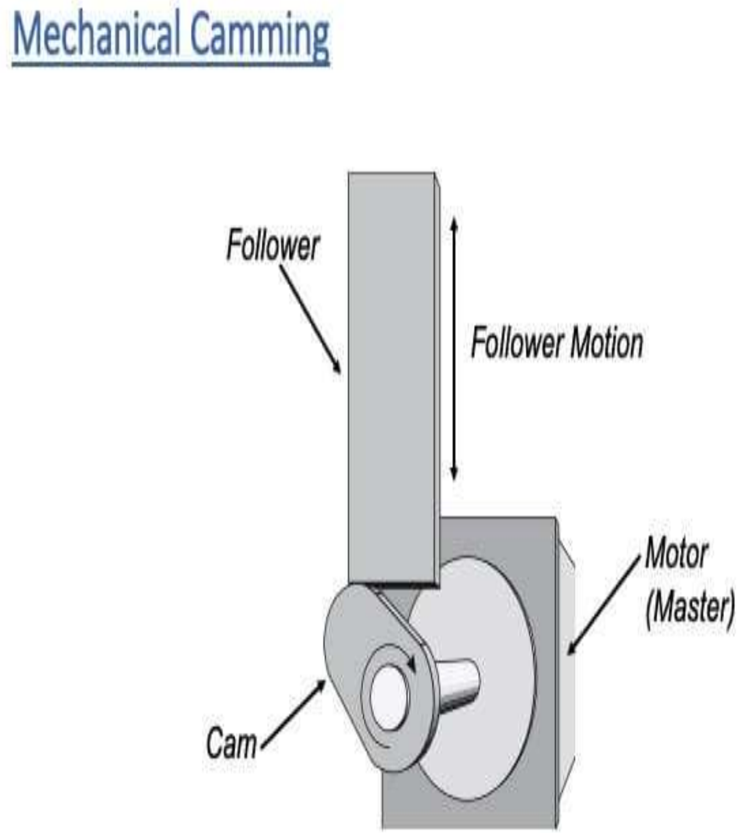
Ball Screws…..

- Overall, ball screws play a vital role in mechatronics by providing efficient, precise, and reliable linear motion, contributing to the advancement of various industries and technologies.

Electronic cams

- Electronic cams, also known as digital or virtual cams, are essential components in mechatronics systems that emulate the functionality of traditional mechanical cams using electronic control.
- In traditional mechanical systems, cams are physical profiles attached to rotating shafts that impart specific motion profiles to follower mechanisms.
- Electronic cams replicate this functionality using software algorithms and control systems without the need for physical cam profiles.





Mechanical cam systems

Working of Electronic cams in Mechatronics systems

- Here is a simplified overview of how electronic cams work in mechatronics systems:

- The desired motion profile is created in a digital format.
- The motion profile is stored in the memory of a controller.
- The controller sends a signal to a servomotor.
- The servomotor generates the desired motion of the follower.

Working of Electronic cams……

- The motion profile can be created using a variety of software tools. Once the motion profile is created, it can be stored in the memory of the controller or in an external device. The controller then uses the motion profile to generate the desired motion of the follower.
- The servomotor is responsible for converting the electrical signal from the controller into mechanical motion. The servomotor is typically a brushless DC motor with a feedback sensor. The feedback sensor measures the position of the motor shaft, and the controller uses this information to ensure that the motor is moving in the correct direction and at the correct speed.

Working of Electronic cams……

- The follower is the part that is attached to the cam and moves up and down as the cam rotates. The follower is typically a linear actuator, such as a ball screw or a lead screw. The follower converts the rotary motion of the cam into linear motion.
- Electronic cams offer a number of advantages over traditional mechanical cams. They are more precise, repeatable, flexible, and durable. As a result, they are becoming increasingly popular in mechatronic systems.

Advantages of Electronic Cams in Mechatronics Systems

- Flexibility: Electronic cams offer greater flexibility compared to traditional mechanical cams. The motion profile can be easily adjusted or changed by modifying the software or data points, without the need for physical changes to the system.
- Complex Motion Profiles: Electronic cams can generate complex motion profiles that may be challenging or impossible to achieve with mechanical cams. This capability is especially useful in applications that require precise and intricate motion control.

Advantages of Electronic Cams…..

- Programmable: The behavior of the electronic cam system can be programmed and easily integrated into larger mechatronics systems, allowing for sophisticated automation and control.
- Reduced Mechanical Wear: As electronic cams do not rely on physical contact between components like traditional mechanical cams, there is typically less mechanical wear and tear, leading to longer service life and reduced maintenance requirements.

Applications of Electronic Cams in Mechatronics Systems

- Packaging and Material Handling: Electronic cams are used in packaging machines and conveyor systems to control the movement of boxes, packages, and materials along predefined paths.
- Robotics: In robotics, electronic cams help generate smooth and precise motion profiles for robotic arms and end effectors, enabling accurate positioning and handling of objects.
- Printing and Labeling: Electronic cams are used in printing and labeling machines to control the positioning and movement of print heads or label applicators.

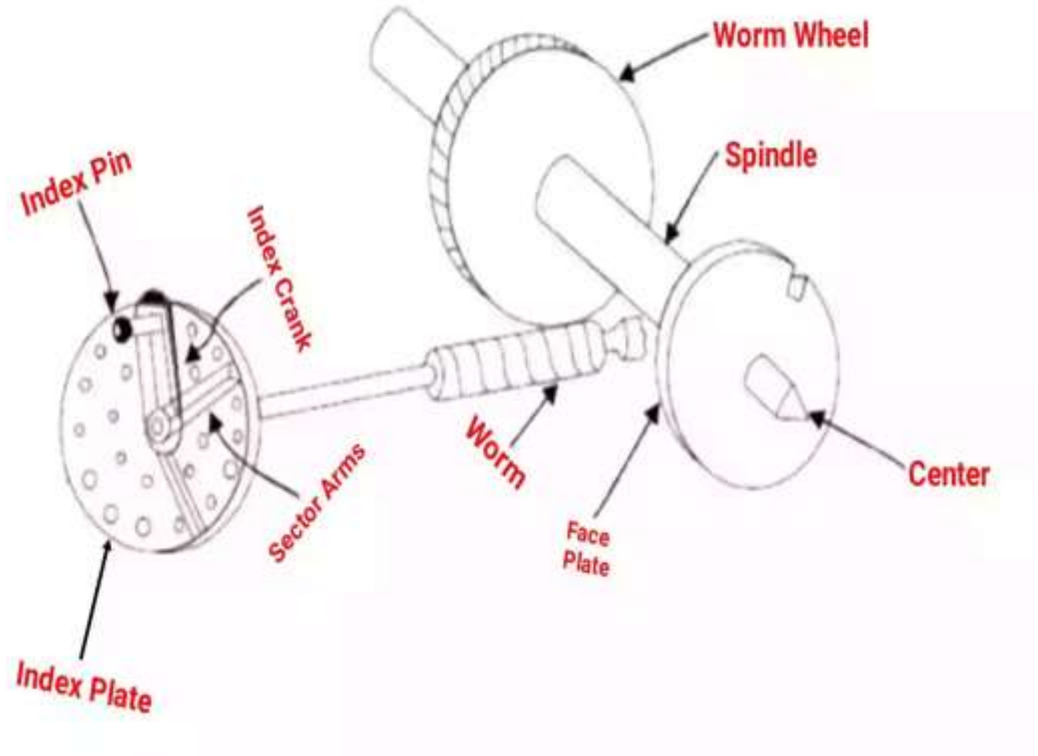
Applications of Electronic Cams…

- CNC Machines: In Computer Numerical Control (CNC) machines, electronic cams play a role in controlling the tool paths and movements of cutting tools to produce complex shapes and patterns.
- Overall, electronic cams in mechatronics systems provide a versatile and programmable solution for achieving controlled and precise motion, allowing for advanced automation and improved performance in various industrial applications

Indexing mechanism

- An indexing mechanism refers to a mechanism or device used to achieve precise and repeatable angular positioning of a component or work piece. It is commonly employed in machines and automated systems where accurate angular indexing or positioning is required for specific operations.
- The indexing mechanism can be mechanical, electrical, or a combination of both, depending on the application requirements. Its primary function is to divide a full rotation into specific angular steps and maintain the desired angular position during operations.

Indexing mechanism .....



Indexing in Milling Machine

Working of indexing mechanisms

- **Mechanical Indexing Mechanisms:** Mechanical indexing mechanisms typically use a combination of gears, cams, levers, and locking mechanisms to achieve precise angular positioning.

- One of the common types is the Geneva drive, which uses a rotating gear with a pin that engages with slots in a driven wheel. When the gear rotates, the pin pushes against the slots, causing the driven wheel to move in discrete angular steps. Mechanical indexing mechanisms are robust and can withstand high loads, making them suitable for heavy-duty applications.

Working of indexing mechanisms….

- Electrical Indexing Mechanisms: Electrical indexing mechanisms utilize stepper motors or servo motors to achieve precise angular positioning. Stepper motors move in discrete steps, and by controlling the number of steps the motor rotates, the indexing mechanism can achieve accurate angular positions.

- Servo motors use feedback control systems to maintain the desired position, providing high accuracy and repeatability. Electrical indexing mechanisms are commonly used in CNC machines, 3D printers, and other automated systems where precise angular positioning is crucial

Benefits of using indexing mechanisms in mechatronic systems:

- Precision: Indexing mechanisms allow for precise positioning of rotating shafts. This is important for applications where precise positioning is required, such as in machine tools.
- Repeatability: Indexing mechanisms are also repeatable, which means that they can move the same distance each time. This is important for applications where consistent positioning is required, such as in robotics.
- Flexibility: Indexing mechanisms are flexible, which means that they can be used in a variety of applications.
- Durability: Indexing mechanisms are durable, which means that they can withstand harsh environments.

Applications of Indexing Mechanisms ……

- Machine Tools: Indexing mechanisms are extensively used in machine tools, such as milling machines, lathes, and rotary tables, to position the workpiece or cutting tool at specific angles for machining operations.

- Packaging Machinery: In packaging machines, indexing mechanisms are used to control the rotation and positioning of containers or packaging material to facilitate filling, sealing, and labeling processes.

- Assembly Lines: Indexing mechanisms are employed in assembly lines to position components accurately during the assembly process, ensuring proper alignment and fit.

Applications of Indexing Mechanisms ……

- Indexing Conveyor Systems: Conveyor systems with indexing mechanisms are used in **manufacturing and material handling** to control the movement and positioning of products along the conveyor.

- Indexing Rotating Platforms: Indexing mechanisms are used in applications where precise angular positioning is required, such as rotating platforms for testing, inspection, or sorting operations.

Applications of Indexing Mechanisms ……

- Robotics: Indexing mechanisms are used in robotics to move the robot arm. This allows the robot to move with precision and accuracy.

- Medical devices: Indexing mechanisms are used in medical devices to move components, such as needles. This allows for precise and controlled movements to be made.

Applications of Indexing Mechanisms ……

- Overall, indexing mechanisms play a crucial role in mechatronics systems by providing controlled and accurate angular positioning, enabling various industrial processes to be carried out with precision and efficiency.