Lecture 8 – Friday March 29, 2013

Motion Control Systems

Objectives

When you have finished this lecture you should be able to:

- Understand the principles of industrial robot control.
- Recognize different types of industrial robot motion control.
- Understand how to model joint's actuator.
- Understand the control laws used to stabilize joint's position.

Outline

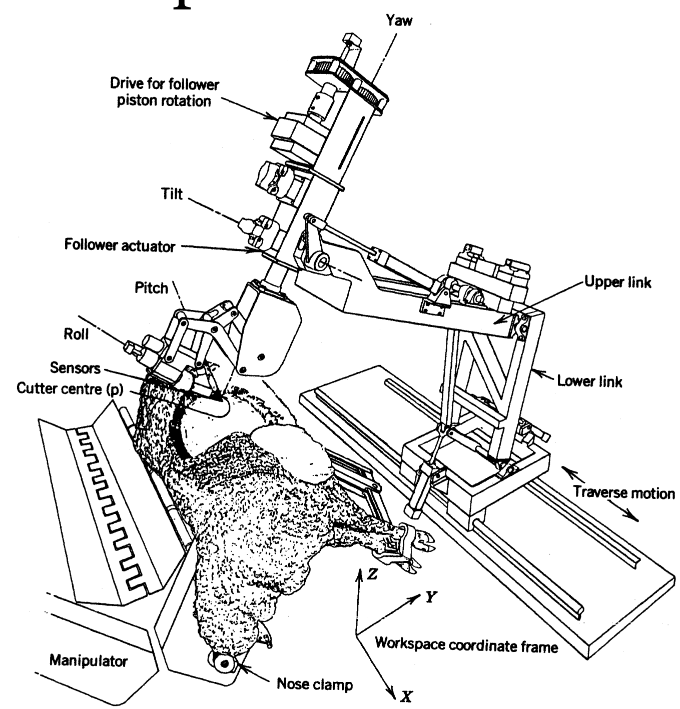
- Industrial Robot Control
- Control Techniques
- Motion Control
- Electromechanical Systems Dynamics
- Position Control
- Summary

Outline

- <u>**Industrial Robot Control**</u>
- Control Techniques
- Motion Control
- Electromechanical Systems Dynamics
- Position Control
- Summary

Industrial Robot Control

- **Robot Control System Task:** is to execute the planned sequence of motions and forces correctly in the presence of unforeseen errors.
- **Error sources:**
  - ◇ Inaccuracies in the model of the robot
  - ◇ Tolerance in the workpiece
  - ◇ Static friction in joints
  - ◇ Mechanical compliance in linkage
  - ◇ Electrical noise on transducer signals
  - ◇ Limitations in the precision of computation (often computation precision is sacrificed to obtain calculation results in real-time).



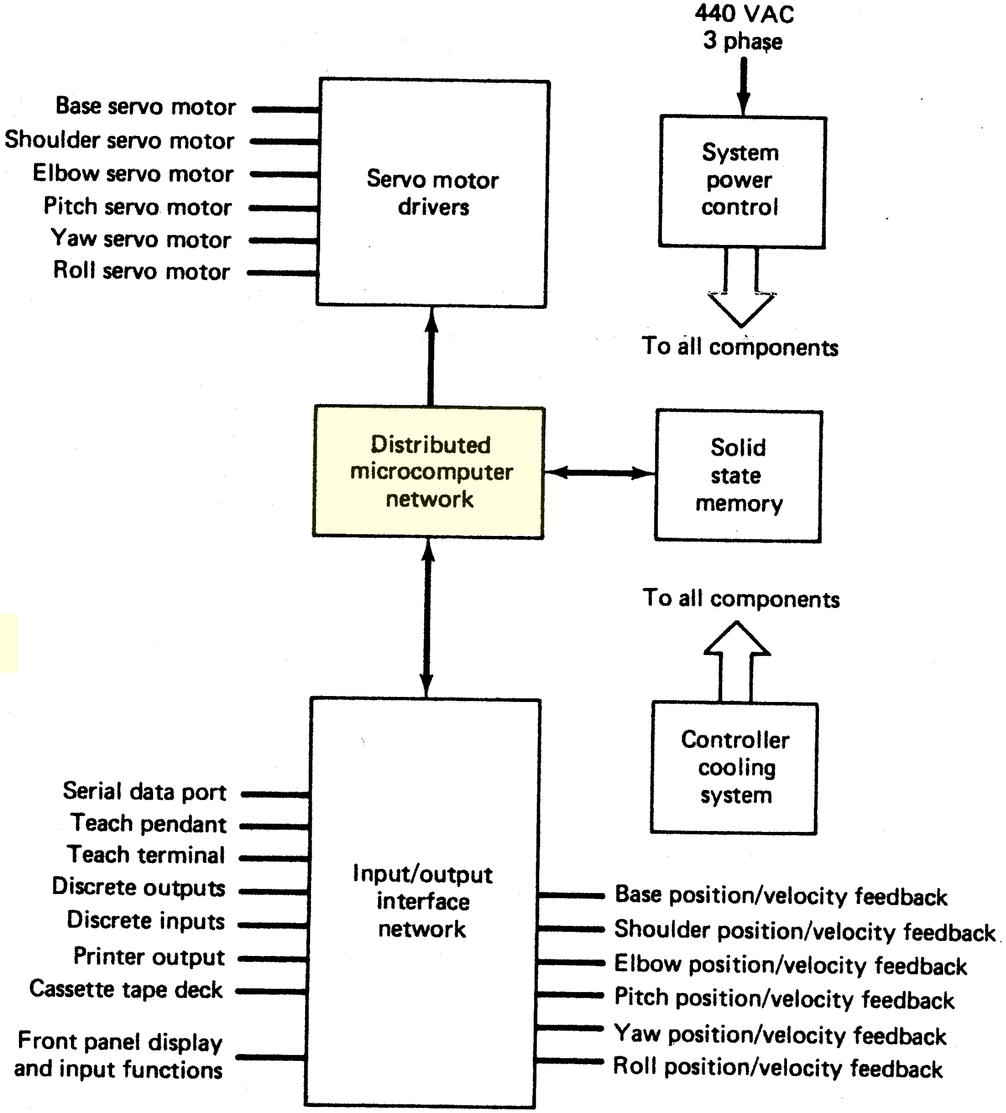
YouTube Sheep-Shearing Robot

Industrial Robot Control

- **Robot Controller Block Diagram**

The controller is basically a special-purpose computer, has all the elements commonly found in computers, such as CPU, memory, and input devices.

Control Unit



Industrial Robot Control

- **Robot Controller Processors**

  ◊ **Monoprocessor:** Unique processor in all the system.

  ◊ **Multiprocessor:** Processor per each control axis.

PUMA 560

  ◊ **Biprocessor:** Principal processor and axis processor.

ABB S3

  ◊ **Triprocessor:** Principal processor, axis processor and communication processor.

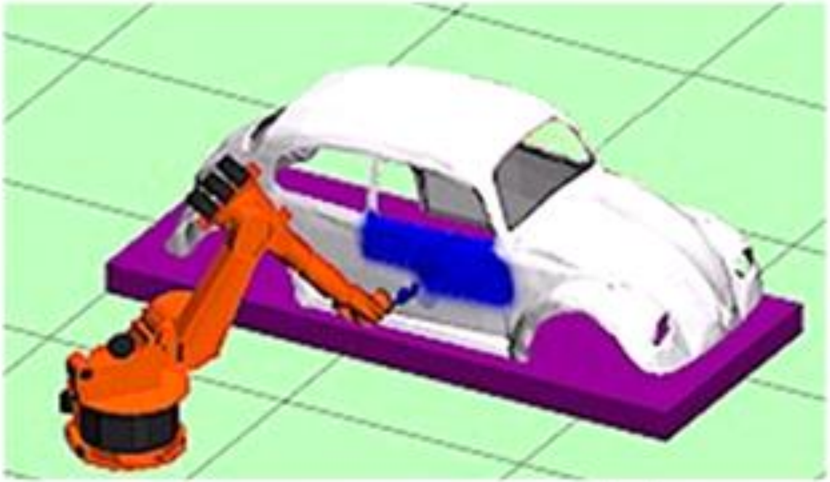
Industrial Robot Control

- The controller has the following functions:
  - ◇ Workspace Sensor Analysis,
  - ◇ Servo,
  - ◇ Kinematics and
  - ◇ Dynamics.

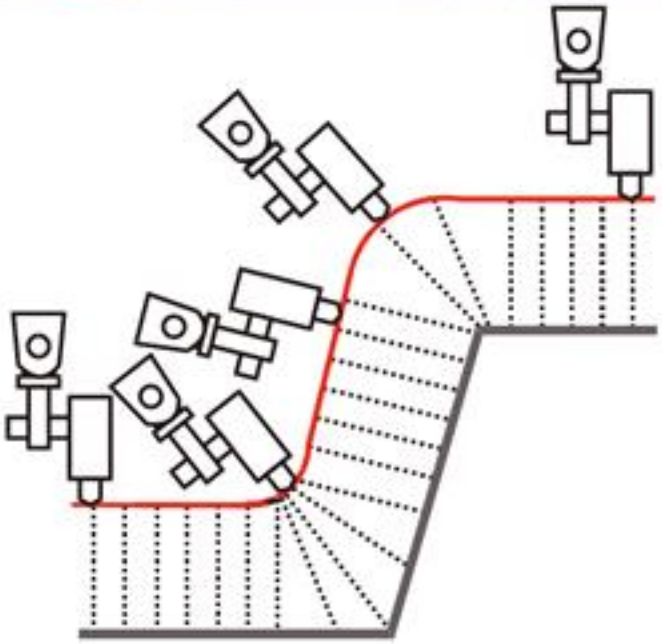
Industrial Robot Control

- **Workplace Sensor Analysis**

Given: the knowledge of the **tasks to be performed**; for example, pick-and-place a workpiece or paint a car chassis.



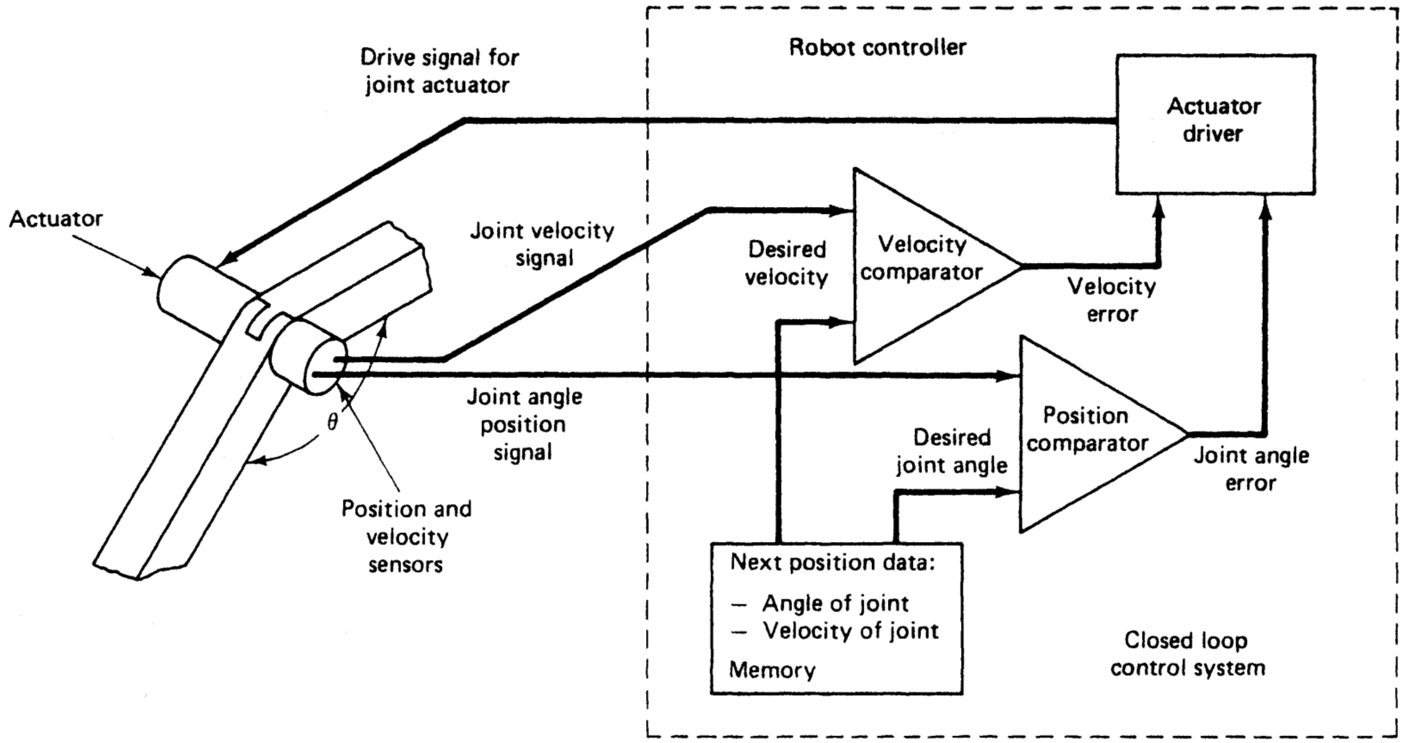
Required: determine the appropriate robot **motion commands**. This may be accomplished through vision or tactile sensing techniques, or by measuring and compensating for forces applied at the end-effector, and so on.



Industrial Robot Control

- **Servo**

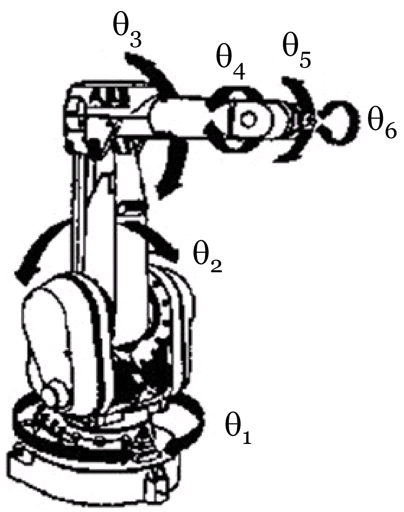
Given: the current position and/or velocity of an actuator.



Required: determine the appropriate drive signal to move that actuator towards its desired position and/or velocity.

Industrial Robot Control

- **Kinematics**



Given: The angle of each joint

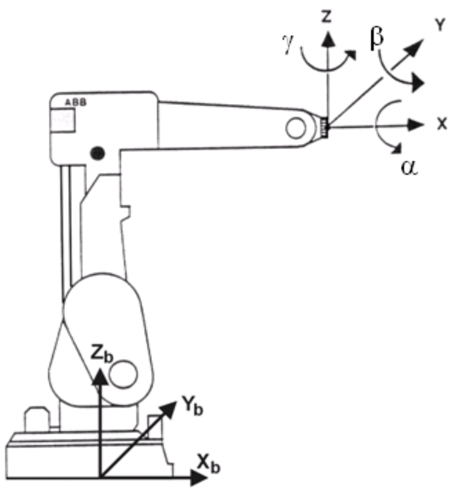
Required: The pose of end-effector (i.e. its position and orientation) $(x,y,z,\alpha,\beta,\gamma)$

Forward Kinematics

Inverse Kinematics

Given: The position of some point in the robot workspace (end-effector's pose)

Required: The angles of each joint needed to obtain that position $(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6)$

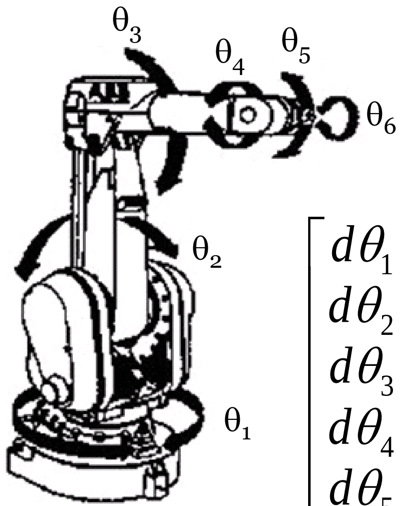


Industrial Robot Control

- **Kinematics**

Given: The positions of all members of the chain and the rates of motion about all the joints.

Required: The total velocity of the end-effector.



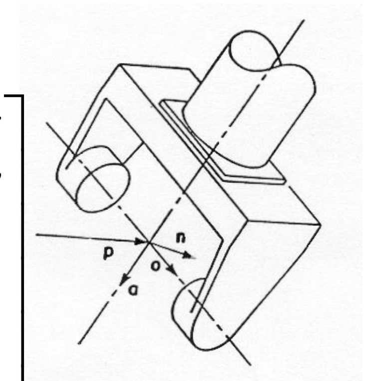
Serial chain manipulator

$$\begin{bmatrix} d\theta_1 \\ d\theta_2 \\ d\theta_3 \\ d\theta_4 \\ d\theta_5 \\ d\theta_6 \end{bmatrix}$$

Forward Instantaneous Kinematics →

← Inverse Instantaneous Kinematics

$$\begin{bmatrix} dx \\ dy \\ dz \\ \delta x \\ \delta y \\ \delta z \end{bmatrix}$$



End-effector

Given: The positions of all members of the chain and the total velocity of the end-effector.

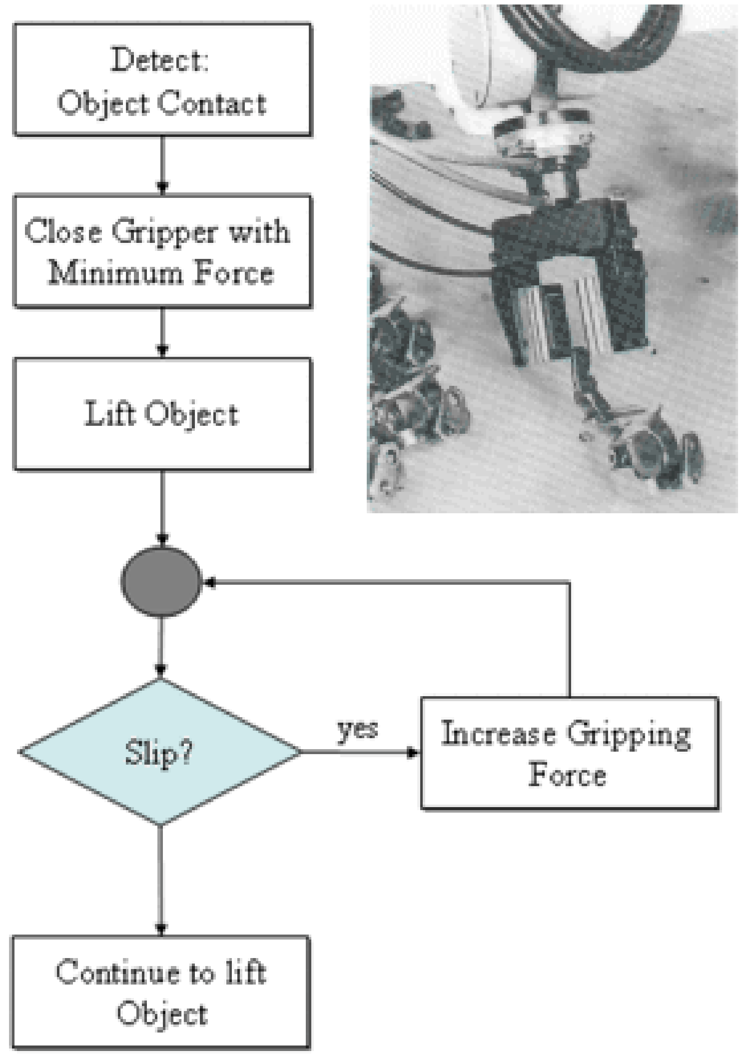
Required: The rates of motion of all joints.

Industrial Robot Control

- **Dynamics**

Given: knowledge of the loads on the arm (inertia, friction, gravity, acceleration).

Required: use this information to adjust the servo operation to achieve better performance.

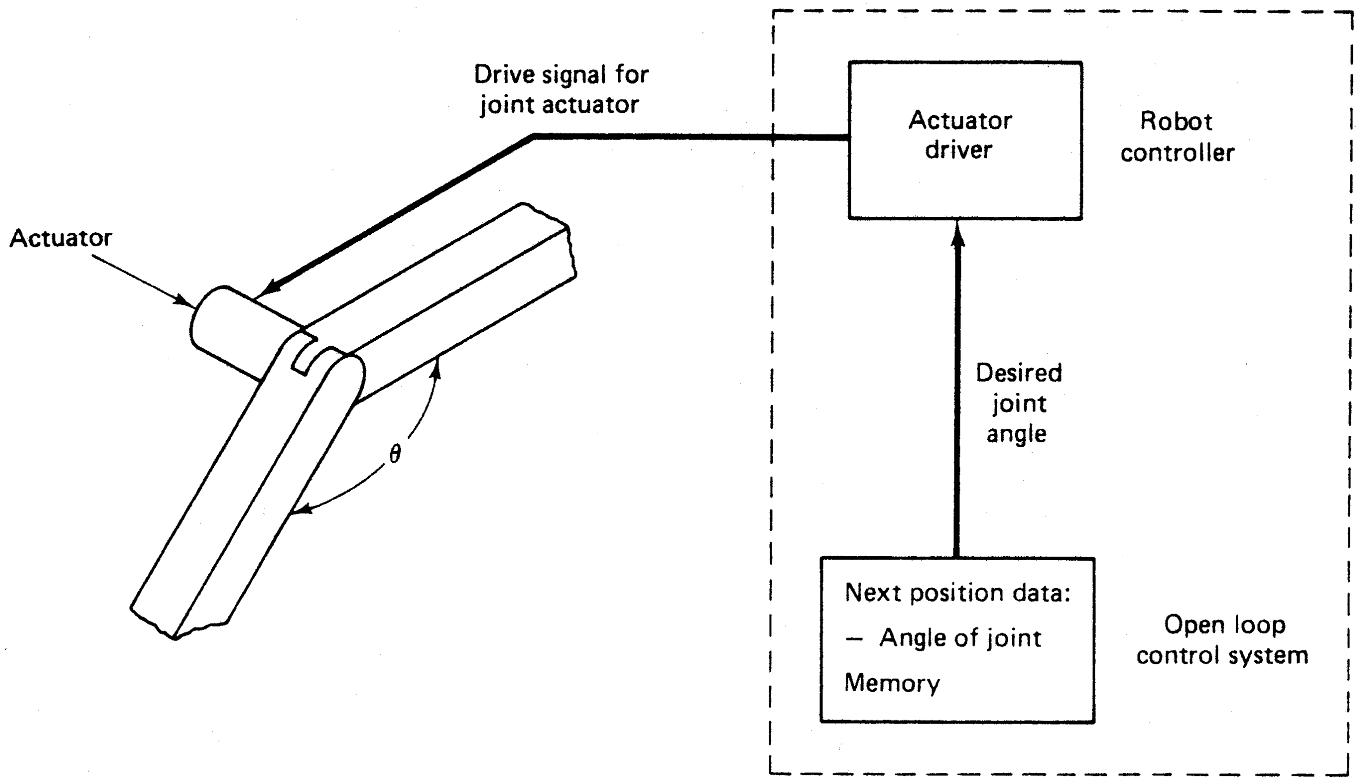


Outline

- Industrial Robot Control
- **Control Techniques**
- Motion Control
- Electromechanical Systems Dynamics
- Position Control
- Summary

Control Techniques

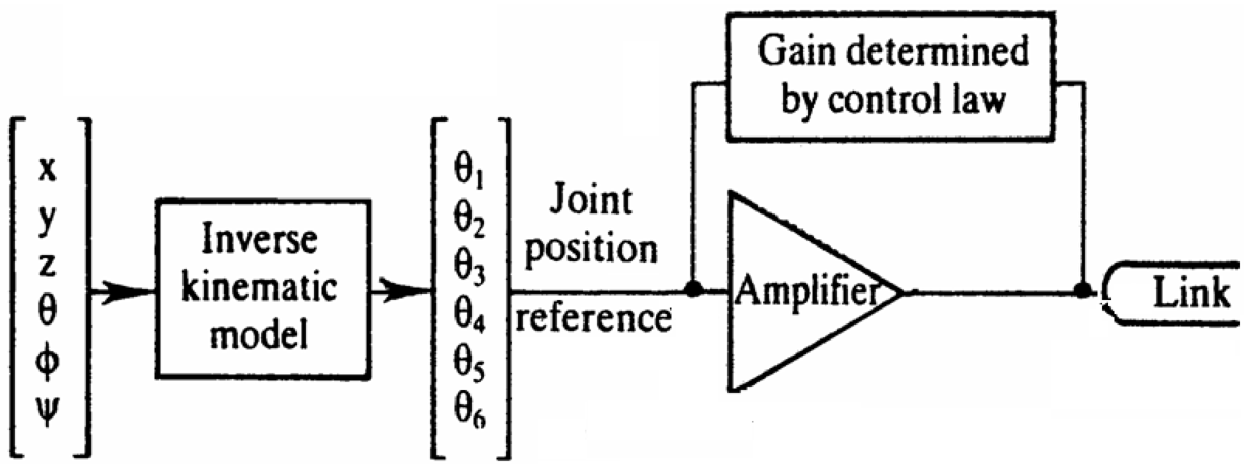
- **Open-Loop / Nonservo**



Open-Loop / Nonservo / stop-to-stop / pick-and-place System

Control Techniques

- **Open-Loop / Nonservo**



In Cartesian space, we use kinematic model to calculate the joint angles that will place the gripper at the required location in space. The joints are moved to these angles and the robot is assumed to be in the correct Cartesian location, as, generally there is no way of measuring whether it is or not. Open-loop control is **as accurate as the model of the process** (in this case the inverse kinematic model), provided there are no disturbance to cause errors.

Control Techniques

- **Open-Loop / Nonservo**

Robots classified as **nonservo or open-loop** do not have position and rate-of-change sensors on any axis; therefore, the controller does not know the position of the arm and tool while the robot is moving from one point to another.

On every axis, however, there is a **fixed stop or limit** at each extreme of travel that provides the positioning accuracy at that point.

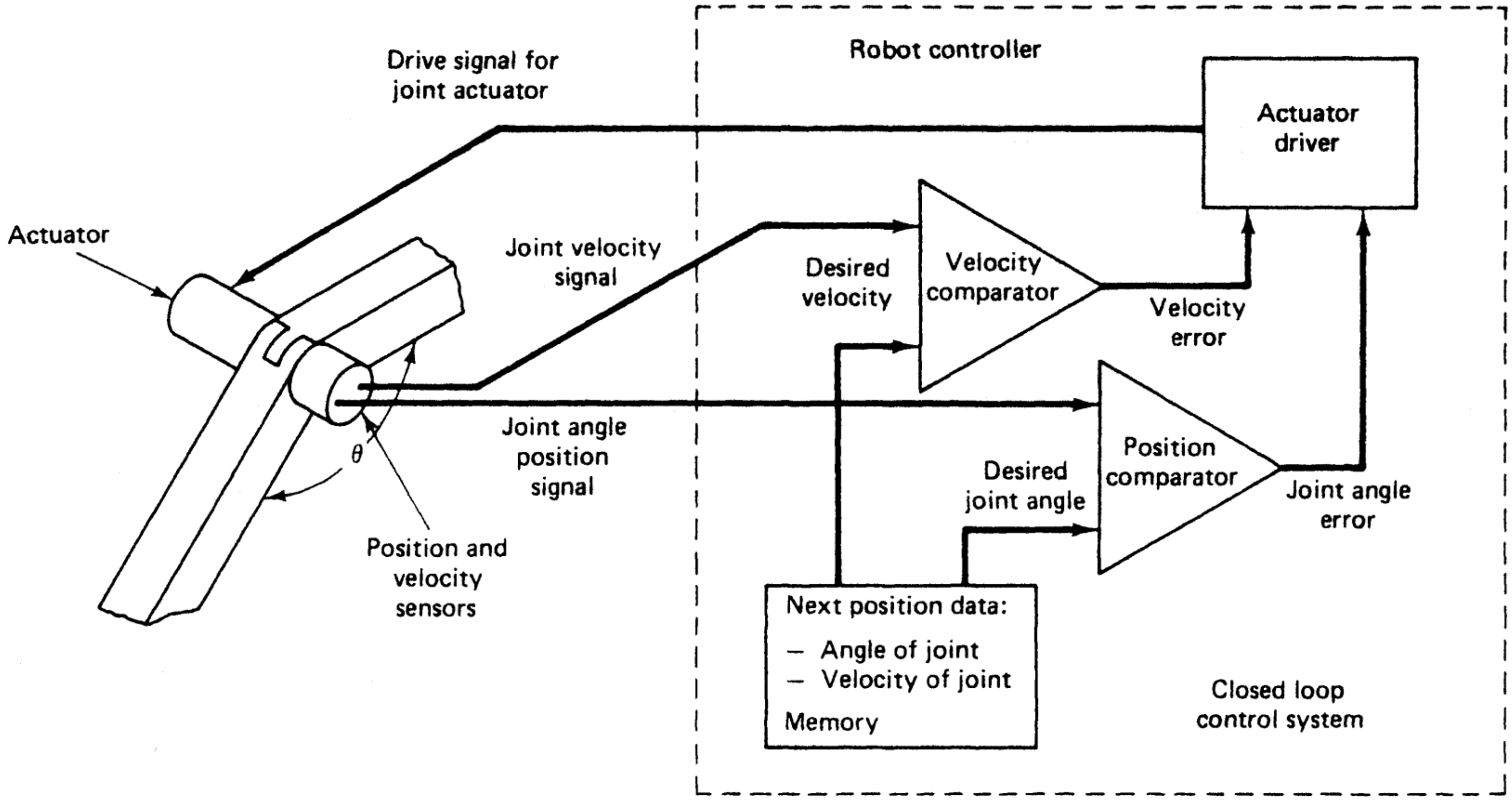
Advantages: the simplicity of the system and the resulting reliability.

Disadvantages: limited and fixed-stop locations and its inability to handle complex manufacturing tasks.

Applications: machine loading-and-unloading.

Control Techniques

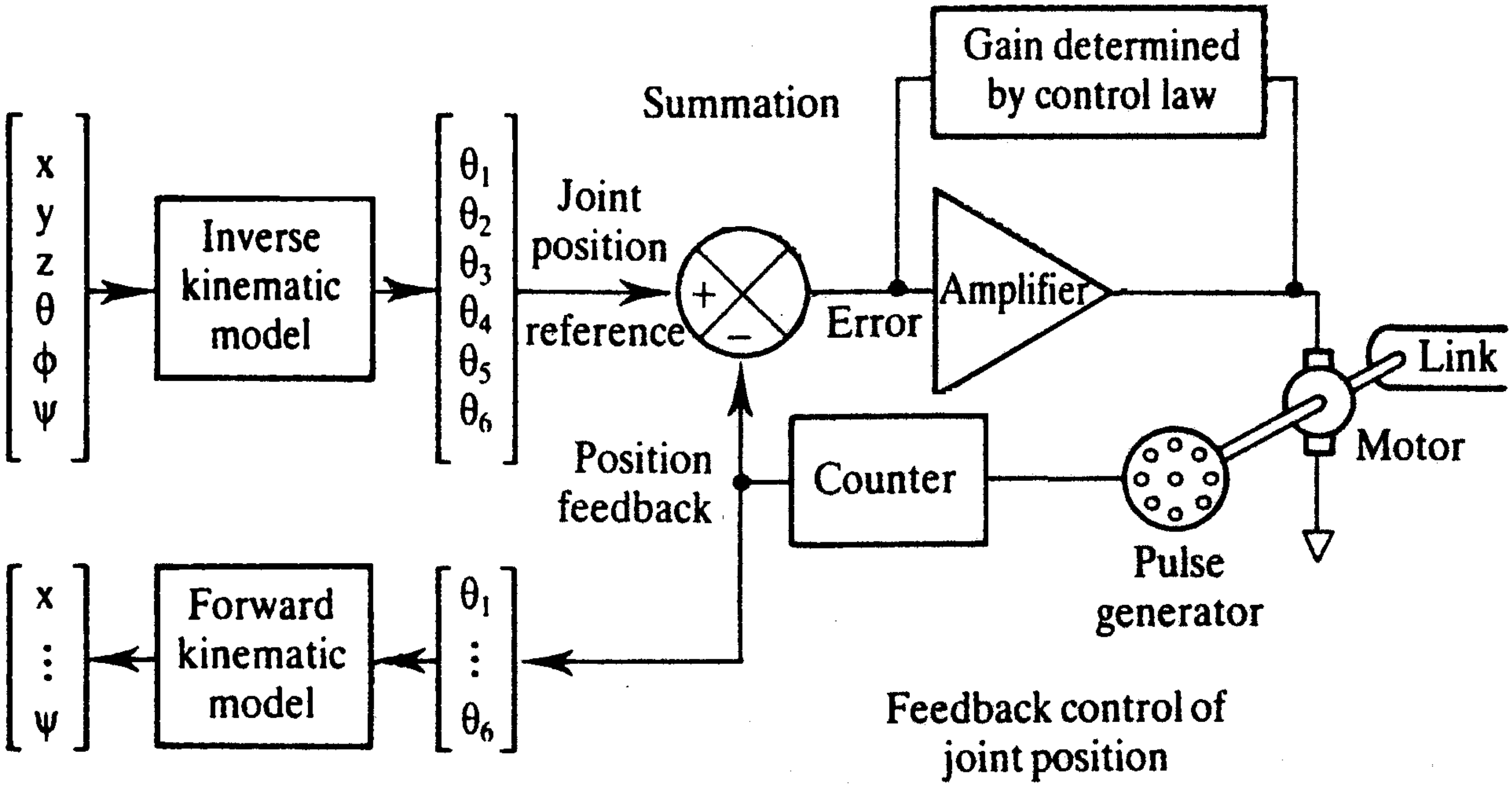
- **Closed-Loop / Servo**



Closed-Loop or Servo System

Control Techniques

- **Closed-Loop / Servo**



Closed-Loop or Servo System

Control Techniques

- **Closed-Loop / Servo**

Advantages:

◊ Flexible program control permits robots to be used in a wide variety of manufacturing jobs and extends the useful lifetime of the machine.

◊ Robots are capable of performing more complex manufacturing tasks

◊ Robots can execute multiple programs to handle varied manufacturing tasks.

Disadvantages:

◊ Bigger capital investment for a machine of this type is required.

◊ Maintenance staff must be highly skilled because of the increased technology in the work cell.

Control Techniques

- **Closed-Loop / Servo**

Applications:

The servo or closed-loop control system is used in any application in which path control is required, such as:

◊ Welding

◊ Coating

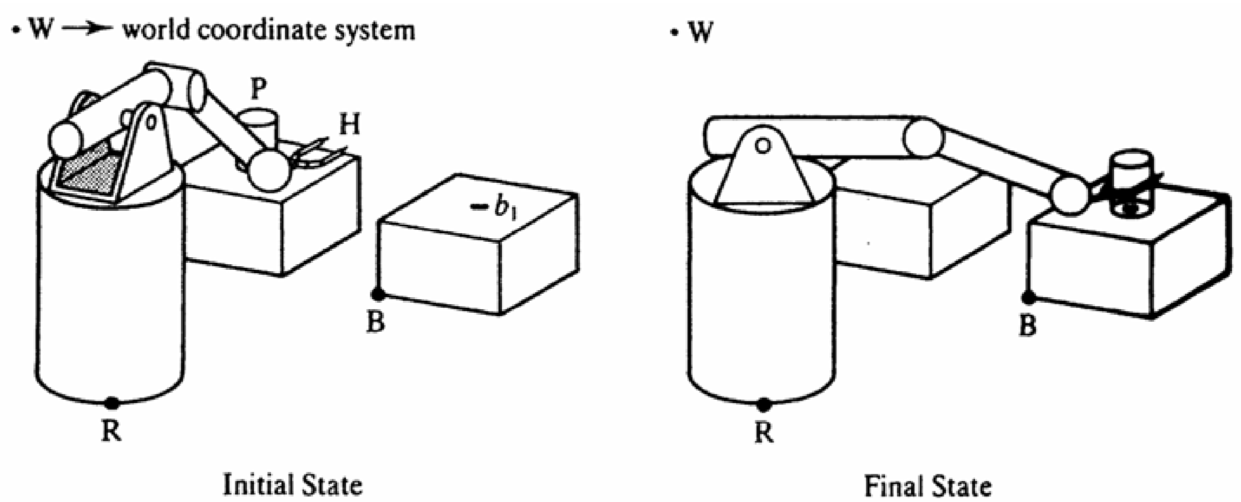
◊ Assembly operations

Outline

- Industrial Robot Control
- Control Techniques
- **Motion Control**
- Electromechanical Systems Dynamics
- Position Control
- Summary

Motion Control

Robot users need to know how much motion control they need for their various applications, because the degree of motion control greatly affects the cost of the robot.



- **At robot level:** an action is decomposed into a sequence of robot motions and forces in Cartesian space (Cartesian-space representation).
- **At joint level:** these motions and forces are decomposed into parallel joint motions and joint torques (Joint-space representation).

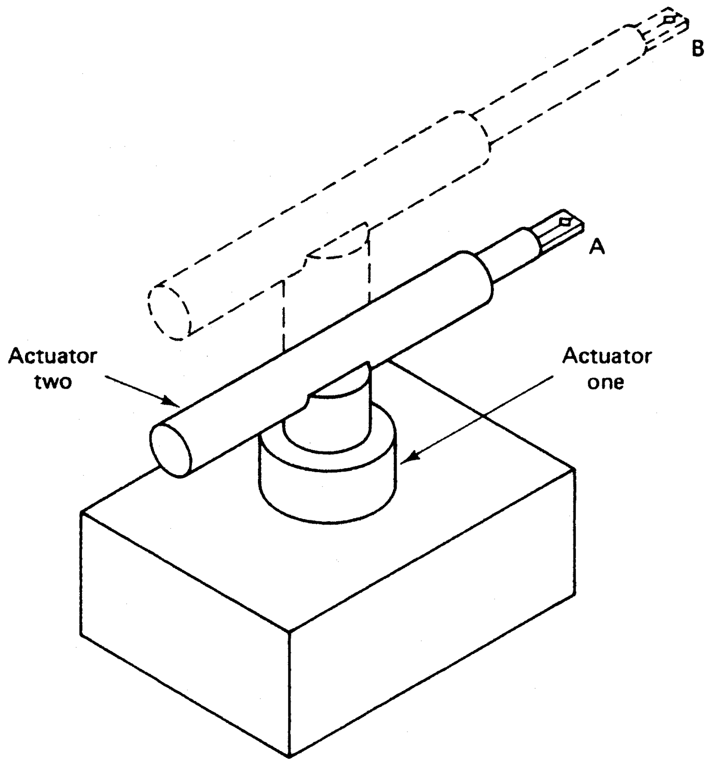
Motion Control

- **Axis Limit or Two-Position or Stop-to-Stop Control**

It is the least sophisticated and therefore the lowest cost mode of robot motion control.

It is an **open-loop control system**, which means that when the axis moves the position and velocity of the axis are not known to the controller.

Each robot axis typically has two extreme points, which can be mechanically adjusted stops or **limit switches**.



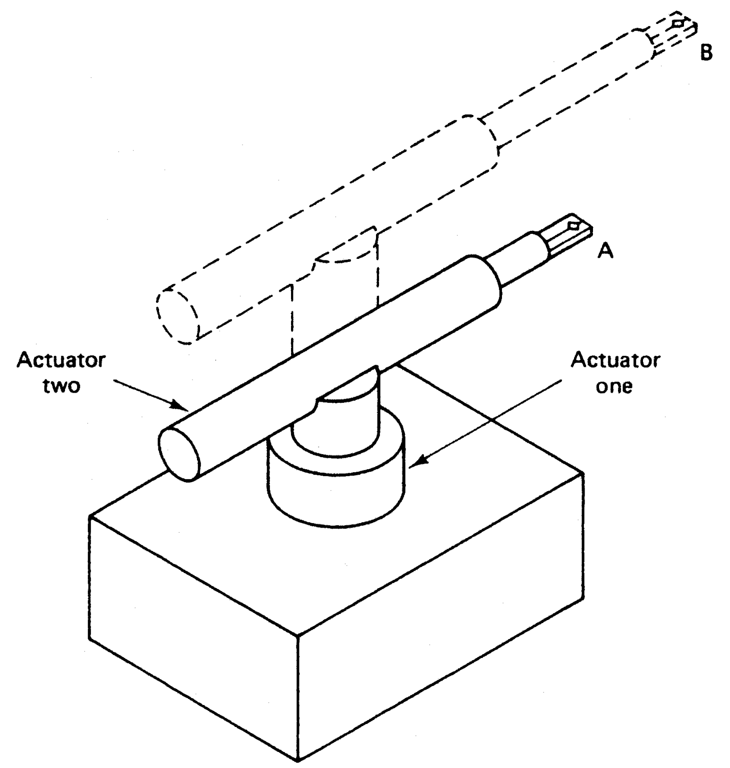
Motion Control

- **Axis Limit or Two-Position or Stop-to-Stop Control**

In the axis-limit robots, the only information stored in the memory is **a sequence list of on-off commands** for each actuator driver. In this case the memory would have on for actuator one followed by on for actuator two.

Axis-limit robots are invariably either **pneumatically or hydraulically** powered.

Typical application for axis-limit robots is in **machine loading and unloading**.

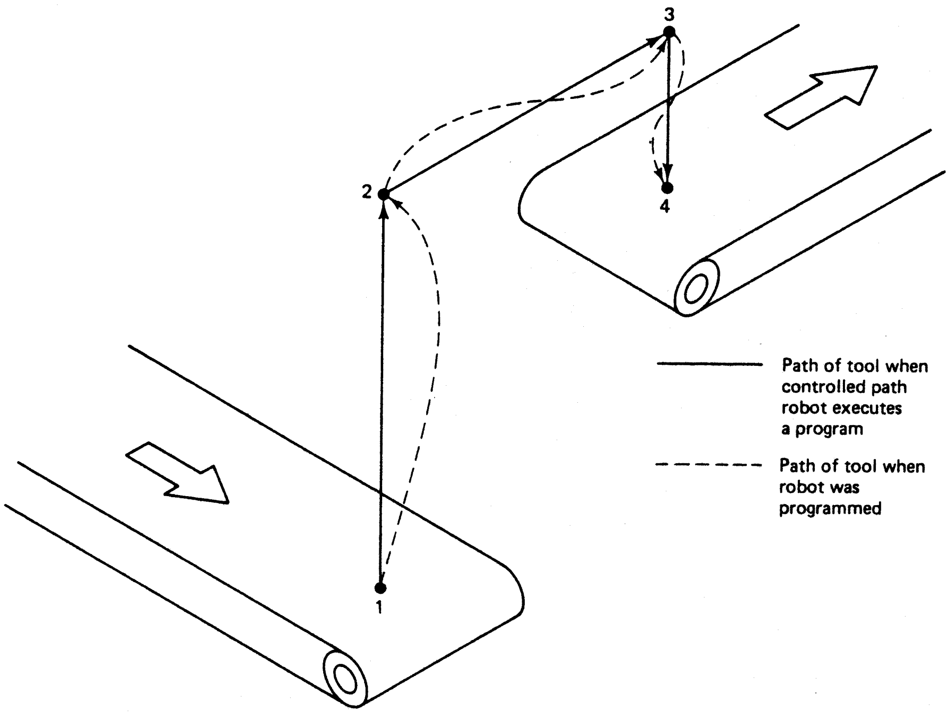


Motion Control

- **Point-to-Point (PTP) Control**

  In this mode, the user can select any point in the robot work envelope and move directly to that point.

  The **path and speed** of the movement en route to the destination point are generally both **uncontrollable.**

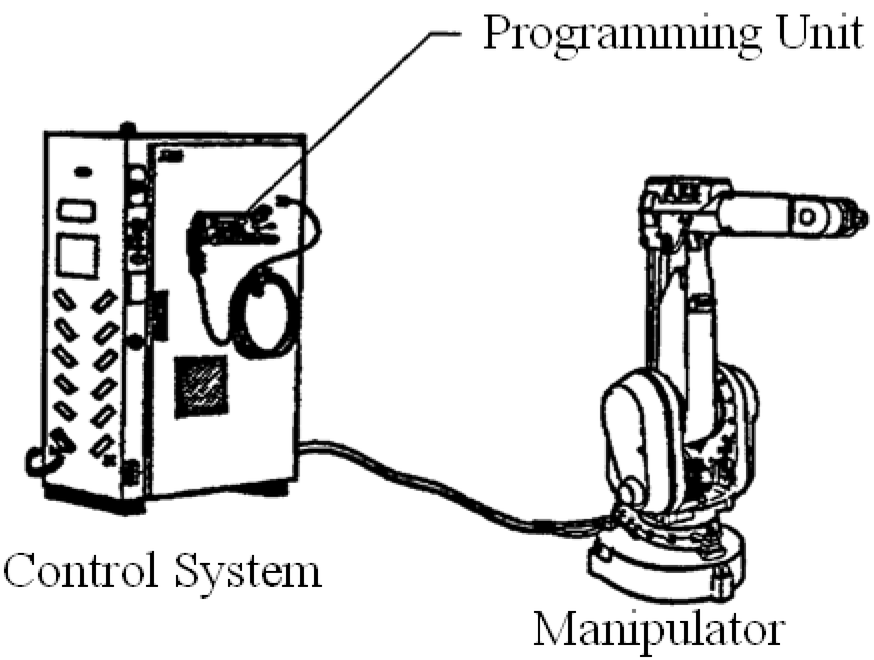


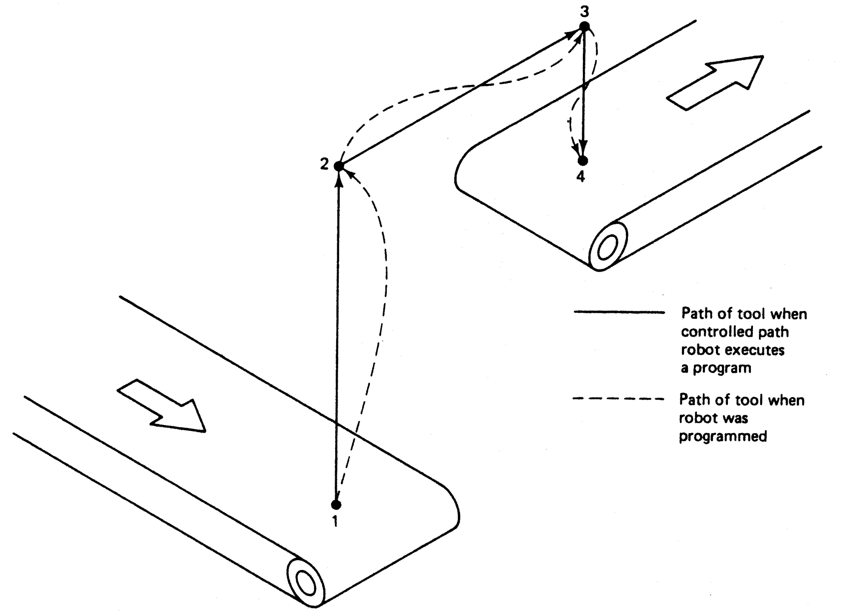
Joint-space motion representation is used in this case. Controller may select the path that minimize energy usage.

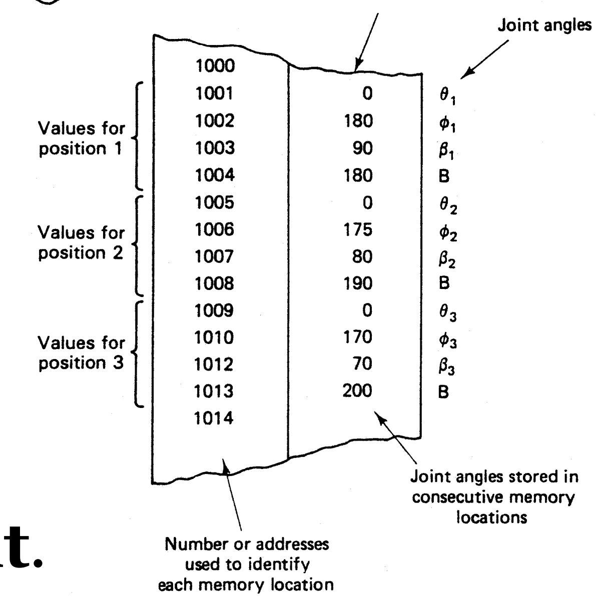
PTP control is good for component insertion, hole drilling, spot welding, crude assembly and machine loading/unloading.

Motion Control

- **Point-to-Point (PTP) Control**





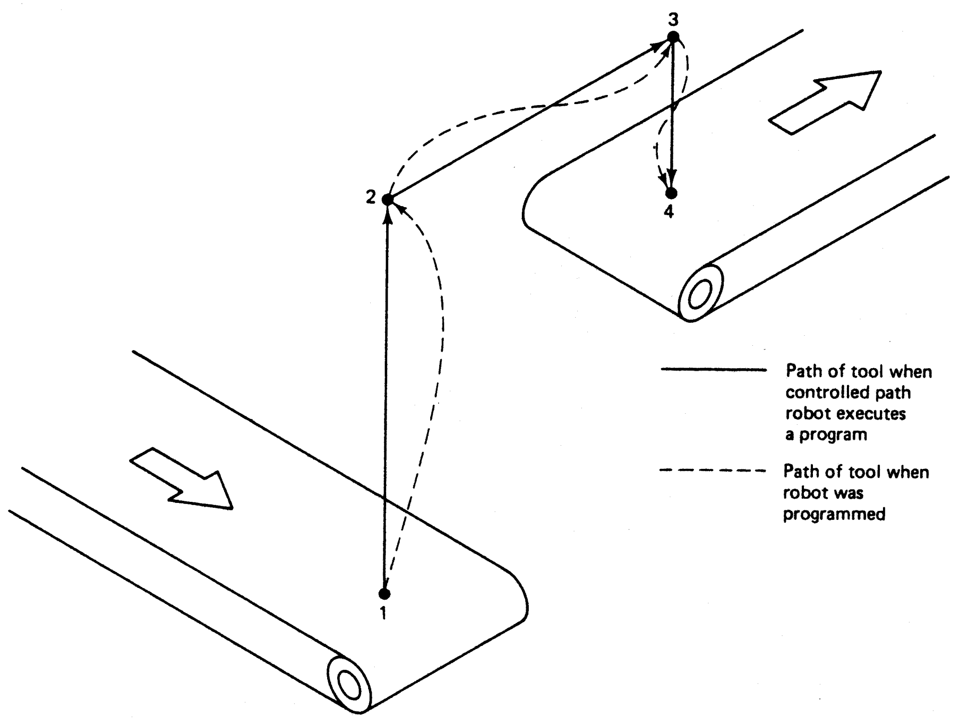


The primary programming device in PTP controllers is the hand-held **teach pendant**.

Motion Control

- **Point-to-Point (PTP) Control**

  The **advantage** of PTP control is that relatively large and **complex program can be obtained** with a system that is **moderate in cost** yet has proven **reliability**.



Motion Control

- **Point-to-Point (PTP) Control**

  The **lack of straight-line control** is considered its primary **disadvantage**,

  To move from 1 to 2:

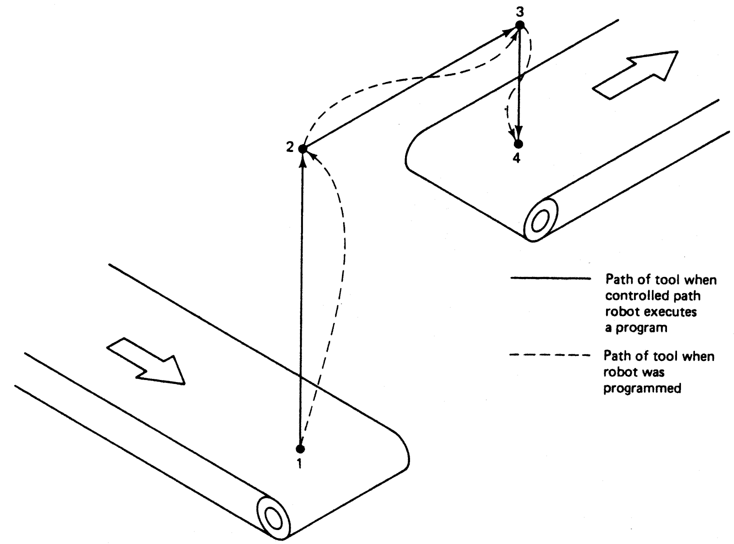
  The controller must change 4 DOFs

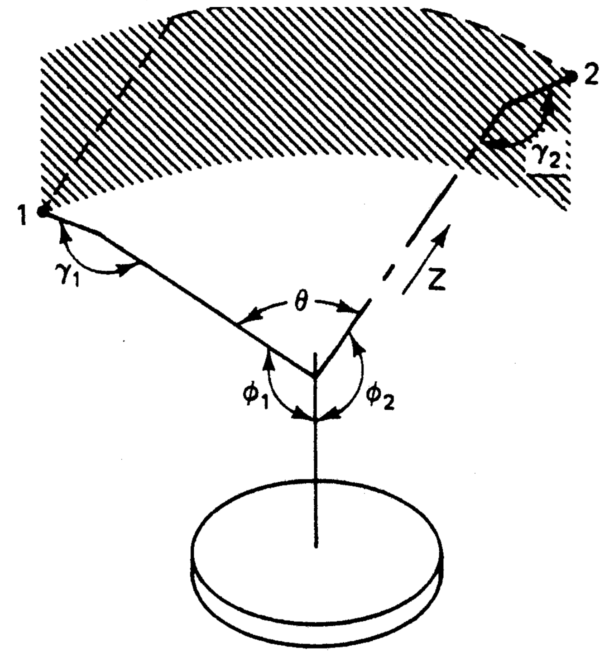
  ◇ The base must rotate through θ

  ◇ The shoulder must go from ϕ_1 to ϕ_2

  ◇ The arm must extend along z to reach to the higher point

  ◇ The wrist must pitch from γ_1 to γ_2





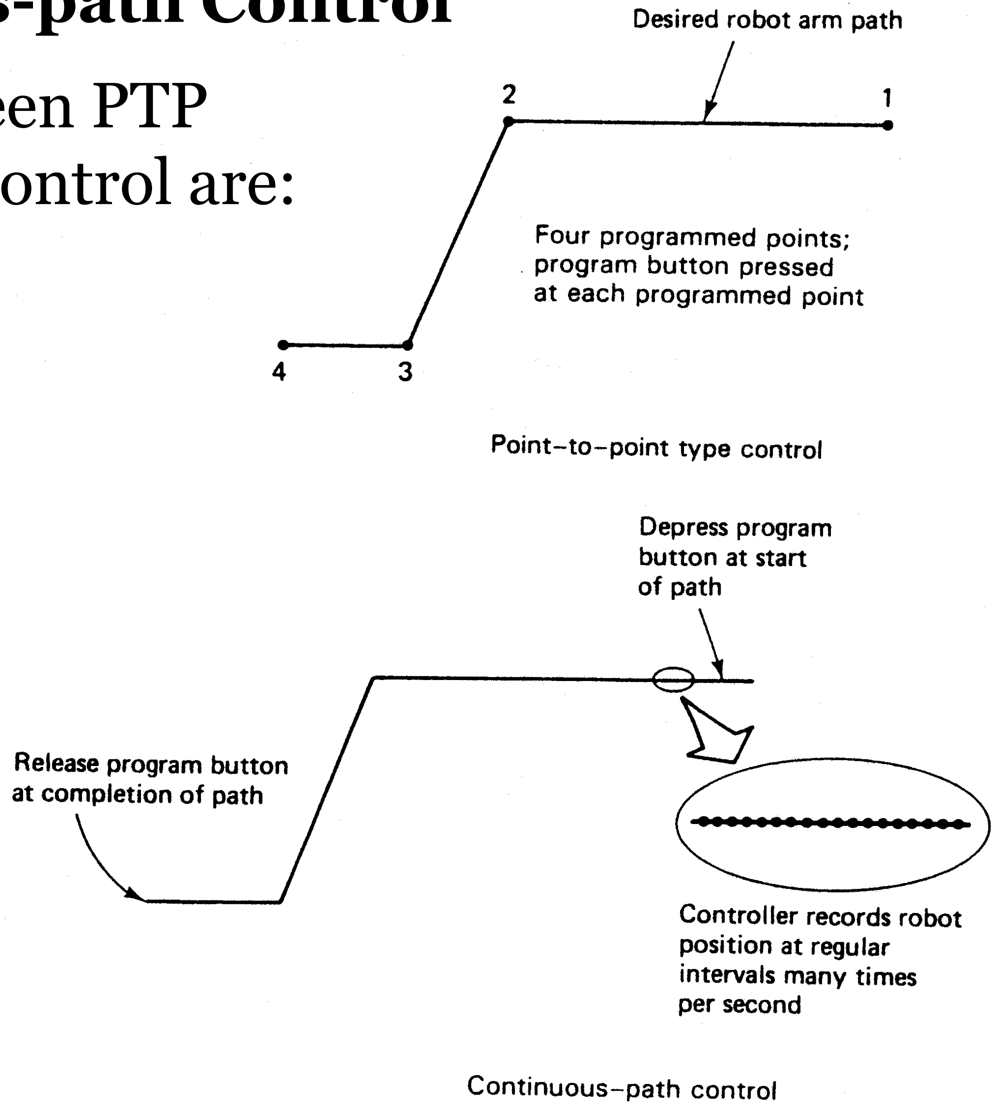
Motion Control

- **Contouring or Continuous-path Control**

  The primary differences between PTP control and continuous-path control are:

  ◊ Added capability to provide control of the end-effector or TCP as the robot moves from one program point to another;

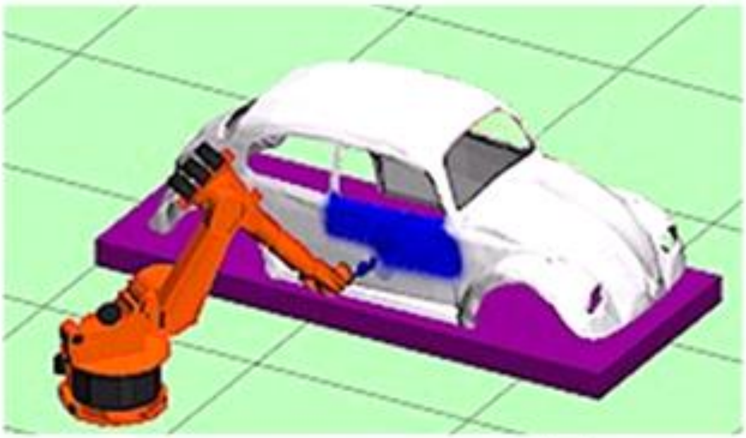
  ◊ Number of programmed points that are saved in controller memory and the method to save them.



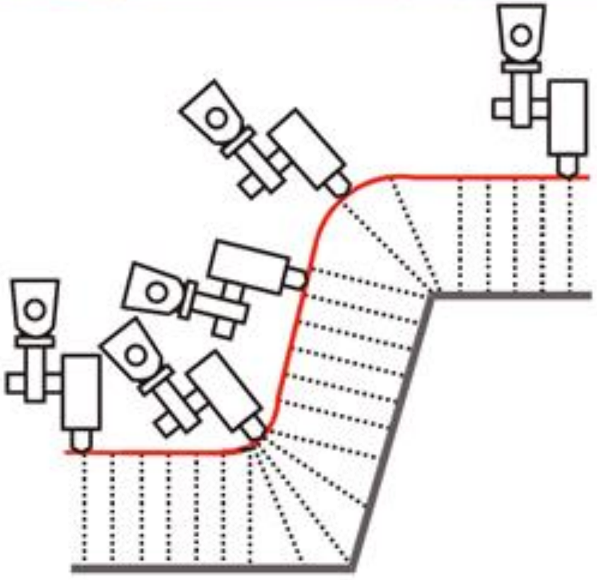
Motion Control

- **Contouring or Continuous-path Control**

Continuous-path controllers are very useful in applications like **paint spraying** in which robot's motion must duplicate the skill of the operator.



Contouring motion control is also essential for most finishing, gluing, and arc welding operations by robots.



Motion Control

- **Line Tracking Control**

One of the most complex contouring motions is called "**line tracking**" – that is, performing an operation while following alongside a continuously moving conveyor.

Example: Spray painting generally is applied to all sides of a piece-part as it is transported by a continuous overhead chain. The robot must be directed at all sides of the part, a feat that can be accomplished most conventionally if the part moves continuously past the work station and if the robot has line-tracking ability

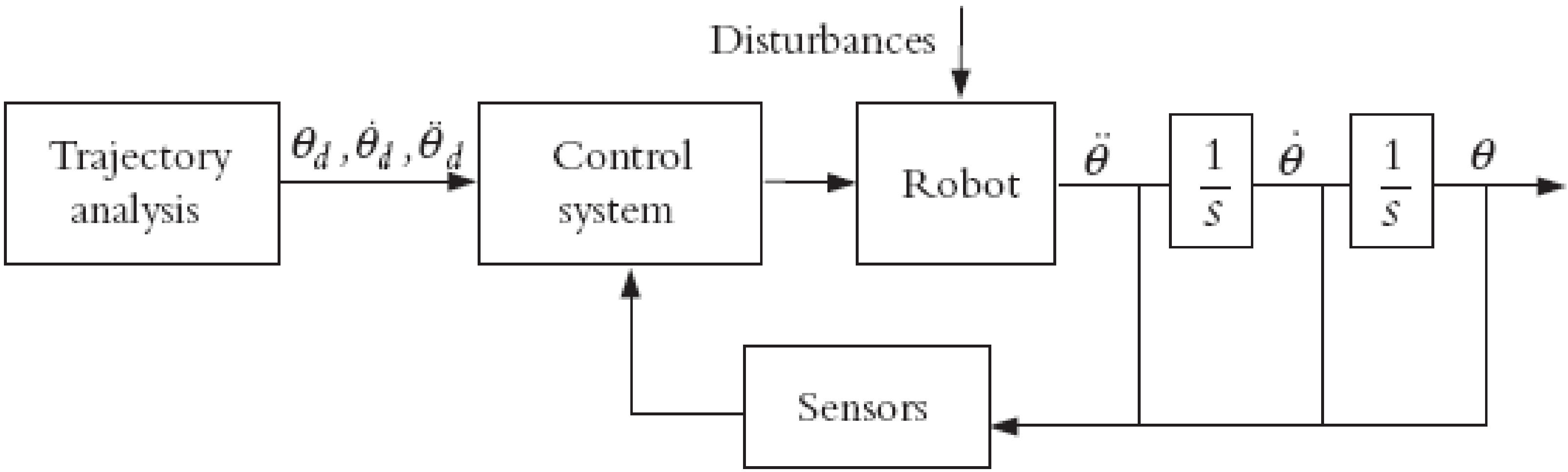
Some robots designed specifically for **line-tracking** have a horizontally transverse on a track for the first DOF.

Outline

- Industrial Robot Control
- Control Techniques
- Motion Control
- **<u>Electromechanical Systems Dynamics</u>**
- Position Control
- Summary

Electromechanical Systems Dynamics

- **Robot Actuation and Control**



The feedback loop of a robot controller.

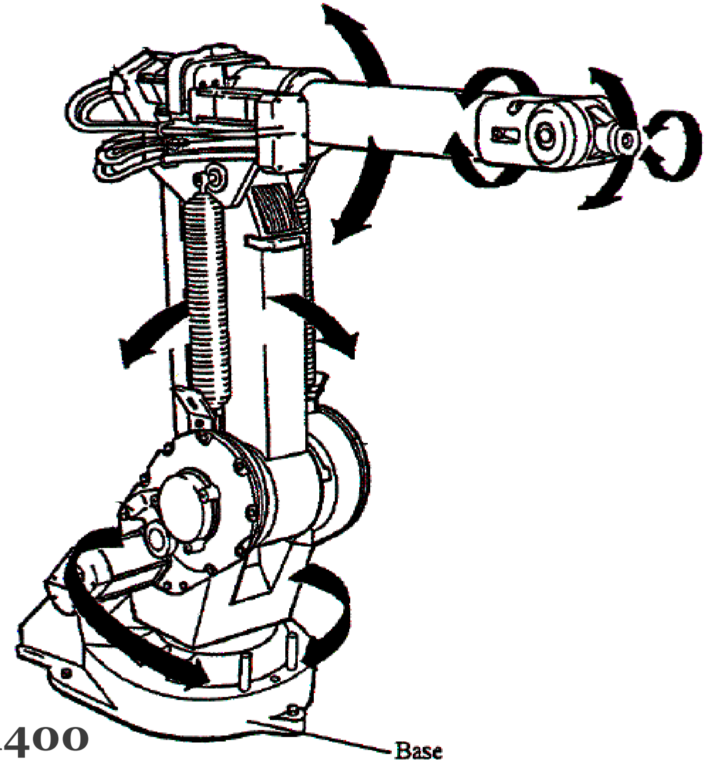
The **joint values** (displacement, velocity, acceleration, and applied forces and torques) are calculated from kinematic, dynamic, and trajectory analyses. These values are sent to the **controller** which, in turn, applies appropriate **actuating signals** to the actuators to run the joints to their destination in a controlled manner. The **sensors** measure the outputs and feed the signals back to the controller, which, in turn, controls the actuating signals accordingly.

Electromechanical Systems Dynamics

- **Independent Joint Control**

A multi-axis robot has **multiple inputs and multiple outputs** for each joint that must be controlled **simultaneously**. However, in most robots, each axis is controlled individually (called **independent joint control**) as a single-input, single-output unit.

The **coupling effects** from other joints are usually treated as **disturbances** and are taken care of by the controller. Although this introduces some error, the error is small for most practical purposes.



Robot ABB IRB1400

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**
  - ◊ For armature-controlled motor:

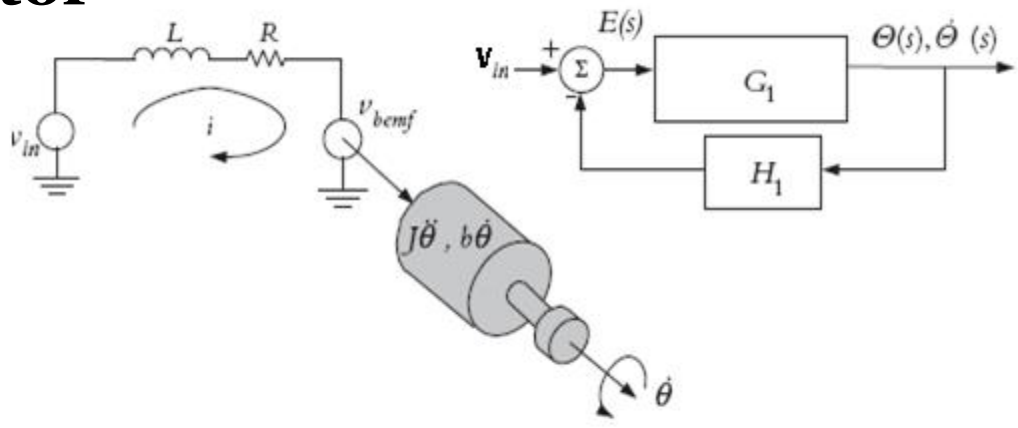
$$Ri + L\frac{di}{dt} = v_{in}(t) - V_{bemf}$$

$$V_{bemf} = K_e\dot{\theta}$$

$$Ri + L\frac{di}{dt} = V_{in}(t) - K_e\dot{\theta}$$

Taking L.T. gives:

$$V_{in}(s) - RI(s) - LsI(s) - K_e s\theta(s) = 0$$



An electromechanical actuating system and its model.

Electromechanical Systems Dynamics

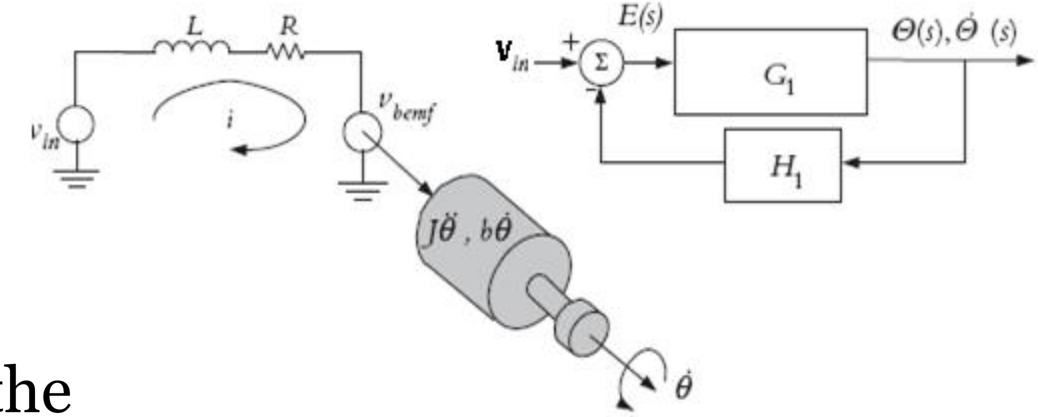
- **Modeling Robot's Actuator**
  - ◊ For the mechanical side of the system :

$$T = K_t i = J\ddot{\theta} + b\dot{\theta}$$

where J is the inertia (of the armature and load) and b is damping coefficient and K_t is the torque constant.

Taking L.T. gives:

$$K_t I(s) = Js^2\theta(s) + bs\theta(s)$$



An electromechanical actuating system and its model.

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**
  - ◇ Parameters for four d.c. motors:

Quantity	Units	High speed micromotor	Low inertia micromotor	High torque direct drive motor	Ordinary motor
V	volts	4	15	-	36
No-load speed	rpm	20300	4300	487	3250
No-load current	Amps	$16x10^{-3}$	$20x10^{-3}$	-	-
Stall torque	Newton metres	$318x10^{-6}$	$110x10^{-3}$	1.356	$53x10^{-3}$
Power	watts	0.2	12	70	-
Bemf constant K_e	volts/1000 rpm	0.181	3.5	-	11
Inductance	Henry	$0.18x10^{-3}$	$0.6x10^{-3}$	-	$2.9x10^{-3}$
Resistance	ohm	20	4.5	-	0.8
Torque const. K_t	N.m/amp	$1.73x10^{-3}$	$33x10^{-3}$	$163x10^{-3}$	$176x10^{-3}$
Inertia	kg.m2	$11.3x10^{-9}$	$32x10^{-7}$	$749x10^{-6}$	$233x10^{-6}$
Friction	N.m/radian/s	$13.3x10^{-9}$	$1x10^{-6}$	-	$67x10^{-6}$
Motor time const	s	$75x10^{-7}$	$13x10^{-3}$	-	$17x10^{-3}$
Elect. time const	s	-	-	$0.7x10^{-3}$	$3.7x10^{-3}$

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**

◇ Combining the previous equations gives:

$$V_{in}(s) = \left[\frac{R(Js^2 + bs)}{K_t} + \frac{Ls(Js^2 + bs)}{K_t} + K_e s \right] \theta(s)$$

In practice, the inductance of the motor **L** is usually much **smaller** than the inertia of the rotor and the load combined and can therefore easily be **ignored** for analysis. Consequently, the above equation may be simplified to:

$$V_{in}(s) = \left[\frac{R(Js^2 + bs)}{K_t} + K_e s \right] \theta(s)$$

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**

◇ The transfer function is:

$$\text{T.F.} = \frac{\theta(s)}{V_{in}(s)} = \frac{K_t}{R(Js^2 + bs) + K_t K_e s} = \frac{K_t / RJ}{s\left(s + \frac{b}{J} + \frac{K_t K_e}{RJ}\right)} = \frac{K}{s(s+a)}$$

where $K = K_t / RJ, \qquad a = \frac{1}{J}\left(b + \frac{K_t K_e}{R}\right)$

If we are interested in the **velocity** of the motor (robot's arm) in response to the input voltage, we may multiply the s in the denominator and θ(s) to get ω(s). Therefore, the transfer function may be written as:

$$\text{T.F.} = \frac{\omega(s)}{V_{in}(s)} == \frac{K}{s+a}$$

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**

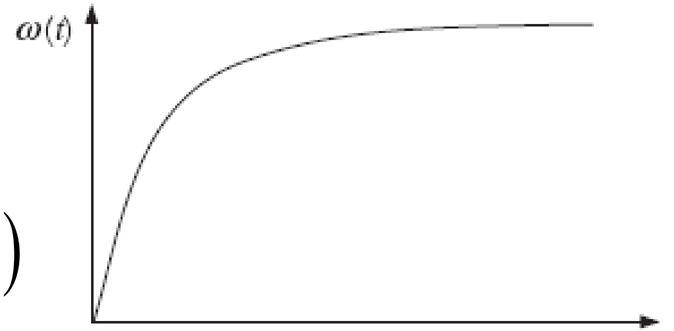
Example: Assume that the input voltage is a step function Pu(t). Determine the response of the motor and its steady-state value.

Solution:

$$\omega(s) = \frac{K}{s+a}\frac{P}{s} = \frac{KP}{s(s+a)} = \frac{a_1}{s+a} + \frac{a_2}{s}$$

where $a_1 = \left| s\left(\frac{KP}{s(s+a)}\right)\right|_{s=0} = \frac{KP}{a}$ and $a_2 = \left|(s+a)\left(\frac{KP}{s(s+a)}\right)\right|_{s=-a} = \frac{KP}{-a}$

Hence, $\omega(\mathrm{s}) = \frac{KP}{sa} - \frac{KP}{(s+a)a} = \frac{KP}{a}\left(\frac{1}{s} - \frac{1}{(s+a)}\right)$



Taking inverse L.T. gives $\omega(t) = \frac{KP}{a}\left(1 - e^{-at}\right)$

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**

Example (cont'd):

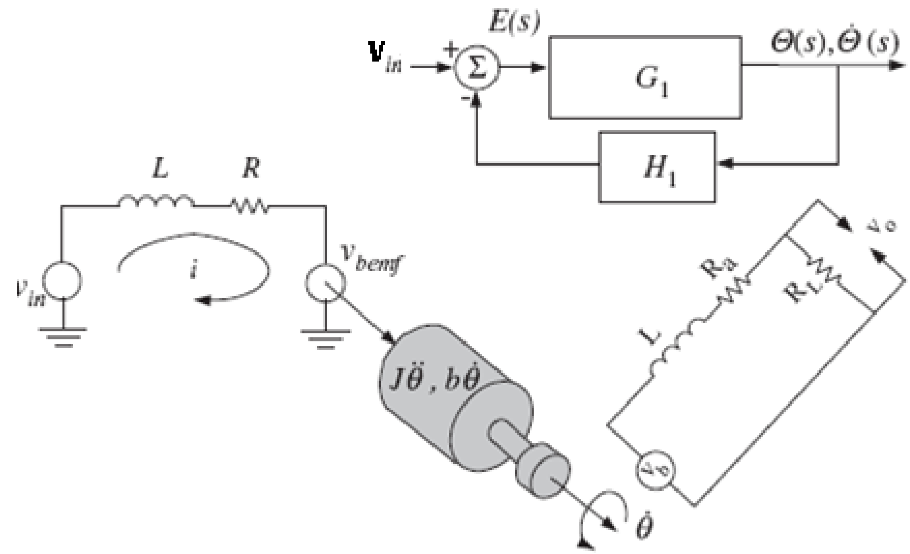
The steady-state velocity output of the motor, using the final value theorem is:

$$\omega_{s.s.}\Big|_{\text{for unit step input}} = \lim_{s\to 0} s\,\frac{KP}{s(s+a)} = \frac{KP}{a}$$

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**

  Now let's add a **tachometer** to the system as a feedback sensor. The tachometer measures the angular speed of the motor in response to the actuating signal.



An electromechanical system with a tachometer sensor.

◇ For the tachometer:

$$v_b = K_f \dot{\theta}$$

The circuit representing the tachometer can be expressed in Laplace domain as:

$$I(s)\times\left(R_a + R_L + Ls\right) = V_b(s) = K_f s\theta(s)$$

$$V_o(s) = I(s)R_L = \frac{K_f s\theta(s)R_L}{R_a + R_L + Ls}$$

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**

The transfer function for the tachometer is:

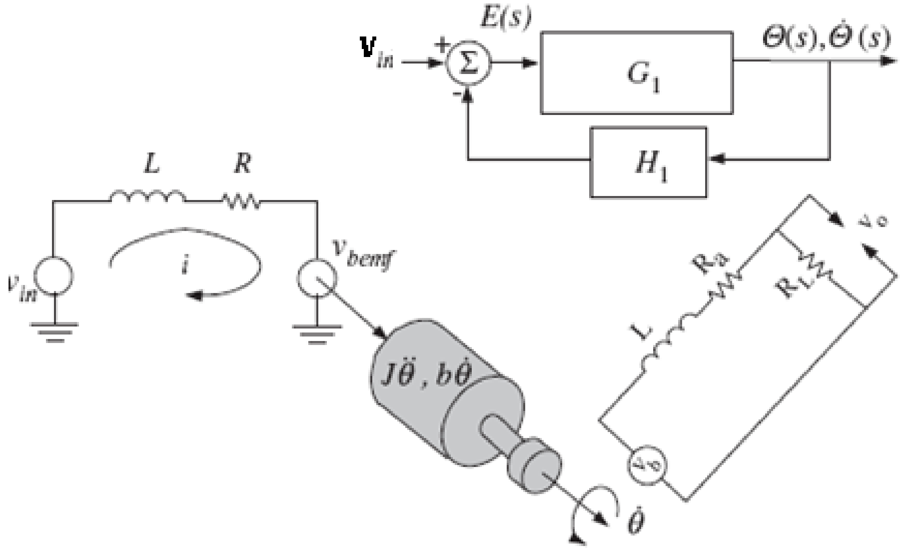
$$\text{T.F.} = \frac{V_o(s)}{s\theta(s)} = \frac{V_o(s)}{\omega(s)}$$

$$= \frac{K_f R_L}{(R_a + R_L + Ls)} = \frac{m}{s+n}$$

where

$$m = \frac{K_f R_L}{L}$$

$$n = \frac{R_a + R_L}{L}$$



An electromechanical system with a tachometer sensor.

Electromechanical Systems Dynamics

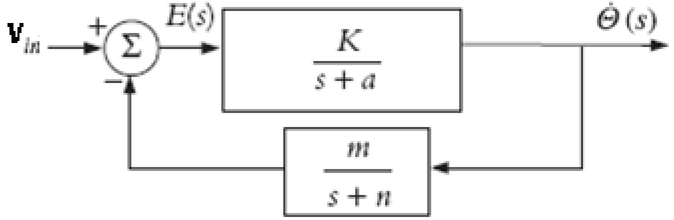
- **Modeling Robot's Actuator**

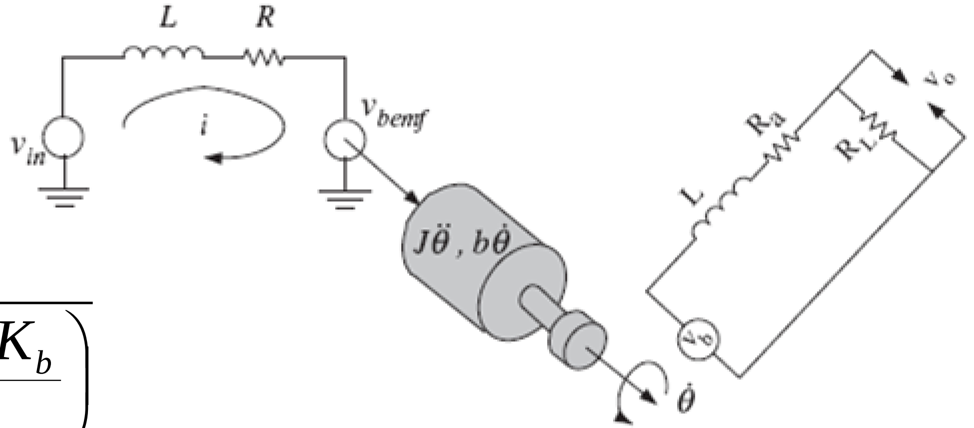
With tachometer, the transfer function between the input voltage and output angular velocity is:

$$\frac{\theta(s)}{V_{in}(s)} = \frac{K_t / LJ}{s\left(s^2 + s(\frac{RJ + Lb}{LJ}) + \frac{Rb + K_t K_b}{LJ}\right)}$$

or

$$\frac{\omega(s)}{V_{in}(s)} = \frac{K_t / LJ}{\left(s^2 + s(\frac{RJ + Lb}{LJ}) + \frac{Rb + K_t K_b}{LJ}\right)}$$





Completed block diagram for the robot's actuating motor.

Electromechanical Systems Dynamics

- **Modeling Robot's Actuator**

$$\frac{\omega(s)}{V_{in}(s)} = \frac{K_t / LJ}{\left(s^2 + s(\frac{RJ+Lb}{LJ}) + \frac{Rb+K_tK_b}{LJ}\right)}$$

Characteristic equation $\rightarrow$ $s^2 + s(\frac{RJ+Lb}{LJ}) + \frac{Rb+K_tK_b}{LJ} = 0$

For quadratic systems $\rightarrow$ $s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$

$$\downarrow$$

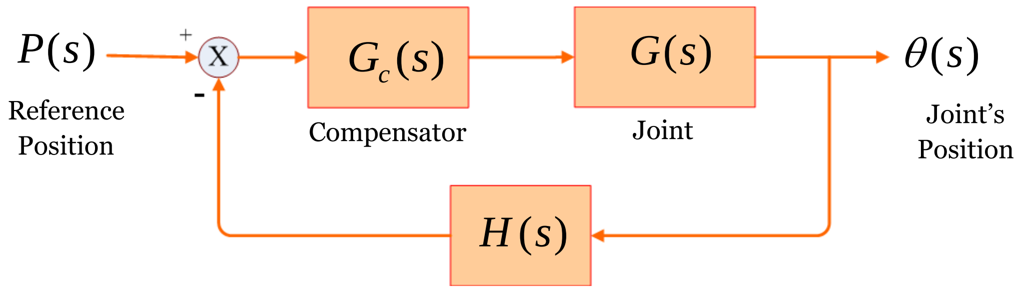
$$\omega_n^2 = \frac{Rb+K_tK_b}{LJ} \quad \text{and} \quad 2\zeta\omega_n = \frac{RJ+Lb}{LJ}$$

Outline

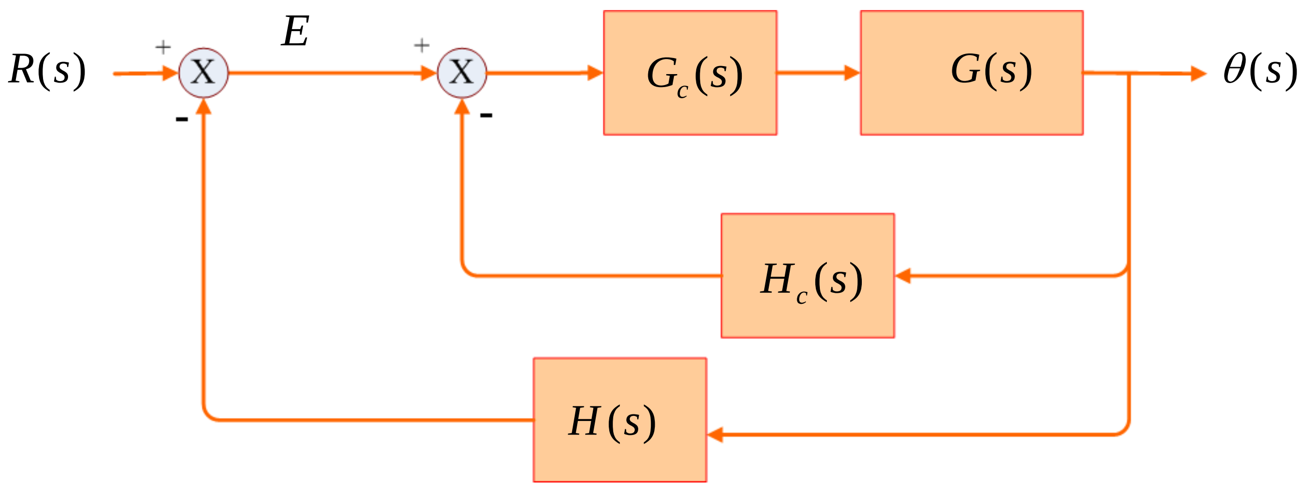
- Industrial Robot Control
- Control Techniques
- Motion Control
- Electromechanical Systems Dynamics
- **Position Control**
- Summary

Position Control

- **Dynamic Compensation**



Cascade/Series Compensation



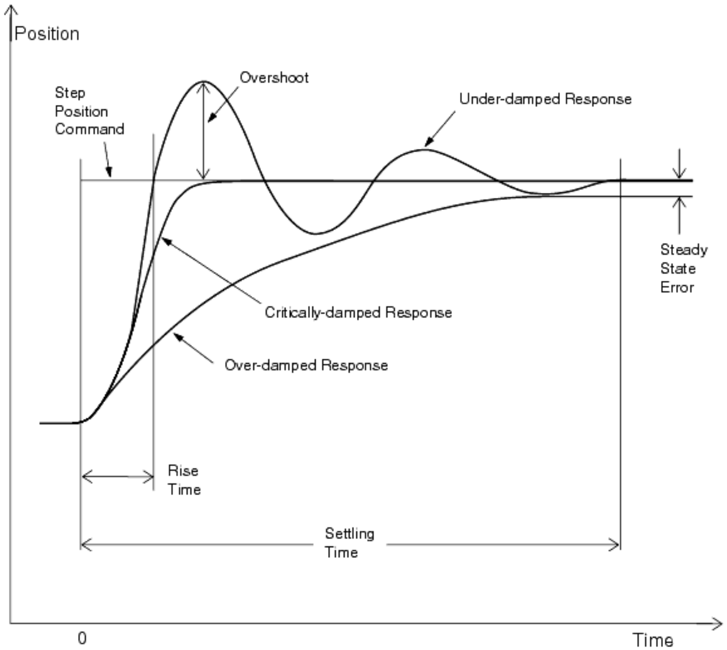
Minor Loop Feedback Compensation

For more info: see MCTR903:Advanced Mechatronics Engineering Course

http://msm.guc.edu.eg/MCTR903/index.html

Position Control

- **Control Modes**



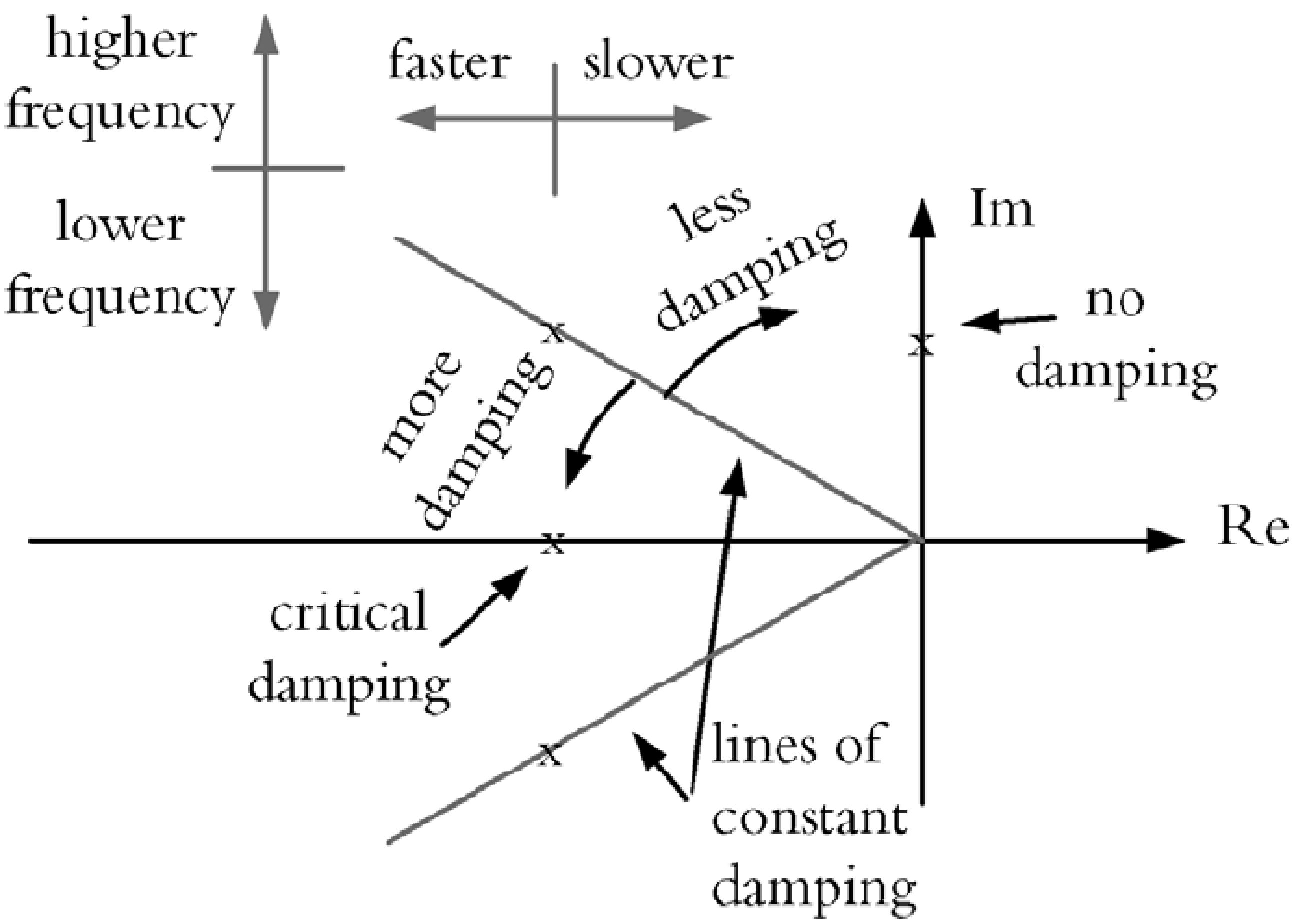
Effect of PID Controllers on Closed-Loop System

	P	I	D
Rise Time	Decreases	Decreases	Small Change
Overshoot	Increases	Increases	Decreases
Settling Time	Small change	Increases	Decreases
S.S. Error	Decreases	Eliminates	Small change

Note that these correlations may not be exactly accurate, because K_P, K_I, and K_D are dependent on each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only be used as a reference when you are determining the values for K_I, K_P and K_D.

Position Control

- **Control Modes**

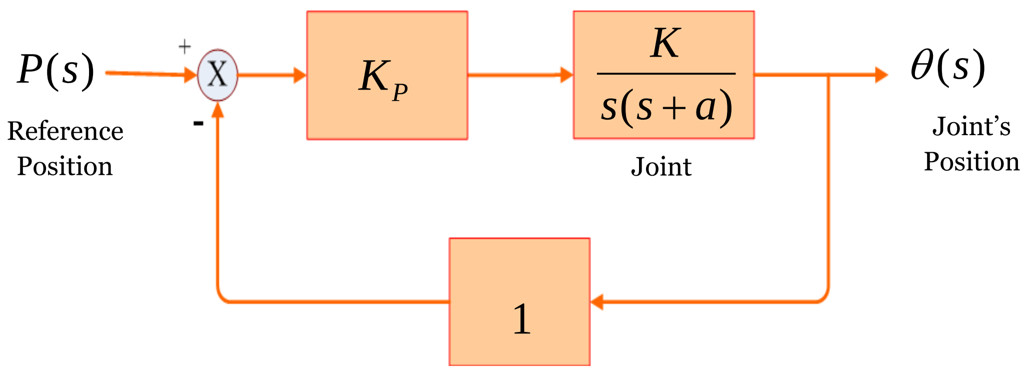


The response of the system changes as the poles move in different directions

Position Control

- **Proportional Mode**

To examine the use of feedback, we will develop a control scheme for joint position using proportional feedback. To simplify this development, we assume that the feedback transducer has unity gain. We calculate the closed loop transfer function for proportional-feedback control of the **low-inertia micromotor**.



Low-inertia Micromotor

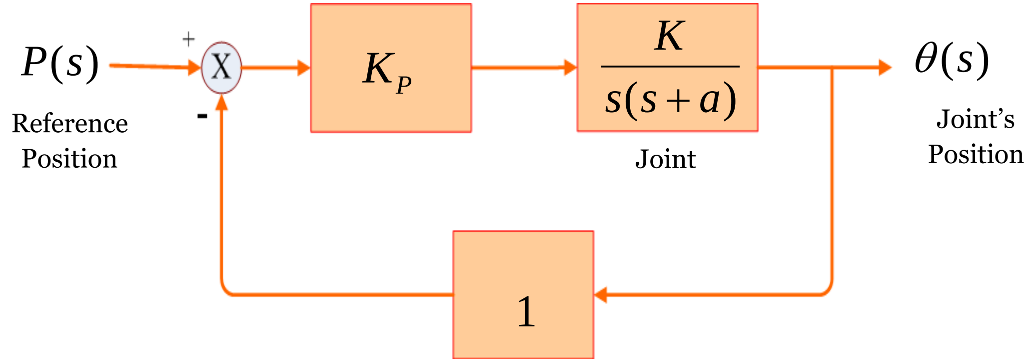
Quantity	Rated Value
V	15 volts
No-load speed	4300 rpm
No-load current	20×10^{-3} Amps
Stall torque	110×10^{-3} N.metres
Power	12 watts
Bemf constant K_e	3.5 v/1000 rpm
Inductance	0.6×10^{-3} Henry
Resistance	4.5 ohm
Torque const. K_t	33×10^{-3} N.m/amp
Inertia	32×10^{-7} kg.m2
Friction	1×10^{-6} N.m/radian/s
Motor time const	13×10^{-3} s

Position Control

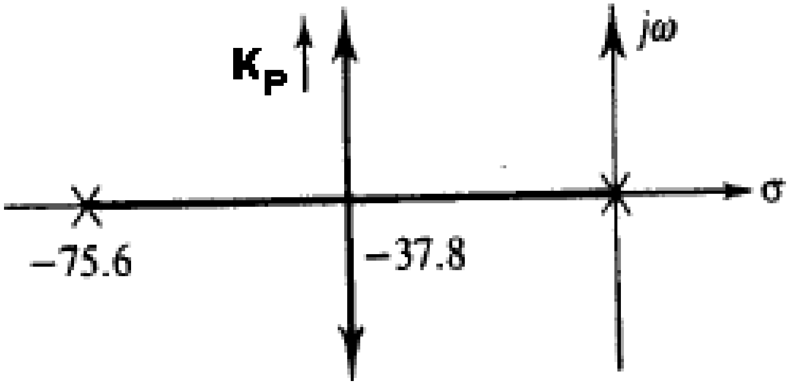
- **Proportional Mode**

The transfer function is:

$$\frac{\theta(s)}{P(s)} = \frac{2292\,K_P}{s^2 + 75.6s + 2292\,K_P}$$



To study the closed-loop response, we examine the pole-zero diagram of this transfer function. The arcs of the root-locus plot start at the open-loop poles and move toward the open-loop zeros. There are as many zeros as poles, with the **unspecified zeros at infinity**.



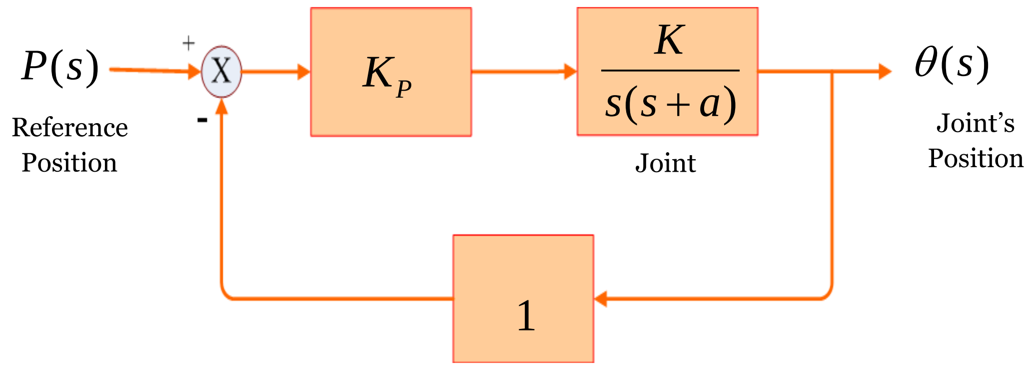
Root Locus

Position Control

- **Proportional Mode**

  Characteristics equation is:

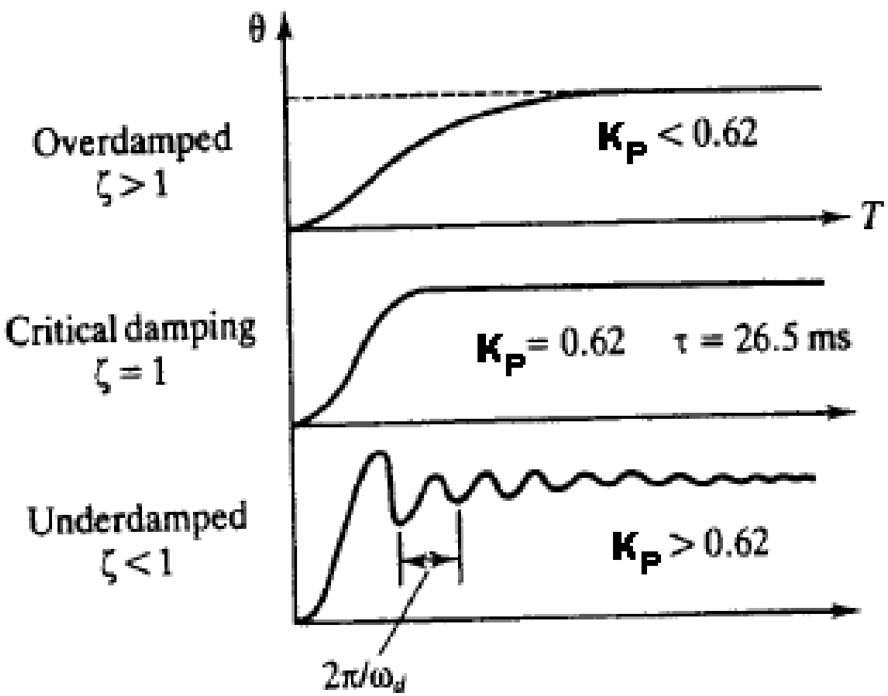
  $$s^2 + 75.6s + 2292\,K_P = 0$$



For quadratic systems → $$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$$

$$\downarrow$$

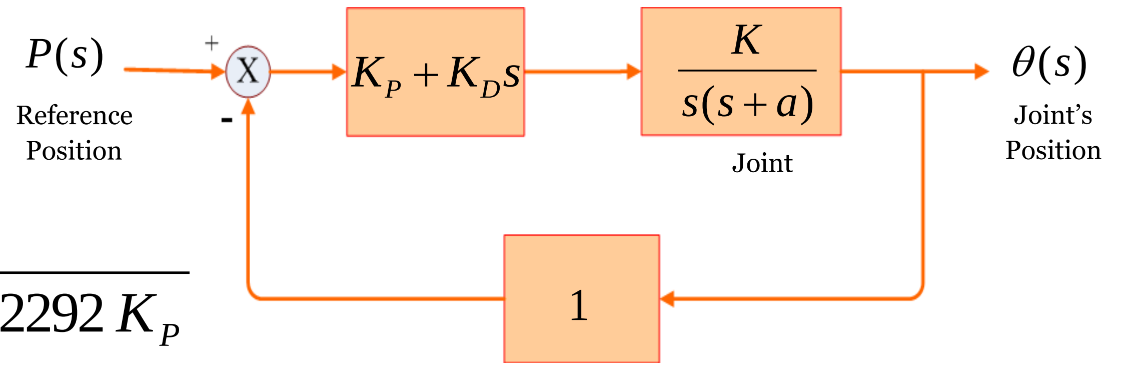
$$\omega_n^2 = 2292\,K_P \quad \text{and} \quad 2\zeta\omega_n = 75.6$$



Note: for low gains, the poles are on the real axis and the control is overdamped. As the gain increases, the poles reach the midpoint between the open-loop poles and the control is critically damped. Increasing the gain further moves the poles parallel to the img. axis, and the control is underdamped.

Position Control

- **PD Mode**

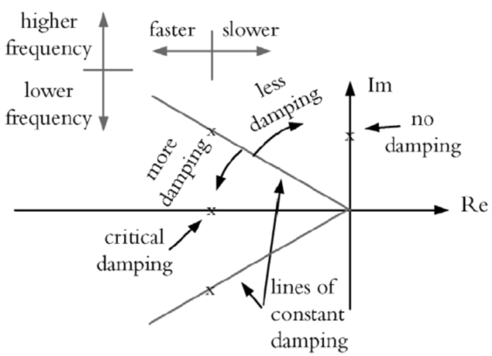


The transfer function is:

$$\frac{\theta(s)}{P(s)} = \frac{2292\,(K_P + K_D s)}{s^2 + (75.6 + 2292\,K_D)s + 2292\,K_P}$$

Characteristic equation $\rightarrow$ $s^2 + (75.6 + 2292\,K_D)s + 2292\,K_P = 0$

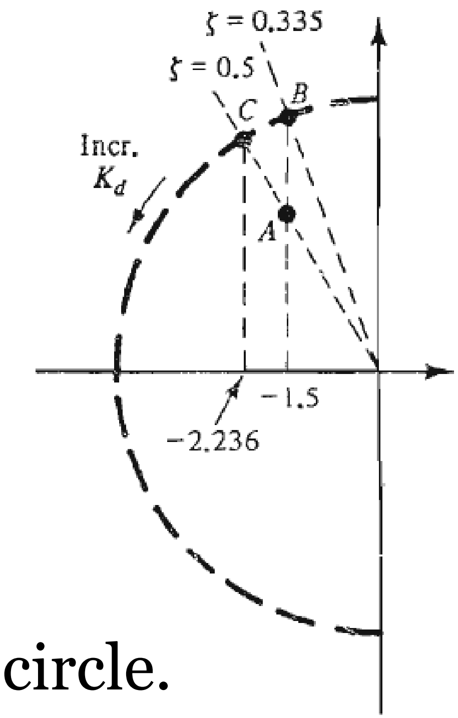
For quadratic systems $\rightarrow$ $s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$



$$\downarrow$$

$\omega_n^2 = 2292\,K_P$ and

$2\zeta\omega_n = (75.6 + 2292\,K_D)$

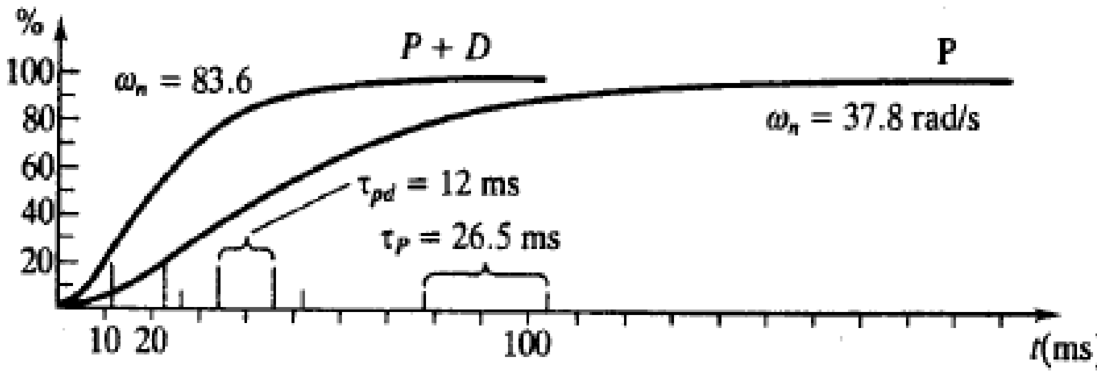


◇ Varying K_P for constant K_D moves the poles vertically, and

◇ varying K_D for constant K_P moves them along a circle.

Position Control

- **PD Mode**
  - ◇ From this plot, we see that the step response for the PD control law is **much faster** than that for the P control law.



Step response for proportional and proportioned plus derivative feedback control of the low-inertia micromotor, with critical damping.

  - ◇ As the zero in the closed-loop transfer function is **moved farther to the left**, the response improves.

Position Control

- **PD Mode**
  - ◊ **Problems with this control mode.**
    - **First**, the derivative of a step input is an impulse so **electrical noise** on the feedback signal may cause undesirable fluctuations in position.
    - **Second**, the **faster response** of the motor is achieved by applying a **higher voltage** to the terminals to produce larger acceleration and deceleration torques.

      Some industrial systems apply up to **twice nominal voltage** to motors for **short periods of time**. This is known as **forcing**.

      However, there is a limit to the amount of forcing which can be applied to a motor without damaging it.

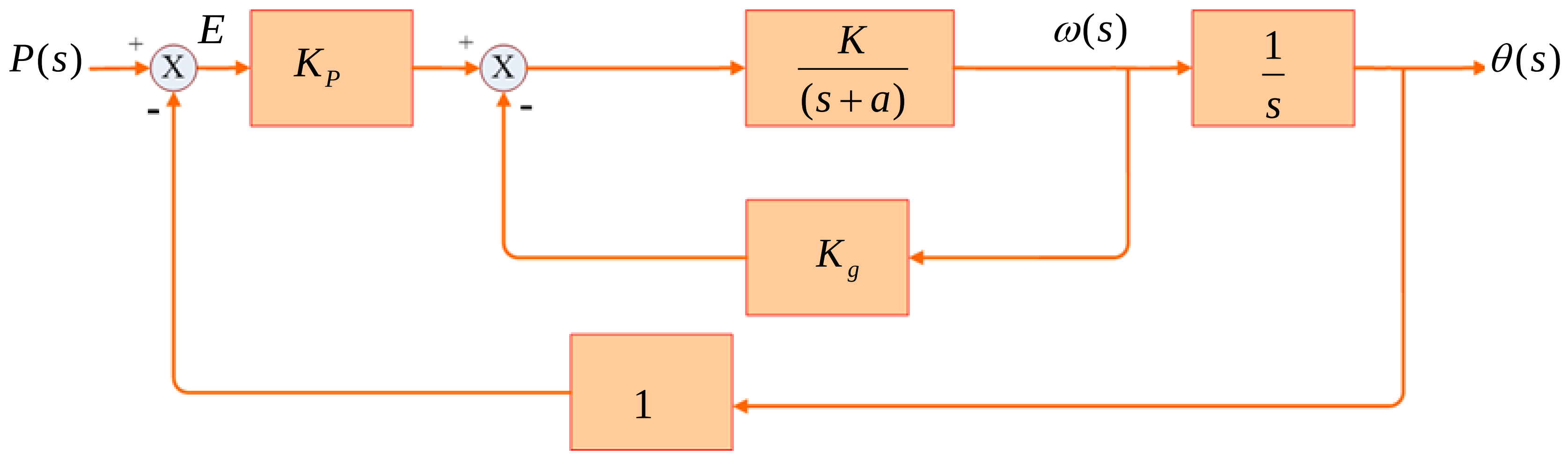
Position Control

- **PD Mode**
  - ◇ In most robot controllers, the speed of response to position errors is limited by the **maximum velocity of the joint**. Often, the **nominal operating velocity** is restricted to be much less than the maximum in order to minimize the effect of the dynamics of the link.
  - ◇ Also, once the forcing limit is reached, the tracking error increases and the **controller may saturate**.
  - ◇ In an analogue controller, **saturation** occurs when the output of an amplifier is driven to its maximum, or minimum, value.
  - ◇ In a **digital controller**, saturation occurs when the calculations **overflow (or reach a limit)**. While the controller is saturated, it has lost control of the system.

Position Control

- **Proportional plus Velocity Control**

The problems caused by the **derivative law amplifying electrical noise** can be eliminated by using velocity feedback

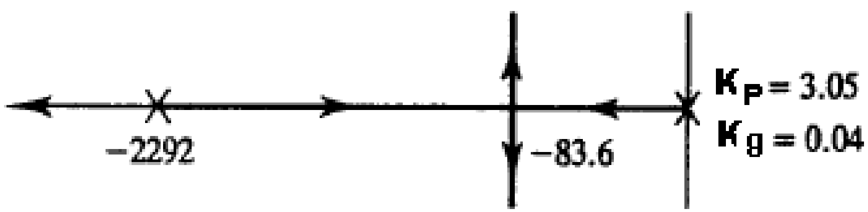


$$GH(s) = \frac{K_P K}{s(s+a+K_g K)} = \frac{2292\,K_P}{s(s+75.6+2292\,K_g)}$$

$$\frac{\theta(s)}{P(s)} = \frac{2292\,K_P}{s^2+(75.6+2292\,K_g)s+2292\,K_P}$$

Position Control

- **Proportional plus Velocity Control**
  - ◇ The closed-loop transfer function for this system has the same characteristic equation as proportional plus derivative control, but no zero.
  - ◇ Consequently, it has the same time response, for the same gains, but a different root locus.



  - ◇ Stable position control has been achieved with fast, critically-damped, response.

Position Control

- **Proportional plus Velocity Control**

From $GH(s)=\dfrac{2292\,K_P}{s(s+75.6+2292\,K_g)}$

◇ **Type number:** the type number of the system is the value of integer n (number of integrators in GH(s))→type 1

◇ **Gain** $K=\lim_{s\to 0} s^n GH(s)$ and a common practice associates the following names and notations with K, depending on *n*:

n=0: K_p=position error constant

n=1: K_v=velocity error constant

n=2: K_a=acceleration error constant

$$\text{Gain } \mathrm{K_v}=\lim_{s\to 0} s\,\frac{2292\,K_P}{s(s+75.6+2292\,K_g)}=\frac{2292\,K_P}{75.6+2292\,K_g}$$

Position Control

- **Proportional plus Velocity Control**

  Steady-state error:

$$e_{ss} = \lim_{s \to 0} \frac{sR(s)}{1 + (Gain/s^n)}\Bigg|_{\text{for step input}} = \lim_{s \to 0} \frac{s.1/s}{1 + (Gain/s)}$$

$$= \lim_{s \to 0} \frac{s}{s + Gain} = 0$$

◇ Without velocity feedback

$$\frac{\theta(s)}{E(s)} = \frac{K_P K}{s(s+a) + K_P K} \quad \rightarrow \text{type 0}$$

$$e_{ss} = \lim_{s \to 0} \frac{sR(s)}{1 + (Gain/s^n)}\Bigg|_{\text{for step input}} = \lim_{s \to 0} \frac{s.1/s}{1 + (Gain)} = \frac{1}{1 + Gain} \neq 0$$

Outline

- Industrial Robot Control
- Control Techniques
- Motion Control
- Electromechanical Systems Dynamics
- Position Control
- **Summary**

Summary

- The task of a robot control system is to execute the planned sequence of motions and forces correctly in the presence of unforeseen errors.
- The open-loop or nonservo robots do not have position and rate-of-change sensors on any axis; therefore, the controller does not know the position of the arm and tool while the robot is moving from one point to another
- In the closed-loop or servo control, the parameter that is being controlled is continuously measured (feedback), compared to a reference (error calculation), and the action modified according to a control law to overcome the error.
- In most robots, each axis is controlled individually (called independent joint control) as a single-input, single-output unit.