DESKFZG561

MECHANISMS & ROBOTICS

Kinematics of Manipulators–Lecture 16

ROBOT CONTROL AND PROGRAMMING

"**Books :**

1. "Robotics : Control, sensing, Vision, and Intelligence", K.S.Fu, R.C.Gonzalez,C.S.G.Lee
2. "Industrial Robotics: Technology, Programming and Application", Mikell Groover, McGraw Hill

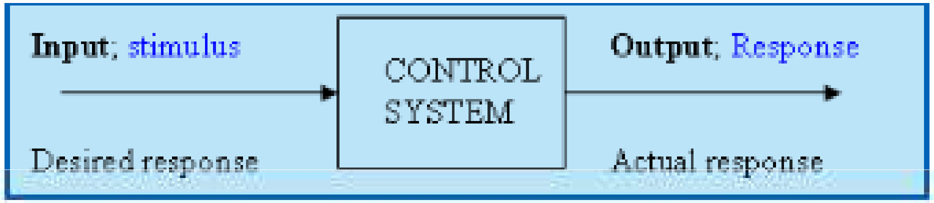
INTRODUCTION TO ROBOT CONTROL

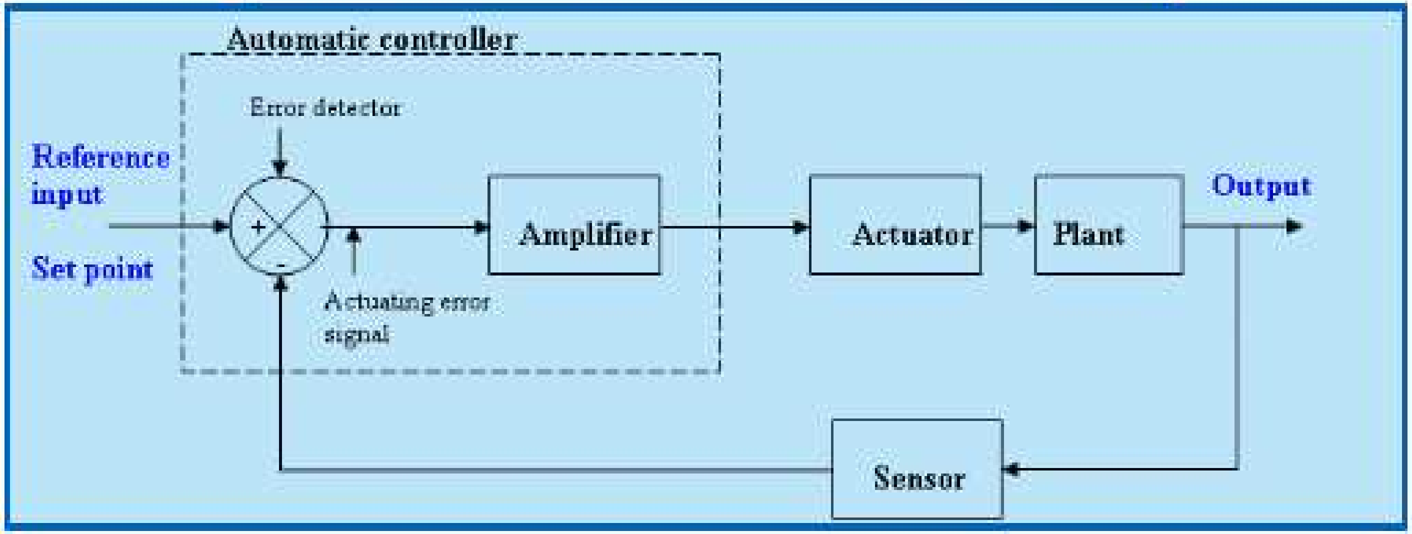
Types of Robot Controls

1. ***Limited sequence Robots-*** Lowest Level, Do not use servo control to indicate relative positions of joints, No Programming required and feed back associated, controlled by setting limit switches and /or mechanical stops. Individual joints can only be moved to their extreme limits of travel. Application only simple motion, Pick and place operations.
2. ***Playback Robot with point to point control-*** More sophisticated, series of motion or positions are taught to the robot, recorded into memory, and repeated under its own control. Servo control – closed loop feed back system.
3. ***Playback Robot with Continuous control-*** Two categories- PTP Point to point and CP continuous path, Control of the sequence of positions is quite adequate for many application- loading unloading, welding, Uses digital computers as controller.
4. ***Intelligent Robot-*** Most Sophisticated, Play back a programmed motion cycle and interact with its environment. Make logical decisions based on sensor data. Communicate with humans or computer based systems. Application – assembly task, arc welding.

INTRODUCTION TO CONTROL

Control System : Simply speaking, a control system provides an output or response for a given input or stimulus. An industrial control system typically consists of an automatic controller, an actuator, a plant and a sensor (measuring element).





Block diagram of an industrial control system

Controller:

It is an important element of Control system. It compares the actual value of the plant output with the reference input (desired value), determines the deviation and produces a control signal that will reduce the deviation to zero or to a small value. The manner in which the controller produces the control signal is called the *control action.* Wise design of controller lead to substantial cost savings and performance improvement.

It detects the actuating error signal, which is usually at a very low power level, and amplifies it to a sufficiently high level. The output of an automatic controller is fed to an actuator, such as an electric motor, a hydraulic motor or a pneumatic motor or a valve. We will see various types of controller & certain

Actuator:

It is a power device that produces the input to the plant according to the control signal so that the output of plant will approach the reference input. In case of Robot control system , actuator is generally electric motor.

Sensor or measuring element:

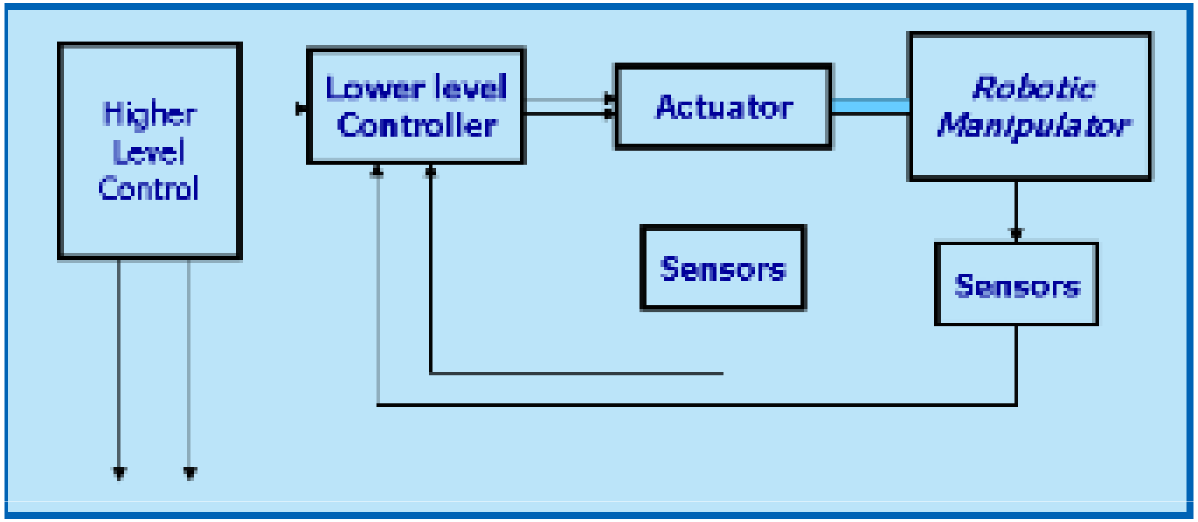
It is a device that converts the output variable into another suitable variable such as a displacement pressure or voltage that can be used to compare the output to the reference input signal. This element is in the feedback path of the closed loop system.

Plant:

It is the one whose output is to be controlled. e.g. In case of Robot control system, plant is the **Robot Manipulator**.

Excluding Higher level controller, the rest of system is same as that of typical industrial control system. Each axis of Robot will have this part of control system excluding higher level controller. Higher level controller generates commands and send it to lower level controllers. Higher level controller has to co-ordinate between various axes of robots. Now we will see controller design issues.

Typical Control system Configuration for Robot manipulator:



Controller Design issues:

Stability of controllers : It should have stability both in numerical implementation & actual performance.

Performance of controllers : As per application need, performance requirement should found out & depending on that decision on control strategy should be taken.

Energy required to achieve high performance: It is the most important issue as there is upper limit on energy input to controller.

Types of Controller:

1. **Proportional Derivative Integral (PID), Proportional & Derivative (PD), or Proportional & Integral (PI)** used in many industries (not suitable for high performance applications).

2. **Nonlinear** (Most of systems in nature are non-linear).

3. **Robust** (to external/internal disturbances).

4. **Adaptive** (adapt to system changes).

Neural network Types

Fuzzy logic (example: washing machine).
Optimal (minimization of cost function).
Passivity based

Control of Manipulator : Need

1. Mathematical modeling of system.

A mathamatical model of system is defined as a set of equations that represents the dynamics of the system accurately or, at least fairly well. e.g. By using Lagrange's formulation we have derived mathmatical model for n-link Robot manipulator. Good understanding of Dynamics is needed to carry out this step.

2. Selection of control strategy.

3. Design of control parameters.

4. Simulation and experimental verification on actual system.

5. It must control the movement and force/torque manipulator applies on environment.

CONTROL OF MANIPULATOR : CONTROL SEQUENCE

•The actual joint and/or end effector positions and their derivatives are fed to the control system via trajectory planner.

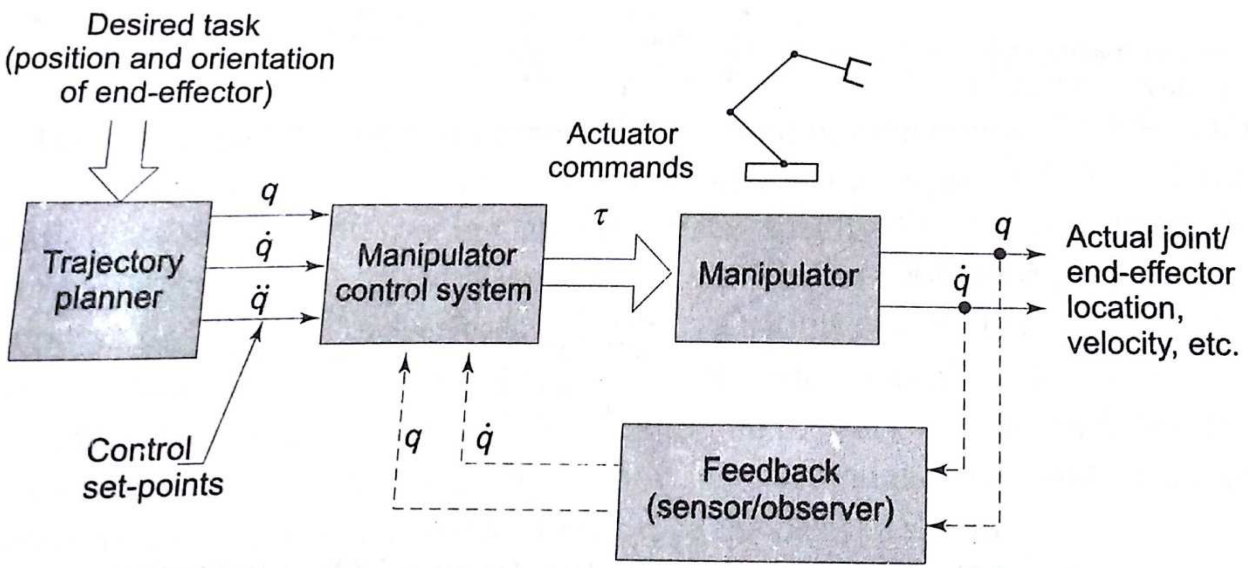
•Manipulator control system commands are based on the "control set points" generated from the set of joint torque time histories obtained by the trajectory planner.

•Actuators receive the commands from manipulator control system.

•Individual joints of a manipulator are powered and driven by actuators that apply force or torque to cause motion of the link.

•Actuators move the manipulator and achieve the specified end effector motion.

•The dotted lines indicate that the control system may or may not employ feedback of the actual joint locations and velocities.



CONTROL OF MANIPULATOR FOR N JOINTS :

•Consider n joint manipulator need to move very slowly or move one joint at a time, the control is simple and coupled dynamic forces are negligible.

•Each joint is controlled independently, producing joint actuator torque/force proportional to the required change in the joint variable.

•This is proportional control algorithm.

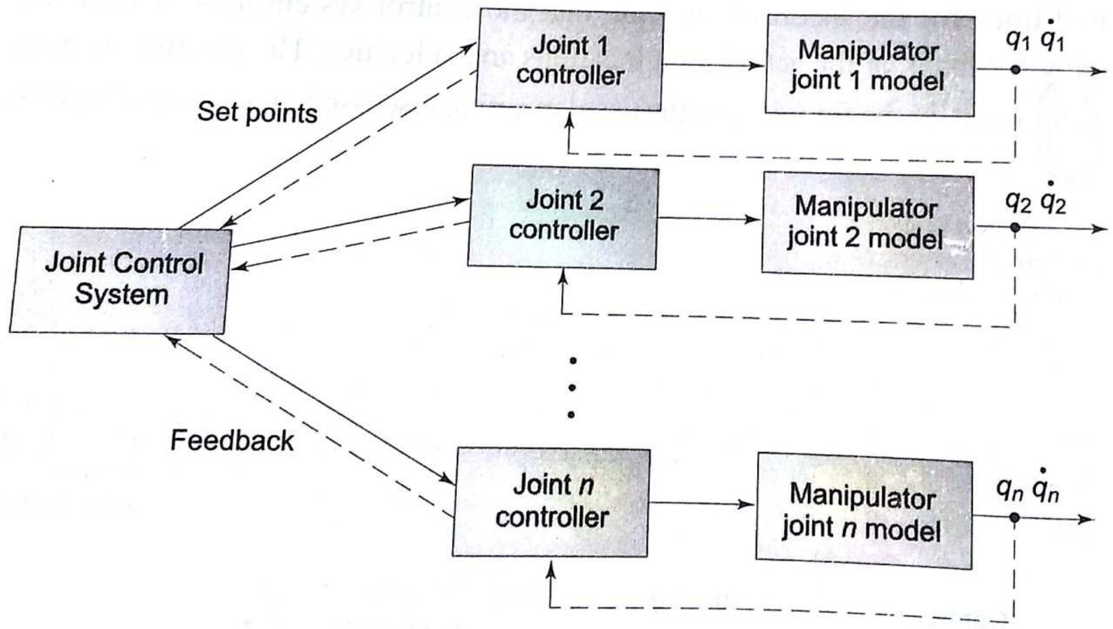


Fig. 8.2 *Robot control architecture for an n-DOF manipulator*

CONTROL OF MANIPULATOR FOR N JOINTS :

•Consider n joint manipulator need to move very fast or move all joint simultaneously, are must for effective robot application, the control is non linear and complex and coupled dynamic forces are significant.

•The joints can not move independently, and complex control algorithm is required.

The master control system to control and synchronize n joints is responsible for sending “set Points” commands to each of the joint controllers. The joint controller may employ feedback of current joint position to the master controller.

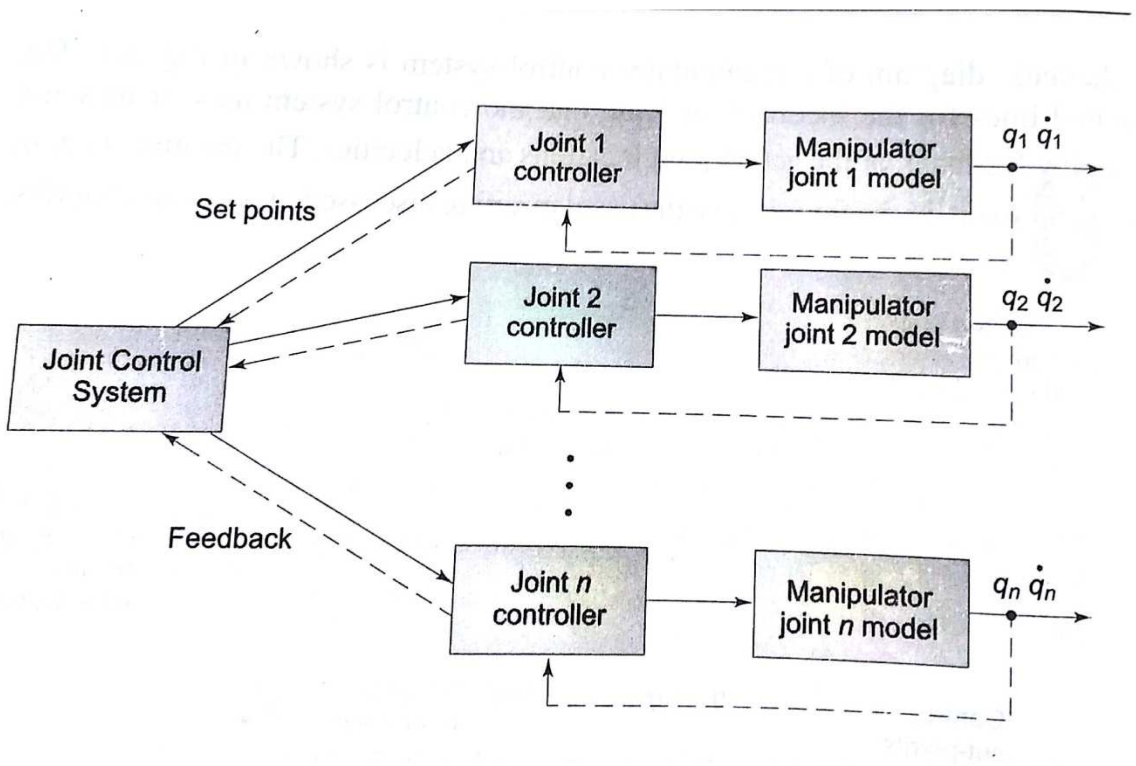


Fig. 8.2 *Robot control architecture for an n-DOF manipulator*

OPEN AND CLOSE LOOP CONTROL

Open loop control (No feed back) –

- The actuator torque is directly calculated from the dynamic model of the manipulator. But the accurate computation of the parameters are difficult. And the model does not include friction, backlash at the joints and other external disturbances or noise. These effects are difficult to model and are highly nonlinear.
- Open loop control has limited trajectory tracking capabilities and very few non precision application.

Closed loop control –

- Limitations of parametric inaccuracies and unmodelled non linear effects are overcome.
- At every instant of time, the actual joint positions and velocities are measured directly by sensors (encoders, Tachometers) mounted at the joints.
- These are used to compute the error between desired and actual positions, velocities of the joints and end effector position and force/torque.
- A control law then computes the joint torques required as a function of these servo errors using the dynamic model.
- The computation of interactive effects of inertia, coriolis, centrifugal and gravitational forces is difficult as vary with time, dynamic model is complex and time consuming.

OPEN AND CLOSE LOOP CONTROL

Initial and final locations of end effector

Computes the desired locations of end effector

Computes the joint position time histories

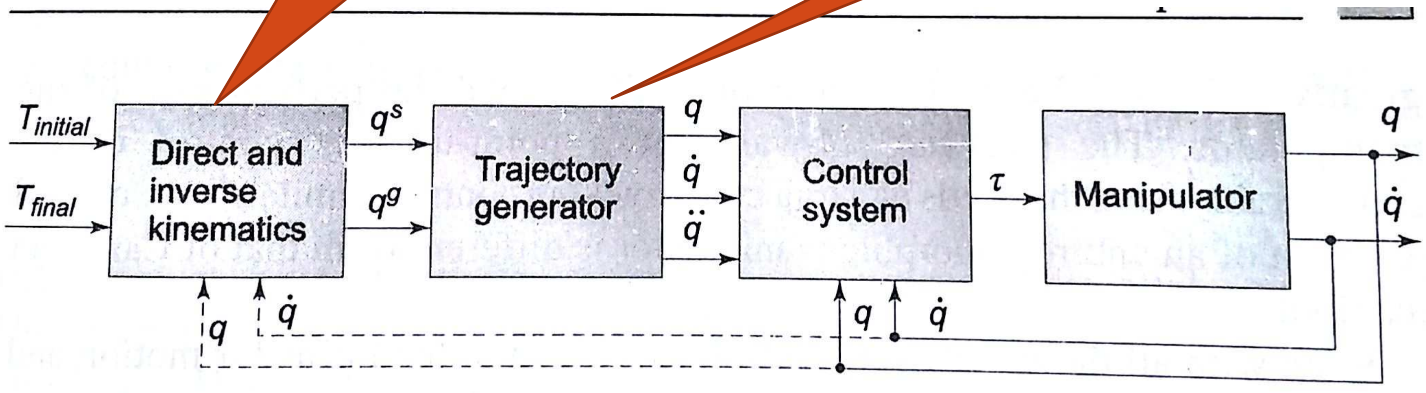


Fig. 8.3 *Operations for a point-to-point motion control of a manipulator*

Depending on the servo error computed from the base reference values and the sensor measurements, the control system commands the individual actuator to achieve the desired motion.

CONTROL STRATEGY

There are a number of ways by which a controller can react to the error signal and supply the output for actuator.

1. The on/off or two step control.
2. The proportional (P) control, which produces a control signal proportional to error.
3. The derivative(D) control, which produces a control signal proportional to the rate of change of error. Derivative control is considered as an anticipatory control that measures the existing rate of change of error, anticipates increasing larger error, and applies correction before the larger error is arrived. Derivative control is never used alone.
4. The integral(I) control, which produces a control signal that is proportional to integral of the error with time. The integral controller can be considered as "looking back", summing all the error and then responding.
5. Combination modes: Combination of all above strategies such as Proportional plus derivative (PD), proportional plus integral (PI), Proportional plus integral plus derivative(PID) are often used to achieve the desired performance.

CONTROL STRATEGY

The linear control scheme is valid for systems behavior can be mathematically modeled by linear differential equations. The linear control technique is as approximate method and joint should be modeled as a linear second order system.

The approximate linear model of an individual joint is obtained by ignoring the configuration dependent nature of the link inertias, interaction inertias and gravity torques. Good approximation and result in a satisfactory trajectory tracking performance for the highly geared joint.

The manipulator control problem is multi input, multi output (MIMO) , involving joint and end effector locations, velocities and force vectors. To simplify, each joint is considered as independent and separately controlled. This single joint model is assumed to have single input (set Point) and single output (Location, Velocity etc.). Hence the n DOF manipulator is modeled as n independent linear second order systems and is controlled by n independent single input, single output(SISO0 control system.

SYSTEM PERFORMANCE, CONTROL SYSTEM WITH DAMPING

- The control system is divided into components as

a) The input to the system

b) The controller and actuating devices

c) The plant (mechanism or process being controlled)

d) The output(the controlled variable)

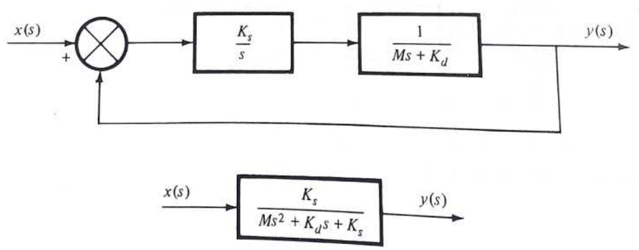
e) Feedback elements(sensors)

For analyzing we must be able to model the system mathematically. It is often useful to provide a schematic representation (Block Diagram) of the system. Block diagram are constructed from four basic elements : Function Blocks, Signal Arrows, Summing Junctions and Takeoff points.

By assembling these components it is possible to describe any linear system in the form of a block diagram.

The characteristic equation for the spring-mass-damper system is

$Ms^2 + K_d s + K_s = 0$ whose block diagram is



SYSTEM PERFORMANCE, CONTROL SYSTEM WITH DAMPING

- The performance of the system depends on the values M, K_d , K_s .
- One aspect of the system performance that can be determined by analyzing the roots of the characteristic equation is the "damping" of the system.
- The root of the characteristic equation is

$$s_{1,2} = -\frac{K_d}{2M} \pm \frac{\sqrt{K_d^2 - 4MK_s}}{2M}$$

- Depending on the values of the parameters in the characteristic equation, the system may respond in one of the four ways.
- Un damped system, Under damped system, Critically damped System, Over damped System.

Although manipulator is mechanically more complex than spring-mass-damper system, it exhibits many same operating features. Mass, stiffness as spring constant, joints has damping. the resulting motions of the robot arm behaves in similar manner to the performance of a system described by second order linear diff eqn. with constant coefficients.

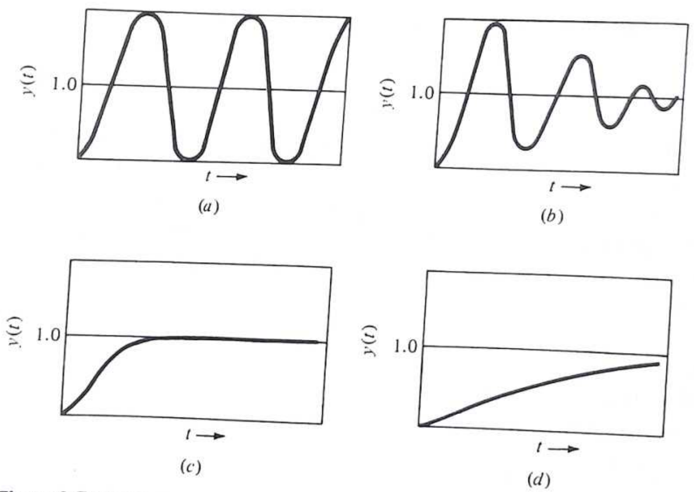
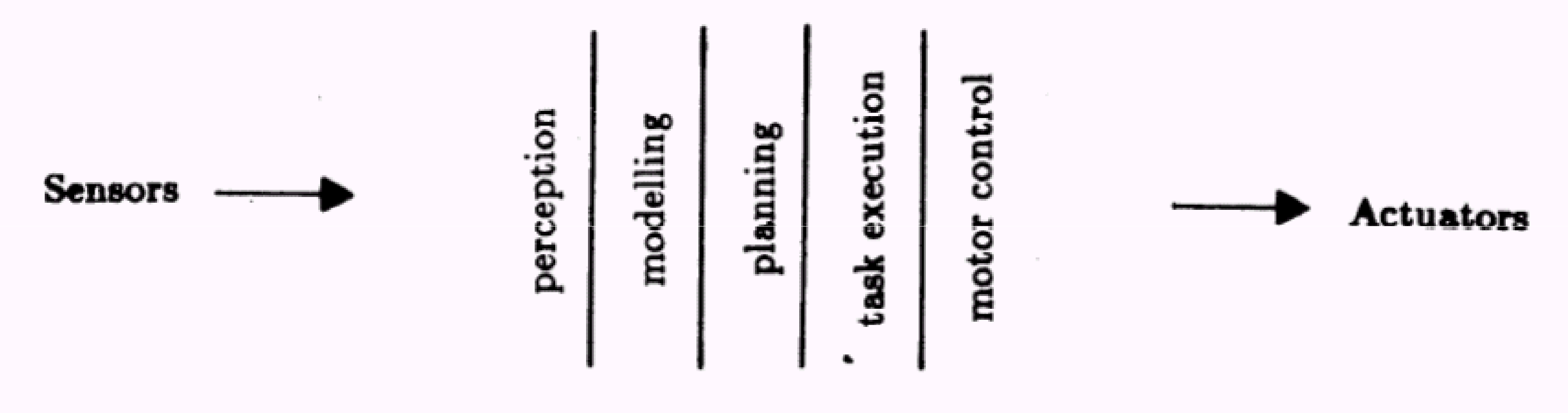


Figure 3-7 Response curves for the four possible cases in a second order linear system. (a) undamped, (b) underdamped, (c) critically damped, (d) overdamped.

ROBOT CONTROL ARCHITECTURES

1) DELIBERATIVE ROBOT CONTROL ARCHITECTURES

- In a deliberative control architecture the robot first plans a solution for the task by reasoning about the outcome of its actions and then executes it
  - Control process goes through a sequence of sensing, model update, and planning steps



Advantages

Reasons about contingencies

Computes solutions to the given task

Goal-directed strategies

Problems

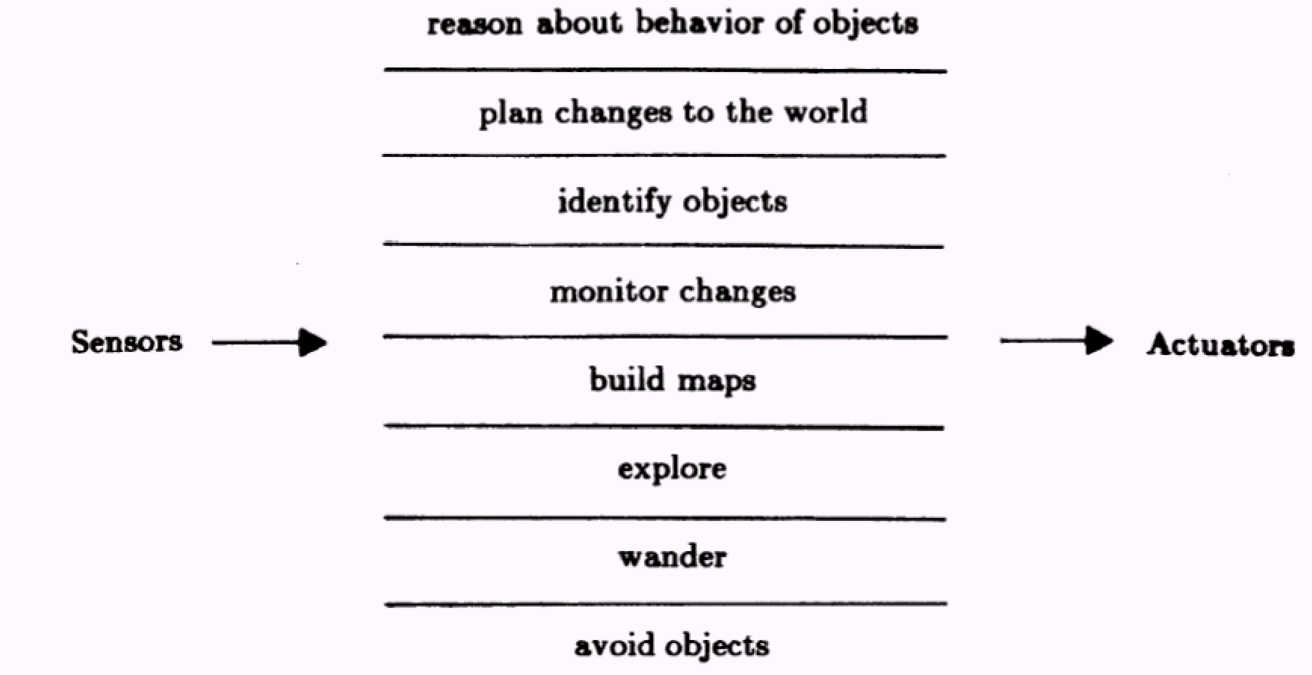
Solutions tend to be fragile in the presence of uncertainty

Requires frequent replanning

Reacts relatively slowly to changes and unexpected occurrences

2) BEHAVIOR-BASED ROBOT CONTROL ARCHITECTURES

In a behavior-based control architecture the robot's actions are determined by a set of parallel, reactive behaviors which map sensory input and state to actions.



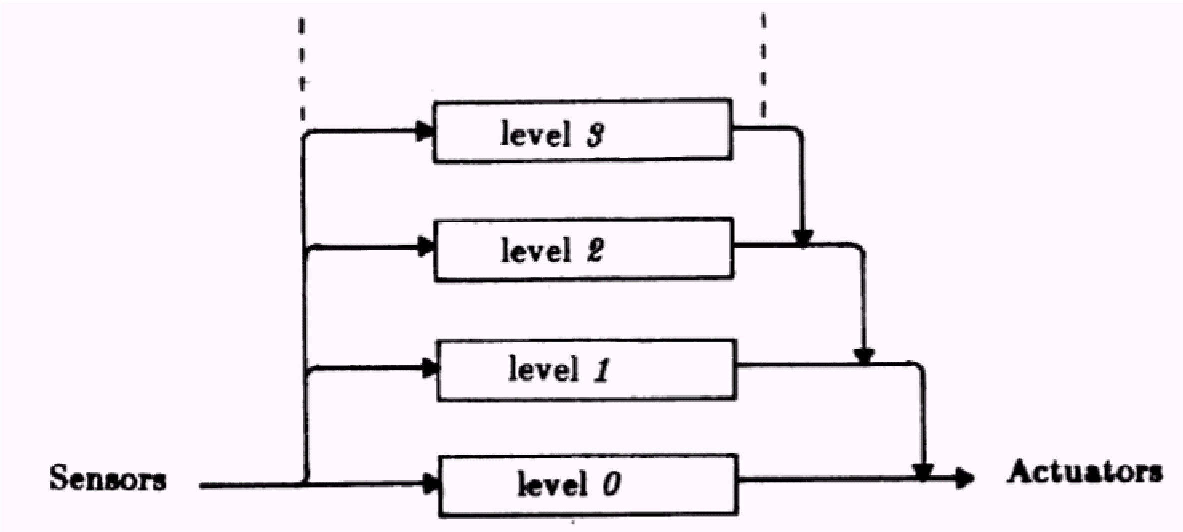
•Reactive, behavior-based control combines relatively simple behaviors, each of which achieves a particular subtask, to achieve the overall task.

- •Robot can react fast to changes
- •System does not depend on complete knowledge of the environment
- •Emergent behavior (resulting from combining initial behaviors) can make it difficult to predict exact behavior
- •Difficult to assure that the overall task is achieved

- Behavior-Based Architectures: Subsumption Example

Subsumption architecture is one of the earliest behavior-based architectures

Behaviors are arranged in a strict priority order where higher priority behaviors subsume lower priority ones as long as they are not inhibited.



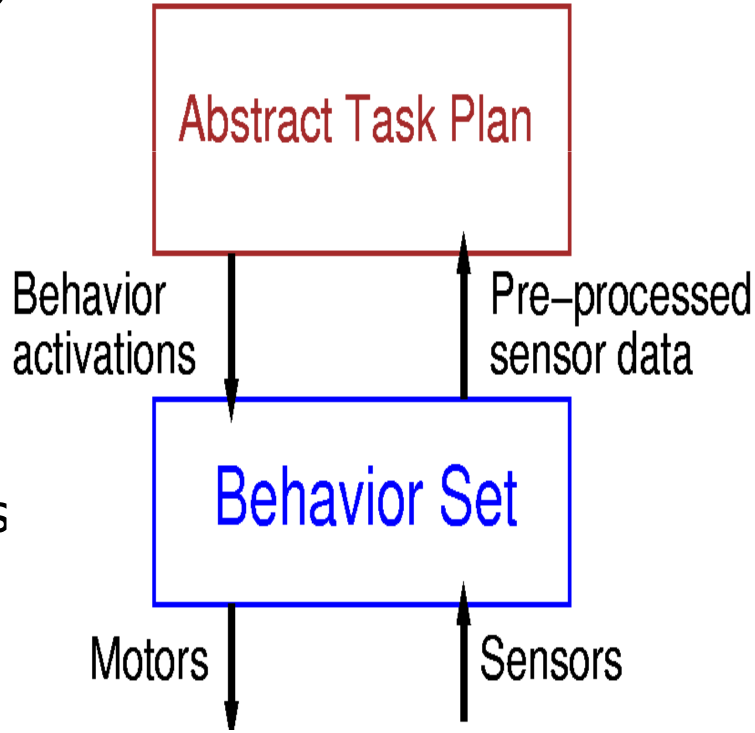
- Reactive, Behavior-Based Control Architectures

Advantages
- Reacts fast to changes
- Does not rely on accurate models
  - "The world is its own best model"
- No need for replanning

Problems
- Difficult to anticipate what effect combinations of behaviors will have
- Difficult to construct strategies that will achieve complex, novel tasks
- Requires redesign of control system for new tasks

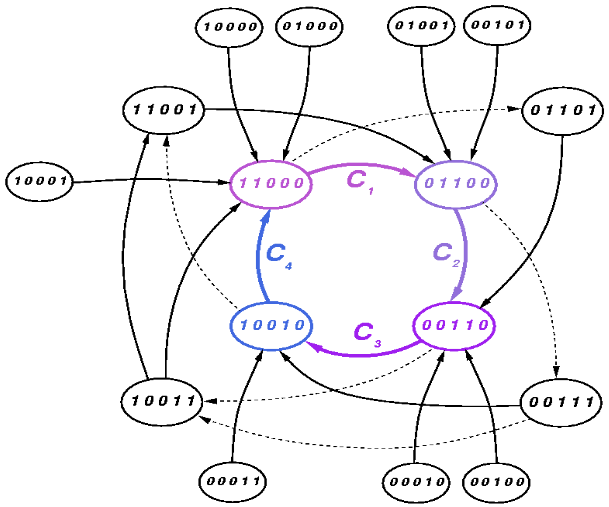
Hybrid Control Architectures

- Hybrid architectures combine reactive control with abstract task planning
  - Abstract task planning layer
    - Deliberative decisions
    - Plans goal directed policies
  - Reactive behavior layer
    - Provides reactive actions
    - Handles sensors and actuators

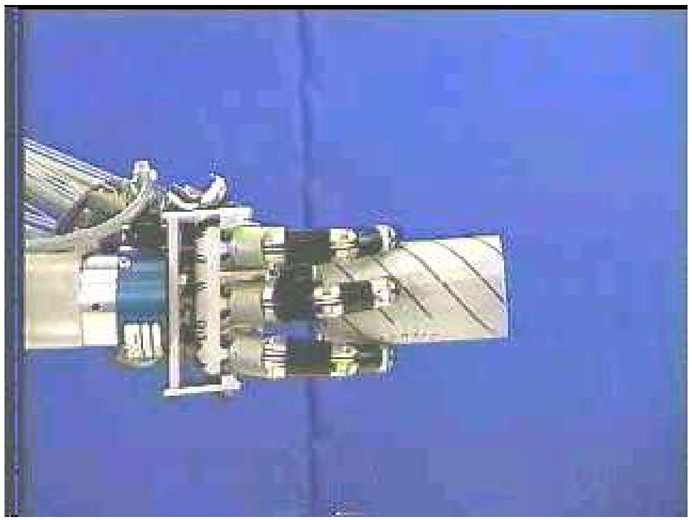


Hybrid Control Policies

Task Plan:



Behavioral Strategy:



Hybrid Control Architectures

Advantages

- Permits goal-based strategies
- Ensures fast reactions to unexpected changes
- Reduces complexity of planning

Problems

- Choice of behaviors limits range of possible tasks
- Behavior interactions have to be well modeled to be able to form plans

ROBOT OROGRAMMING

A robot program is a path in the space that to be followed by the manipulator, combined with peripheral actions that support the work cycle. To program a robot, specific commands are entered into the robot's controller memory, and these actions may be performed in a number of ways. Limited sequence robot programming is carried out when limit switches and mechanical stops are set to control the end-points of its motions. A sequencing device controls the occurrence of motions, which in turn controls the movement of the joints that completes the motion cycle.

Lead-through Programming:

For industrial robots with digital computers as controllers, three programming methods can be distinguished. These are lead-through programming; computer-like robot programming languages; and off-line programming. Lead-through methodologies, and associated programming methods, are

Computer-like Programming

These are computer-like languages which use on-line/off-line methods of programming. The advantages of textual programming over its lead-through counterpart include:

- The use of enhanced sensor capabilities, including the use of analogue and digital inputs
- Improved output capabilities for controlling external equipment
- Extended program logic, beyond lead-through capabilities
- Advanced computation and data processing capabilities
- Communications with other computer systems

ROBOT OROGRAMMING

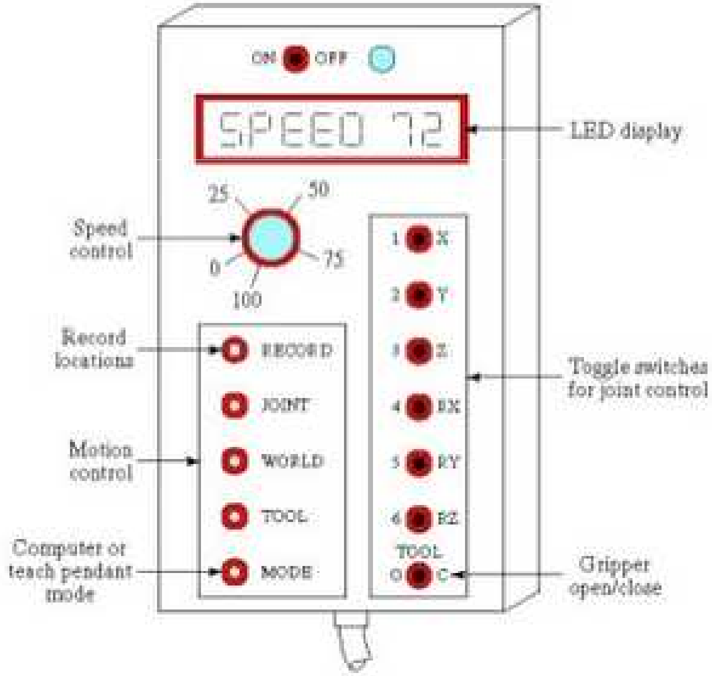
- Leadthrough programming
  - Work cycle is taught to robot by moving the manipulator through the required motion cycle and simultaneously entering the program into controller memory for later playback
- Robot programming languages
  - Textual programming language to enter commands into robot controller
- Simulation and off-line programming
  - Program is prepared at a remote computer terminal and downloaded to robot controller for execution without need for leadthrough methods

ROBOT OROGRAMMING

Method	Description
Lead-through programming	• Task is 'taught' to the robot by manually moving the manipulator through the required motion cycle, and simultaneously entering the program into the controller memory for playback. • Two methods are used for teaching: powered lead-through; and manual lead-through.
Motion programming	• To overcome the difficulties of co-coordinating individual joints associated with lead-through programming, two mechanical methods can be used: the world-co-ordinate system—whereby the origin and axes are defined relative to the robot base; and the tool-co-ordinate system—whereby the alignment of the axis system is defined relative to the orientation of the wrist faceplate. • These methods are typically used with Cartesian co-ordinate robots, and not for robots with rotational joints. • Robotic types with rotational joints rely on interpolation processes to gain straight line motion. • Two types of interpolation processes are used: straight line interpolation—where the control computer calculates the necessary points in space that the manipulator must move through to connect two points; and joint interpolation—where joints are moved simultaneously at their own constant speed such that all joints start/stop at the same time.

Leadthrough Programming

1. Powered leadthrough
   - Common for point-to-point robots
   - Uses teach pendant
2. Manual leadthrough
   - Convenient for continuous path control robots
   - Human programmer physical moves manipulator



Leadthrough Programming Advantages

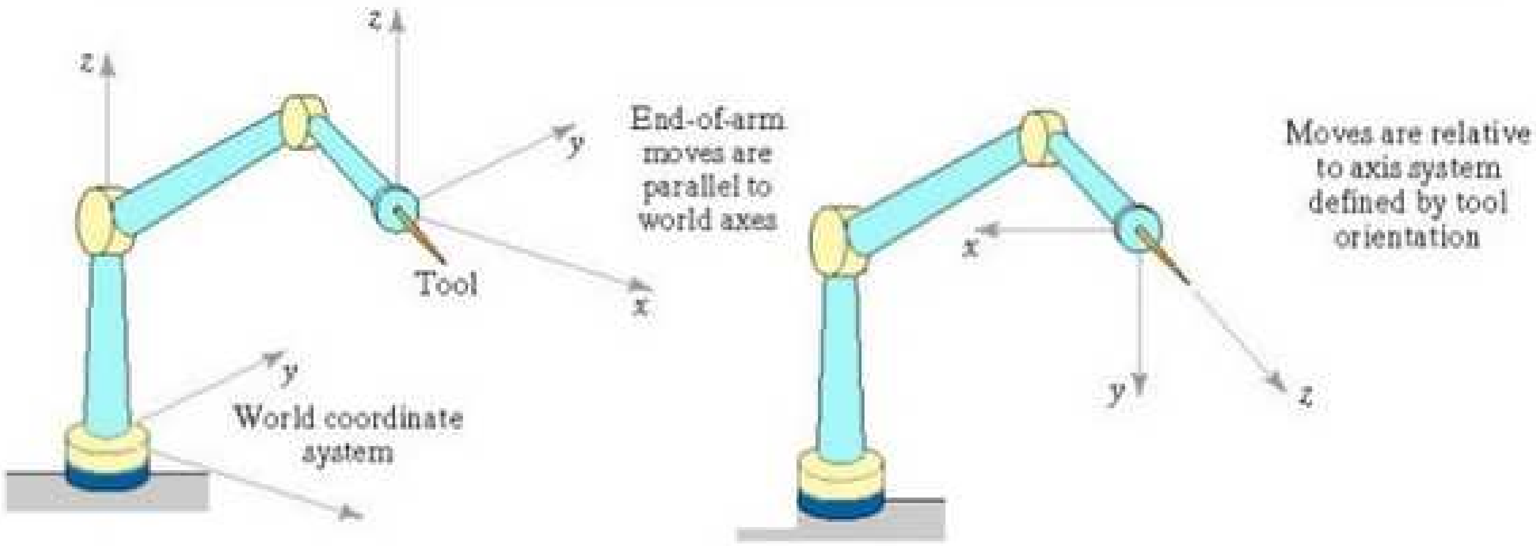
- Advantages:
  - Easily learned by shop personnel
  - Logical way to teach a robot
  - No computer programming
- Disadvantages:
  - Downtime during programming
  - Limited programming logic capability
  - Not compatible with supervisory control

ROBOT OROGRAMMING

Robot Programming

- Textural programming languages
- Enhanced sensor capabilities
- Improved output capabilities to control external equipment
- Program logic
- Computations and data processing
- Communications with supervisory computers

Coordinate Systems



World coordinate system

Tool coordinate system

Motion Commands

MOVE P1

HERE P1 - used during lead through of manipulator

MOVES P1

DMOVE(4, 125)

APPROACH P1, 40 MM

DEPART 40 MM

DEFINE PATH123 = PATH(P1, P2, P3)

MOVE PATH123

SPEED 75

Interlock and Sensor Commands

Interlock Commands

WAIT 20, ON

SIGNAL 10, ON

SIGNAL 10, 6.0

REACT 25, SAFESTOP

Gripper Commands

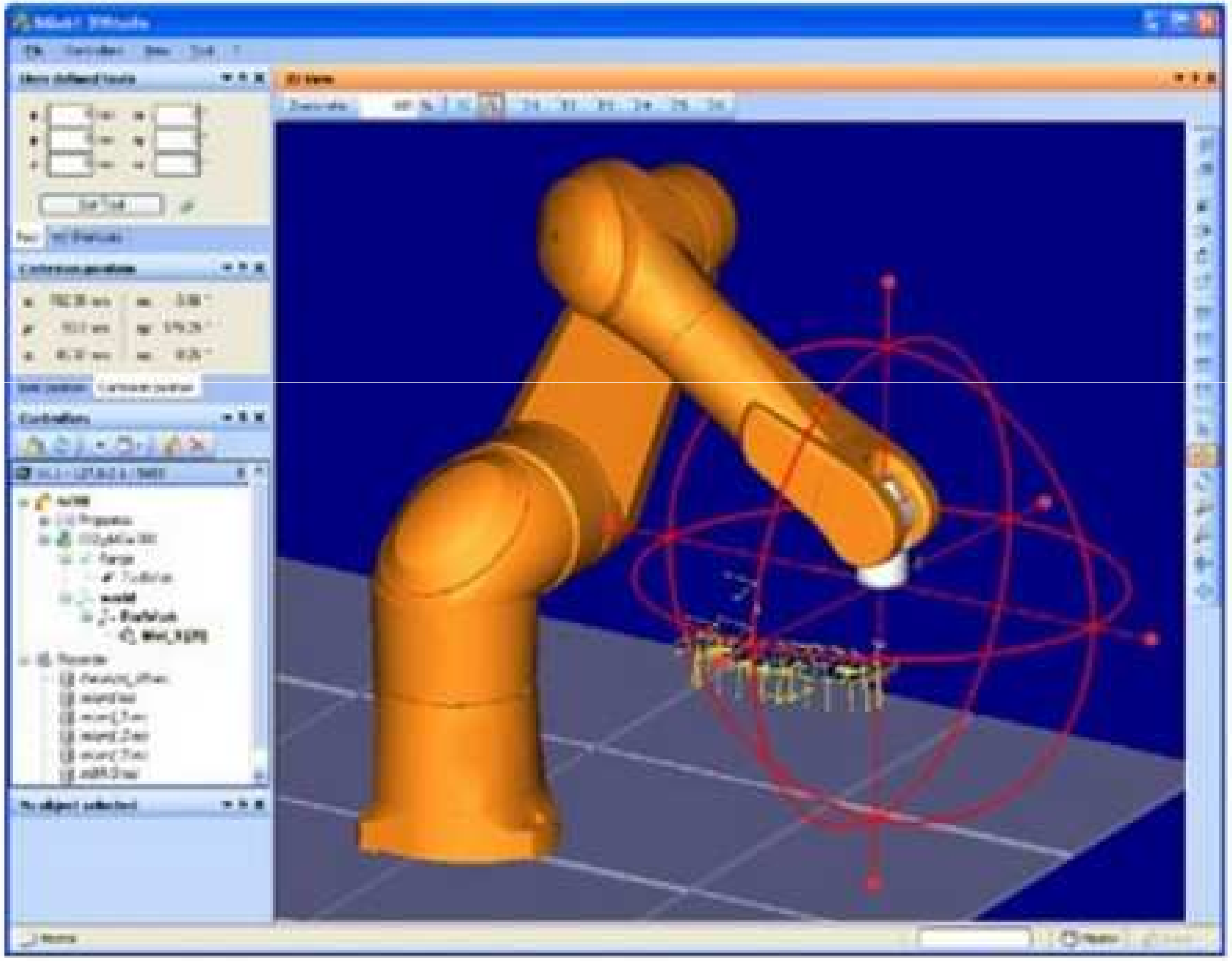
OPEN

CLOSE

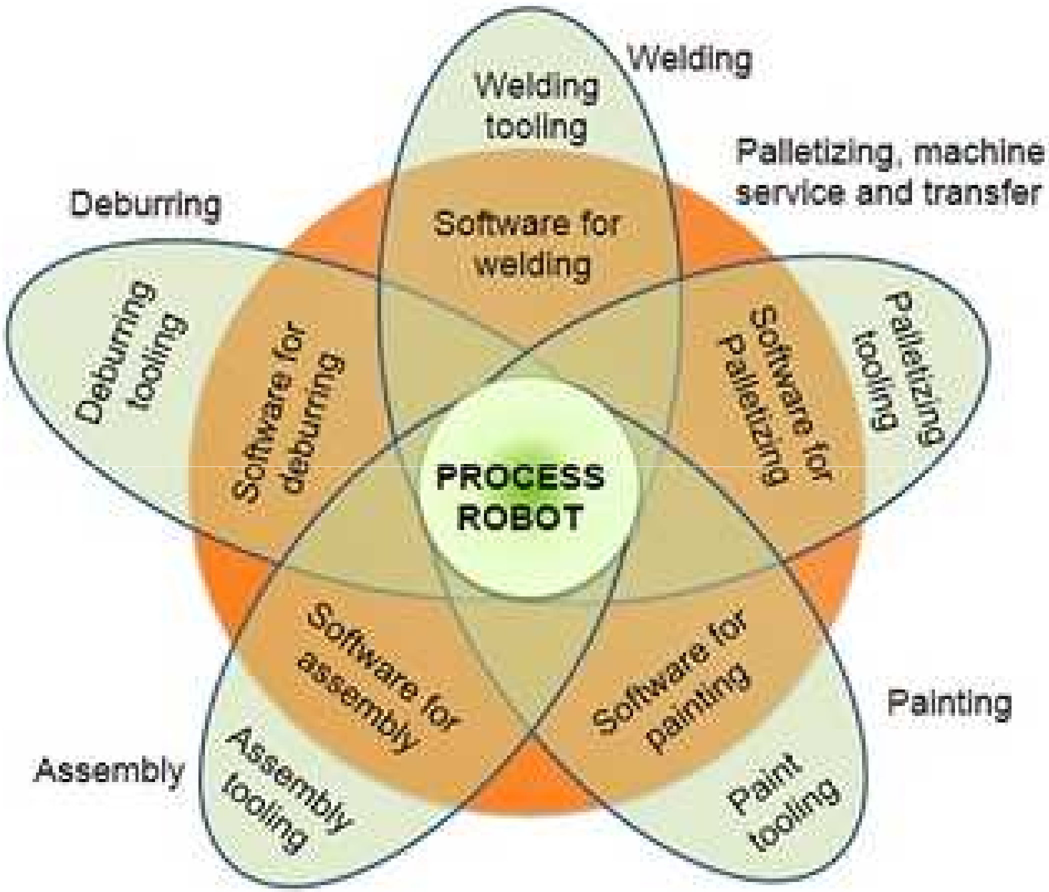
CLOSE 25 MM

CLOSE 2.0 N

Simulation and Off-Line Programming



ROBOT APPLICATIONS



Applications of robots in industry and manufacturing

ROBOT APPLICATIONS

Characteristics of situations where robots may substitute for humans

Situation	Description
Hazardous work environment for humans	In situations where the work environment is unsafe, unhealthy, uncomfortable, or otherwise unpleasant for humans, robot application may be considered.
Repetitive work cycle	If the sequence of elements in the work cycle is the same, and the elements consist of relatively simple motions, robots usually perform the work with greater consistency and repeatability than humans.
Difficult handling for humans	If the task requires the use of heavy or difficult-to-handle parts or tools for humans, robots may be able to perform the operation more efficiently.
Multi-shift operation	A robot can replace two or three workers at a time in second or third shifts, thus they can provide a faster financial payback.
Infrequent changeovers	Robots' use is justified for long production runs where there are infrequent changeovers, as opposed to batch or job shop production where changeovers are more frequent.
Part position and orientation are established in the work cell	Robots generally don't have vision capabilities, which means parts must be precisely placed and oriented for successful robotic operations.