ENPM 692
MANUFACTURING AND AUTOMATION

INDUSTRIAL ROBOTICS

Dr. Mahesh Mani, PhD
Email: mmani@umd.edu

Recorded Lecture to review

Contents

Industrial robot

"An industrial robot is a general-purpose, programmable machine possessing certain anthropomorphic characteristics."

- Can be **substituted for humans** in hazardous or uncomfortable work environments.
- Performs its work cycle with **consistency and repeatability** that cannot be attained by humans.
- Can be **reprogrammed.**
- Are controlled by computers and can be connected to other computer systems to achieve **integrated manufacturing.**

Industrial robot (cont'd)

- Most obvious anthropometric characteristic is mechanical arm.
- Human-like characteristics are the capabilities to respond to sensory inputs, communicate with other machines and make decisions.
- Typical production applications include spot welding, material transfer, machine loading, spray painting, and assembly.

Industrial robot – Alternate Definition

ISO 8373:2012

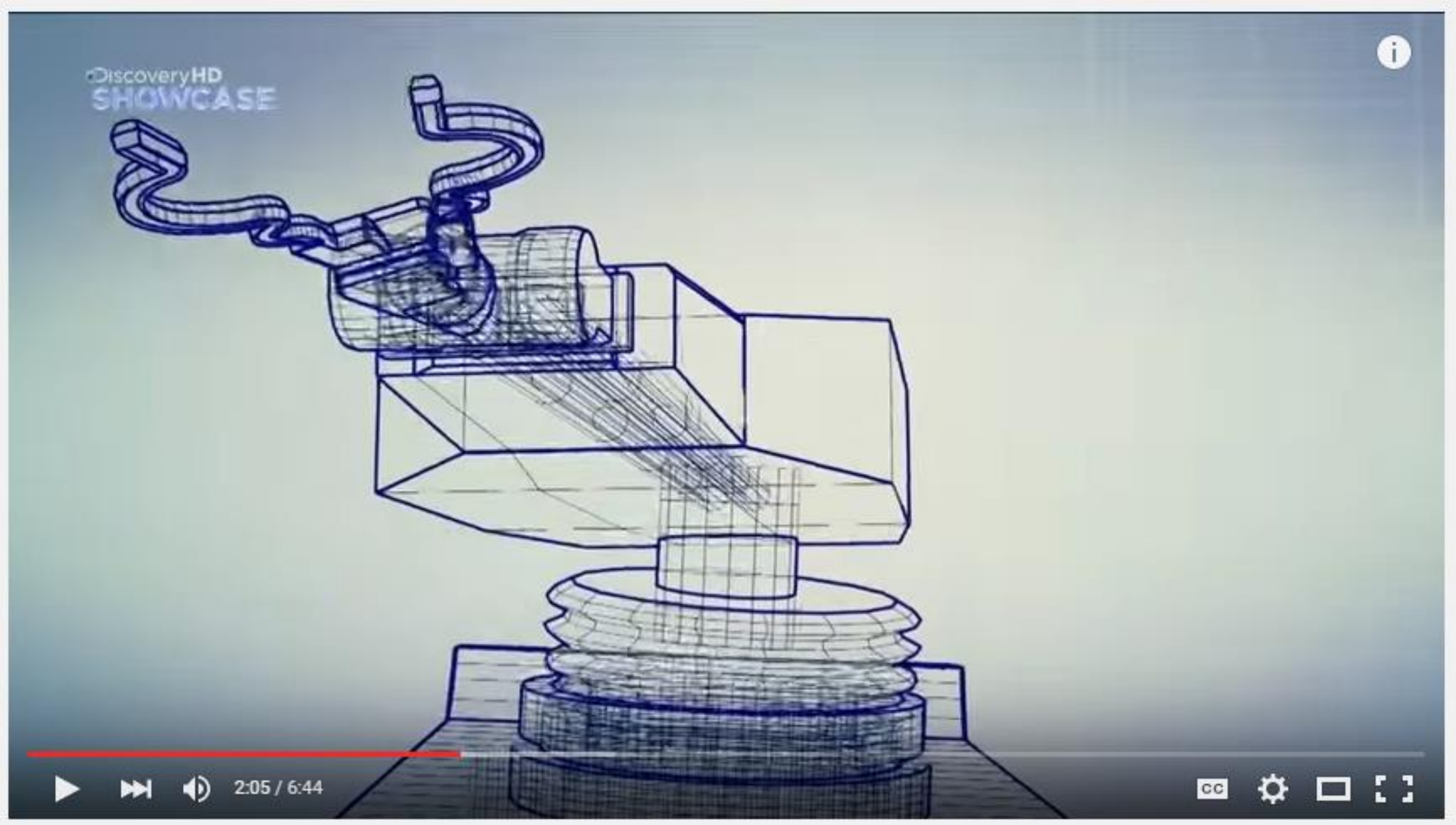
"An automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications."

- Reprogrammable: designed so that the programmed motions or auxiliary functions can be changed without physical alteration;
- Multipurpose: capable of being adapted to a different application with physical alteration;
- Physical alteration: alteration of the mechanical system;
- Axis: direction used to specify the robot motion in a linear or rotary mode;

History of Industrial Robots

- Czech word “**robota**” means forced worker
- 1920s – word “robot” in Czechoslovakian play “*Rossum’s Universal Robots*”
- 1954 British Cyril W. Kenward – manipulator that moved in x-y-z axis system
- American George C. Devol
  - 1946 - A device – electrical signals could be played back to control the operation of machinery
  - 1950s – A robotic device “**Programmed Article Transfer**” – parts handling
- Commercialization
  - 1962 – Joseph Engelberger founded Unimation, Inc. – first industrial robot – “**Unimate**” a polar configuration robot – first application was unloading a die casting machine at GM plant in NJ

Industrial Robots History



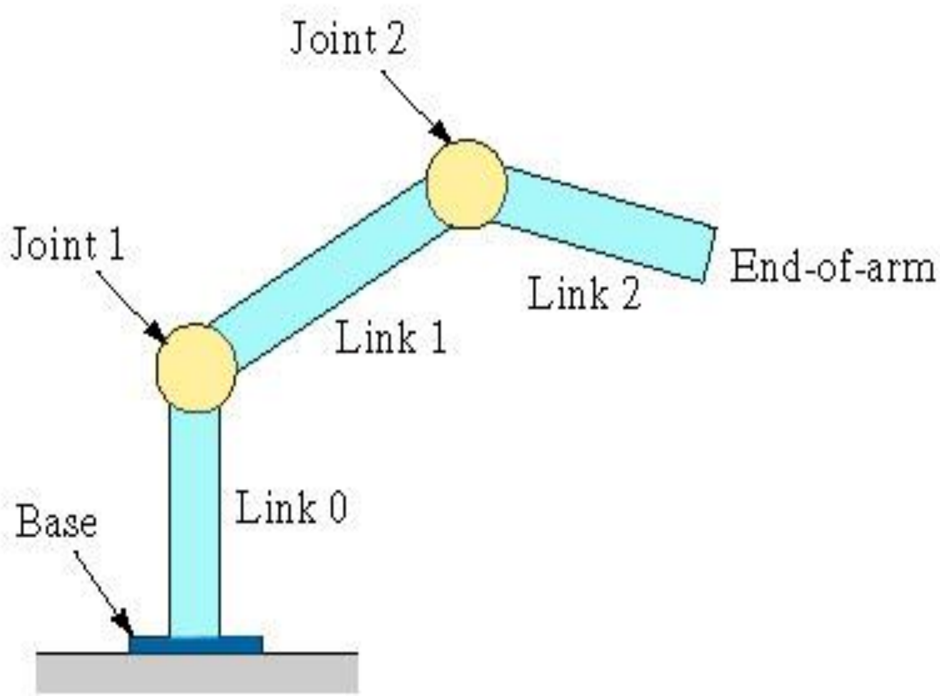
- https://www.youtube.com/watch?v=zMKkq2FiWJE

Robot Anatomy

- **Manipulator** consists of joints and links
    - Joints provide relative motion
    - Links are rigid members between joints
    - Various joint types: linear and rotary
    - Each joint provides a “degree-of-freedom”
    - Most robots possess five or six degrees-of-freedom

- Robot manipulator consists of two sections:
    - Body-and-arm –for positioning of objects in the robot's work volume
    - Wrist assembly –for orientation of objects

Joints and Links



Note: Robots are often classified according to the total number of d.o.f. they possess

Figure: Robot manipulator – series of joint-link combinations

Types of Joints

Translational motion

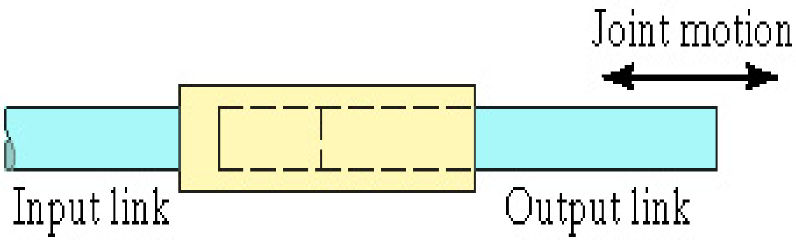
1. Linear joint (type L joint)
2. Orthogonal joint (type O joint)

Rotary motion

1. Rotational joint (type R joint)
2. Twisting joint (type T joint)
3. Revolving joint (type V joint)

Translational Motion

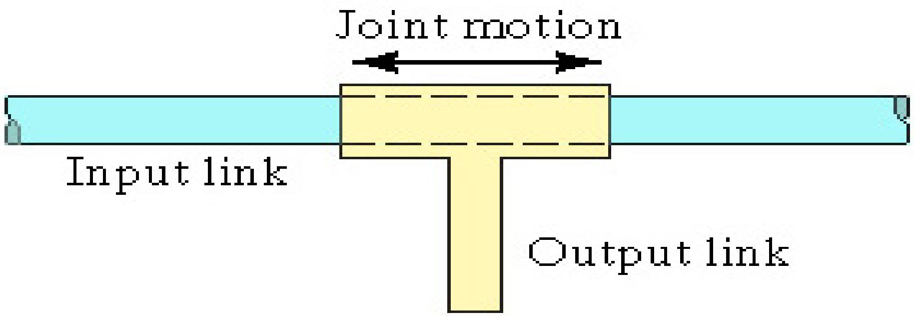
Linear joint
(type L)



1. Linear joint (type L joint) – translational sliding motion; axes of the 2 links parallel

2. Orthogonal joint (type O joint) – translational sliding motion; links perpendicular

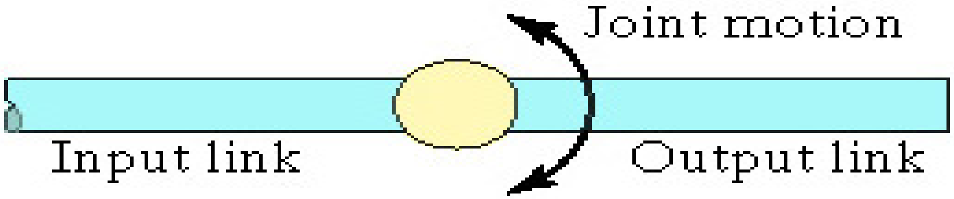
Orthogonal joint
(type O)



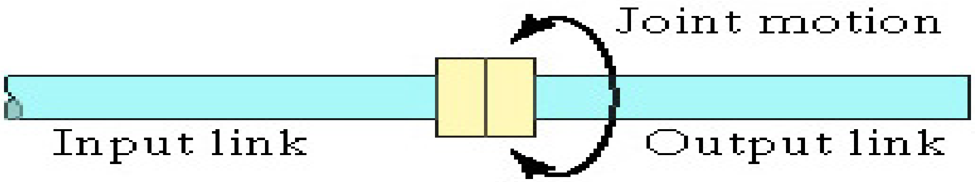
Rotary Motion

Rotational joint

(type R)



3. Rotational joint (type R joint) – rotational relative motion; axis of rotation perpendicular to the axes of the 2 links
4. Twisting joint (type T joint) – rotary motion; axes of rotation parallel to axes of the 2 links

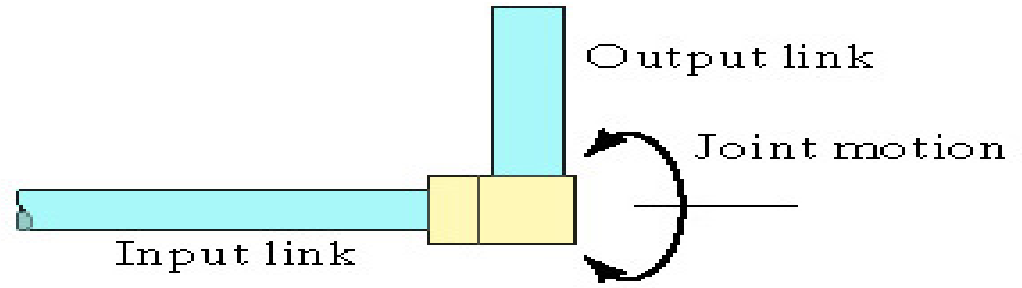


Twisting joint

(type T)

Rotary Motion (Cont.)

Revolving joint
(type V)



5. Revolving joint (type V joint) – axis of the input link is parallel to the axis of rotation and axis of the output link perpendicular to the axis of rotation

Joint notation system

- Letter symbols for the 5 joint types
  - **L, O, R, T,** and **V**
- Manipulator is described by the joint type that make up the body-and-arm assembly, followed by the joint symbols that make up the wrist; colon separates them

E.g., **TLR : TR** represents a 5 d.o.f. manipulator; body-and-arm assembly consists of twisting (T), linear (L), and rotational (R) joints; wrist consists twisting (T) and rotational (R) joints

Robot configurations

Robot **manipulator** sections:

- **body-and-arm assembly** with usually 3 d.o.f.; positions the end effector
- **wrist assembly** with 2 or 3 d.o.f.; orients the end effector

"**End effector**" – device at the end of the manipulator's wrist related to the task by the robot

Gripper, for holding a workpart

or

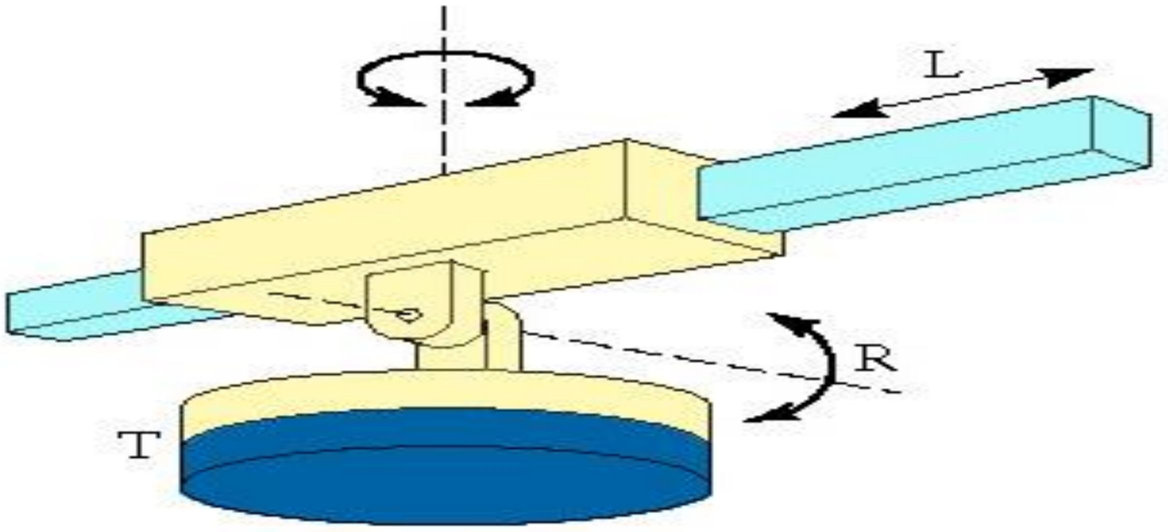
Tool, for performing some process

Body-and-arm configurations

1. Polar configuration
2. Cylindrical configuration
3. Cartesian coordinate robot
4. Jointed-arm robot
5. Selective Compliance Assembly Robot Arm (SCARA)

Note: Function of body-and-arm assembly is to position an end effector (e.g., gripper, tool) in space

Polar coordinate body-and-arm assembly



Notation TRL

A sliding arm (L joint) actuated relative to the body, which can rotate about both a vertical axis (T joint) and a horizontal axis (R joint)

Polar coordinate body-and-arm assembly

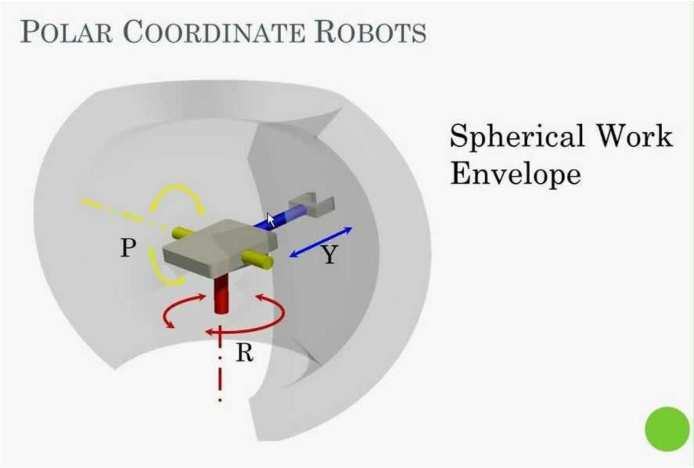
It is a robot whose axes form a polar coordinate system.

What would be the shape of the work envelope?

Sphere

Applications

- Spot Welding
- Die casting
- Gas Welding
- Arc Welding
- Handling Machine Tools or Materials



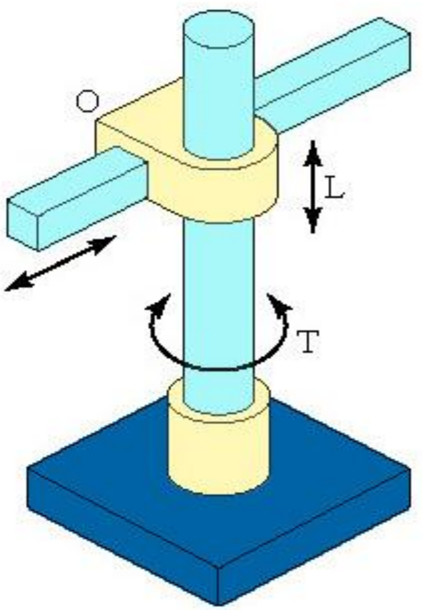
https://www.youtube.com/watch?v=veiz1xvkzx4&t=2s

Cylindrical body-and-arm assembly

A vertical column relative to which an arm assembly is moved up and down. Also, arm can be moved in and out relative to the axis of the column.

Figure:

- Consists of a vertical column relative to which an arm assembly is moved up and down
- The arm can be moved in and out relative to the column



Notation TLO

T joint to rotate the column about its axis
L joint to move the arm assembly vertically along the column
O joint to achieve radial movement of the arm

Cylindrical body-and-arm assembly

It is a robot whose axes form a cylindrical coordinate system.

What would be the shape of the work envelope?

Cylindrical

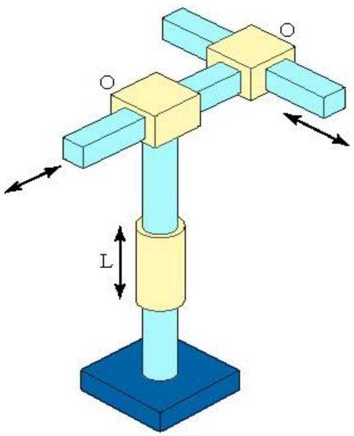
Applications

- Assembly operations
- Spot Welding
- Die casting
- Handling Machine Tools or Materials

https://www.youtube.com/watch?v=Hj7PxjeH5y0&t=17s

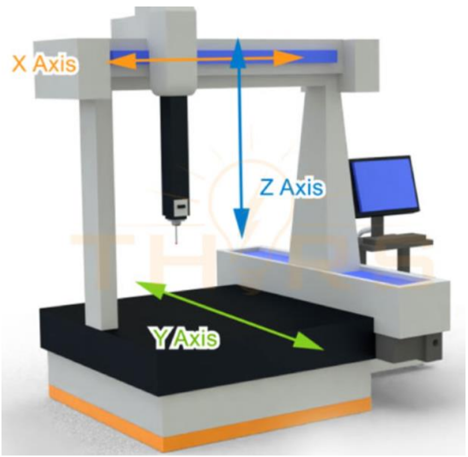
Cartesian coordinate body-and-arm assembly

Other names: rectilinear robot and *x-y-z* robot
Three sliding joints, two of which are orthogon



Notation LOO
The three sliding joints correspond to moving the wrist up-down, in-out and back-forth.

What would be the shape of the work envelope?
Cuboid



Applications

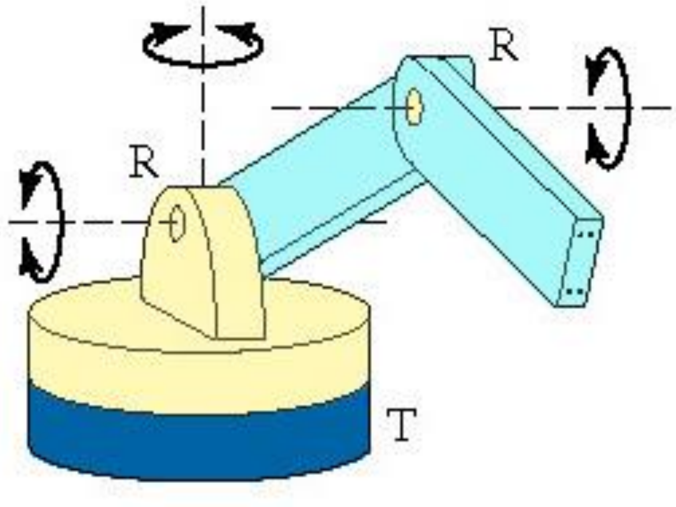
- Packaging and Inspection
- Assembly operations
- Handling machine tools
- Arc welding

https://www.youtube.com/watch?v=qaLPjcqaL0g&t=58s

Jointed arm robot / Articulated robot

- Vertical column swivels about the base using T joint
- At the top is a shoulder joint (R joint) whose output link connects to an elbow joint (another R joint)

Notation TRR



Applications

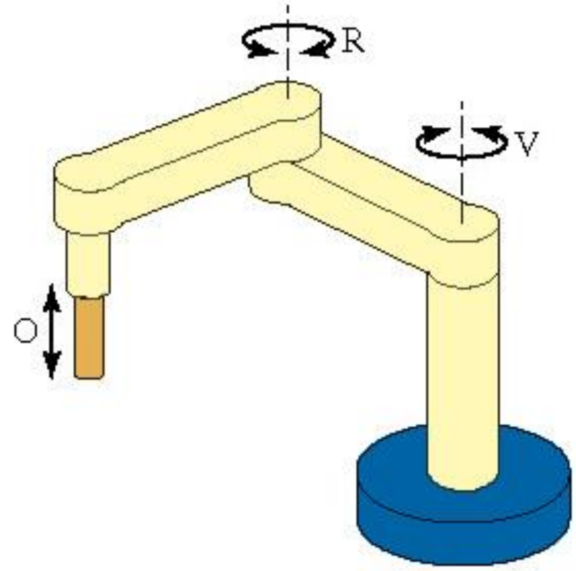
- Painting/Coating
- Welding
- Packaging

https://www.youtube.com/watch?v=wNY01XEi_nI&t=1s

SCARA

- Selective compliance assembly robot arm
- Arm is rigid in the vertical direction, but compliant in the horizontal direction – helps insertion tasks (for assembly) in vertical direction as in side-to-side alignment

Notation VRO



Applications

- Pick and place operation
- Assembly Operations
- Handling Machine Tools
- Application of Sealant

https://www.youtube.com/watch?v=e9geaPrEW3E&t=47s

Note: Typically does not have a wrist assembly

DETLA / Parallel Robots

- Three arms connected to a single base
- Can move both delicately and precisely at high speeds

Applications

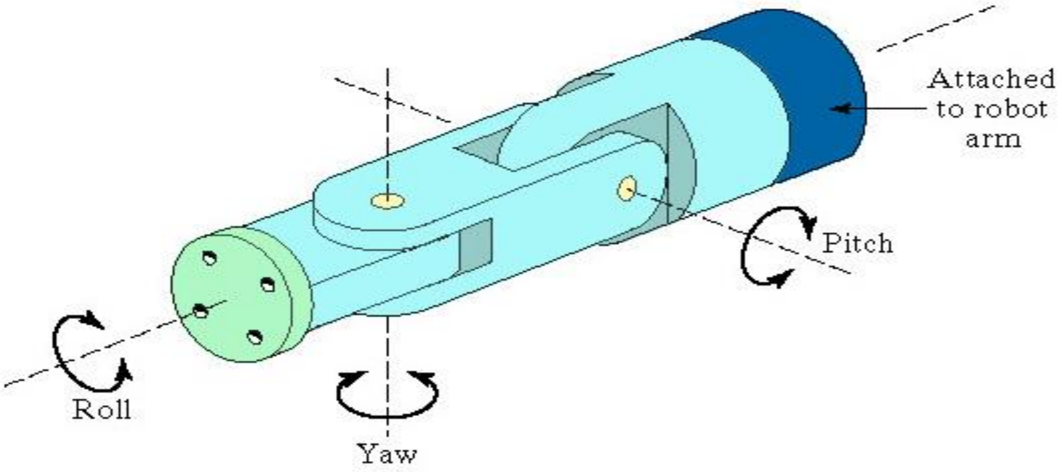
- Rapid pick and place
- Soldering
- Packaging

https://www.youtube.com/watch?v=8j5hPlHTZI8&t=1s

Wrist configurations

- Wrist assembly is attached to end-of-arm
- End effector is attached to wrist assembly
- Used to establish the orientation of the end effector

Notation RRT



Note: Body-and-arm determines global position of end effector

Wrist configurations (cont'd)

2 or 3 degrees-of-freedom

1. **Roll** – rotation about the arm axis with T joint
2. **Pitch** – up-and-down rotation with R joint
3. **Yaw** – right-and-left rotation with R joint

Note: A 2 d.o.f. typically includes only roll and pitch joints

Work volume / work envelope

"… envelope or three-dimensional space within which the robot can manipulate the end of its wrist."

- Determined by the number and types of joints, ranges of various joints, and physical sizes of the links
- Shape depends on robot's configuration
  - Polar – partial sphere
  - Cylindrical – cylindrical
  - Cartesian – rectangular

The workspace/work is often broken down into a reachable workspace and a dexterous workspace.

- Reachable workspace : entire set of points reachable by the manipulator
- Dexterous workspace : Consists of those points that the manipulator can reach with an arbitrary orientation of the end-effector.

Dexterous workspace is a subset of the reachable workspace.

Joint drive systems

1. **Electric Drive System**
   - use electric motors (like servomotors or stepper motors)
   - used in sophisticated industrial robots
   - readily adaptable to computer control; relatively accurate
2. **Hydraulic Drive System**
   - use devices such as linear pistons and rotary vane actuators
   - used in sophisticated industrial robots
   - better speed and strength
   - noted for their high power and lift capacities
3. **Pneumatic Drive System**
   - use devices such as linear pistons and rotary vane actuators
   - limited to smaller robots in simple material transfer applications

Joint drive systems (cont'd)

Dynamic response: depends on drive system, position sensors (or speed sensors) and feedback control systems for the joints

Speed of response: time required to move from one point in space to the next – enhances robot's cycle time which affects the production rate in the application

Stability: amount of overshoot and oscillation that occurs in the robot motion at the end of arm during attempts of move – more oscillation indicates less stability

Load carrying capacity: depends on physical size, construction, and force and power transmitted to the end of the wrist

Robot control systems

1. **Limited Sequence Control**

   Simple motion cycles like pick-and-place operations.

2. **Playback with Point-to-Point Control**

   Sophisticated form of control, memory to record sequence of motions in a given work cycle as well as the locations and other parameters associated with each motion and then subsequently play back the work cycle during execution of the program.

3. **Playback with Continuous Path Control**

   Capable of greater storage capacity and/or interpolation calculations.

4. **Intelligent Control**

   Exhibits behavior that makes it seem intelligent like interact with its environment, make decisions when things go wrong during the work cycle, communicate with humans, make computations during the motion cycle, and respond to advanced sensor inputs such as machine vision.

Robot control systems (cont'd)

Microprocessor-based controllers: organized in hierarchical structure; each joint has feedback control system and supervisory controller coordinates.

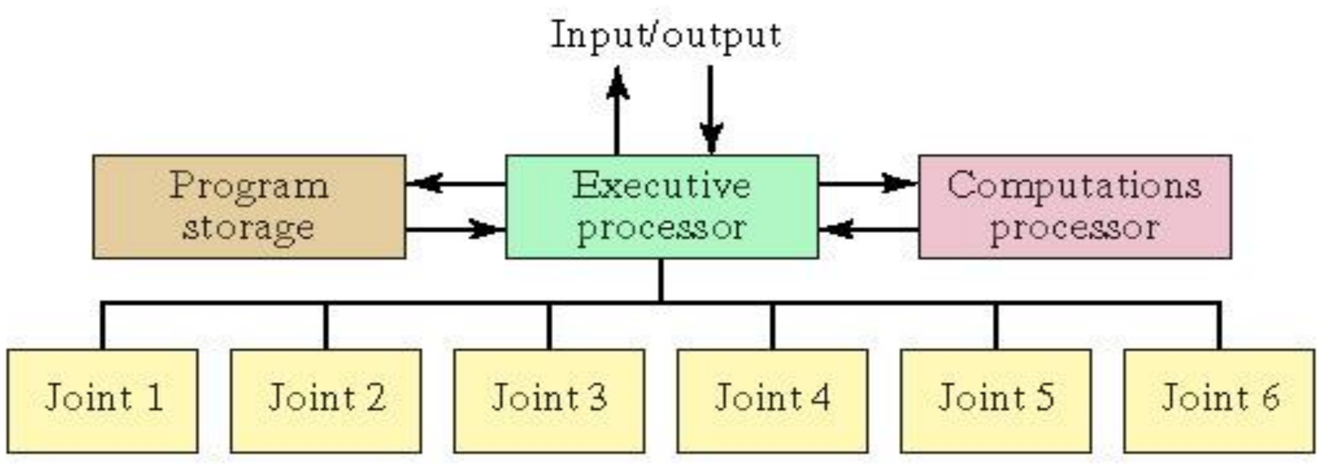


Figure illustrates hierarchical structure of robot microcomputer controller

End effectors

End effectors usually attached to the robot’s wrist; enables to accomplish a specific task; custom-engineered and fabricated for each different application

Grippers

- Used to grasp and manipulate objects during the work cycle;
  - E.g., machine loading and unloading applications
- Types used are mechanical grippers, vacuum grippers, magnetized devices, simple mechanical devices
- Mechanical grippers are most common; advances include dual grippers, interchangeable fingers, sensory feedback, multiple fingered grippers, standard gripper products

Tools

- Used to perform processing operations on the workpiece (may use multiple tools during the work cycle)
  - Examples include welding tool, spray painting gun, rotating spindle for drilling, routing, grinding, etc.
- Robot must be able to transmit control signals to the tool for starting, stopping, and otherwise regulating its actions

Gripper Technologies

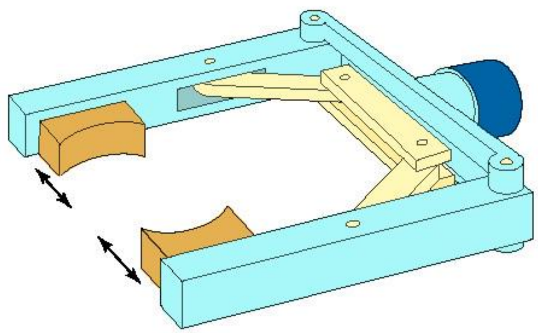


Fig.8.10a Robot mechanical gripper

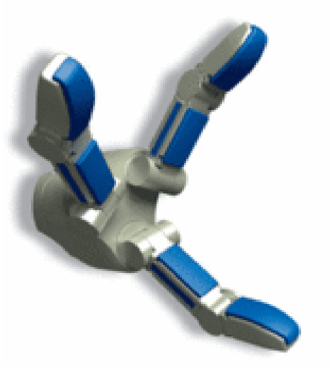


Fig.8.10b 3-Finger Hands

Fig.8.10c Anthropomorphic Hands

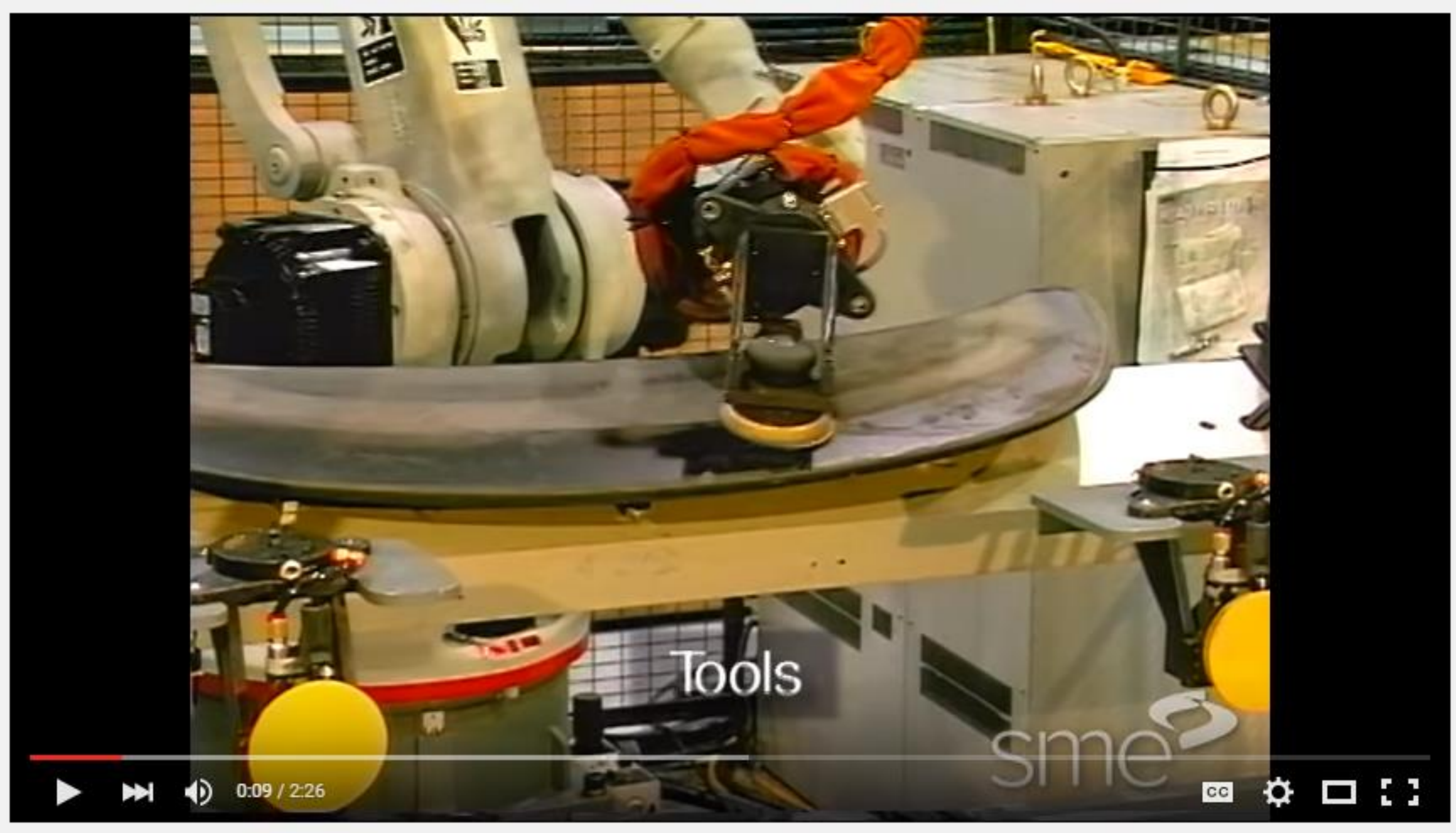
Fig.8.10d Soft Grasping

Fig.8.10e Vacuum Suction

How 6-Axis Industrial Robots Work

- https://www.youtube.com/watch?v=Mw7jns-1Fdg

End effectors



- https://www.youtube.com/watch?v=MpHglE8661Y

Sensors in robotics

- **Internal sensors**: used to control the positions and velocity of the various joints; e.g., potentiometers, optical encoders, tachometers, etc.
- **External sensors**: used to coordinate the operations with other equipment in the cell; e.g., limit switches, tactile sensors, proximity sensors, optical sensors, machine vision, etc.

Robot Application Characteristics

General characteristics of industrial work situations that promote the use of industrial robots:

- Hazardous work environment for humans
- Repetitive work cycle
- Difficult handling task for humans
- Multishift operations
- Infrequent changeovers
- Part position and orientation are established in the work cell

Industrial robotics applications

Material handling applications

Moves materials or parts from one place to another; equipped with gripper; includes material transfer, machine loading and/or unloading (die casting, plastic molding, metal machining operations, forging, pressworking, heat treating)

Processing operations

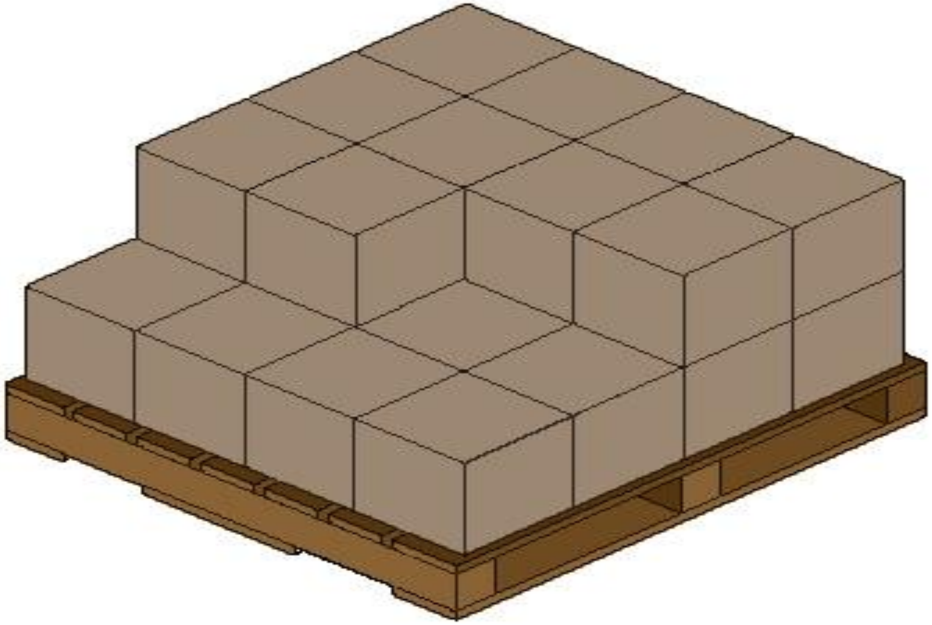
Performs some processing operation; equipped with some type of tool; includes spot welding, arc welding, spray coating, machining and rotating spindle processes, waterjet cutting, laser cutting

Industrial robotics applications(cont'd)

Assembly and inspection

Involve either handling of materials or manipulation of a tool; assembly involves combination of two or more parts to form a new entity; inspection involves making sure that a given process has been completed, ensuring that parts have been added in assembly as specified and identifying flaws in raw materials and finished parts

Palletizing and Depalletizing



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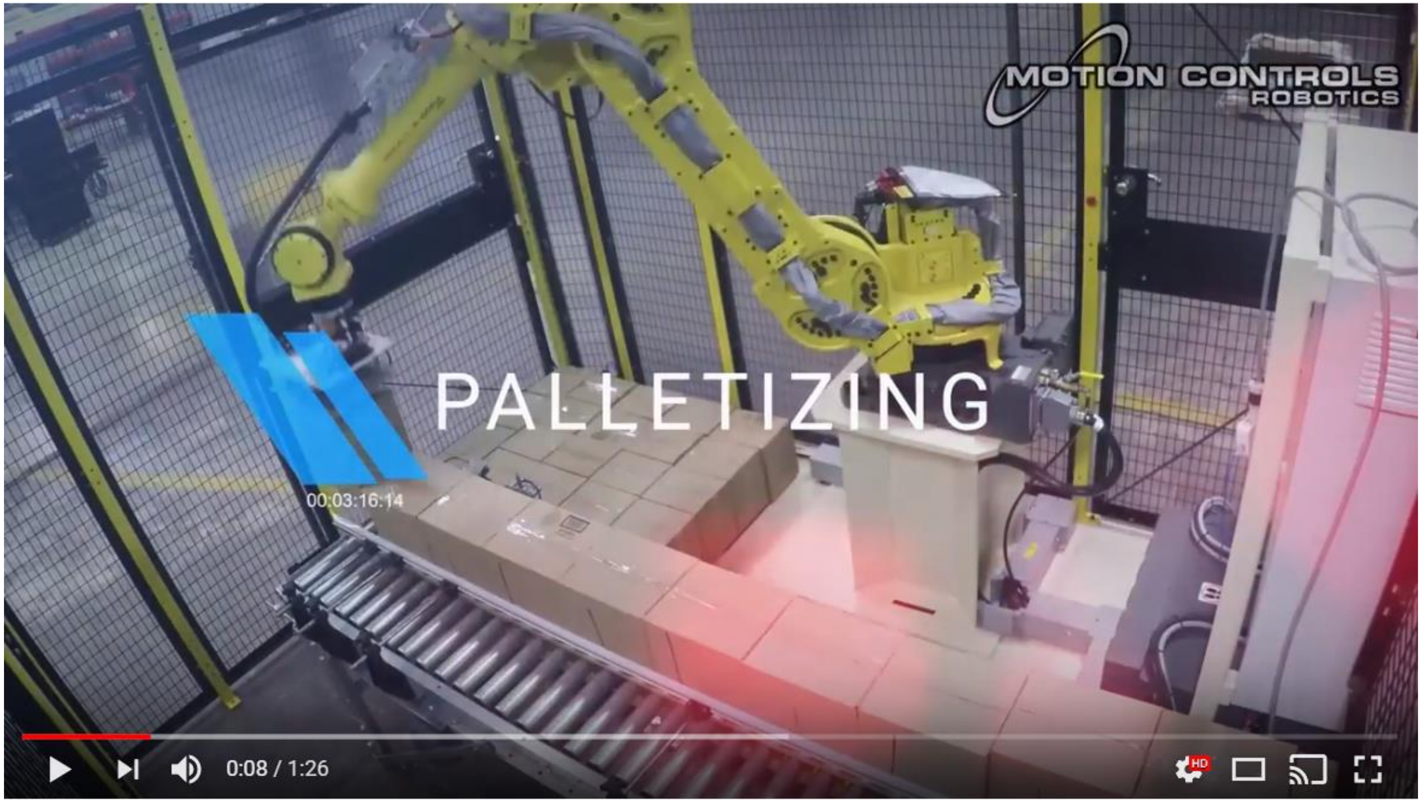
Palletizing and Depalletizing(cont'd)



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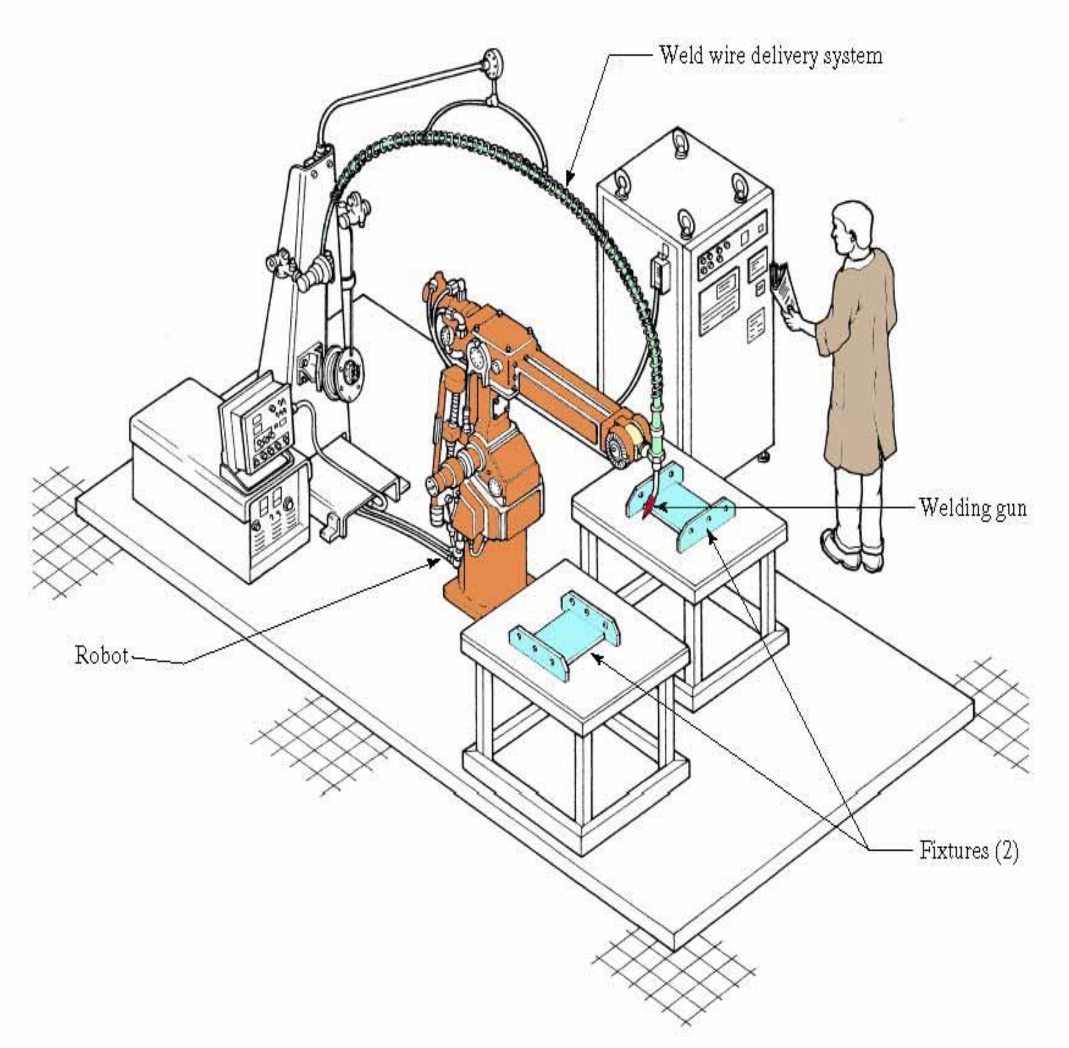
Robotic Arc-welding Cell

Robot performs flux-cored arc welding (FCAW) operation at one workstation while fitter changes parts at the other Workstation.



Robotic Arc-welding Demo

https://www.youtube.com/watch?v=HUU3HdxOqZs

Spray Painting Robot

- https://www.youtube.com/watch?v=O0ScFQ1rbe4
- https://www.youtube.com/watch?v=gUWCljX7oa0

Robot Programming

- A robot program is defined as a path in space to be followed by the manipulator, combined with peripheral actions that support work cycle
- A robot must be programmed to perform its motion cycle.
- A robot is programmed by entering the programming commands into its controller memory
- Setting limit switches and mechanical stops, wiring the sequencer are akin to manual setup
- Today, nearly all industrial robots have digital computers as their controllers and compatible storage devices as their memory units

Robot Programming Methods

1. Leadthrough Programming

The task is taught to the robot by moving the manipulator through the required motion cycle, simultaneously entering the program into the controller memory for subsequent playback.

- **Powered leadthrough**: common for point-point robots; used for playback robots; involves use of teach pendant that has toggle switches and/or contact buttons for controlling the movement of the manipulator joints
- **Manual leadthrough**: used for playback robots with continuous path control; requires operator to physically grasp the end-of-arm or the tool that is attached to the arm and move it through the motion sequence, recording the path into memory; is equipped with trigger handle; motion is recorded as a series of closely spaced points

Motion programming: two alternative methods for controlling movement are – world-coordinate system and tool-coordinate system

Teach Pendant for Powered Leadthrough Programming

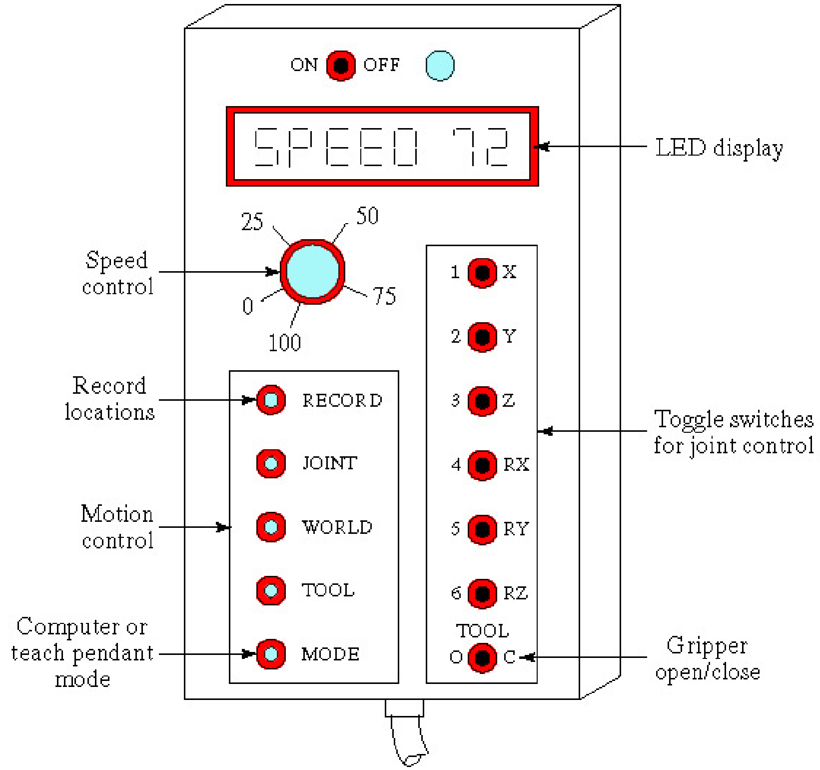


Figure 8.13 A typical robot teach pendant.

World Coordinate System

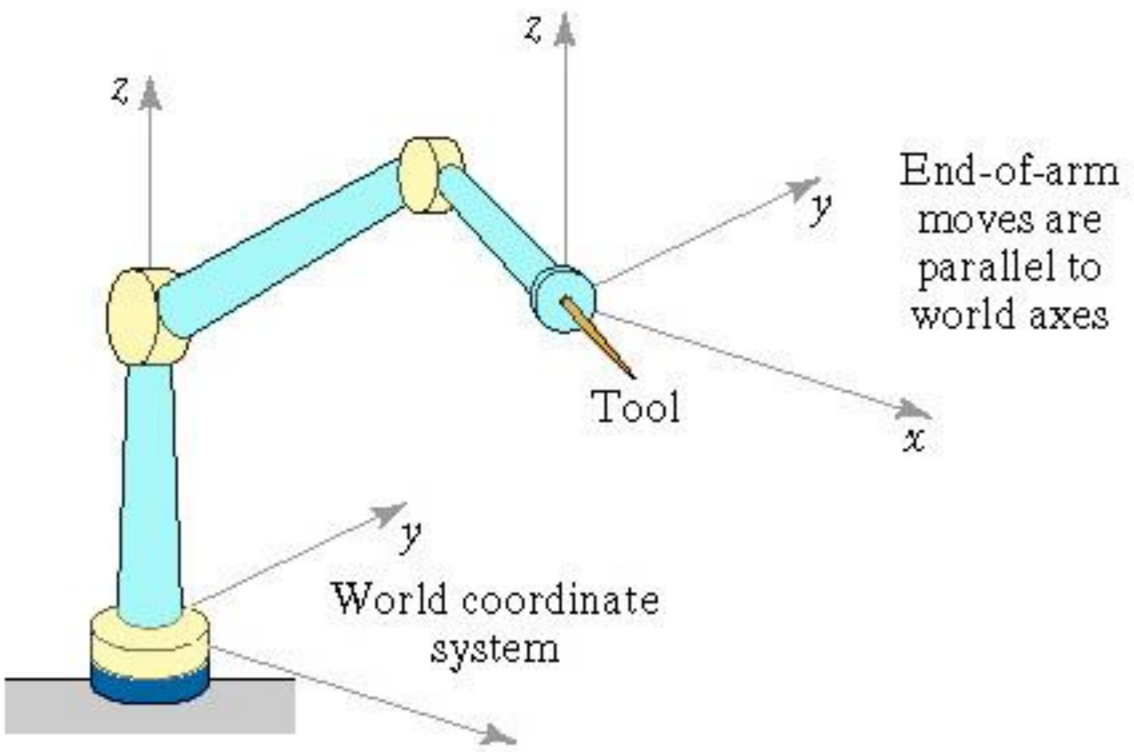


Fig 8.14 a. World coordinate system

Tool Coordinate System

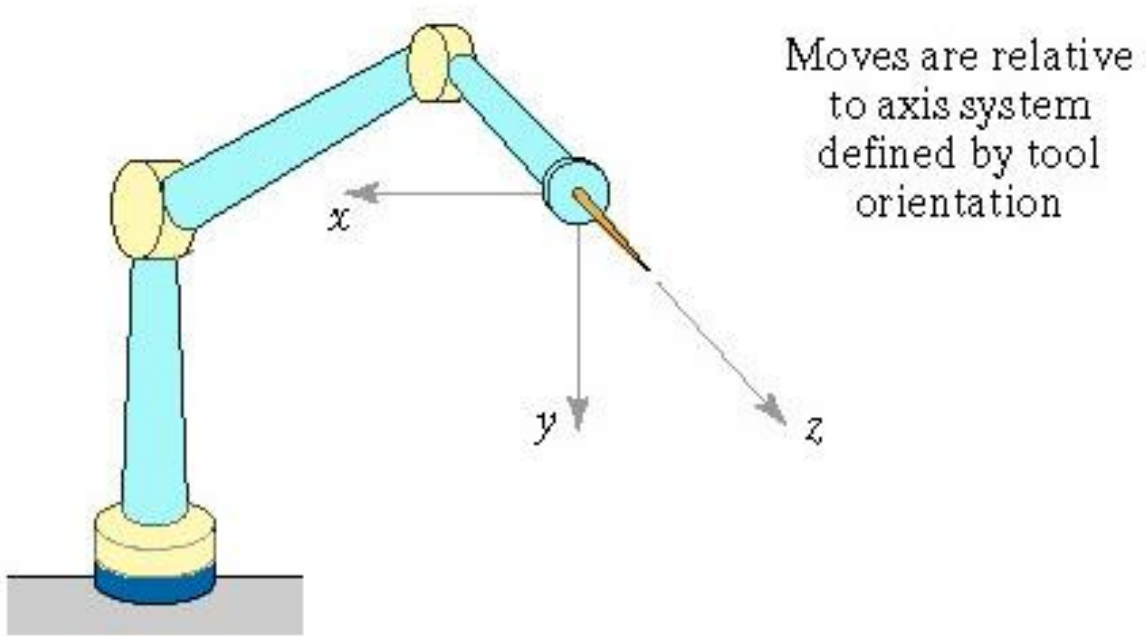


Fig 8.14 b. Tool coordinate system

Leadthrough Programming Advantages

Advantages:

- Can readily be learned by shop personnel
- A logical way to teach a robot
- Does not require knowledge of computer programming

Disadvantages:

- Downtime - Regular production must be interrupted to program the robot
- Limited programming logic capability
- Not readily compatible with modern computer-based technologies

Robot Programming Methods (cont’d)

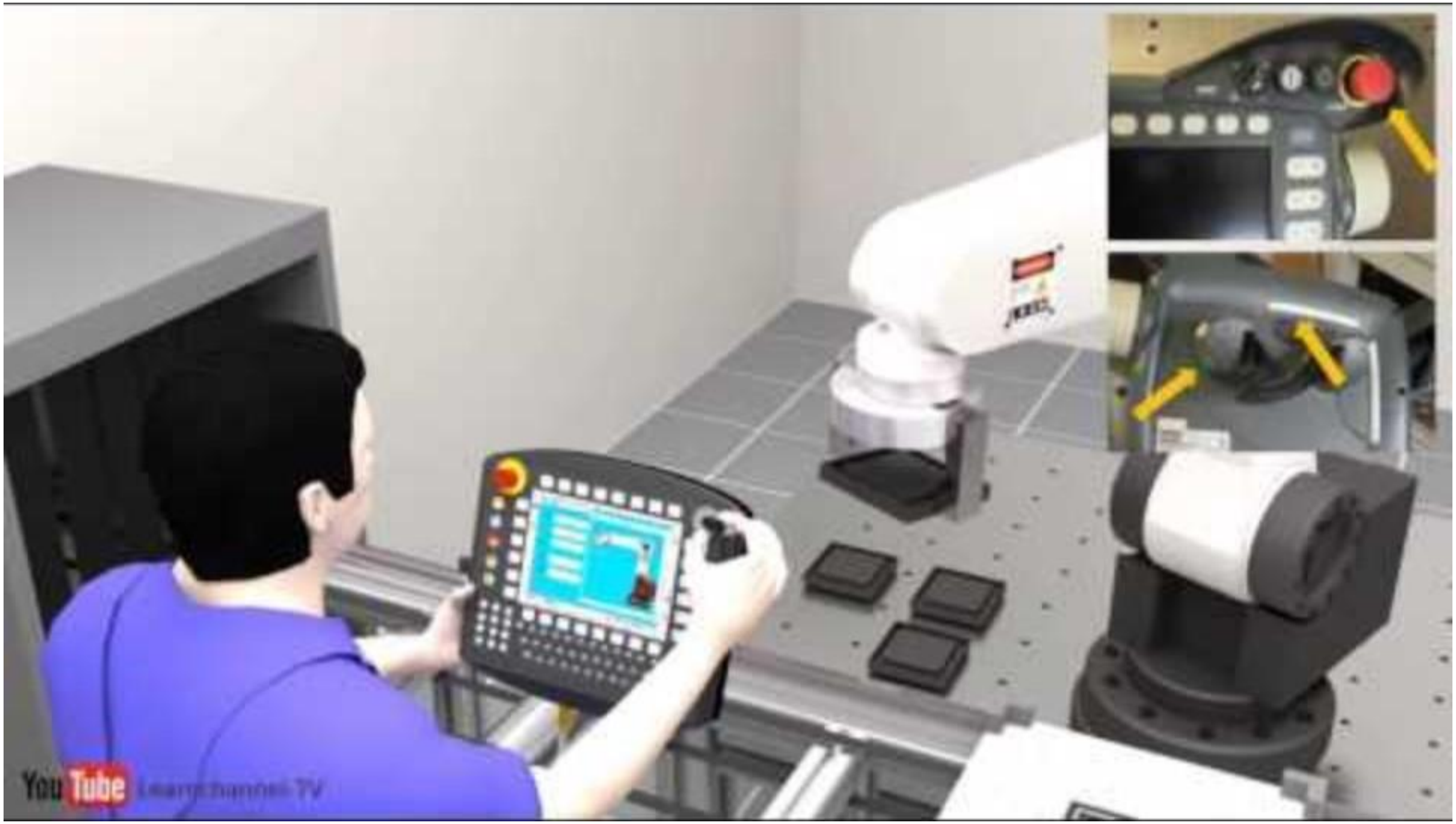
2. **Robot Programming Languages**

- **Textual programming languages** provide opportunities for enhanced sensor capabilities, improved output capabilities, program logic, computations and data processing, communications with other computer systems
- **Motion programming (on-line/off-line programming)** requires a combination of textual statements and leadthrough techniques

3. **Simulation and Off-Line Programming**

Off-line programming permits the robot program to be prepared at a remote computer terminal and downloaded to the robot controller for execution without interrupting production. Some form of graphical computer simulation is required to validate the programs developed off-line

Robot Programming Methods



- https://www.youtube.com/watch?v=I-M1x6aWPs8

Robot Accuracy and Repeatability

The capacity of a robot to position and orient the end of its wrist with accuracy and repeatability is an important control attribute in nearly all industrial applications

Control resolution: capability of the robot’s positioning system to divide the range of the joint into closely spaced points, called addressable points, to which joint can be moved by the controller; defined as the distance between adjacent addressable points

Repeatability: measure of the robot’s ability to position its end-of-wrist at a previously taught point in the work volume

Accuracy: robot’s ability to position the end of its wrist at a desired location in the work volume

Popular Applications

- https://www.youtube.com/watch?v=fH4VwTgfyrQ

Popular Applications

- https://www.youtube.com/watch?v=lR7c2rEFOH0

Mobile Industrial Robots

- Used for automation of internal transport
- Beneficial for warehouse automation

https://www.youtube.com/watch?v=AQVDwW7uKZE

Popular Applications

- https://www.youtube.com/watch?v=jwu9SX3YPSk

Hardware Components for Automation

- Sensors
- Actuators
- Analog-to-Digital Conversion
- Digital-to-Analog Conversion
- Input/Output Devices for Discrete Data

Computer-Process Interface

- To implement process control, the computer must collect data from and transmit signals to the production process
- Components required to implement the interface:
  - Sensors to measure continuous and discrete process variables
  - Actuators to drive continuous and discrete process parameters
  - Devices for ADC and DAC
  - I/O devices for discrete data

Computer Process Control System

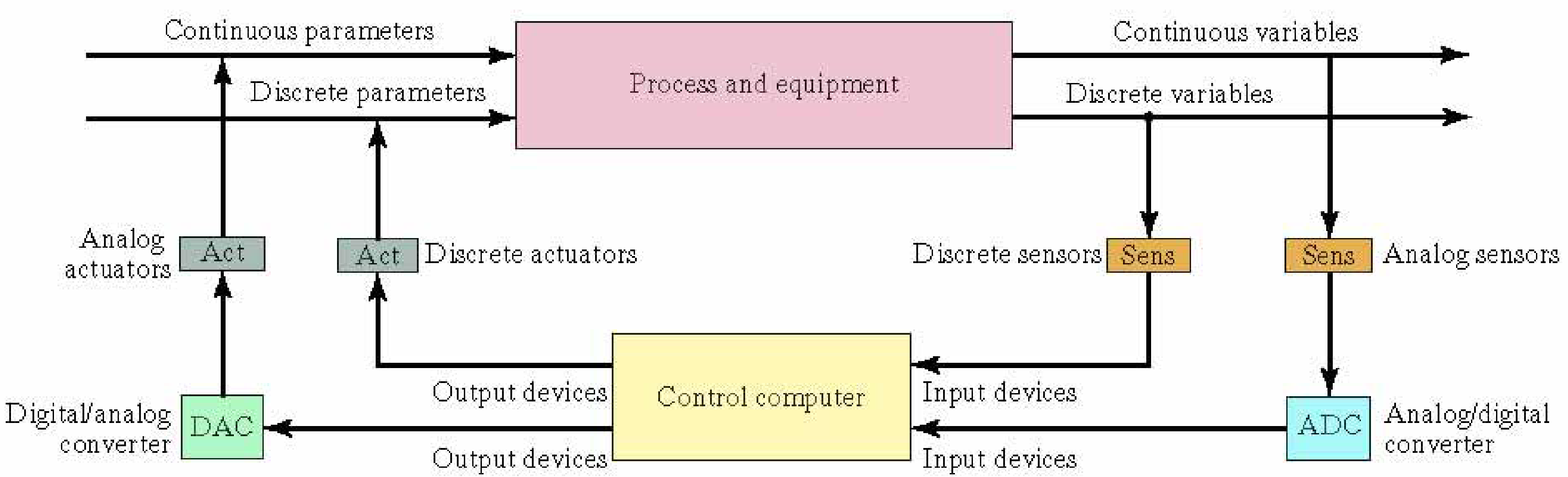


Figure 6.1 Process control system

Sensor

- A sensor is a transducer that converts a physical stimulus from one form into a more useful form to measure the stimulus
- Two basic categories:
  1. Analog
  2. Discrete
     - Binary
     - Digital (e.g., pulse counter)

Sensor Transfer Function

The relationship between the value of the physical stimulus and the value of the signal produced by the sensor in response to the stimulus

$$S = f(s)$$

where S= output signal, s= stimulus, and $f(s)$ is the functional relationship between them

Example

Stimulus Category	Physical Variable
Mechanical	Position (displacement, linear and angular), velocity, acceleration, force, torque, pressure, stress, strain, mass, density

Actuators

- Hardware devices that convert a controller command signal into a change in a physical parameter
  - The change is usually mechanical (e.g., position or velocity)
  - An actuator is a transducer because it changes one type of physical quantity into some alternative form
  - An actuator is usually activated by a low-level command signal, so an amplifier may be required to provide sufficient power to drive the actuator

Types of Actuators

- Electrical actuators
  - Electric motors
  - DC servomotors
  - AC motors
  - Stepper motors
  - Solenoids
- Hydraulic actuators
  - Use hydraulic fluid to amplify the controller command signal
- Pneumatic actuators
  - Use compressed air as the driving force

Analog-to-Digital Conversion

An ADC converts a continuous analog signal from transducer into digital code for use by computer

- ADC consists of three phases:

1.Sampling –converts the continuous signal into a series of discrete analog signals at periodic intervals

2.Quantization –each discrete analog is converted into one of a finite number of (previously defined) discrete amplitude levels

3.Encoding –discrete amplitude levels are converted into digital code

Digital-to-Analog Conversion

- Converts the digital output of the computer into a continuous analog signal to drive an analog actuator (or other analog device)
- DAC consists of two steps:

1.Decoding –digital output of computer is converted into a series of analog values at discrete moments in time

2.Data holding –each successive value is changed into a continuous signal that lasts until the next sampling interval

Input/Output Devices for Discrete Data

Binary data:

- Contact input interface –input data to computer
- Contact output interface –output data from computer

Discrete data other than binary:

- Contact input interface –input data to computer
- Contact output interface –output data from computer

Pulse data:

- Pulse counters -input data to computer
- Pulse generators -output data from computer

Human Robot Collaboration (HRC)

- Human and machine work together. The human operator controls and monitors production, the robots perform the physically strenuous work. Both contribute their specific capabilities.
- The machine does not replace the human, but complements his capabilities and relieves him/her of arduous tasks.
- Autonomous, collaborative robots are used effectively in production workstations.

In Smart Manufacturing, there is no separation between automated and manual workstations. Humans and robots collaborate for safe and optimal production.

https://www.kuka.com/en-us/technologies/human-robot-collaboration

Advantages of HRC

Human-robot collaboration is revolutionizing industrial production and manufacturing in the factory of the future.

- **Maximum flexibility** in production
- **Reduce fatigue** by performing ergonomically unfavorable work steps that could not previously be automated
- **Reduced risk** of injuries and infections, for example with special HRC grippers
- **High-quality performance of reproducible processes** for improved efficiency
- **Increased productivity** and improved system complexity thanks to integrated sensors

Example of HRC System

Innovative Human-Robot Collaboration for BMW/MINI Crash Can Assembly

“This cell was designed to assist a human operator in reducing repetitive, non-ergonomic tasks that historically required fully manual assembly for the crash can structure located at the front of a BMW/MINI vehicle. Not only did the cell improve ergonomics, it also reduced overall cycle time for the operation”

- https://www.youtube.com/watch?v=keh99z1M5LI

There are so many more examples…

Limitations of Collaborative robot systems

- Collaborating robots may require a restricted working area to ensure employee’s safety, Work speed can be hampered if there are safety measures put in place, the cobot robot may stop every time it senses the presence of a human being in its working environment.

- Because robots are collaborative, sometimes they cannot work without human assistance and supervision.

- Collaborative robots employing the power and force limiting approach have compliance in case of impacts, but lack speed, accuracy and payload capabilities.

- In order to be safe, Collaborative robots aren’t as powerful as most six-axis robots, High-speed applications can’t be solved with a collaborative robot, just like speed, the lower power limits the applications of the Collaborative robots.

Interesting Links

- How Robots Will Change the World (BBC Documentary)
https://www.youtube.com/watch?v=LWk-8L9TP6s

- NIST colloquium series
https://m.youtube.com/watch?v=FMy6tJODymc

- The Robot revolution
https://www.youtube.com/watch?v=HX6M4QunVmA

- Prof. SK Gupta’s Blog
http://unorthodoxideas.blogspot.com/2015/10/my-ten-favorite-robots.html