ME5402/EE5106 Advanced Robotics (AY21-22 Semester 2) ME5408 Kinematics of Robot Manipulators (AY21-22 Mini Semester 2A)

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About Me…

- PhD, Biomedical Precision Engineering Lab, The University of Tokyo, Japan, 2004
- MSc (By Research), BSc (Hon), National University of Singapore, Singapore
- Research interests: Medical devices and robotics, imaging and simulation
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Course Mechanics

- Lecture: Monday (6:00pm-9:00pm) via Zoom
- Class info, lecture slides, notes and tutorials can be found in LumiNUS

Main Text

- John J Craig, “Introduction to Robotics: Mechanics and Control”, Pearson, 2014, ISBN 10:1-292-04004, ISBN 13:978-1-292-04004-2
- Haruhiko Asada and Jean-Jacques E Slotine, “Robot Analysis and Control”, John Wiley and Sons, 1986, ISBN:0-471-83029-1
- Other references will be announced in class or via LumiNUS.

ME5402/EE5106

Continuous Assessment (CA) – 70%

Part I (35%)

- Online Quiz (10%) – Recess Week
- Computing Project (25%) – Due on Week 13; a group of at most 3 students
  - Model a robot manipulator, kinematics analysis, computer simulation of the robot manipulation

Part II (35%) – To be announced

Final Exam – 30%

- Two questions (each with multiple parts) for Parts I and II respectively

ME5408

Continuous Assessment (CA) – 100%

- Online Quiz (30%) – Recess Week
- Mini Computing Project (70%) – Due on Recess Week; individual

Chapter 0 – Introduction to Robotics

CHUI Chee Kong, PhD
Control & Mechatronics Group
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What is a robot?

Originally from Czech language, *robota*, which means forced labour

The word *Robot* was introduced to the public by the Czech writer Karel Čapek in his play *R.U.R. (Rossum's Universal Robots)*, published in 1920.

- Dictionary.com
  - 1. a machine that resembles a human and does mechanical, routine tasks on command.
  - 2. any machine or mechanical device that operates automatically with humanlike skill.

Contents

1. History and Applications
2. Mechanics: Kinematics and Dynamics
3. Design
4. Trajectory Generation
5. Control
6. Programming

1. History and Applications

- Middle of 20th century
  - Research in artificial intelligence (AI) – connection between human intelligence and machines
  - First robot
    - 1948 – William Grey Walter invented robots Elmer and Elsie that mimic lifelike behavior using simple electronics
    - 1954 – George Devol invented the first digitally operated and a programmable robot called the Unimate.
    - 1956 – Devol and his partner Joseph Engelberger formed the world's first robot company.
    - 1961 – First industrial robot, Unimate, went online in a General Motors automobile factory in USA.
  - Advances in mechanics, controls, computers and electronics
  - Robotics: The science & technology of robots

History (continue)

- 1960s:
  - Numerical control machines for precise manufacturing
  - Teleoperators for remote radioactive material handling
- Late 1970s:
  - Industrial robots became essential components in the automation of flexible manufacturing systems
- 1980s:
  - Robotics: defined as the science which studies the intelligent connection between perception and action

History (continue)

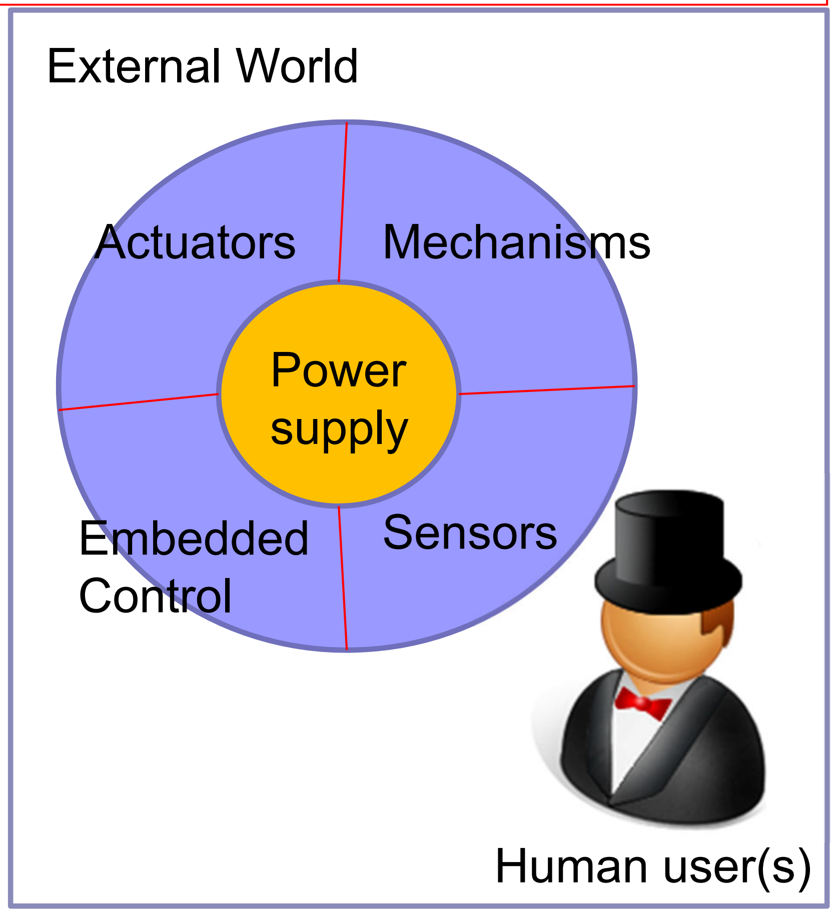
- 1990s:
  - Field robotics to address human safety in hazardous environments
  - Human augmentation
  - Service robotics
- 2000 and beyond:
  - Human-centered and life-like robotics

Reference: Bellis, Mary. "Who Invented Robots?" ThoughtCo, Oct. 16, 2017, thoughtco.com/timeline-of-robots-1992363.

Robots and Robotics

Robotics is the engineering science and technology of robots, and their design, manufacture, application, and structural disposition.

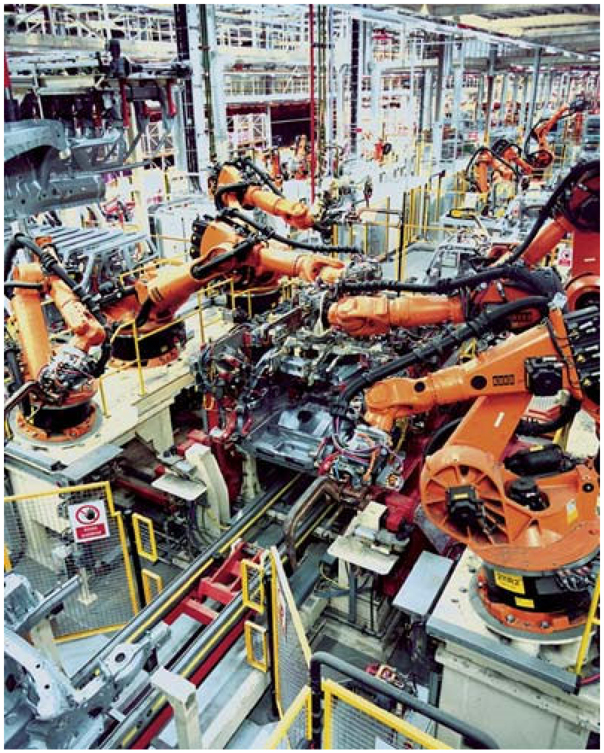
The Honda Humanoid Robot ASIMO (http://world.honda.com/ASIMO)



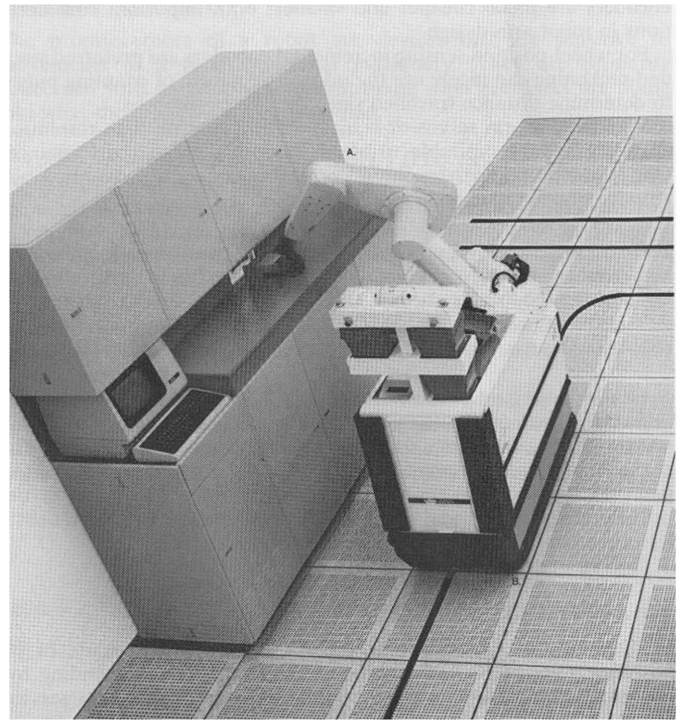
Robotics is the study of *system science* that involves

- Perception
- Cognition
- Action

Applications: Manufacturing



Assembly line

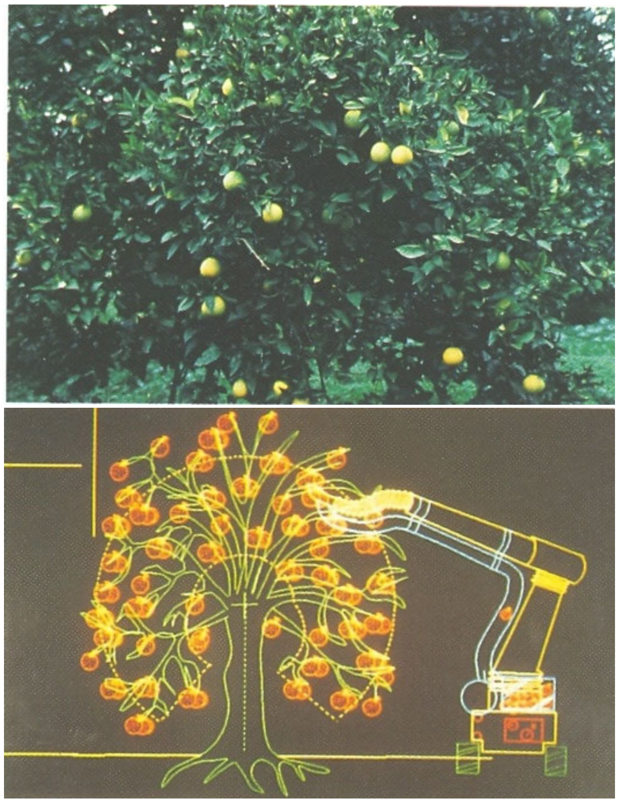


Material handling system (Vecco Integrated Automation, Inc)

Applications: Construction

Construction robots developed by the Takenaka Company: A crane robot is used to place steel reinforcing bars (left), another distributes concrete (right) (Takenama Komuten Co Ltd)

Applications: Farming



Citrus-picking robot (concept)

Sheep-shearing robot (University of Western Australia)

Applications: Farming (continue)

The prototype robot is part of the Robot-Assisted Precision Irrigation Delivery (RAPID) system developed by researchers from UC Berkeley, UC Davis and UC Merced, USA.

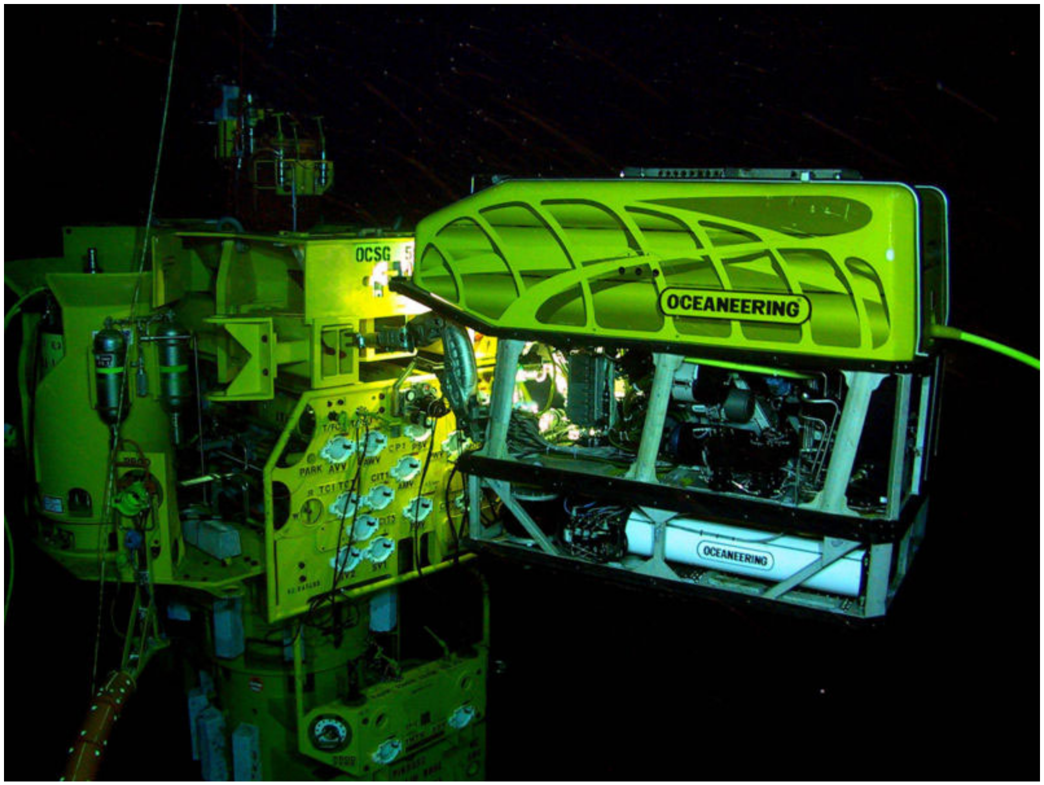
IEEE The Institute: Special issue on agtech, April 2018, http://theinstitute.ieee.org/static/special-report-agtech

Applications: Military service and other hazardous work

The US Army’s Autonomous Land Vehicle

A prototype of the Explosive Ordinance Disposal robot (OAO Corporation)

Applications: Underwater/Oil and gas

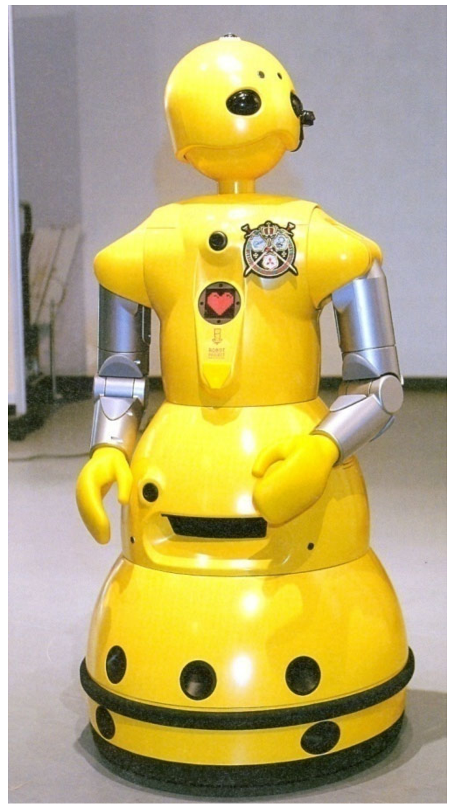


ROV working on a subsea structure

ROV: remotely operated underwater vehicle, is a tethered underwater vehicle.

Applications: Service industry

Robot street cleaner



Robot usher

Security guard

Applications: Entertainment

Applications: Education

Lego mindstorm NXT

Applications: Aiding the handicapped and the elderly

Robot aids walking

Autonomous wheelchair

Applications: Robot-assisted surgeries

ORTHODOC

Zeus

daVinci

From Industrial Needs to Medical Robotics

A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks. (Robot Institute of America, 1979)

Need for machine to assist and/or replace worker

Industrial Robotics

(www.kuka-robotics.com)

Industrial Automation

Service Robotics

(www.mobilerobots.com)

Medical Robotics

(www.davincisurgery.com)

Clinical Applications

Medical robotics includes a number of devices used for surgery, medical training, rehabilitation therapy, prosthetics, and assisting people with disabilities.

- This module focuses on mechanics and control of mechanical manipulator

Classical Robotics == the study of industrial robotic manipulator, which is an integrated approach of

- Kinematics: study of geometry of motion
- Statics: study of a manipulator at equilibrium
- Dynamics: study of causes of motion
- Trajectory planning: generating the path the robot must trace
- Control strategy: executing the path
- Physical hardware: building the robot

2. Mechanics: Kinematics and Dynamics

Kinematics is the study of position and derivatives of position without regard to forces which cause the motion.

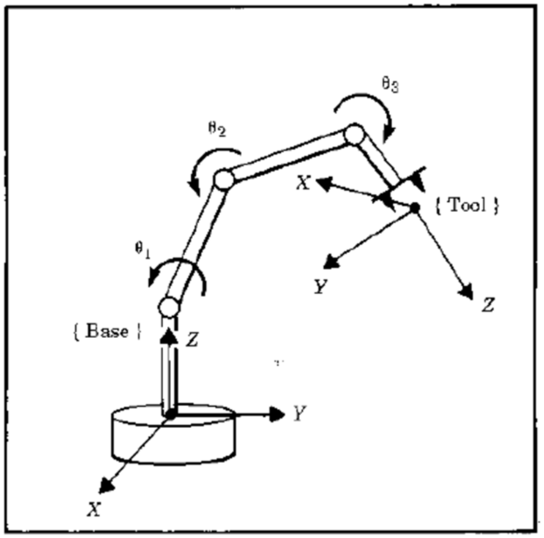
Dynamics concerns with the motion of bodies under the action of force.

2.1 Kinematics

- Kinematics: Study of motion without regard to forces/torques that cause it
- Interested in position, velocities, accelerations, etc. of each joint and link
- Forward and inverse kinematics: Relationship between "joint's position" and "position and orientation of end-effector"

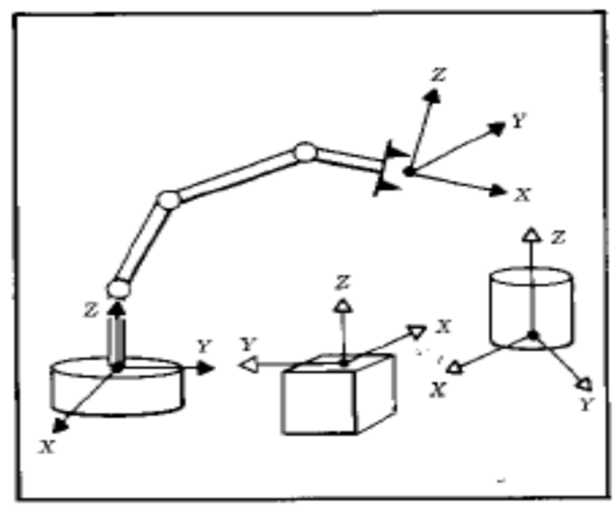
Joint Space $\xrightarrow{\text{forward kinematics}}$ Cartesian Space (End-effector)

Cartesian Space (End-effector) $\xrightarrow{\text{inverse kinematics}}$ Joint Space



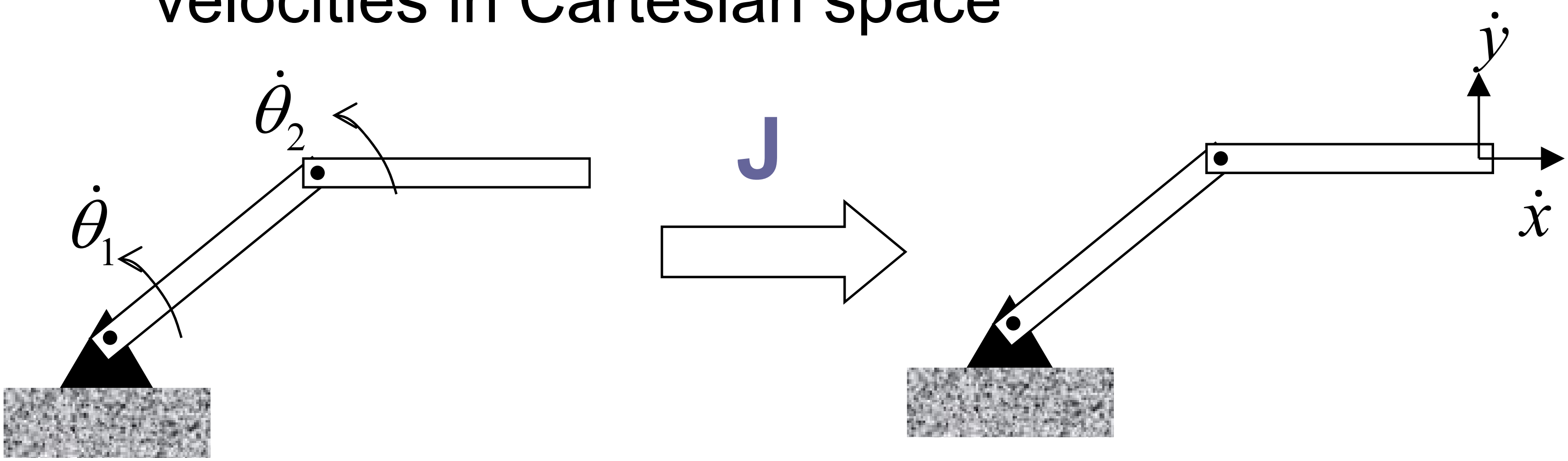
Position and Orientation Representation

- How to locate objects (e.g links of manipulator, Parts, Tools, etc) in three-dimensional space
  - Frame: a coordinate system rigidly attached to each object
  - How to describe position and orientation of one frame with respect to another frame



Differential (Instantaneous) Kinematics

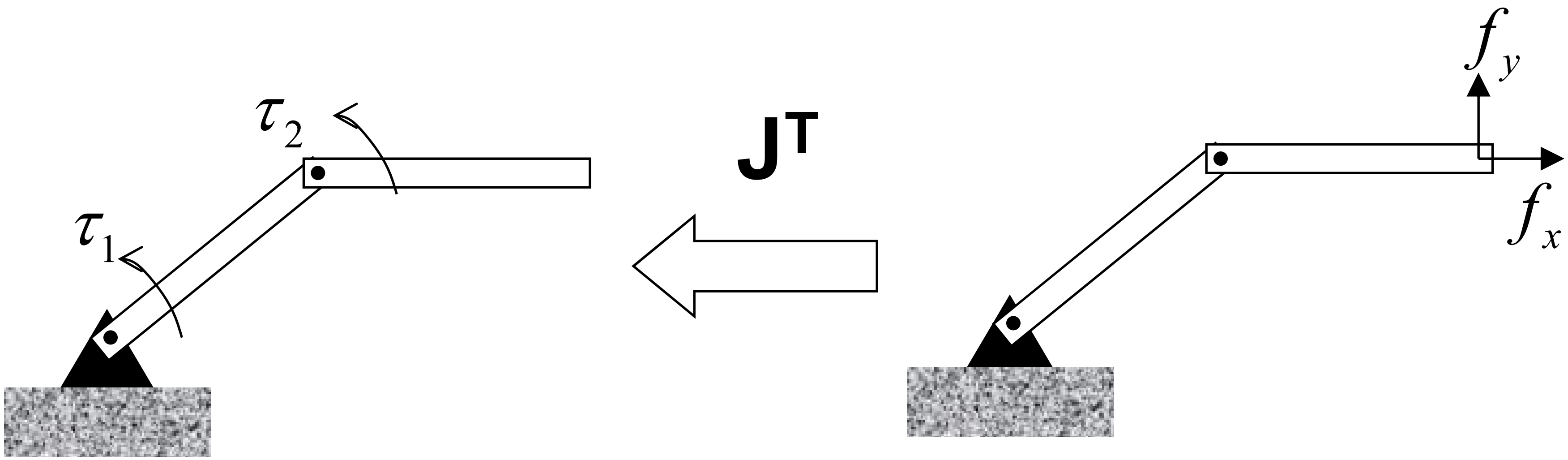
- Jacobian of manipulator, J
  - Mapping from velocities in joint space to velocities in Cartesian space



- Singularities: When mapping not invertible

Differential (Instantaneous) Kinematics

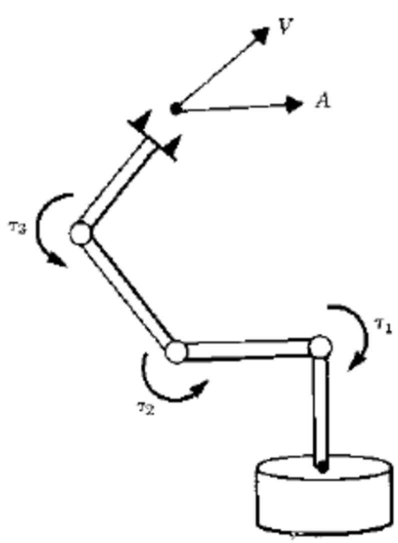
- Jacobian also used to map static force in Cartesian space to joint torques in joint space



2.2 Dynamics

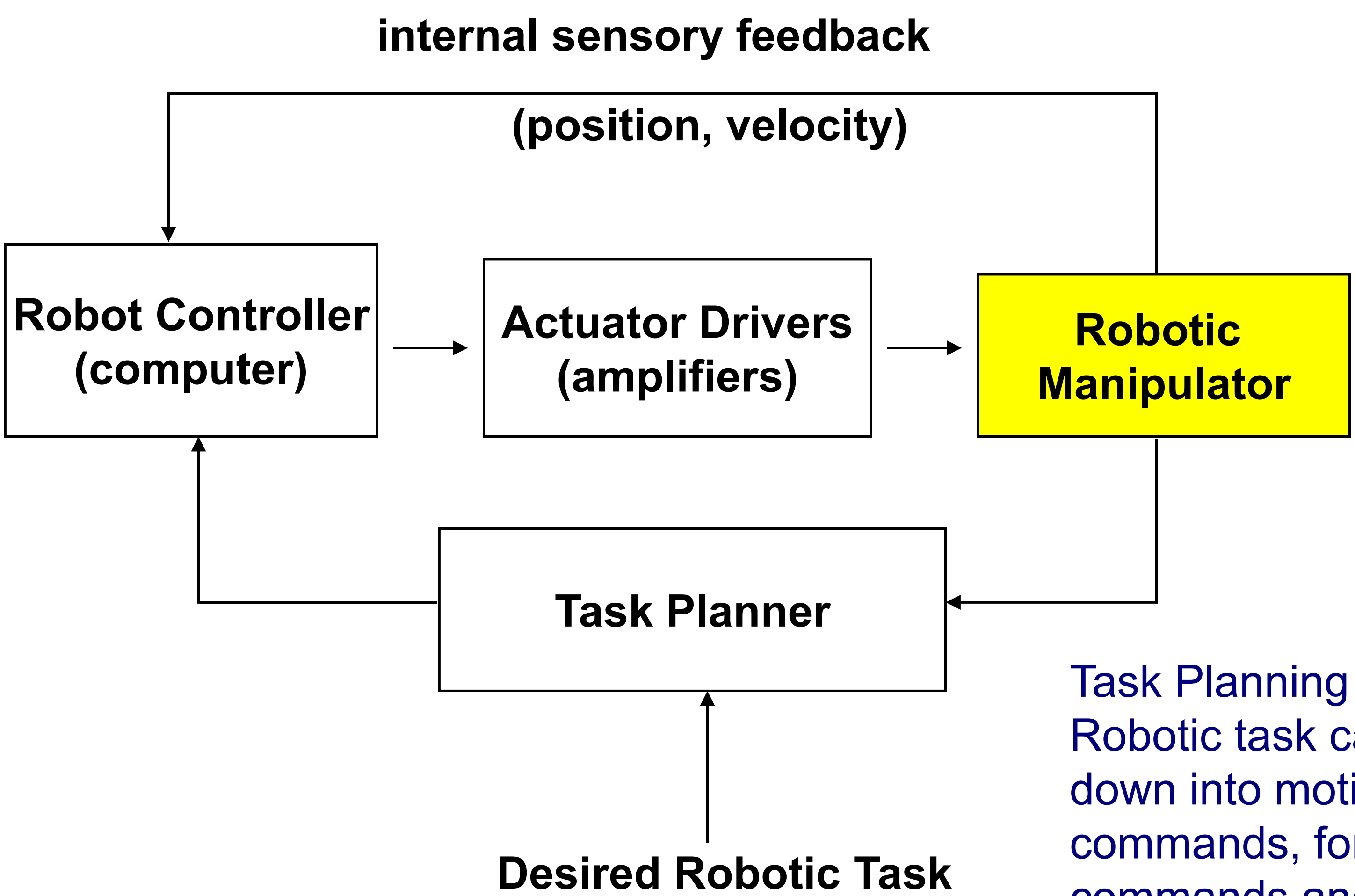
- Equations of Motion of the Robotic Manipulator: Describe forces required to cause motion

Joint Forces and/or Torques ⟺ Joint Motion / Motion of Each Link



$$\underbrace{\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}}_{\text{Inertia}} + \underbrace{\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}}_{\text{Centrifugal and Coriolis}} + \underbrace{\mathbf{g}(\mathbf{q})}_{\text{Gravity}} = \underbrace{\boldsymbol{\tau}}_{\text{Joint torques}}$$

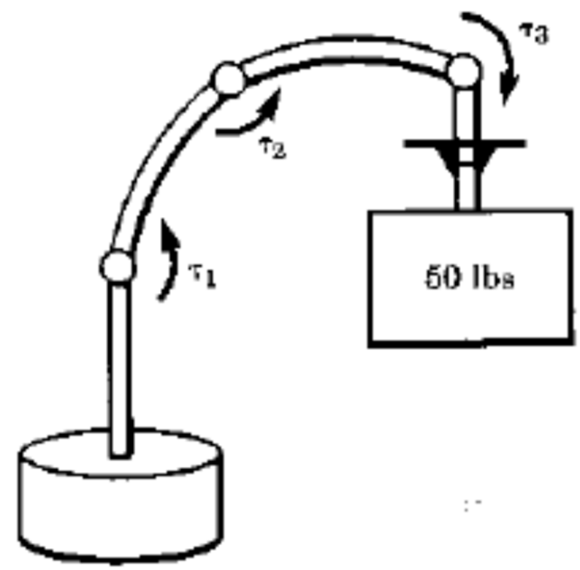
2.3 Robot System Components



Task Planning -
Robotic task can be broken down into motion commands, force/torque commands and strategies to react to forces/torques.

3. Design

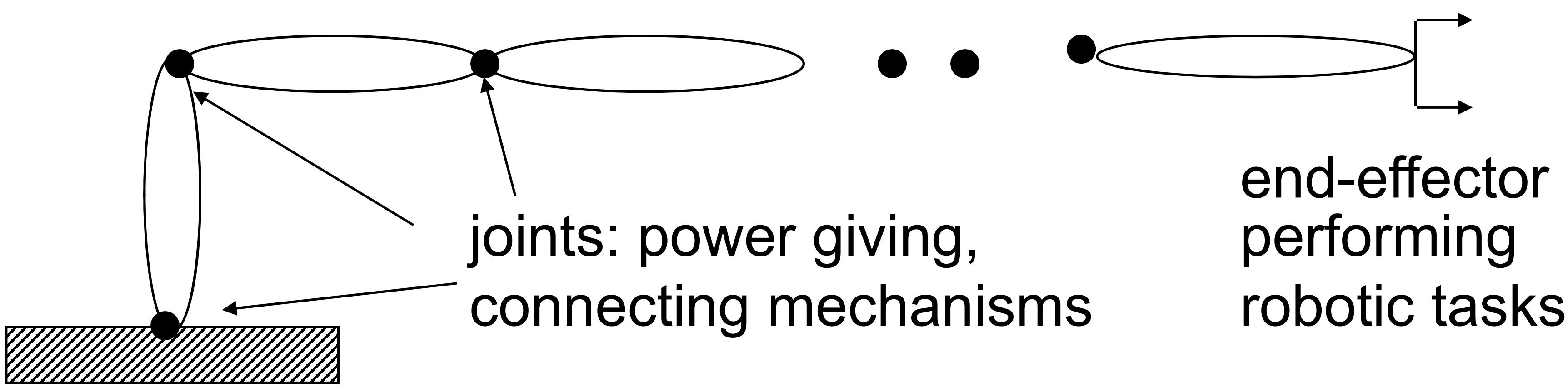
- Type of joints
- Actuators and power transmission
- Degrees of freedom
- Specialized vs universal (min 6 joints)
- Dexterity Considerations (Geometry, Workspace)
- Speed, size, load capability
- Rigid vs Flexible
- Sensors



Robotic Tasks

- positioning/orienting
- force/moment exerted on environment

An Open Kinematic Chain, Serially Connected



Robot Joints

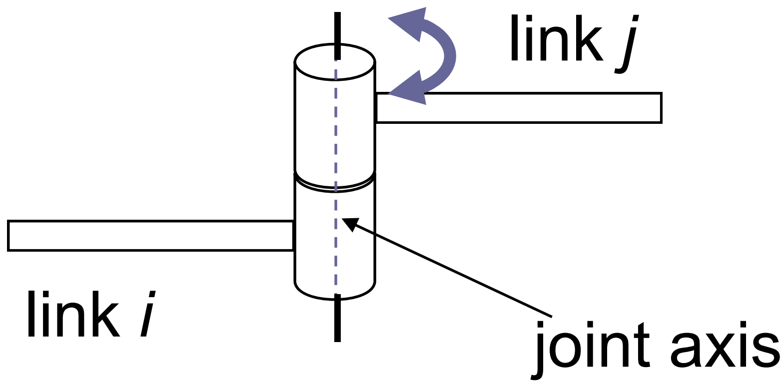
	Rotational	*Translational*
Accuracy	Non-Uniform	Consistent
Kinematics	Complex	Simple
Control	Coupled, Difficult	Decoupled, Easy
Link Design	Simple	Complex
Dexterity	Good	Bad

As the number of rotational joints increase,

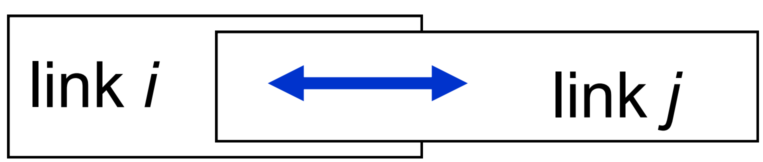
- task planning complexity $\uparrow$
- control algorithm complexity $\uparrow$
- dexterity $\uparrow$
- accuracy $\downarrow$

Types of Robot Joints

Two basic types:



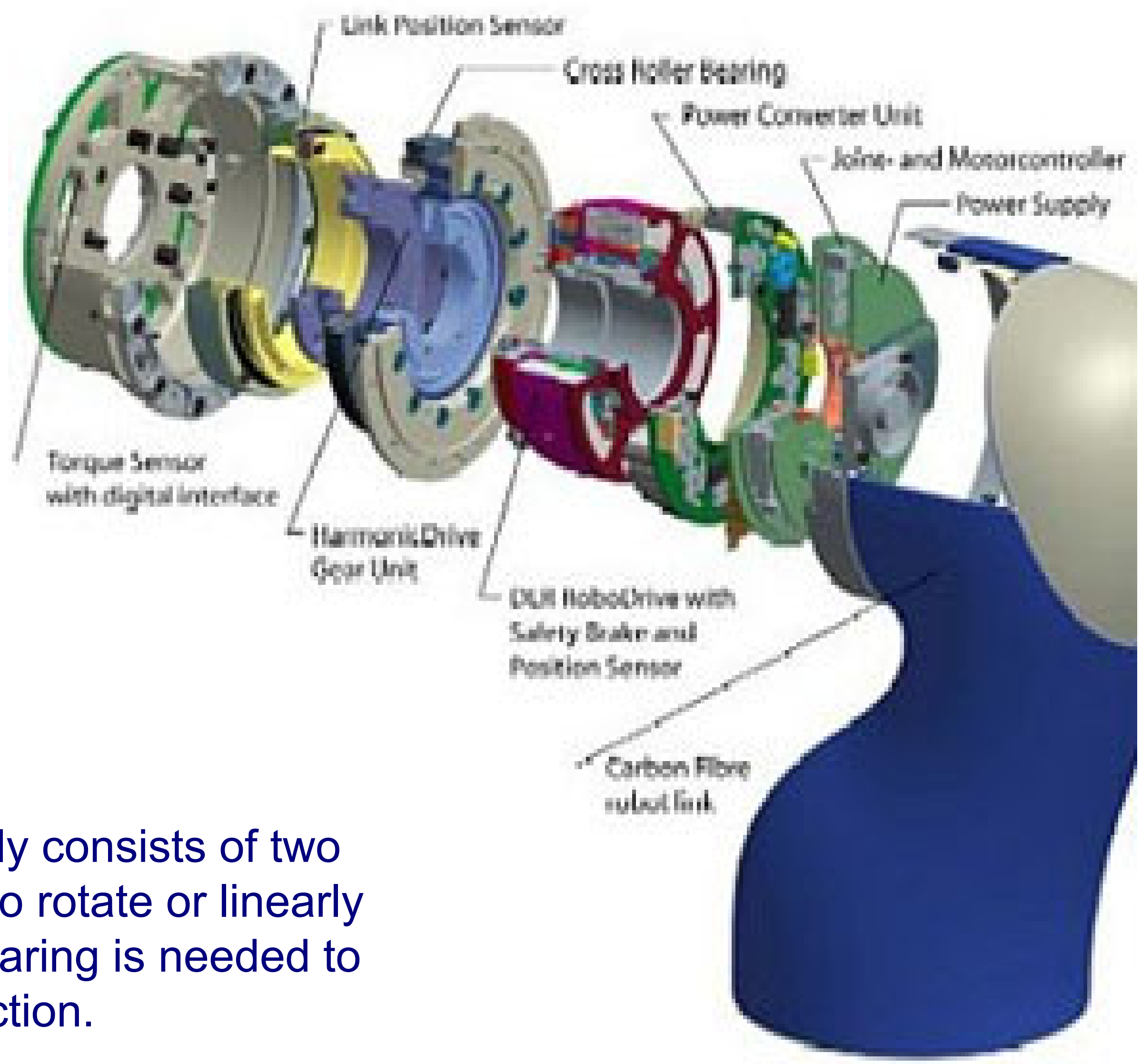
Rotational/Revolute/ Rotary



Translational/Prismatic/ Linear

Joints

- Each consists of an actuator (e.g. motor), mechanical transmission, physical structure, sensors, etc



German Aerospace Center (DLR) Light Weight Robot (LWR)

Physical structure typically consists of two rigid pieces constrained to rotate or linearly move wrt each other. Bearing is needed to reduce the movement friction.

Actuator Technologies

Source of power to drive joints:

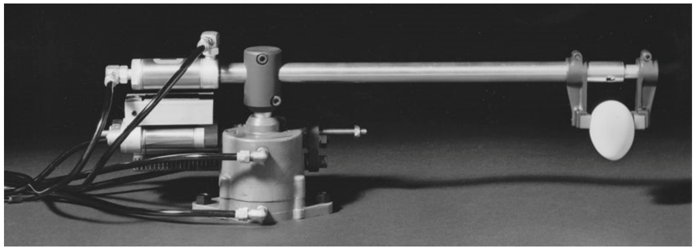
Pneumatic:
- energy efficient
- hard for feedback control

Electric Motor:
- clean
- choice of today

Hydraulic:
- can deliver large forces
- bulky, leakage problems

Note: Air-activated tools have built-in compliance important when manipulating objects to prevent damage

⇨ End-effectors: often are pneumatic tools



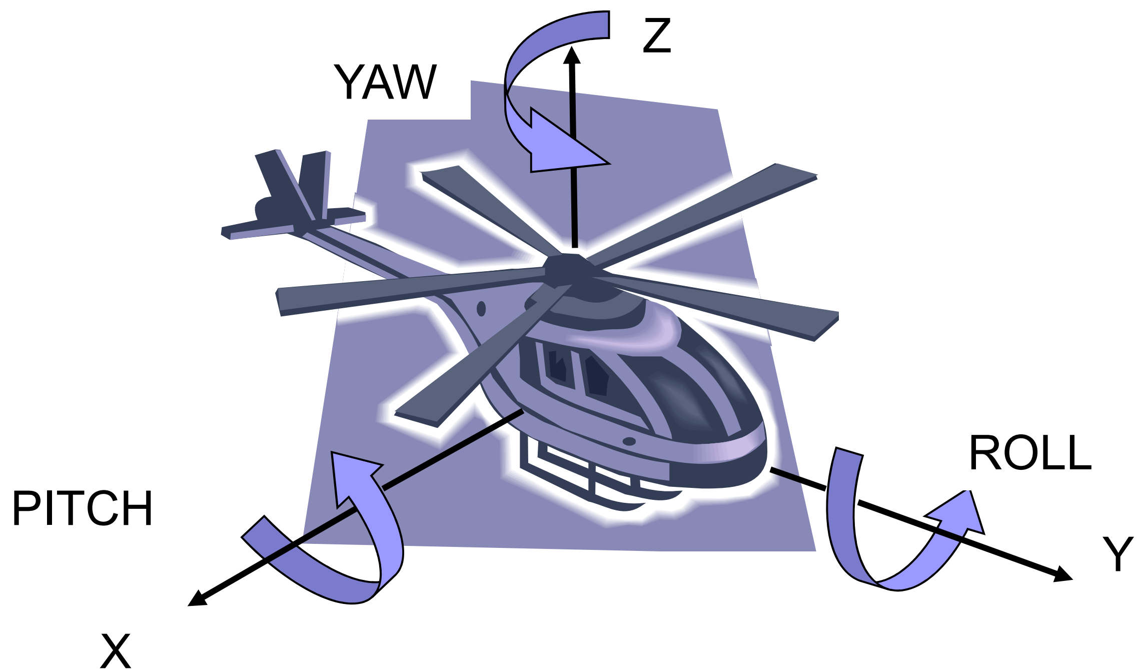
- Mechanical transmission: takes actuator motion and direct it to the joint
  - Enable change of rotational direction
  - Enable change of axis
  - Torque multiplication (or reduction)
  - Speed reduction (or multiplication)
  - Convert rotary motion to linear motion
  - Provide a “match” between the actuator & load in order that the maximum energy is transferred to the load
- Ideal gears
  - Assumptions:
    - Gears are perfectly round
    - Rotae on their true centers
    - Inertialess
    - Frictionless → No loss
    - Rigid shaft attached to the gears

Degrees-of-Freedom (DOF)

Rigid body in 3D Space → 6 DOF

3 for position

3 for orientation

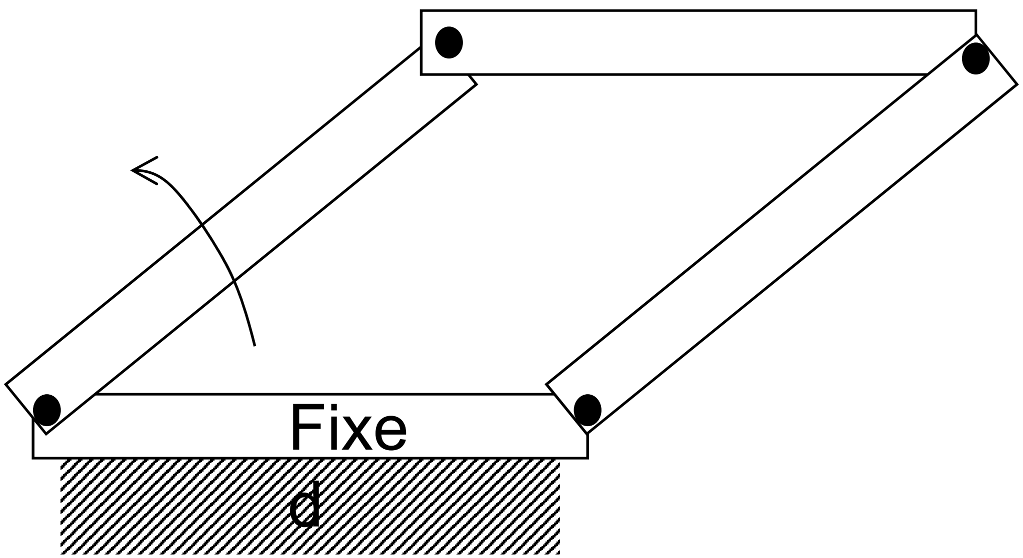


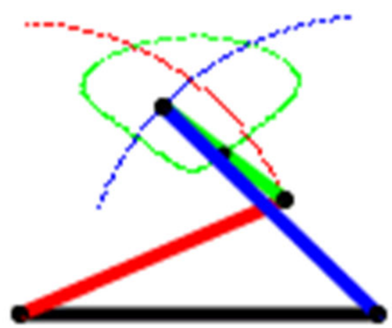
Degrees-of-Freedom (DOF)

In robotics/mechanism,

DOF = number of independent position variables that would have to be specified to locate all parts of the (rigid-body) mechanism

E.g. Planar four-bar linkage only one DOF
(even though having three moving members)





Degrees-of-Freedom

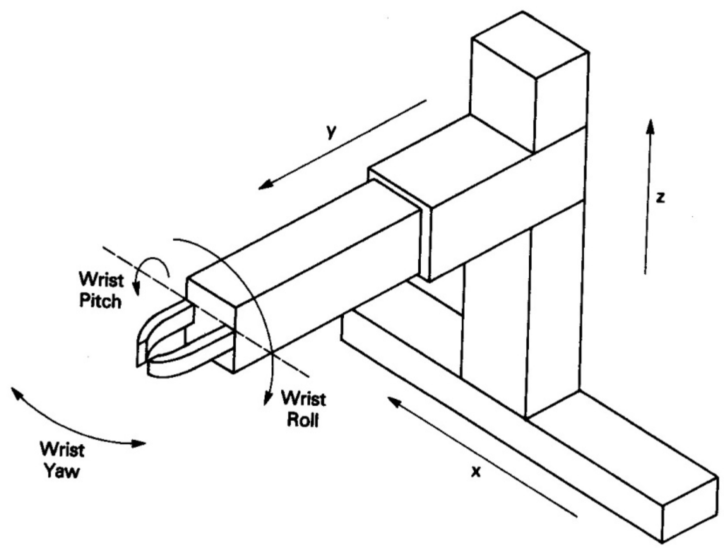
In robotics,

DOF = number of independently driven joints

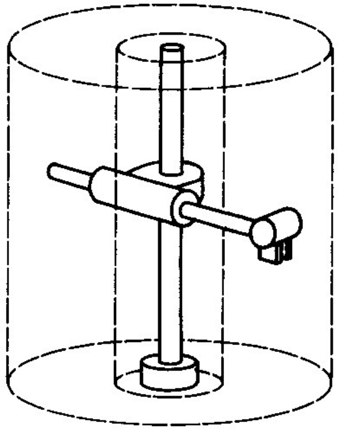
As DOF $\uparrow$ positioning accuracy $\downarrow$
computational complexity $\uparrow$
cost $\uparrow$
flexibility $\uparrow$
power transmission is more difficult

Classification by Coordinate Systems

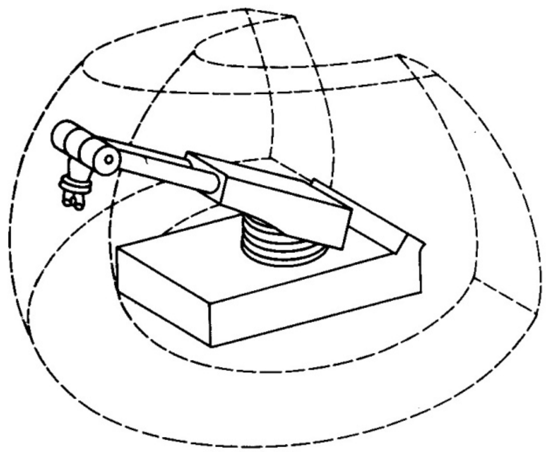
Cartesian



Cylindrical



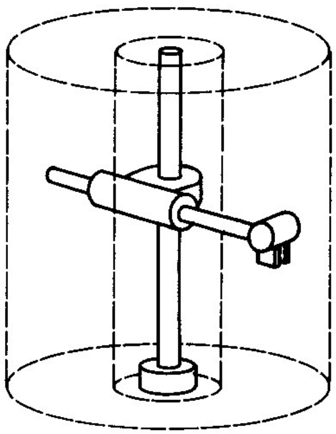
Spherical

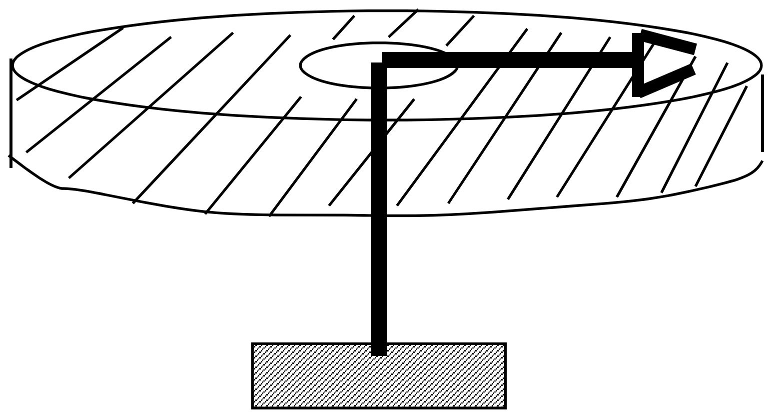


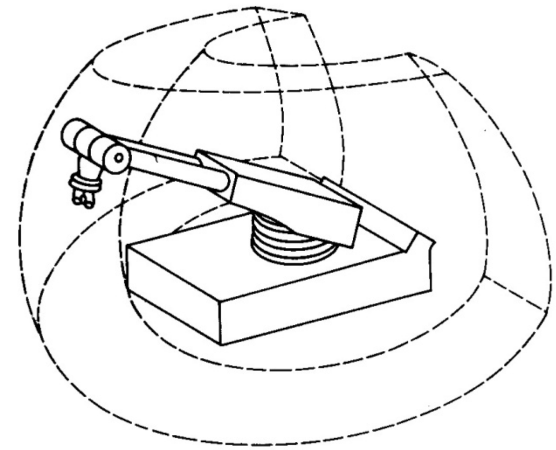
Cartesian: x, y, z (three linear coordinates)
Cylindrical: z, r, theta (two linear and one angular coordinates)
Spherical: r, and two angles (one linear and two angular coordinates)

Workspace

Workspace is the locus of positions and orientations achievable by the end-effector of a manipulator.







Dextrous Workspace

“locus of tool positions for which the tool can be oriented in all possible ways”

Reachable Workspace

“locus of tool positions for which the tool can reach regardless of its orientation”

Dextrous workspace is usually much smaller than reachable workspace

Operating Environment

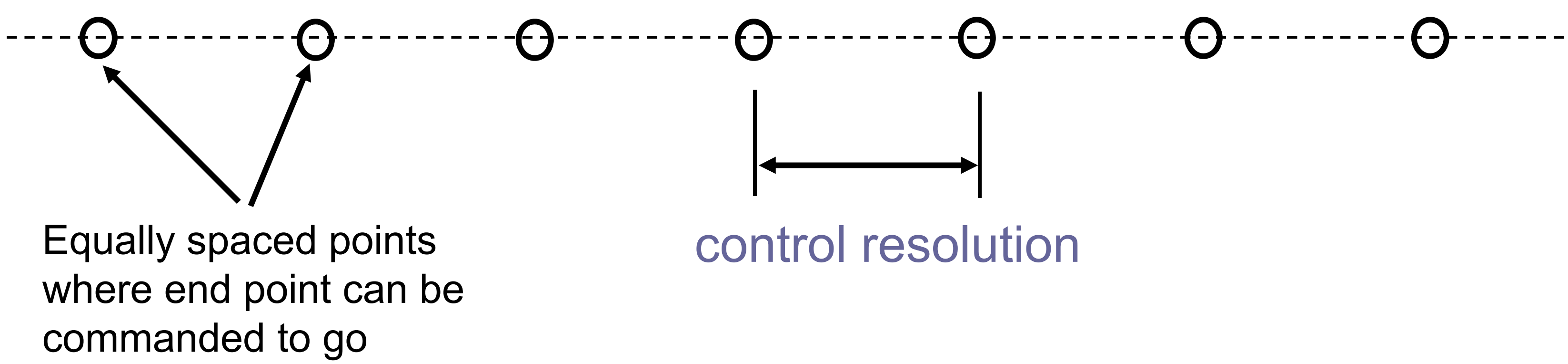
- Clean room robots
  - evacuated internally with suction in order to scavenge particles generated by friction surfaces
  - use special non-shedding materials and employ magnetic washers to hold ferromagnetic lubricants in place
- Harsh environments (e.g. spray painting)
  - clothed in a shroud in order to minimize the contamination of its joints by the airborne paint particles

Courtesy of AIST, Japan

Performance/Specifications

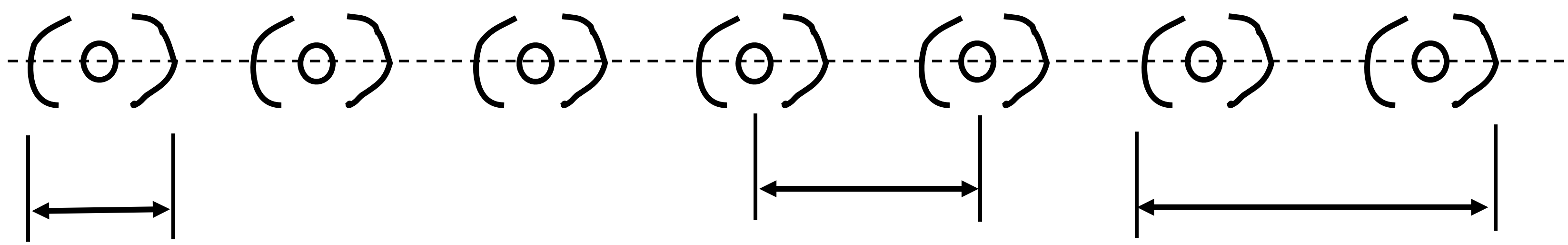
- Resolution
  - Control resolution: Smallest incremental change in tool position that (servo) control system can distinguish (assume no deadband, sensor errors, computational problems)
    - depend on types of joints, resolution of joint position sensors, number of joints, etc.

One-dimensional illustration of resolution



Performance/Specifications

- **Resolution (cont)**
  - If include effects of mechanical inaccuracies and sensor errors, there is a zone about the ideal point where it may stop.
  - Spatial resolution: worst-case distance between two adjacent positions.



Variation due to mechanical inaccuracies and sensor errors

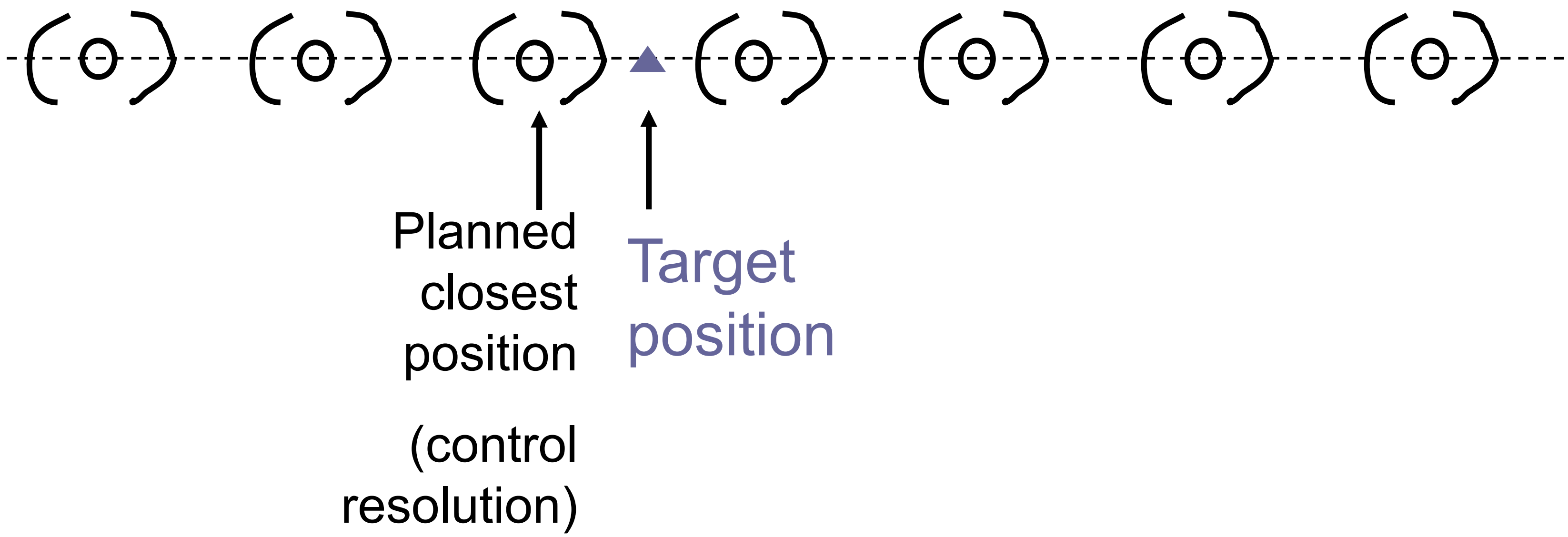
control resolution

Spatial resolution

Performance/Specifications

- Accuracy
  - measure of the ability to place the tool tip at an arbitrarily prescribed location in the workspace

One-dimensional illustration of accuracy

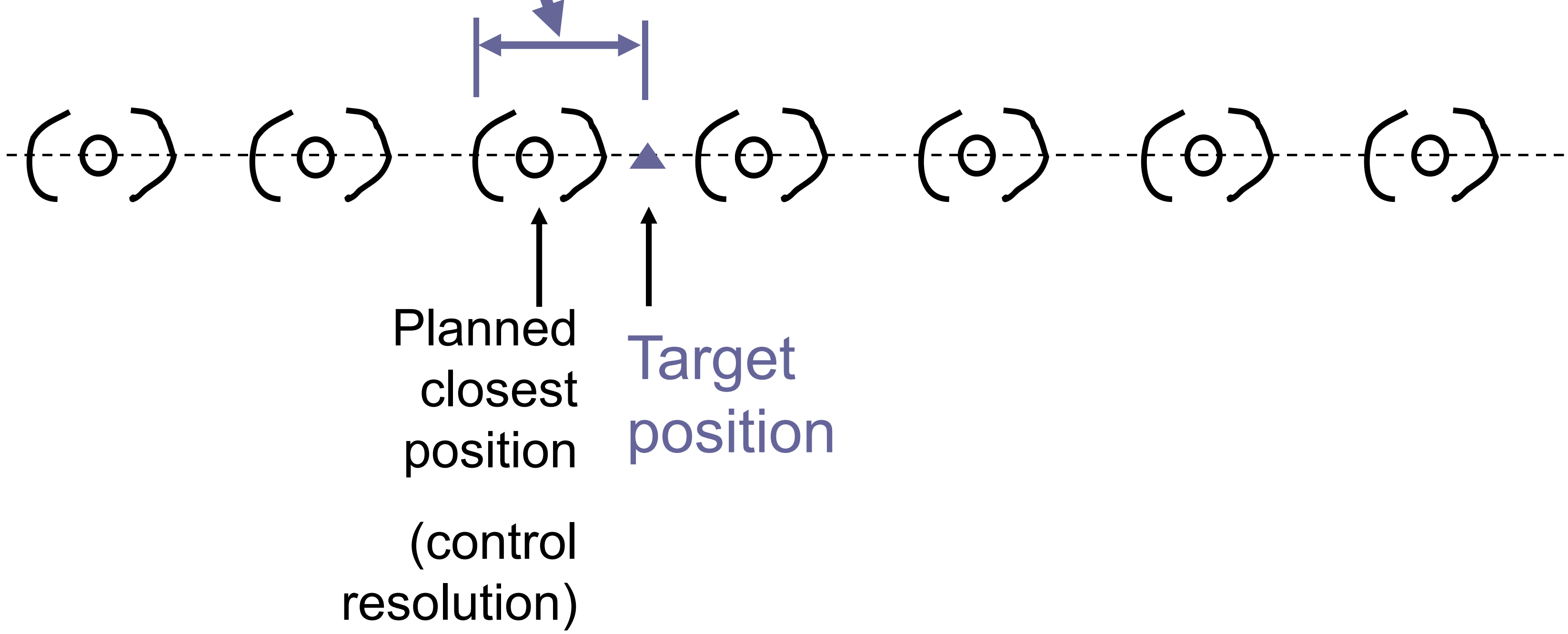


Performance/Specifications

- Accuracy
  - measure of the ability to place the tool tip at an arbitrarily prescribed location in the workspace

    = worst-case distance from target position

    = ½ x Spatial resolution



Performance/Specifications

- Accuracy
  - measure of the ability to place the tool tip at an arbitrarily prescribed location in the workspace

Global vs Local accuracy

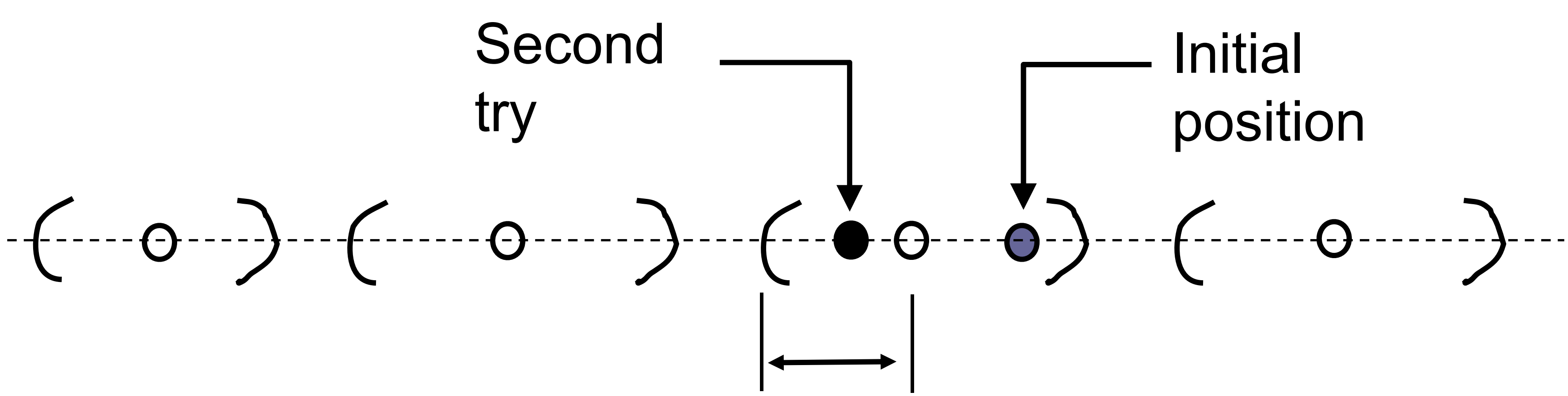
Considering entire workspace

In neighborhood of specified points

Performance/Specifications

- Repeatability
  - ability of a manipulator to reposition its tool tip at a position to which it was previously commanded.
  - important for repetitive tasks

One-dimensional illustration of repeatability



Maximum Speed

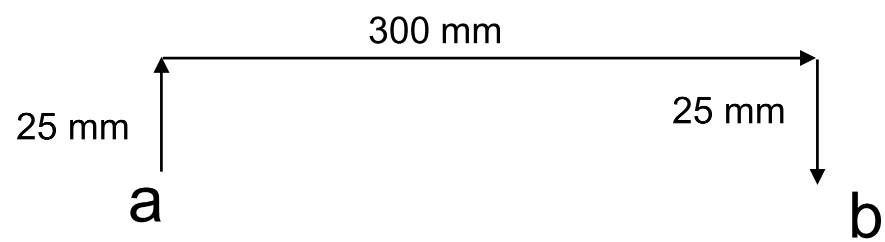
tool tip speed

92 mm/sec → 9,000 mm/sec

Westinghouse Series 4000 — Adept One SCARA

Cycle Time :

Adept “Stroke”

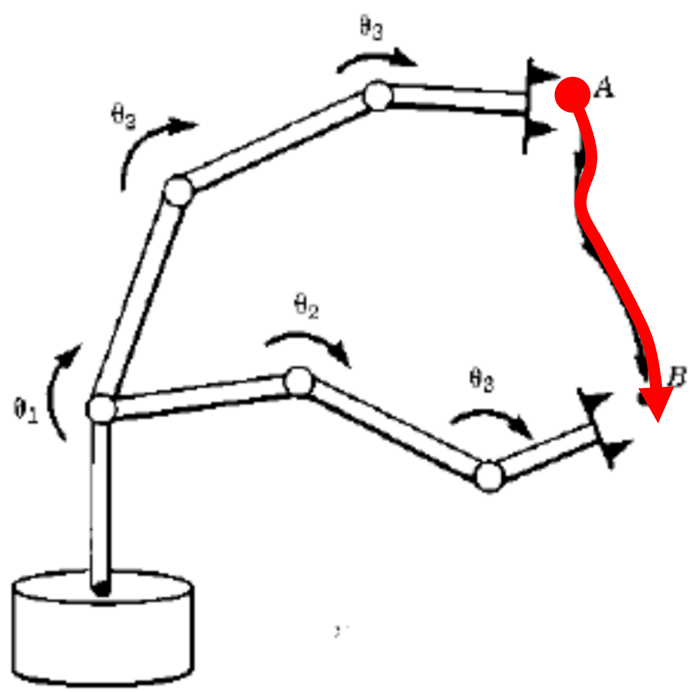


For AdeptOne

Payload	*Cycle Time*
1 lb	0.9 sec
13 lbs	1.3 sec
20 lbs	1.7 sec

4. Trajectory Generation

- Each joint is prescribed with a smooth function of time
- Coordinated motion of joints to provide desired end-effector motion



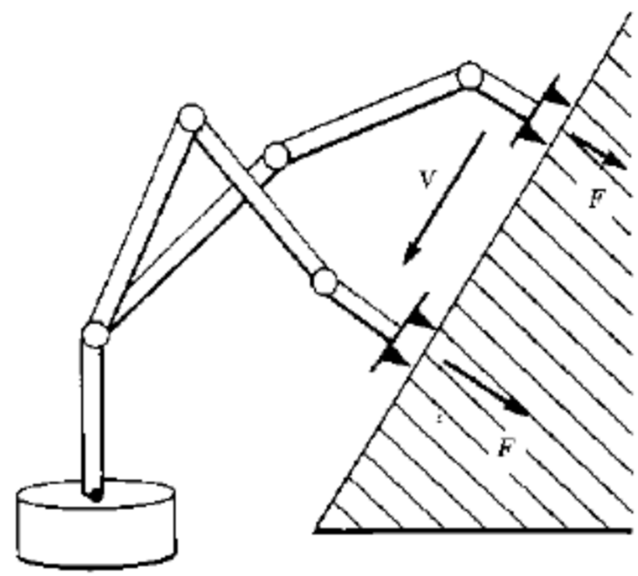
Trajectory is a time based function which specifies the position (and higher derivatives) of the robot mechanism for any value of time.

5. Control

- Motion (position) Control
  - Stable and robust algorithm to coordinate joint motion and enable the robot to follow a specified trajectory
    - Point-to-Point
    - Trajectory Following
- Independent Joint Control
- Inverse Dynamics Control (Computed Torque)
- Nonlinear control approach
  - Robust control
  - Adaptive control

Control

- Force Control
  - Ability of manipulator to control forces of contact
  - Complementary to position control
  - Hybrid position/force control, e.g. window washing task
- Compliance control
- Impedance control



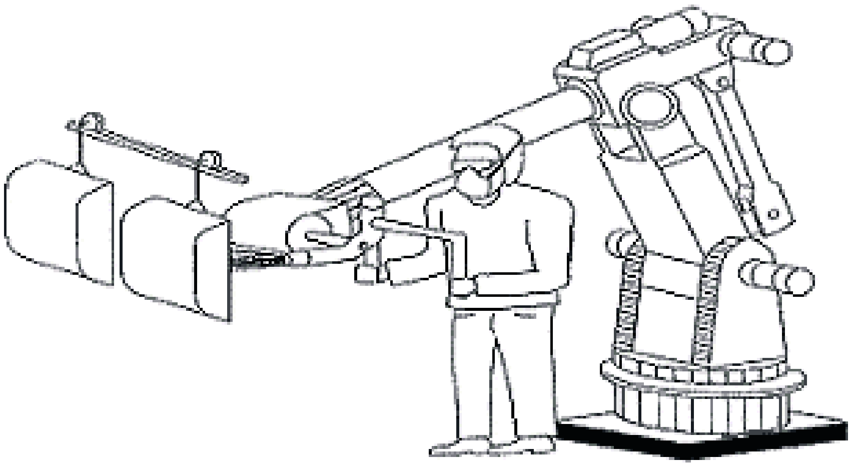
Motion Control Methods

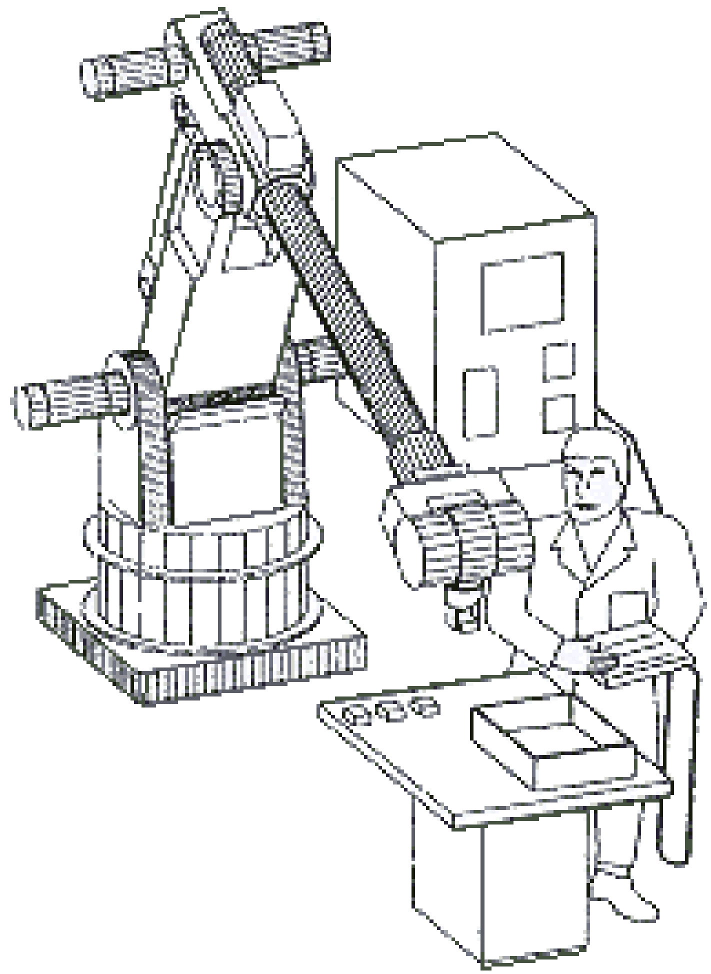
- Point to Point
  - Path between points not explicitly controlled
  - Applications
    - spot welding
    - pick and place
    - loading and unloading
- Continuous Path
  - end-effector must follow a prescribed path in 3D space
  - speed may vary or may need to be accurately controlled
  - Applications
    - spray painting
    - arc welding
    - gluing

6. Programming

- Robot programming:
  - Lead-through programming
  - Textual robot languages
- Lead-through programming: Desired movements are stored in controller memory
  - Powered lead-through: Using teach pendant
    - Pros: Simple for point-to-point movements
    - Cons: Tedious for complex movements
    - Key applications: spot welding, material handling, etc.
  - Manual lead-through (also called walk-through): Robot's end-effector moved physically by programmer, mainly used for continuous path movements
    - Cons: Difficult for large robot arm
    - Key applications: Spray painting, arc welding, etc.

Lead-through programming:





- Textual robot languages:
  - 1979: VAL, a common textual robot language developed by Stanford University
  - 1984: VAL II (Updated version of VAL)
- Other textual robot languages:
  - Manufacturing control language (MCL)
  - RAIL
  - Automatic programming tooling (APT)
  - AML & AUTOPASS by IBM for assembly operations
  - Etc.
- How could desired motions be easily implemented on robot?

Task description (In plain English)

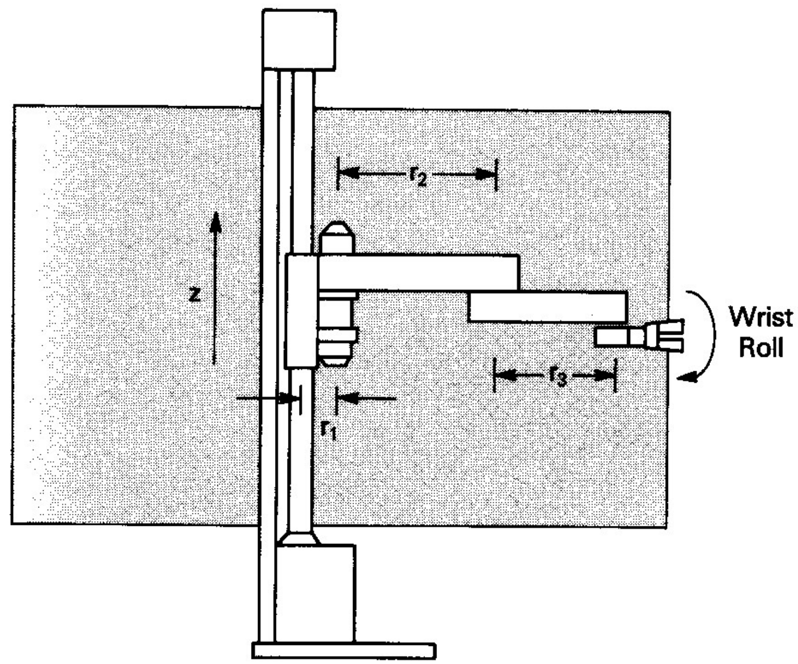
```
Move to P1 (a general safe position)
Move to P2 (an approach to P3)
Move to P3 (a position to pick the object)
Close gripper
Move to P4 (an approach to P5)
Move to P5 (a position to place the object)
Open gripper
Move to P1 and finish
```

VAL

```
PROGRAM PICKPLACE
  1. MOVE P1
  2. MOVE P2
  3. MOVE P3
  4. CLOSEI 0.00
  5. MOVE P4
  6. MOVE P5
  7. OPENI 0.00
  8. MOVE P1
.END
```

EXAMPLE: SCARA

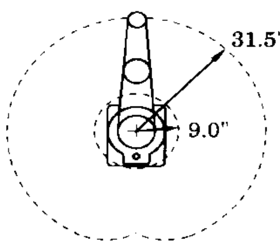
- **Selective Compliance Assembly Robot Arm**
- Jointed cylindrical manipulator
- Joints 1 and 2 are not gravity loaded
- Joints are direct-drive motors →End-effector compliance can be controlled to a certain extent (Useful for assembly operations which require pegs or screw insertions

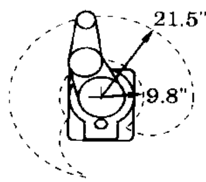


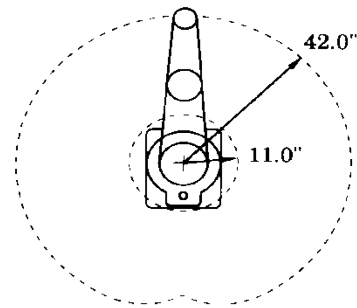
Robots

	AdeptOne	AdeptTwo	AdeptThree
Reach	31.5" (800 mm)	21.5" (546 mm)	42.0" (1067 mm)
Vertical Stroke	7.7" (196 mm) or 11.6" (295 mm)	8.0" (203 mm)	12.0" (305 mm)
Maximum Payload	20 lbs (9 kg)	20 lbs (9 kg)	55 lbs (25 kg)
Repeatability	0.001" (0.025 mm)	0.001" (0.025 mm)	0.001" (0.025 mm)
12" cycle time (1 lb)	0.9 sec	0.9 sec	1.1 sec
12" cycle time (20 lbs)	1.7 sec	1.7 sec	1.4 sec
Option Compatibility			
High-accuracy Positioning System (HPS)	Yes	Yes	No
Fifth Axis (servo pitch)	Yes	No	Yes
Robot Mounted Camera	Yes	Yes	Yes
Cleanroom Package	Yes	No	No

Work Envelope







Robot Controllers

	Adept MC	Adept CC
Operating System	V	V
System Processor	1 Mb 68000 (10 MHz)	1 Mb 68000 (10 MHz)
Robot Motion Processors	Two 68000 (10 MHz)	Two 68000 (10 MHz)
Serial Ports	Five RS-232C	Five RS-232C
Maximum Digital I/O	96 internal/512 total	32 internal/512 total
Option Compatibility		
Robot Control	Any Adept robot	Any Adept robot
AdeptVision	Any AdeptVision system	AdeptVision II/AdeptVision XGS-II
Adept V+	Yes	Yes
68020 System Processor	Yes	Yes
AdeptMotion I	Yes	Yes
NEMA 12	Yes	No

Classical robotics == the study of industrial robotic manipulator

An integrated approach of

- Kinematics: study of geometry of motion
- Statics: study of a manipulator at equilibrium
- Dynamics: study of causes of motion
- Trajectory planning: generating the path the robot must trace
- Control strategy: executing the path
- Physical hardware: building the robot

Homework

- Linear Algebra Review
- Matlab Total Academic Headcount license
  - https://nusit.nus.edu.sg/services/software_and_os/software/software-student/

2021 Year of Robots?

https://youtu.be/BFK9lkez32E