Introduction

Advanced Robotic - MAE 263B - Introduction

Instructor: Jacob Rosen

Office: Engineering IV – Rm. 37-146

Lab: Bionics Lab - Engineering IV, Rm. 18-111

E-mail: jacobrosen@ucla.edu

Office Hours: Wed 12:00-2:00

Advanced Robotic - MAE 263B - Introduction

Summary: 263B. Advanced Robotics. (4)
- Lecture - 4 hours per week
- Outside study – 8 hours per week

Dynamics models of serial and parallel robotic manipulators including review of spatial descriptions and transformations along with direct and inverse kinematics, linear and angular velocities, Jacobian matrix (velocity and force), velocity propagation method, force propagation method, explicit formulation of the Jacobian matrix, manipulator dynamics (Newton-Euler formulation, Lagrangian formulation), trajectory generation, introduction to parallel manipulators
Recommended preparation: courses 263A (Enforced); 255B (Recommended)

Assignments & Grading:

HW Assignments	**20%**
Paper Review	**5%**
Midterm Exam (Take Home)	**30%**
Final Exam (Take Home)	**40%**
Participation	**5%**

Class Web Site: http://bionics.seas.ucla.edu/education/classes_index.html

Advanced Robotic - MAE 263B - Introduction

List of Topics

Week	Topic
1	Review: Special Description & Transformation
2	Review Direct & Inverse Manipulator Kinematics
3	Linear and Angular Velocities
4	Jacobian Matrix - Velocity propagation method
5	Jacobian Matrix - Force propagation method; Explicit formulation
6	Linear and angular Acceleration (Vector and Matrix Approach)
7	Manipulator dynamics (Newton-Euler formulation)
8	Manipulator dynamics (Langrangian formulation)
9	Trajectory generation
10	Feedback Control

- **Midterm Exam – Take Home**
- **Final Exam – Take Home**

Description of Positioning Task

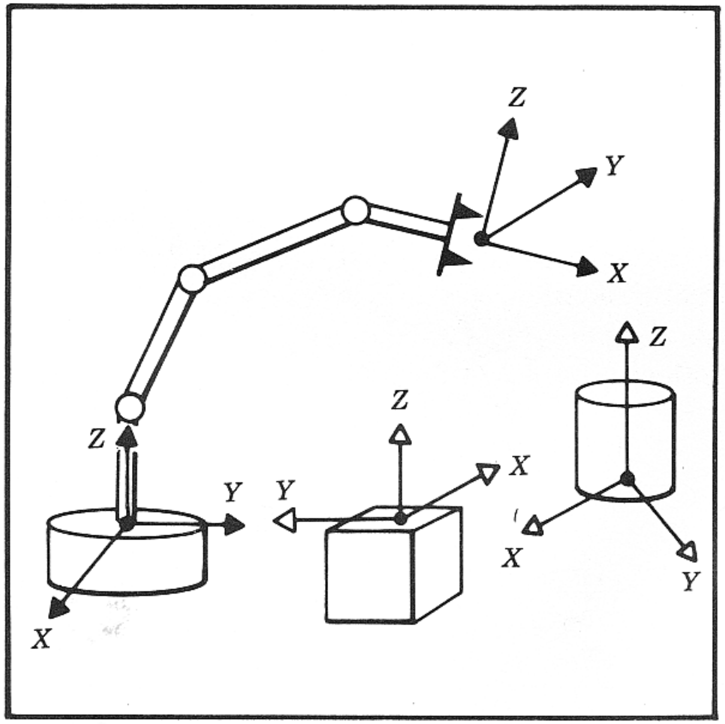
Problem

Given: *The manipulator geometrical parameters*

Specify: *The position and orientation of manipulator*

Solution

Coordinate system or "Frames" are attached to the manipulator and objects in the environment



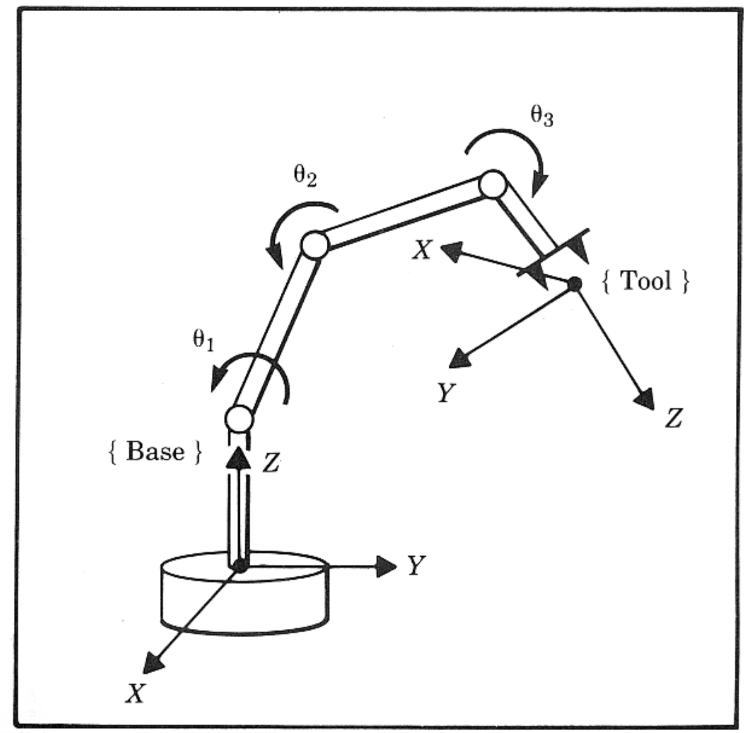
Forward (Direct) Kinematics

Problem

Given: *Joint angles and links geometry*
Compute: *Position and orientation of the end effector relative to the base frame*

Solution

Kinematic Equations - Linear Transformation (4x4 matrix) which is a function of the joint positions (angles & displacements) and specifies the EE configuration in the base frame.



Inverse Kinematics

Problem

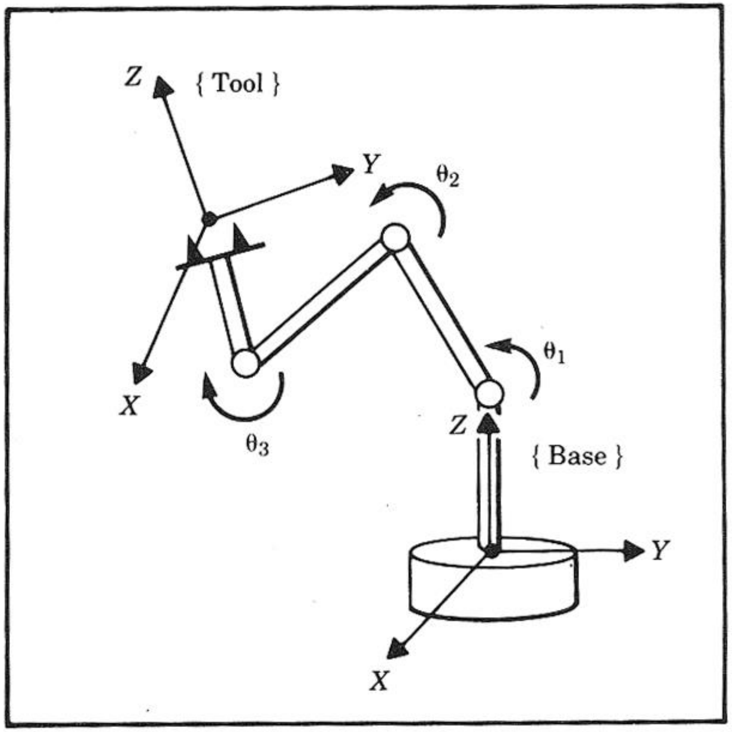
Given: *Position and orientation of the end effector relative to the base frame*

Compute: All possible sets of joint angles and links geometry which could be used to attain the given position and orientation of the end effetor

Solution

There are three approaches for the solution:

- **Analytical Approach** - Kinematic Equations - Linear Transformation (4x4 matrix) which is a function of the joint positions (angles & displacements) and specifies the EE configuration in the base frame. This linear transformation defines 12 non linear equations A subset of these equations are used for obtaining the invers kinematics
- **Geometric Approach** – Projecting the arm configurations on specific planes and using geometrical consideration to obtain the invers kinematics
- **Hybrid Approach** - Synthesizing the analytical and the geometrical approaches



Velocity Transformation

Problem

Given: *Joint angles and velocities and links geometry along with the transformation matrixes between the joints*

Compute: *The Jacobian matrix that maps between the joint velocities in the joint space* $\dot{\Theta}$ *to the end effector velocities in the Cartesian space or the end effector space* ν

$$\nu = \mathbf{J}\ (\Theta)\dot{\Theta}$$

$$\dot{\Theta} = \mathbf{J}^{-1}(\Theta)\nu$$

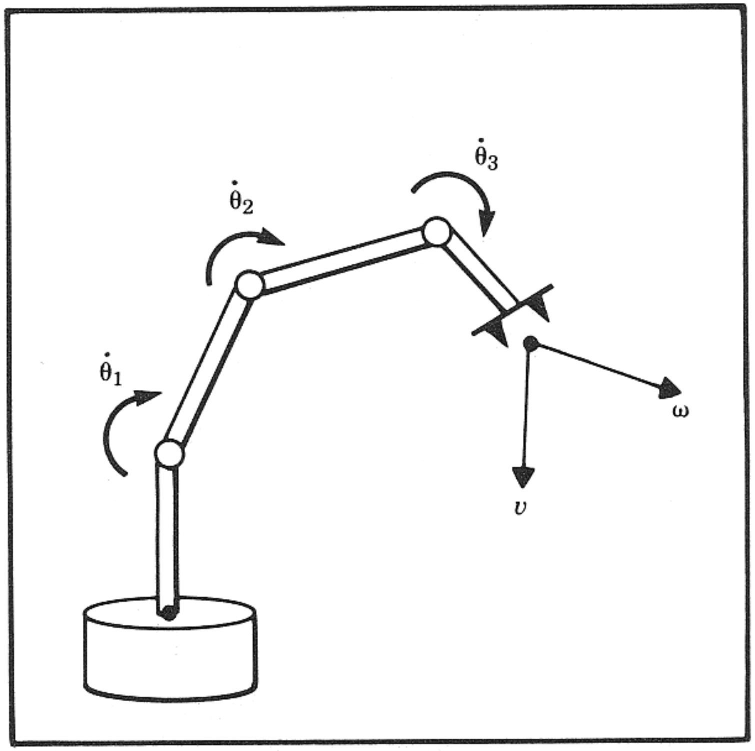
Solution – There are two approaches to the solution:

- **Velocity Propagation** - A velocity propagation approach is taken in which velocities are propagated stating form the stationary base all the way to the end effector. The Jacobian is then extracted from the velocities of the end effector as a function of the joint velocities.
- **Time derivative of the end effector position and ordinations** – The time derivative of the explicit positional and orientation is taken given the forward kinematics. The Jacobian is then extracted from the velocities of the end effector as a function of the joint velocities.

Notes:

Spatial Description – The matrix is a function of the joint angle.

Singularities - At certain points, called ***singularities***, this mapping is not invert-able and the Jacobian Matrix J loosing its rank and therefore this mathematical expression is no longer valid.



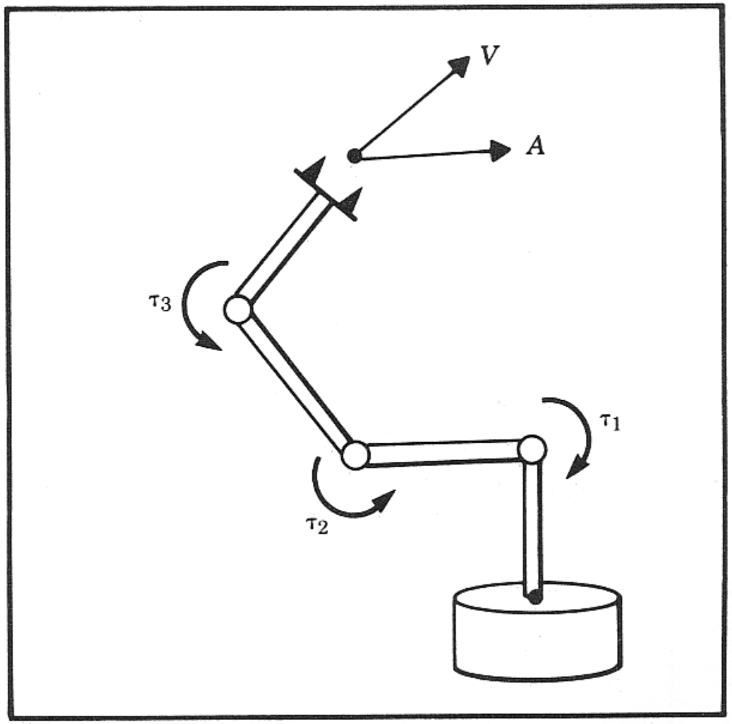
Force Transformation

Problem

Given: *Joint angles, links geometry, transformation matrixes between the joints, along with the external loads (forces and moments) typically applied on the end effector*

Compute: *The transpose Jacobian matrix* f *that maps between the external loads* τ *(forces and moments) typically applied at the end effector space* joint torques at the *joint space*

$$\tau = \mathbf{J}^T f$$



Solution

- **Force/Moment Propagation** - A force/moment propagation approach is taken in which forces and moments are propagated stating form the end effector where they can be measured by a F/T sensor attached between the gripper and the arm all the way to the base of the arm. The Jacobian transposed is then extracted from the joint torques as a function of the force/moment applied on the end effector

Note

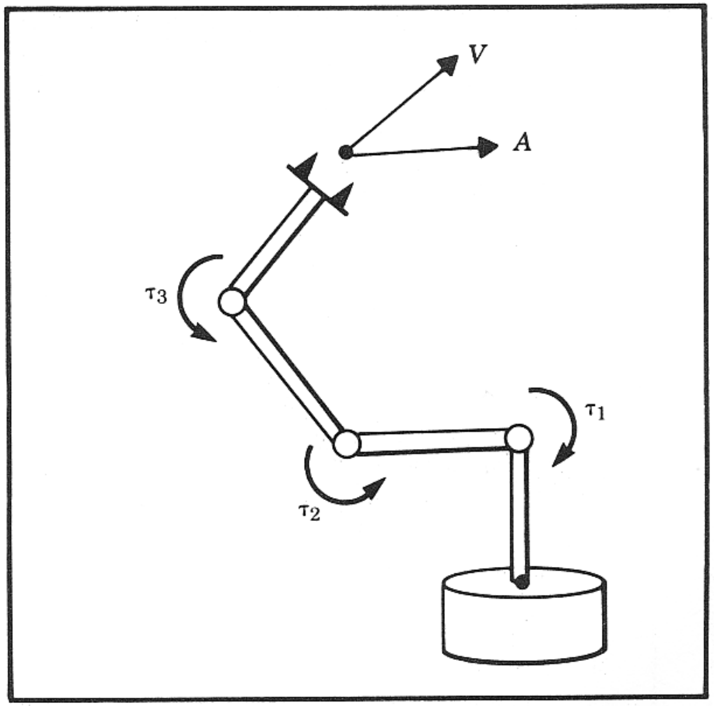
- Static or quasi static conditions

Forward Dynamics

Problem

Given: *Joint torques and links geometry, mass, inertia, friction*

Compute: *Angular acceleration of the links*
(solve differential equations)



Solution

Dynamic Equations - Newton-Euler method or Lagrangian Dynamics

$$\boldsymbol{\tau} = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) + F(\Theta,\dot{\Theta})$$

Inverse Dynamics

Problem

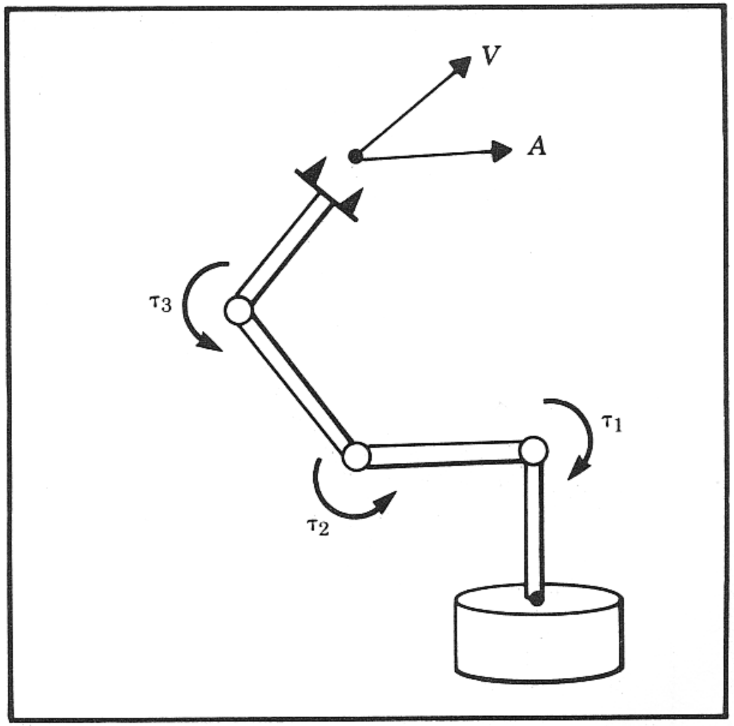
Given: Angular acceleration, velocity and angels of the links in addition to the links geometry, mass, inertia, friction

Compute: Joint torques

Solution

Dynamic Equations - Newton-Euler method or Lagrangian Dynamics

$$\boldsymbol{\tau} = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) + F(\Theta,\dot{\Theta})$$

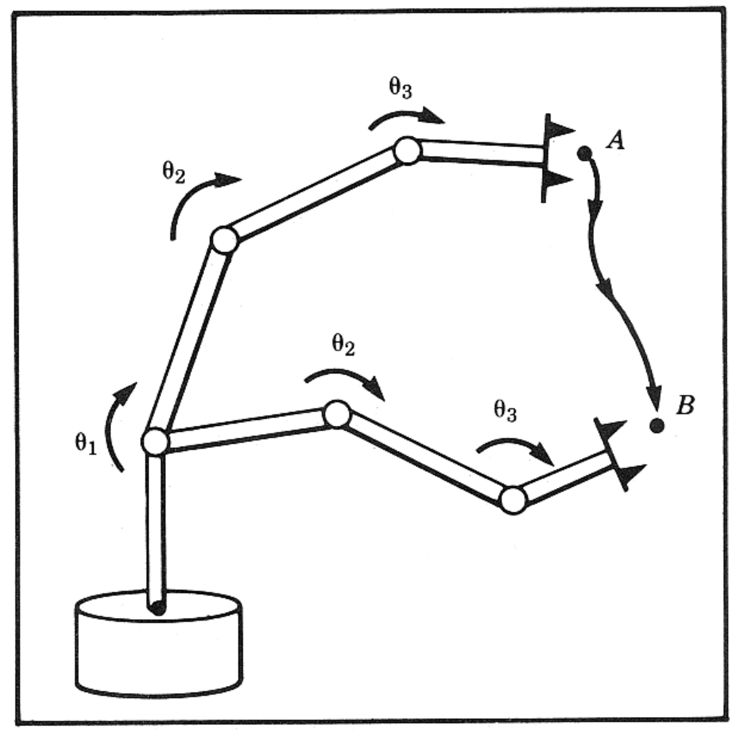


Trajectory Generation

Problem

Given: Manipulator geometry

Compute: The trajectory of each joint such that the end efferctor move in space from point A to Point B



Solution

Third order (or higher) polynomial spline

Position Control

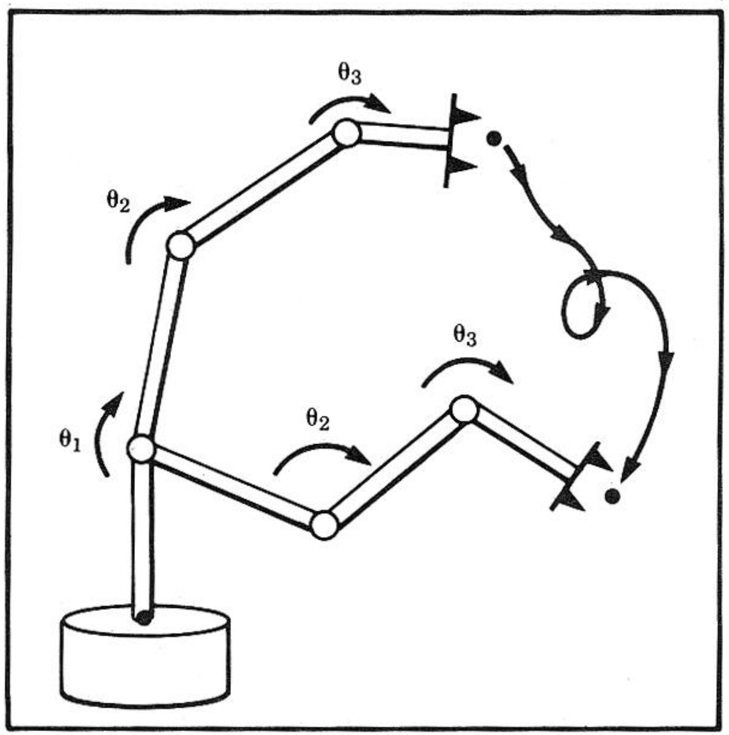
Problem

Given: Joint angles (*sensor readings) links geometry, mass, inertia, friction*

Compute: Joint torques to achieve an end effector trajectory

Solution

Control Algorithm (PID - Feedback loop, Feed forward dynamic control)

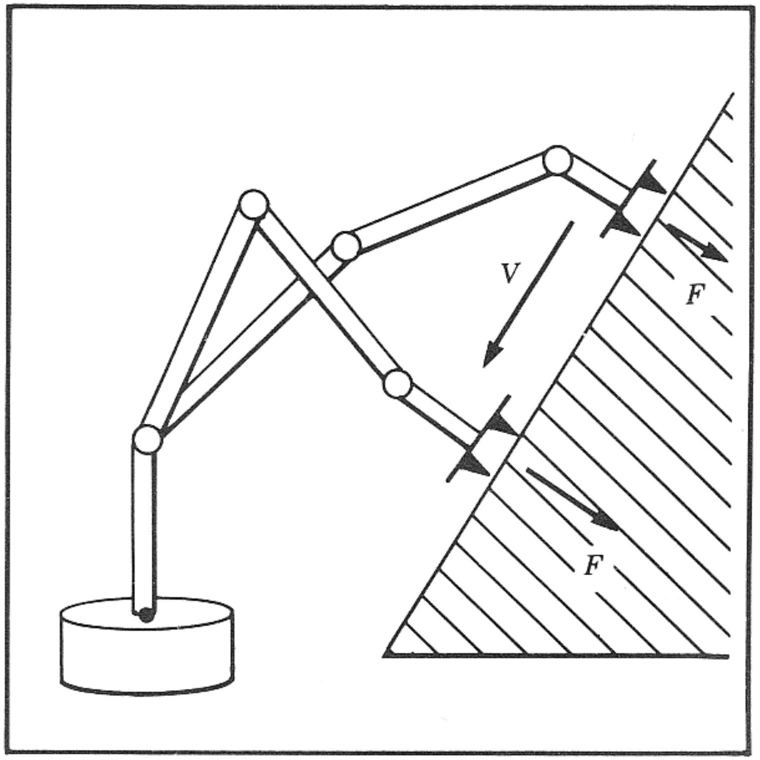


Force Control

Problem

Given: Joint torque or end effector Force/torque interaction (sensor readings) links geometry, mass, inertia, friction

Compute: Joint torques to achieve an end effector forces an torques



Solution

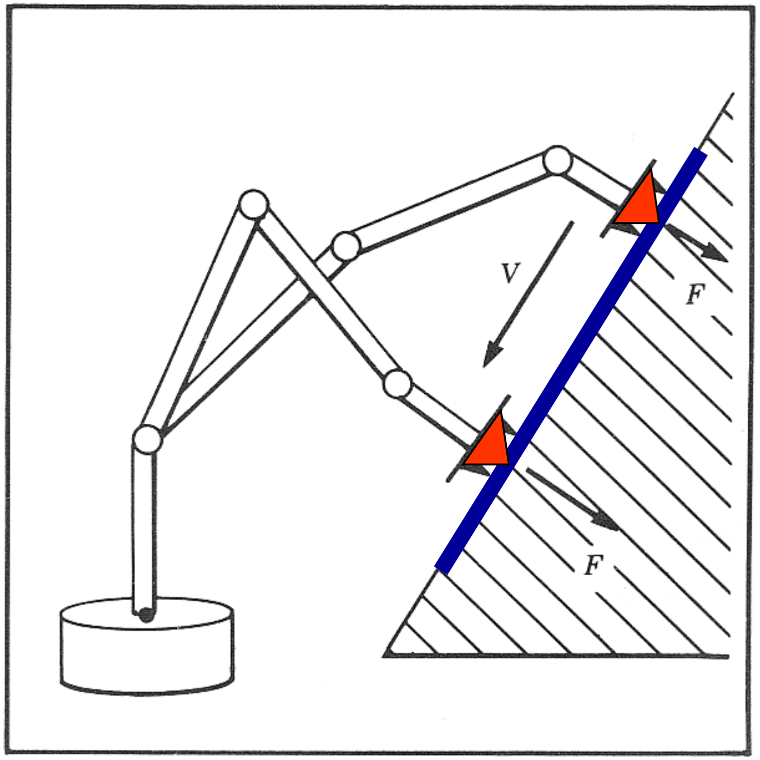
Control Algorithm (force control)

Hybrid Control

Scraping paint from a surface

Control type: Hybrid Control

Note: It is possible to control position (velocity) **OR** force (torque), but not both of them simultaneously along a given DOF. The environment impedance enforces a relationship between the two



Assumption:

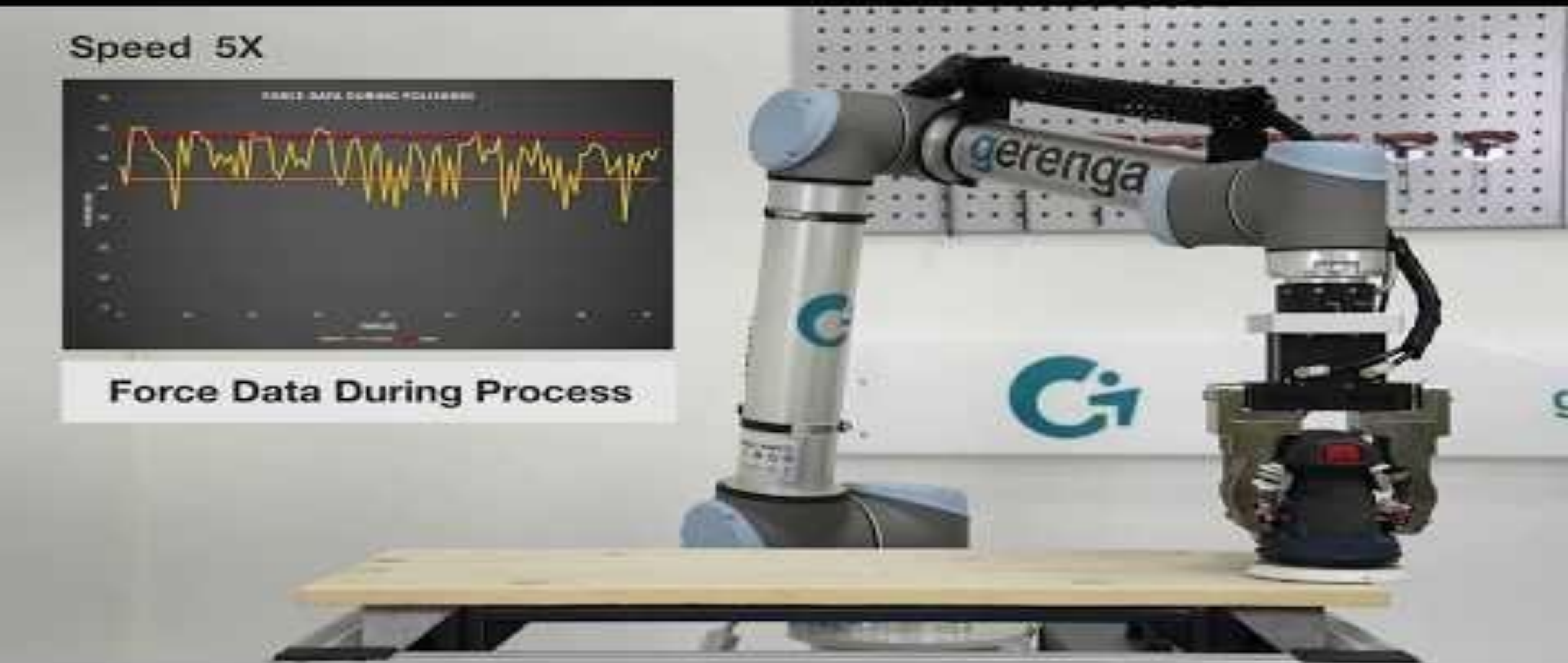
(1) The tool is stiff

(2) The position and orientation of the window is NOT known with accurately respect to the robot base.

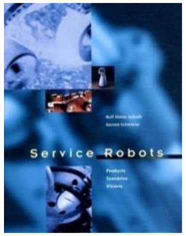
(3) A contact force normal to the surface transmitted between the end effector and the surface is defined

(4) Position control - tangent to the surface

(5) Force control – normal to the surface



Universal Robots "Force Control Surface Grinding"



Hybrid Control - Robotic Systems - Cleaning

SKYWASH

AEG, Dornier, Fraunhofer Institute, Putzmeister - Germany

Using 2 Skywash robots for cleaning a Boeing 747-400 jumbo jet, its grounding time is reduced from 9 to 3.5 hours. The world´s largest cleaning brush travels a distance of approximately 3.8 kilometers and covers a surface of around 2,400 m² which is about 85% of the entire plane´s surface area. The kinematics consist of ***5 main joints*** for the robot´s arm, and an additional ***one for the turning circle*** of the rotating washing brush.The Skywash includes ***database that contains the aircraft-specific geometrical data***. A ***3-D distance camera*** accurately positions the mobile robot next to the aircraft. The 3-D camera and the computer determine the aircraft´s ideal positioning, and thus the cleaning process begins.

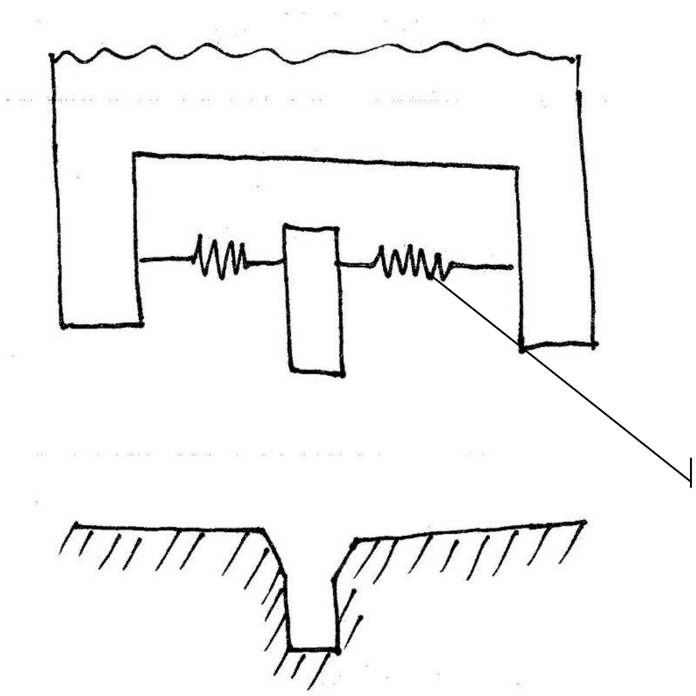
NORDIC DINO - Superior Aircraft washing machine

Impedance Control

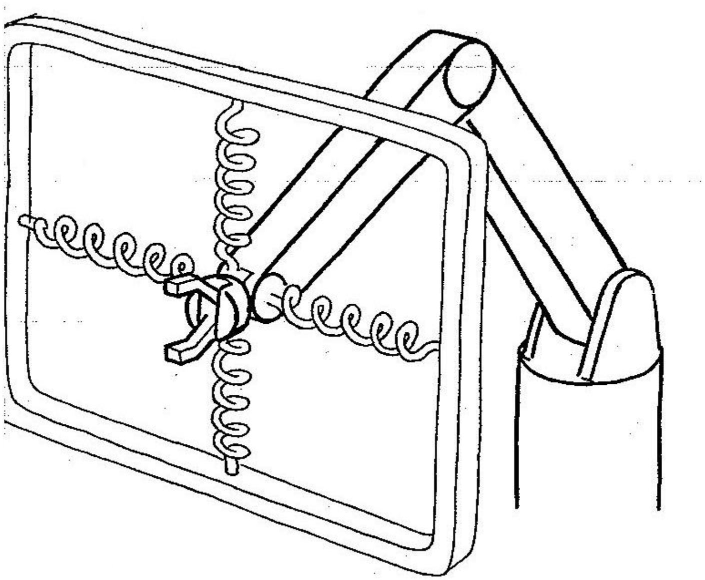
- Controlling a DOF in strict position or force control represent control at two ends of the servo stiffness
  - **Ideal position servo** is infinitely stiff $K = dF/dX = \infty$ and reject all force disturbance acting on the system
  - **Ideal force servo** exhibits zero stiffness $K = dF/dX = 0$ and maintain a desired force application regardless of the position disturbance.

Controlling variable		Stiffness
Position (P)	$P_d - P = 0$	$K = dF/dX = \infty$
Force (F)	$F_d - F = 0$	$K = dF/dX = 0$

Impedance Control



Virtual Springs



Impedance Control for Soft Robots

Manipulability – Human Arm Posture - Writing

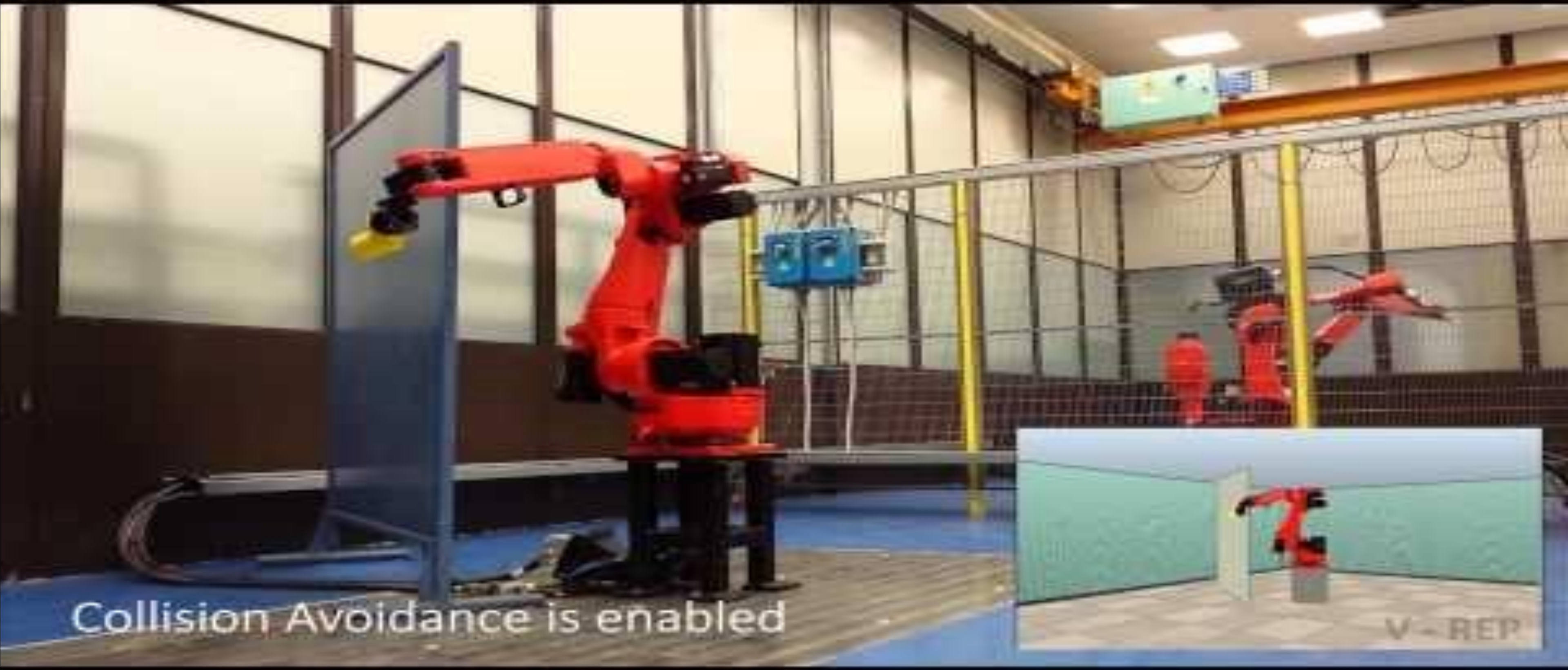
- Arm posture during writing
  - Elbow joint angle – 90 Deg
- Human arm model (writing)
  - 2 DOF
  - Two links (equal length)
- Manipulability is maximized when the Elbow joint angle is set to 90 Deg
  - Maximizing joint angles (shoulder /elbow) to end effector (hand) velocity transformation

Redundant Manipulators

- Task Definition - Position (3 DOF - x, y, z) and orient the end effector (3 DOF - $\theta_{pitch}, \theta_{roll}, \theta_{yaw}$) in is a 3D space (6 DOF)

- No. of DOF (6 DOF) = No. of DOF of the task (6 DOF)
  – Limited number of multiple solutions

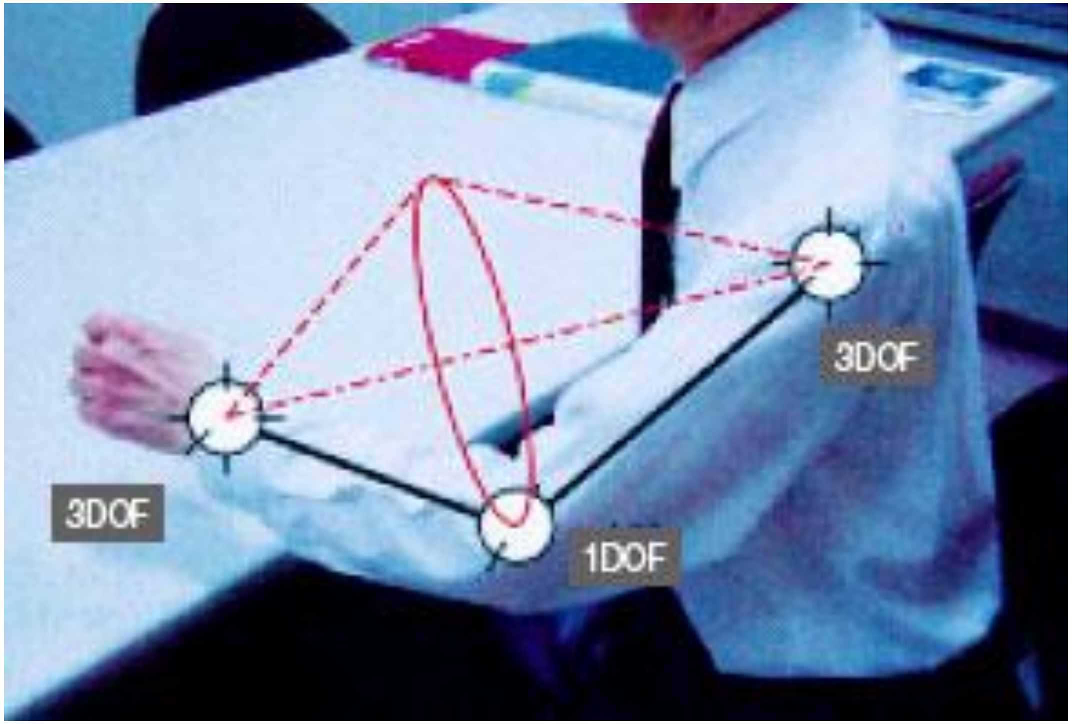
- No. of DOF (e.g. 7 DOF) > No. of DOF of the task (6 DOF)
  – Number of solution: ∞ (adding more equations)
  – Self Motion - The robot can be moved without moving the the end effector from the goal



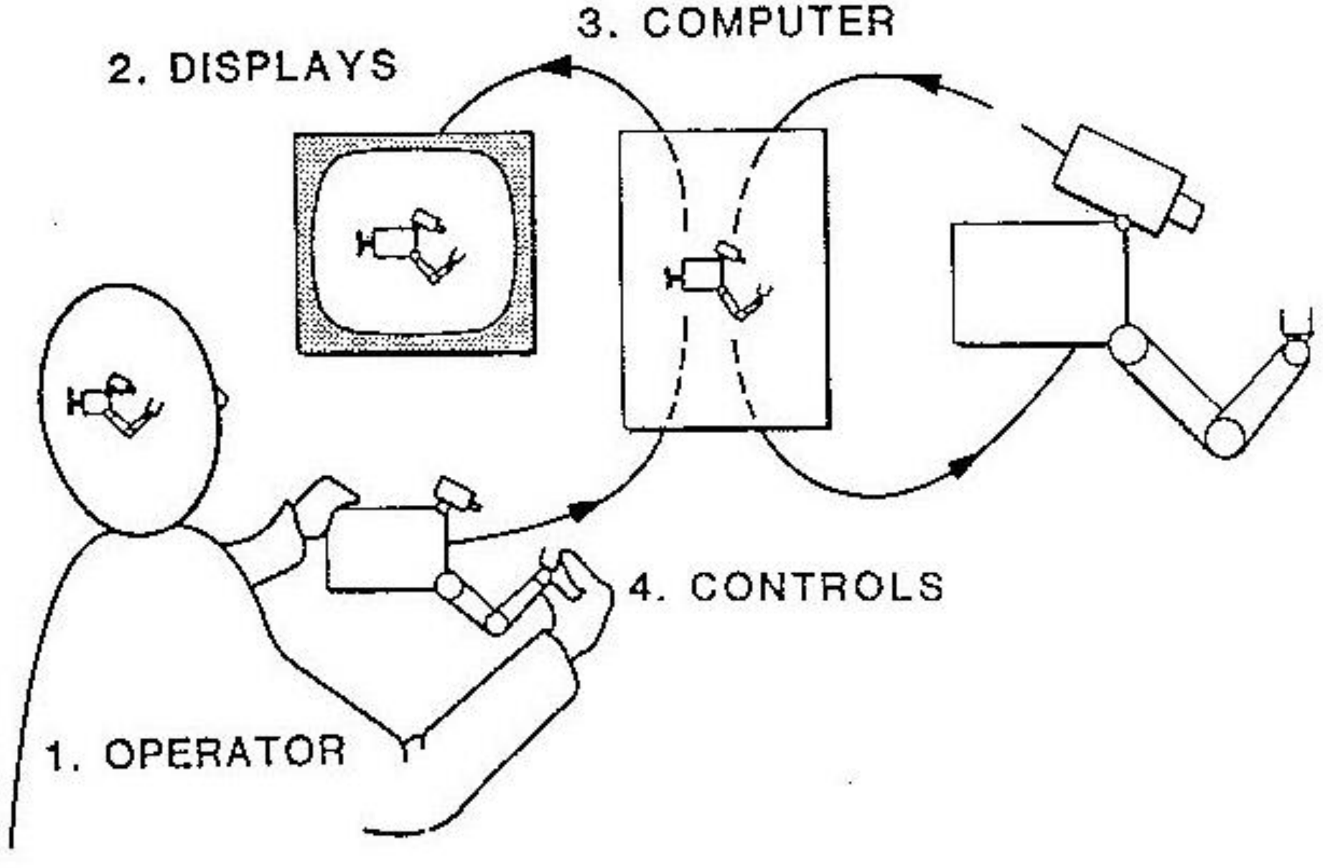
Collision avoidance: tests with a 7-dof redundant robot and a static obstacle

KUKA - Kinematic Redundancy

Redundant Manipulators – Human Arm



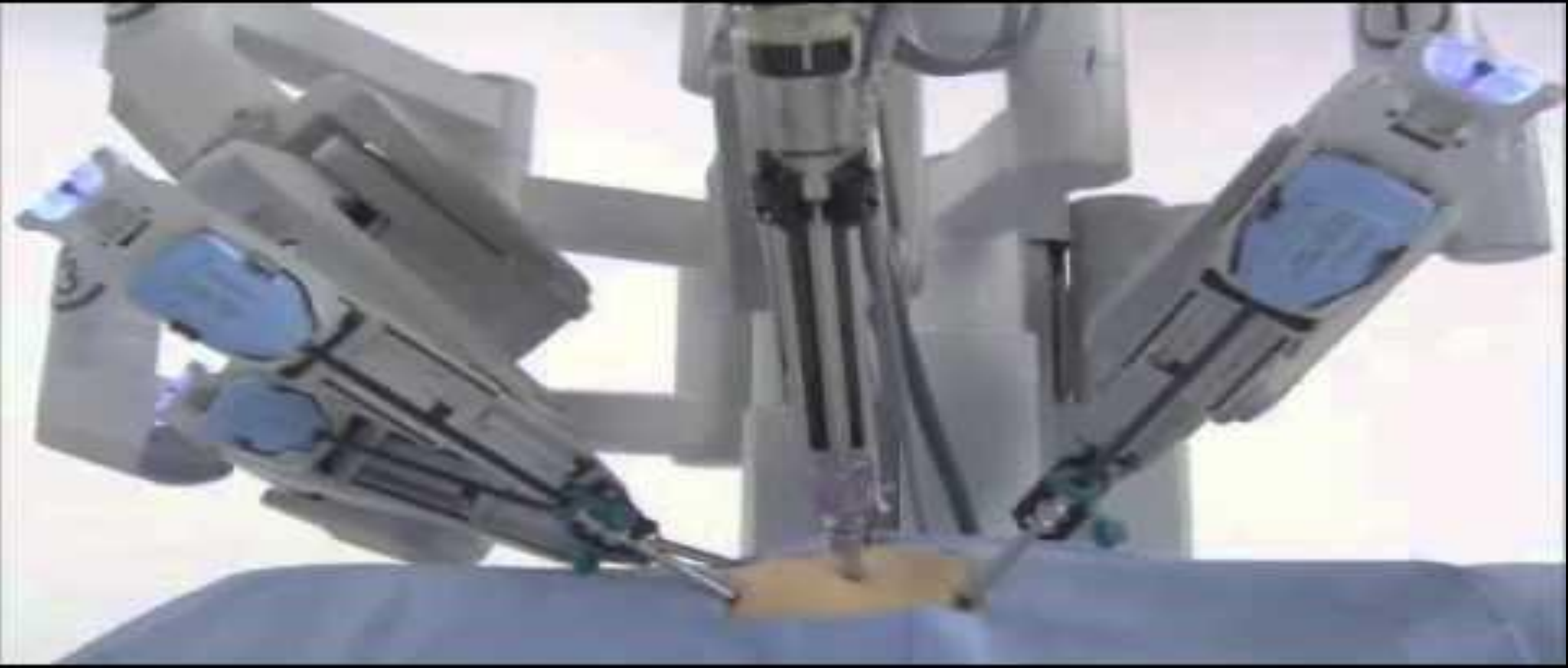
Teleoperation



Surgical robot teleoperation with BBZ console

Teleoperation

Video Hyperlink



da Vinci® Surgery - How It Works

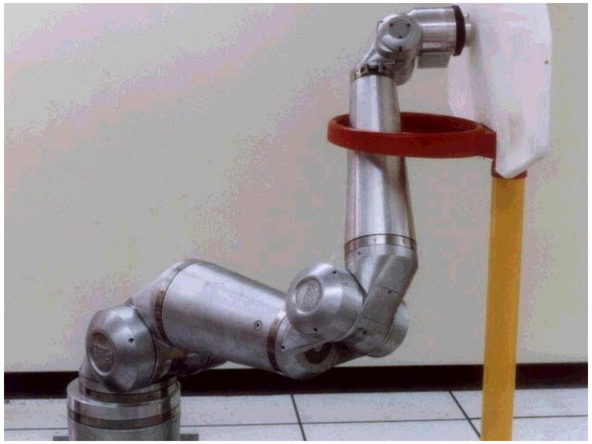
Kinematic Chain - Joint / Link - Definition

Kinematic Chain consists of nearly rigid *links (members)* which are connected with *joints (kinematics pair)* allowing relative motion of the neighboring links.

Closed Loop Chain - Every link in the kinematic chain is connected to any other link by at least two distinct paths

Open Loop Chain - Every link in the kinematic chain is connected to any other link by one and only one distinct path

Parallel (Close Loop) Robot



Serial (Open Loop) Robot Video Hyperlink

Parallel Robot – Gough-Stewart Platform – Thomas FX Motion Base

Parallel Robot – Gough-Stewart Platform - Adept Quattro Robot handling steel balls on conveyor

Close Chain Manipulators - DOF

- DOF of close chain manipulator – Grubler's formula

$$F = 6(l - n - 1) + \sum_{i=1}^{n} f_i$$

  - F - The total number of DOF in the mechanism
  - l - The number of links (including the base and the platform)
  - n - Total number of joints
  - f_i - The number of DOF associated with the i'th joint

- Example – Stewart Platform

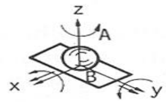
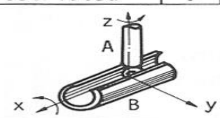
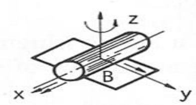
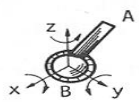
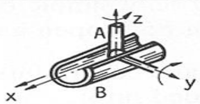
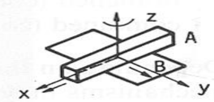
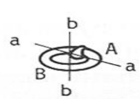
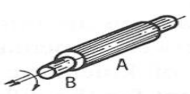
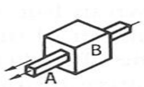
$$F = 6(14 - 18 - 1) + \sum_{i=1}^{6} 6 = 6$$

Close Chain Manipulators - Gough-Stewart Platform

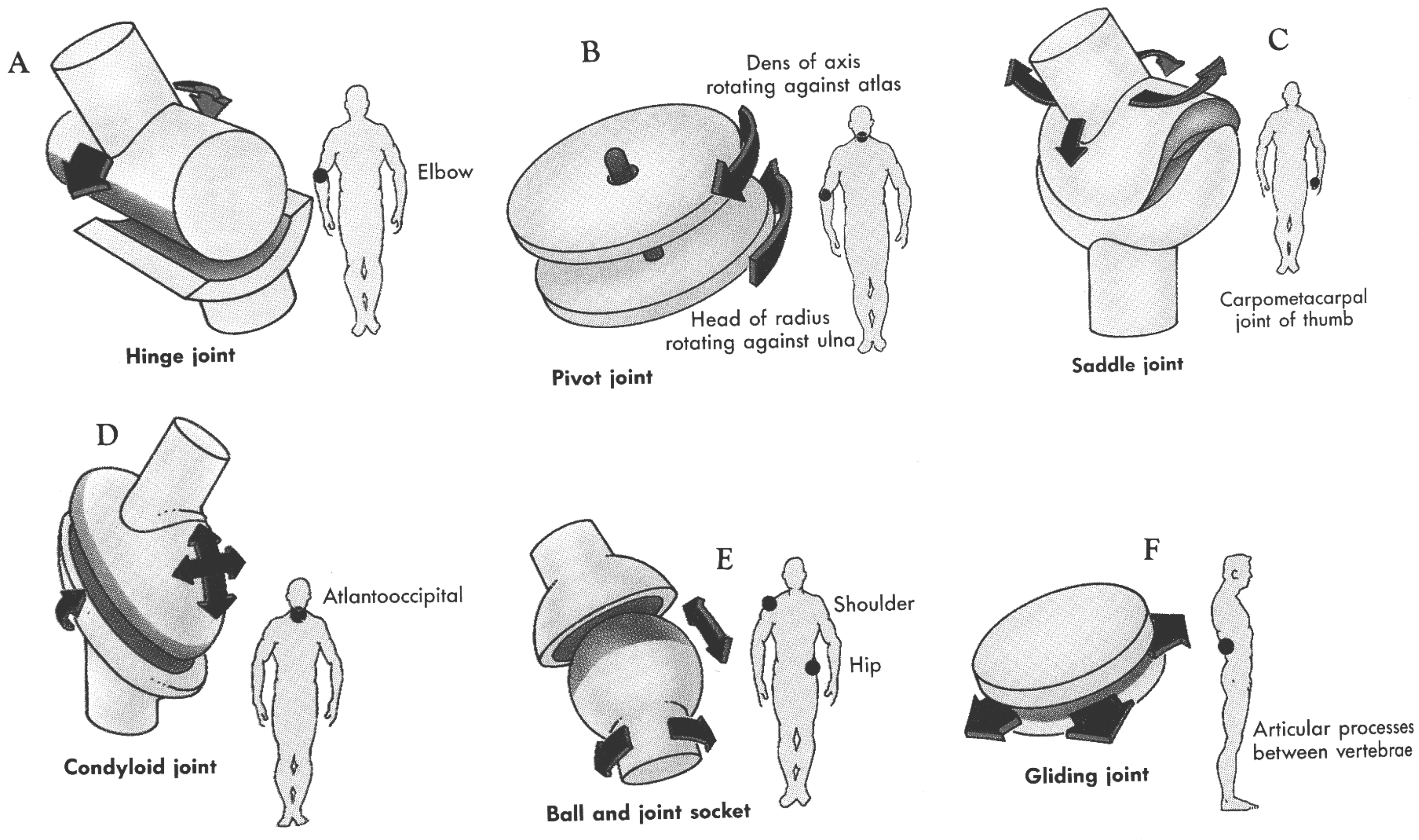
Parallel Robot – Gough-Stewart Platform - A320 Full Flight Simulator – Part I

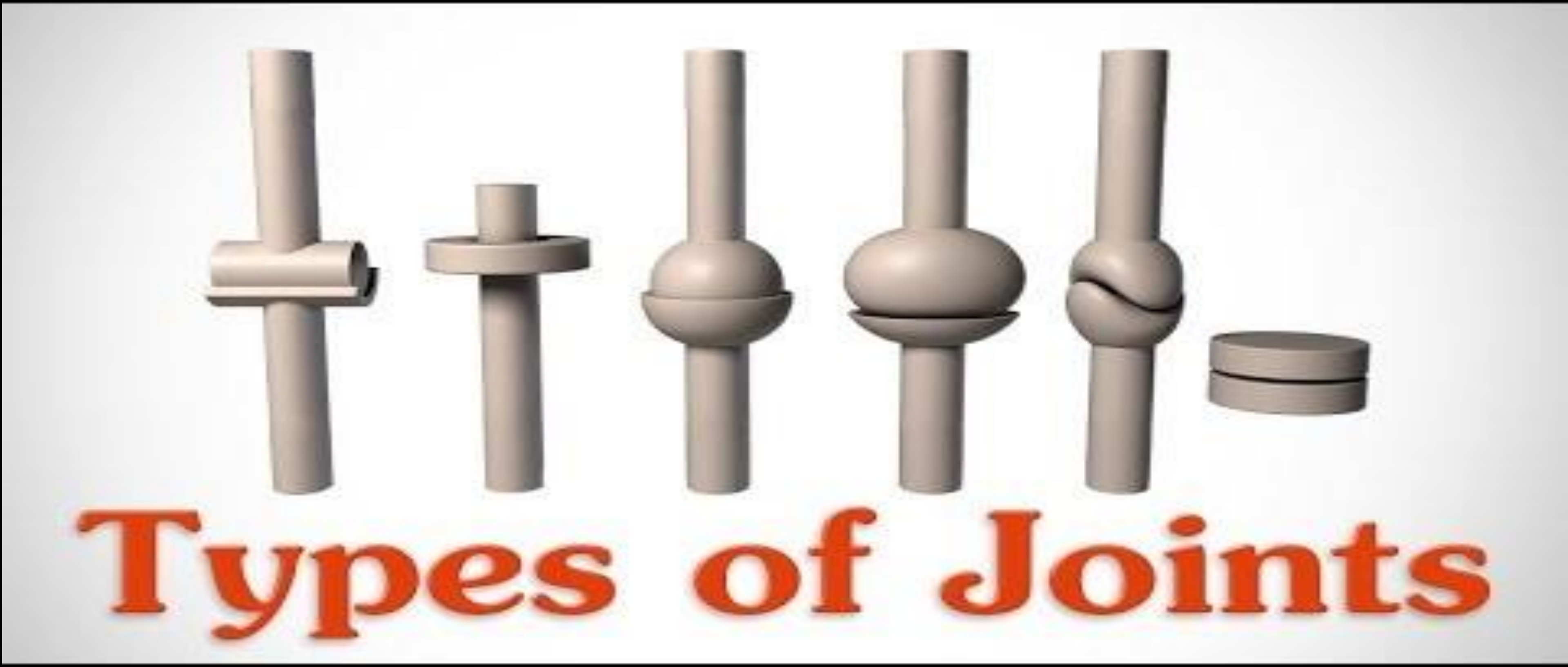
Parallel Robot – Gough-Stewart Platform - A320 Full Flight Simulator – Part II

Joint Classification

class of task	nr. of links	nr. of d.o.f.	TYPES OF PAIRS I	TYPES OF PAIRS II	TYPES OF PAIRS III
I	1	5	nr. of movem. / rot. / lin. allowed / 3 / 2 restricted / 0 / 1 		
II	2	4	nr. of movem. / rot. / lin. allowed / 3 / 1 restricted / 0 / 2 	nr. of movem. / rot. / lin. allowed / 2 / 2 restricted / 1 / 1 	
III	3	3	nr. of movem. / rot. / lin. allowed / 3 / 0 restricted / 0 / 3 	nr. of movem. / rot. / lin. allowed / 2 / 1 restricted / 1 / 2 	nr. of movem. / rot. / lin. allowed / 1 / 2 restricted / 2 / 1 
IV	4	2	nr. of movem. / rot. / lin. allowed / 2 / 0 restricted / 1 / 3 	nr. of movem. / rot. / lin. allowed / 1 / 1 restricted / 2 / 2 	
V	5	1	nr. of movem. / rot. / lin. allowed / 1 / 0 restricted / 2 / 3 	nr. of movem. / rot. / lin. allowed / 0 / 1 restricted / 3 / 2 	

Synovial (Anatomical) Joints





The 6 Types of Joints - Human Anatomy

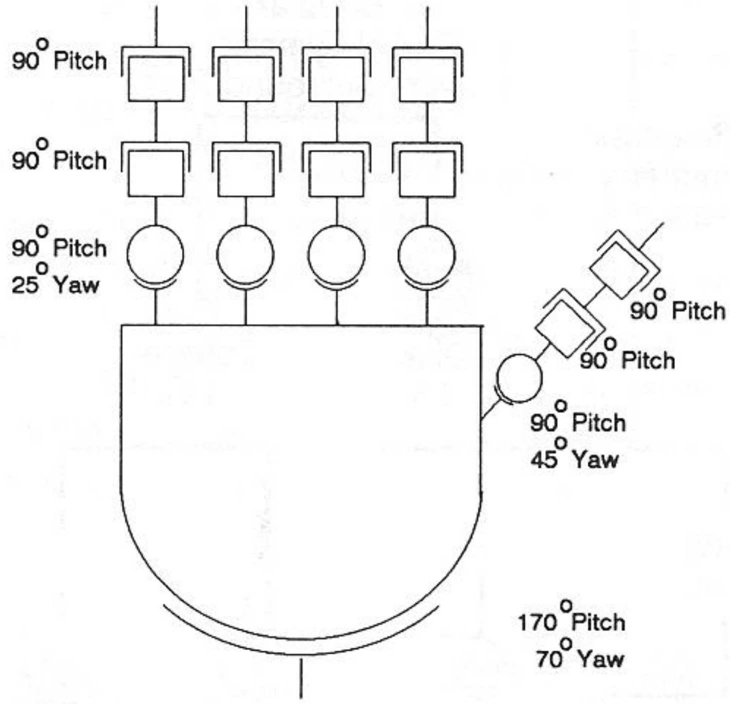
Degrees of Freedom (DOF)

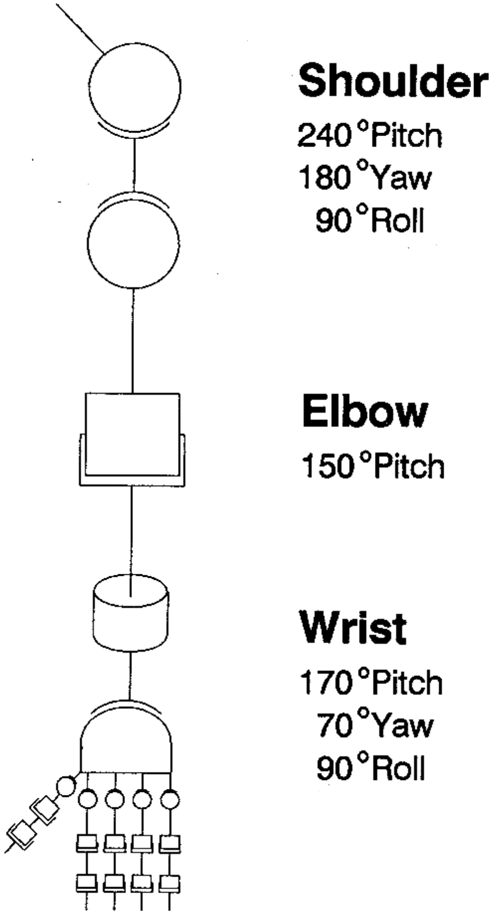
The number of ***Degree of Freedom*** that a manipulator possesses is the number independent position variable which would have to be specified in order to locate all parts of the mechanism.

Ideally, a manipulator should poses 6 DOF in order to manipulate an object in a 3D space

- **General Purpose Robot** - # DOF = 6
- **Redundant Robot** - # DOF >7
- **Deficient Robot** - # DOF < 6

Human Arm - DOF





Workspace - Definition

- **Workspace** - The volume of space that the end-effector can reach

- **Dexterous Workspace** - The volume of the space which every point can be reach by the end effector in all possible orientations.

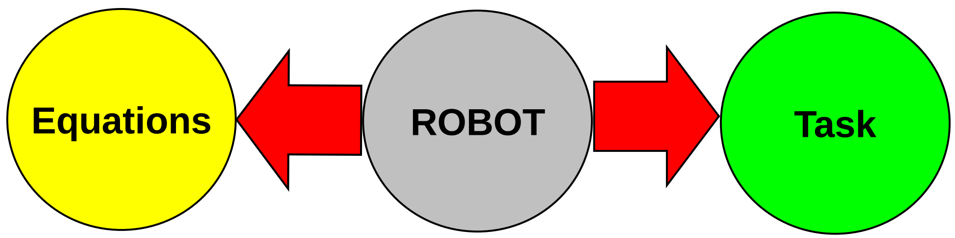
- **Reachable Workspace** - The volume of the space which every point can be reach by the end effector in at least one orientation.

Jointed Spherical Arm Geometry (Articularted)

Manipulator Mechanical Design

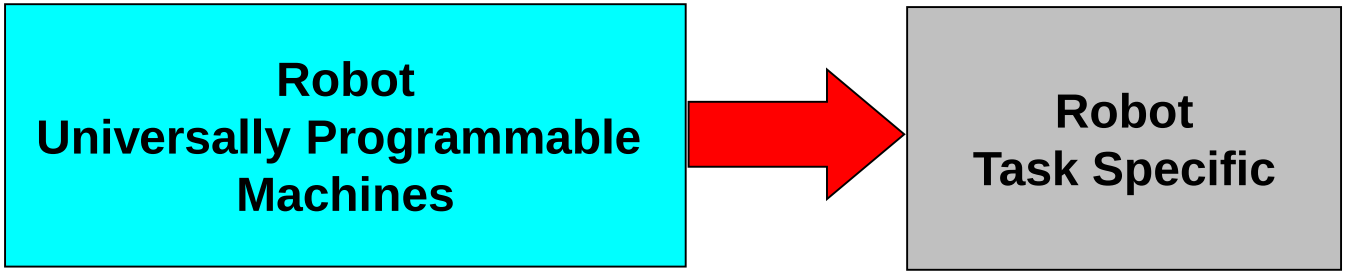
- **Particular structure of a manipulator influences the kinematic and dynamic analysis**

- **The tasks that a manipulator can perform will also very greatly with a particular design (load capacity, workspace, speed, repeatability)**



- **The elements of a robotic system fall roughly into four categories**
  - The manipulator mechanism, actuation, and proprioceptive sensors
  - The end-effector or end of the arm tooling
  - External sensors (e.g. vision system) or effectors (e.g. part feeders)
  - The Controller

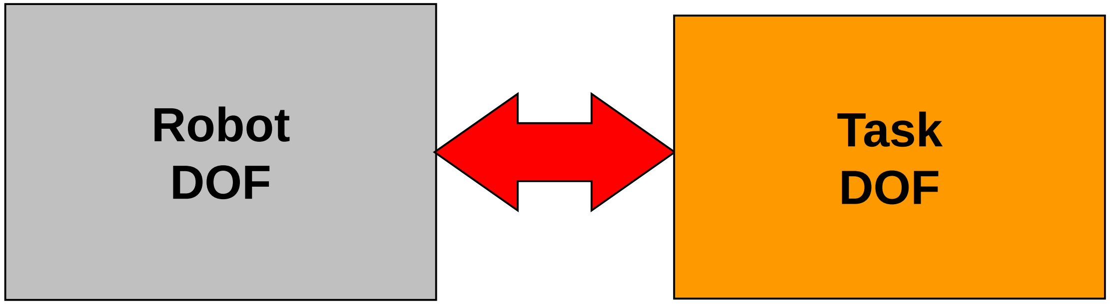
Manipulator Mechanical Design - Task Requirements



- **General Definition for Robot** - "A re-programmable, multifunctional mechanical manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks."-- From the Robot Institute of America, 1979
- **Task Specific Design Criteria**
  - Number of degrees of freedom
  - Workspace
  - Load capacity
  - Speed
  - Repeatability accuracy

Task Requirements - Number of DOF

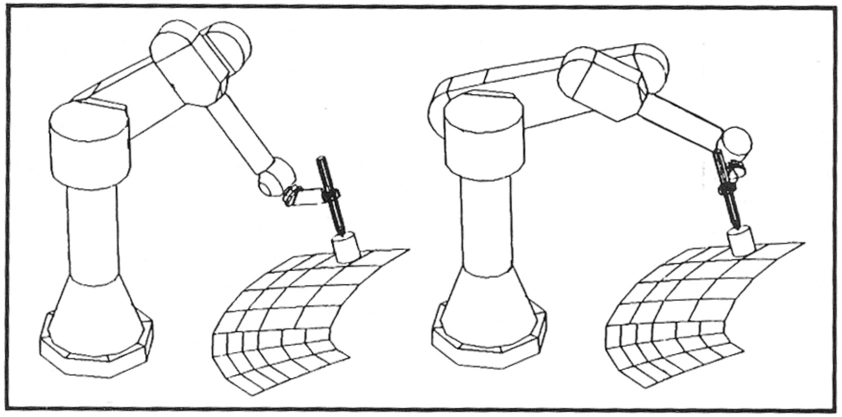
- The number of DOF in a manipulator should match the number of DOF required by the task.

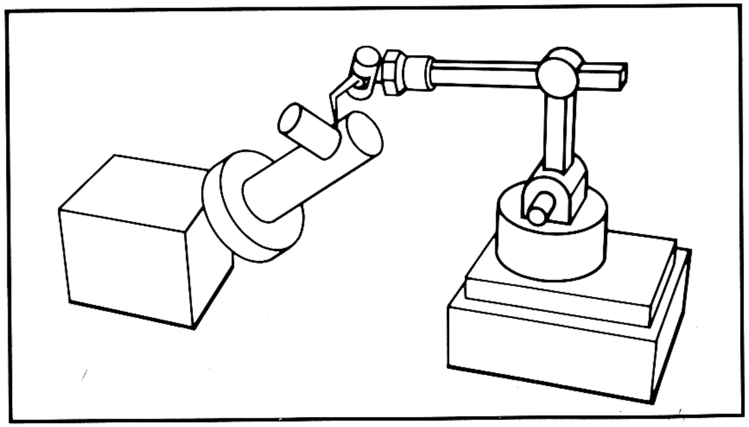


Task Requirements

- **Not all the tasks required 6 DOF for example:**
  - End effector with an axis of symmetry - Orientation around the axis of symmetry is a free variable,
  - Placing of components on a circuit board - 4 DOF x, y, z, θ

- **Dividing the total number of DOF between a robot and an active positioning platform**





Robotic Welding - Panasonic VR-6 Robots in PerformArc 350 Workcell

Kawasaki Robot-Painting Robots

Task Requirements

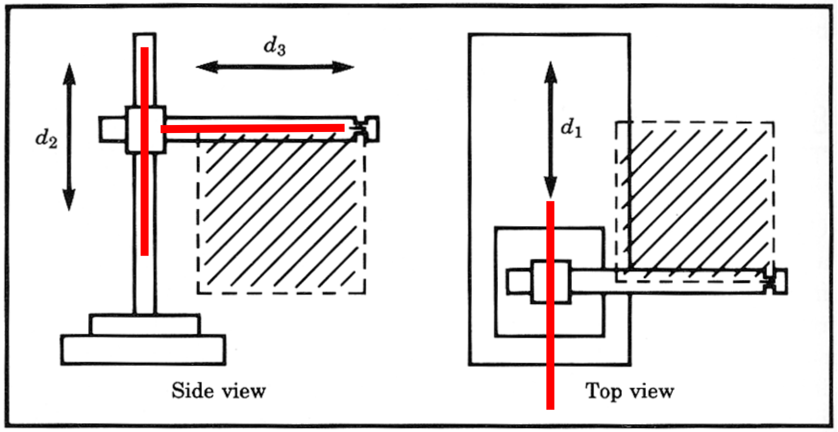
- **Workspace (Work volume, Work envelope)**
  - Placing the target (object) in the work space of the manipulator
  - Singularities
  - Collisions
- **Load Capacity**
  - Size of the structural members
  - power transmission system
  - Actuators
- **Speed**
  - Robotic solution compete on economic solution
  - Process limitations - Painting, Welding
  - Maximum end effector speed versus cycle time
- **Repeatability & Accuracy**
  - Matching robot accuracy to the task (painting - spray spot 8 +/-2 ")
  - Accuracy function of design and manufacturing (Tolerances)

Kinematic Configuration

- **Joints & DOF** -
  - For a serial kinematic linkages, the number of joints equal the required number of DOF
- **Overall Structure**
  - Positioning structure (link twist 0 or +/- 90 Deg, 0 off sets)
  - Orientation structure
- **Wrist**
  - The last *n-3 joints orient the end effector*
  - *The rotation axes intersect at one point.*

Kinematic Configuration - Cartesian

- **Joints**
  - Joint 1 - Prismatic
  - Joint 2 - Prismatic
  - Joint 3 - Prismatic

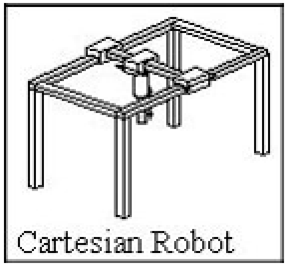


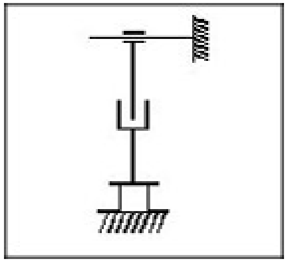
- **Inverse Kinematics** - Trivial

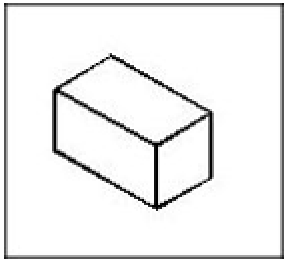
- **Structure -**
  - Stiff Structure -> Big Robot
  - Decoupled Joints - No singularities

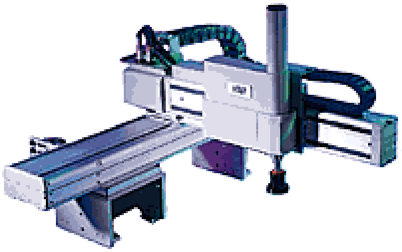
- **Disadvantage**
  - All feeder and fixtures must lie “inside” the robot

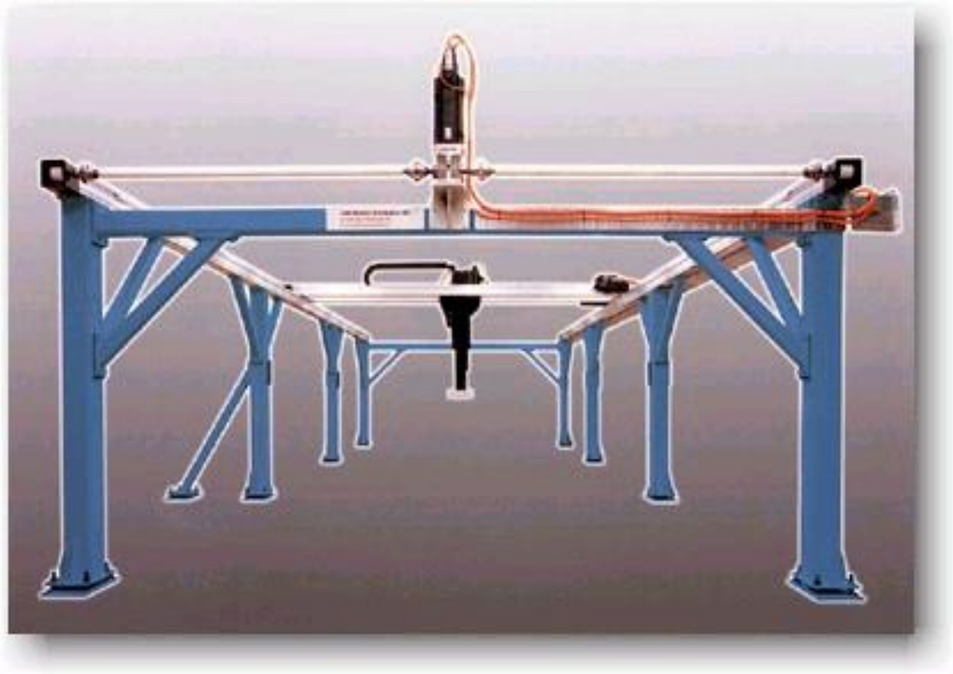
Kinematic Configuration - Cartesian







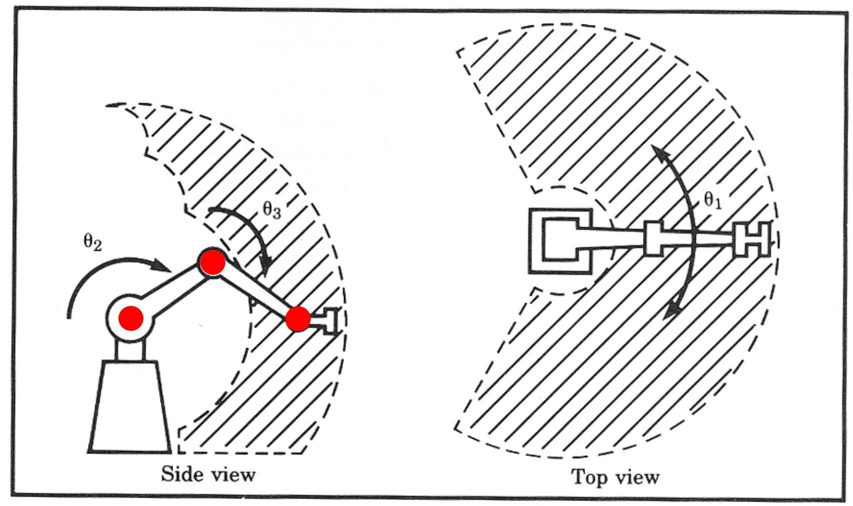




Gantry

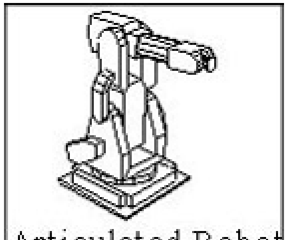
Gantry Robot - Solid surface countertop stacking

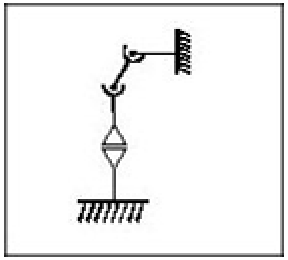
Kinematic Configuration - Articulated

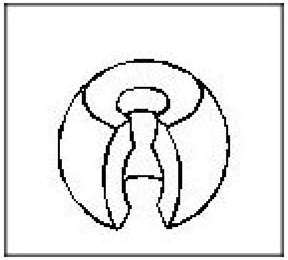


- **Joints**
  - Joint 1 - Revolute -Shoulder
  - Joint 2 - Revolute - Elbow
  - Joint 3 - Revolute - Wrist
- **Workspace**
  - Minimal intrusion
  - Reaching into confine spaces
  - Cost effective for small workspace
- **Examples**
  - PUMA
  - MOTOMAN

Kinematic Configuration - Articulated


Articulated Robot



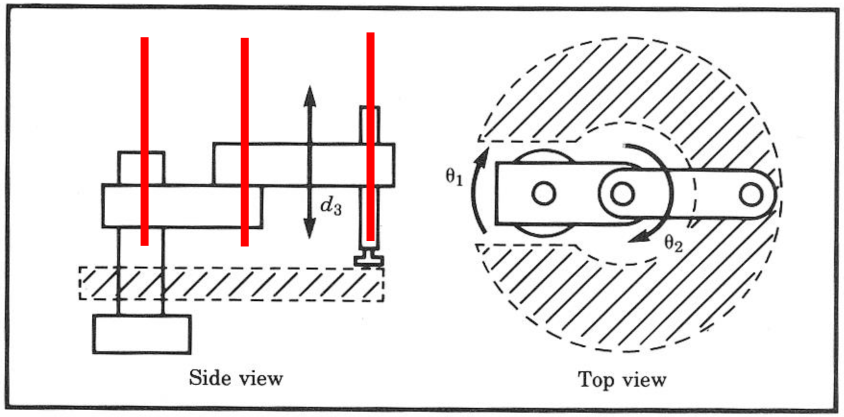


Video Clip

Fanuc – Full Human Body

Kinematic Configuration - SCARA

- **Joints**
  - Joint 1 - Revolute
  - Joint 2 - Revolute
  - Joint 3 - Revolute
  - Joint 4 - Prismatic
  - Joint 1,2,3 - In plane

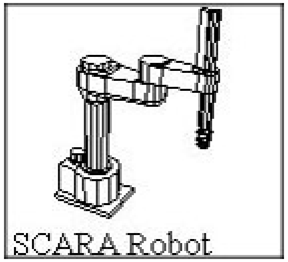


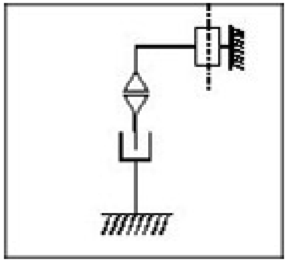
- **Structure**
  - Joint 1,2,3, do not support weight (manipulator or weight)
  - Link 0 (base) can house the actuators of joint 1 and 2

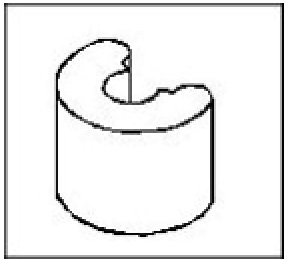
- **Speed**
  - High speed (10 m/s), 10 times faster then the most articulated industrial robots

- **Example** - SCARA (Selective Compliant Assembly Robot Arm)

Kinematic Configuration - SCARA



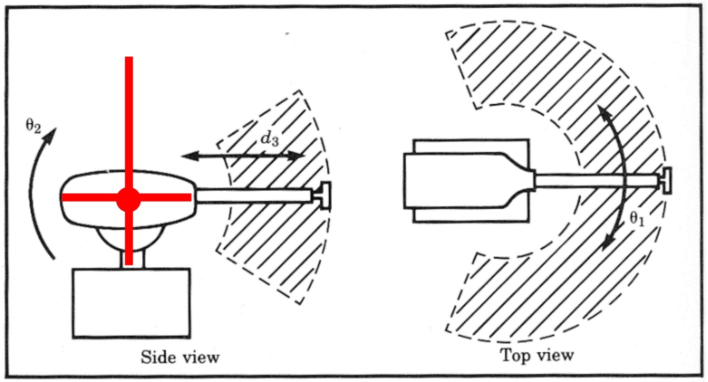




Kawasaki Robot-Painting Robots

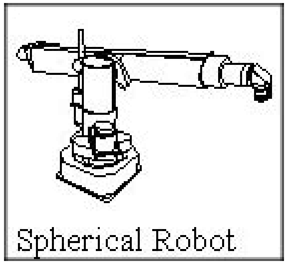
Kinematic Configuration - Spherical

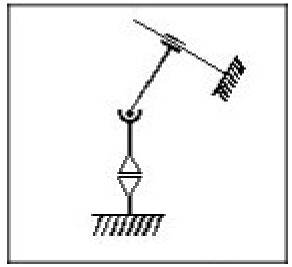
- **Joints**
  - Joint 1 - Revolute (Intersect with 2)
  - Joint 2 - Revolute (Intersect with 1)
  - Joint 3 - Prismatic

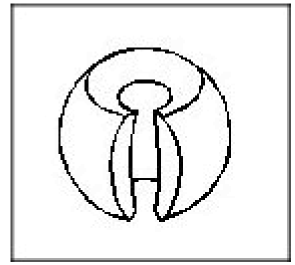


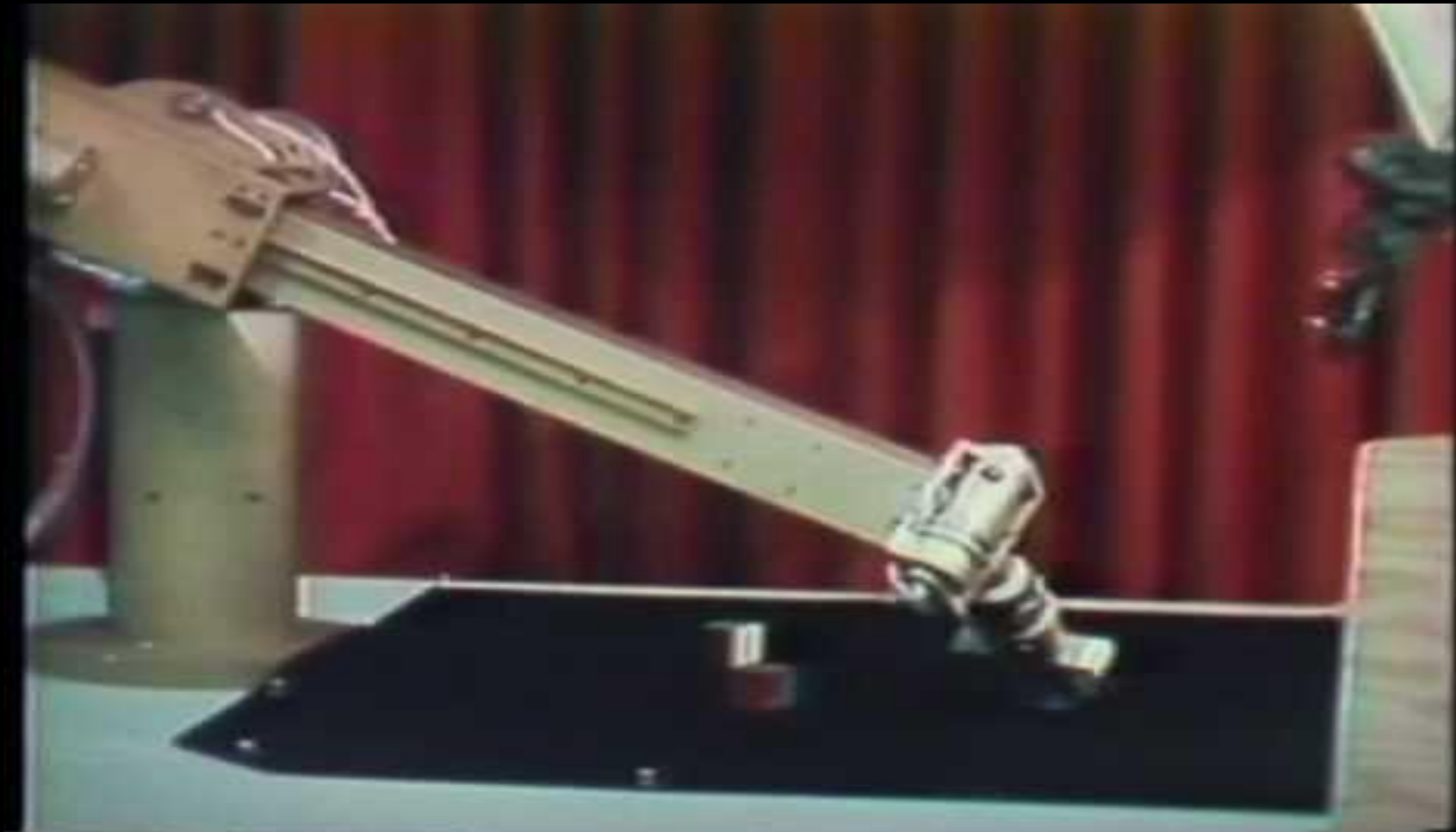
- **Structure**
  - The elbow joint is replaced with prismatic joint
  - Telescope

Kinematic Configuration - Spherical





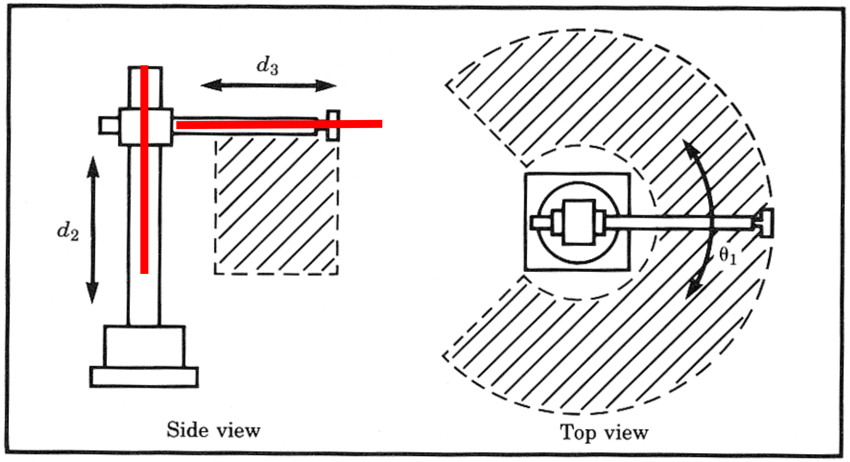




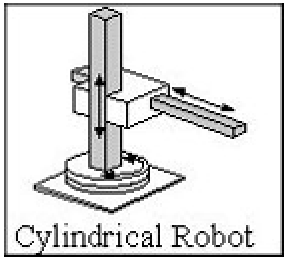
Stanford Arm

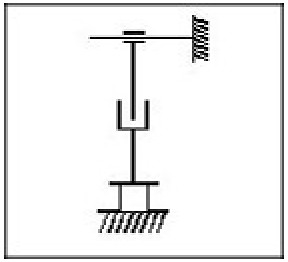
Kinematic Configuration - Cylindrical

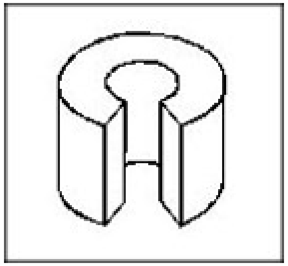
- **Joints**
  - Joint 1 - Revolute
  - Joint 2 - Prismatic
  - Joint 3 - Prismatic

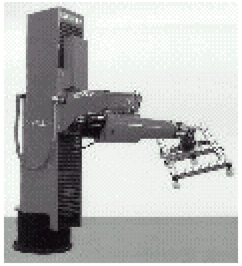


Kinematic Configuration - Cylindrical

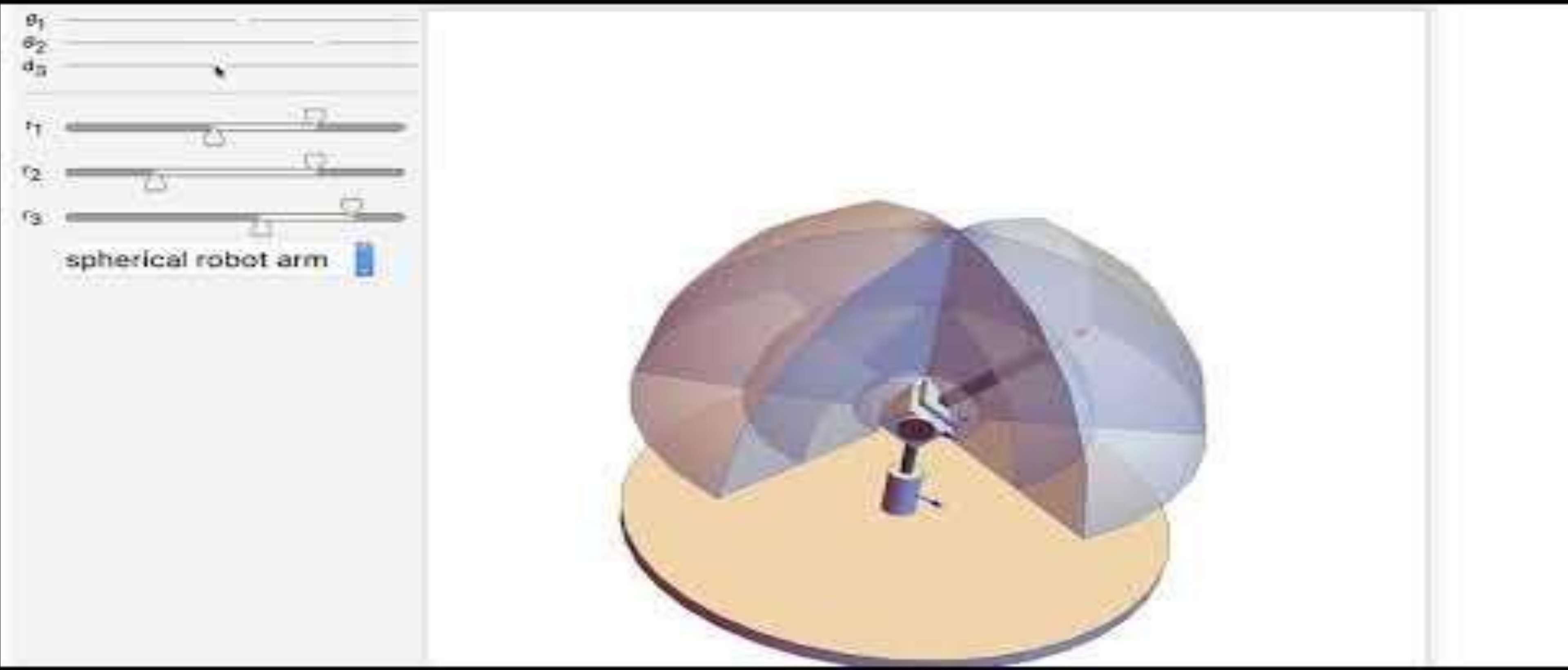








Robotic Arm Geometry



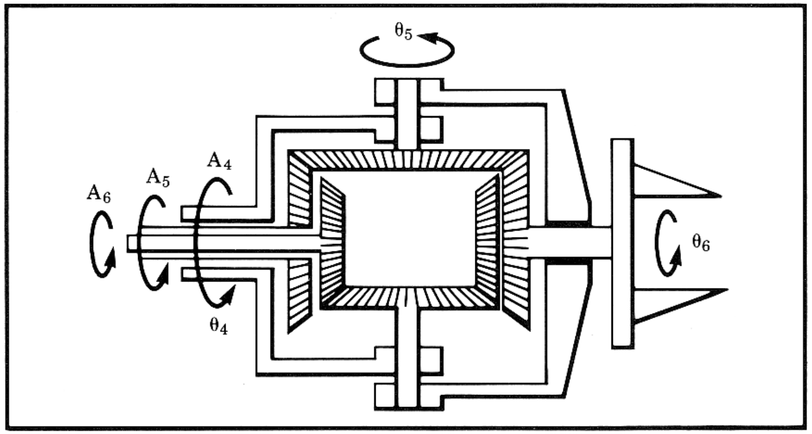
Robotic Arm Geometry

Kinematic Configuration - Wrist

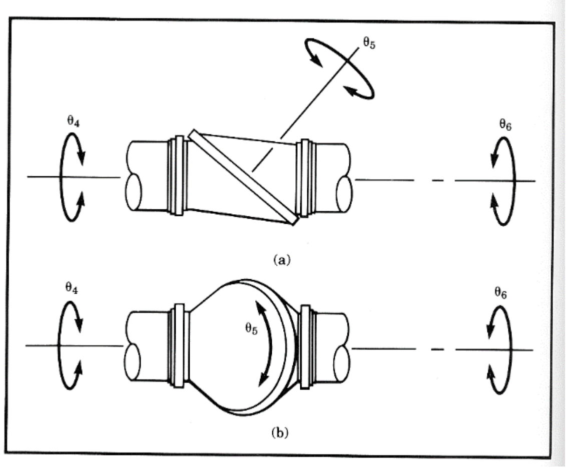
- **Joints**
  - Three (or two) joints with orthogonal axes
- **Workspace**
  - Theoretically - Any orientation could be achieved (Assuming no joint limits)
  - Practically - Severe joint angle limitations
- **Kinematics**
  - Closed form kinematic equations

Kinematic Configuration - Wrist

- Three intersecting orthogonal Axes
  Bevel Gears Wrist
- Limited Rotations

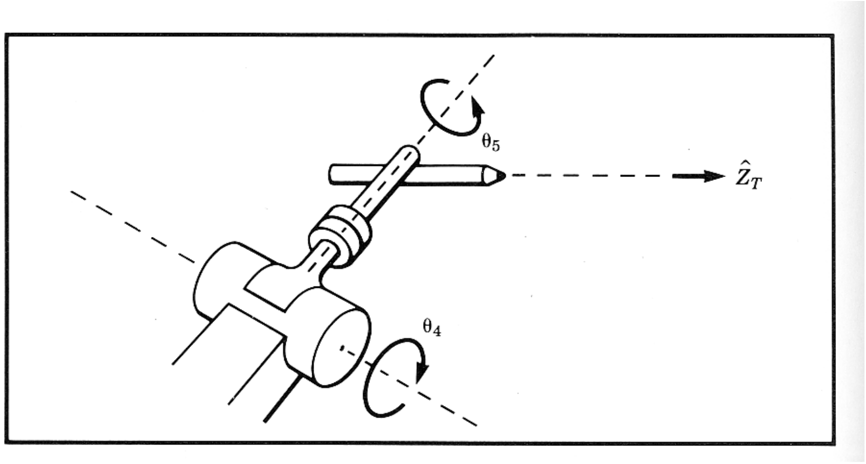


- Three Roll Wrist (Cincinatti Milacron)
- Three intersecting non-orthogonal Axes
- Continues joint rotations (no limits)
- Sets of orientations which are impossible to reach



Kinematic Configuration - Wrist

- 5 DOF Welding robot (2 DOF wrist) - Symmetric tool
- The tool axis $\hat{Z}_T$ is mounted orthogonal to axis 5 in order to reach all possible orientations



Video Clip

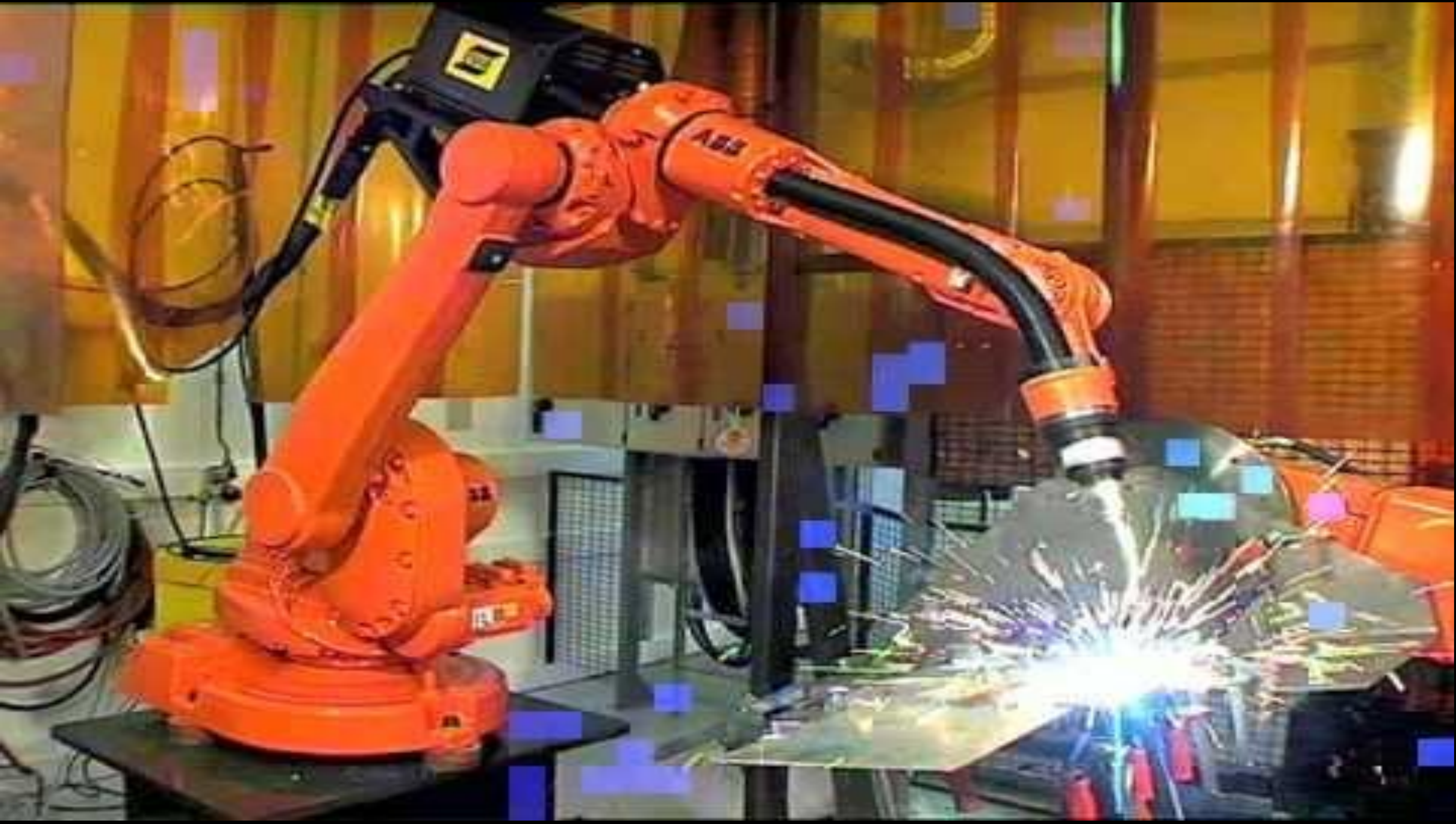
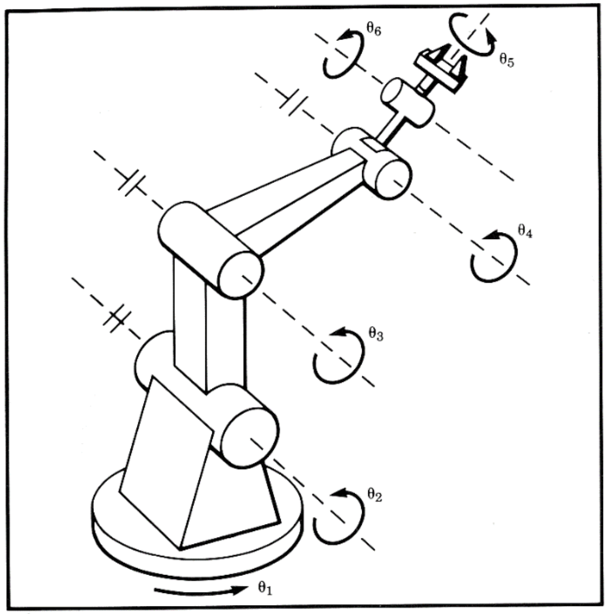


ABB Robotics - Arc Welding

Kinematic Configuration - Wrist

- **Non intersecting axes wrist**
- A closed form inverse kinematic solution may not exist

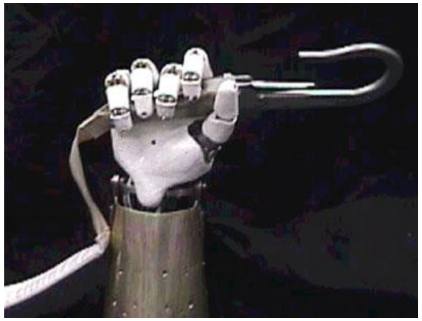
- **Special Cases** (Existing Solution)
  - Articulated configuration
    Joint axes 2,3,4 are parallel
  - Cartesian configuration
    Joint axes 4,5,6 do not intersect



Kuka KR 500 wrist mechanics - Axis 4, 5 & 6

End Effector (EE)

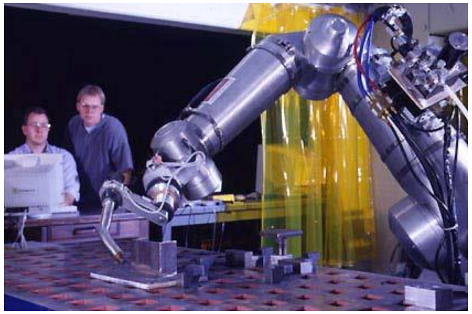
At the free end of the chain of links which make up the manipulator is the end effector. Depending on the intended application of the robot the end effector may be a gripper welding torch, electromagnet or other tool.



ROBONAUT - Hand (NASA)

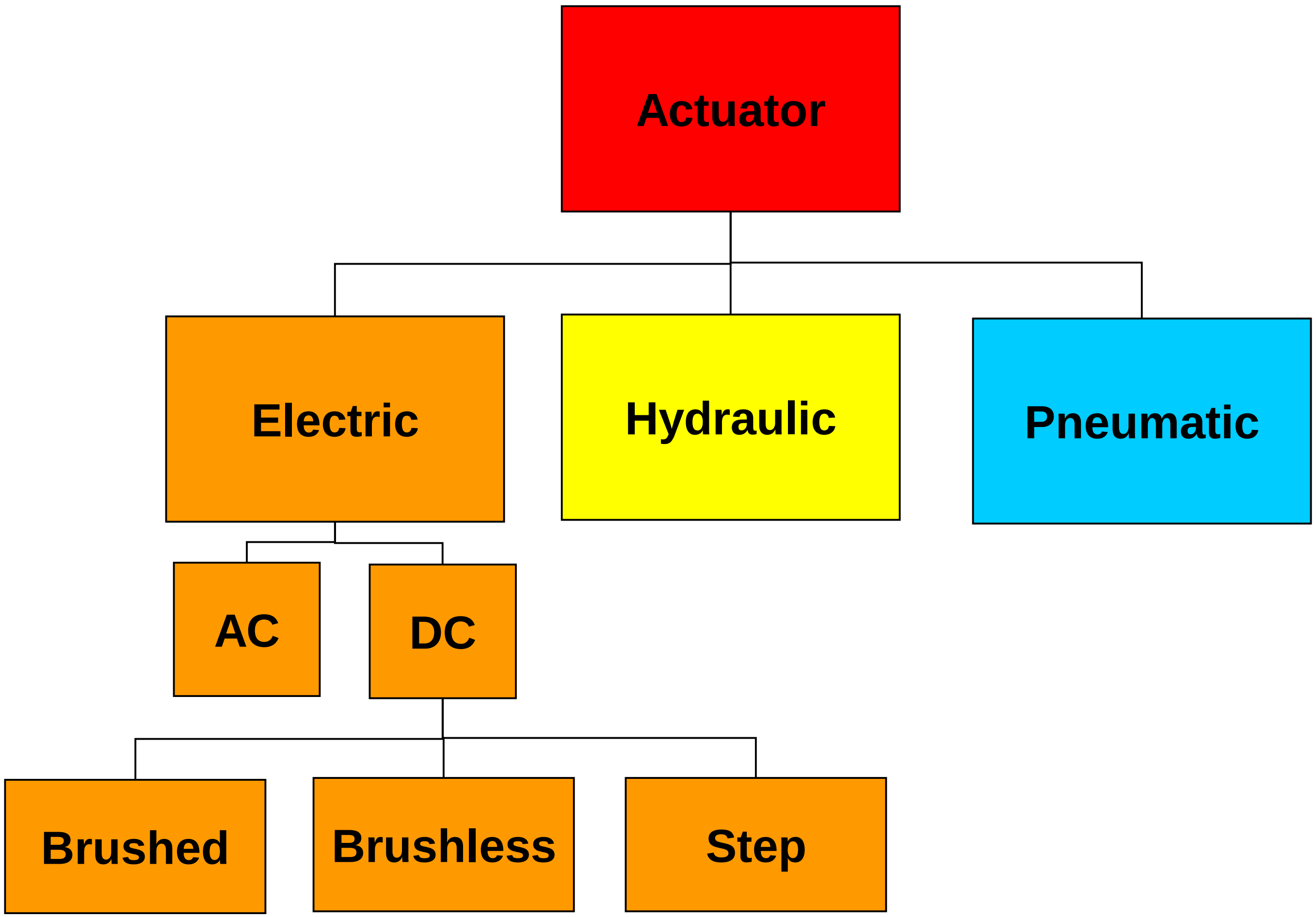
Stanford / JPL- Hand (Salsilbury)

Utha / MIT Hand

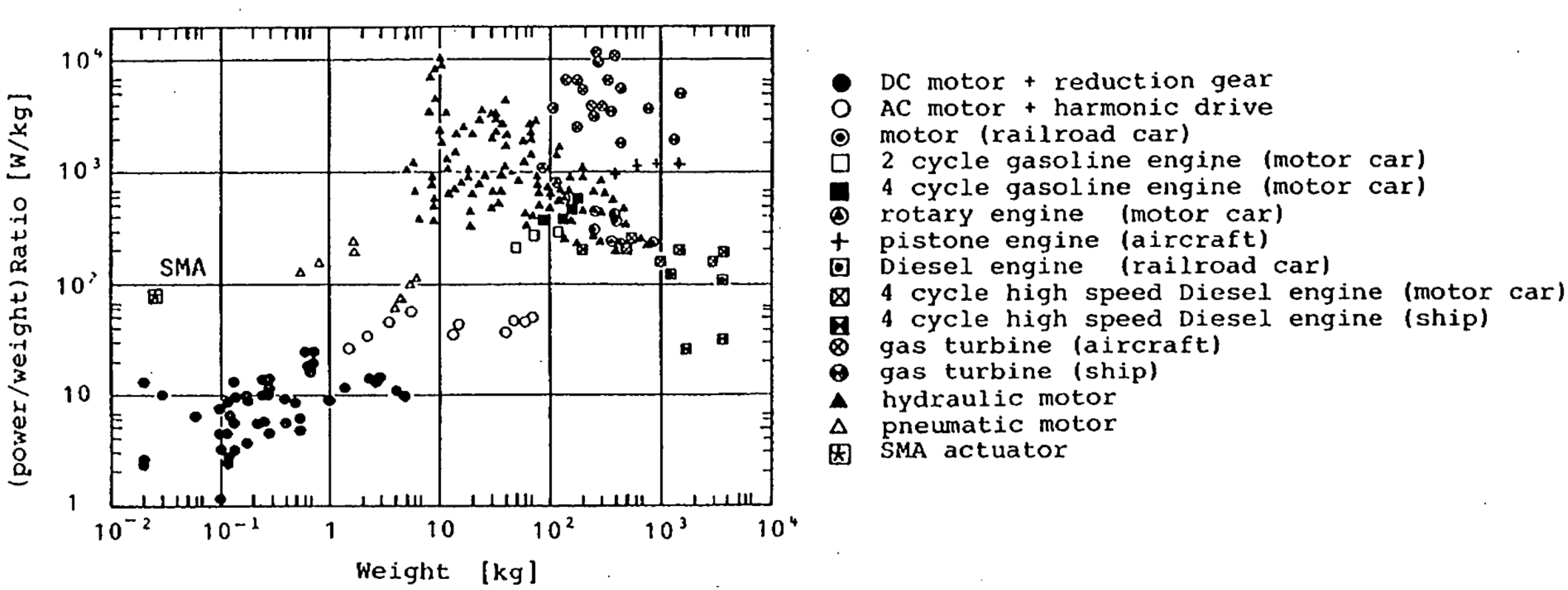


NIST - Advanced Welding Manufacturing System

Actuation

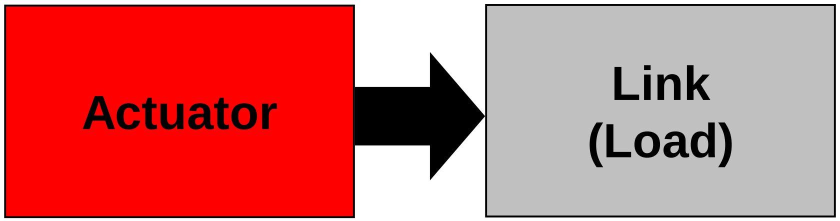

Actuator
Electric
Hydraulic
Pneumatic
AC
DC
Brushed
Brushless
Step

Actuation – Power to Weight Ratio

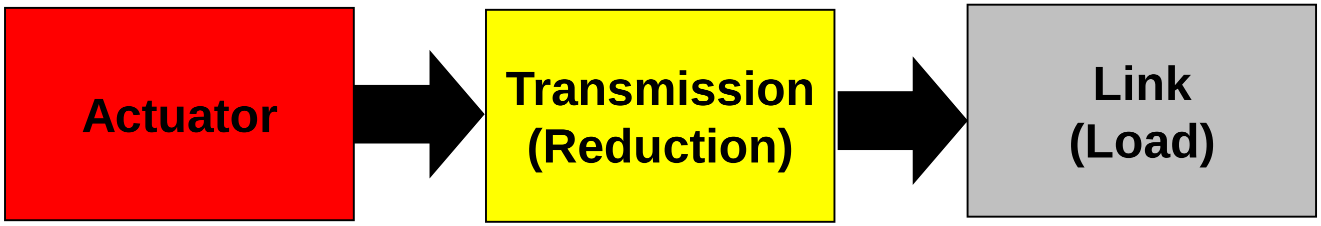


Actuation Schemes

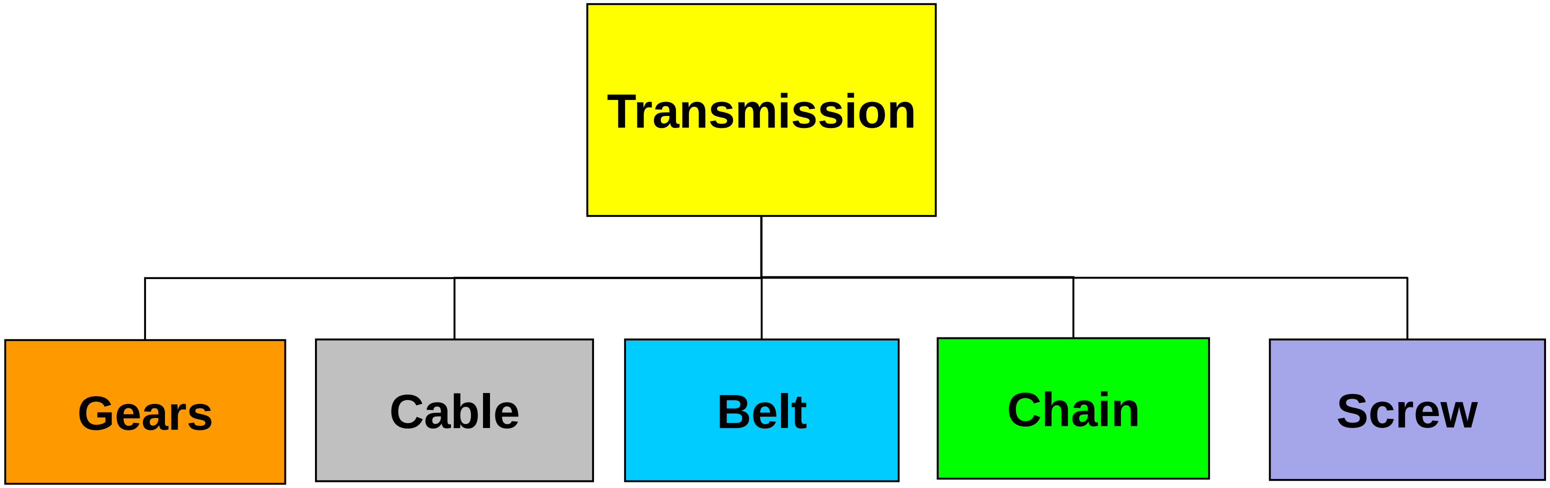
- Direct Drive

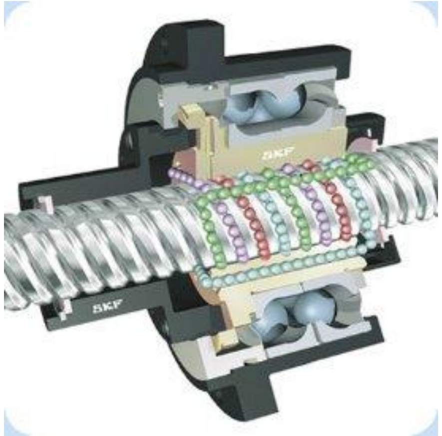


- Non Direct Drive



Reduction & Transmission Systems





Types of Gears

Super Gears

Helical Gears

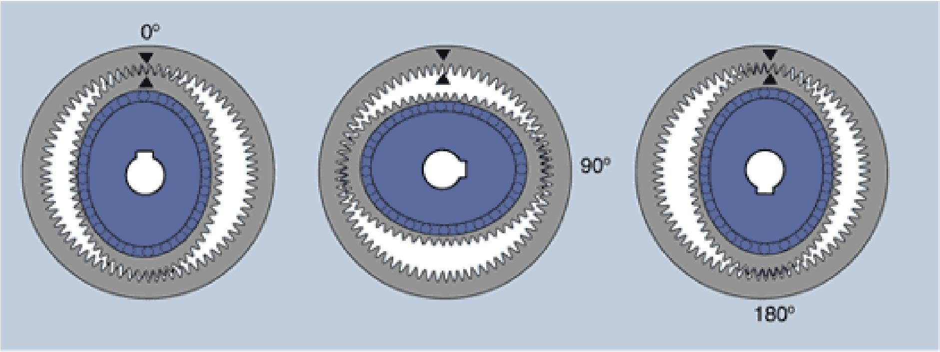
Rack & Pinion Gears

Bevel Gears

Hypoid Gears

Worm Gears

Gearbox / Gearhead



Harmonic Drive

Reduction & Transmission Systems

$$\mu \, P_{in} = P_{out}$$

$$\mu \, T_{in} \omega_{in} = T_{out} \omega_{out}$$

$$\frac{T_{out}}{\mu \, T_{in}} = \frac{\omega_{in}}{\omega_{out}} = n \qquad (n > 1)$$

$$\mu \approx 0.5 - 0.9$$

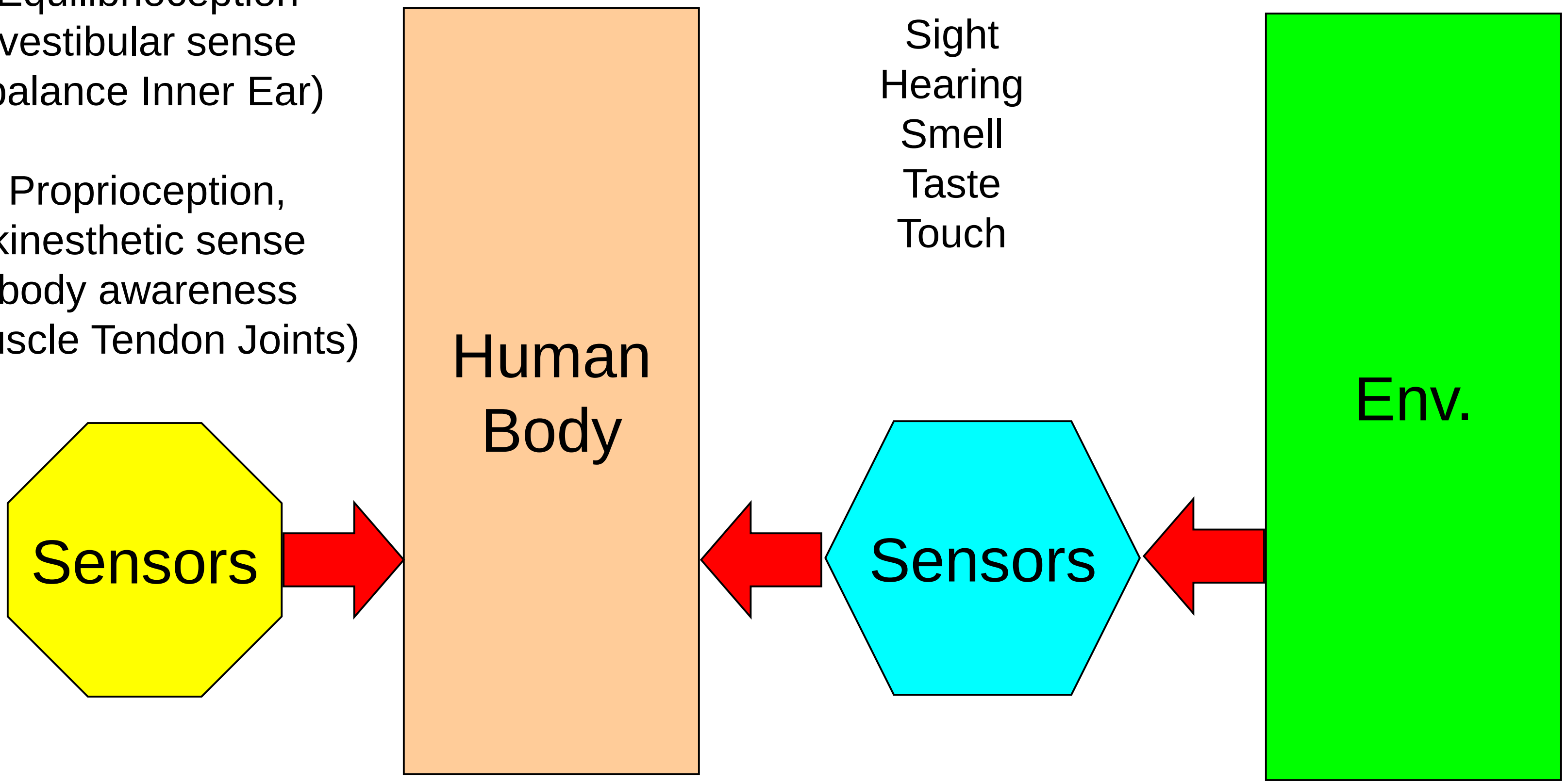
Limiting Factors ω_{in}, T_{out}

Sensors – Human Body

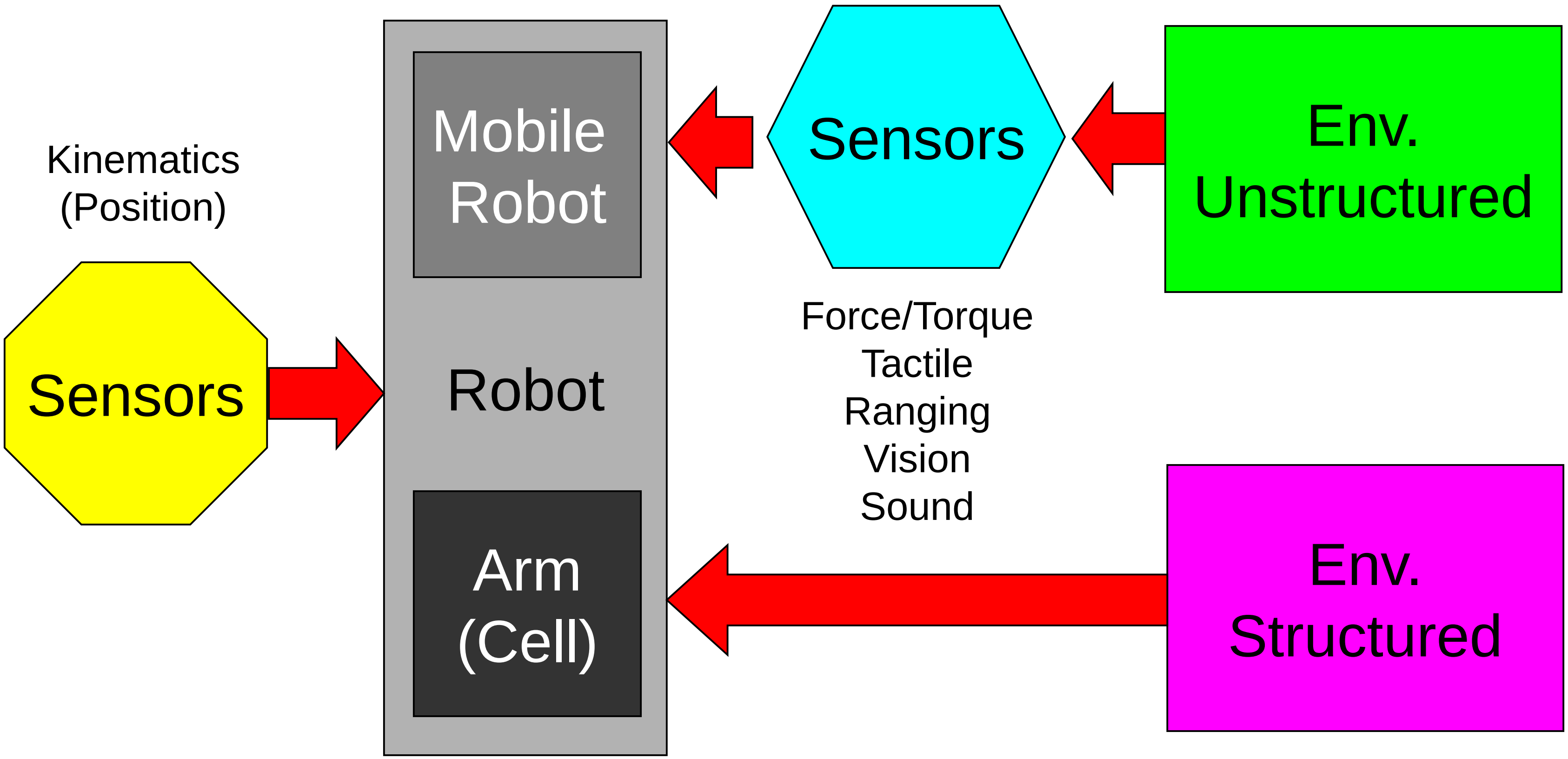
Equilibrioception
vestibular sense
(balance Inner Ear)

Proprioception,
kinesthetic sense
body awareness
(Muscle Tendon Joints)

Sight
Hearing
Smell
Taste
Touch



Sensors – Robot



Manipulator Design

- Requirements
  - Task
  - Load
  - Time (speed / cycle-time)
  - Environment
  - Cost
- Design
  - No. of DOF
  - Workspace
  - Kinematics configuration
  - Dynamics properties
  - Actuation
  - Sensors
  - Accuracy
  - Reputability
- Analysis
  - Kinematics
  - Link length optimization
  - Singularities
  - Dynamics
  - Actuation optimization
  - Trajectory Analysis
  - Modal Analysis
  - Cost Analysis
  - Control
    - Low level (servo)
    - High level (sensor fusion)

Robotic Systems – Medical – Wearable Robot

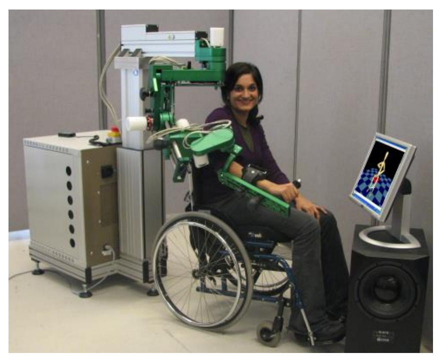
Exos

Exo-UL7
Bionics Lab - UCLA

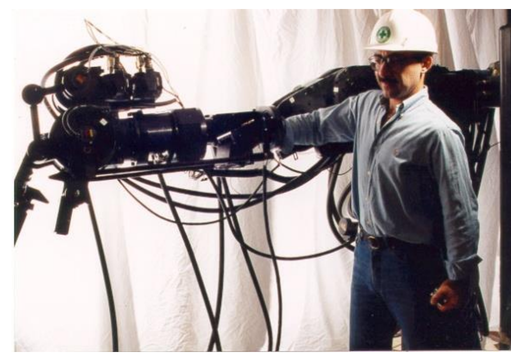
MGA
Maryland-Georgetown Army

Panasonic

Percro
University of Pisa - Italy

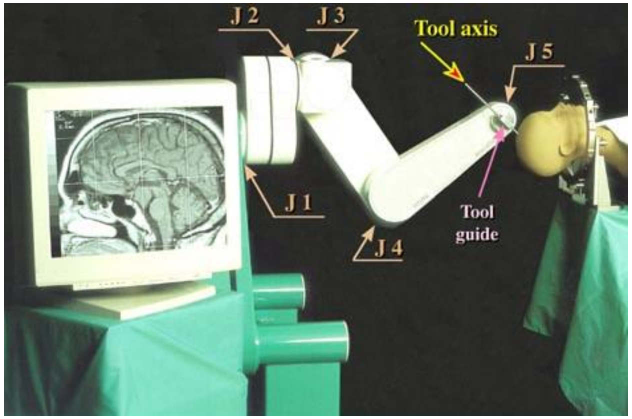


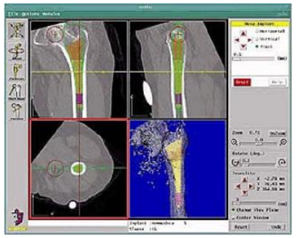
ARMin
Catholic University of America

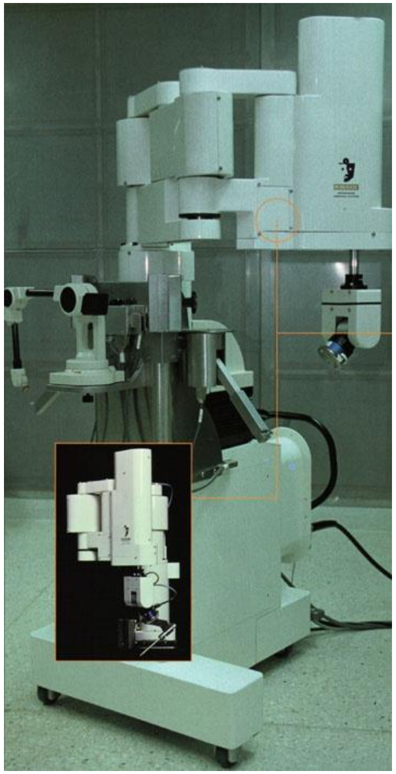


Human Power Extender
UC Berkeley

Robotic Systems – Medical – Surgical Robot







Neuromate

Integrated Surgical System (ISS)

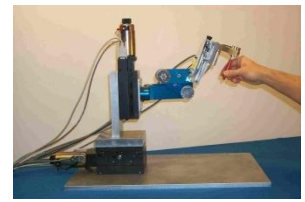
RoboDoc

Integrated Surgical System (ISS)

Robotic Systems – Medical – Surgical Robot





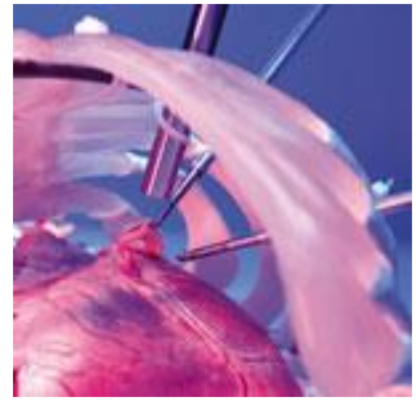






M7	*Zeus*	*DaVinci*		*Steady Hand*	*Raven*
SRI	*Computer Motion*	*Intuitive Surgical*	*UC Berkley*	*Hopkins*	*University of Washington*

Robotic Systems – Medical – Surgical Robot



AESOP
Computer Motion, Inc.
Goleta, CA

The AESOP Endoscope Positioner is a seven degree-of-freedom robotic arm, which mimics the form and function of a human arm to position an endoscope during minimally invasive surgery.

Using predefined voice commands, the surgeon is able to directly control a stable, responsive surgical image during long, complex procedures. The AESOP system provides a level of stability that is impossible to achieve with a human endoscope holder and frees up the medical professional for other patient- and surgeon-oriented duties.

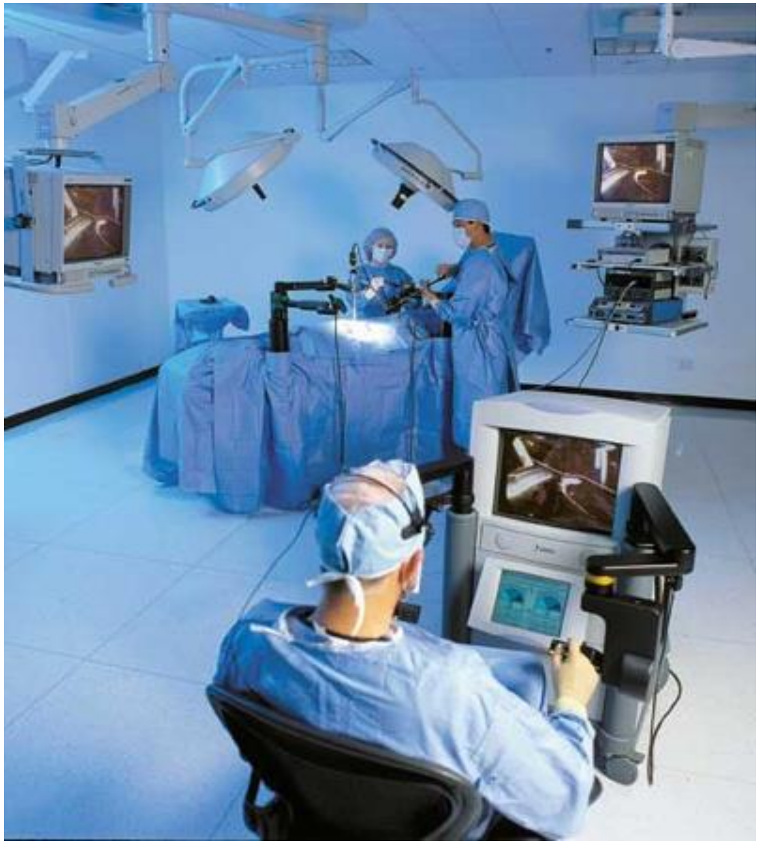
www.computermotion.com

Robotic Systems – Medical – Surgical Robot

ZEUS
Computer Motion, Inc.
Goleta, CA

The ZEUS Robotic Surgical System is comprised of an ergonomic surgeon console and three table-mounted robotic arms, which act as the surgeon's hands and eyes during minimally invasive surgery. While sitting at the console, the surgeon controls the right and left robotic arms that translate to real-time manipulation of the surgical instruments within the patient's body. The third arm incorporates the AESOP technology, providing the surgeon with a controlled and steady view of the internal operative field.

www.computermotion.com

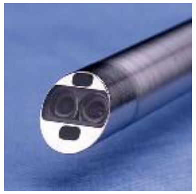


Robotic Systems – Medical – Surgical Robot

da Vinci
Intuitive Surgical, Inc.
Mountain View, CA

The da Vinci™ Surgical System consists of a surgeon's console, a patient-side cart, a high performance vision system and our proprietary instruments. Using the da Vinci Surgical System, the surgeon operates while seated comfortably at a console viewing a 3-D image of the surgical field. The surgeon's fingers grasp the instrument controls below the display with wrists naturally positioned relative to his or her eyes. Our technology seamlessly translates the surgeon's movements into precise, real-time movements of our surgical instruments inside the patient.

www.intuitivesurgical.com



Robotic Systems – Medical – Surgical Robot

Integrated Surgical Systems, Inc.
Davis, CA

ROBODOC

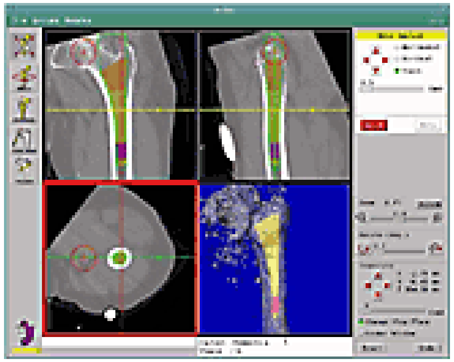
Total hip replacement- The robot mills a cavity in the femur for a prosthetic implant. The system is designed to accurately shape the cavity for a precise fit with the implant.

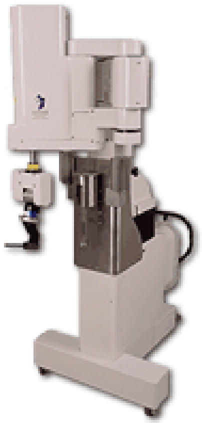
Total knee replacement - The robot planes knee surfaces on the femur and tibia to achieve a precise fit for the implant.

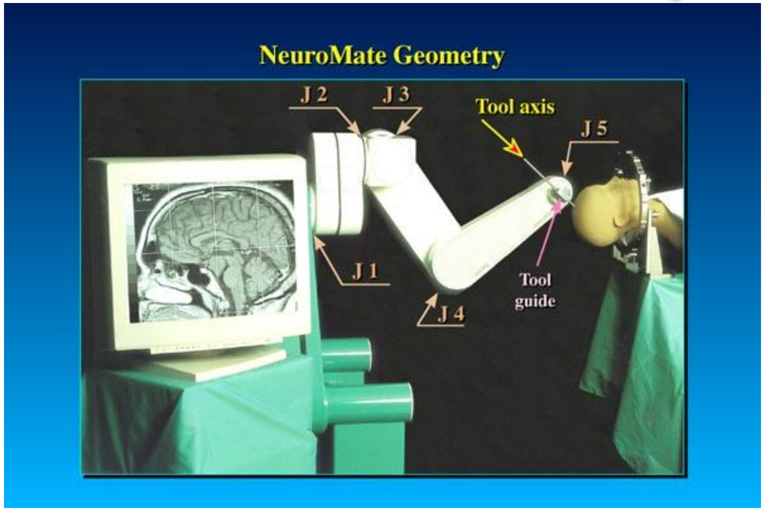
NeuroMate is a computer-controlled, image-directed robotic system for stereotactic functional brain surgeries. The Frameless NueroMate System eliminates the need to use the cumbersome and very painful frames that are traditionally used for many brain surgeries.

The system orients and positions a variety of surgical tools.

www.robodoc.com





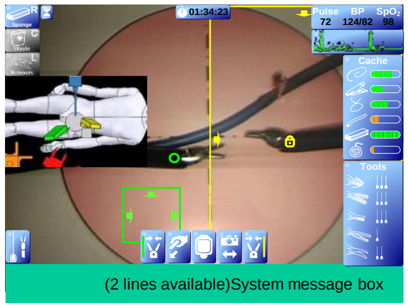


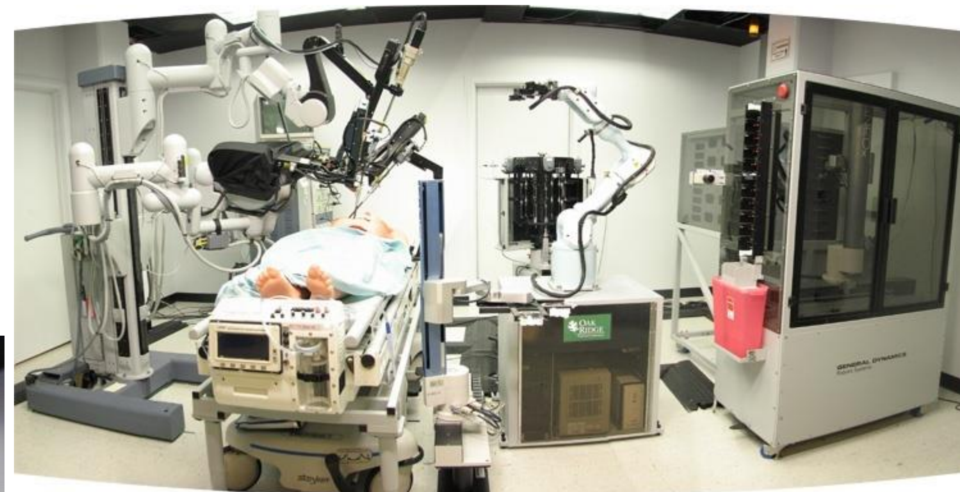
Robotic Systems – Medical – Surgical Robot

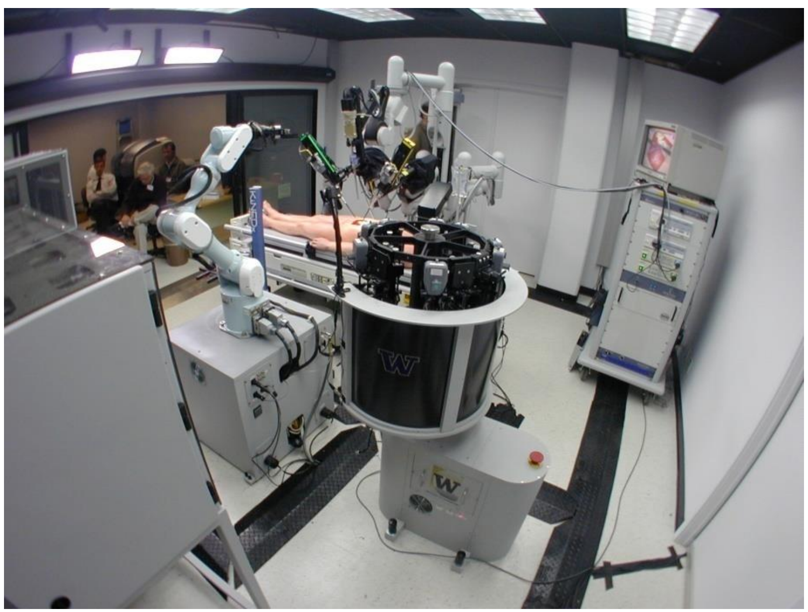
Raven I – Surgical Robot

Robotic Systems – Medical – Surgical Robot

Trauma Pod (SRI)







Trauma Pod Phase I – DARPA Project – Demo