MODULE 1: INTRODUCTION TO ROBOTIC SYSTEMS

Nicholas HO, PhD
Institute of System Science, NUS

About Nicholas Ho

- nicholas.ho@nus.edu.sg

- Lecturer at NUS ISS; Courses covered include:
  - ➢Robotic Systems
  - ➢Autonomous Robots and Vehicles
  - ➢Human-Robot System Engineering
- BEng and PhD degree from School of Mechanical Engineering, NUS
- Specialized in architecture, design & development
  - ➢Artificial Intelligence
  - ➢Augmented/Virtual Reality
  - ➢Internet-of-Things (IoT) & Cyber-Physical System (CPS)

About Liu Fan

- Lecturer in Software Systems Practice
- PhD degree from School of Electrical and Electronic Engineering, NTU
- Worked at GovTech as Data Scientist, handling Big Data Analytics for Smart Nation Platform
- Her research interests lie in big data engineering, fuzzy neural networks and machine learning

Course Outline

- Day 1 Module 1: Introduction to Robotic Systems

  Module 2: Autonomous Behaviour
- Day 2 Module 3: Robotic Sensory Systems
- Day 3 Module 4: Robotic Locomotion
- Day 4 Module 5: Robotic Pathway Planning
- Day 5 Module 6: Fuzzy Behaviour

  Final assessment

Reference (Optional)

- Vadakkepat et. al. EE4308 Advances in Intelligent Systems and Robotics
- Chew et. al. ME5402/EE5106R Advanced Robotics
- Siegwart, R., Nourbakhsh, I. R., Scaramuzza, D., & Arkin, R. C. (2011). *Introduction to autonomous mobile robots*. MIT press.
- Siciliano, B., Sciavicco, L., Villani, L., & Oriolo, G. (2010). *Robotics: modelling, planning and control*. Springer Science & Business Media.
- Jazar, R. N. (2010). *Theory of applied robotics: kinematics, dynamics, and control*. Springer Science & Business Media.

Topics

- Introduction to robotic systems
- Development and Architecture of robotic systems
- Applications within various industries
- Robotics Systems for Industry 4.0 and Smart Nation

Introduction to Robotic Systems

Robots and robotics

- Many definitions exist. Not many that are universally accepted.
  - Versatile machines with sensors and actuators that are capable of doing certain physical human work?
  - Any device that replaces human labour?
  - A machine capable of intelligent action in the real world?
    - Eg., tea kettles or lawn mowers are not robots.
    - Intuitively, a lawn mower capable of going out and mowing the lawn by itself could be called a robot. (Why?)

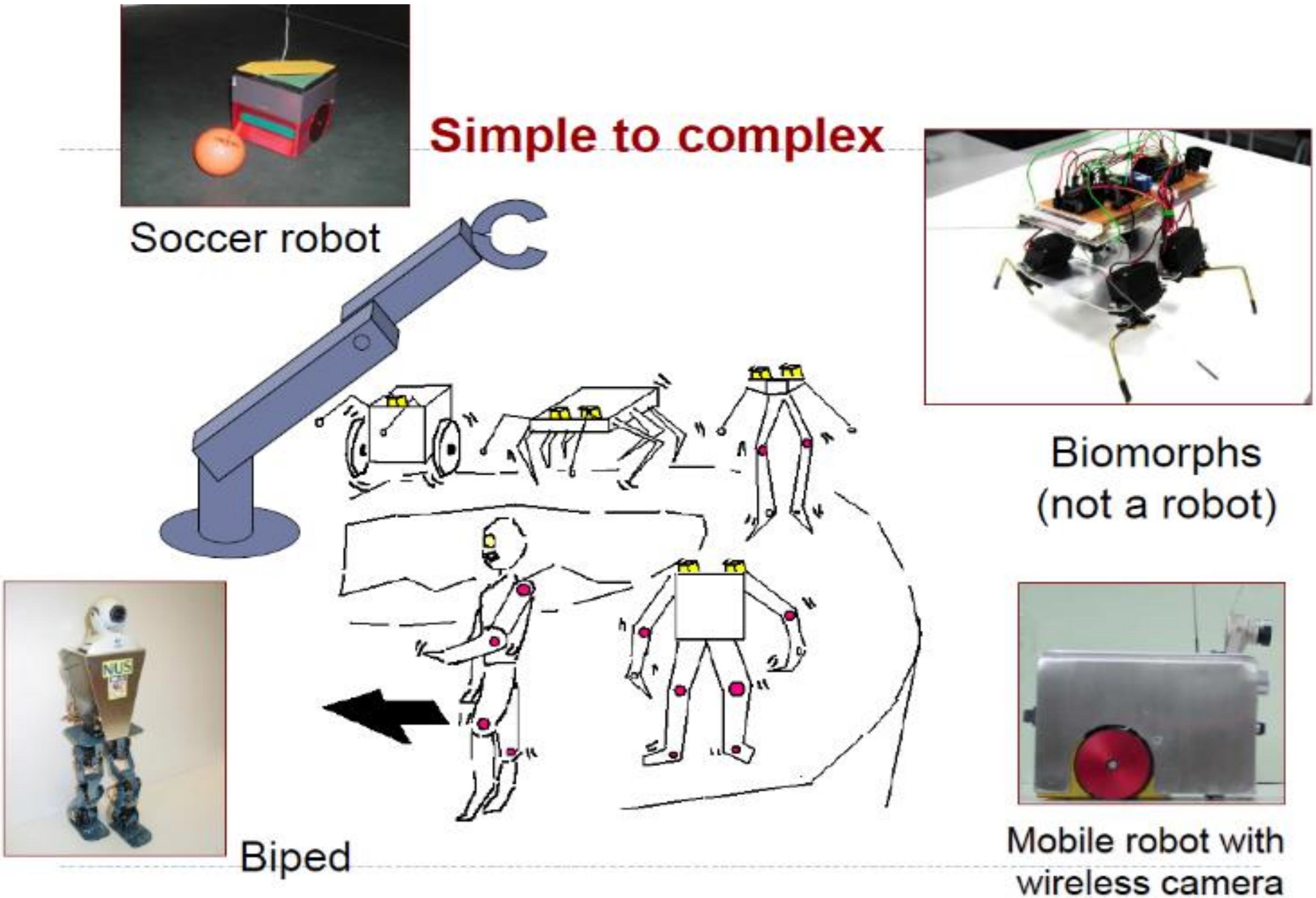
- Robotics Industries Association definition
  - A robot is a reprogrammable, multifunctional machine designed to manipulate materials, parts, tools or specialised devices, through variable programmed motions for the performance of a variety of tasks.

Industrial Robots & Mobile Robots

History

- Middle of 20th century – Research in artificial intelligence (AI) – connection between human intelligence and machines – First robot – Advances in mechanics, controls, computers and electronics – **Robotics: The science & technology of robots**
- 1960s – numerical control machines (e.g. CNC) 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 was defined as the science which studies the **intelligent connection between perception and action**
- 1990s – field robotics to address human safety in hazardous environments - human augmentation – service robotics
- 2000 and beyond – **human-centered and life-like robotics**

Evolution of Robot



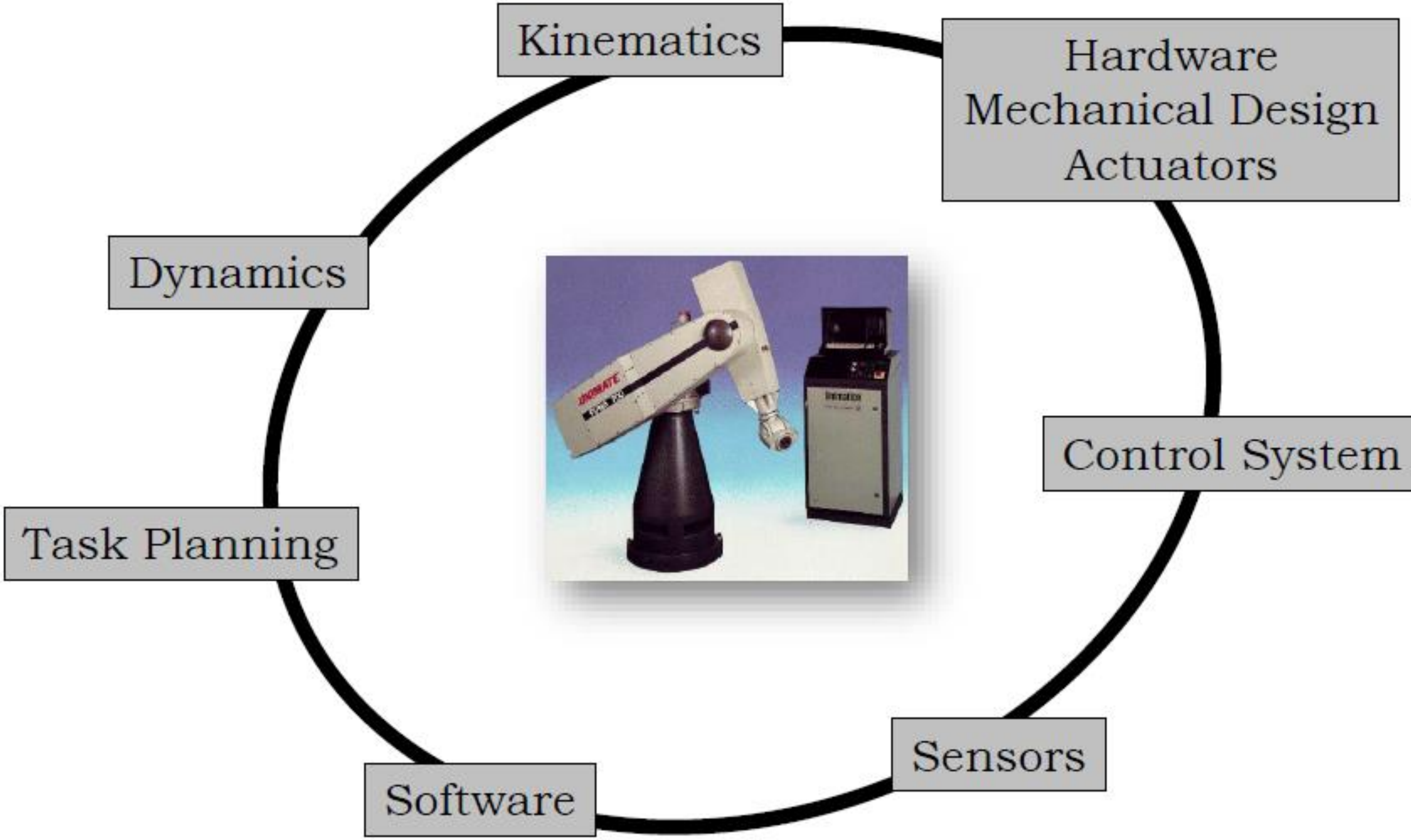
Classical Robotics

- We will concentrate on *classical* robotics, i.e., the study of industrial robotic manipulators;
- Our aim is to understand how to design, analyse and control such machines.

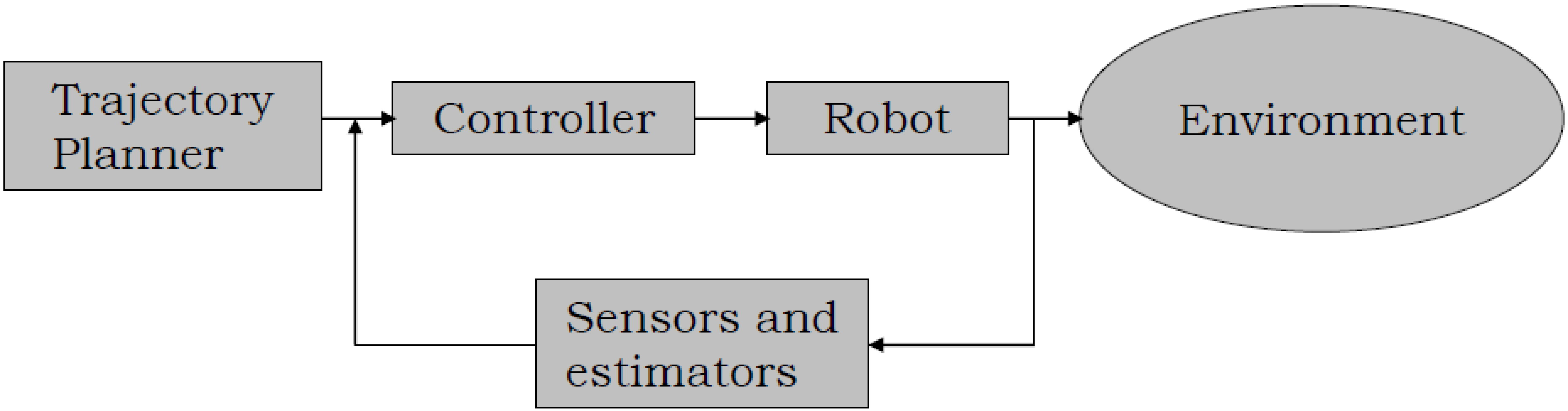
Requires an integrated approach	
Kinematics	Study of Geometry of motion
Statics	Study of a manipulator at equilibrium
Dynamics	Study of causes of motion
Trajectory Planning	Generating the path the robot must trace
Control strategy	Executing the path
Physical Hardware	Building the robot

Development and Architecture of Robotic Systems

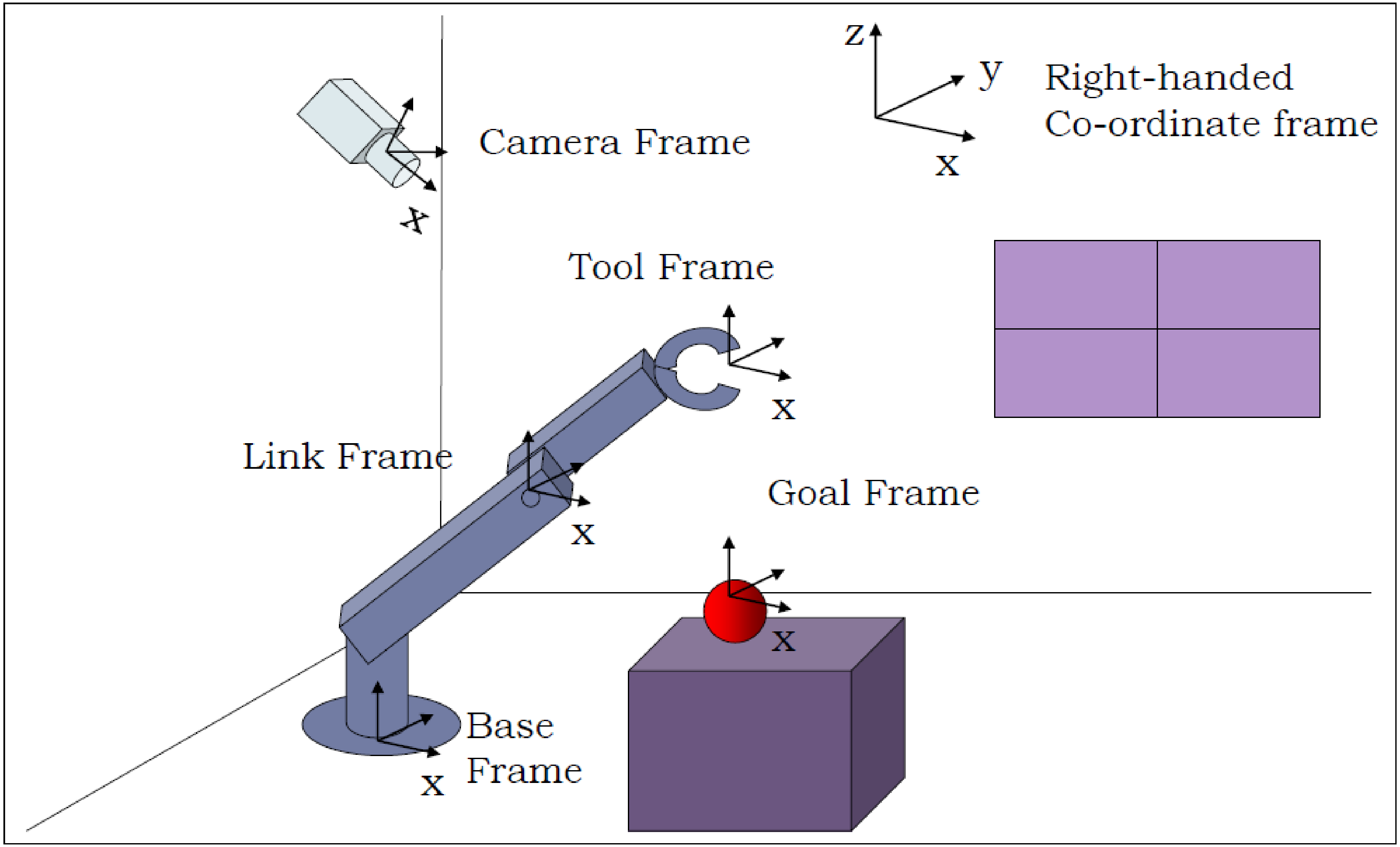
The Robotic System



Basic Blocks



Coordinate Frames



Kinematics

- KINEMATICS - the analytical study of the geometry of motion of a robot arm:
  - with respect to a fixed reference co-ordinate system.
  - with out regard to the forces or moments that cause the motion.

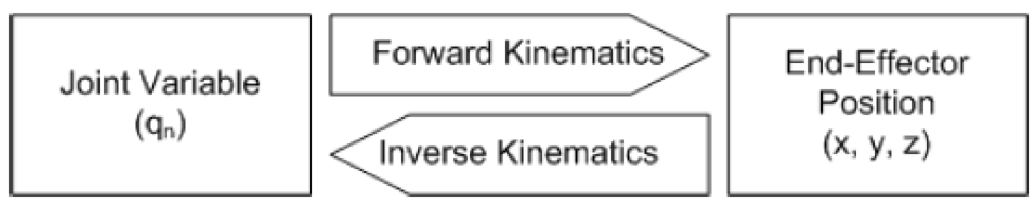
- No mass is involved in kinematical equations. We just want to know how things move.

- From a mechanical viewpoint, a manipulator is a kinematic chain of mass-less rigid bodies (links) connected by revolute or prismatic joints.

- Kinematics helps us to determine the relation between end-effector position, orientation, velocity and acceleration, and the configurations, velocities and accelerations of the individual joints.

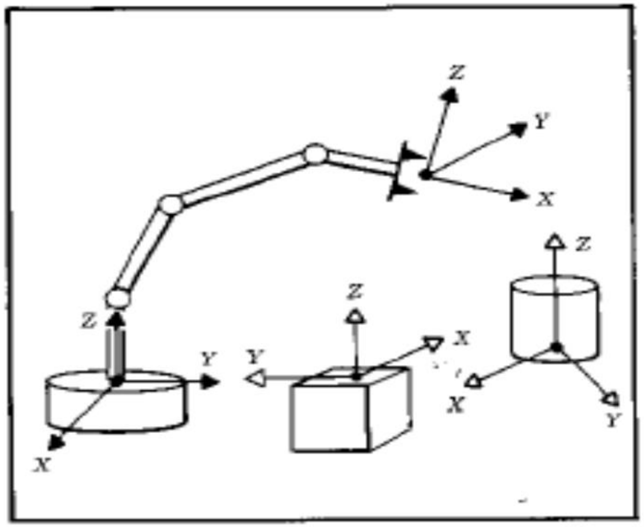
Kinematics Consideration

- Using kinematics to describe the spatial configuration of a robot provides us two approaches:
  - Forward Kinematics (direct)
    - Given the joint angles for the robot, what is the orientation and position of the end effector?
  - Inverse Kinematics
    - Given a desired end effecter position, what are the joint angles to achieve this?



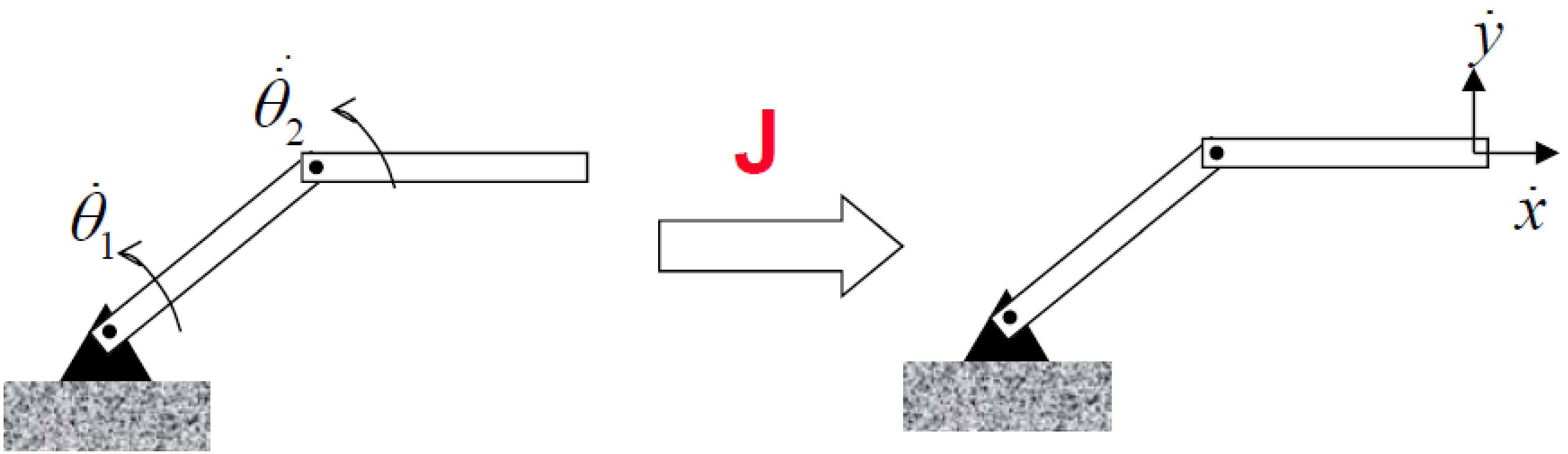
Position and Orientation Representation

- How to locate objects (e.g links of manipulator, Parts, Tools, etc) in 3D 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
(FYI; Not Important in this course)

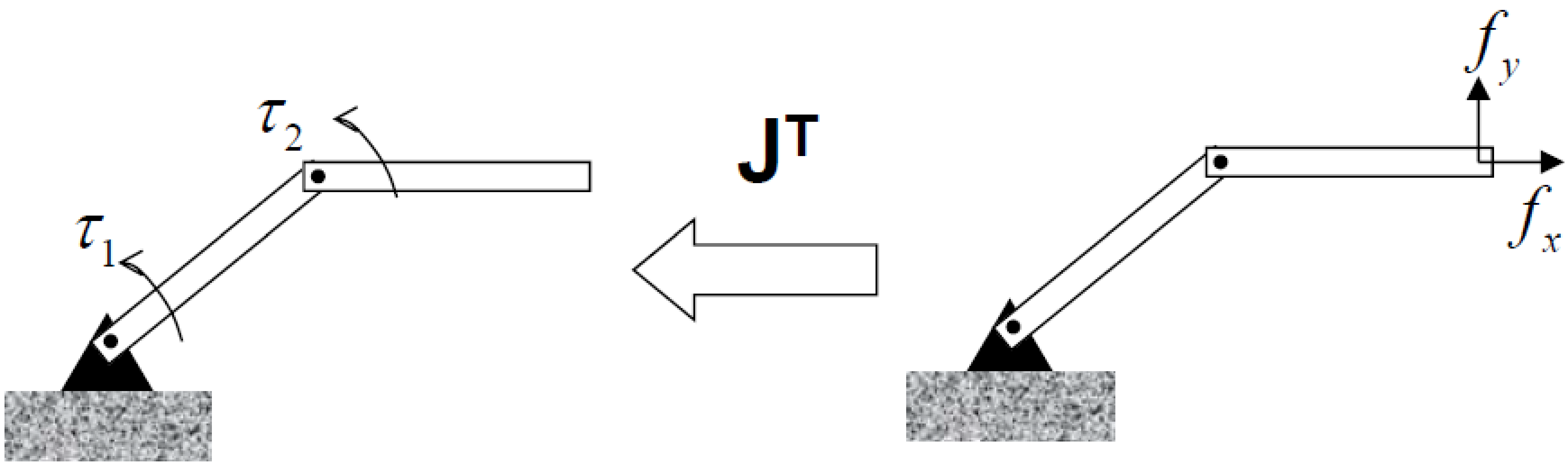
- **Jacobian** of manipulator, **J**
  - Mapping from velocities in joint space to velocities in Cartesian space



- **Singularities:** When mapping not invertible

Differential (Instantaneous) Kinematics
(FYI; Not Important in this course)

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



Inverse Kinematics

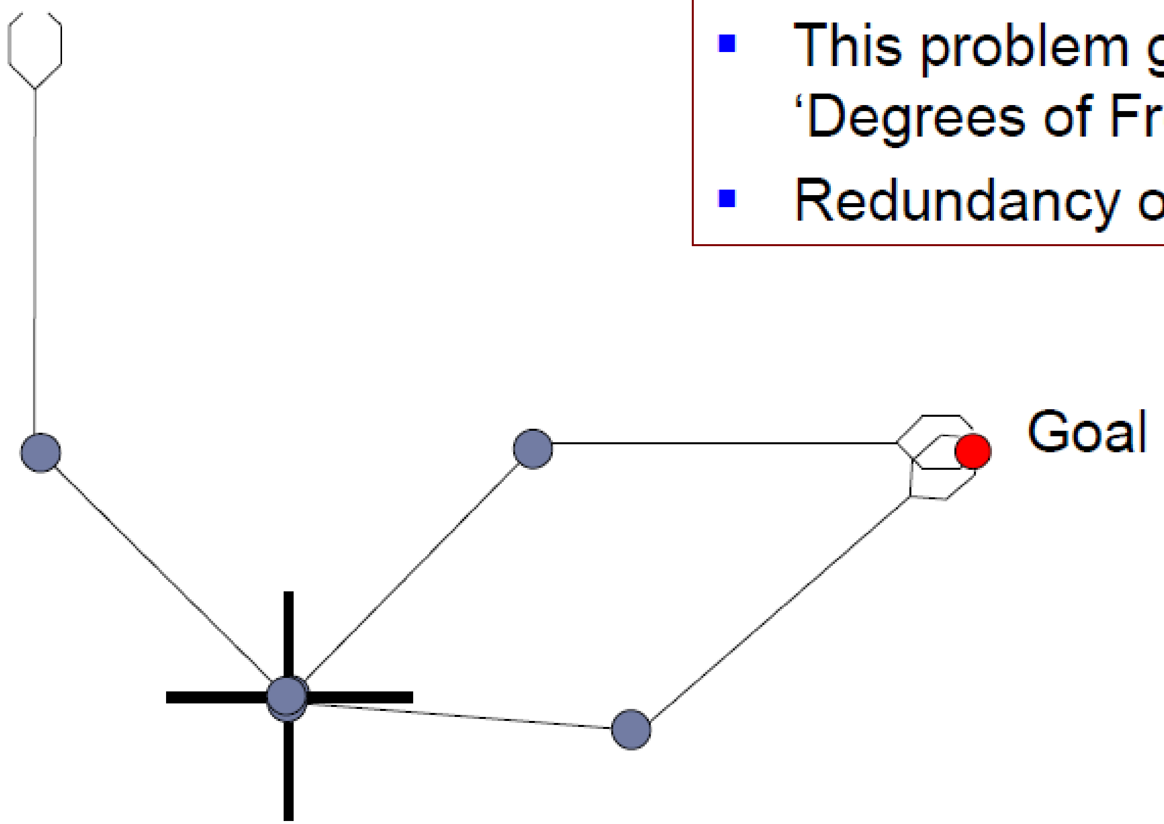
- For a robot system the inverse kinematic problem is one of the most difficult to solve.
- The robot controller must solve a set of non-linear simultaneous equations.
- The problems can be summarised as:
  - The existence of multiple solutions.
  - The possible non-existence of a solution.
  - Singularities.

Deriving Kinematics

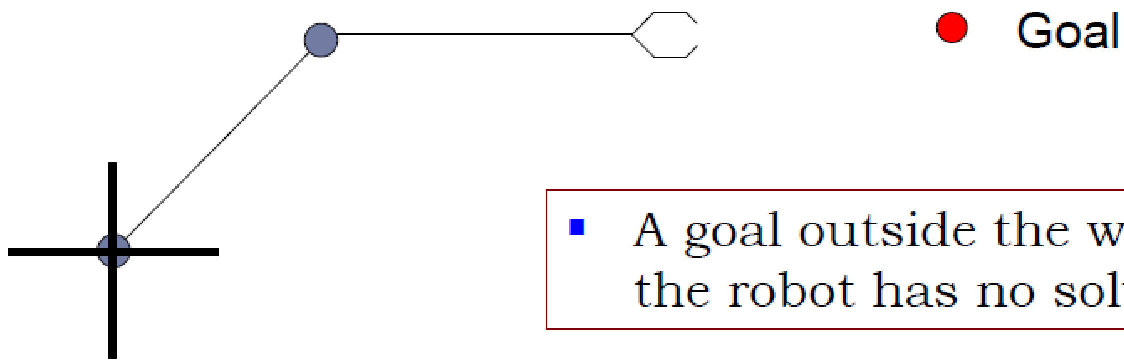
- If the manipulator is simple enough, kinematics can be computed by a direct geometric analysis.
- As the complexity and the number of joints of the manipulator increases, it is preferable to adopt a less direct method, which nevertheless is based on a systematic, general procedure.
- This principle (direct methods when the manipulator is simple, indirect, "algorithmic" methods when the manipulator is complex) is applicable to manipulator statics and dynamics as well.
- Though the *derivation* of the algorithmic methods may seem involved, their application itself is quite easy.

Multiple Solutions

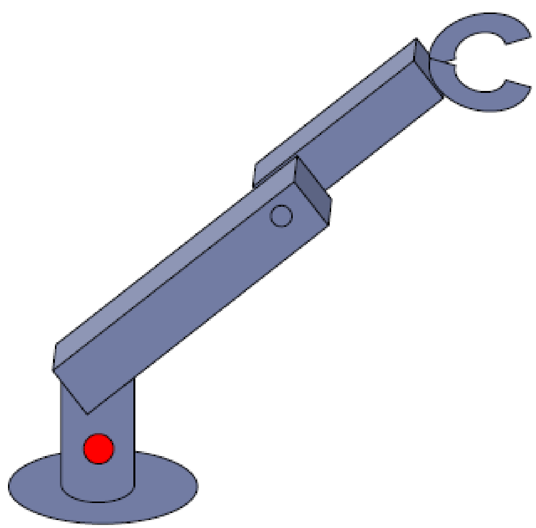
- This two link planar manipulator has two possible solutions
- This problem gets worse with more 'Degrees of Freedom.'
- Redundancy of movement.



Non Existence of Solution



- A goal outside the workspace of the robot has no solution.



- An unreachable point can also be within the workspace of the manipulator - physical constraints.
- A singularity is a place of infinite (∞) acceleration - trajectory tracking.

Statics

- Statics is the study of rigid bodies at rest
  - i.e., in equilibrium.
- Incorporates the study of centre of gravity and moment of inertia.
  - All forces and torques acting on a body in equilibrium are counterbalanced by equal and opposite forces.
  - Mass is involved.
- The goal is to determine the relationship between the generalised forces applied to the end-effector and the generalised forces applied at the joints – forces for prismatic joints, torques for revolute – with the manipulator at an equilibrium configuration.

Dynamics
(FYI; Not Important in this course)

- Dynamics is the study of the causes of motion
  - how forces and torques applied on the manipulator cause it to move.

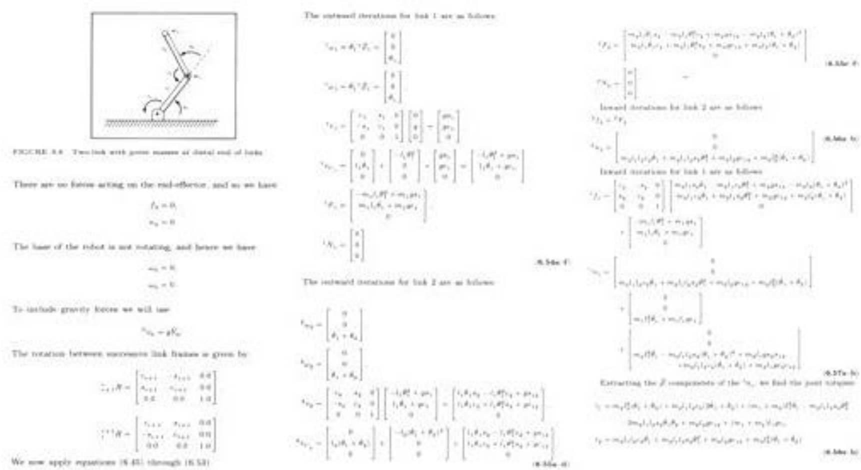
- The three laws of Newton are most fundamental to the study of dynamics.

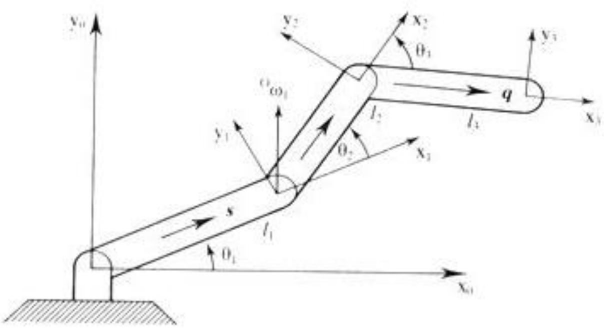
- Dynamics gives the mathematical relation between forces and torques acting on the manipulator joints, the masses and moments of inertia of the links, the gravitational force and the behaviour of the system.

Kinematics vs Dynamics
(FYI; Not Important in this course)

kinematics	dynamics
The effect of a robot's geometry on its motion.	The effect of all forces (internal and external) on a robot's motion.
from sort of simple to sort of complex	Aaargh!

two-link manipulator

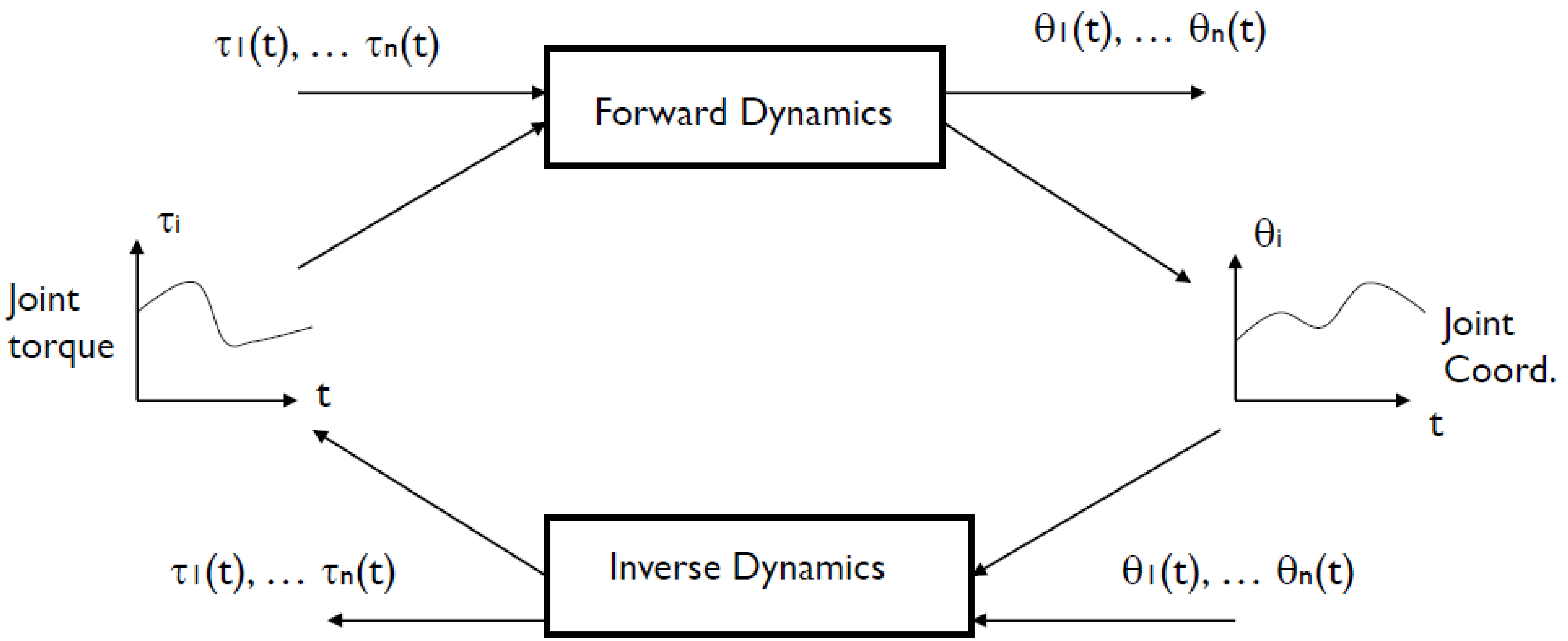




three-link manipulator

represented by a 4x4 matrix

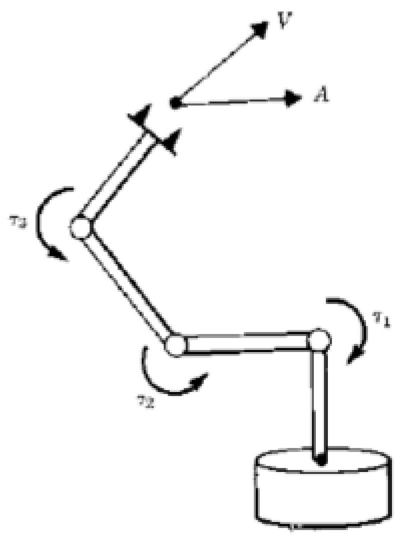
Forward & Inverse Dynamics



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



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

Why study Robot Dynamics

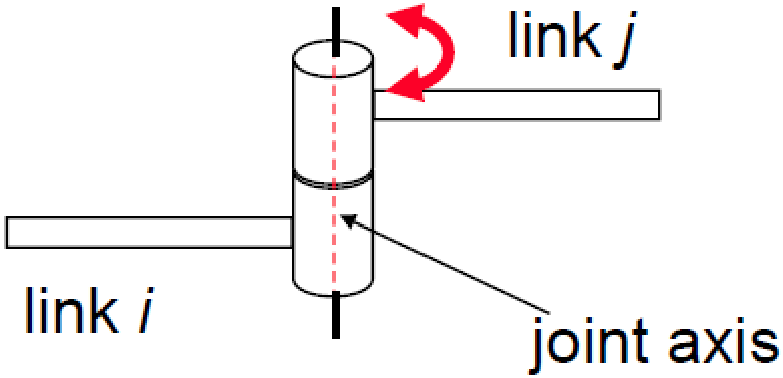
- Robot dynamic equations are used for:
  - Simulation
    - To design prototype robots and to test the control strategies without the expenses of working with actual robots (economical).
  - Controller Design
    - Most control design techniques are based on plant models.
    - Model-based controllers are superior to non-model-based controllers.

Design

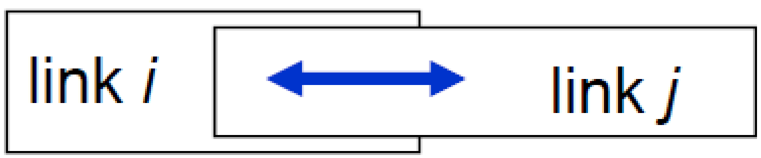
- Type of joints
- Actuators and power transmission
- Degrees of freedom
- Specialized vs universal (min 6 joints)
- Dexterity Considerations (Geometry, Workspace)
- Speed, size, load capability
- Rigid vs Flexible
- **Sensors (Most important in this course!)**

Types of Robot Joints

Two basic types:



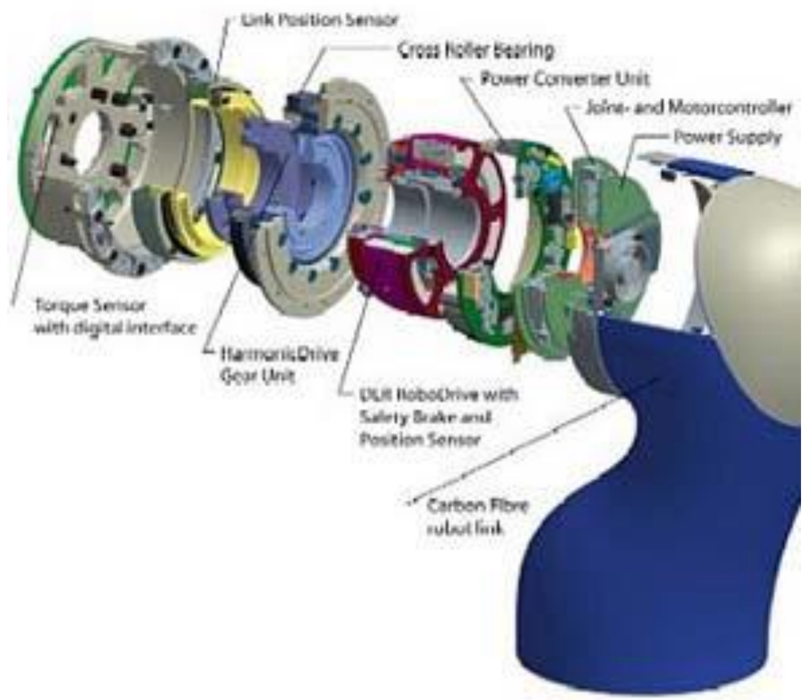
Rotational/Revolute/ Rotary



Translational/Prismatic/ Linear

Joints

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



DLR Light Weight Robot (LWR)

Actuator Technologies

Source of power to drive joints:

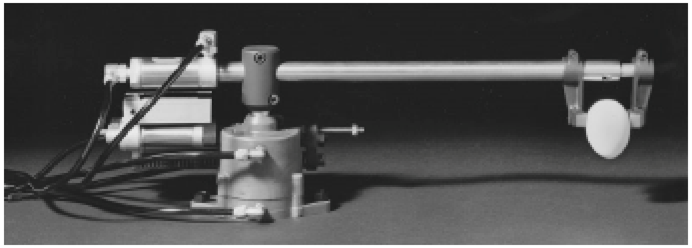
Pneumatic:
- energy efficient
- hard for feedback control

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

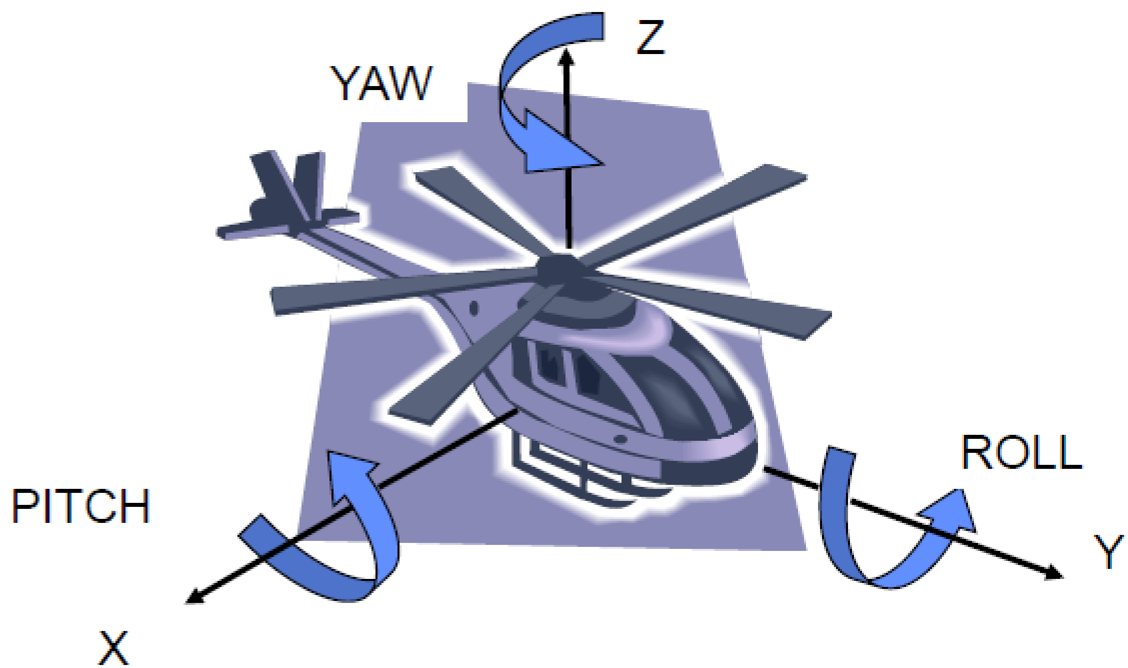
⇨ End-effectors: often are pneumatic tools



Degrees-of-Freedom (DOF)

Rigid body in 3D Space → 6 DOF

- 3 for position
- 3 for orientation

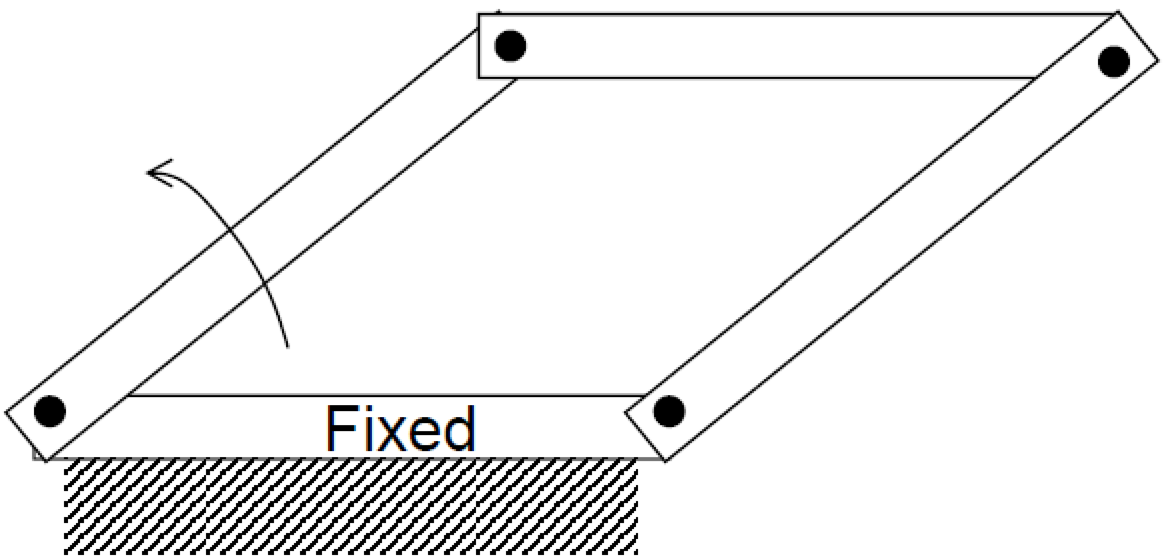


Degrees-of-Freedom (DOF)

In robotics/mechanism,

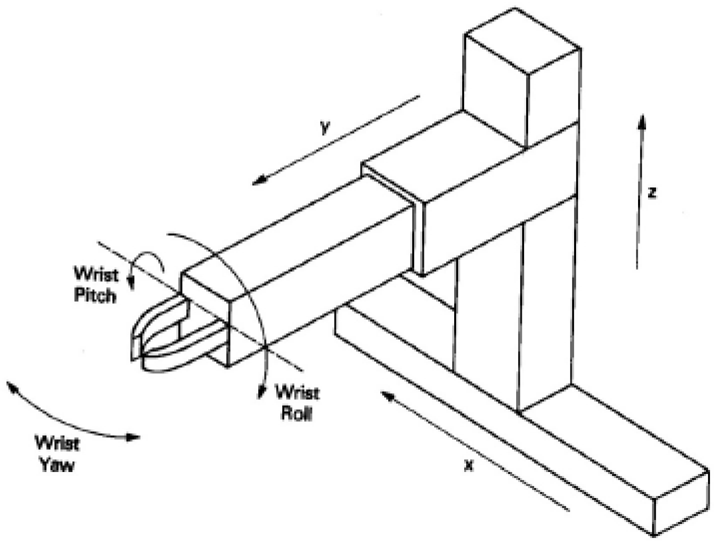
DOF = number of independent position variables that would have to be specified to locate all parts of the (rigid-body) mechanism

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

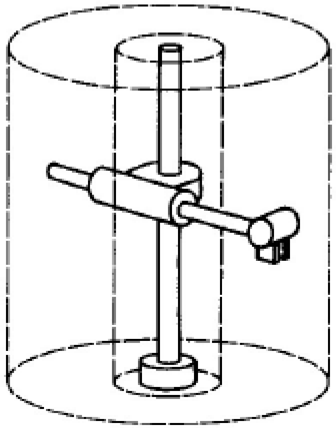


Classification by Coordinate Systems

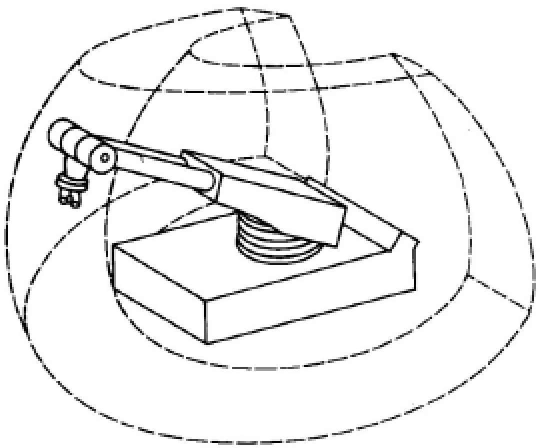
Cartesian



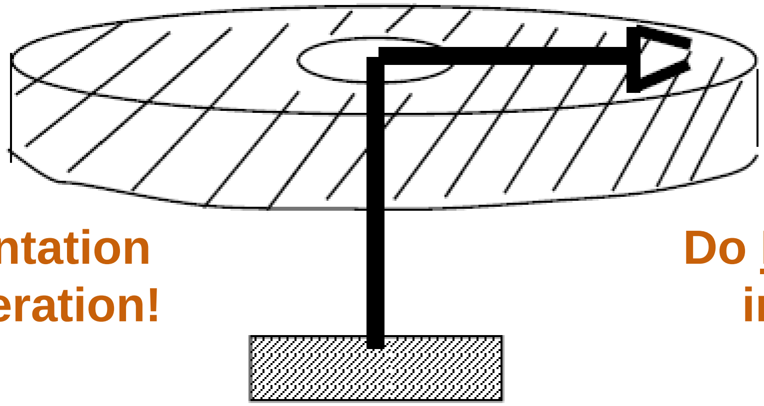
Cylindrical



Spherical



Workspace



Taking orientation into consideration!

Dextrous Workspace

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

Do NOT take orientation into consideration!

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

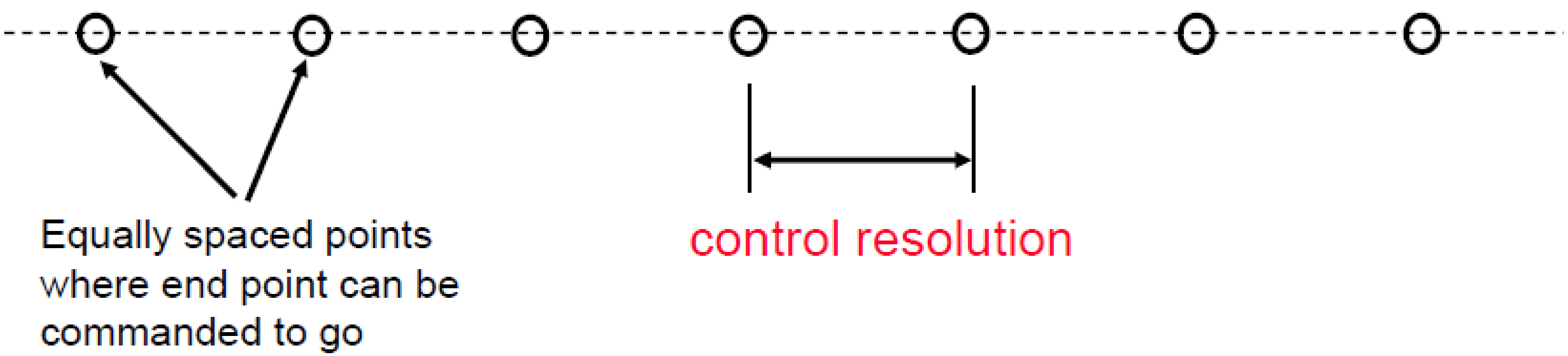
Operating Environment

- 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

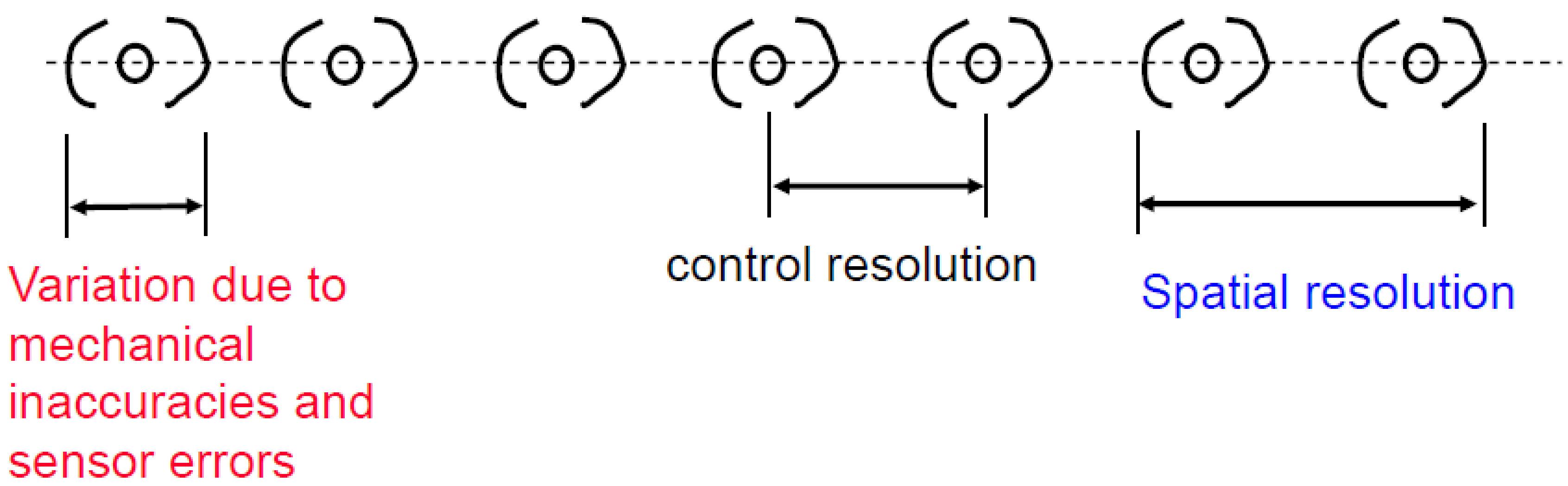
Performance/Specifications

- 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



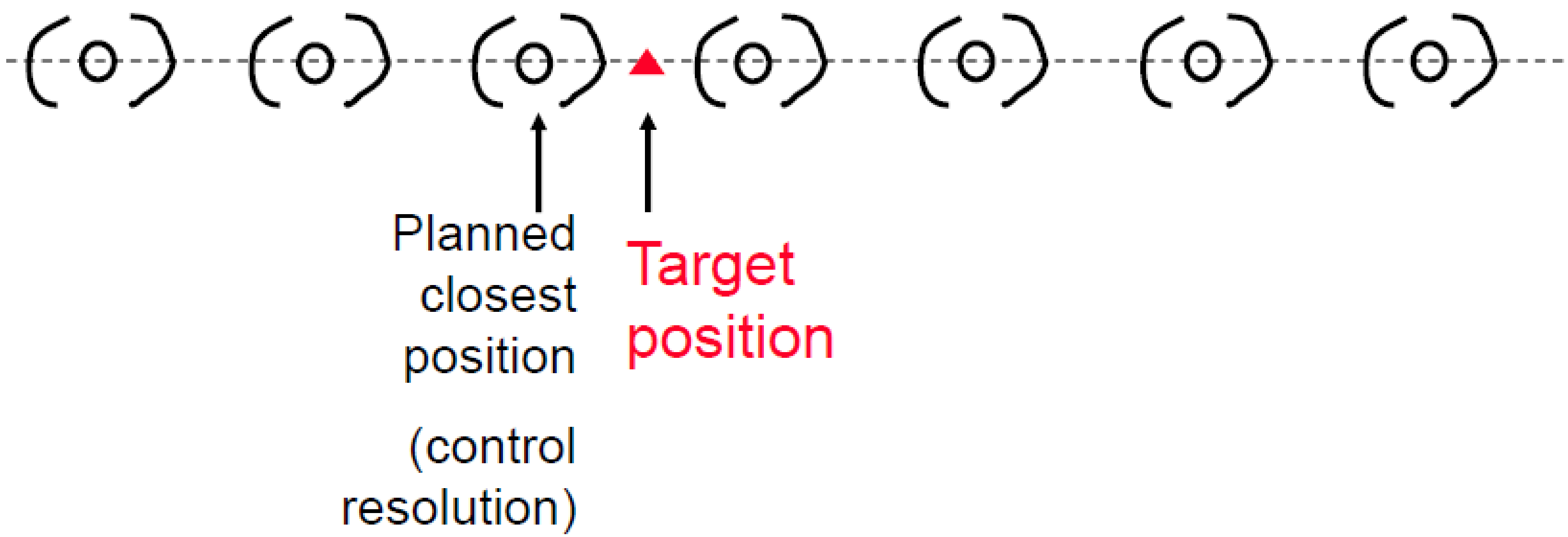
Performance/Specifications

- 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.



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

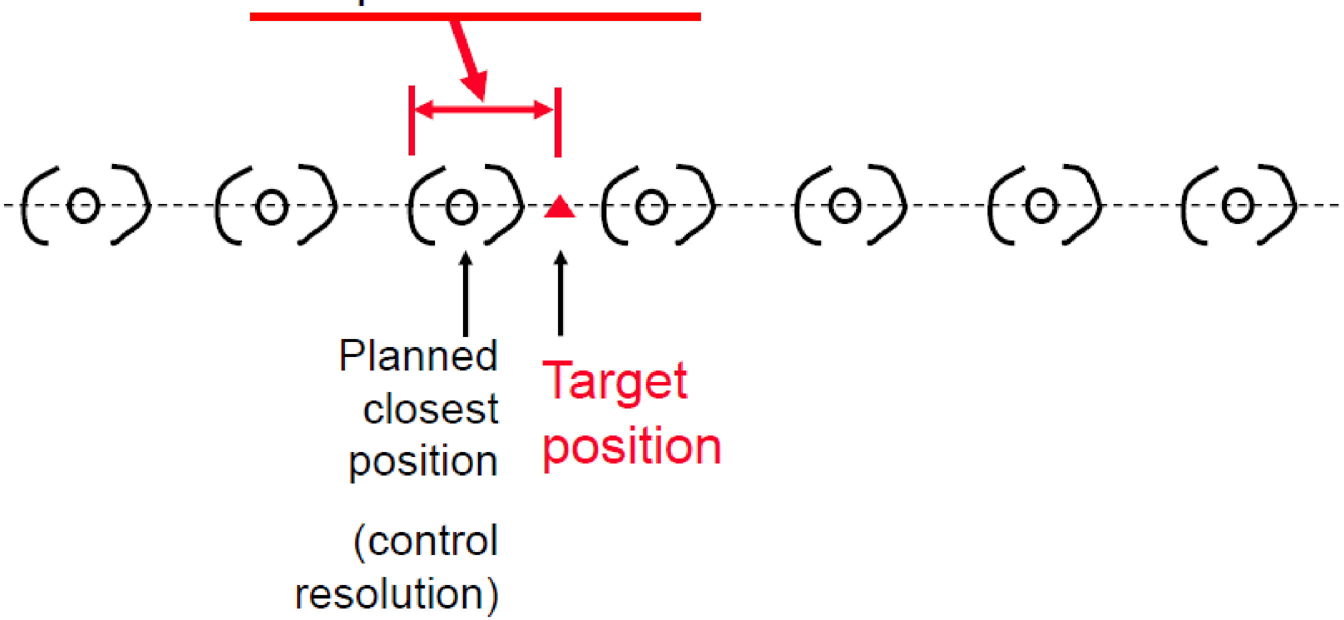


Performance/Specifications

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

= worst-case distance from target position

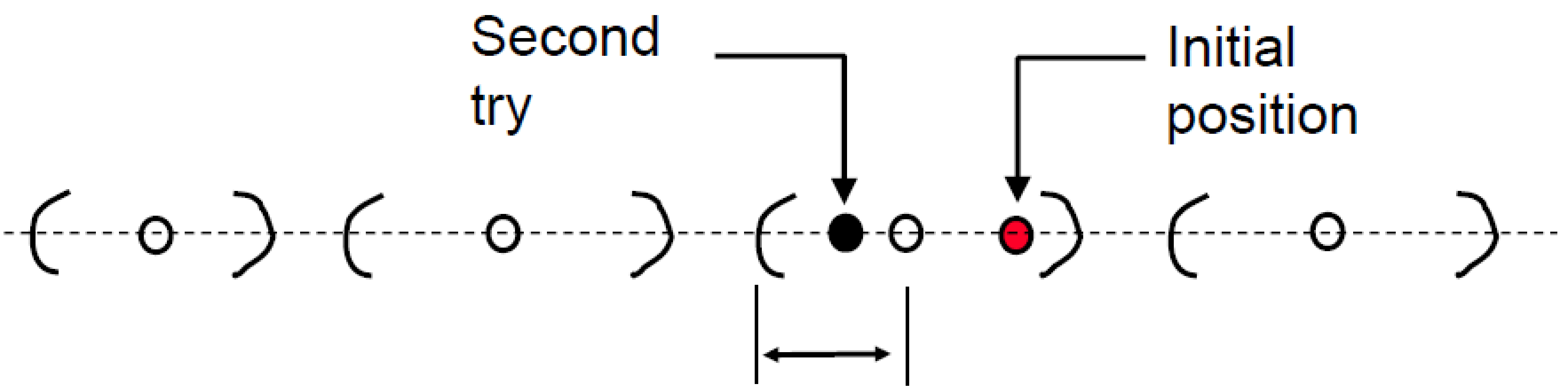
= ½ x Spatial resolution



Performance/Specifications

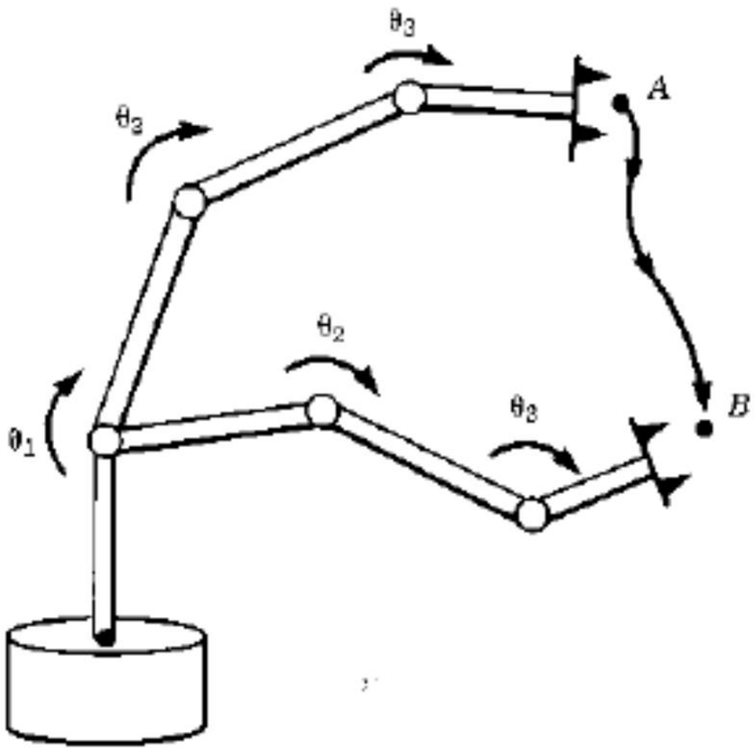
- Repeatability
  - ability of a manipulator to reposition its tool tip at a position to which it was previously commanded.
  - important for repetitive tasks
  - One-dimensional illustration of repeatability

One-dimensional illustration of repeatability



Trajectory Generation

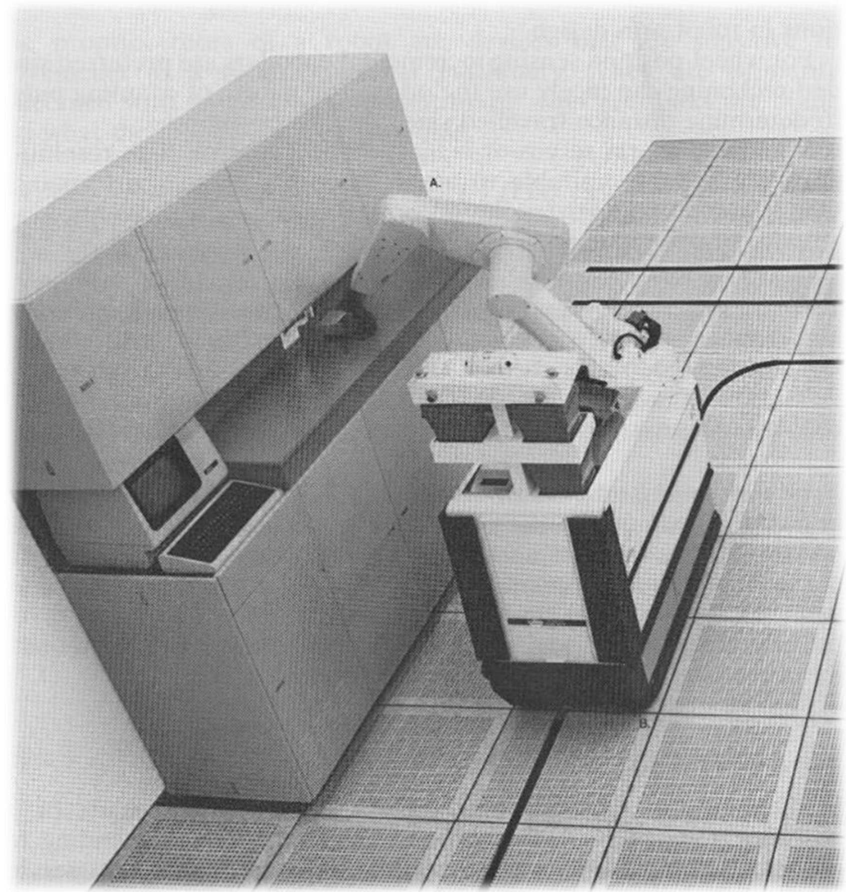
- Each joint is prescribed with a smooth function of time
- Coordinated motion of joints to provide desired end-effector motion



Applications within Various Industries

Applications: Manufacturing

Manufacturing/Assembly line



Material handling system

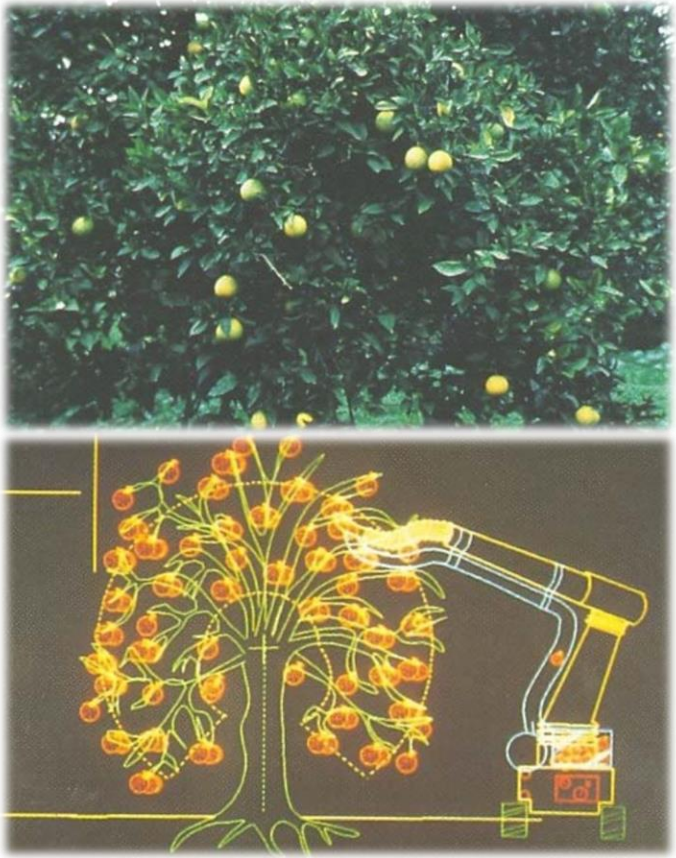
(Vecco Integrated Automation, Inc)

Applications: Construction

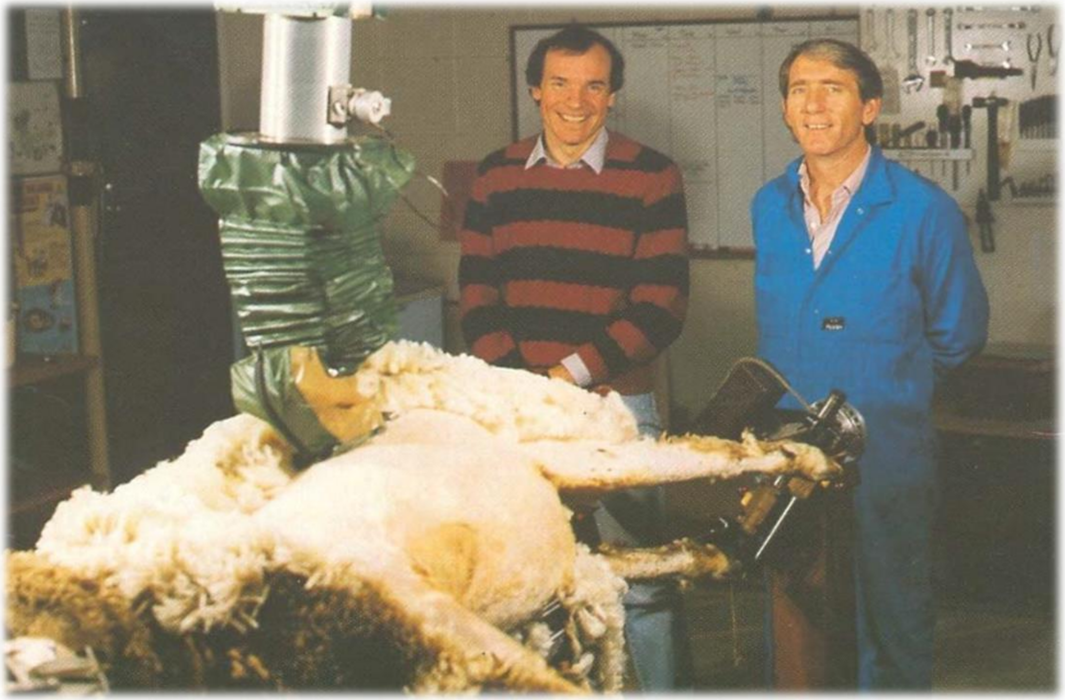
Construction robots developed by the Takenaka Company

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: Military service & other hazardous work

The US Army's Autonomous Land Vehicle

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

Applications: Aiding the handicapped and the elderly

Robot aids walking

Autonomous wheelchair

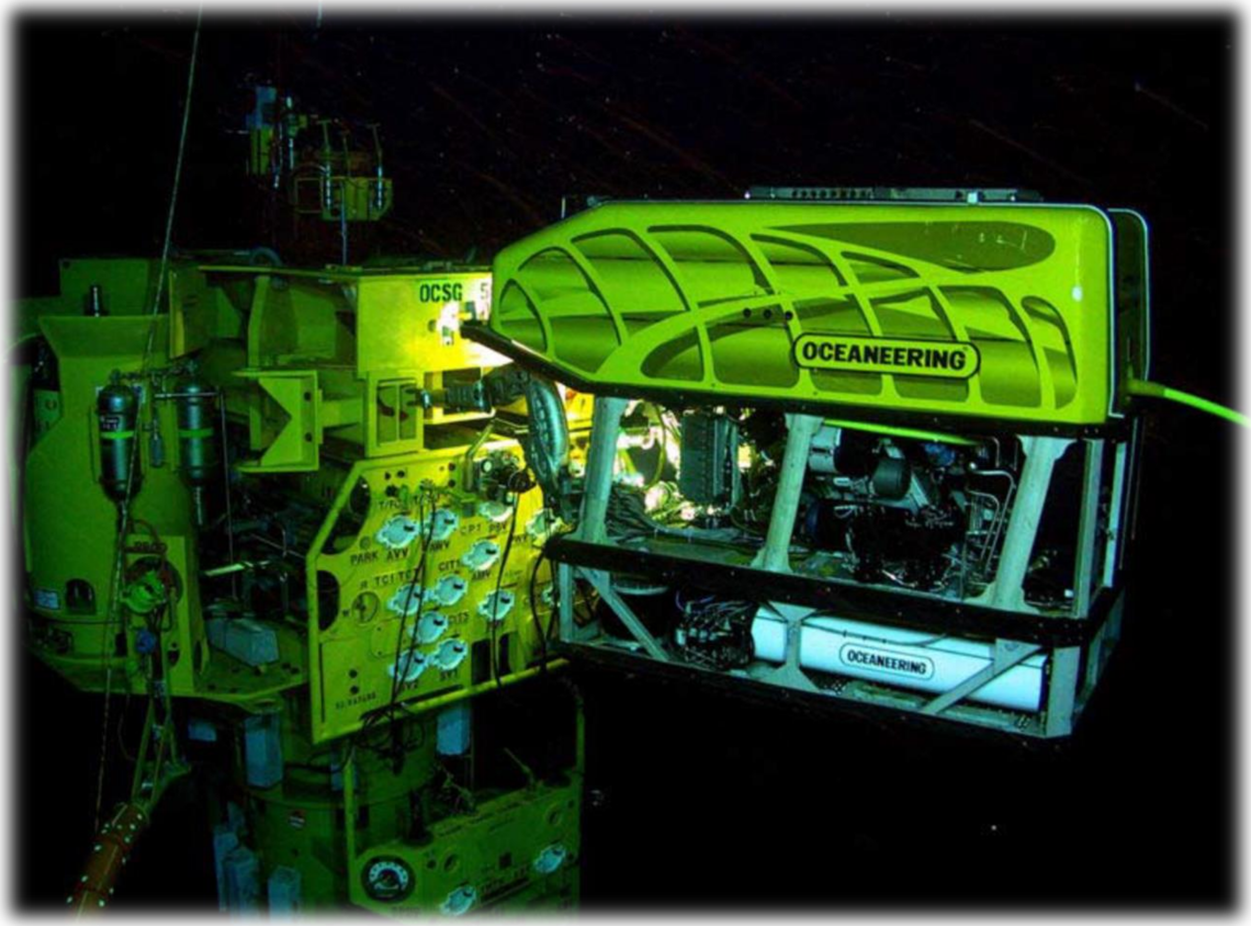
Applications: Service industry


Robot street cleaner


Robot usher


Security guard

Applications: Underwater/Oil and gas

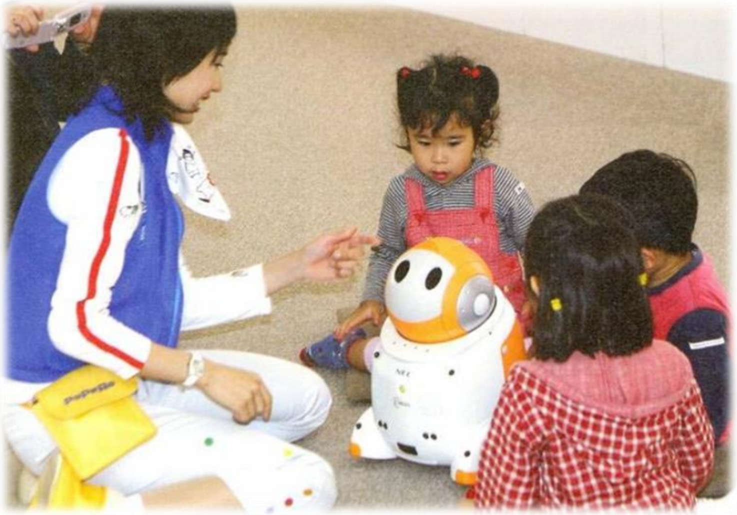


ROUV (Remotely operated underwater vehicle) working on a subsea structure

Applications: Entertainment

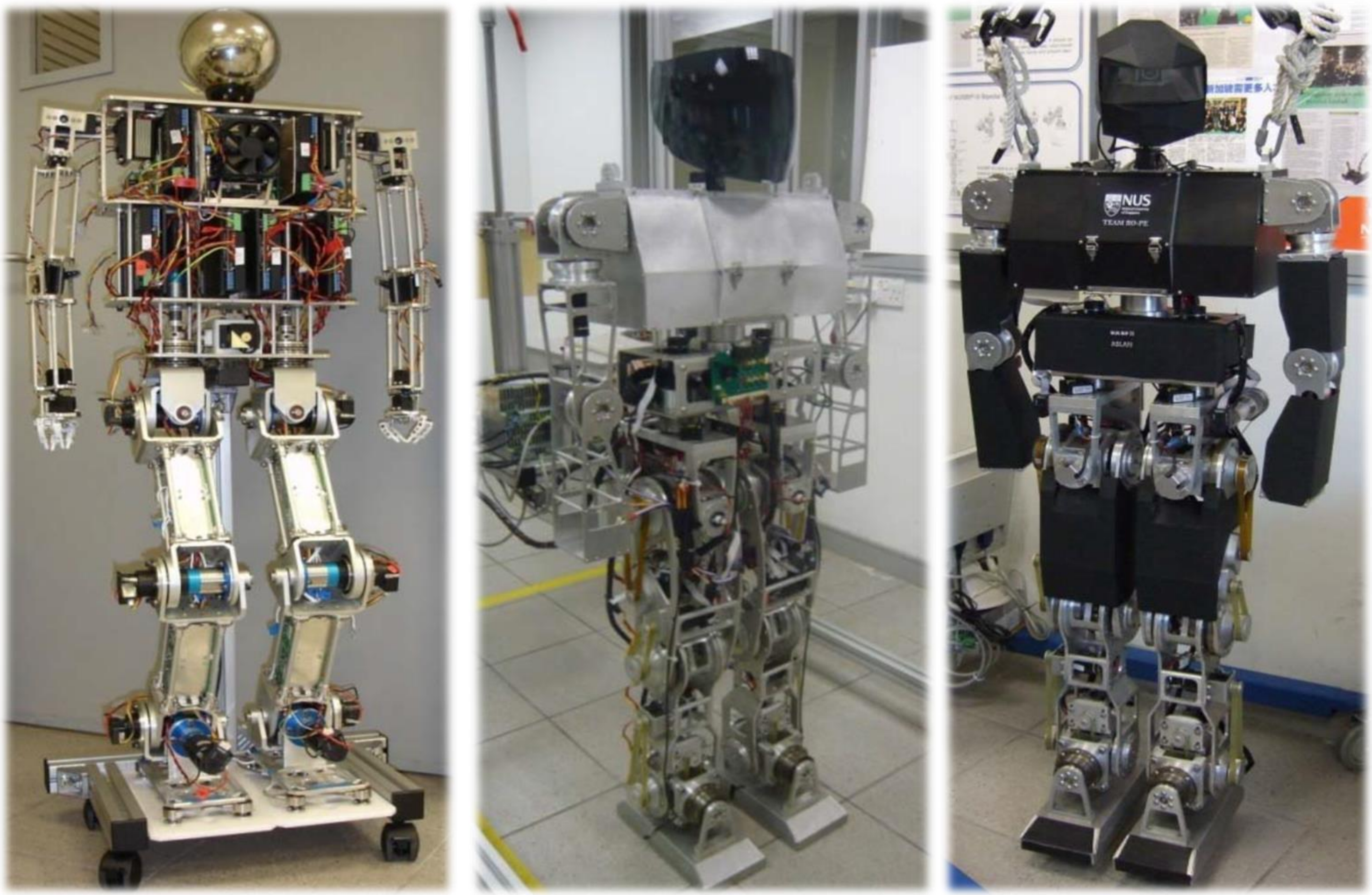
Applications: Education

NUS Team ROPE



Lego mind-
storm NXT

Applications: Humanoid Robots



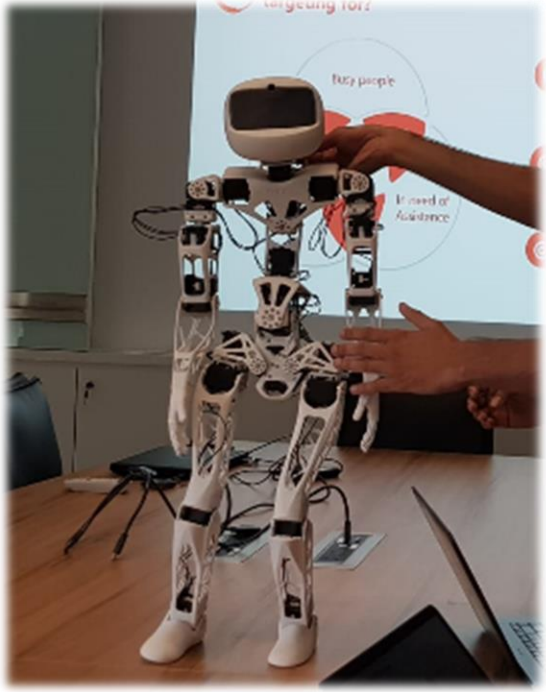
NUSBIPs

Bernard: Our friendly ISS Humanoid

Current Features

- Facial recognition and personalized response
- Machine learning for Human-like training
- Gesture mimicking

https://youtu.be/s2mJiWkBNbQ



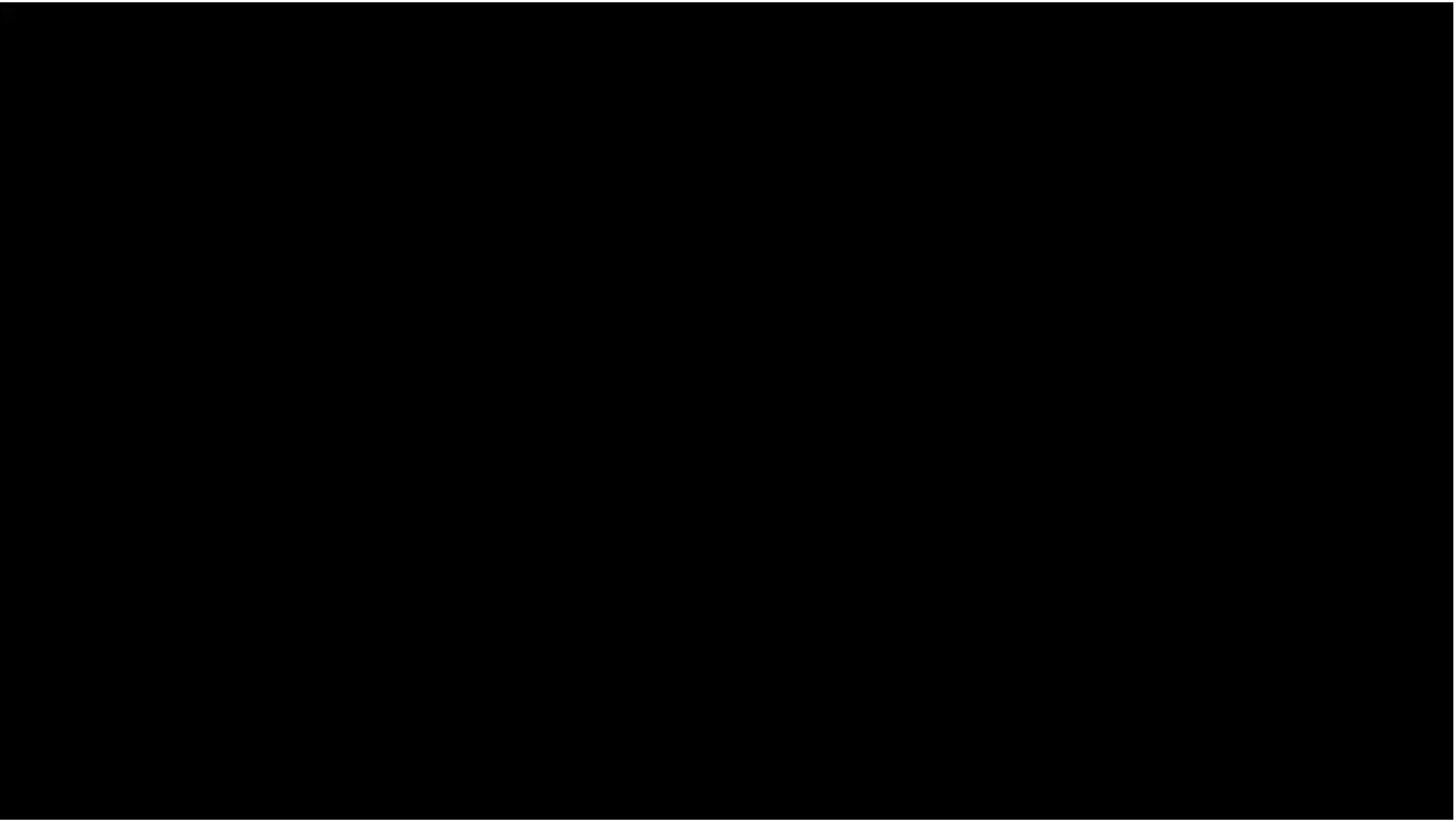
Next Variant

- Walking Bipedal Humanoid
- Ability to mimic full human range of motion

Competition

- Singapore Robotics Games 2019 Jan
- Humanoid Category

Bernard: Our friendly ISS Humanoid



Multi-Arm Surgical Co-bot

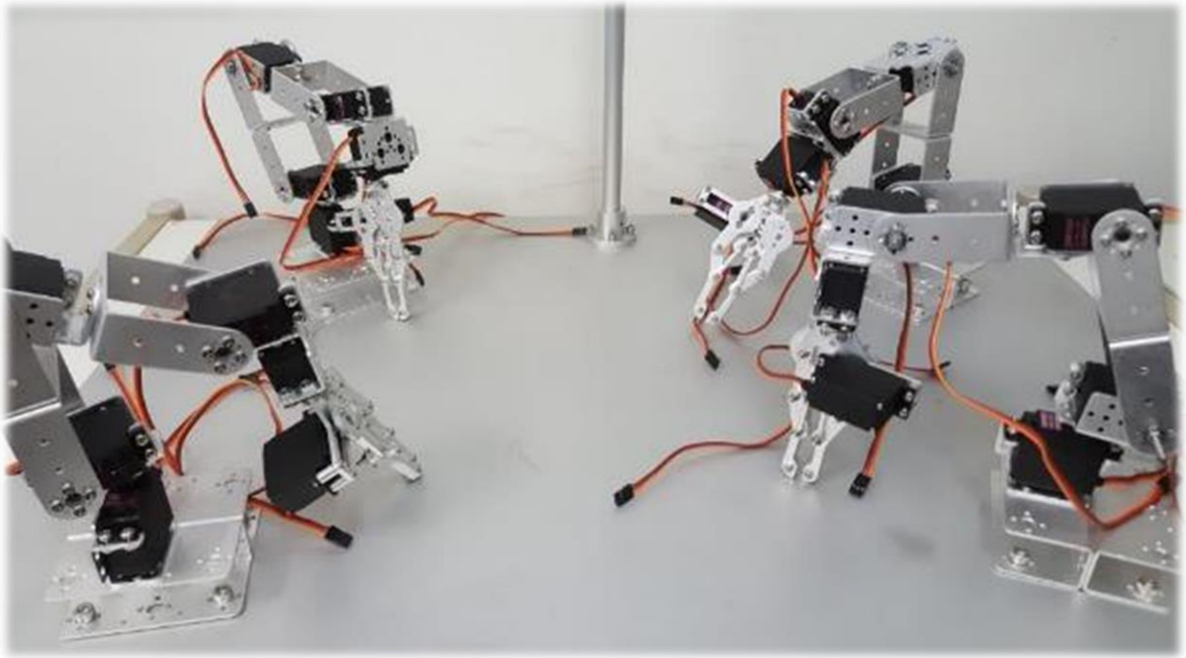
Collaboration between ISS and SingHealth Surgeons

Features

- 4 robotic arms with 6 DOF
- Synchronous Operation
- Human Intention Recognition System

Benefits

- One Surgeon to operate instead of multiple
- Possibility for Remote Surgery
- Cost savings for patients
- Modular system with high repeatability



ISS Autonomous Drone

Features

- Image Recognition Capabilities
- Obstacle avoidance and path planning
- Assisted User Control

Competition

- Took part in Singapore Amazing Flying Machine Competition 2018 (April)
- Semi-autonomous Category

https://www.youtube.com/watch?v=XABt8sB7l0c

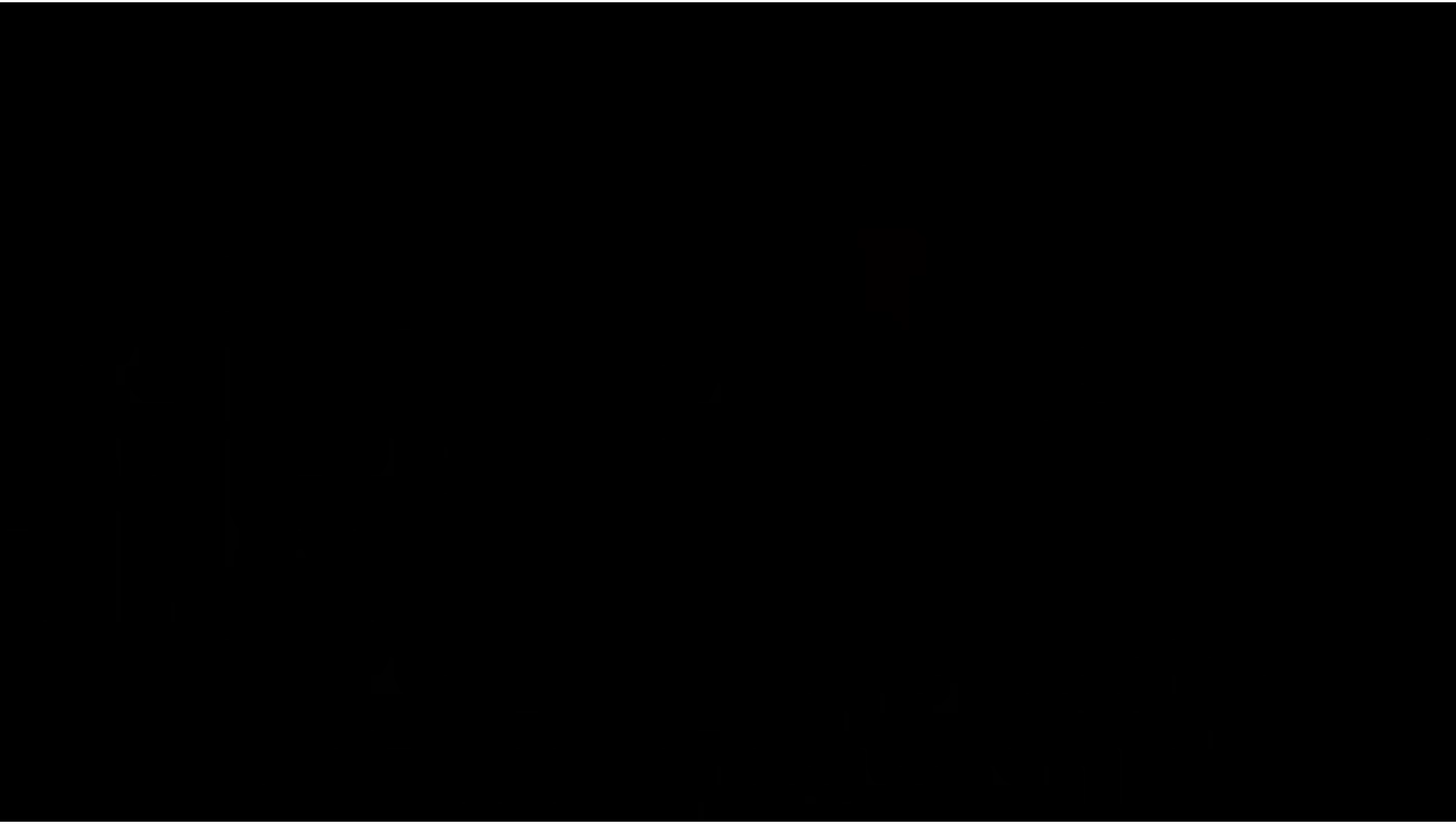
ISS Autonomous Drone

Robotics Systems for Industry 4.0 and Smart Nation

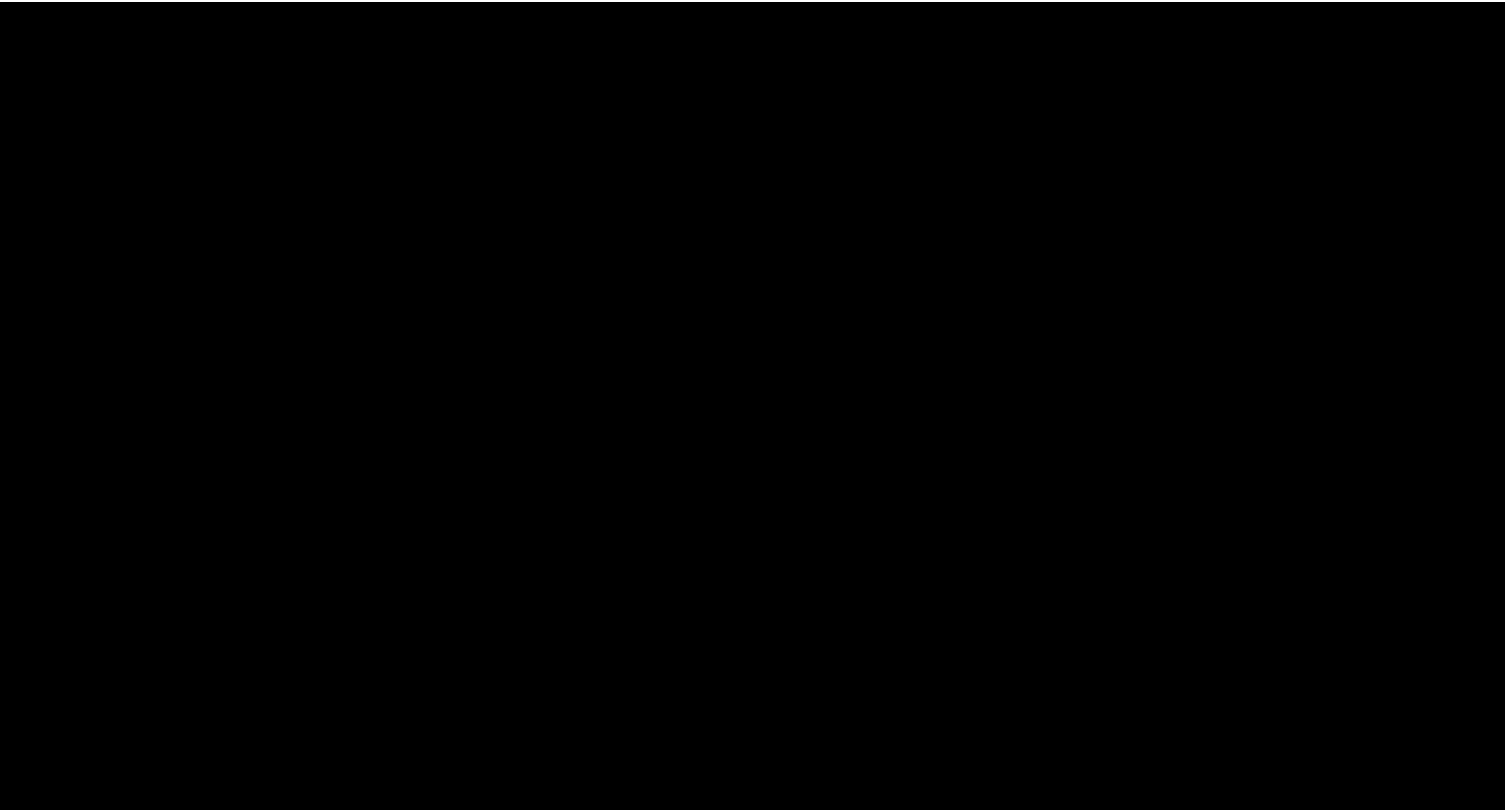
Futuristic Humanoids

https://www.youtube.com/watch?v=Bg_tJvCA8zw&t=332s

Futuristic Humanoids

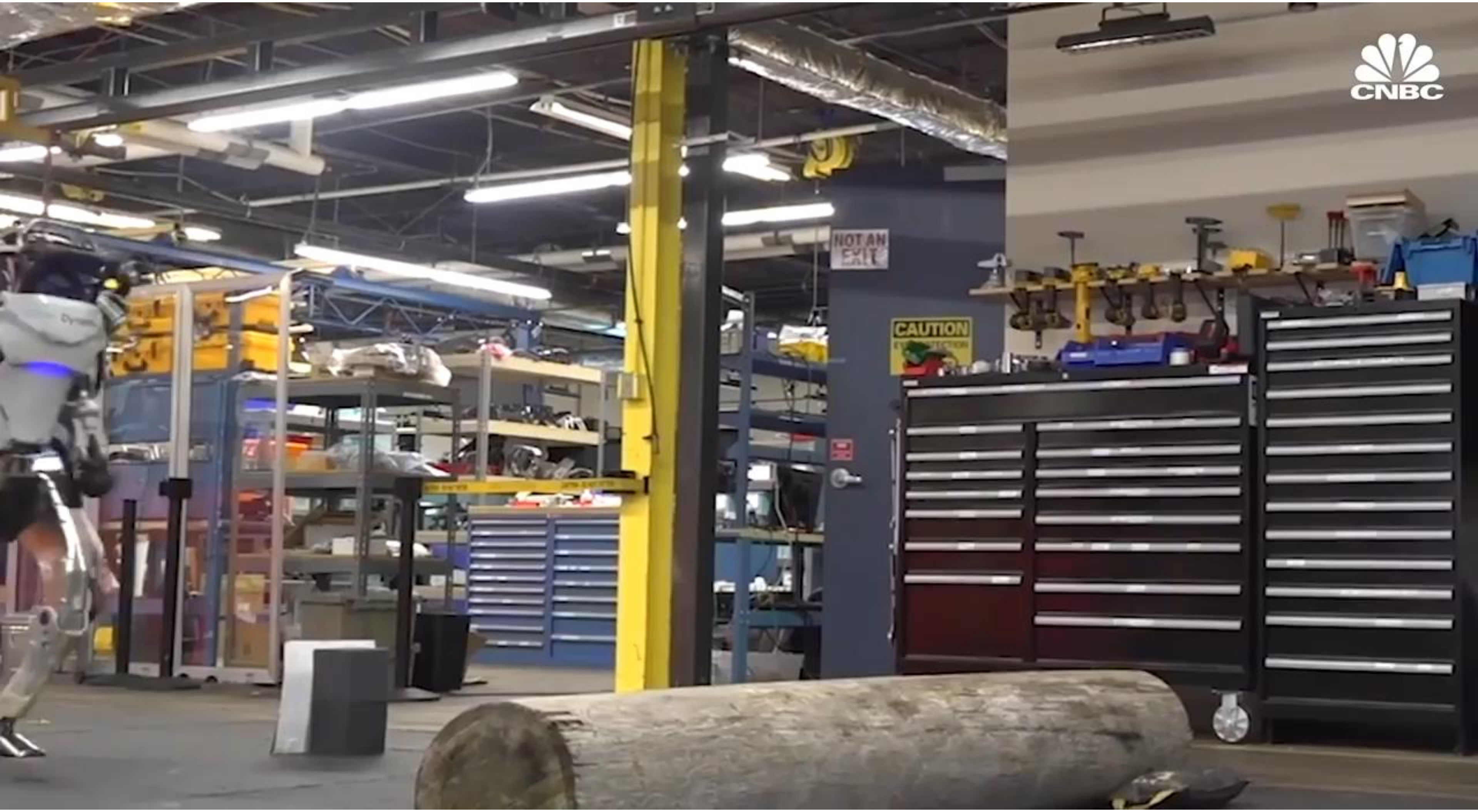


Robotic Chef



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

Agile Robotics
(Boston Dynamics)



https://www.youtube.com/watch?v=hSjKoEva5bg

End of Module 1

