MODULE 1: INTRODUCTION TO ROBOTIC SYSTEMS

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About Nicholas Ho

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- Artificial Intelligence System (AIS) Lecturer at NUS ISS; Courses covered include:
  - Robotics Systems
  - Autonomous Robots and Vehicles
  - Human Robot Systems Engineering
- Consultant for SME manufacturing company; Services provided include:
  - Design an Intelligent Voice Prosthesis Manufacturing Workcell system, integrated with advanced AI, IoT and other state-of-the-art technologies
  - Technical expertise in AI and IoT to optimize the performance of the Intelligent Workcell
  - Research on the latest AI and IoT technologies to continuously improve the system's capabilities
- BEng and PhD degree from School of Mechanical Engineering, NUS

Dr Nan Zhou Myo LEE

- Senior Lecturer in Software Systems Practice
- PhD and Bachelor of Mechanical Engineering with Robotics Specialization from NTU
- More than 14 years of sensorization, software simulation, intelligent system, digital solution development and integration using industrial IoT and automation technologies in both public and private sectors
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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

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 labor?
  - A machine capable of intelligent action in the real world?
    - ➢ E.g. 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?)
- **Robotic Industries Association (RIA) definition:**
  - ○ A robot is a reprogrammable, multifunctional machine designed to manipulate material, parts, tools or specialized devices, through variable programmed motions for the performance of a variety of tasks.

Industrial Robots & Mobile Robots

History

- Middle of 20th century: The dawn of AI marked the beginnings of robotics as a field. The first robots were developed, showcasing advances in mechanics, controls, computers, and electronics – **Robotics = The science & technology of robots**
- 1960s: The introduction of numerical control machines, like **CNC**, revolutionized precision manufacturing. Additionally, **teleoperators** were developed for remote handling of radioactive materials, which is crucial for human safety in environments that are otherwise inaccessible or hazardous.
- Late 1970s: **Industrial robots** became essential components in the automation of flexible manufacturing systems, contributing significantly to efficiency and safety in production processes.
- 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, which included developments in **human augmentation** and the emergence of **service robots**

History

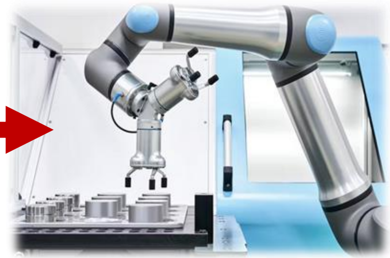
- 2000s: The new millennium introduced a paradigm shift towards **human-centered and life-like robotics**. This era emphasized robots designed to work alongside humans, assisting in everyday tasks and adapting to human environments
- 2010s: With the integration of **cloud computing and IoT**, robots became increasingly interconnected and intelligent, capable of sharing information and learning from collective experiences
- 2020s: The proliferation of **machine learning** and **deep learning** technologies has resulted in robots with unprecedented levels of **autonomy and cognitive abilities**. Developments in **soft robotics** are leading to machines that are safer and more adaptable to working intimately with humans

History

- <u>2030s (projected):</u> Anticipated advancements include further integration of robotics with **biotechnology** and **nanotechnology**, leading to breakthroughs in **medical robots** and **microscopic robots** for environmental and health monitoring
- <u>2040s and beyond (projected):</u> The convergence of AI, quantum computing, and robotics is expected to lead to **quantum robotics**, providing exponential increases in computational capabilities and the emergence of robots with problem-solving abilities far beyond today's standards

Evolution of Robot

Automated Guided Robots



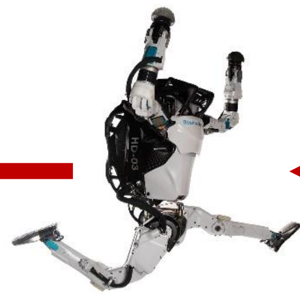
Robotic Arms

Mobile Robots

Service Robots

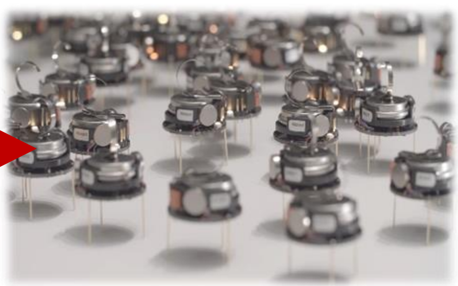
UAVs

Autonomous Vehicles



Humanoids

Social Robots



Swarm Robots

Bio-hybrid Robots

Cognitive Robots

Classical Robotics

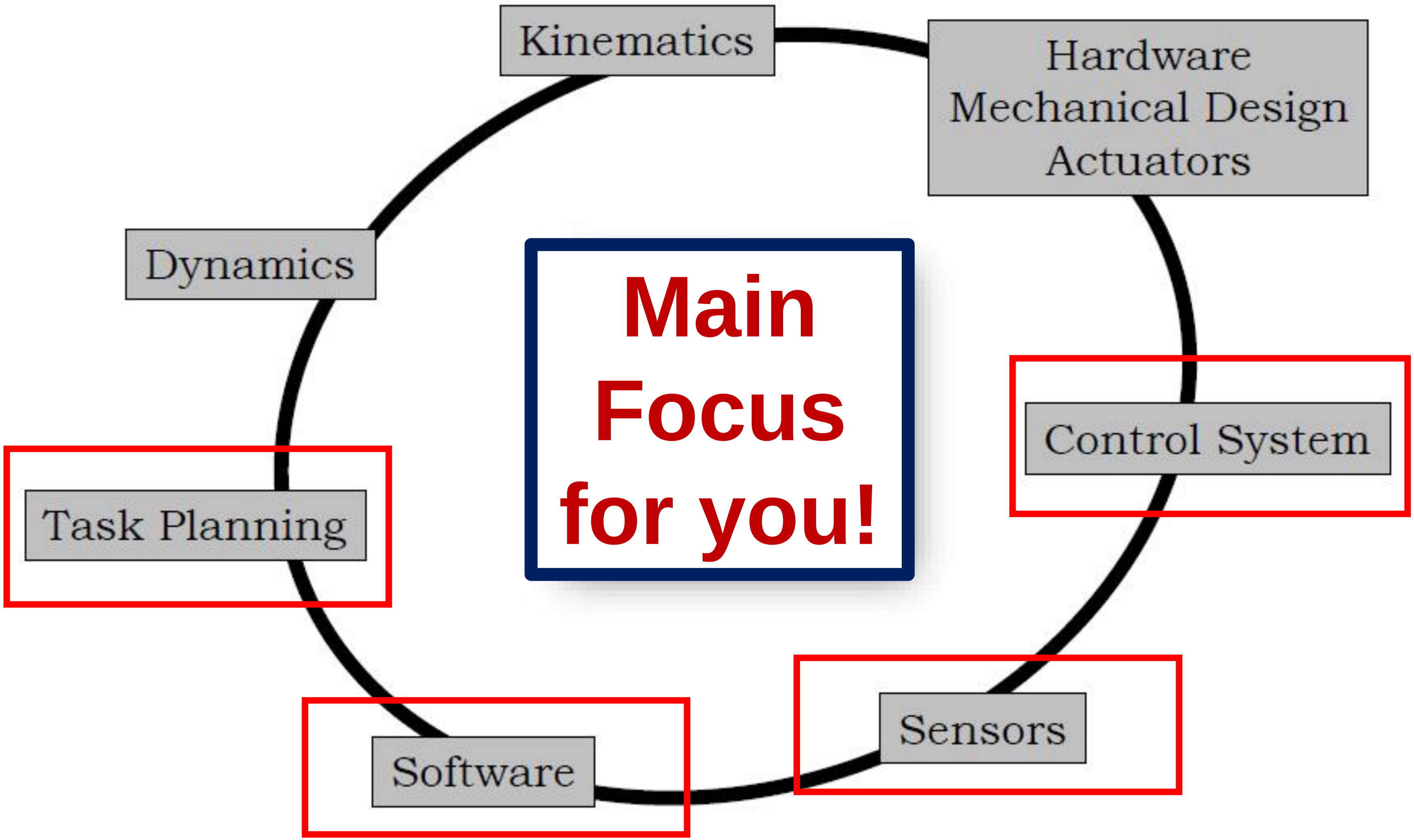
Understanding classical robotics first:

- Focuses on the design, construction, and operation of robots that perform predefined tasks in structured environments.
- Typically programmed to follow specific rules and algorithms, and they do not possess the advanced learning or adaptive capabilities found in modern, cognitive robotics.

Crucial components of classical robotic systems	
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	Includes mechanical structure (links, joints, frames), actuators, sensors, and electronic components. Assembling these parts will result in a functional robot system

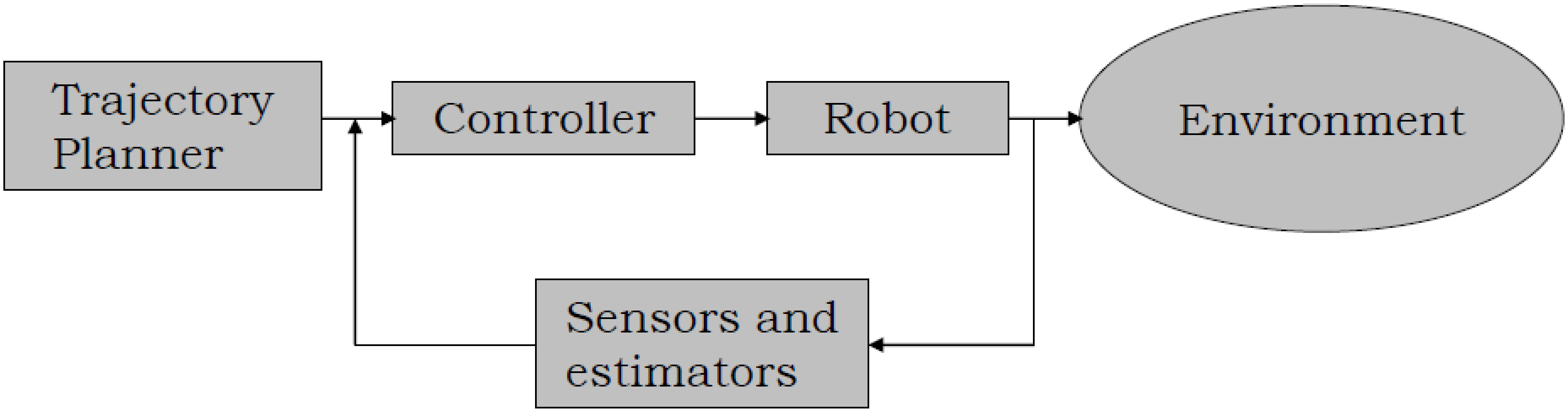
Development and Architecture of Robotic Systems

The Robotic System

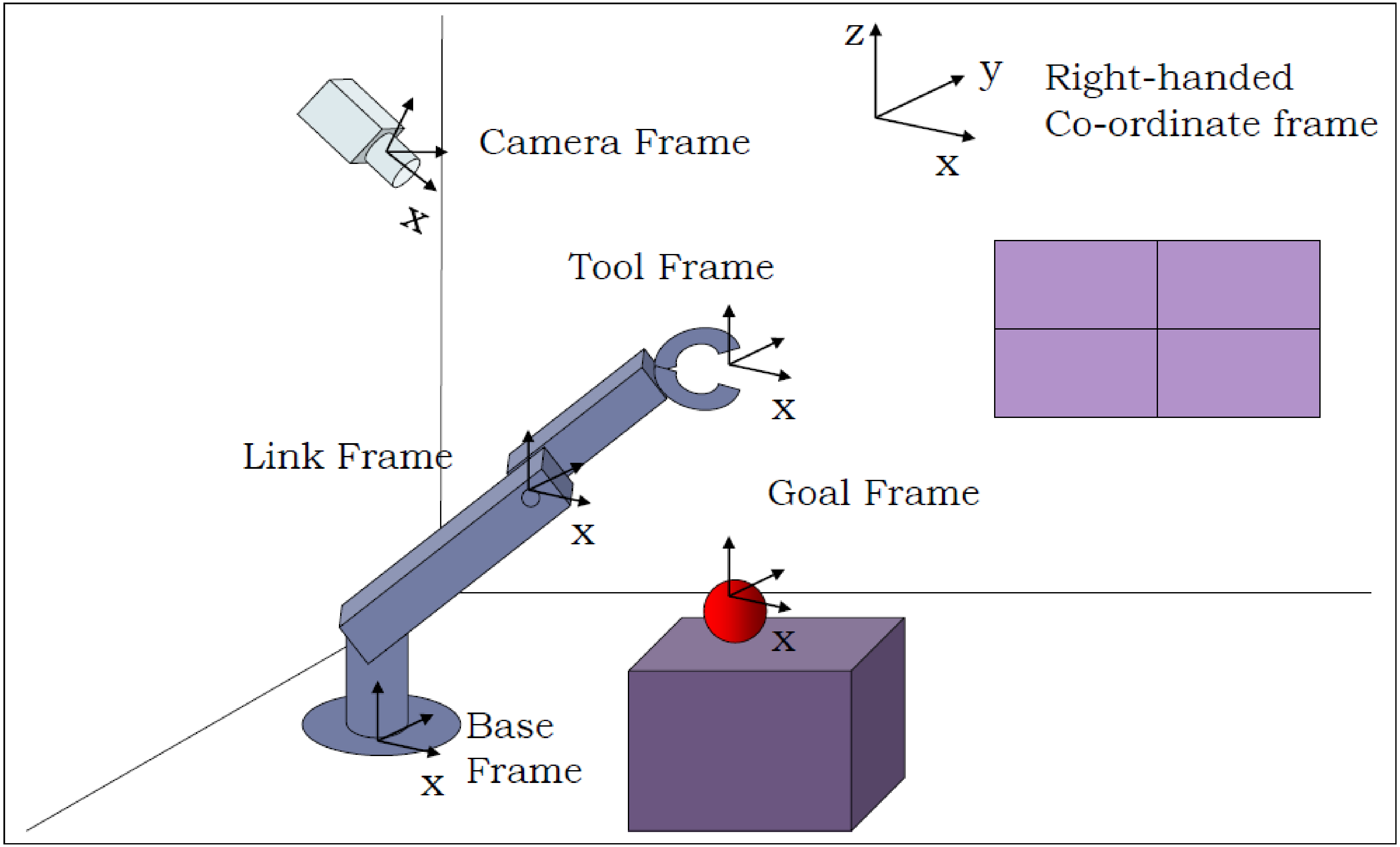


Basic Blocks of a Typical Robotic System

Closed-loop Robot Control System:



Coordinate Frames



Kinematics

- KINEMATICS - the analytical study of the geometry of motion of a robot arm:
  - with respect to a fixed reference coordinate 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 massless 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

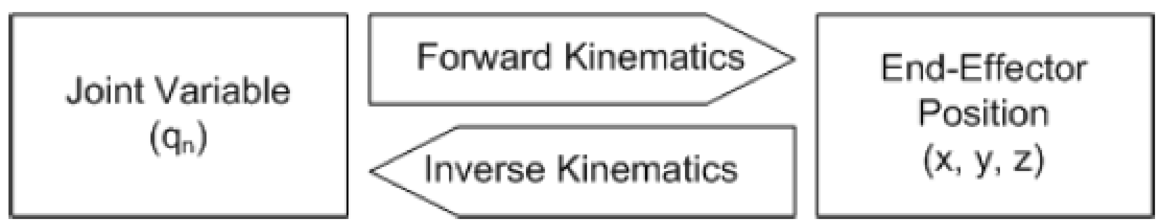
Using kinematics to describe the spatial configuration of a robot provides us **2 approaches:**

1. Forward Kinematics (direct)

- Given the joint angles for the robot, what is the orientation and position of the end effector?

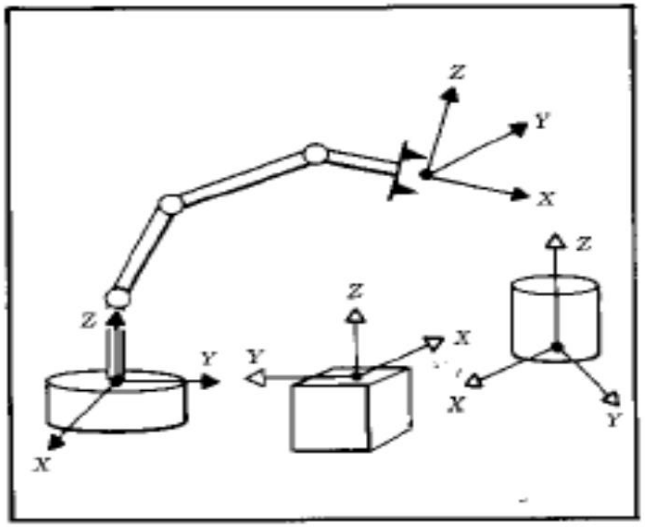
2. Inverse Kinematics

- Given a desired end effector 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



Inverse Kinematics

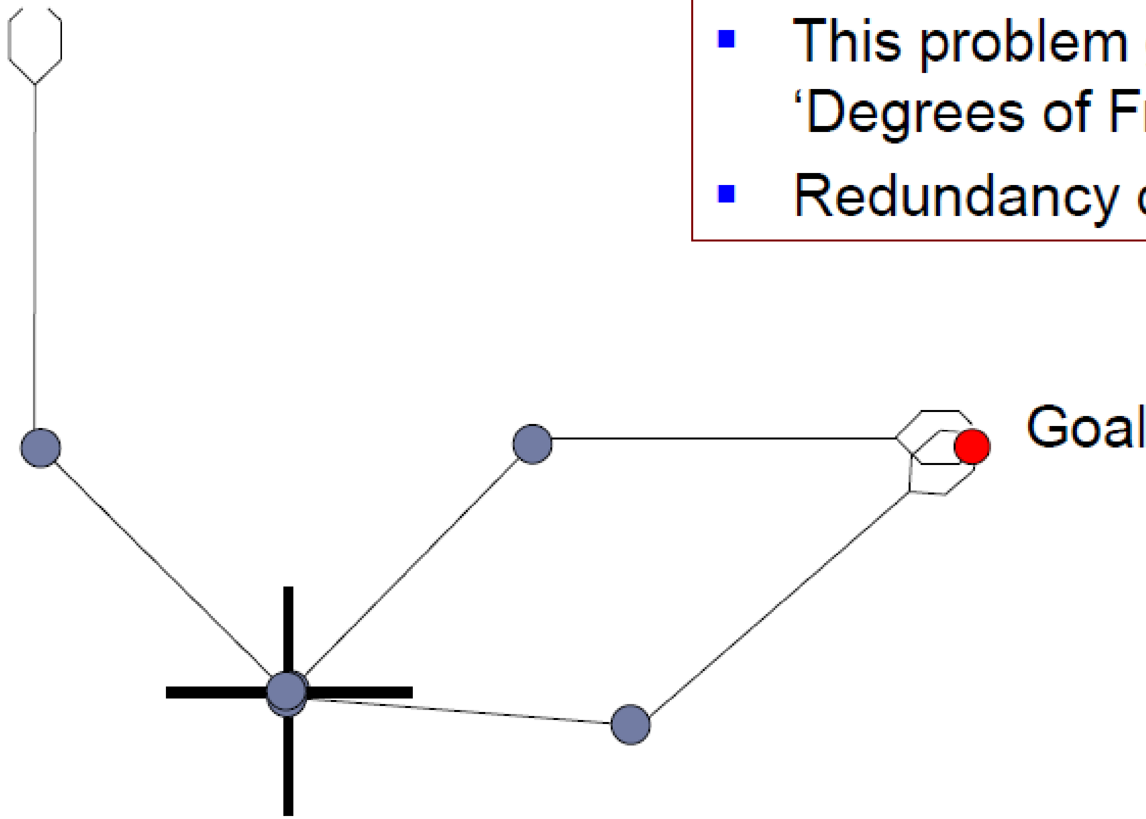
- For a robot system the **inverse kinematic problem is one of the most difficult to solve.**
- The robot controller must solve **a set of non-linear simultaneous equations.**
- The problems can be summarized as:
  - The existence of **multiple solutions.**
  - The possible **non-existence of a solution.**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

Deriving Kinematics

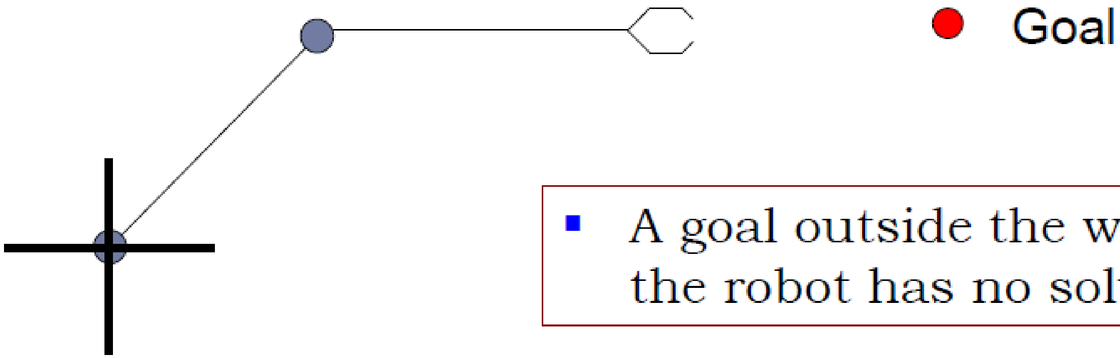
- If the manipulator is simple enough, kinematics can be computed by a direct geometric analysis.
- As the complexity and the number of joints of the manipulator increases, it is preferable to adopt a less direct method, which nevertheless is based on a systematic, general procedure.
- This principle (**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

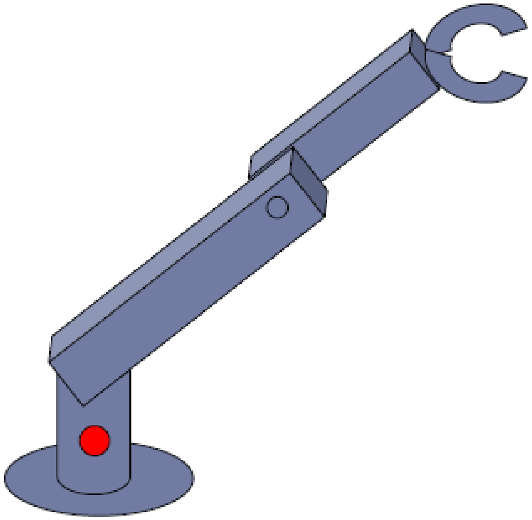
- This two link planar manipulator has two possible solutions
- This problem gets worse with more 'Degrees of Freedom.'
- Redundancy of movement.



Non Existence of Solution

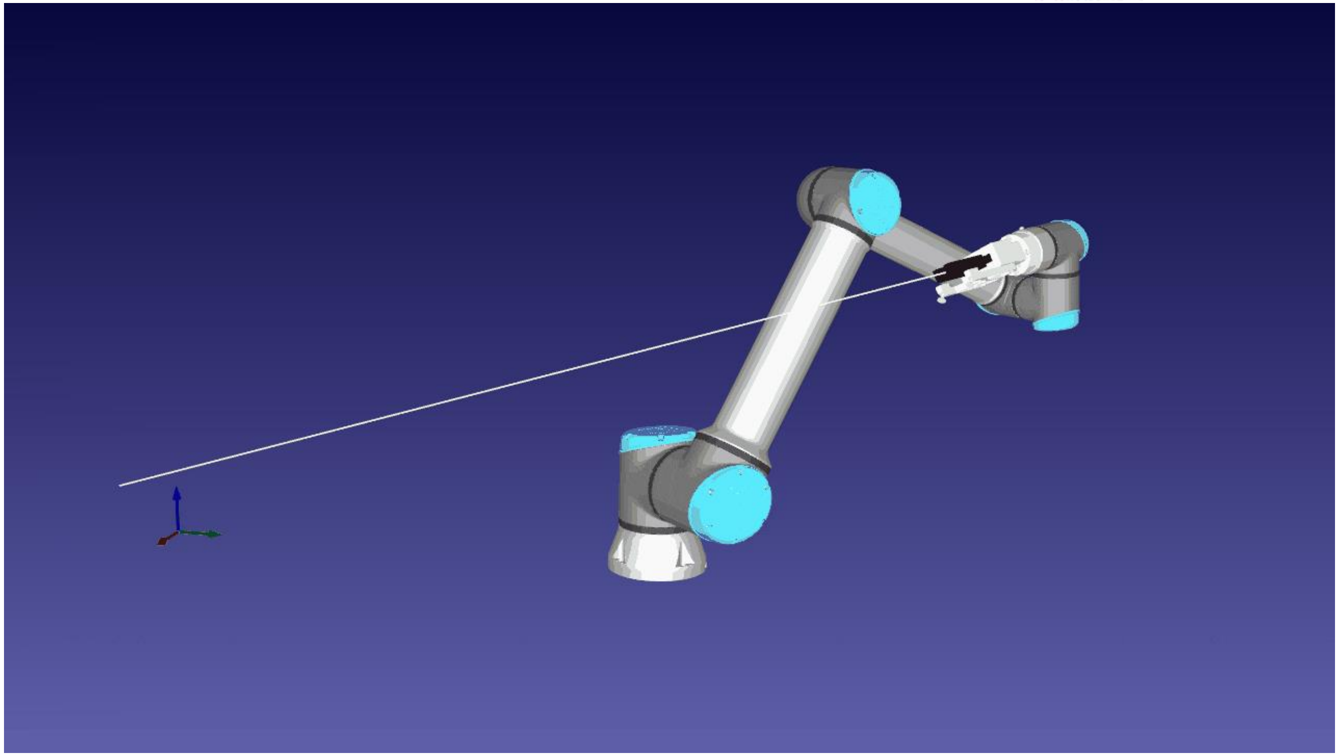


- A goal outside the workspace of the robot has no solution.



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

Singularities

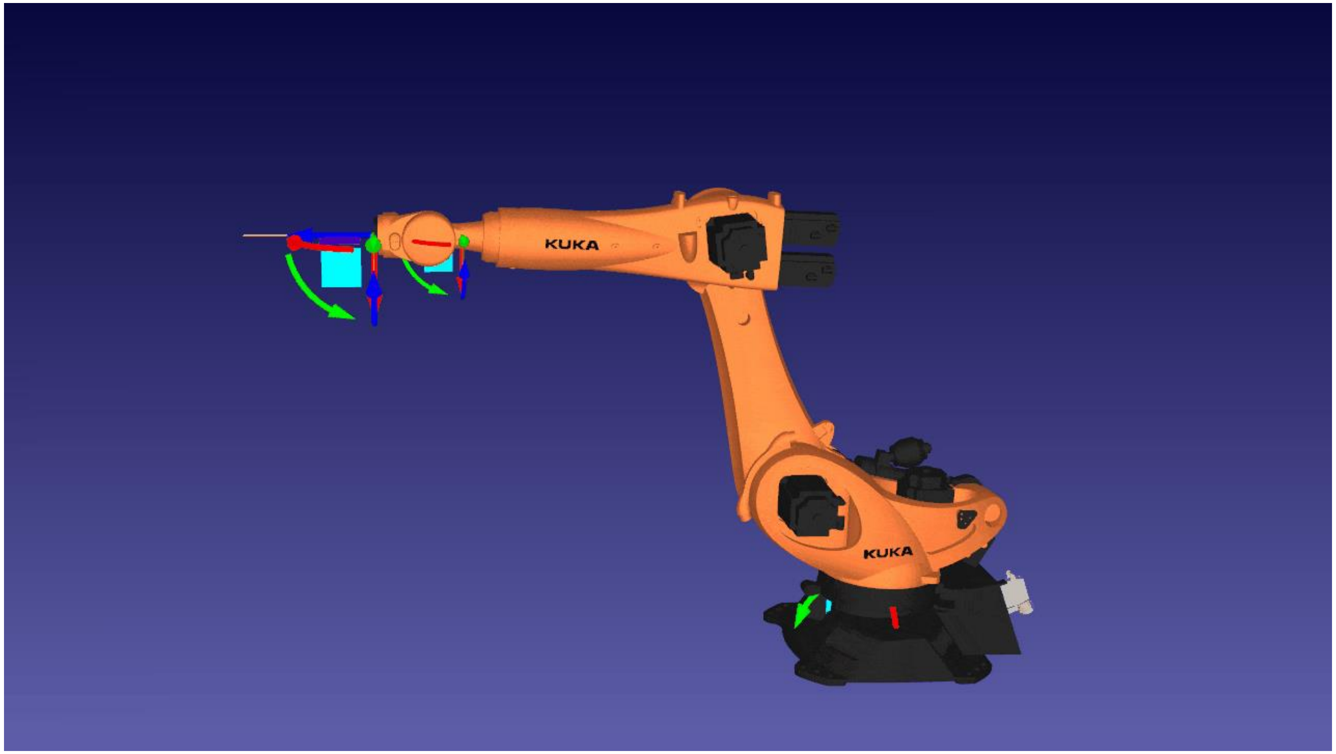


Wrist Singularities
[Joint 4 & 6 become “coincident”]

When a robot reaches a wrist singularity, its end effector stays motionless while Joints 4 and 6 rotate at top speed in opposite directions. The robot then continues along its path.

Note that, in this animation, the wrist joints are moving infinitely fast in the middle of the line. If this was a physical robot, this movement would be impossible to achieve while preserving the constant velocity of the end effector.

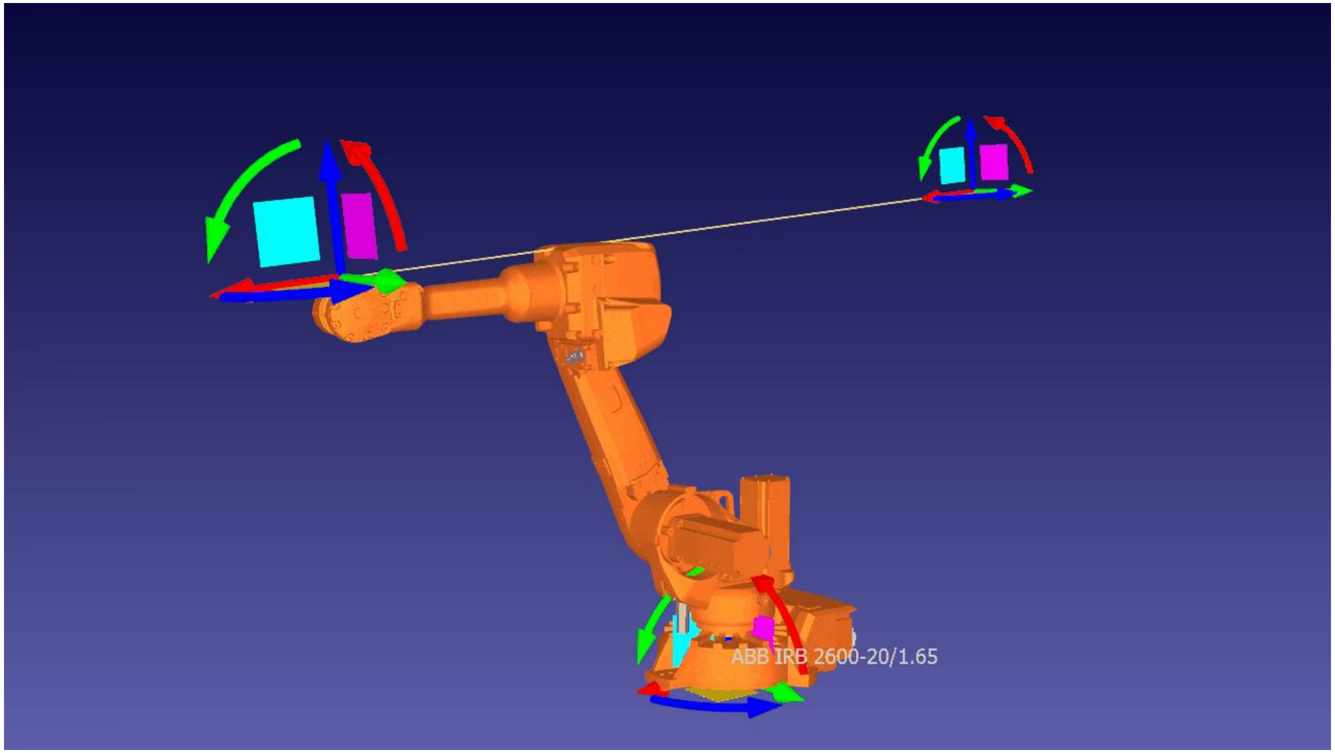
Singularities



Elbow Singularities

Can usually recognize an elbow singularity because it looks like the robot has "stretched too far"

Singularities



Shoulder Singularities
[Joint 1 & 6 become “coincident”]

As the robot approaches a shoulder singularity, the motors in Joints 1 and 4 try to spin 180° at infinite speed, which is not feasible in practice.

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 understand how to **balance the forces at the robot's end-effector with the necessary forces and torques at its joints to keep the robot arm stable and unmoving.** For joints that slide (prismatic), this means figuring out the pushing/pulling force required. For joints that rotate (revolute), we need to calculate the torque needed.
- E.g. when the robot is holding something or in a specific position (an equilibrium configuration), it remains perfectly still and controlled, without any part of it moving unintentionally.

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.

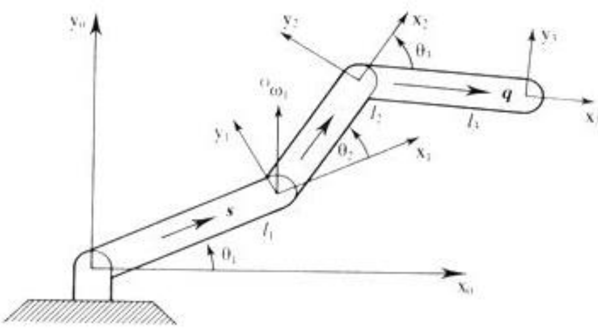
- Dynamics gives **the mathematical relation between forces and torques acting on the manipulator joints, the masses and moments of inertia of the links, the gravitational force and the behaviour of the system.**

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

kinematics

The effect of a robot's geometry on its motion.

from sort of simple to sort of complex



three-link manipulator

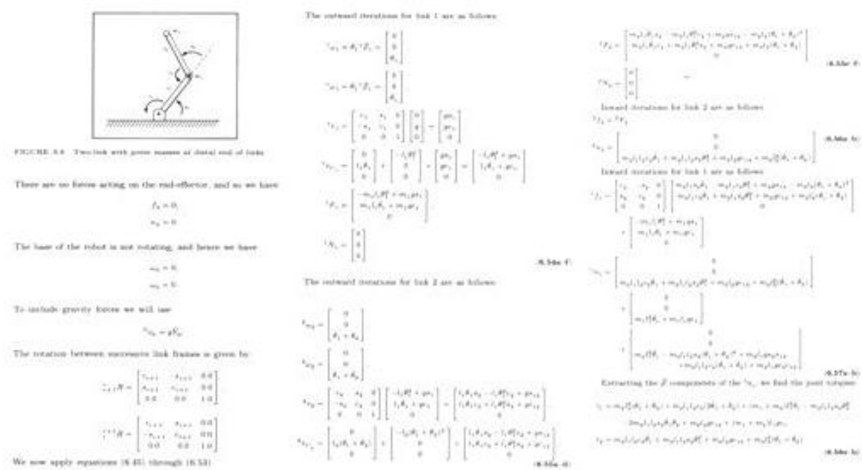
represented by a 4x4 matrix

dynamics

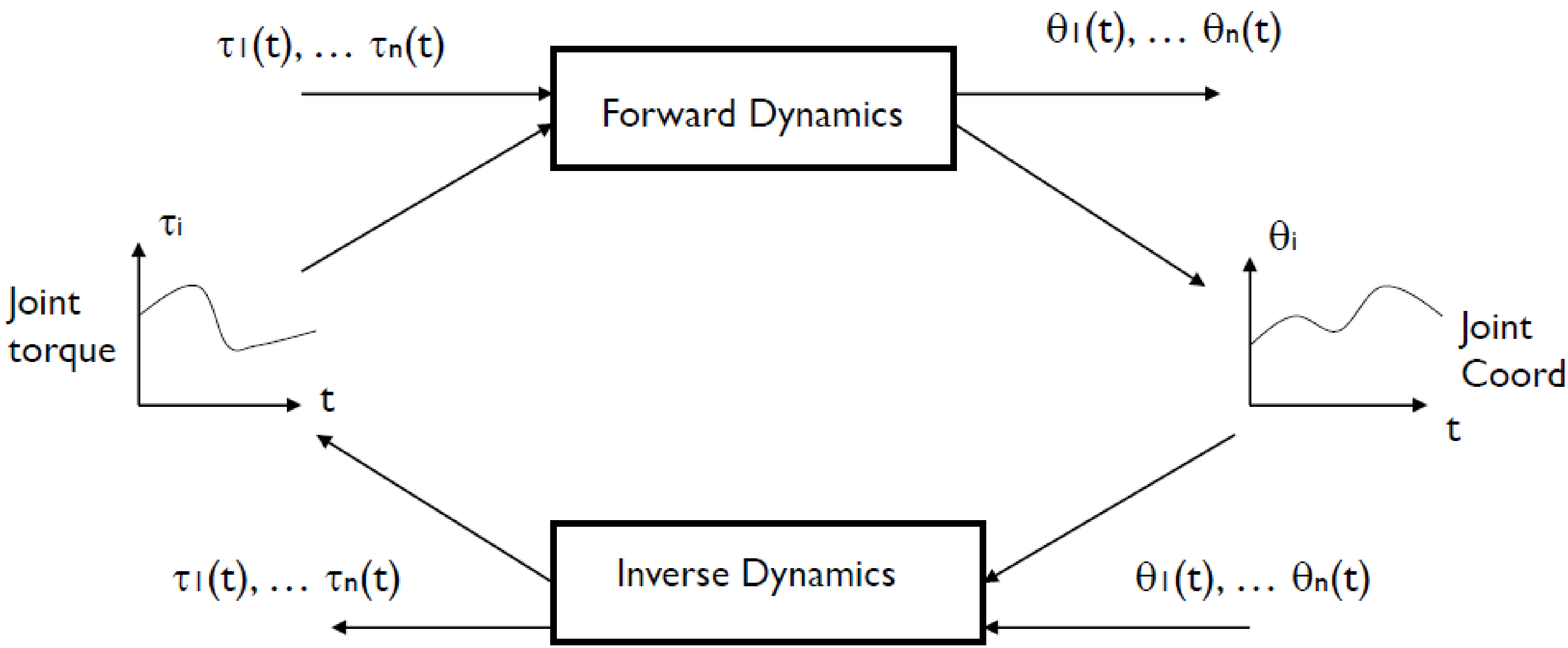
The effect of all forces (internal and external) on a robot's motion.

Aaargh!

two-link manipulator



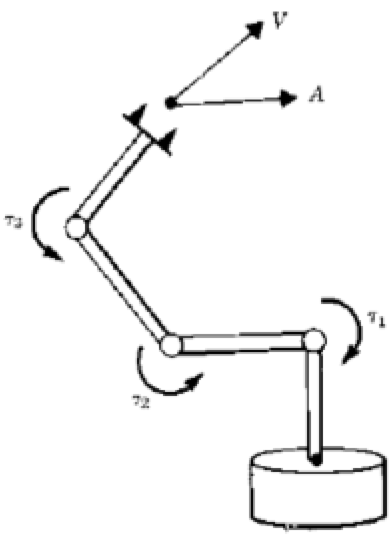
Forward & Inverse Dynamics



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:

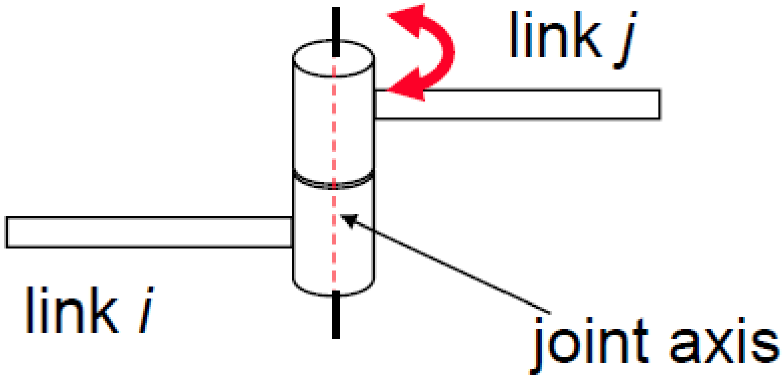
1. **Simulation**
   - **Designing prototype robots** virtually to save costs.
   - **Testing control strategies** in simulations to avoid the expense and risk of immediate real-world implementation.
   - Allowing for **economical** adjustments and improvements before physical production.
2. **Controller Design**
   - **Constructing precise mathematical models** that capture how the robot's joints react to various forces and torques.
   - **Crafting controllers that allow for predictive responses to physical interactions**, leading to smoother and more precise movements.
   - **Adjusting control strategies based on dynamic analyses to effectively manage physical factors** such as friction between moving parts, the inertia of heavy components, and external forces like gravity that influence the robot's motion.

Design

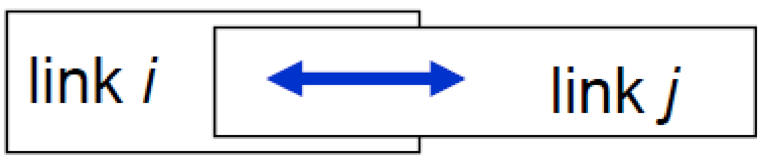
- Type of joints
- Actuators and power transmission
- Degrees of freedom
- Specialized vs universal (min 6 joints)
- Dexterity Considerations (Geometry, Workspace)
- Speed, size, load capability
- Rigid vs Flexible
- **Sensors (Most important in this course!)**

Types of Robot Joints

Two basic types:



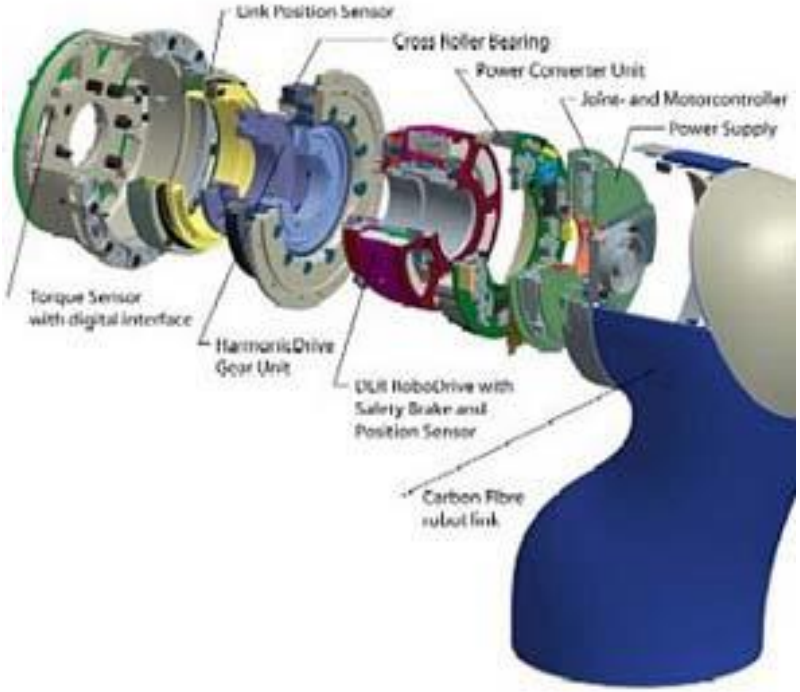
Rotational/Revolute/ Rotary



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:

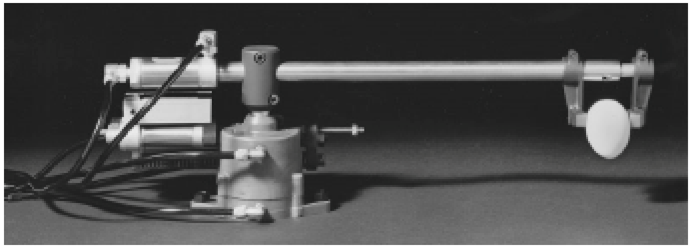
Pneumatic:
- energy efficient
- hard for feedback control

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

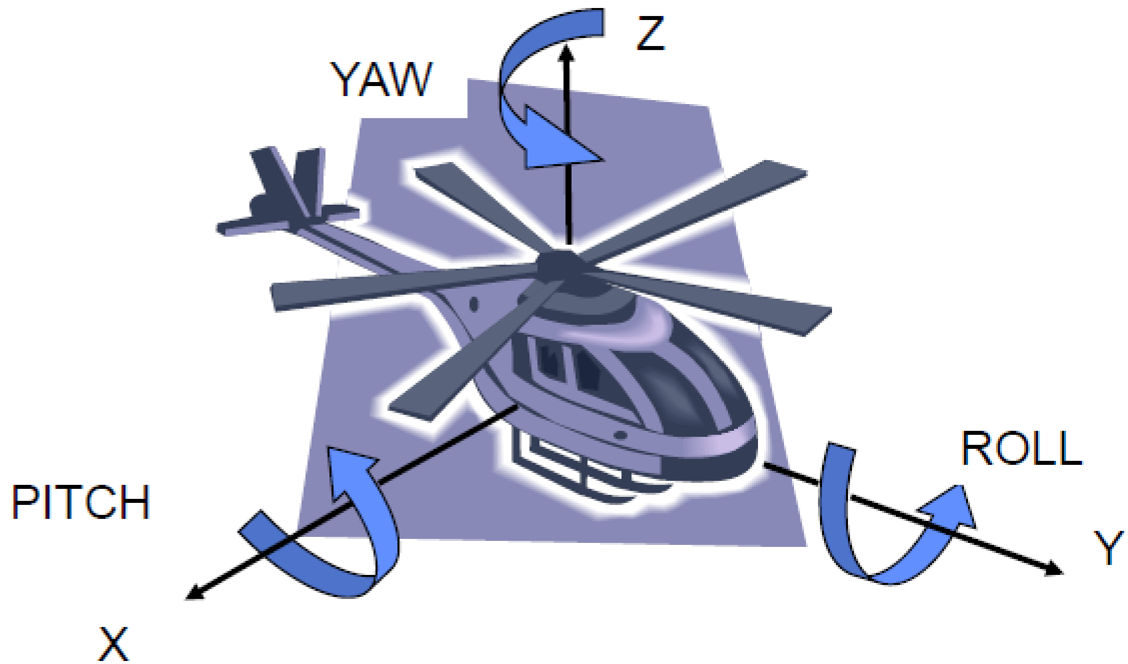
⇒ End-effectors: often are pneumatic tools



Degrees-of-Freedom (DOF)

Rigid body in 3D Space → 6 DOF

- 3 for position
- 3 for orientation

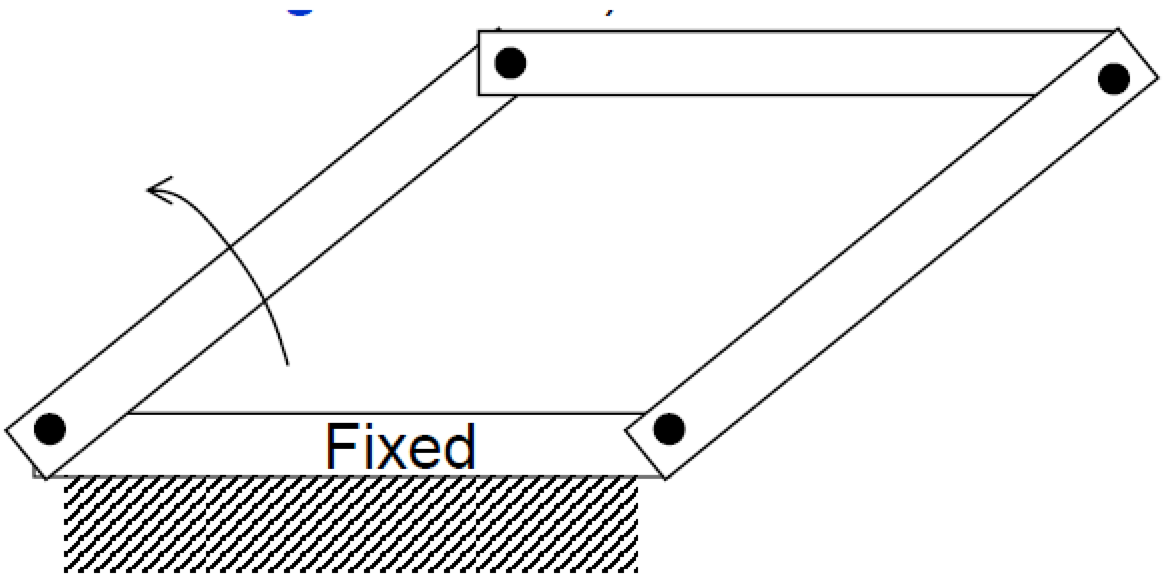


Degrees-of-Freedom (DOF)

In robotics/mechanism,

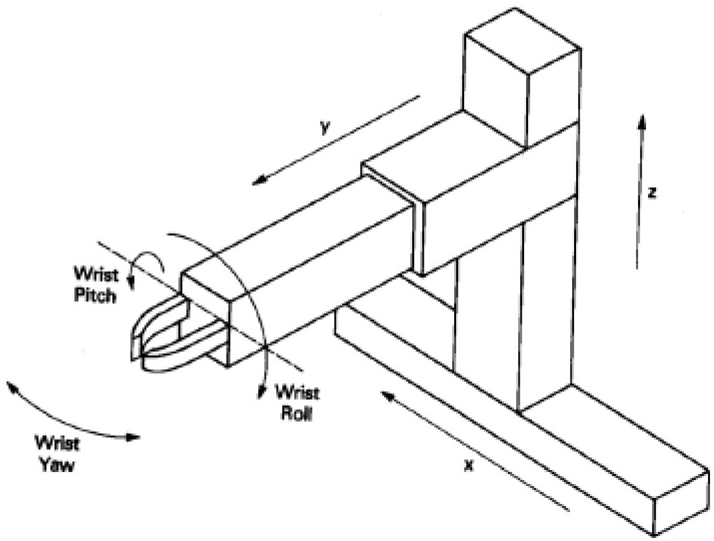
DOF = number of independent position variables that would have to be specified to locate all parts of the (rigid-body) mechanism

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

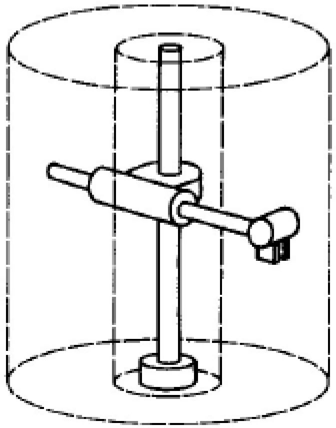


Classification by Coordinate Systems

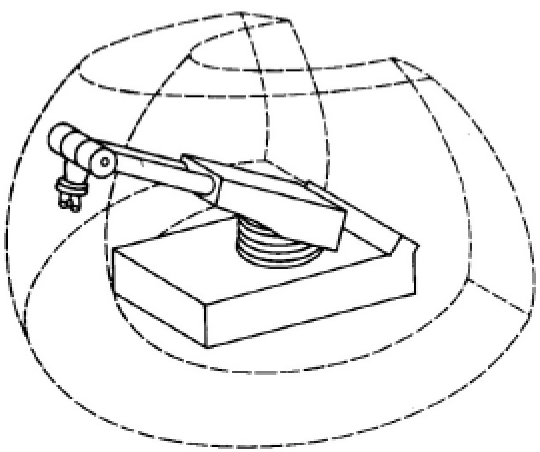
Cartesian



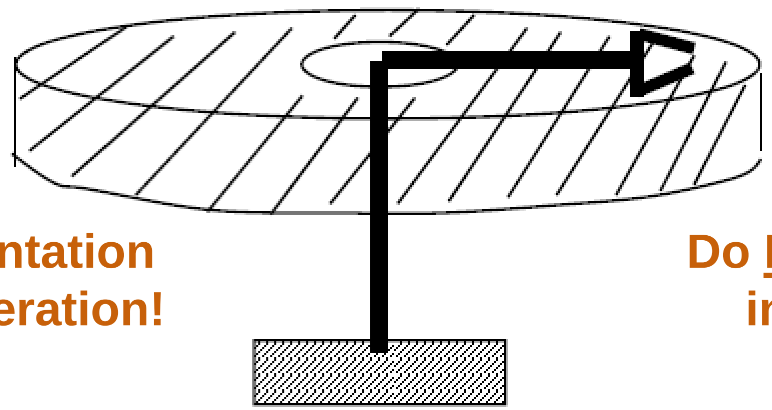
Cylindrical



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!

↓

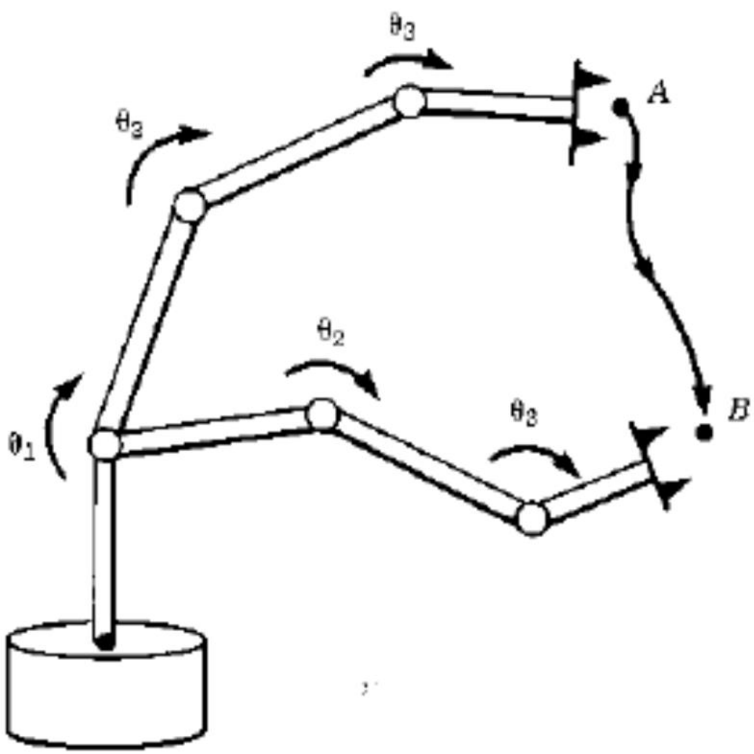
Reachable Workspace

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

Dextrous workspace is usually much smaller than reachable workspace

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

Manufacturing:
Tesla Gigafactory in Berlin

Source: https://www.youtube.com/watch?v=7-4yOx1CnXE

Cleaning:
SOMATIC Bathroom Cleaning Robot

Source: https://www.youtube.com/watch?v=RaTKObI1xyc

Logistics/Warehouse:
ULTRA BLUE Mobile Robot

Source: https://www.youtube.com/watch?v=uBh74Jg7J6U

Farming: Fruit Picking Drones

Source: https://www.youtube.com/watch?v=IzaaSIEDg7s

Healthcare: Mirokai Robots

Source: https://www.youtube.com/watch?v=ugOHxveRiyM

Healthcare:
Autonomous Wheelchair

Source: https://www.youtube.com/watch?v=XZx4KpR2TqY

Underwater: BeeX

Source: https://www.youtube.com/watch?v=9urCtjUAnt0

Military: Robot Dogs in China

Source: https://www.youtube.com/watch?v=xYRtuBPFPDI

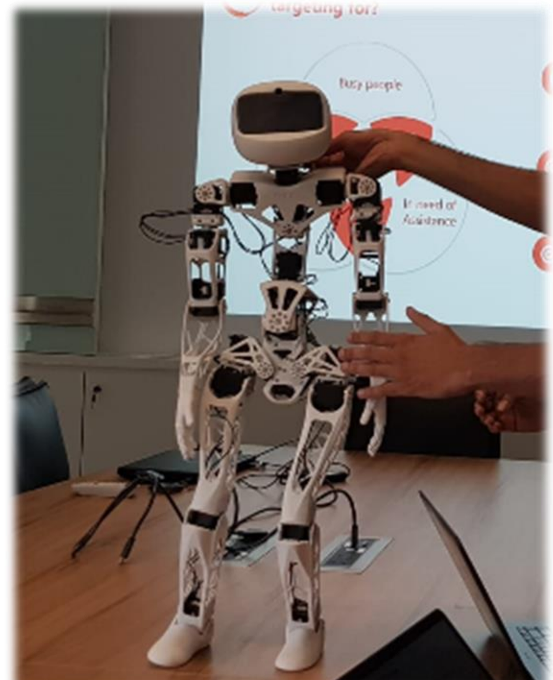
Past NUS-ISS Large-Scale Robotics Projects

Bernard: Our friendly ISS Humanoid

Current Features

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

https://youtu.be/s2mJiWkBNbQ



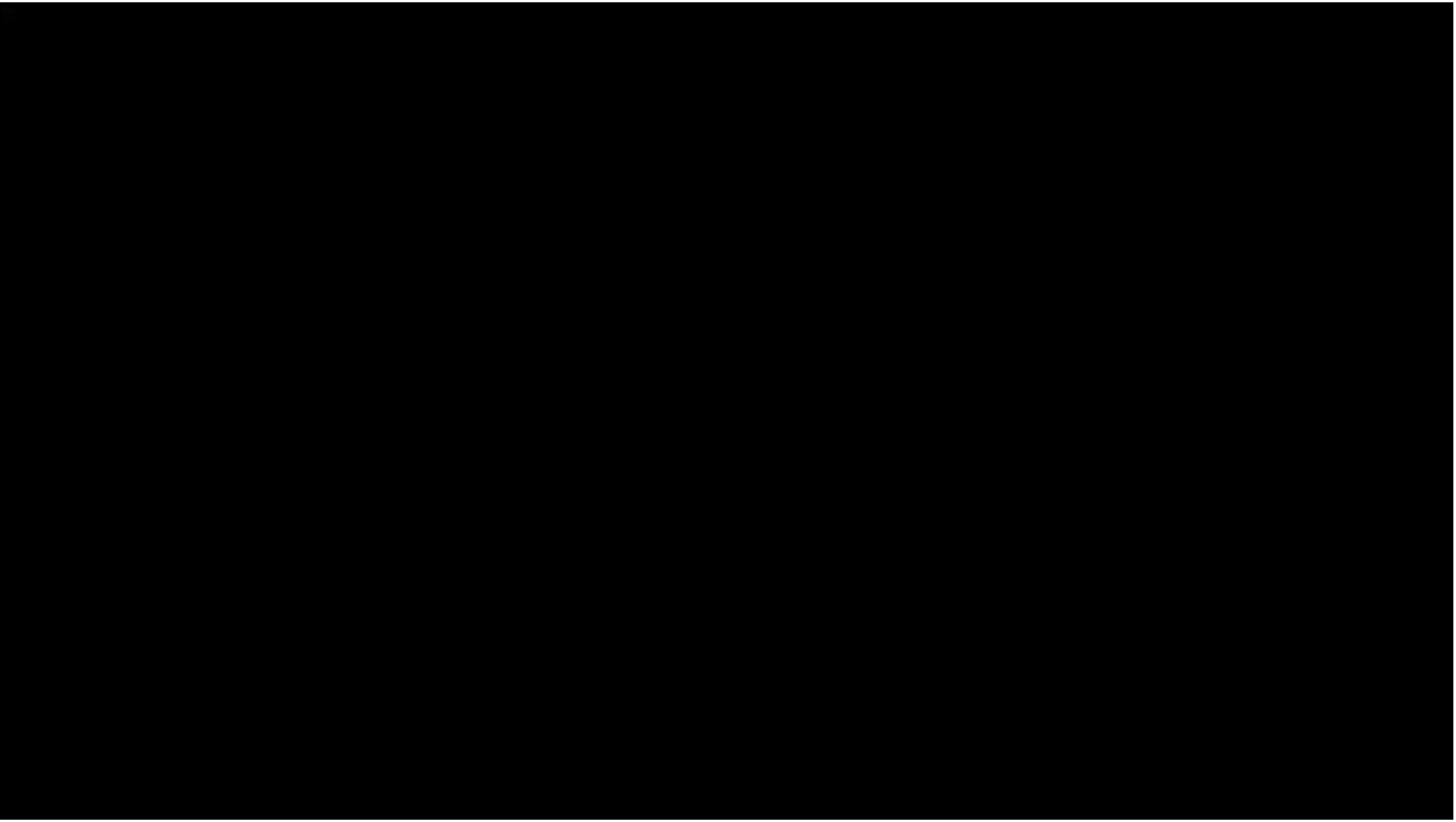
Next Variant

- 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

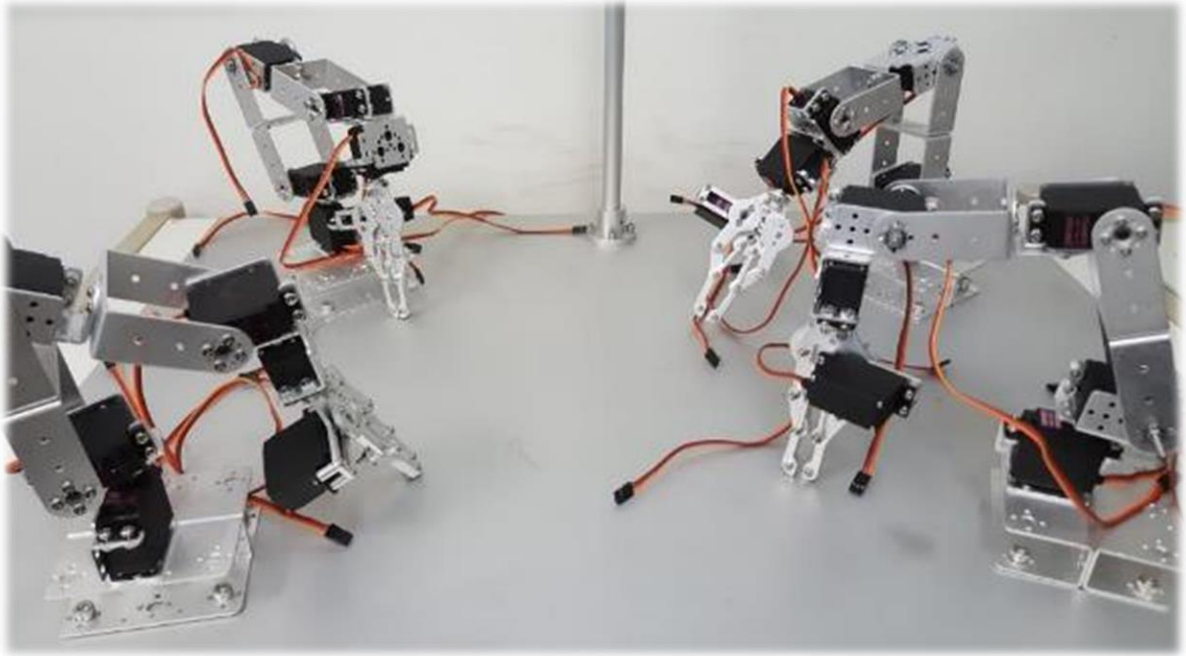
Collaboration between ISS and SingHealth Surgeons

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

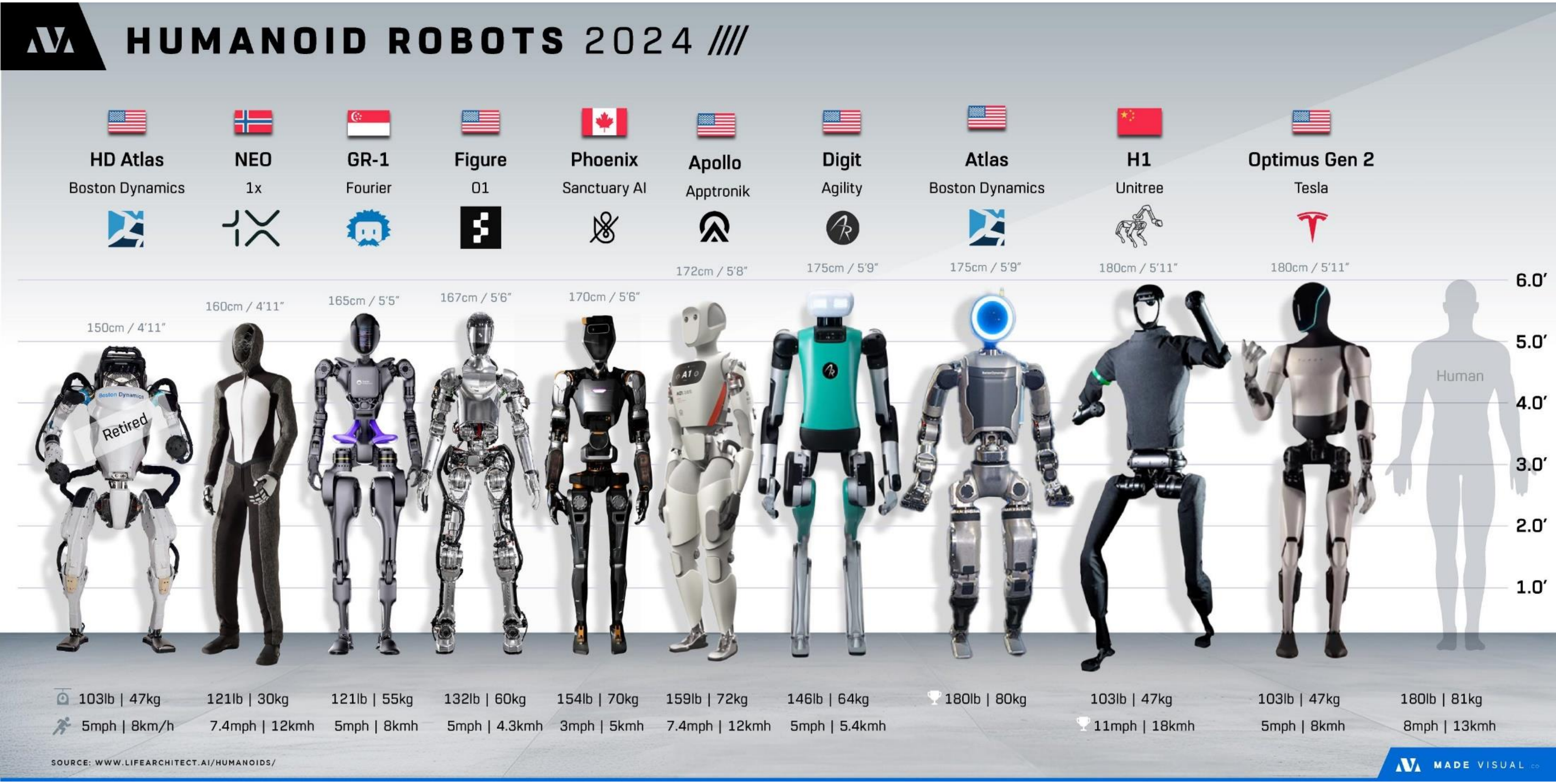
- Took part in Singapore Amazing Flying Machine Competition 2018 (April)
- Semi-autonomous Category

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

ISS Autonomous Drone

Robotics Systems for Industry 4.0 and Smart Nation

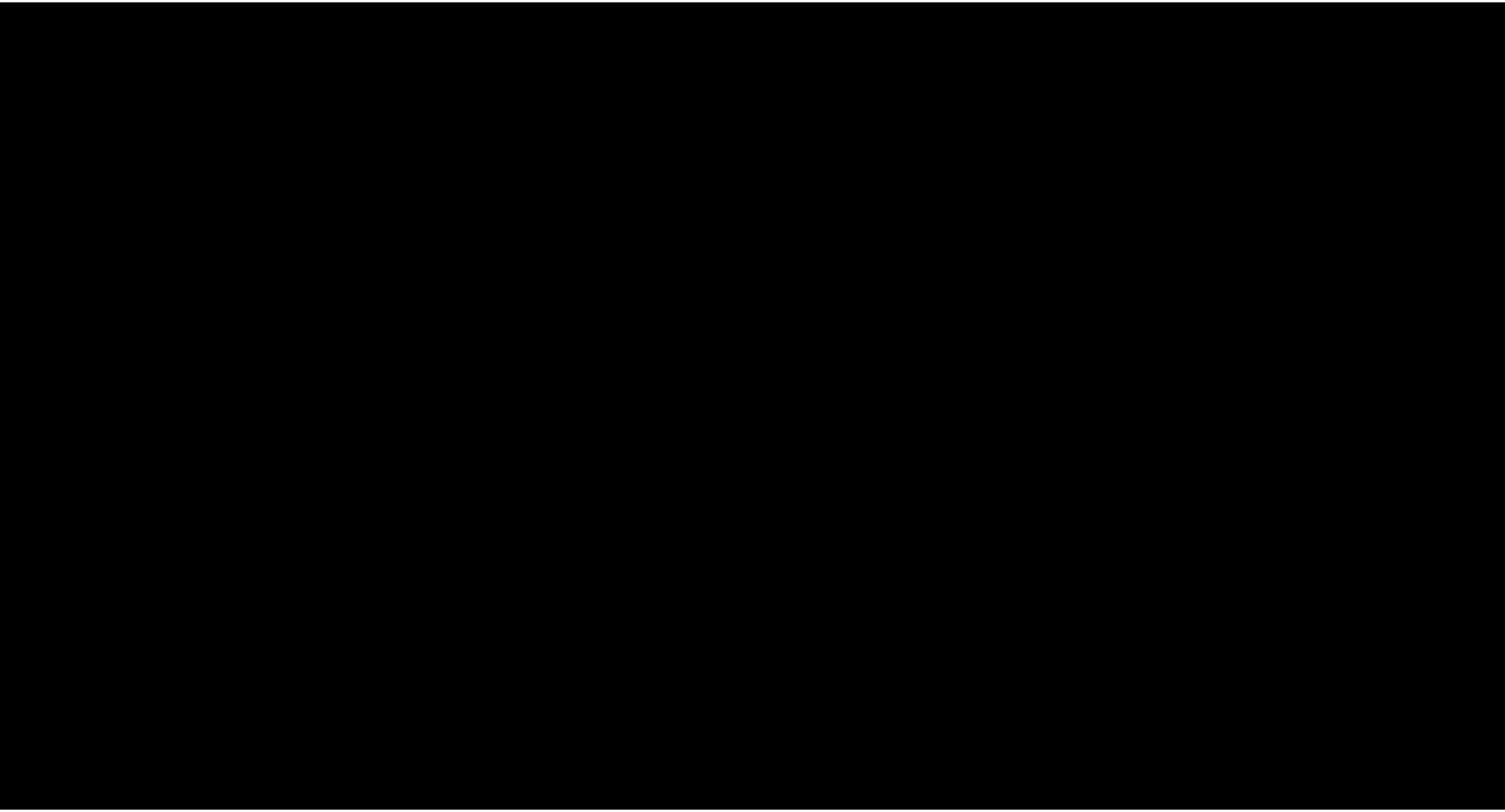
Futuristic Humanoids



Futuristic Humanoids:
Tesla Optimus Robot

https://www.youtube.com/watch?v=cFbK951XkGo

Robotic Chef



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

Agile Robotics:
Boston Dynamics Atlas – Early Version

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

Agile Robotics:
Boston Dynamics Atlas – Next Gen Humanoid Robot

https://www.youtube.com/watch?v=29ECwExc-_M

End of Module 1