ECE 470: Introduction to Robotics

Lecture 01

Liangjing Yang
Assistant Professor, ZJU-UIUC Institute
liangjingyang@intl.zju.edu.cn

Wechat ID: Liangjing_Yang

Course Introduction

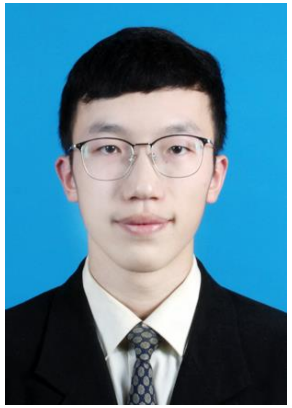
Introduction to Robotics

Introducing Your Teaching Team

Instructor: Liangjing Yang
Assistant Professor, ZJUI
(liangjingyang@intl.zju.edu.cn)

Robotics, Computer Vision & Medical Image Processing

Graduate TA: Xiao Songjie
PhD Student, ZJU
(songjiexiao@zju.edu.cn)



Surgical Robots

TAs: Zhefan Lin, Shuren Li, Zhenyu Zong, Boyang Zhou

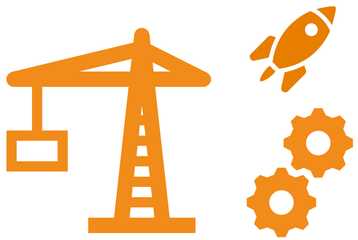
Consultation Hours

TBA (welcome to make appointment)

Self-Introduction: Teaching

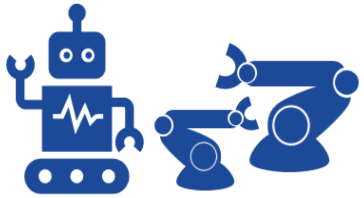
- ME340 Dynamics of Mechanical Systems
- ME360 Signal Processing
- <u>ECE470/ME445 Introduction to Robotics</u>
- ECE486 Control System

Dynamics

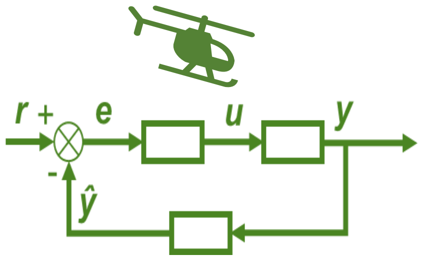


Signal Processing

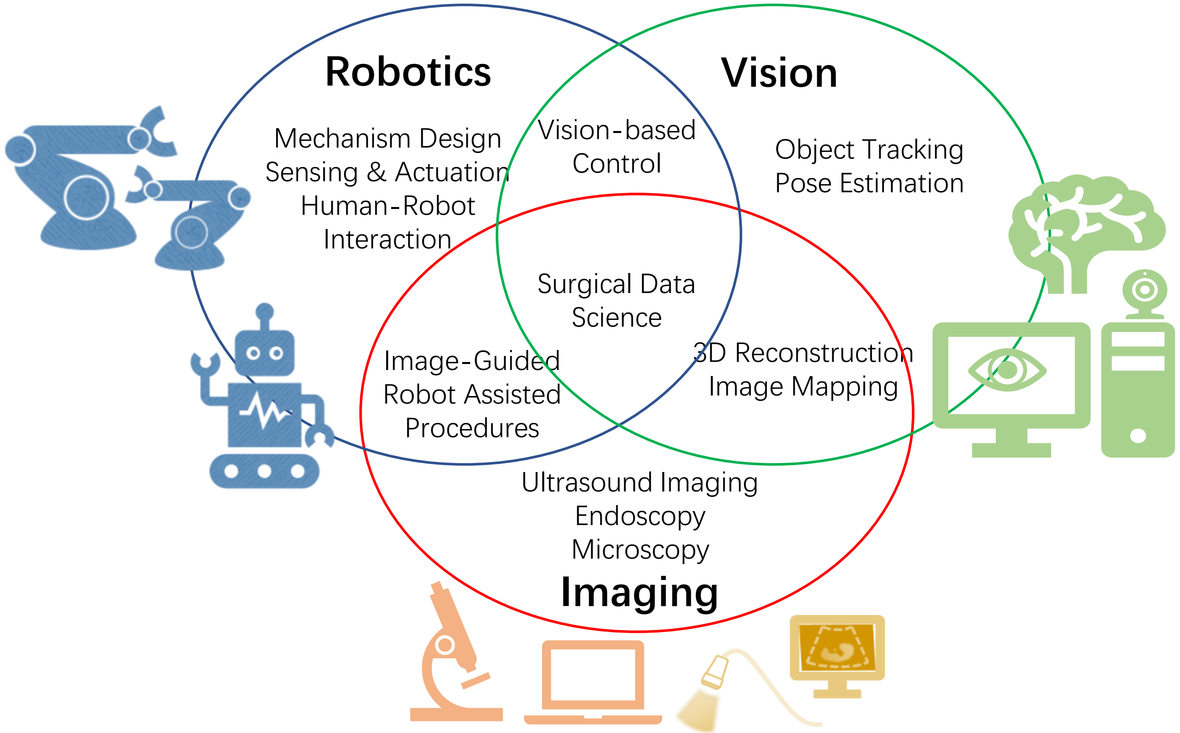
Robotics



Controls



Self-Introduction: Research



Syllabus and Schedule

- **Lecture**

O. Overview
- Science & Engineering in Robotics

I. Spatial Representation & Transformation
- Coordinate Systems; Pose Representations; Homogeneous Transformations

II. Kinematics
- Multi-body frame assignment; D-H Convention; Joint-space; Work-space; Forward/Inverse Kinematics

III. Velocity Kinematics and Static Forces
- Translational/Rotational Velocity; Joint torque; Generalized Force Coordinates; Jacobian; Singularity

Fundamentals
Week 1-4
Revision/ Quiz on Week 5

IV. Dynamics
- Lagrangian Formulation; Newton-Euler Equations of Motion

V. Control
- Independent Joint/Feedforward/Inverse Dynamics Controls; Controller Architectures

VI. Planning
- Joint-based Motion Planning; Cartesian-based Path Planning

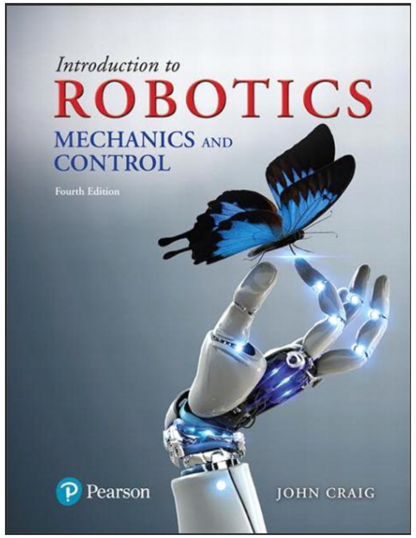
Essentials
Week 6-9
Revision/ Quiz on Week 10

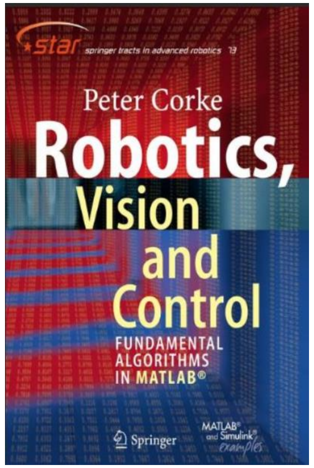
VII. Robot Vision (and Perception)
- Image Formation; Image Processing; Visual Tracking & Pose Estimation; Vision-based Control & Image-guided robotics

Applied
Week 11-13
Revision/Reading Wk/ Exam on Week 14-16

Admin. Matters

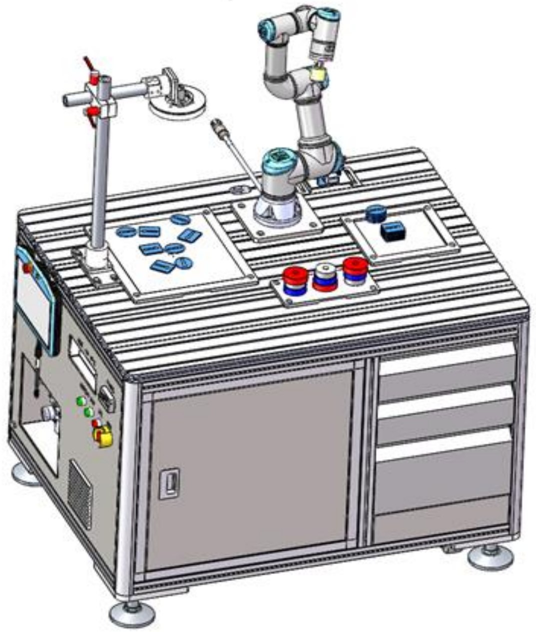
- **Prerequisite:** One of MATH 225, MATH 286, MATH 415, MATH 418
- **Recommended Textbook:**
  - **Fundamentals/ Essentials:** John J. Craig, Introduction to Robotics: Mechanics and Control (3rd~4th Edition), Pearson, 2018. ISBN-10: 0133489795
  - **Applied:** Peter Corke, Robotics, vision and control: fundamental algorithms in MATLAB® (2nd Edition), Springer, 2017. ISBN-10: 3319544128
- **Assessment:** Homework: 20%, Labs: 20%, Quizzes: 20%, Final: 40%
- **Lecture:** Tue; Thu 1000-1150
- **Lab:** Friday 0800-0950; 1000-1150





Lab. Sessions

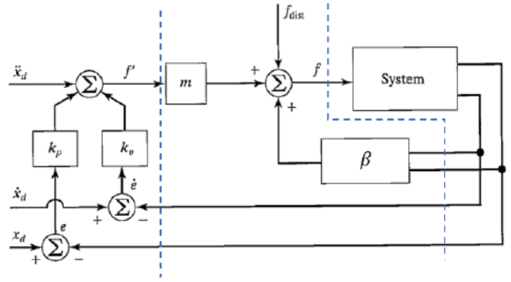
- **Lab Session**
  1. Introduction to UR3
  2. The Tower of Hanoi
  3. Forward Kinematics
  4. Inverse Kinematics
  5. Image Processing
  6. Camera Calibration



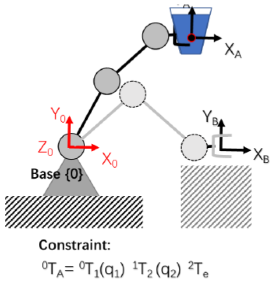
Virtual Labs

- **Graduate Students (Welcome undergrads to try out)**
  1. System Interface and Development Platform
  2. Manipulator Control: Forward Kinematics
  3. Manipulator Planning: Inverse Kinematics
  4. Image Processing
  5. Camera Calibration
  6. Robotics Challenge: (combining Lab 1-5 to solve a research/real-world problem)

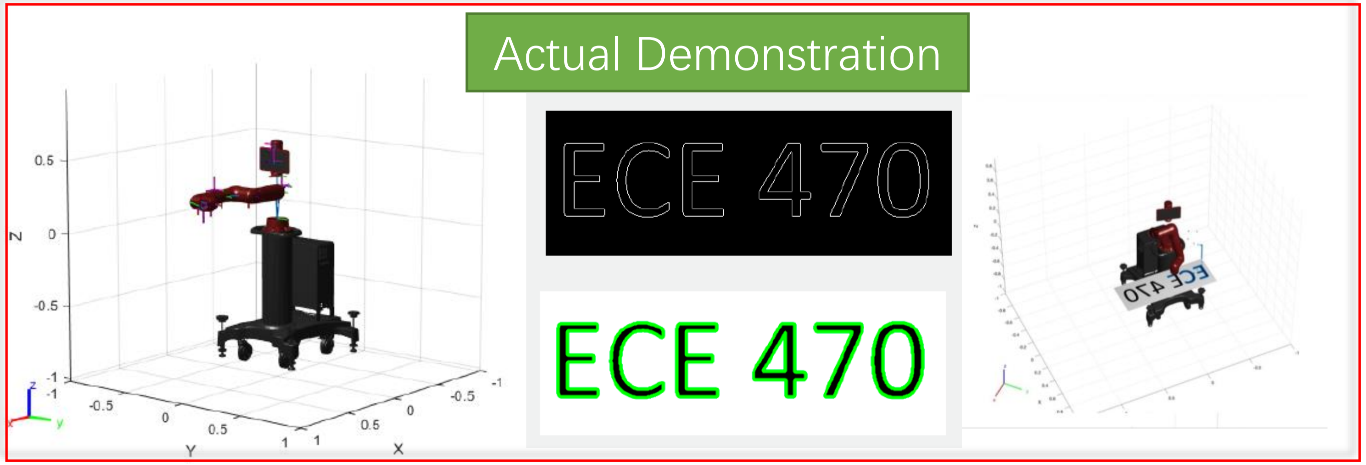
$$\tau = M(q)[\ddot{q}_d + K_v\dot{E} + K_pE] + V(q,\dot{q}) + G(q)$$

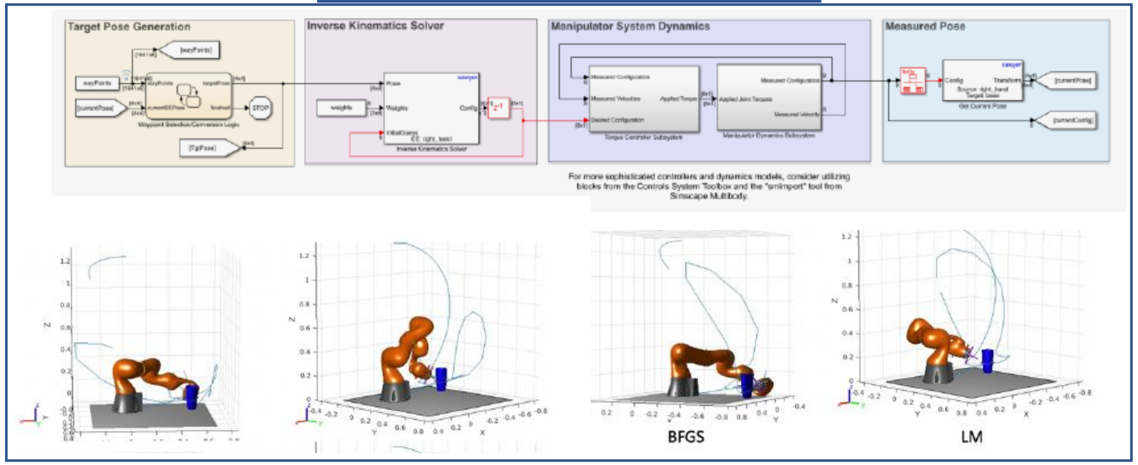


Classroom Knowledge



Virtual Simulation

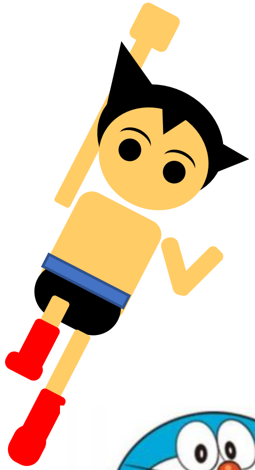




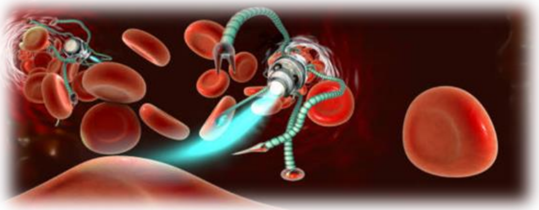
What is Robotics

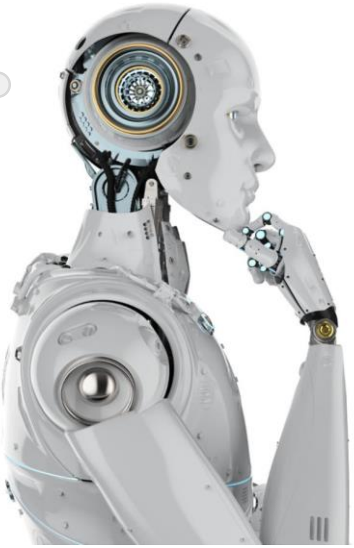
Introduction to Robotics: Defining the Scope

What is a robot?

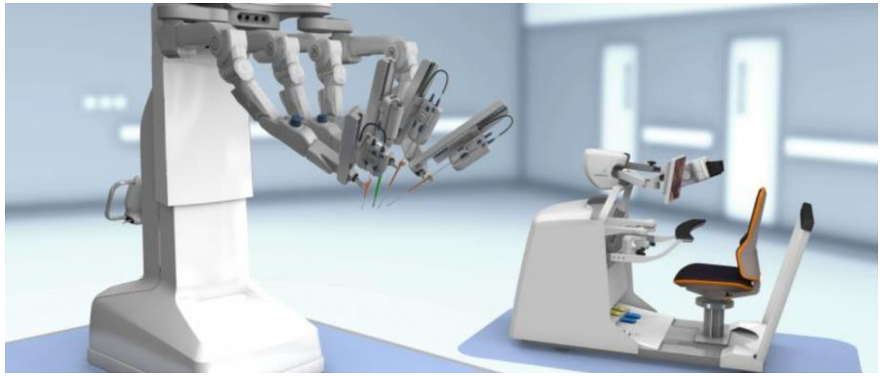


What am I?





What is a robot?



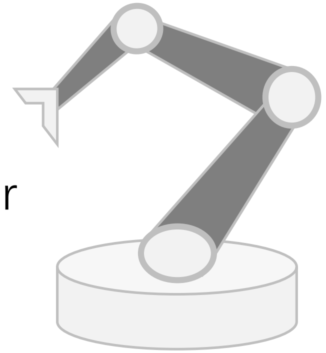
What is a robot?

- Various types of robot for different tasks in different environment

Humanoid

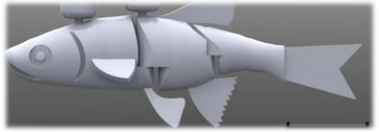
Drone

Manipulator



Snake Robot

Fish Robot



What is a robot?

- A machine/agent designed to complete a task(s) while interacting with the environment

Agent

Tasks

Environment

Scope of Robotics

- A machine/agent designed to complete a task(s) while interacting with the environment
- Agents need the ability of <u>sensing, perceiving, planning and acting </u>(with varying levels of autonomy)
  - Mechanism Design
  - Sensing, actuation and control
  - Perception and Planning

Case Example: Boston Dynamics

- Think about the robot, the tasks, and the environment

Content Overview

Introduction to Robotics: What you will learn

What you will learn

Structured into (A) Fundamentals, (B) Essentials and (C) Applied

A. Familiarized with the fundamentals
   - spatial representation, homogeneous transformations, forward and inverse kinematics, velocity kinematics

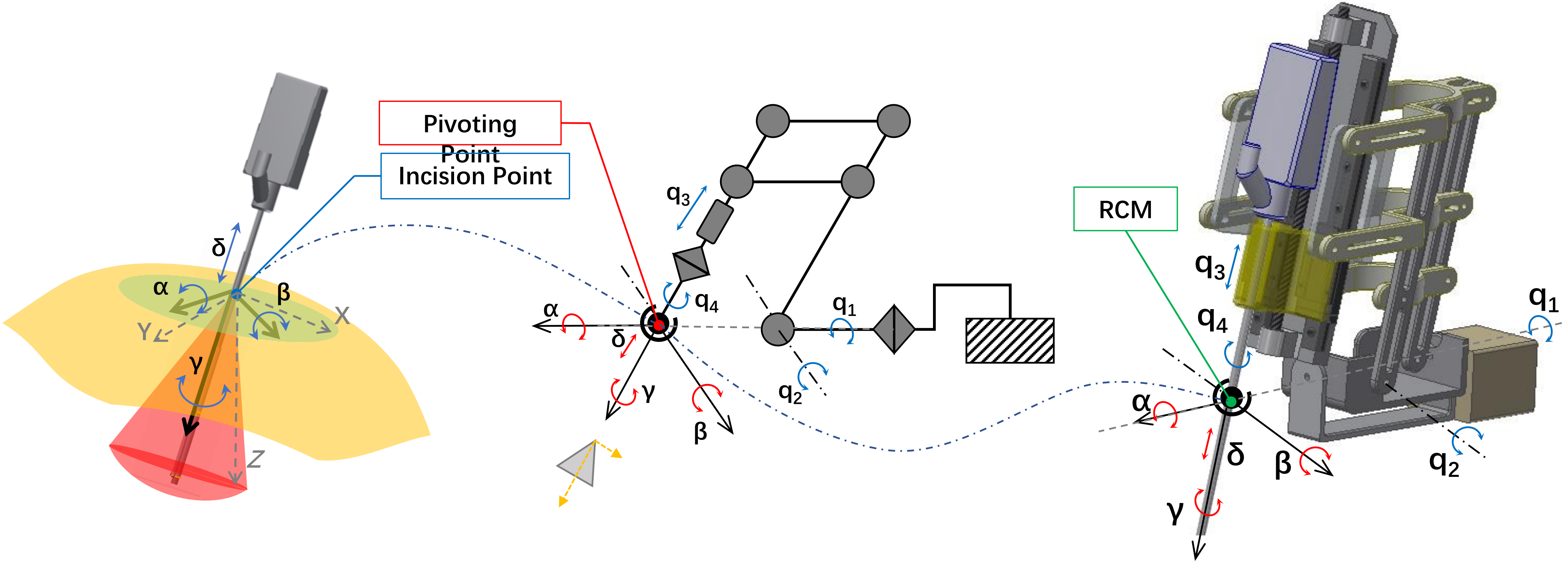
B. Acquainted to the essentials
   - robot dynamics, planning and controls

C. Apply knowledge to applied topics in robot vision/ perception
   - image formation, processing and analysis, visual tracking, vision-based control and image-guided robotics

Overview: Kinematics

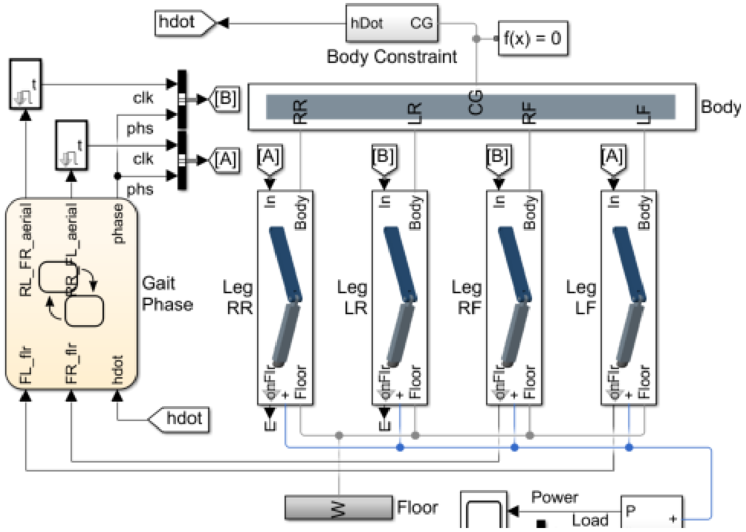
- Example: Surgical Robot

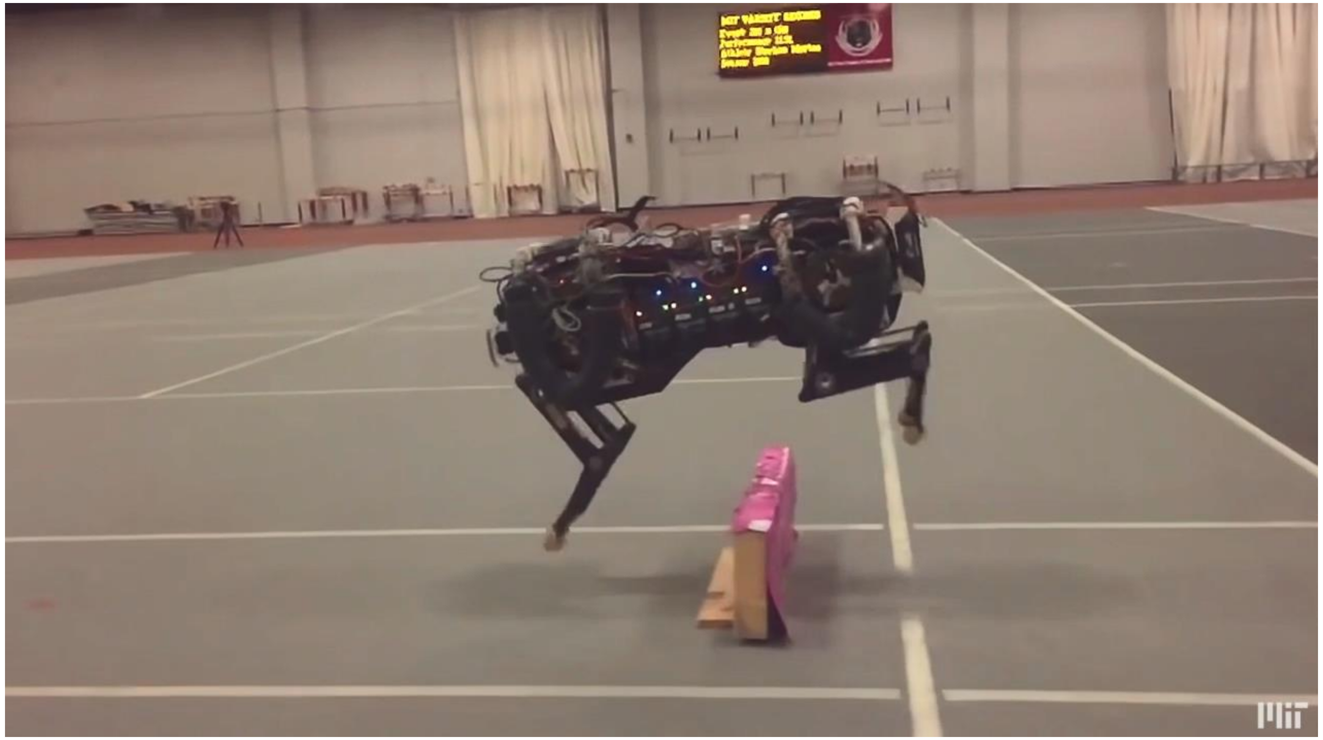
Workspace Requirement	Kinematic Specification	Manipulator Application

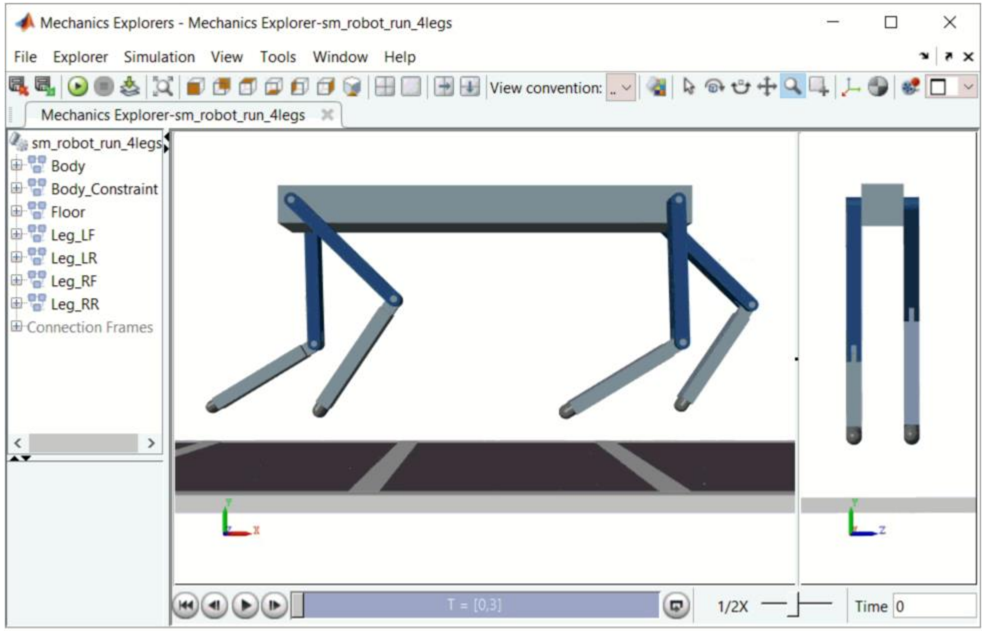


Overview: Dynamics

- Example: Quadrupedal Robot

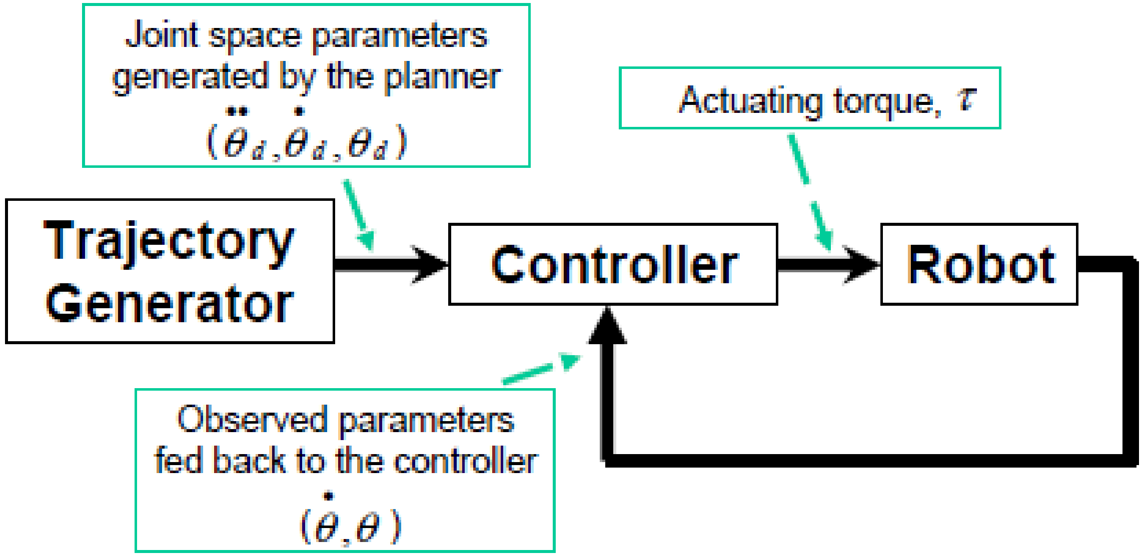






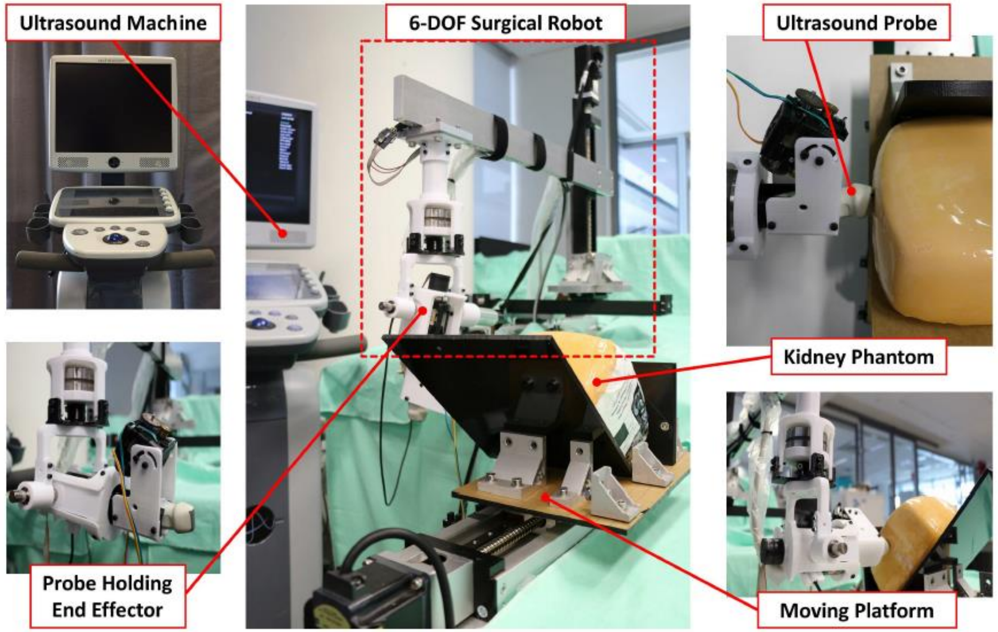
Overview: Control

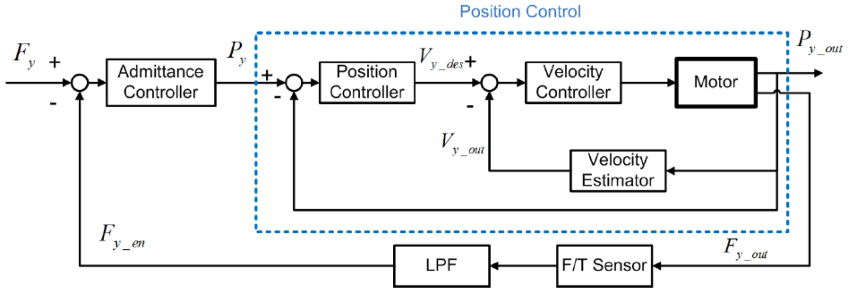
- Block diagram of a typical robot control

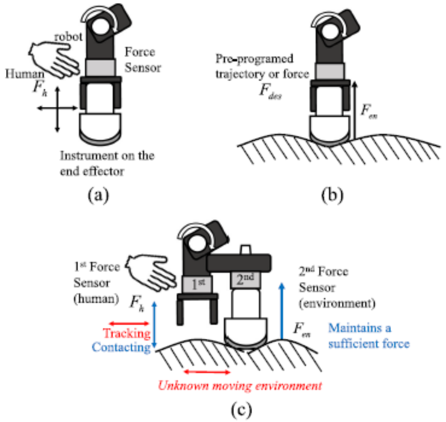


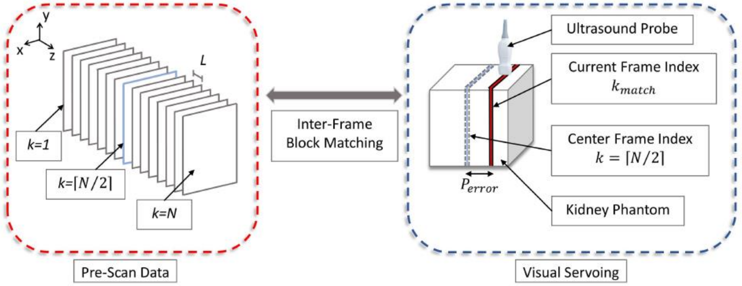
Overview: Control

- Example: Ultrasound Image-Guided Robot



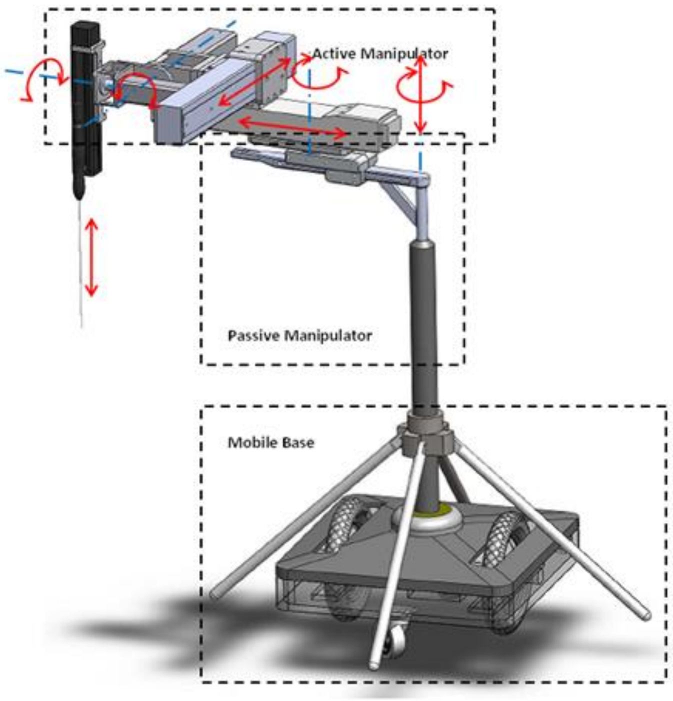


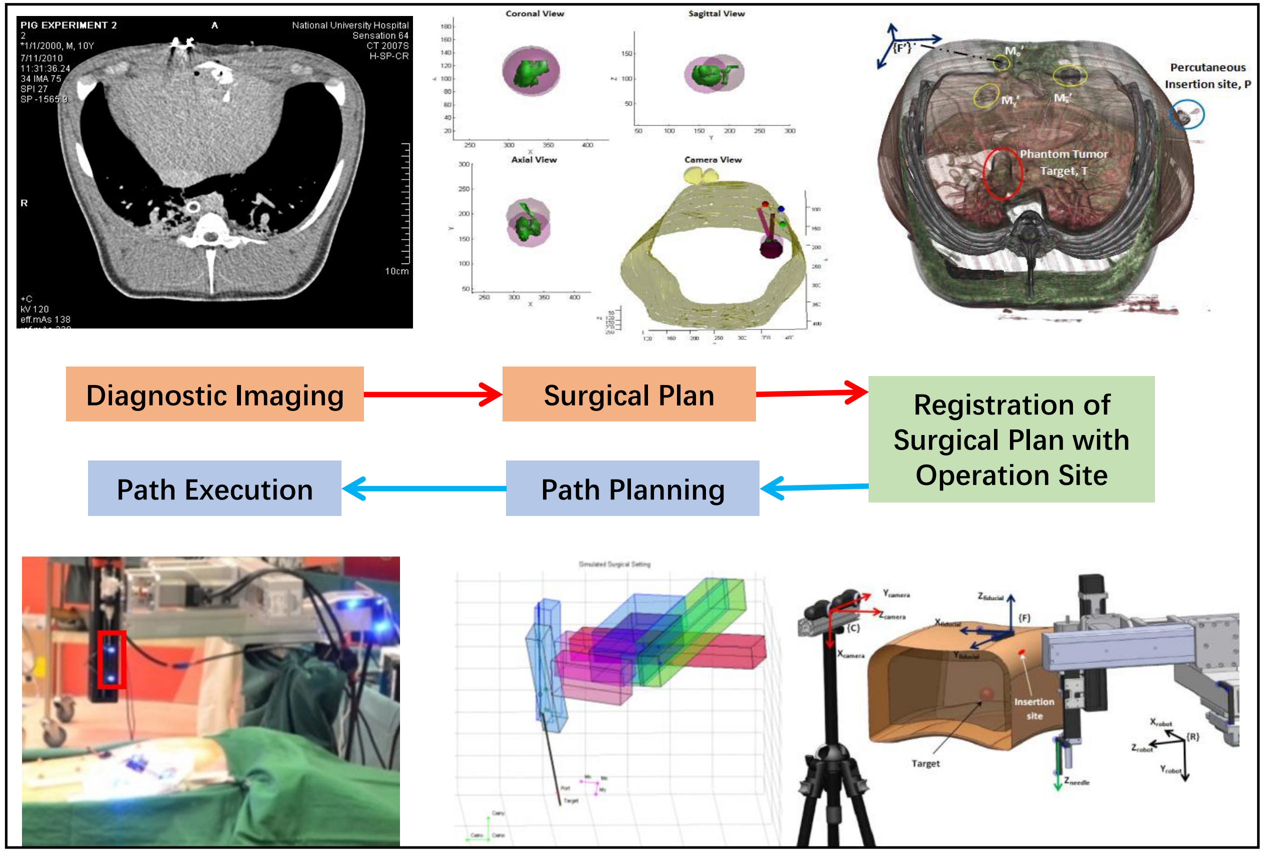




Overview: Planning

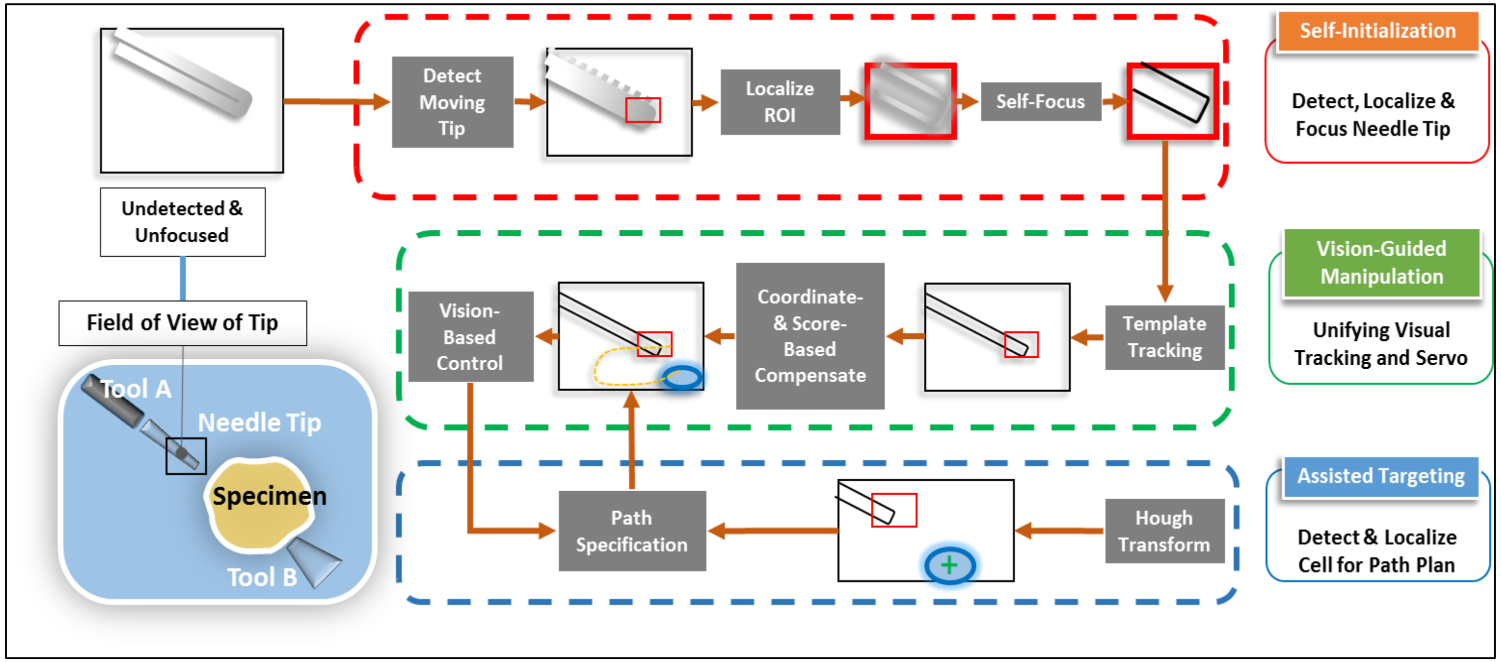
- Example: Planned needle insertion

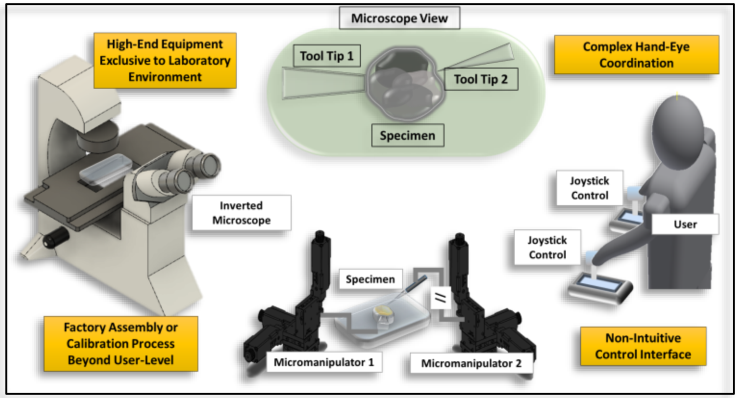


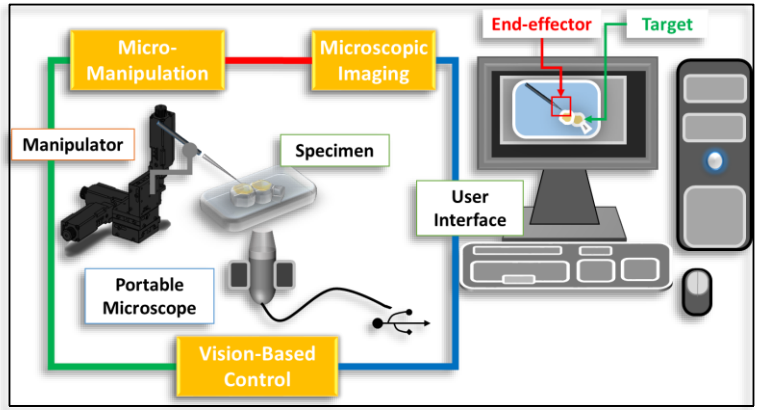


Overview: Vision

- Example: Micromanipulator Vision-Based Control

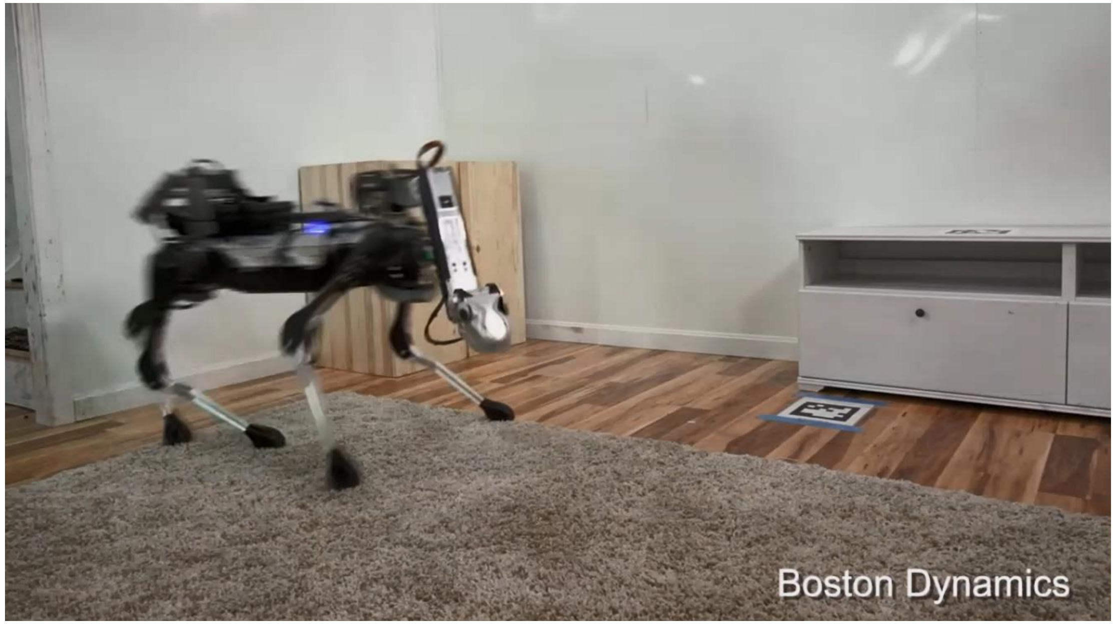


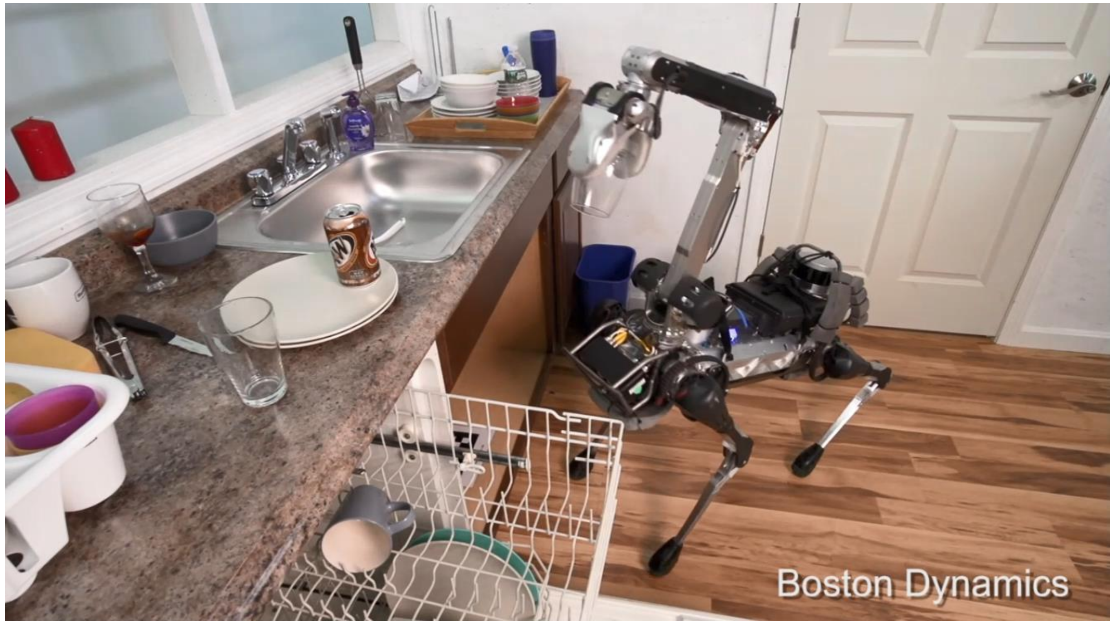




Overview: Mechanics, Control & Perception

- Quadrupedal Robot + Manipulator + Vision



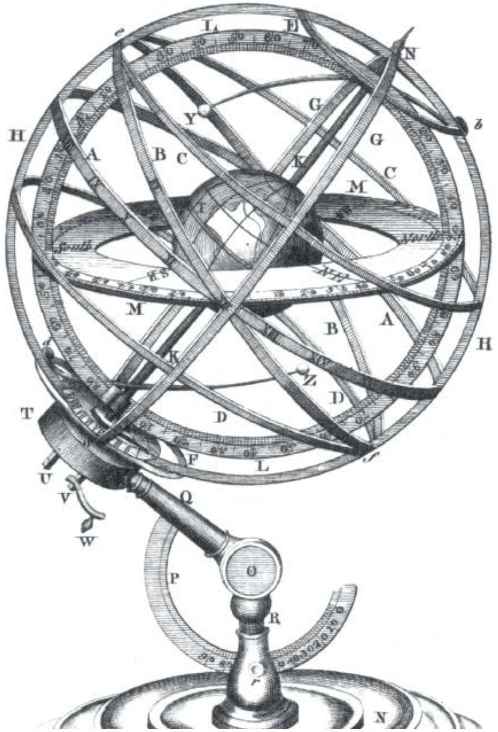


Boston Dynamics: http://www.bostondynamics.com/

Spatial Representation & Transformation

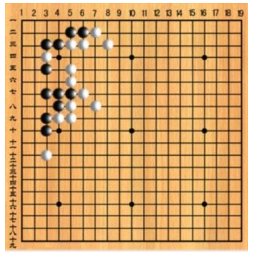
Introduction to Robotics: Fundamentals

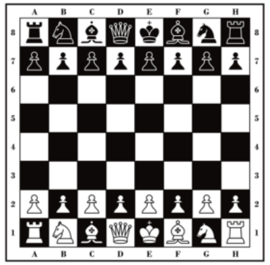
Coordinate Systems

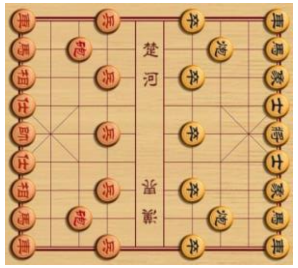


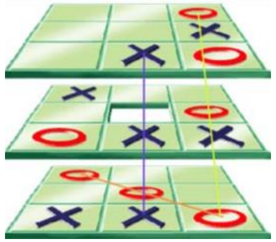
Coordinate Systems

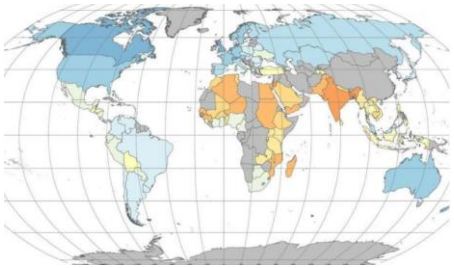
- Everyday-Examples of Coordinate Systems?
  - On boardgames, on maps …… even the unit number on your address
  - Can be 2D, (partial) 3D, Projective……

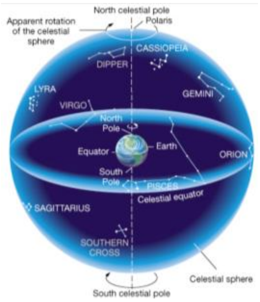








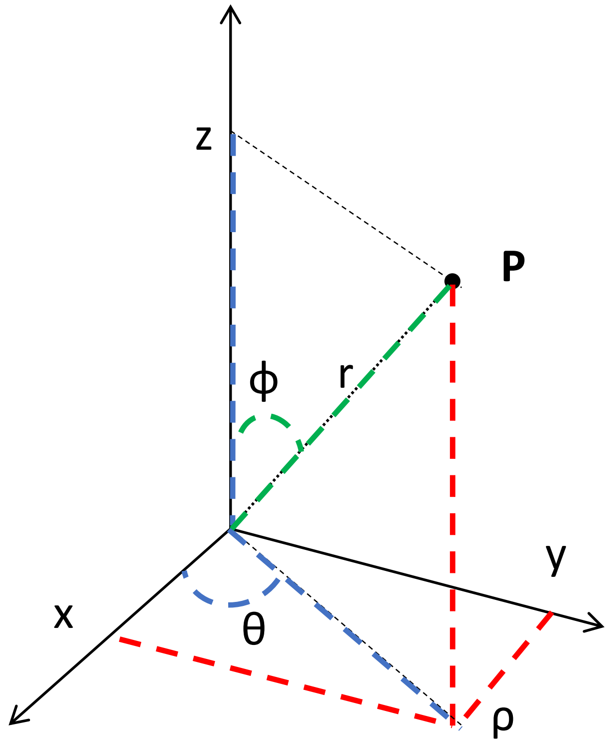




Coordinate Systems

- Examples of Coordinate Systems:
  - Cartesian (x, y, z)
  - Spherical (r, θ, ϕ)
  - Cylindrical (ρ, θ, z)

⋮



Coordinate Systems

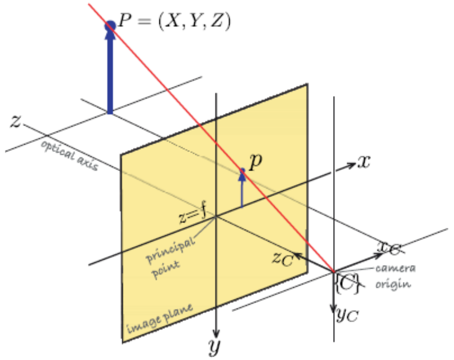
- Examples of Coordinate Systems:
  - Cartesian (x, y, z)
  - Spherical (r, θ, ϕ)
  - Cylindrical (ρ, θ, z)

⋮

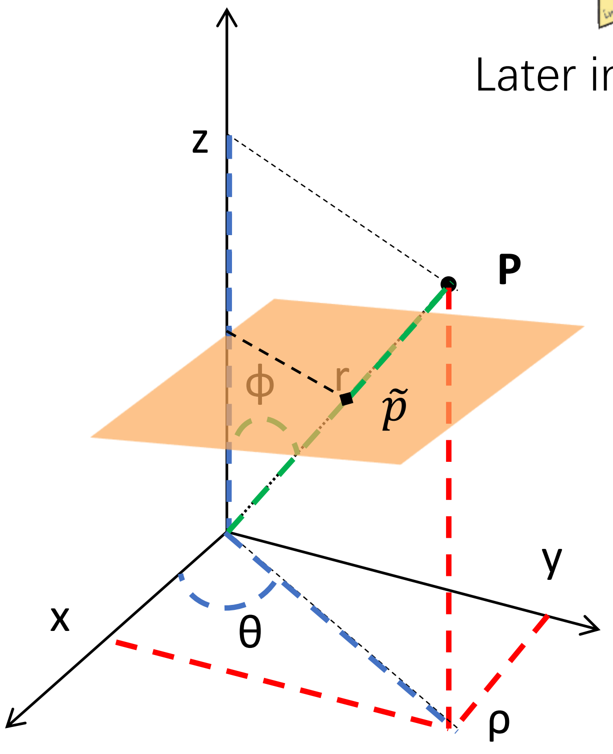
  - Homogenous Coordinate System

⋮

  - Projective coordinates

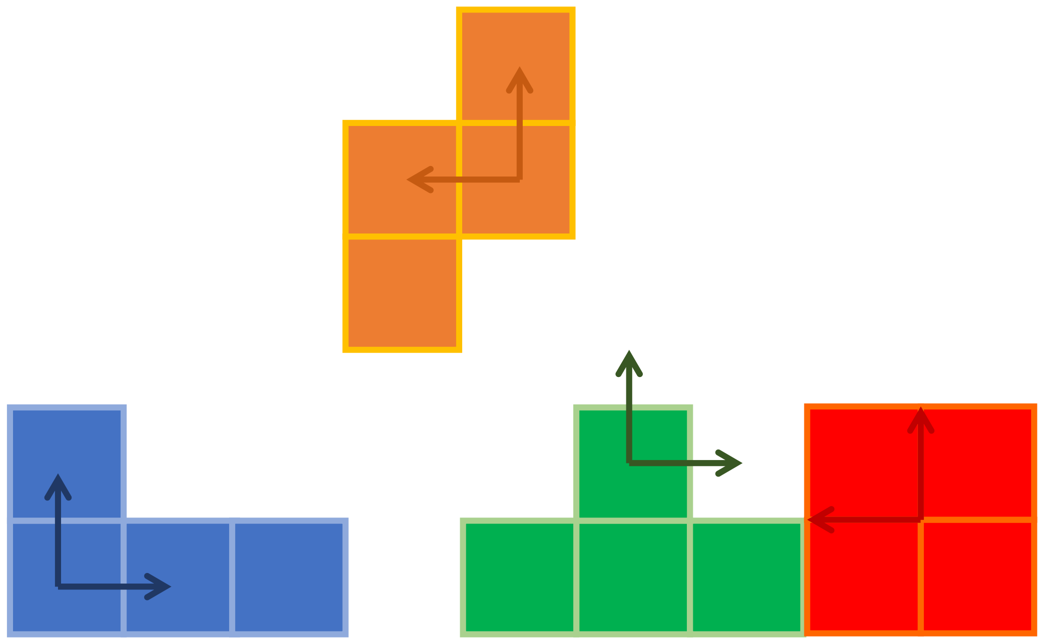


Later in robot vision



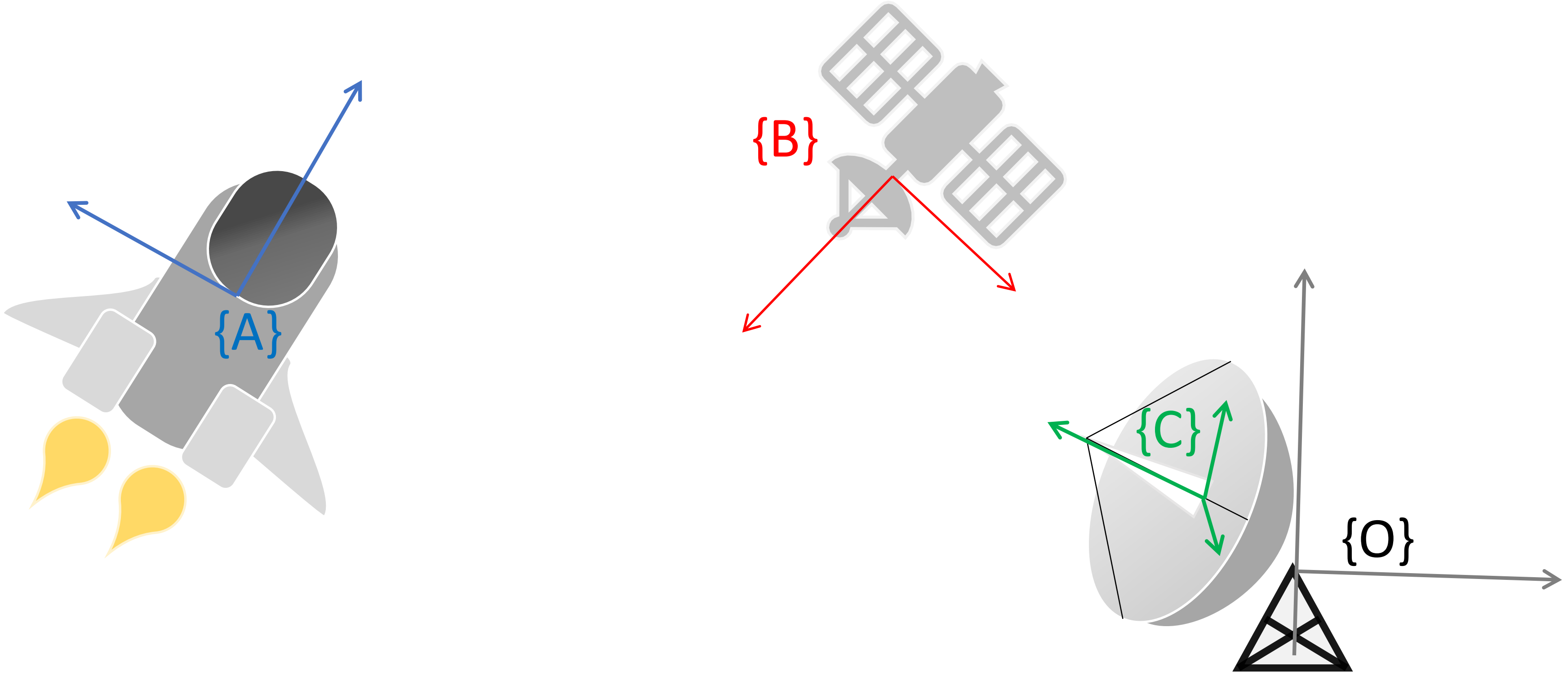
Reference Frames

- **Frame** is a coordinate system usually specified in position and orientation relative to other assigned coordinate systems



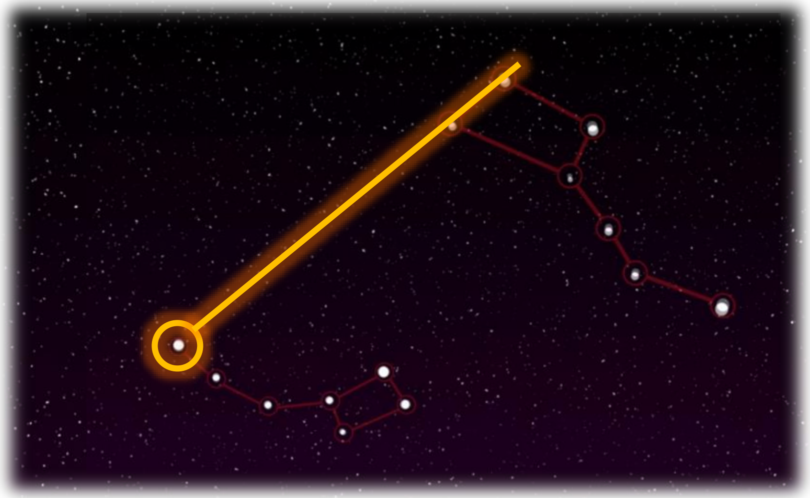
Reference Frames

- **Reference frames** can be assigned to rigid bodies for the description of object poses and motions



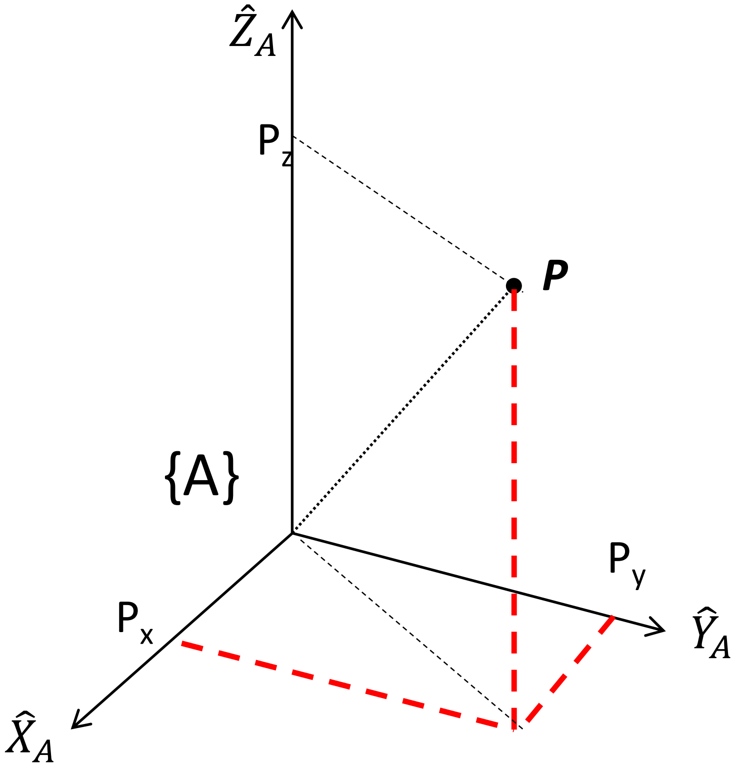
Spatial Description

- Pose Representation (in ECE 470)
  - Position and Orientation w.r.t a **frame of reference**
  - **Vector** to represent position
  - **Matrix** to represent orientation



Position

- Represented as n-by-1 (column) vector in R^n
- ${}^{A}P = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}$, in 3D space
  - The positional vector ${}^{A}\boldsymbol{P}$ is the vector from origin of frame {A} to point P
- ${}^{A}\tilde{p} = \begin{pmatrix} P_x \\ P_y \\ P_z \\ 1 \end{pmatrix}$
  - The position in homogenous coordinates



Orientation

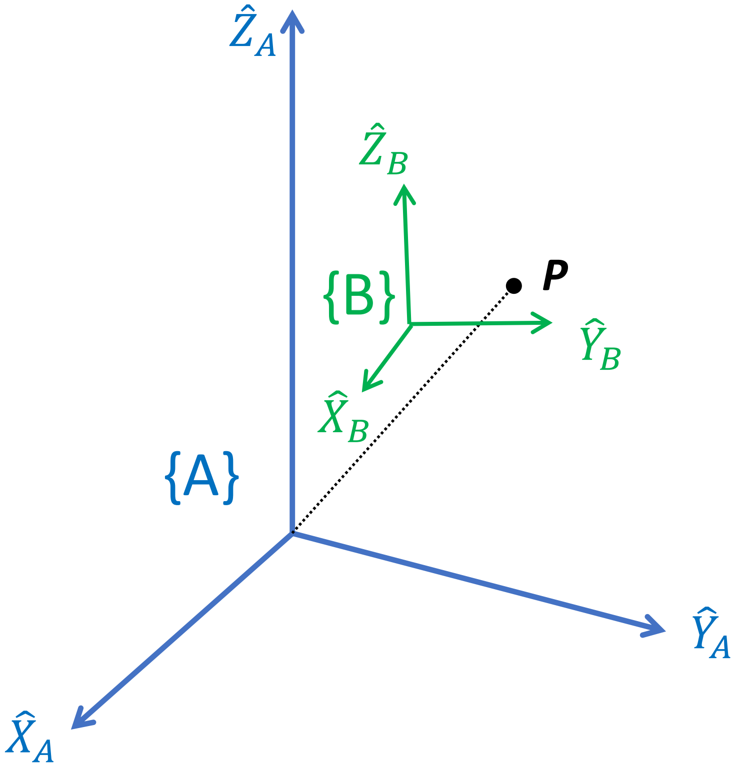
- Represented by *n*-by-*n* orthogonal matrix of unit (column) vectors

{A} is global frame while {B} is attached to object

$$ {}^{A}_{B}R = \left[{}^{A}\hat{X}_B \ {}^{A}\hat{Y}_B \ {}^{A}\hat{Z}_B \right] = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} $$

– ${}^{A}\hat{X}_B \ {}^{A}\hat{Y}_B \ {}^{A}\hat{Z}_B$ are the principal unit vectors of {B} in {A}

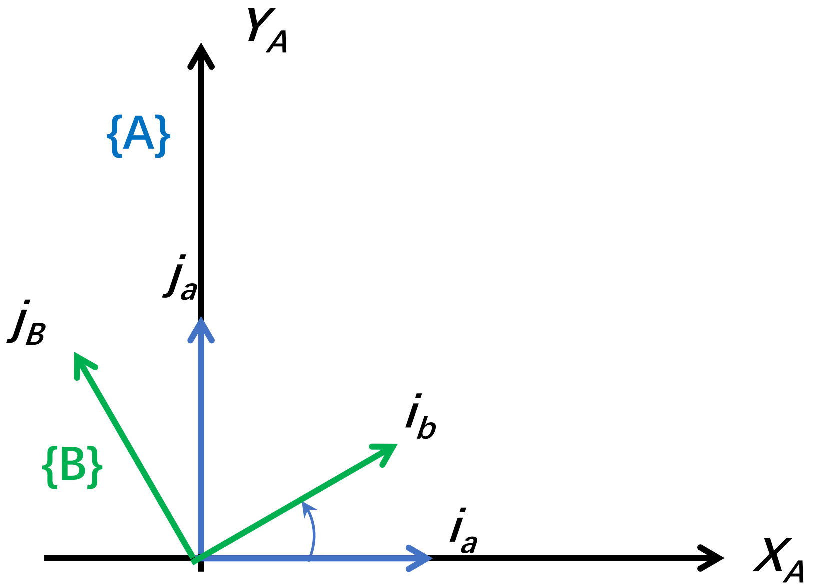
$$ {}^{A}_{B}R = \left[{}^{A}\hat{X}_B \ {}^{A}Y_B \ {}^{A}\hat{Z}_B \right] = \begin{bmatrix} \hat{i}_B \cdot \hat{i}_A & \hat{j}_B \cdot \hat{i}_A & \hat{k}_B \cdot \hat{i}_A \\ \hat{i}_B \cdot \hat{j}_A & \hat{j}_B \cdot \hat{j}_A & \hat{k}_B \cdot \hat{j}_A \\ \hat{i}_B \cdot \hat{k}_A & \hat{j}_B \cdot \hat{k}_A & \hat{k}_B \cdot \hat{k}_A \end{bmatrix} $$



Orientation in 2D

- Take a 2D-Example
- Represented by *2*-by-*2* orthogonal matrix of unit vectors

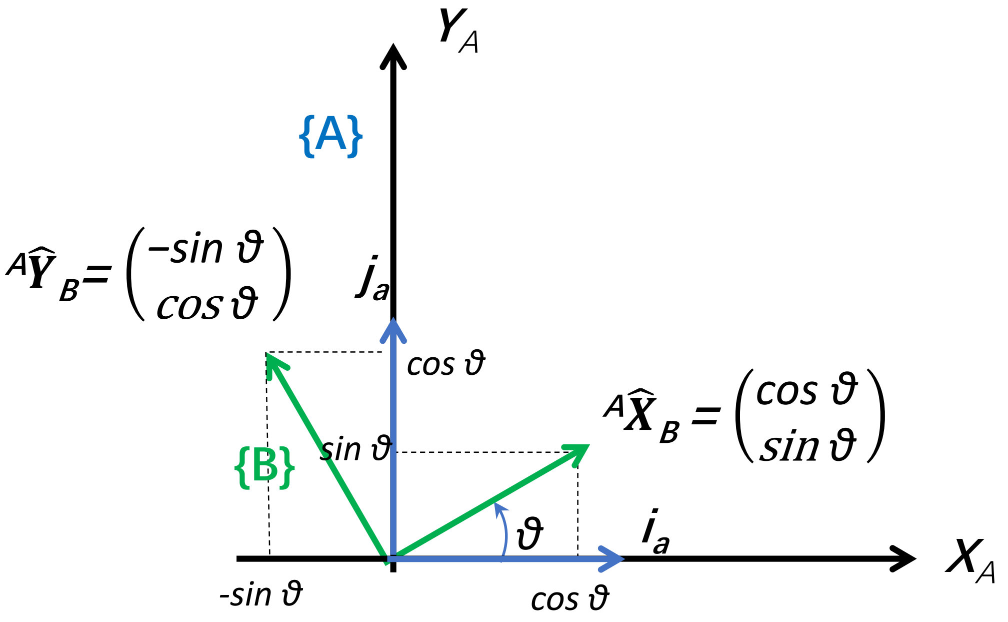
$$^{A}\mathbf{R}_{B} = [{}^{A}\hat{\mathbf{X}}_{B} \quad {}^{A}\hat{\mathbf{Y}}_{B}]$$



Orientation in 2D

- Take a 2D-Example
- Represented by *2*-by-*2* orthogonal matrix of unit vectors

$$
{}^{A}\mathbf{R}_B = [{}^{A}\hat{\mathbf{X}}_B \quad {}^{A}\hat{\mathbf{Y}}_B] = \begin{bmatrix} \cos\vartheta & -\sin\vartheta \\ \sin\vartheta & \cos\vartheta \end{bmatrix}
$$

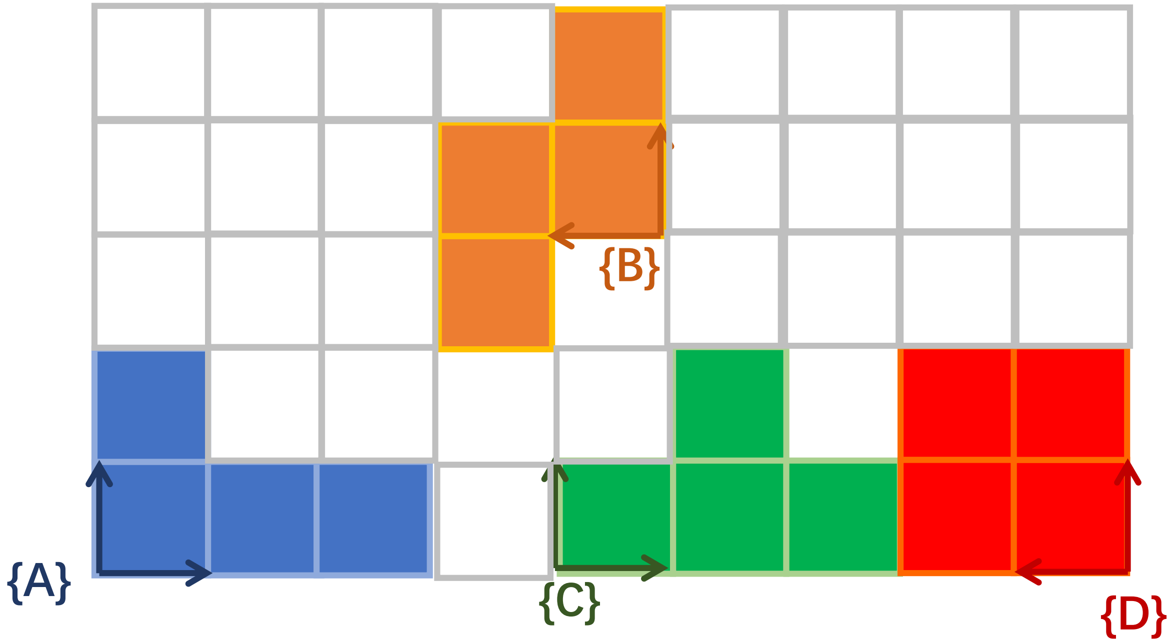


The same can be generalized to 3D-Space

Q1.1: Concept Check

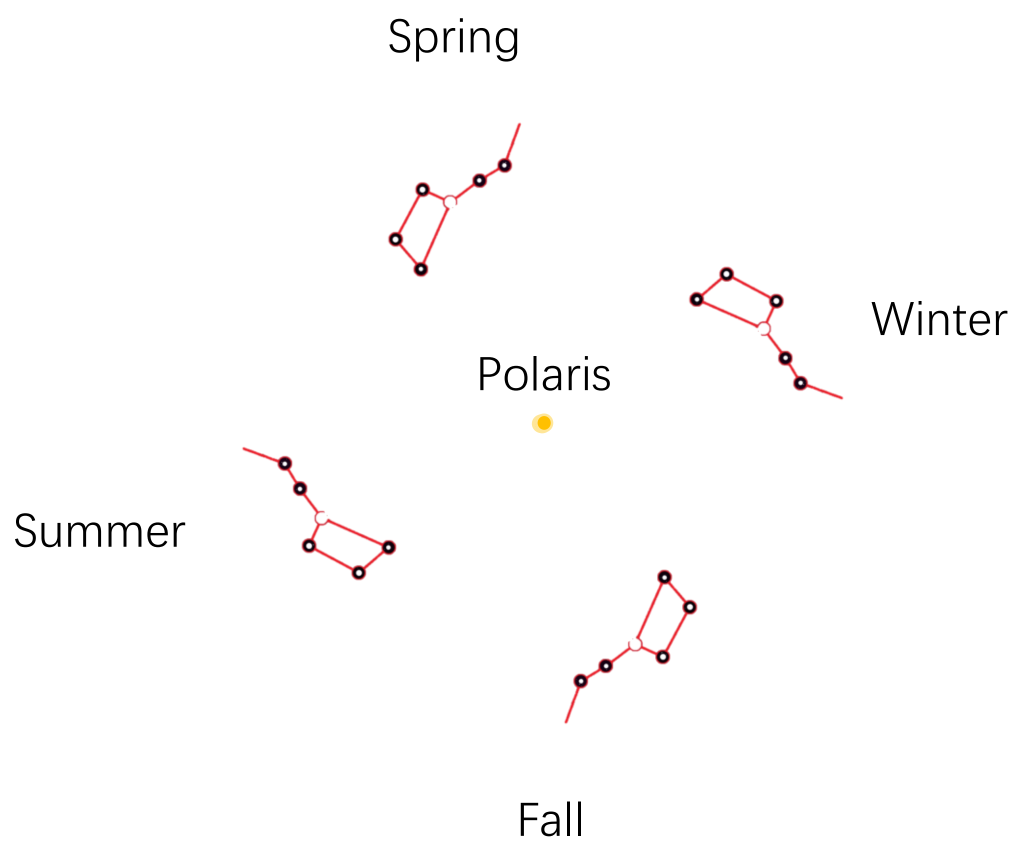
a. Write down the position vector of {B} in {A}
b. Write down the orientation matrix of {B} in {A}
c. Use trigonometry functions to express the matrix elements in (b)

Assuming Z-axes are all pointing out of page



Spatial Transformation

- Change in pose or reference frame (in ECE 470)
  - Translation and Rotation
  - **Vector** to represent translation
  - **Matrix** to represent rotation



Recall Orientation in 2D

- Represented by *2*-by-*2* orthogonal matrix of unit vectors

$$ {}^{A}\mathbf{R}_{B} = [{}^{A}\hat{\mathbf{X}}_{B} \quad {}^{A}\hat{\mathbf{Y}}_{B}] = \begin{bmatrix} \cos\vartheta & -\sin\vartheta \\ \sin\vartheta & \cos\vartheta \end{bmatrix} $$

- Equivalent to the operation

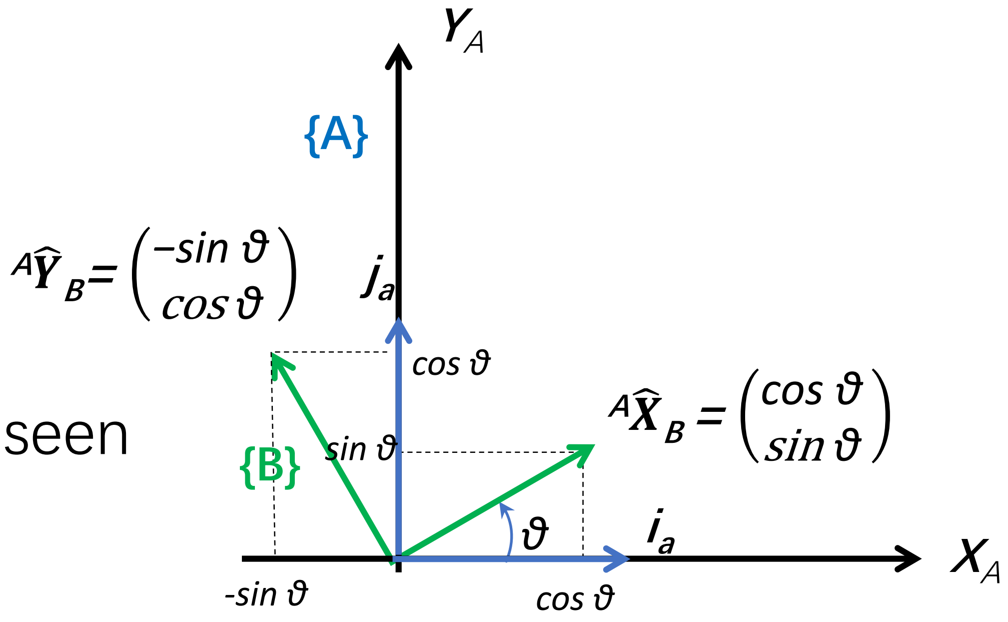
  rotating ϑ in the Z-axis

  Denoted by $R_z(\vartheta)$

- following the Right-Hand-Grip rule, C.C.W. is the positive direction

→Orientation of one frame in another can be seen as a Rotation of the coordinate systems

The same can be generalized to 3D-Space



Transformation of Coordinate System

- Imagine an <u>observer in {B}</u> reporting the coordinates of point P,

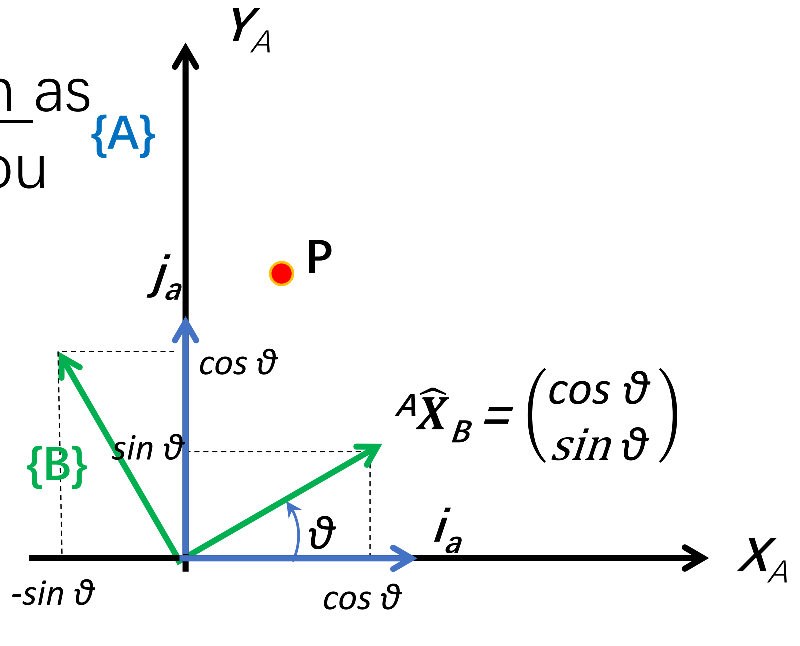
$$ {}^{B}\mathbf{P} = \begin{bmatrix} X_B \\ Y_B \end{bmatrix} = \begin{bmatrix} {}^{B}P_X \\ {}^{B}P_Y \end{bmatrix} $$

- You are interested in coordinates of <u>P in {A}, ${}^{A}\mathbf{P}$</u>
- Assuming that the observer is <u>at the same location</u> as you but <u>orientated ϑ in the CCW</u> direction from you

i.e. $ {}^{A}R_B = \begin{bmatrix} \cos\vartheta & -\sin\vartheta \\ \sin\vartheta & \cos\vartheta \end{bmatrix} $

- New coordinates in your reference frame {A}

$$ \boxed{{}^{A}\mathbf{P} = {}^{A}R_B\,{}^{B}\mathbf{P} = \begin{bmatrix} \cos\vartheta & -\sin\vartheta \\ \sin\vartheta & \cos\vartheta \end{bmatrix} \begin{bmatrix} {}^{B}P_X \\ {}^{B}P_Y \end{bmatrix}} $$



Transformation of Coordinate System

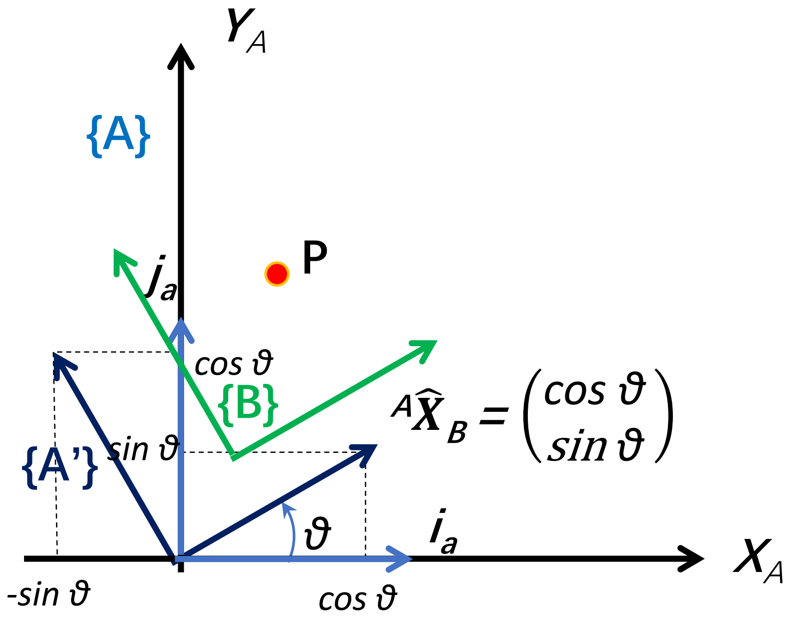
- In general the observer may not be in the same location

$$ {}^{B}P = \begin{bmatrix} X_B \\ Y_B \end{bmatrix} = \begin{bmatrix} {}^{B}P_X \\ {}^{B}P_Y \end{bmatrix} $$

- You are interested in coordinates of <u>P in {A}, ^{A}P</u>

$$ \boxed{{}^{A}P = {}^{A}R_{A'}\,{}^{A'}R_{B}\,{}^{B}P + {}^{A}P_{B}} $$

$$ \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} $$



Homogenous Transformation

- Transformed coordinates of ***p*** in {B} to coordinates in {A}

$$ {}^{A}P = {}^{A}_{B}R\,{}^{B}P + {}^{A}P_{BORG} $$

$$ {}^{A}P = {}^{A}_{B}T\,{}^{B}P $$

$$ \begin{bmatrix} {}^{A}P \\ 1 \end{bmatrix} = \boxed{\left[\begin{array}{ccc|c} & {}^{A}_{B}R & & {}^{A}P_{BORG} \\ \hline 0 & 0 & 0 & 1 \end{array}\right]} \begin{bmatrix} {}^{B}P \\ 1 \end{bmatrix} $$

Homogeneous Coordinates | **Homogeneous Transformation** | Homogeneous Coordinates

Can be seen as a multiplication operator of 4 x 4 Matrix