ECE 470: Introduction to Robotics

Lecture 20: Quiz II

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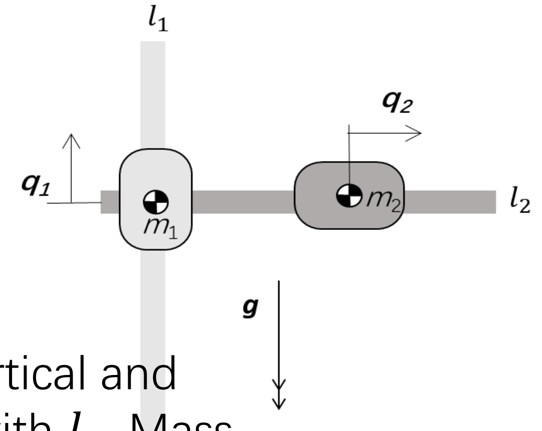
Quiz II

ECE 470 Introduction to Robotics

Question 1 (a)



- Dynamics

Consider the cartesian positioning robot with lump mass m_1 and m_2 positioned by a vertical and horizontal axis of control. Masses m_1 and m_2 move vertically in q_1 direction, together with l_2. Mass m_2 also moves in q_2 direction horizontally along l_2. You may ignore any drag or frictional force.

i) Show that the total kinematic energy can be expressed as
$K = \frac{1}{2} m_1 \dot{q}_1{}^2 + \frac{1}{2} m_2 \dot{q}_1{}^2 + \frac{1}{2} m_2 \dot{q}_2{}^2$

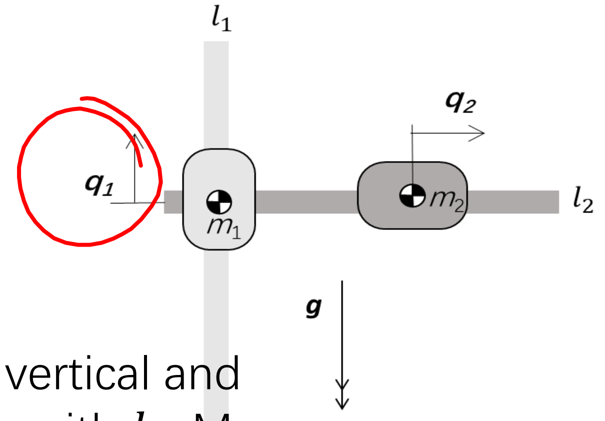
ii) Obtain an expression for the total potential energy V

iii) Write down the Lagrangian L

iv) Obtain the expressions for $\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i}$ and $\frac{\partial L}{\partial q_i}$ with $i = 1, 2$

v) Assume motion q_1 and q_2 are driven by two actuators attached to m_1 and m_2 with force output f_1 and f_2 respectively, write down the expression of $(f_1, f_2)^{\mathrm{T}}$ describing the dynamics of the robot.

Question 1 (a)



- Dynamics

Consider the cartesian positioning robot with lump mass m_1 and m_2 positioned by a vertical and horizontal axis of control. Masses m_1 and m_2 move vertically in q_1 direction, together with l_2. Mass m_2 also moves in q_2 direction horizontally along l_2. You may ignore any drag or frictional force.

Kinetic

i) Show that the total ~~kinematic~~ energy can be expressed as

$$K = \frac{1}{2}m_1\dot{q}_1^{\ 2} + \frac{1}{2}m_2\dot{q}_1^{\ 2} + \frac{1}{2}m_2\dot{q}_2^{\ 2}$$

$L = K - V$

ii) Obtain an expression for the total potential energy V

$$\boxed{\tau_i = \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i}}$$

iii) Write down the Lagrangian L

iv) Obtain the expressions for $\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i}$ and $\frac{\partial L}{\partial q_i}$ with $i = 1, 2$

v) Assume motion q_1 and q_2 are driven by two actuators attached to m_1 and m_2 with force output f_1 and f_2 respectively, write down the expression of $(f_1, f_2)^{\mathrm{T}}$ describing the dynamics of the robot.

Question 1(b)

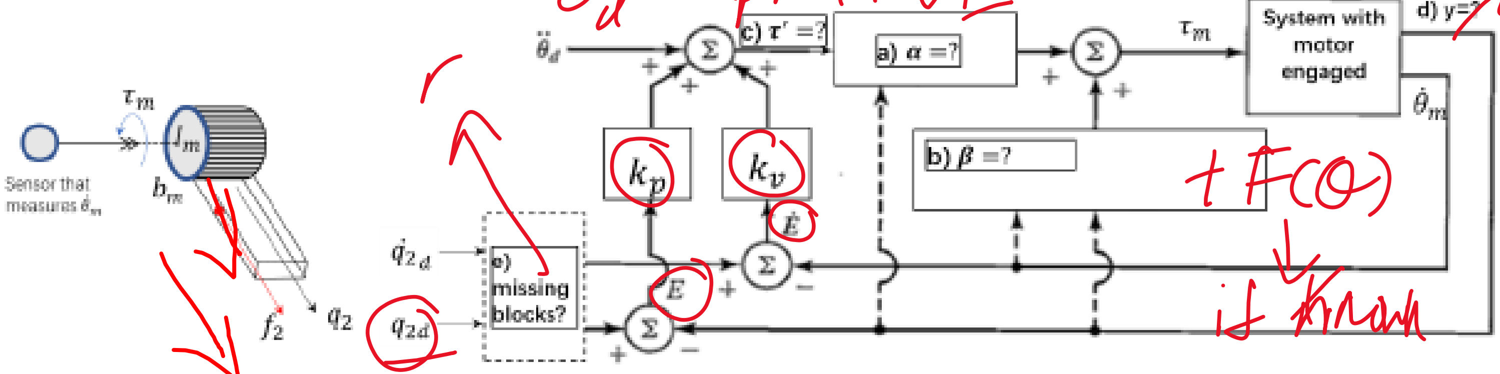
b) A DC motor, with rotor inertia I_m and viscous coefficient b_m, outputting a motor torque τ_m can transmit the required force for motion q_2 through the rack-and-pinion mechanism as shown.

i) Show that the dynamic equation with the motor parameters incorporated can be written as

$$\tau_m = (m_2 r^2 + I_m)\ddot{\theta}_m + b_m \dot{\theta}_m$$

(2 Points)

$\ddot{\theta}_d + k_p E + k_v \dot{E}$



$r \times F = \tau$

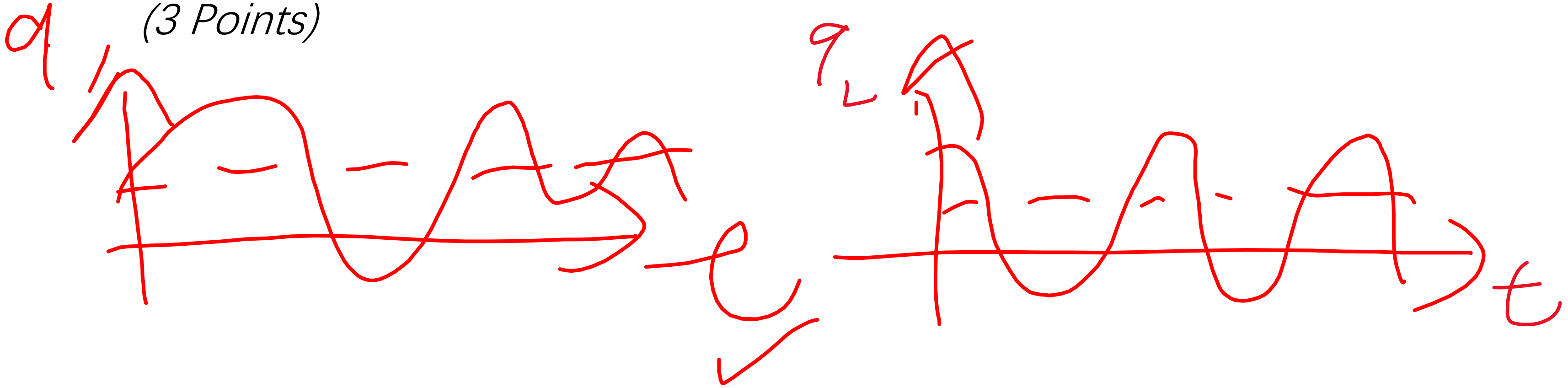
$n = \frac{r}{r_1}$

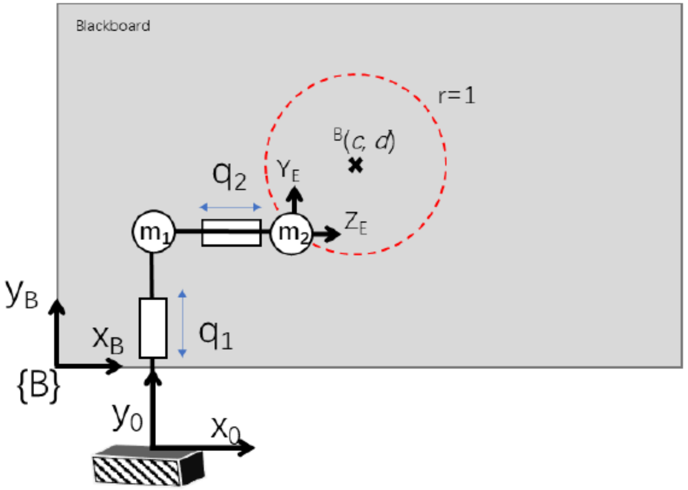
ii) Fill in the missing expression (a)-(e) in the control block diagram in consideration of the motor dynamics as well.

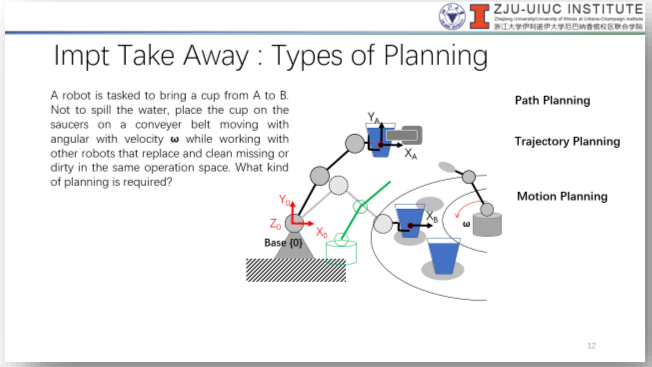
(5 Points)

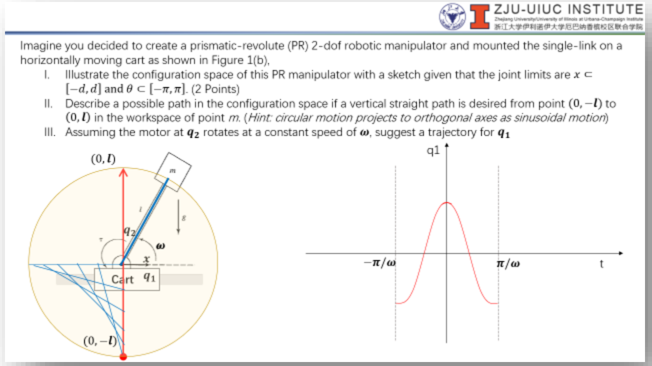
Question 2

a) Sketch and explain a set of possible joint trajectories for q_1 and q_2 to trace a circular path with its center at coordinate (c, d) in frame {B} and a radius r=1. *(3 Points)*

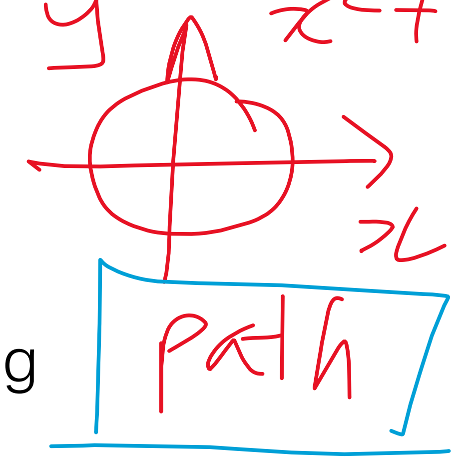




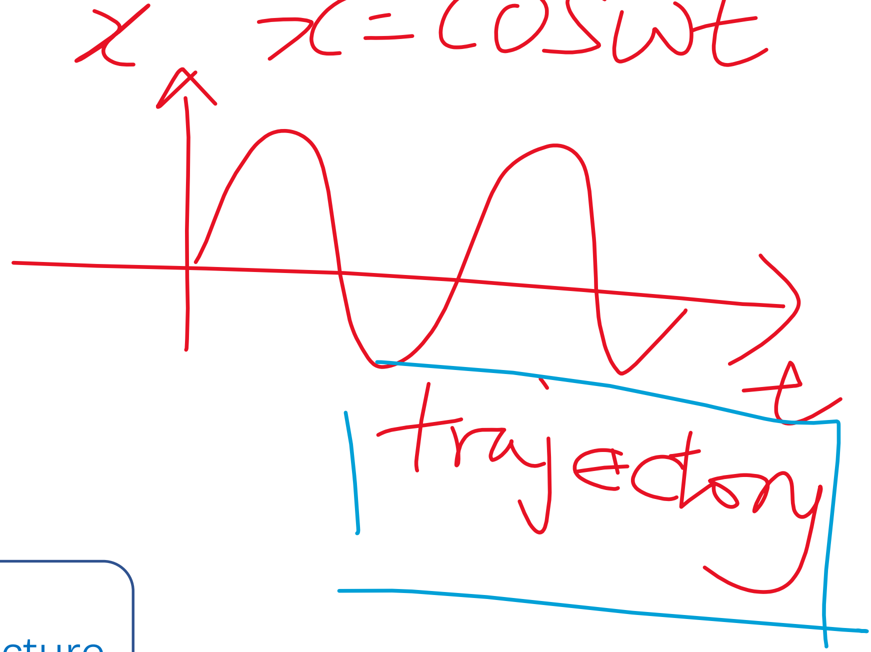




Quick Recap



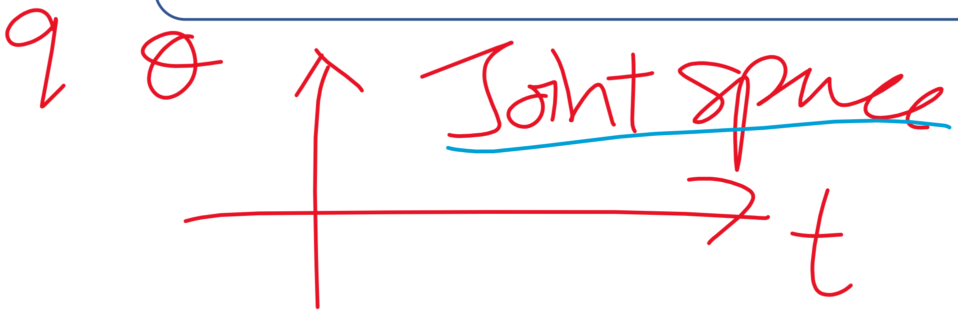
$x^2 + y^2 = r^2$

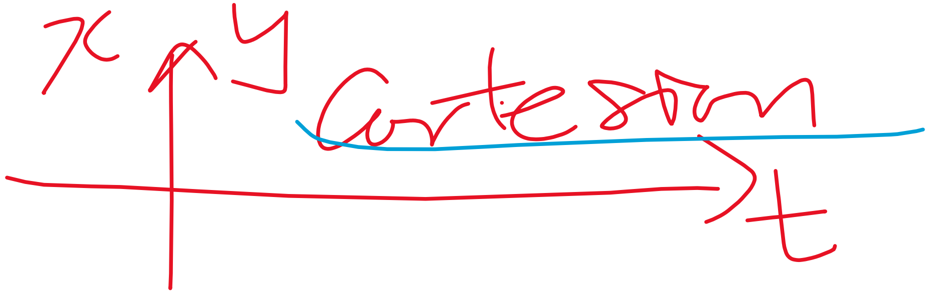


$x = \cos \omega t$

- Last week
  - The overview of Robot Planning
    - Path
    - Trajectory
    - Motion
  - Trajectory Generation
    - Joint-Space Scheme
    - Cartesian-Space Scheme
  - Issues and Challenges in Motion Planning

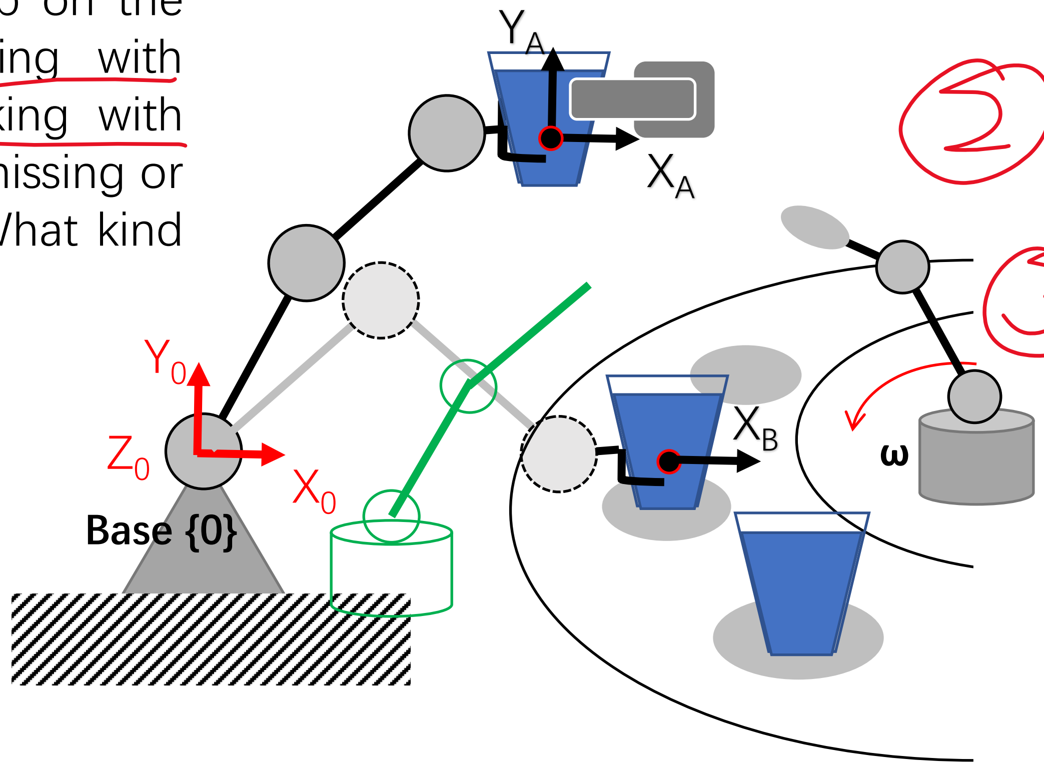
This Lecture





Impt Take Away : Types of Planning

1 A robot is tasked to bring a cup from A to B.
Not to spill the water, place the cup on the saucers on a conveyer belt moving with
2 angular with velocity **ω** while working with
3 other robots that replace and clean missing or dirty in the same operation space. What kind of planning is required?



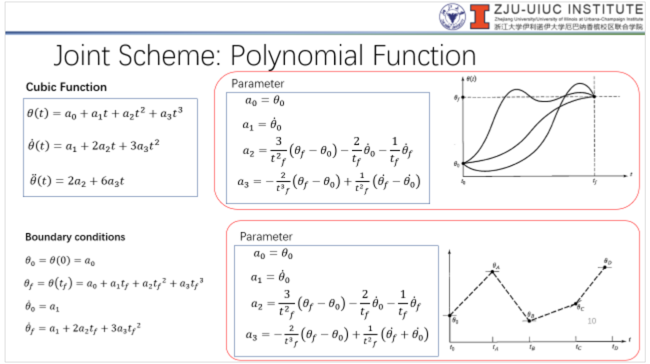
1 **Path Planning**

2 **Trajectory Planning**

3 **Motion Planning**

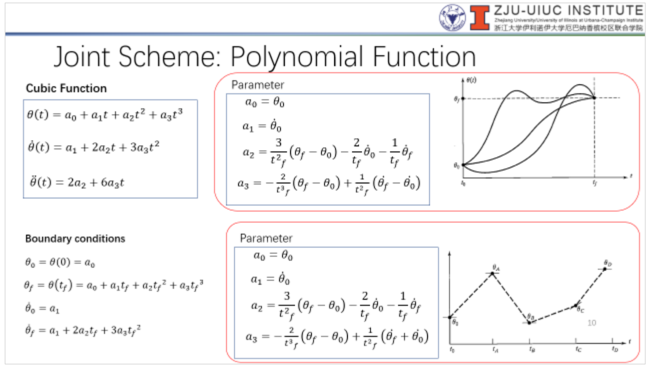
Question 2

b) For Joint q_1, determine the parameters of a 2-segment cubic trajectory where $y_0 = 0.2\ m$ is the initial position, $y_v = 0.5\ m$ is the via point and $y_g = 1.1\ m$ is the goal point. Assume that each segment spans a duration of 3 seconds and the velocity at the via point is 0.25 m/sec. *(8 Points)*



Question 2

20° 50° 110°



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Smooth and continuous

$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$

$\dot{\theta}(t) =$

$\ddot{\theta}(t) =$

$\downarrow \frac{d}{dt}$

1st segment:

$\theta_0 = y_0 =$

$\dot{\theta}_0 = \dot{y}_0 =$

$\theta_f = y_v =$

$\dot{\theta}_f = \dot{y}_v =$

$t_f =$

2nd segment:

$\varphi_0 = y_v =$

$\dot{\varphi}_0 = \dot{y}_v =$

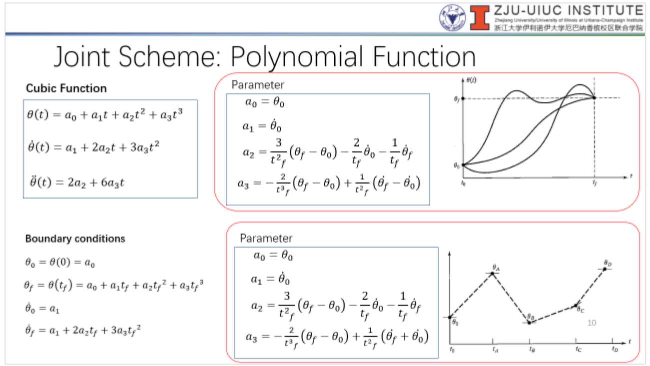
$\varphi_f = y_f =$

$\dot{\varphi}_f = \dot{y}_f =$

$t_f =$

Question 2

b) For Joint q_1, determine the parameters of a 2-segment cubic trajectory where $y_0 = 0.2\ m$ is the initial position, $y_v = 0.5\ m$ is the via point and $y_g = 1.1\ m$ is the goal point. Assume that each segment spans a duration of 3 seconds and the velocity at the via point is 0.25 m/sec. *(8 Points)*



Smooth and continuous

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3,$$
$$\dot{\theta}(t) = a_1 + 2a_2 t + 3a_3 t^2,$$
$$\ddot{\theta}(t) = 2a_2 + 6a_3 t.$$

1st segment:

$\theta_0 = y_0 = 0.2$

$\dot{\theta}_0 = \dot{y}_0 = 0$

$\theta_f = \boxed{y_v} = 0.5$

$\dot{\theta}_f = \dot{y}_v = 0.25$

$t_f = 3$

2nd segment:

$\varphi_0 = y_v = 0.5$

$\dot{\varphi}_0 = \dot{y}_v = 0.25$

$\varphi_f = y_f = 1.1$

$\dot{\varphi}_f = \dot{y}_f = 0$

$t_f = 3$

Joint Scheme: Polynomial Function

Cubic Function

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

$$\dot{\theta}(t) = a_1 + 2a_2 t + 3a_3 t^2$$

$$\ddot{\theta}(t) = 2a_2 + 6a_3 t$$

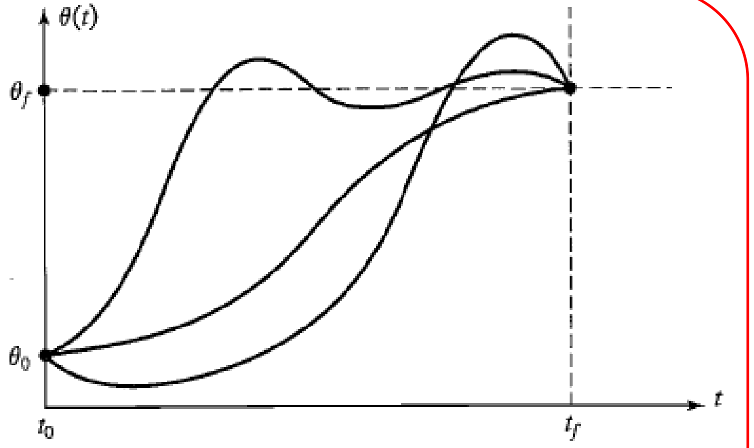
Parameter

$$a_0 = \theta_0$$

$$a_1 = \dot{\theta}_0$$

$$a_2 = \frac{3}{t^2{}_f}(\theta_f - \theta_0) - \frac{2}{t_f}\dot{\theta}_0 - \frac{1}{t_f}\dot{\theta}_f$$

$$a_3 = -\frac{2}{t^3{}_f}(\theta_f - \theta_0) + \frac{1}{t^2{}_f}\underbrace{(\dot{\theta}_f \overset{+}{\cancel{-}} \dot{\theta}_0)}_{\dot{\theta}_f + \dot{\theta}_0}$$



☆ Error in lecture

Boundary conditions

$$\theta_0 = \theta(0) = a_0$$

$$\theta_f = \theta(t_f) = a_0 + a_1 t_f + a_2 t_f{}^2 + a_3 t_f{}^3$$

$$\dot{\theta}_0 = a_1$$

$$\dot{\theta}_f = a_1 + 2a_2 t_f + 3a_3 t_f{}^2$$

Parameter

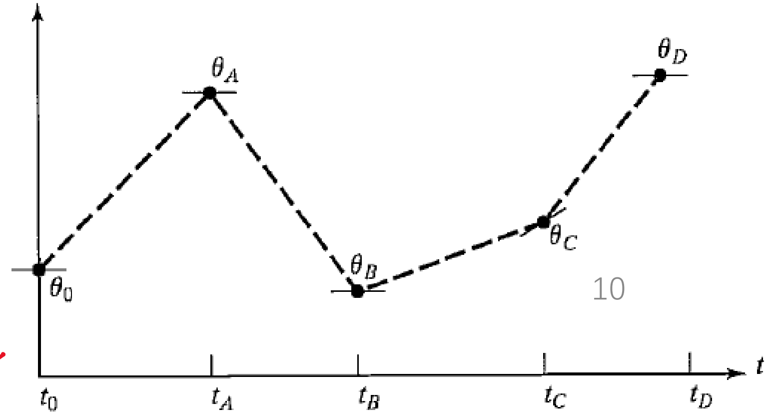
$$a_0 = \theta_0$$

$$a_1 = \dot{\theta}_0$$

$$a_2 = \frac{3}{t^2{}_f}(\theta_f - \theta_0) - \frac{2}{t_f}\dot{\theta}_0 - \frac{1}{t_f}\dot{\theta}_f$$

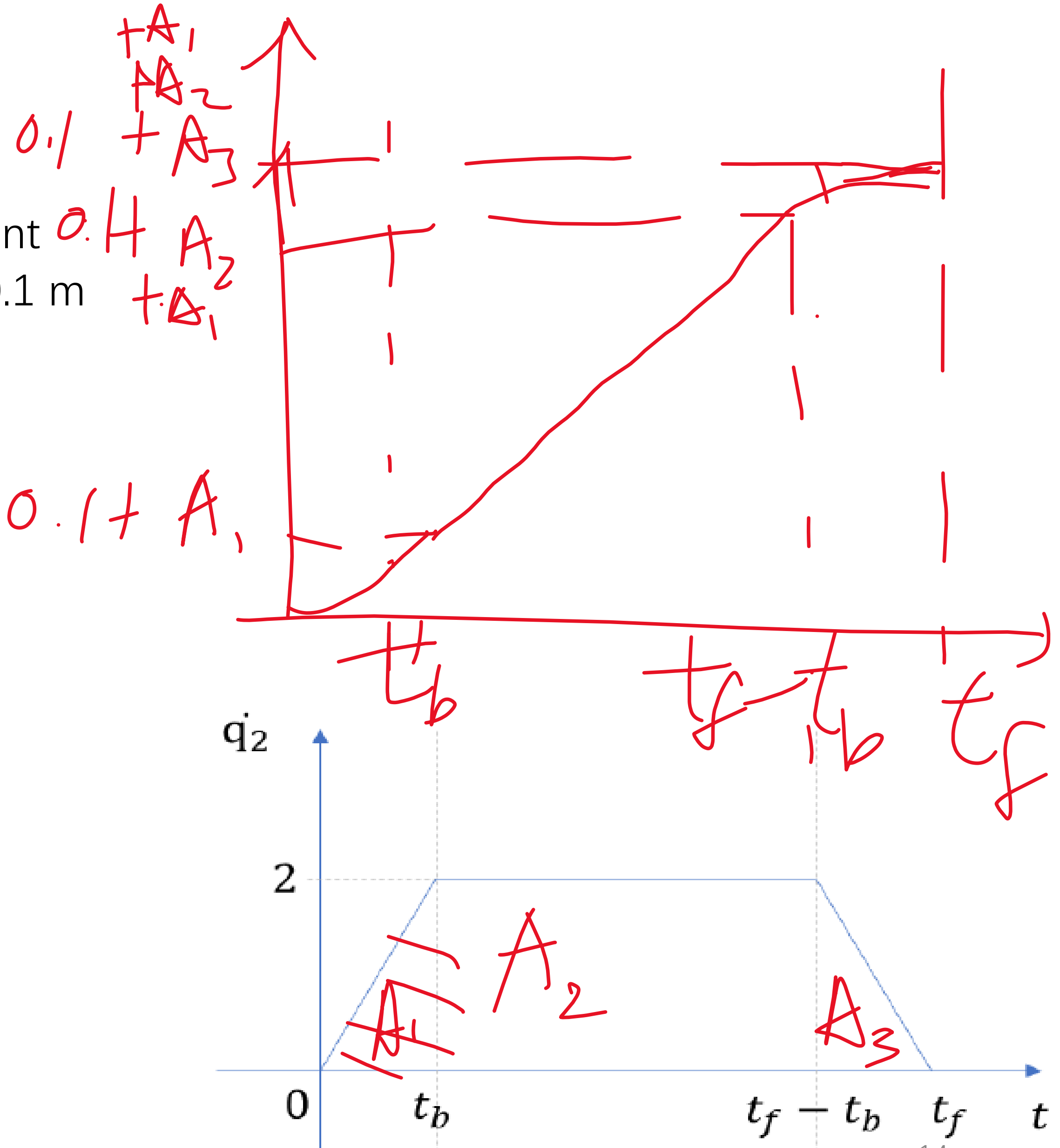
$$a_3 = -\frac{2}{t^3{}_f}(\theta_f - \theta_0) + \frac{1}{t^2{}_f}(\dot{\theta}_f + \dot{\theta}_0)$$

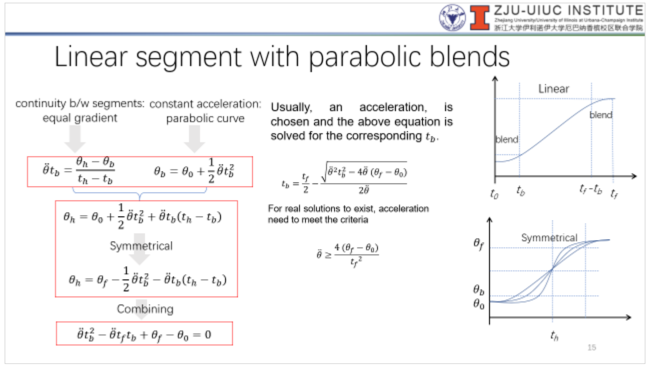
error in lecture



Question 2

c) For Joint q_2, sketch the joint trajectory (i.e. displacement over time) given that it starts from an initial position of 0.1 m according to the velocity profile as shown. *(4 Points)*





Question 2

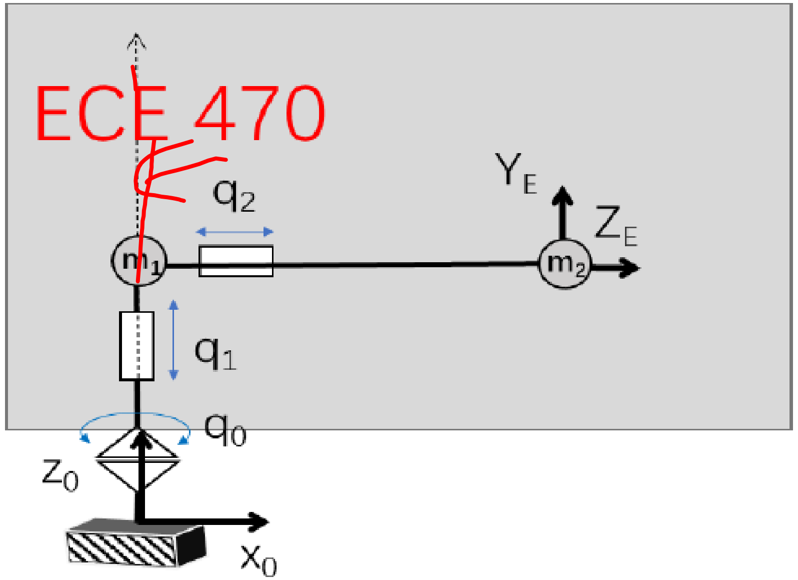
d) A student wanted to program the planar robot to write on the blackboard and realized that the writing chalk needs to be in contact with the blackboard surface at a force $F_{desired}$ to write.

He fixed the arm on a rotating Joint q_0 to control the contact force with the joint torque τ_0 while controlling the position with Joint q_1 and q_2 as shown.

i. Express the torque τ_0 of Joint q_0 in term of the Joint variables and $F_{desired}$. *(1 Points)*

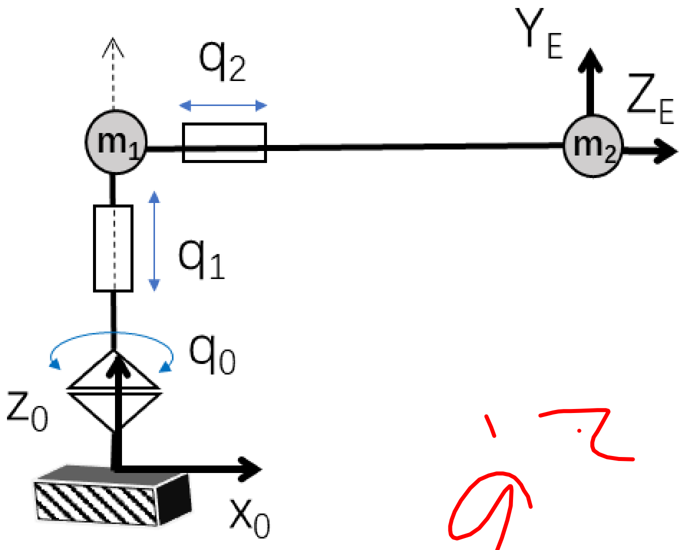
ii. If Joint q_0 can produce a maximum torque of 3 Nm, what is the writing space if $F_{desired} = 1.5$N using the student's control approach? You may assume NO joint displacement limits (i.e. q_0, q_1, q_2 can take values from $-\infty$ to ∞). *(2 Points)*

iii. If the robot is programmed to write "ECE 470" on the blackboard as shown, explain if there might be any problem and suggest solution to overcome it. *(2 Points)*



Question 3

Considering the joint variables $(q_0, q_1, q_2)^{\mathrm{T}}$) as the generalized coordinates, the generalized forces can be denoted by $(\tau_0, f_1, f_2)^{\mathrm{T}}$. Using the result in **Question 1** (v), obtain the expression for (f_1, f_2) now that it is attached to the rotational base. (You need not obtain τ_0.)



ECE 470: Introduction to Robotics
Lecture 21: Robot Vision

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Schedule Check

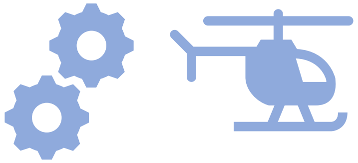
Learning Roadmap （学习蓝图）

O. Overview

I. Spatial Transformation 空间坐标与转换

II. Kinematics 运动学

III. Jacobian/ Static Forces 雅可比/静力



基础 **Fundamentals**
Wk 1-4
Revision/ Quiz on Wk 5

IV. Dynamics 动力学

V. Control 控制理论

VI. Planning 路径规划

要素 **Essentials**
Wk 6-9
Revision/ Quiz on Wk 10

VII. Robot Vision (Perception)
机器人视觉（感知）

应用 **Applied**
Wk 11-14
Reading/Exam Wk 15

Our Learning Roadmap

- **Schedule Check on our Learning Roadmap**

Fundamentals

Week 1-4

Revision/ Quiz on Week 5

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

Essentials

Week 6-9

Revision/ Quiz on Week 10

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

V. Control
- Closed-Loop Control and Feedback, Control of 2^{nd} order system, Independent Joint Control, Force Control

VI. Planning
- Joint-Based Scheme; Cartesian-Based Scheme; Collision Free Path Planning

Applied

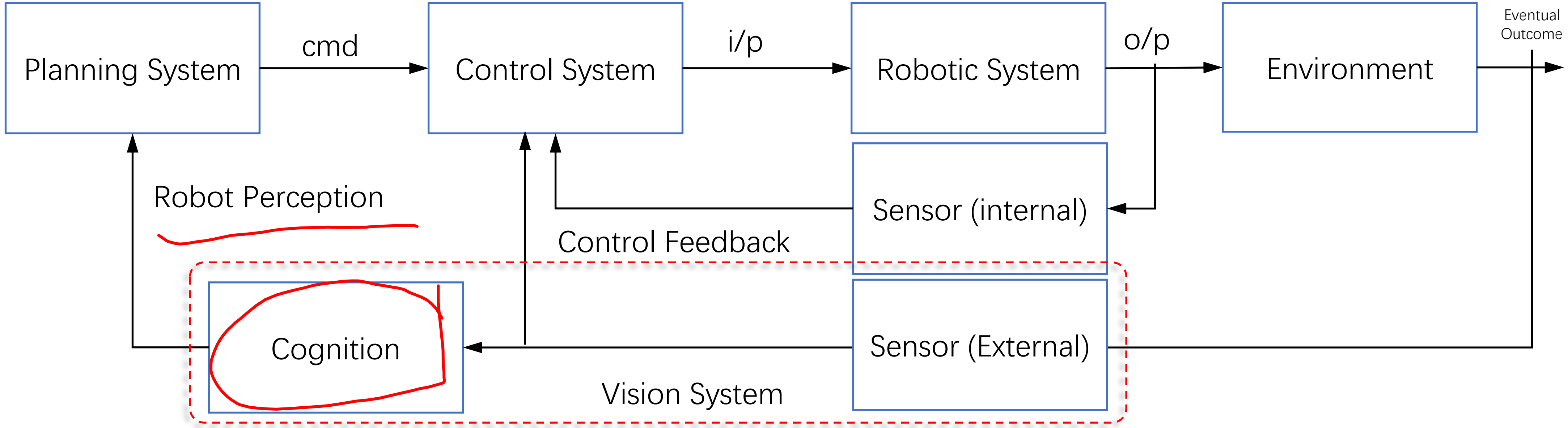
Week 11-14

Reading Wk/ Exam on Week 15-16

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

Robot Vision: Closing the final loop

- Model **kinematics** and **dynamics** of the robotic system
- Design **control** for appropriate input to achieve desired outcome
- **Planning system** to send the command to **control** system
- **Perceive** and interact with environment to achieve goal

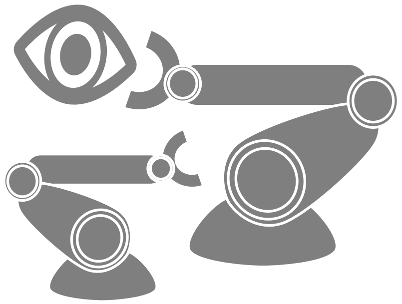


Vision as Perception

- What is really happing when we see and interpret?

Introduction to Robot Vision

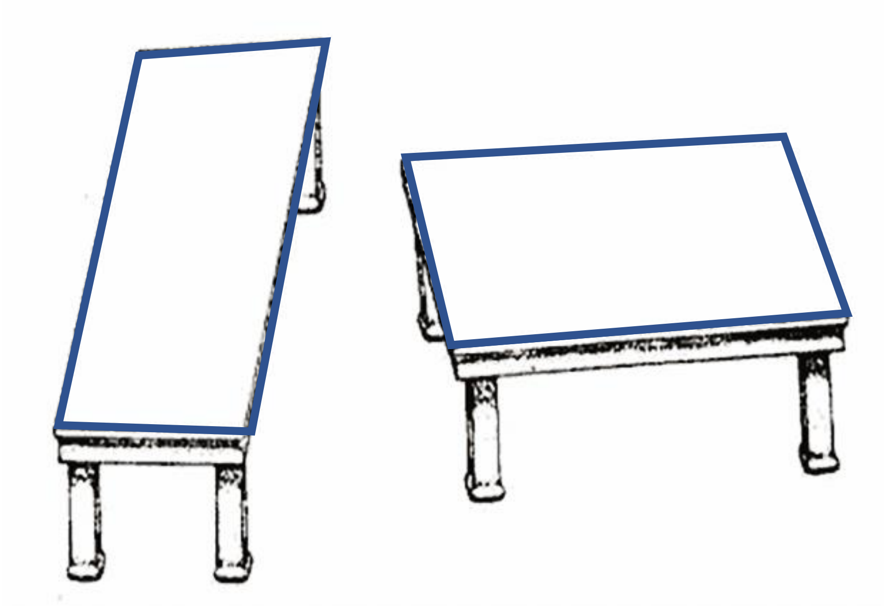
“Teaching the Robot to make sense of what they see”



What is Vision?

Teaching robot to see; Is it simple?

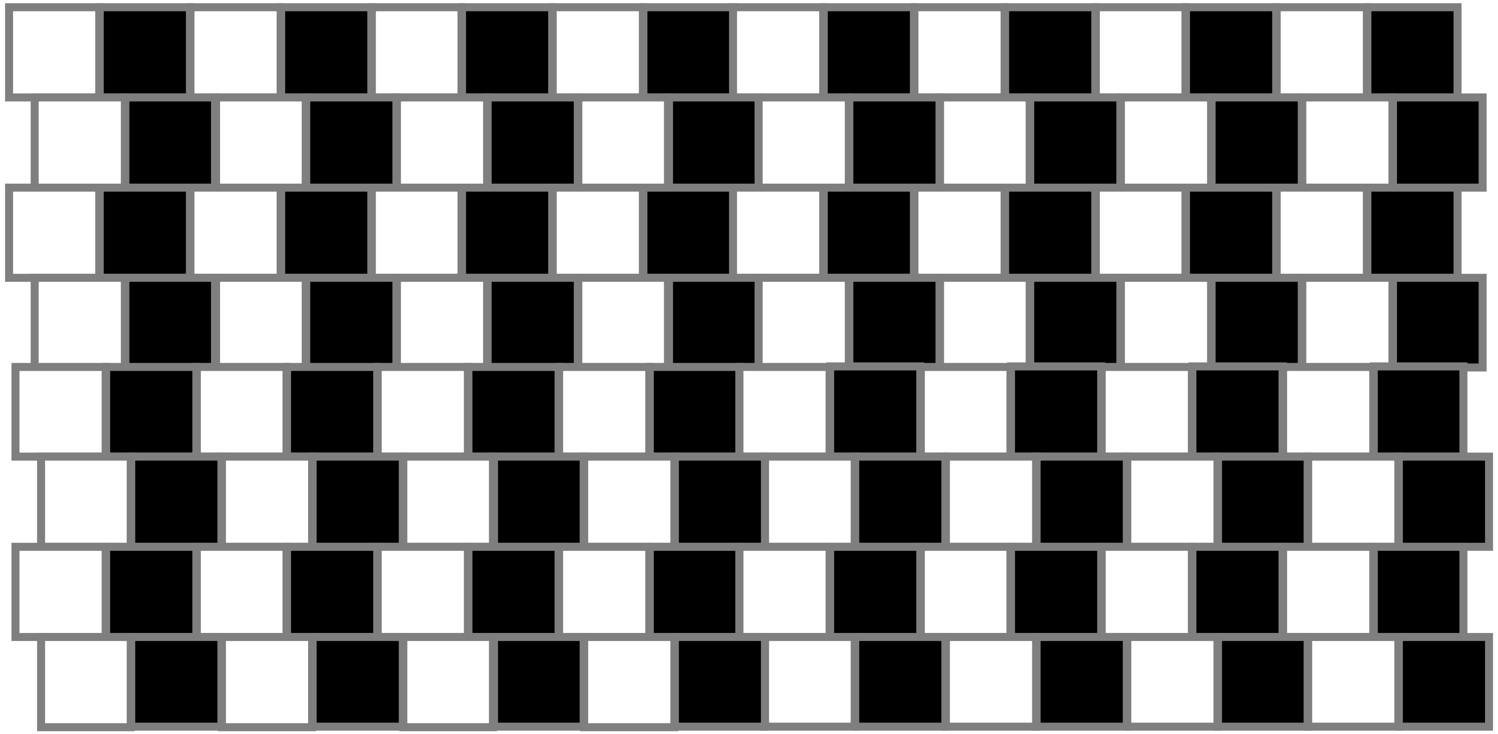
What is really happing when we see and interpret?



http://brainden.com/optical-illusions.htm

What is Vision?

- Is seeing perceiving?
- What is really happing when we see and interpret?



http://brainden.com/optical-illusions.htm

What is Vision?

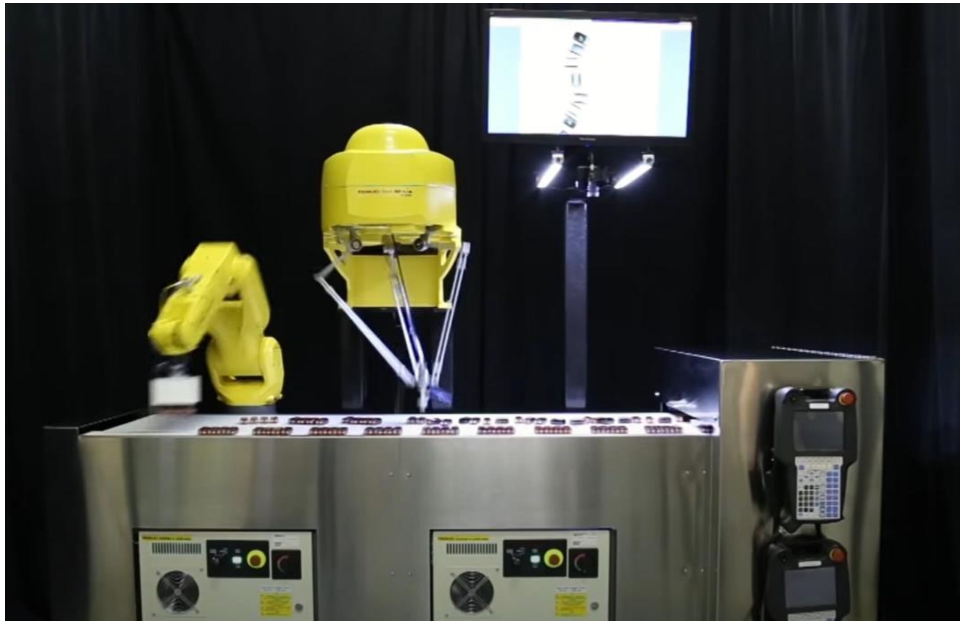
- Vision is the ability to recognize images and process them (seeing & perceiving)

  - Recognize colors, brightness, texture, geometry
  - Human vision range (visible light range): Blue (λ=400 nm) – Red (λ=700 nm)
  - Many animals can not see visible light

What is Robot Vision?

- **Computer Vision** is the science of imparting sense of vision to machines
  - Feed images to a computer and process them
  - Machines with vision – **Better Control**
- Computer vision system consists of
  - Image Acquisition system – Camera
  - Processing unit – Computer / Processor
  - Actuation system – Control action (optional)
- Applications of computer vision
  - Telecommunications, Robotics, Remote Sensing, Diagnostics, Material Science, Defense & Security, Entertainment, etc..

Computer Vision Applications: Industrial Robotics



Fanuc America Corporation
http://robot.fanucamerica.com/products/robots/automotive-robots.aspx

https://www.youtube.com/watch?v=FnIzl6sBOsA#t=37

Computer Vision Applications: Diagnostics & Medical Imaging

Magnetic Resonance Imaging

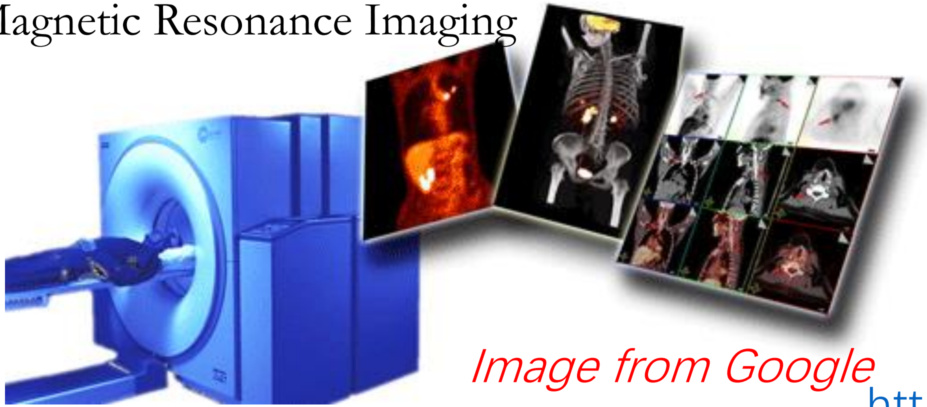


Image from Google

Other Diagnostic Techniques:

Ultra sound scan

CT Scan

Endoscopy

Ref: *Image from dreamstime.com*

https://www.youtube.com/watch?v=GYAmSH2zwic

Ref: *http://www.ucdmc.ucdavis.edu/surgicalservices/images/body/robotic_photoBanner.jpg*

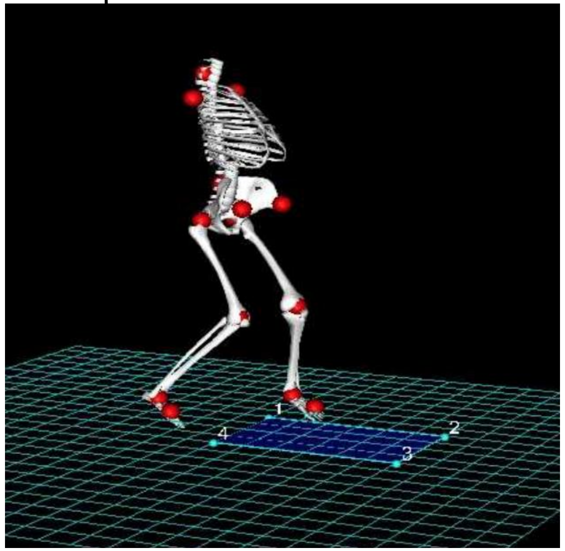
Computer Vision Applications: Biomechanics

Human Body Kinematics

Motion Markers / Sensors

Camera

Computer Model



Computer Vision enabled mapping of human body kinematics to improve prosthetic, rehabilitation and sports medicine

Figures Courtesy: *Prof. Vladimir Medved, University of Zagreb, Croatia*

Overview of Robot Vision

ECE 470 Introduction to Robotics

Overview

O. Introduction to Robot Vision
  - What is Robot Vision?

I. Image Formation
  - The science behind computer/machine vision

II. Image Processing
  - Common techniques to manipulate, enhance & analyse images

III. Robot Vision Applications
  - 3D Vision, Photogrammetry, Vision-based techniques in robotics- visual servo, pose estimation, localization, mapping, navigation

Image Formation

ECE 470 Introduction to Robotics

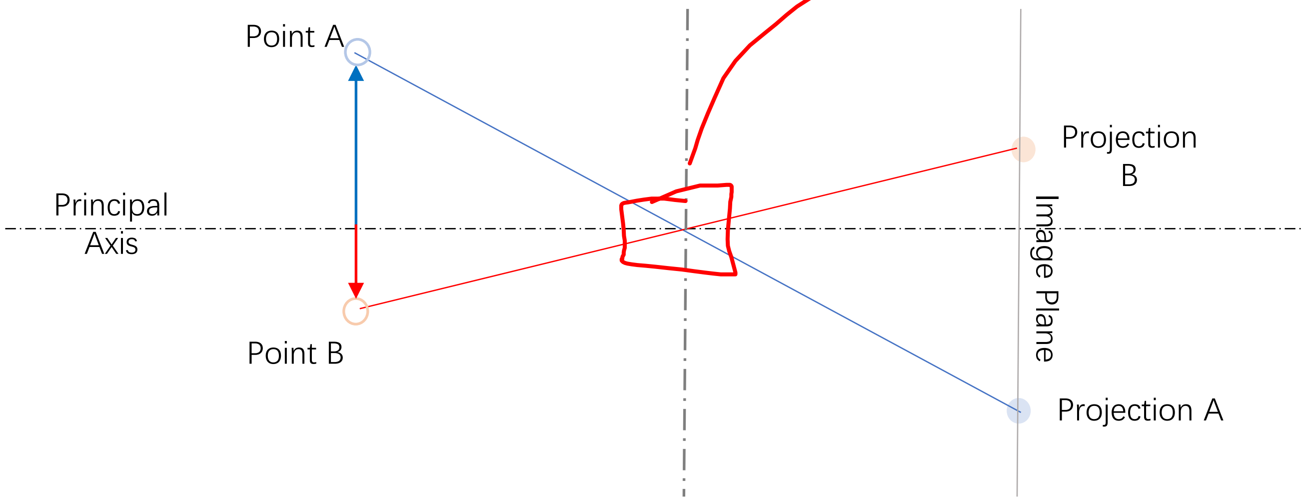
Image Formation

- Camera Model
  - How is image formed?
- Imaging System
  - How is it acquired?
- Digital Image Representation
  - How is it represented in computer?

Camera Model

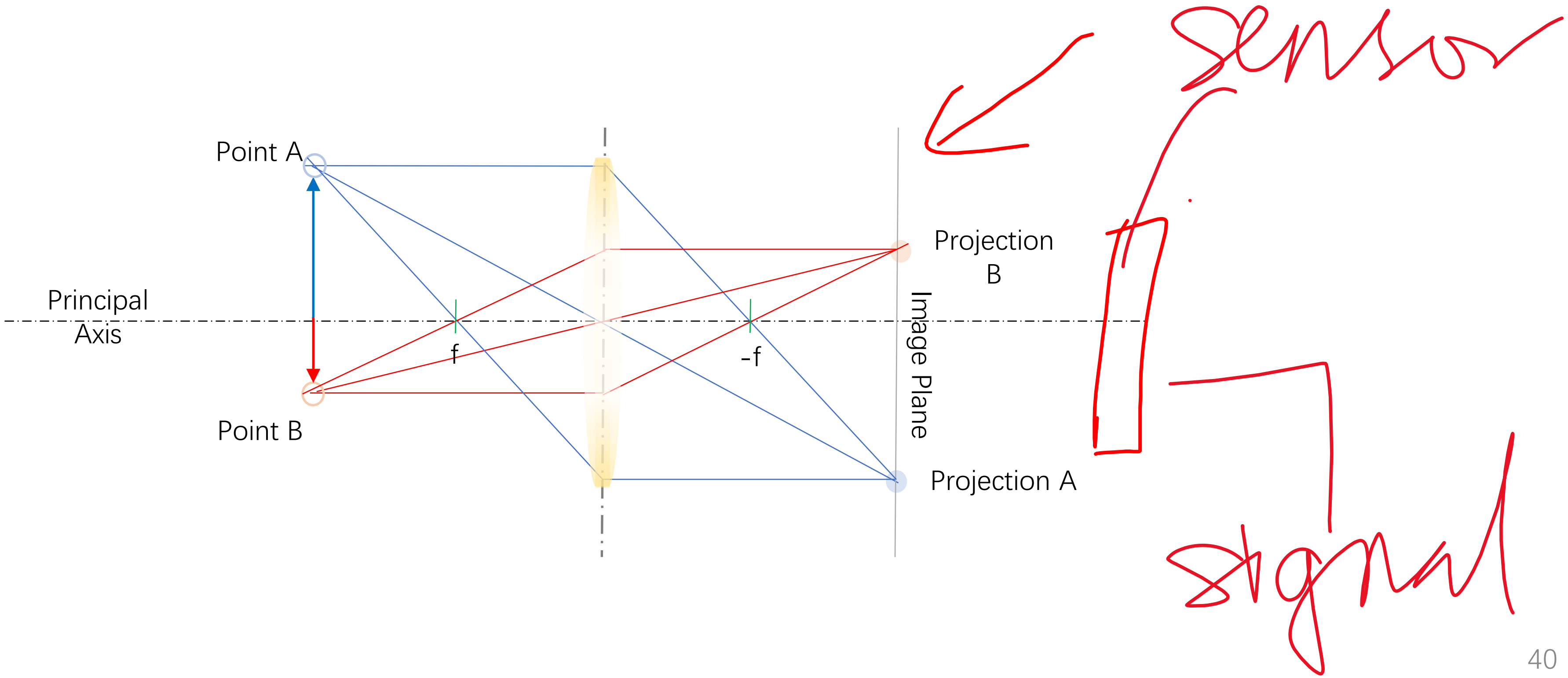
- Pin-hole Camera Model
  - describes the relationship between points and their projections on an image plane via a small opening

limit



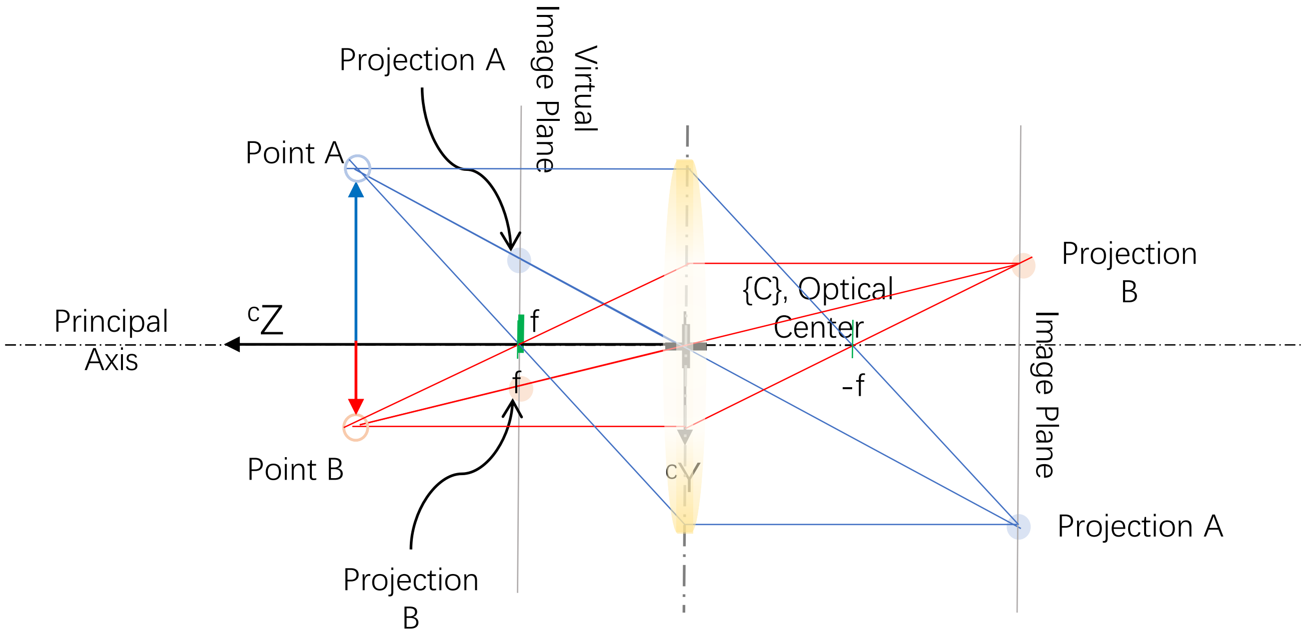
Camera Model

- Convex Focusing Lens with Pin-hole Effect
  - same image formation geometry but light passing not restrict



Camera Model

- Central Projection Camera Model
  - A simplified model for camera geometry



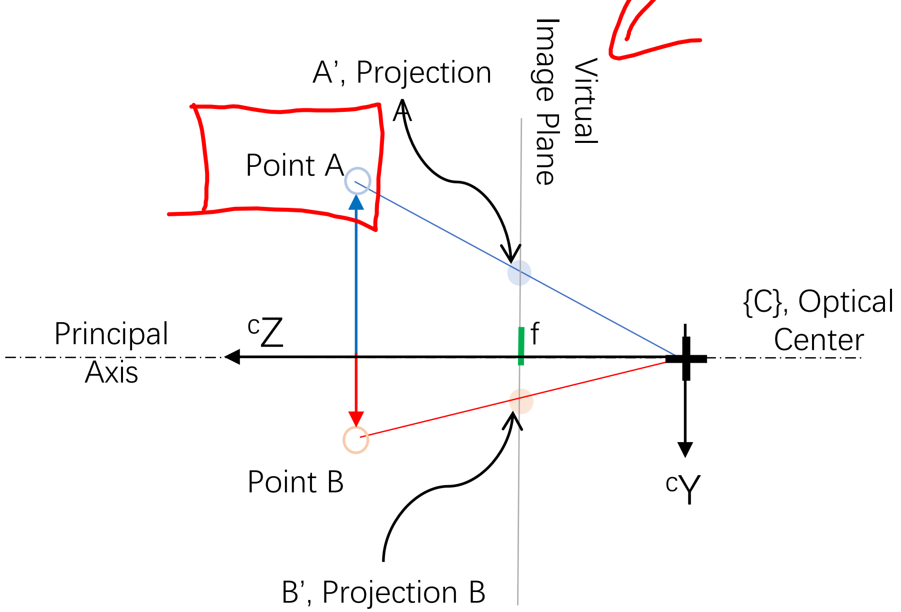
Camera Model

(x, y, Z) (u, v)

- Central Projection Camera Model
  - A simplified model for camera geometry

principal Axis

Image plane



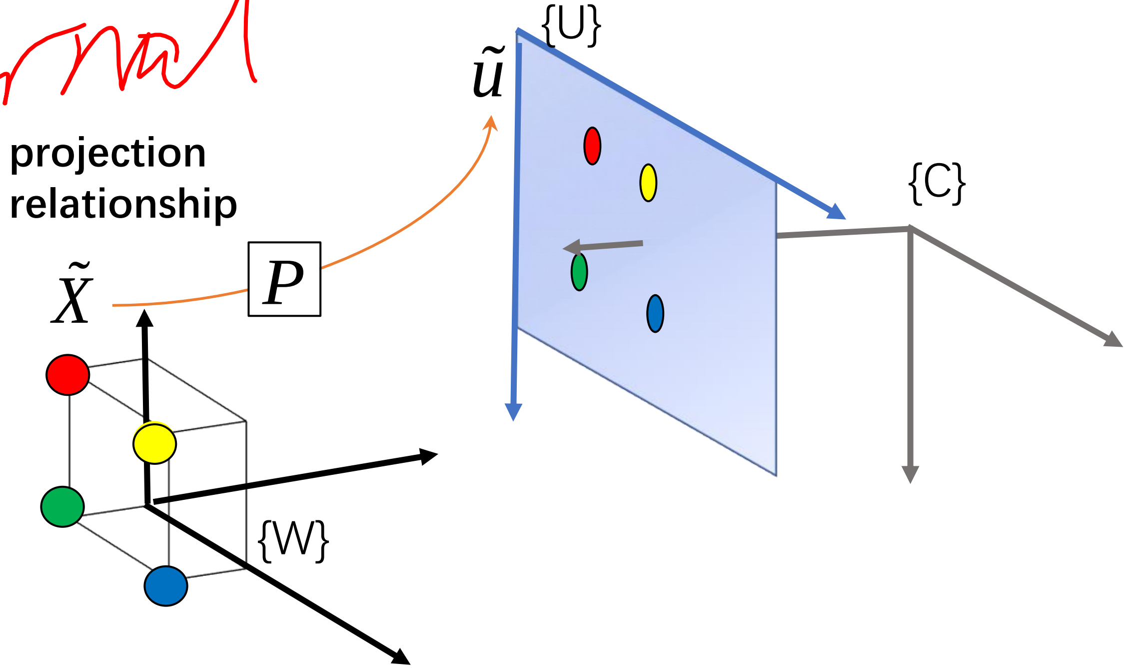
Camera Model

- Camera Matrix, P
  - Relates world with image coord. System
  - 2 Components: → External
    - Extrinsic Matrix
    - Intrinsic Matrix → Internal

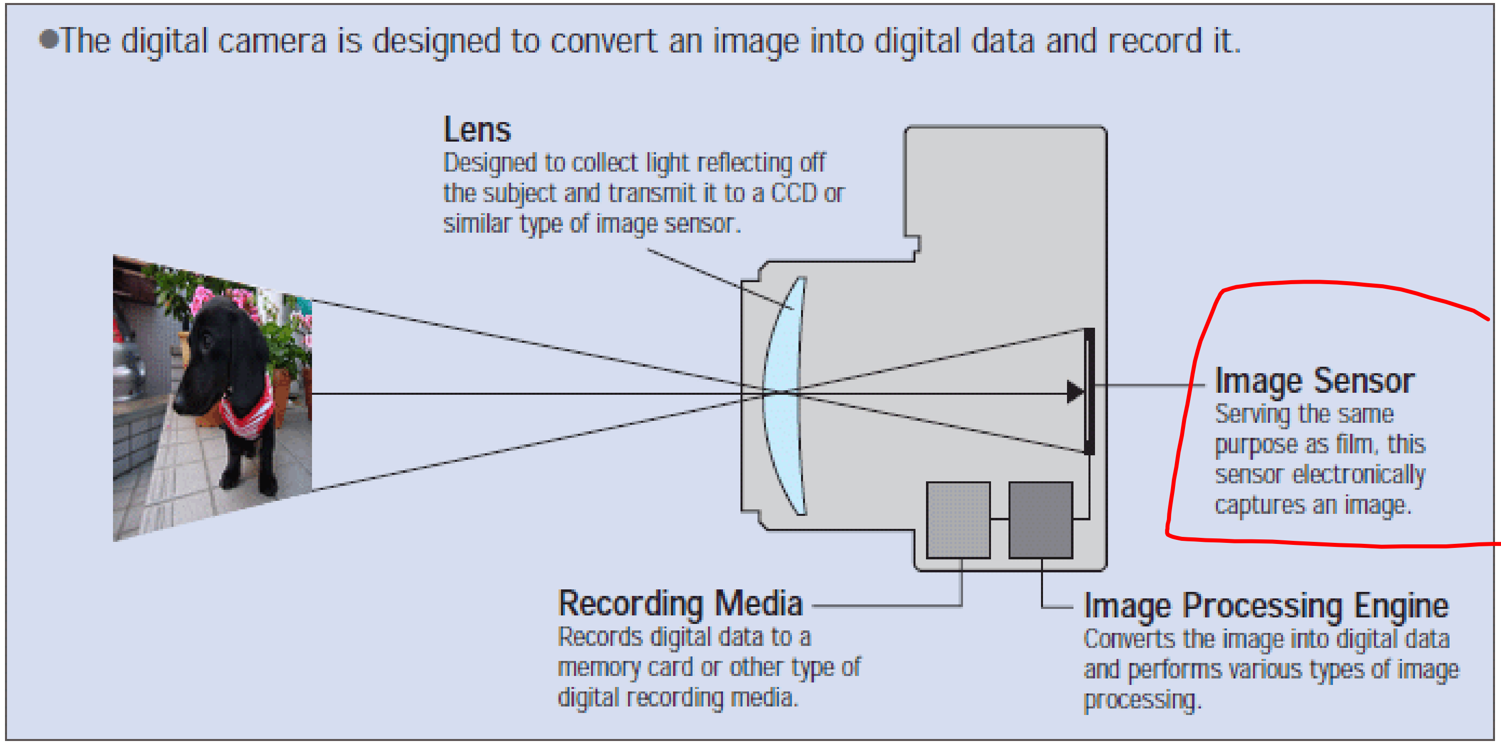
Camera Matrix, *P*

For a given set of points
${}^{W}\tilde{X}$ in 3D,
the projected set of points can be expressed as
$s\tilde{u} = P\,{}^{W}\tilde{X}$.

where $P = K\,{}^{C}[R\,|\,t]_{W}$,
K = intrinsic matrix
$[R\,|\,t]$ = extrinsic matrix



Camera Working Principle



From panasonic.com

Cameras

Key Factors:

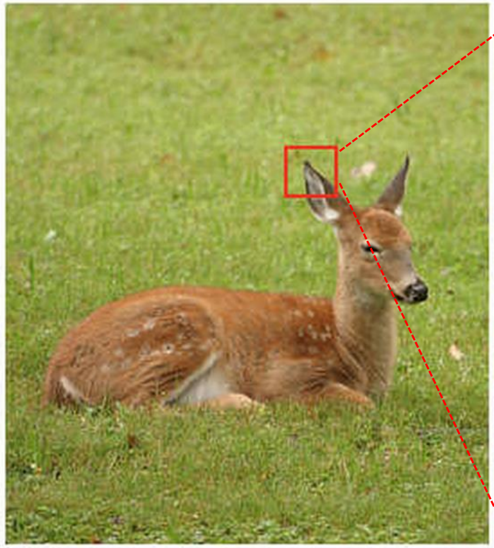
- Resolution
- Zoom
- Shutter Speed (SS)
- Aperture
- Frames Rate (FPS)
- Memory (Frame Buffer)
- File Transfer Mode

Different Types of Cameras & Features:
http://www.adept.net.au/cameras/stdMono.shtml

Cameras - Resolution

Resolution

- No of pixels on the sensor
- Each pixel has single intensity value for each color (RGB or Gray)
- High no. of pixels indicate greater level of details in the image captured - fineness


Original Image


Detail showing pixels

	3MP	4MP	5MP
Largest Image (typical)	2048 x 1536	2272 x 1712	2592 x 1944

MP= Mega Pixels

Ref: *http://photo.net/equipment/digital/basics/*

Cameras – Frame Rate (FPS) Time

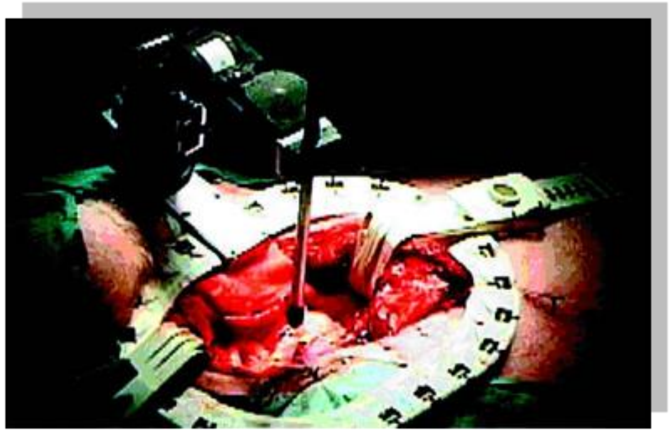
- Number of frames per sec (FPS) of the camera determine the capability of motion capture (Video)
- 24 FPS is human perception of continuous motion
- Need high speed cameras to record slow motion

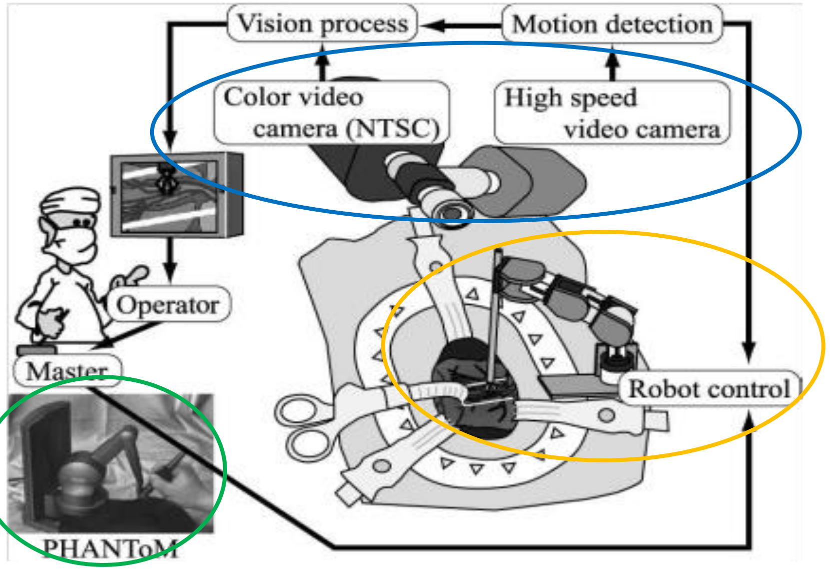
Ref: *http://photo.net/equipment/digital/basics/*

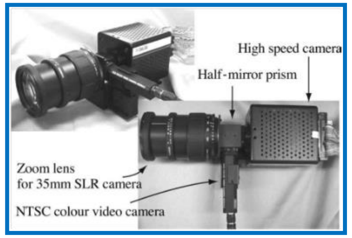
Concept Check

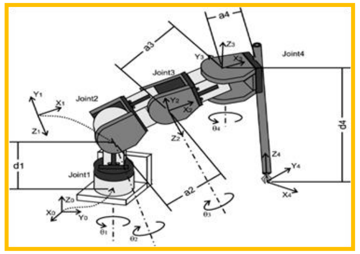
Knowing the typical frequency and amplitude range of the motion determine the appropriate acquisition rate and resolution

heart surgery



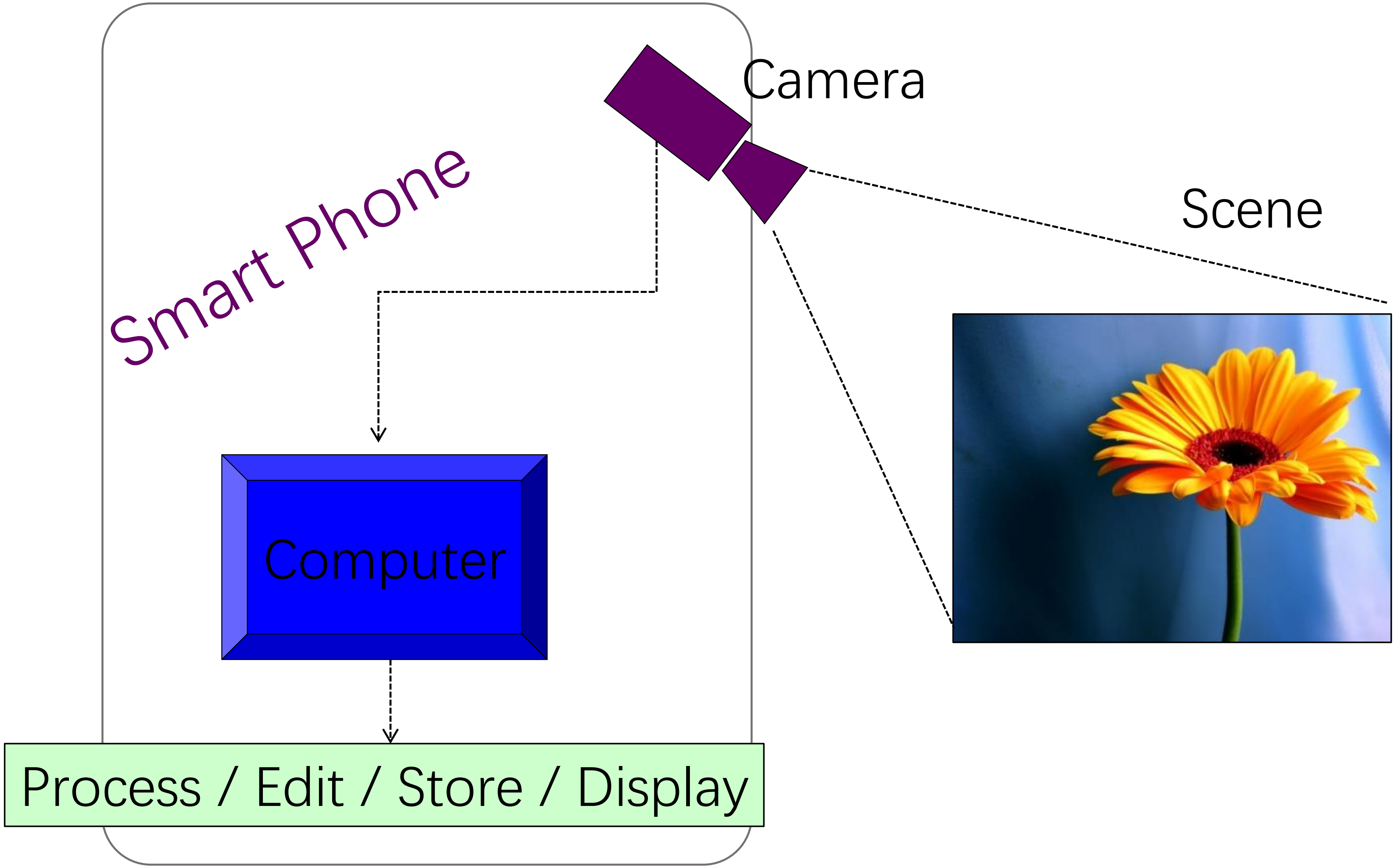






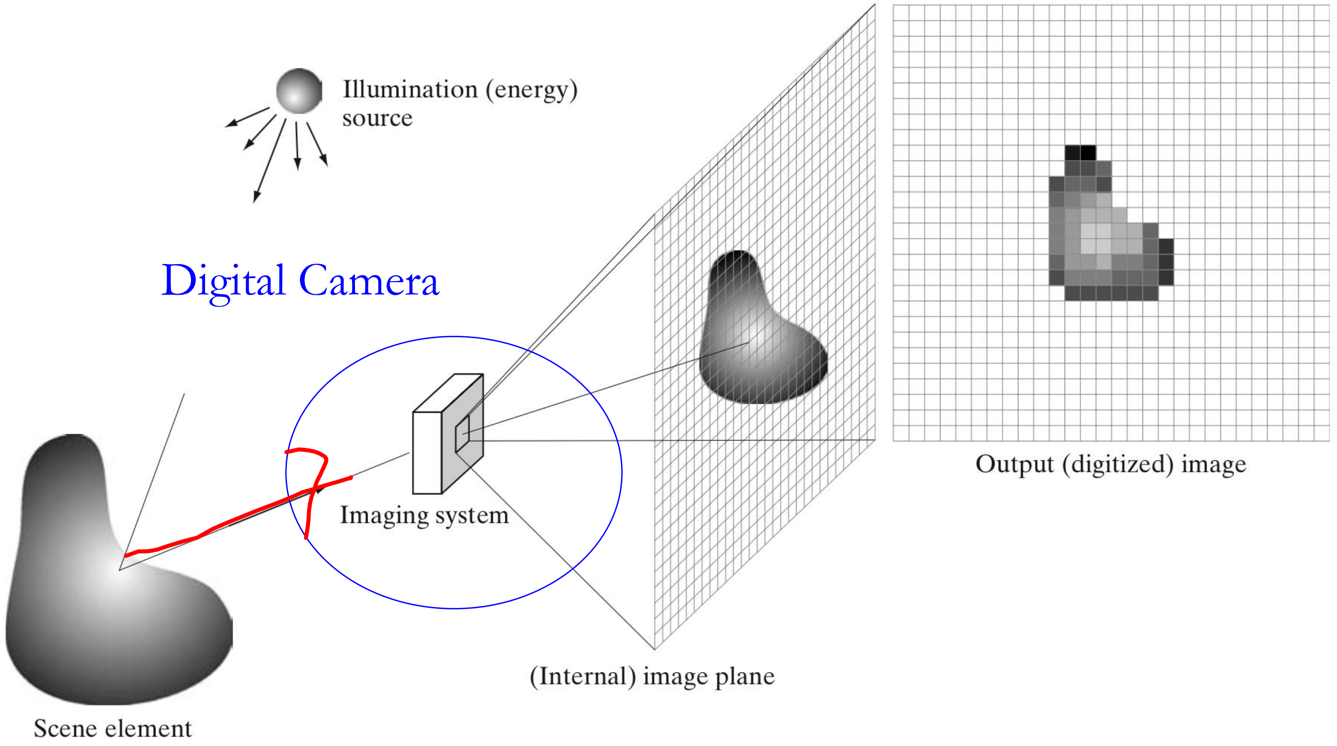
Y. Nakamura et al., "Heartbeat synchronization for robotic cardiac surgery," in *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, 2001, pp. 2014-2019 vol.2

Computer Vision System Components



Imaging System

Robot
understand



Ref: Gonzalez, Woods, "Digital Image Processing", Prentice Hall, 2008.

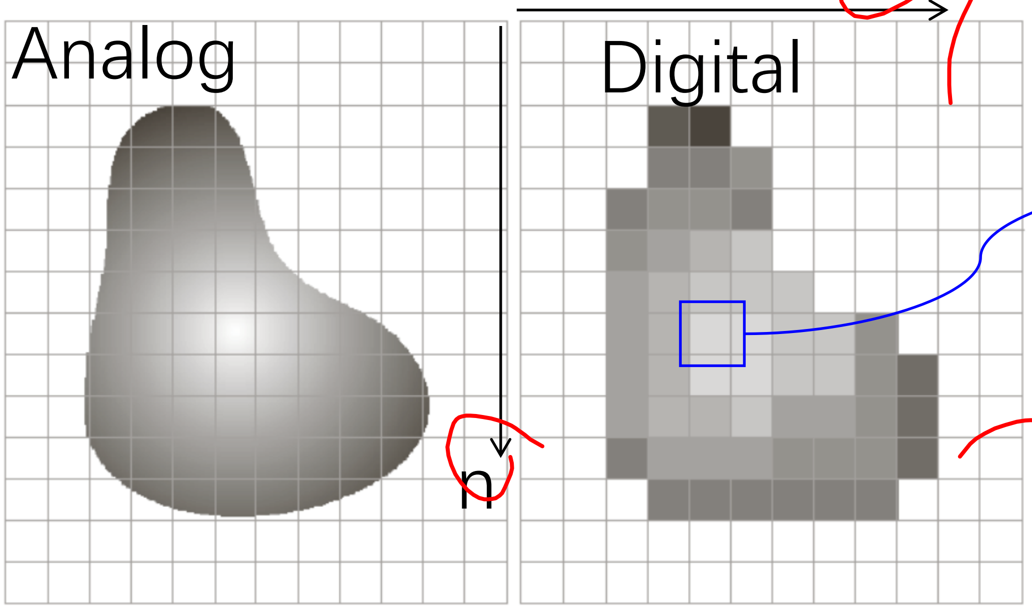
Can Computer See?

picture element

- It can process images in the form of "digits'
- For computer an ***image is a matrix of numbers representing the intensity at that region (pixel)***
- Computer can handle digital images only.

pixel

Image



I (i,j) = X
$0 \leq X \leq 255$
Black, X=0 → dark
White, X=255 → bright

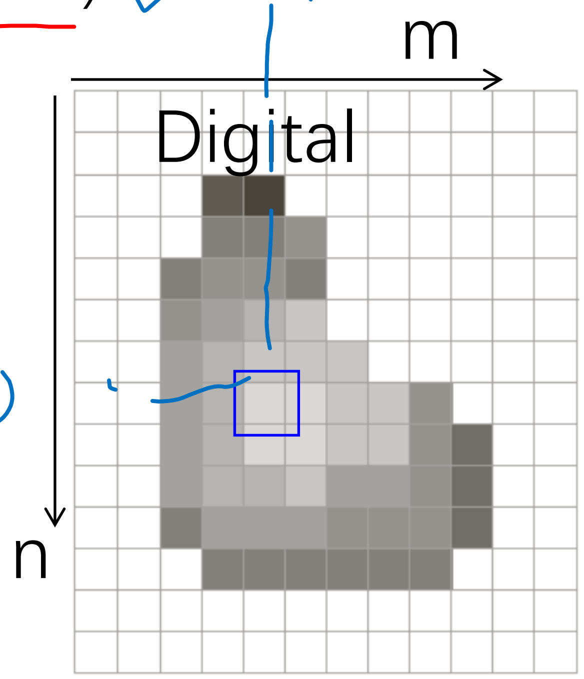
(1,1)

Ref: António R. C. Paiva, 2010

Image Representation

- Digital Image
- *N* X *M* Array of Pixels (2D matrix)
  - Pixel Position (Coordinates)
  - Pixel Values (Intensity)

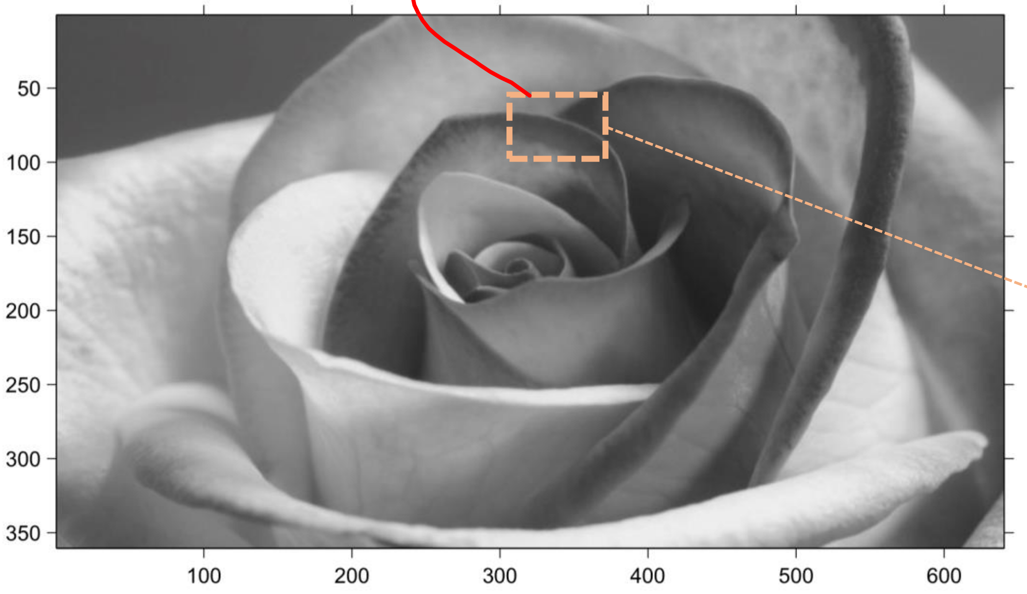
$I(i, j)$



Computer Interpretation of Images

Gray scale Images

Image



Intensity , I(*i*,*j*)

0 = black
gray
255 = white

j →

i ↓

	345	346	347	348	349	350	351	352	353	354	355
70	67	64	61	61	60	59	60	61	60	59	59
71	74	69	65	63	63	61	60	60	61	60	59
72	86	79	72	70	68	66	64	63	63	62	61
73	96	97	94	87	81	77	72	67	66	64	62
74	75	83	91	97	98	95	88	81	69	65	63
75	72	74	75	78	84	93	101	104	92	84	75
76	68	68	68	69	73	81	88	92	101	101	96
77	67	67	67	69	71	72	73	74	81	94	102
78	69	67	65	66	67	68	71	74	73	80	85
79	67	67	68	69	70	68	67	68	74	74	71
80	70	69	68	68	67	66	66	69	70	70	73

Matlab Commands:

```
img_gray=rgb2gray(img1);
imshow(img_gray)
imsub_gray=img_gray(70:80,345:355,:)
```
– for printing intensity matrix