MTRN 3060: ROBOTICS and AUTOMATIONS

Week 2: Transformation operators, Component of Robots

03 August 2023

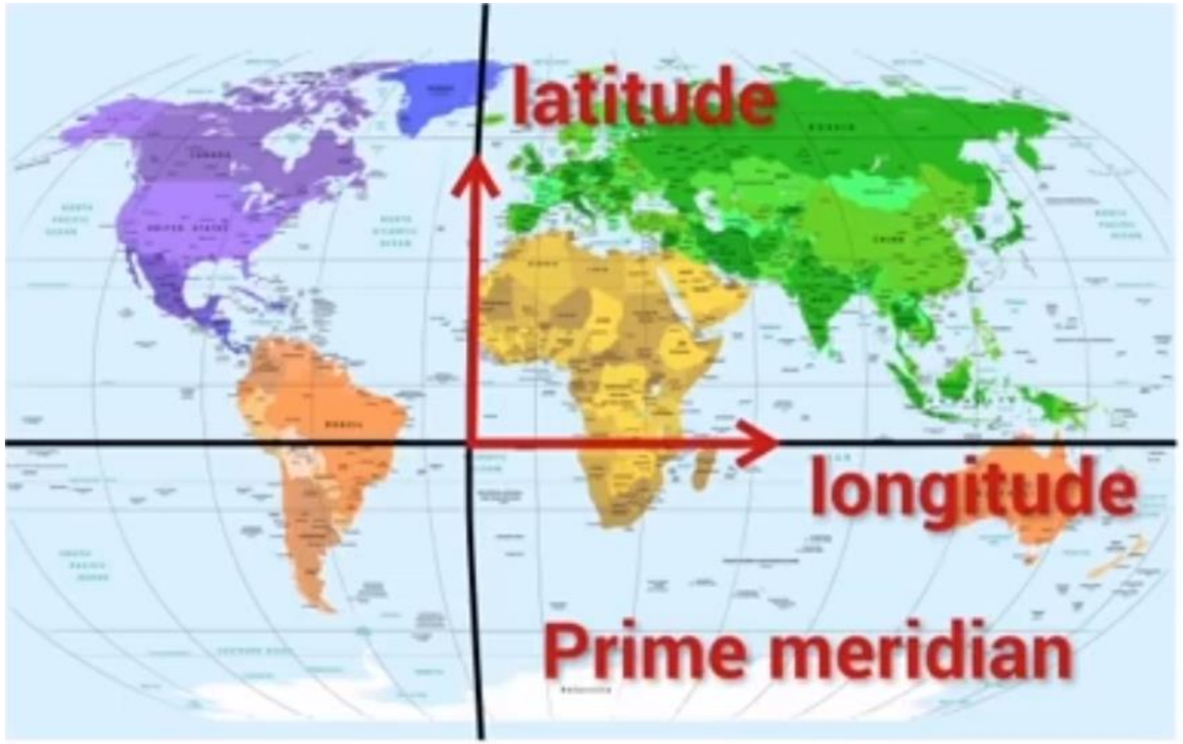
Lecture/Workshop learning objects

- Describe object in 3D space
- Map object in 3D space
- Transformation operators
- Transformation matrices

Practical learning objects

- Lab safety
- Robotic arm
- gripper safety
- Movement and coordinates

Create our own frame of reference



Greenwich Meridian 2008

Leon Brocard | CC BY 2.0.

Greenwich Meridian 2011

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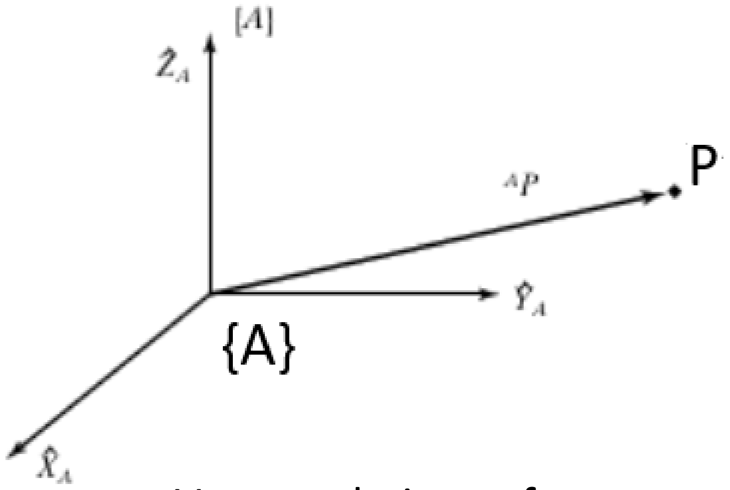
Position

Define the position of point “P” relative to coordinate frame {A}

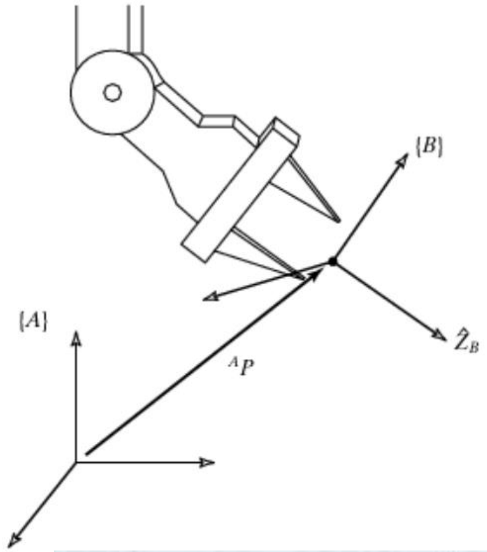


Vector relative to frame

Individual elements of a vector are given the subscripts x, y, z $\quad {}^{A}P = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}$

In –class exercise: Describe and draw the position of point “P” relative to coordinate frame {B} if point “P” is positioned at 2, 4and 3 in x, y and z of frame {B}

Orientation



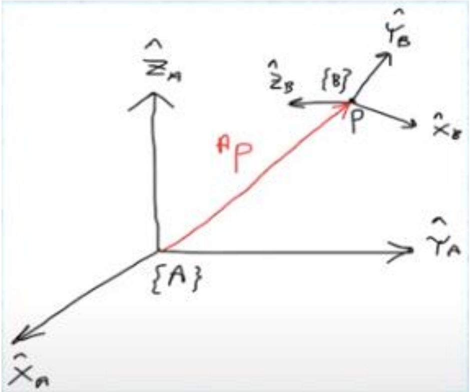
Define the orientation of an object relative to coordinate frame {A} regardless of position. A new frame {B} on the object is required,

Unit vector {B} are $\hat{X}_B$, $\hat{Y}_B$, and $\hat{Z}_B$

- When written in terms of {A} they become

$$^{A}\hat{X}_B \quad ^{A}\hat{Y}_B \quad ^{A}\hat{Z}_B$$

- The rotation matrix can be defined as:



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

$$^{A}_{B}R = \left[\, ^{A}\hat{X}_B \; ^{A}\hat{Y}_B \; ^{A}\hat{Z}_B \,\right] = \begin{bmatrix} \hat{X}_B \cdot \hat{X}_A & \hat{Y}_B \cdot \hat{X}_A & \hat{Z}_B \cdot \hat{X}_A \\ \hat{X}_B \cdot \hat{Y}_A & \hat{Y}_B \cdot \hat{Y}_A & \hat{Z}_B \cdot \hat{Y}_A \\ \hat{X}_B \cdot \hat{Z}_A & \hat{Y}_B \cdot \hat{Z}_A & \hat{Z}_B \cdot \hat{Z}_A \end{bmatrix}$$

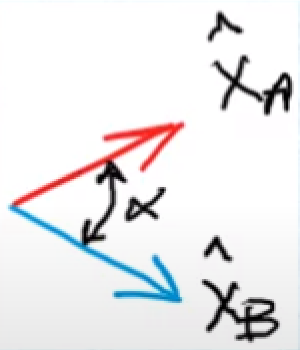
$$^{A}_{B}R = \left[\, ^{A}\hat{X}_B \quad ^{A}\hat{Y}_B \quad ^{A}\hat{Z}_B \,\right] = \begin{bmatrix} ^{B}\hat{X}_A^{T} \\ ^{B}\hat{Y}_A^{T} \\ ^{B}\hat{Z}_A^{T} \end{bmatrix}$$

Orientation

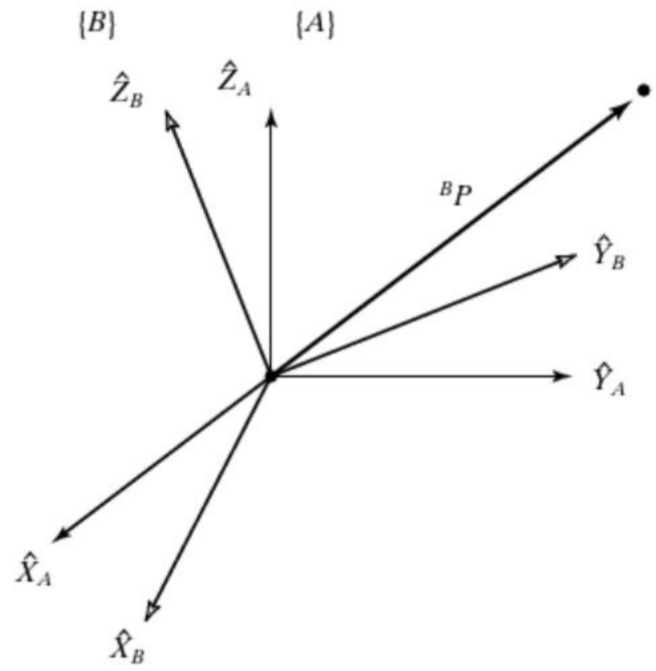
From linear Algebra, the inverse of a matric with orthogonal columns is the same as its transpose. Therefore:

$$ {}^{A}_{B}R = {}^{B}_{A}R^{-1} = {}^{B}_{A}R^{T} $$

When α is the angel between two vectors, then:



$$ \hat{X}_A \cdot \hat{X}_B = \cos\alpha $$

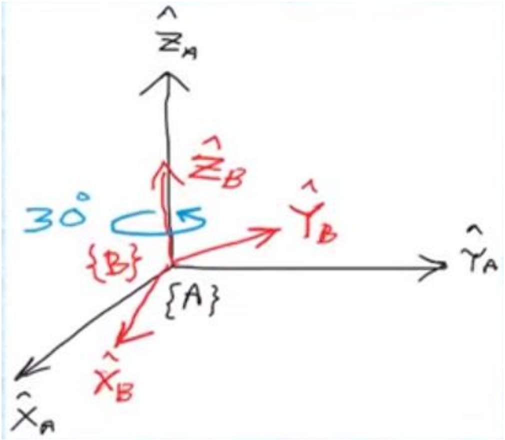


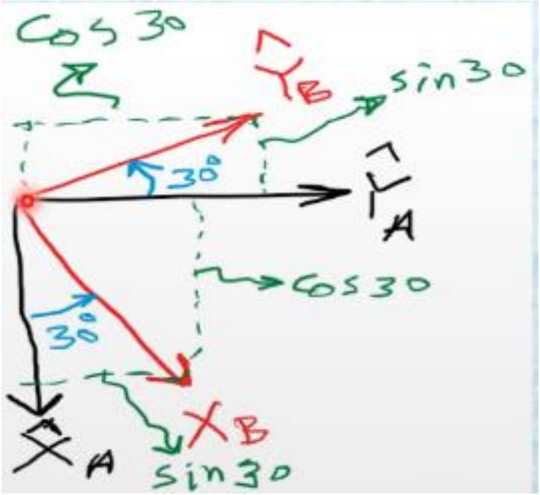
The above matric is direction cosine matrix

$$ {}^{A}_{B}R = \begin{bmatrix} \cos(\hat{X}_B, \hat{X}_A) & \cos(\hat{Y}_B, \hat{X}_A) & \cos(\hat{Z}_B, \hat{X}_A) \\ \cos(\hat{X}_B, \hat{Y}_A) & \cos(\hat{Y}_B, \hat{Y}_A) & \cos(\hat{Z}_B, \hat{Y}_A) \\ \cos(\hat{X}_B, \hat{Z}_A) & \cos(\hat{Y}_B, \hat{Z}_A) & \cos(\hat{Z}_B, \hat{Z}_A) \end{bmatrix} $$

Example-Orientation

Find the rotation matric of point “P” if its frame {B} is rotated 30 degrees about the z-axis relative to frame {A}





Solution:

$$
{}^{A}_{B}R = \begin{bmatrix} \cos 30 & \cos 120 & \cos 90 \\ \cos 60 & \cos 30 & \cos 90 \\ \cos 90 & \cos 90 & \cos 0 \end{bmatrix} = \begin{bmatrix} \cos 30 & -\sin 30 & 0 \\ \sin 30 & \cos 30 & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

Exercise-Orientation

Find the rotation matrix of point “P” if its frame {B} is rotated 30 degrees about the x-axis relative to frame {A}

Rotation Matrices in 3D

$$\mathbf{R_z} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Rotation around the Z-Axis

$$\mathbf{R_y} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

Rotation around the Y-Axis

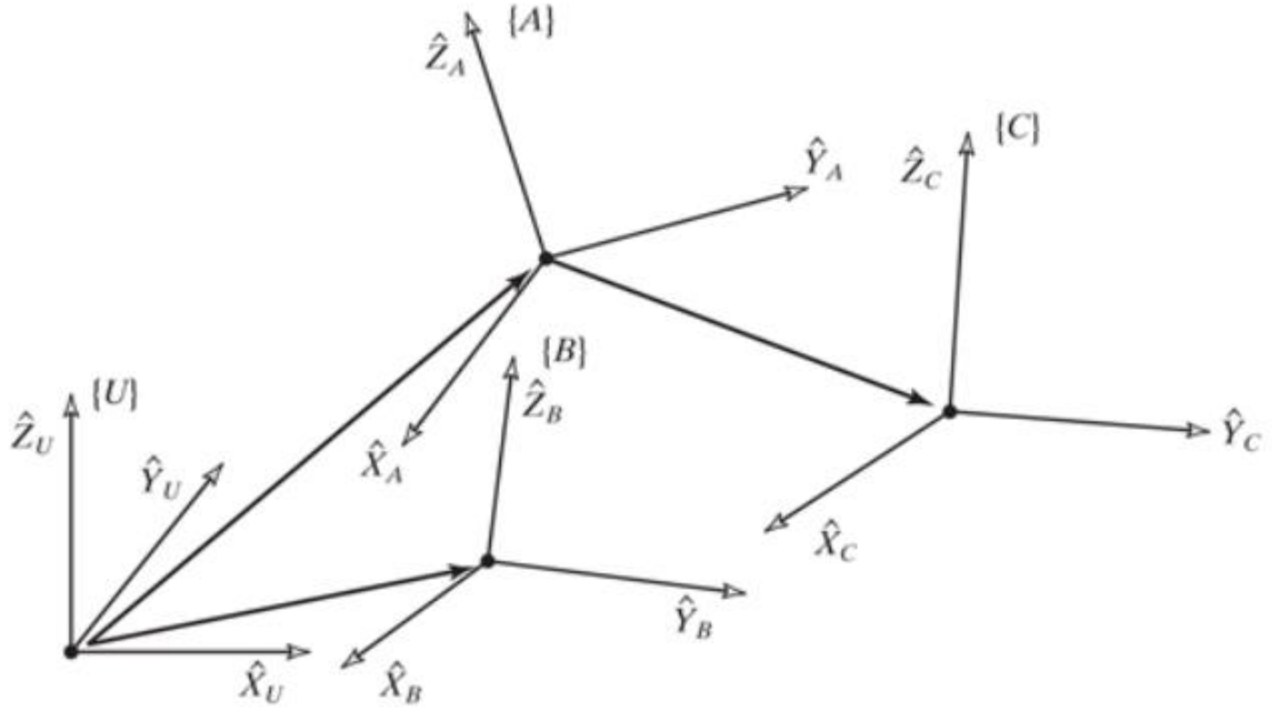
$$\mathbf{R_z} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

Rotation around the X-Axis

$$\boxed{{}^{A}_{B}R = {}^{B}_{A}R^{-1} = {}^{B}_{A}R^{T}.}$$

Description of a Frame

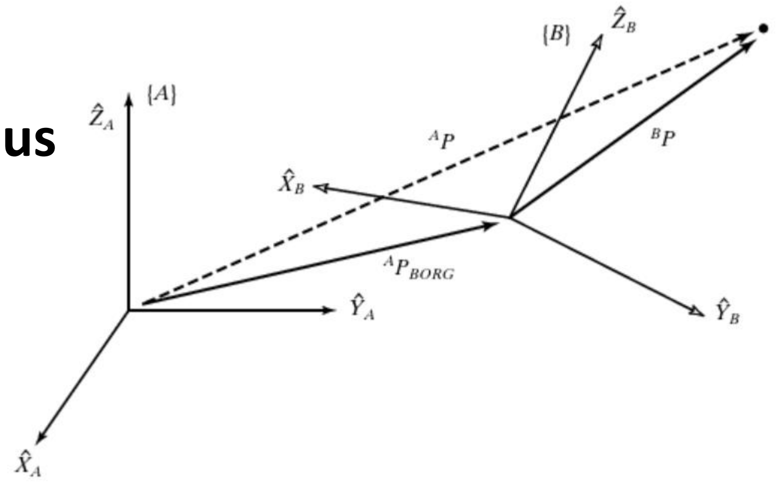
Frame can be used as a description of one coordinate system relative to another. A frame encompasses two ideas by representing both position and orientation, and so may be thought of as a generalization of those two ideas. Positions could be represented by a frame whose rotation-matrix part is the identity matrix and whose position-vector part locates the point being described. Likewise, an orientation could be represented by a frame whose position-vector part was the zero vector.



$$\{B\} = \{{}^A_B R,\ {}^A P_{BORG}\}.$$

Mapping involving general frames

- Define the position and orientation of an object relative to coordinate frame {A}. A new frame {B} on the object is required



To simply this matrix/vector combination, we use the "**Homogeneous Transformation**" matrix as follows:

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

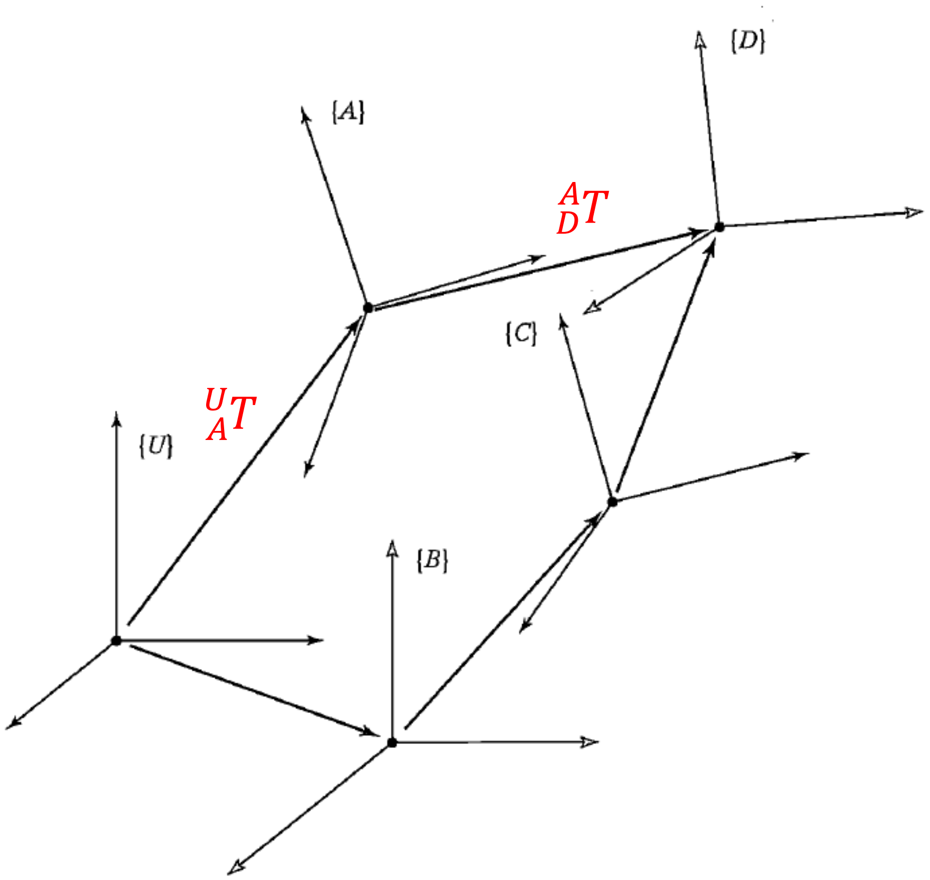
$$\boxed{{}^{A}P = {}^{A}_{B}T\;{}^{B}P.}$$

1. a "1" is added as the last element of the 4×1 vectors;
2. a row "[0 0 0 1]" is added as the last row of the 4×4 matrix.

The description of frame {B} relative to {A} is ${}^{A}_{B}T$

Frames relative to other frames

Describe frames relative to other frames



$^{A}_{D}T$ Transformation matrix of D related to A

Example

Describe frame {B} relative to frame {A} of the origin of {B} is positioned at: -2, 3, and 5 in x, y and z relative to frame {A}, and {B} is rotated 30 degrees about the z-axis relative to frame {A}.

Exercise

Describe frame {B} relative to frame {A} if the origin of {B} is positioned at: 5, -12 and -4 in x, y, and z relative to frame {A}, and {B} is rotated 45 degrees about the x-axis relative to frame {A}.

Summary

We have introduced three interpretations of this homogeneous transform:

1. It is a *description of a frame*. ${}^{A}_{B}T$ describes the frame $\{B\}$ relative to the frame $\{A\}$. Specifically, the columns of ${}^{A}_{B}R$ are unit vectors defining the directions of the principal axes of $\{B\}$, and ${}^{A}P_{BORG}$ locates the position of the origin of $\{B\}$.
2. It is a *transform mapping*. ${}^{A}_{B}T$ maps ${}^{B}P \rightarrow {}^{A}P$.
3. It is a *transform operator*. T operates on ${}^{A}P_1$ to create ${}^{A}P_2$.

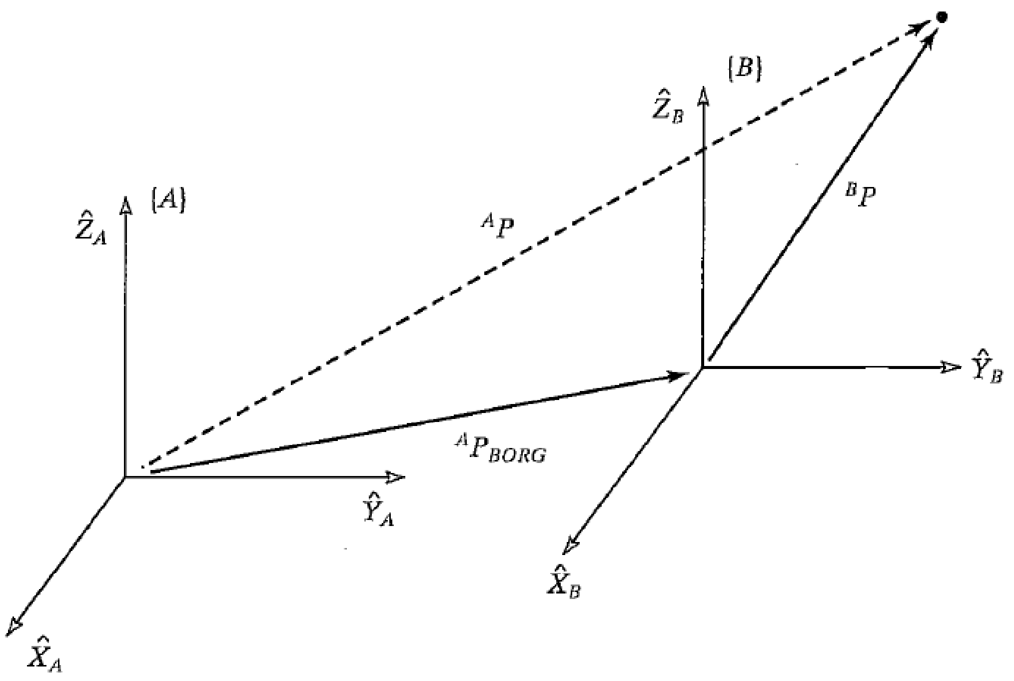
Mapping

Change the description of a point from being relative to a frame to being relative to another frame

a) Translation only

The second frame is translated (without rotation) relative to the first frame

$${}^{A}P = {}^{B}P + {}^{A}P_{BORG}.$$



Example

Frame {B} is translated 10 units in X_A and 5 units in Y_A . Find A_P if B_P =[3 7 0]^T

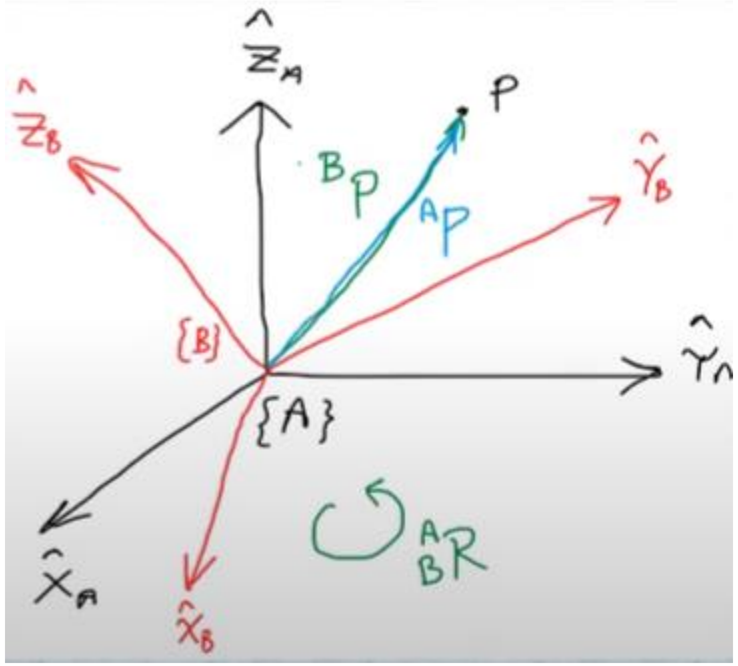
Frame {B} is translated 12 units in X_A and 7 units in Y_A and −3 units in Z_A Find A_P if B_P =[-6 7 0]^T

Mapping

b) Rotation only

The second frame is rotated (without translation) relative to the first frame

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



Example:

Figure 2.6 shows a frame {B} that is rotated relative to frame {A} about $\hat{Z}$ by 30 degrees. Here, $\hat{Z}$ is pointing out of the page.

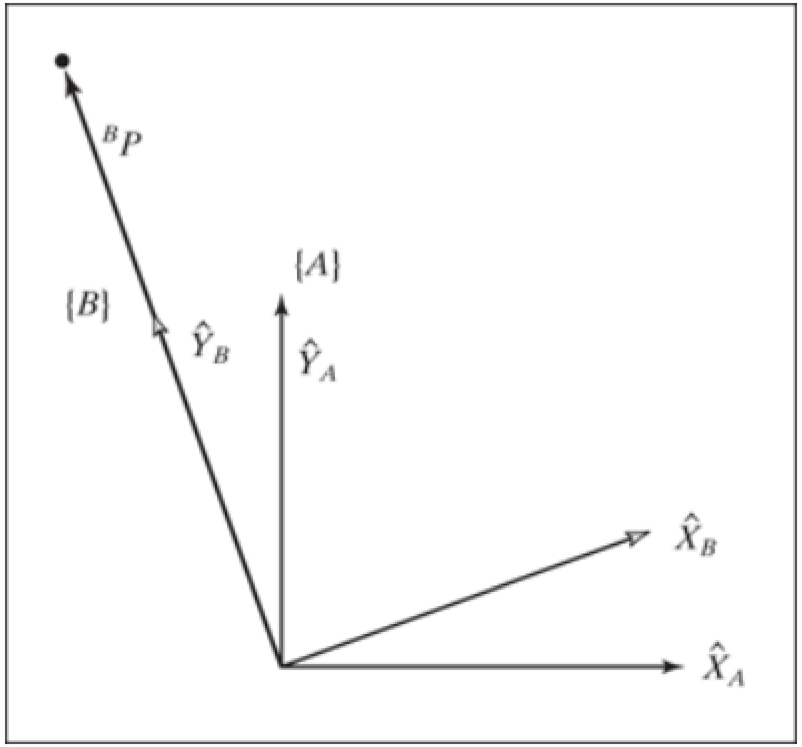


FIGURE 2.6:

Solution:

Writing the unit vectors of {*B*} in terms of {*A*} and stacking them as the columns of the rotation matrix, we obtain

$$ {}^{A}_{B}R = \begin{bmatrix} 0.866 & -0.500 & 0.000 \\ 0.500 & 0.866 & 0.000 \\ 0.000 & 0.000 & 1.000 \end{bmatrix}. \tag{2.14} $$

Given

$$ {}^{B}P = \begin{bmatrix} 0.0 \\ 2.0 \\ 0.0 \end{bmatrix}, \tag{2.15} $$

we calculate ${}^{A}P$ as

$$ {}^{A}P = {}^{A}_{B}R \; {}^{B}P = \begin{bmatrix} -1.000 \\ 1.732 \\ 0.000 \end{bmatrix}. \tag{2.16} $$

Here, ${}^{A}_{B}R$ acts as a mapping that is used to describe ${}^{B}P$ relative to frame {*A*}, ${}^{A}P$. As was introduced in the case of translations, it is important to remember that, viewed as a mapping, the original vector *P* is not changed in space. Rather, we compute a new description of the vector relative to another frame.

Example

Frame {B} is rotated relative to frame {A} about z-axis by 30 degrees. Find ${}^{A}_{B}R$ the find A_P if B_P =[0 2 0]^T

Frame {B} is rotated relative to frame {A} about y-axis by 60 degrees. Find ${}^{A}_{B}R$ the find A_P if B_P =[3 2 0]^T

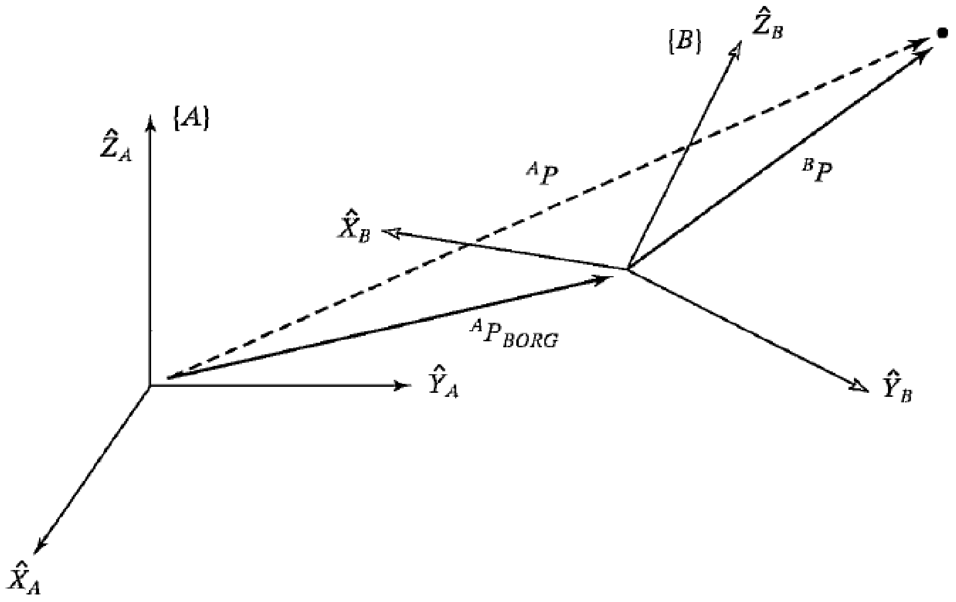
Mapping

c) Translation and Rotation:

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

Or we can use the homogeneous transformation matri

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



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

Example

Figure 2.8 shows a frame {B}, which is rotated relative to frame {A} about $\hat{Z}_A$ by 30 degrees, translated 10 units in $\hat{X}_A$, and translated 5 units in $\hat{Y}_A$. Find ${}^{A}P$, where ${}^{B}P = [3.0 \quad 7.0 \quad 0.0]^T$.

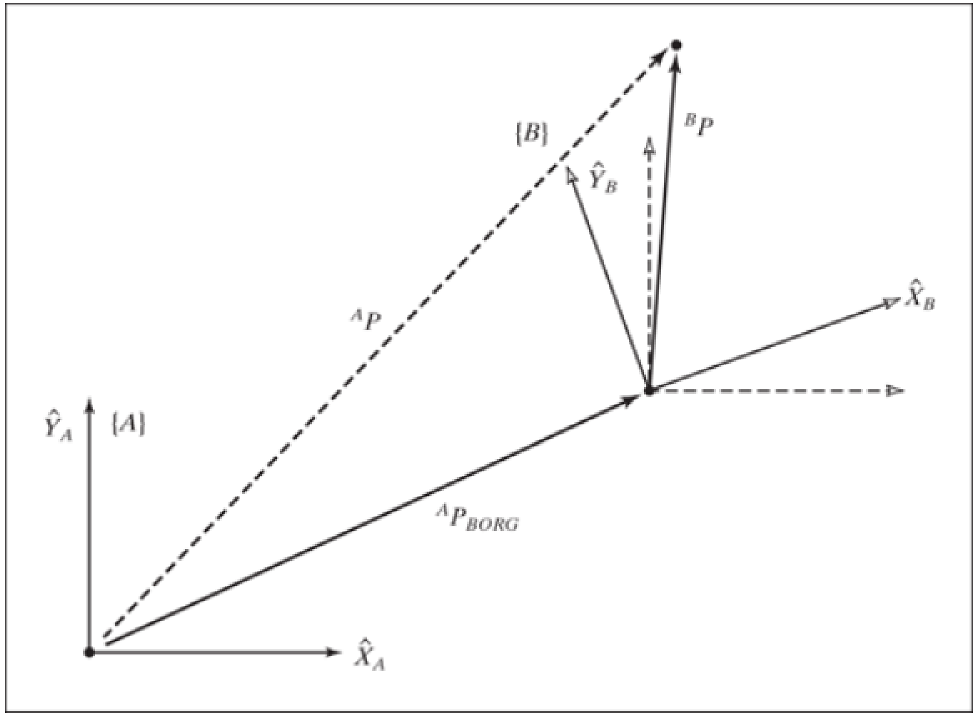


FIGURE 2.8:
Frame {B} rotated and translated.

The definition of frame $\{B\}$ is

$$
{}^{A}_{B}T = \begin{bmatrix} 0.866 & -0.500 & 0.000 & 10.0 \\ 0.500 & 0.866 & 0.000 & 5.0 \\ 0.000 & 0.000 & 1.000 & 0.0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{2.21}
$$

Given

$$
{}^{B}P = \begin{bmatrix} 3.0 \\ 7.0 \\ 0.0 \end{bmatrix}, \tag{2.22}
$$

we use the definition of $\{B\}$ just given as a transformation:

$$
{}^{A}P = {}^{A}_{B}T\ {}^{B}P = \begin{bmatrix} 9.098 \\ 12.562 \\ 0.000 \end{bmatrix}. \tag{2.23}
$$

Example

Figure 2.8 shows a frame $\{B\}$, which is rotated relative to frame $\{A\}$ about $\hat{Z}$ by 30 degrees, translated 10 units in $\hat{X}_A$, and translated 5 units in $\hat{Y}_A$. Find ${}^AP$, where ${}^BP = [3.0\,7.0\,0.0]^T$.

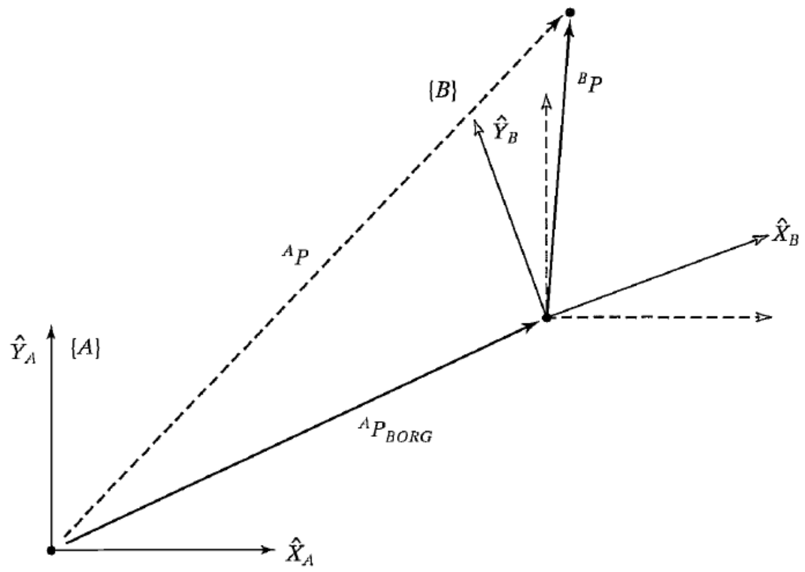


FIGURE 2.8: Frame $\{B\}$ rotated and translated.

Example

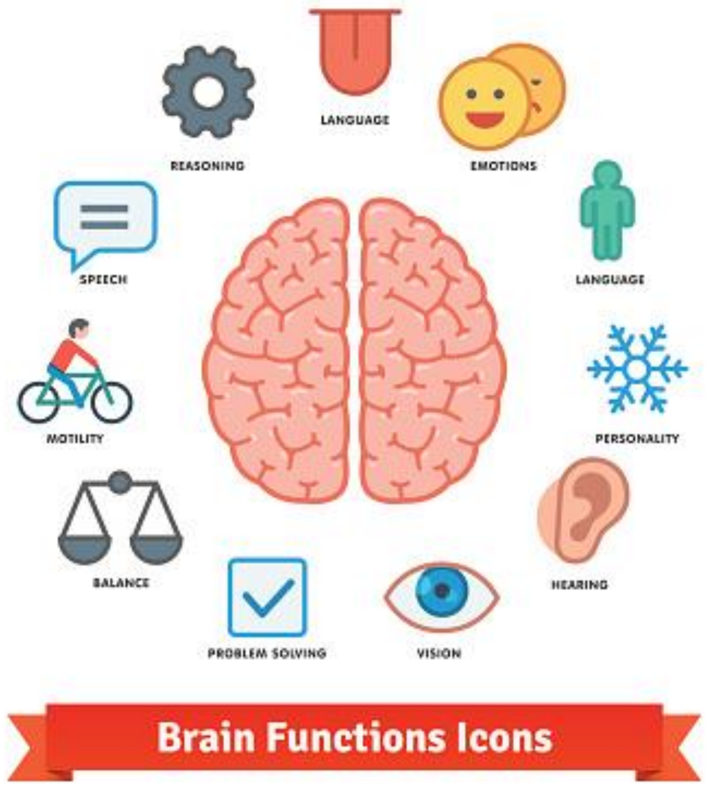
Frame {B} is rotated relative to frame {A} about X-axis by 45 degrees , then translated -12 units in X_A, 3 units in Y_A, and 10 units in Z_A. Define frame {B}relative to frame {A}, then find A_P if $B_P = [-2 \;\; 6 \;\; -5]$

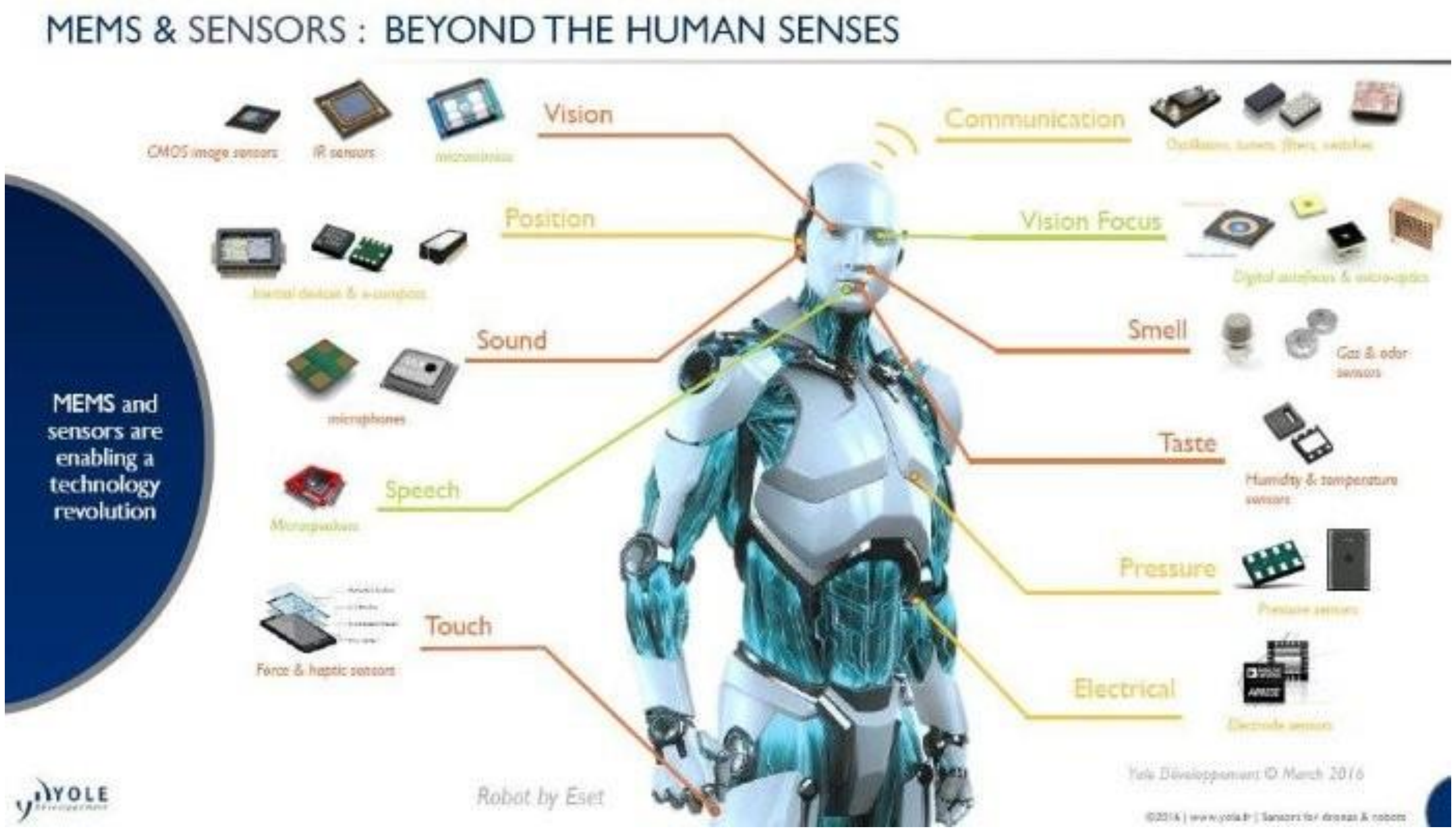
Week 2: workshop

Component of Robots

Robots share a lot of similarities with human

1) Human use sensors to get information from surrounding





Component of Robots

In a systems discipline, even if each individual component is optimized, the overall system may be highly sub-optimized

2) Brain

- Understanding of the word
- Makes decision
- Connect all parts of bodies and sensors
- Brain can be simple (like a single function robot) or complex (self driving car)

Robotic is a system discipline

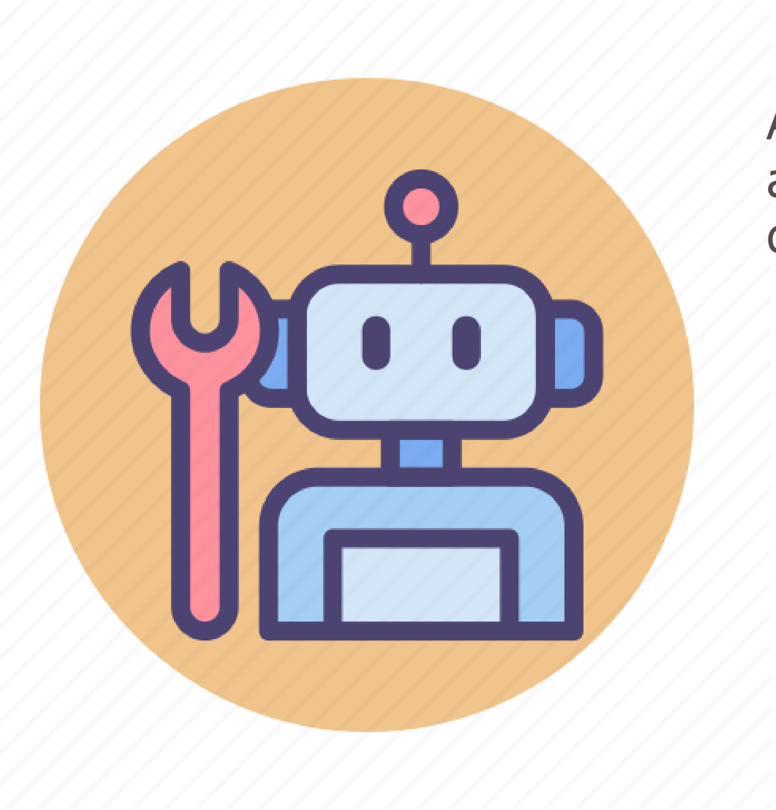
Has the expertise to design and develop systems across various levels

Can take the problem statement to design a robot system and design and optimize the components across that entire robotics system

Hardware	What mechanism will be used to latch onto the objects?
Task/ manipulation planning	What strategy will the robot use to acquire the object?
Perception	How will the objects be perceived?

Robotic Solutions (Manipulation planning)

Robots have to learn to grasp based on the object (as human do)



Algorithms can plan under uncertainty while exploiting contact and reasoning about sensor events during planning for high dimensional motion problems.

https://www.youtube.com/watch?v=K6XRrJWlNN0

Robotic Solutions (Manipulation planning)

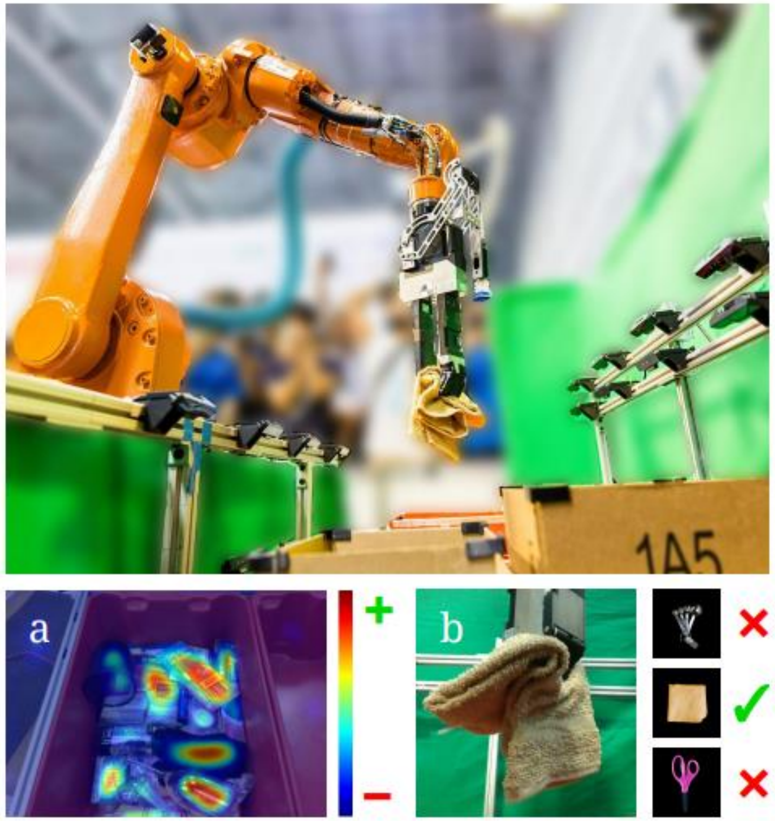


Figure 1. Our picking system computing pixel-wise affordances for grasping over visual observations of bins full of objects, (a) grasping a towel and holding it up away from clutter, and recognizing it by matching observed images of the towel (b) to an available representative product image. The key contribution is that the entire system works out-of-the-box for novel objects (unseen in training) without the need for any additional data collection or re-training.

Zeng et al. (2018b). Robotic Pick-and-Place of Novel Objects in Clutter with Multi-Affordance Grasping and Cross-Domain Image Matching

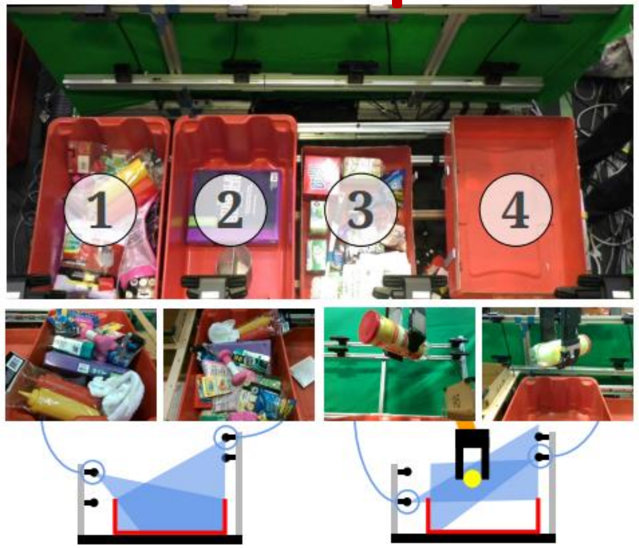


Figure 2. The bin and camera setup. Our system consists of 4 units (top), where each unit has a bin with 4 stationary cameras: two overlooking the bin (bottom-left) are used for inferring grasp affordances while the other two (bottom-right) are used for recognizing grasped objects.

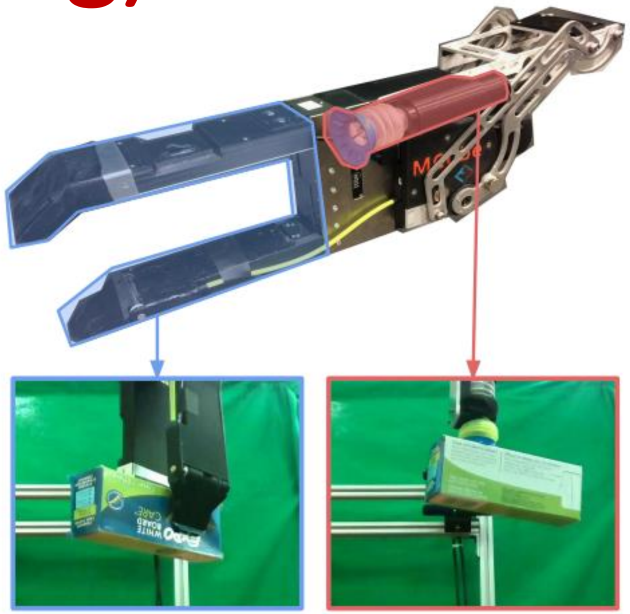


Figure 3. Multi-functional gripper with a retractable mechanism that enables quick and automatic switching between suction (pink) and grasping (blue).

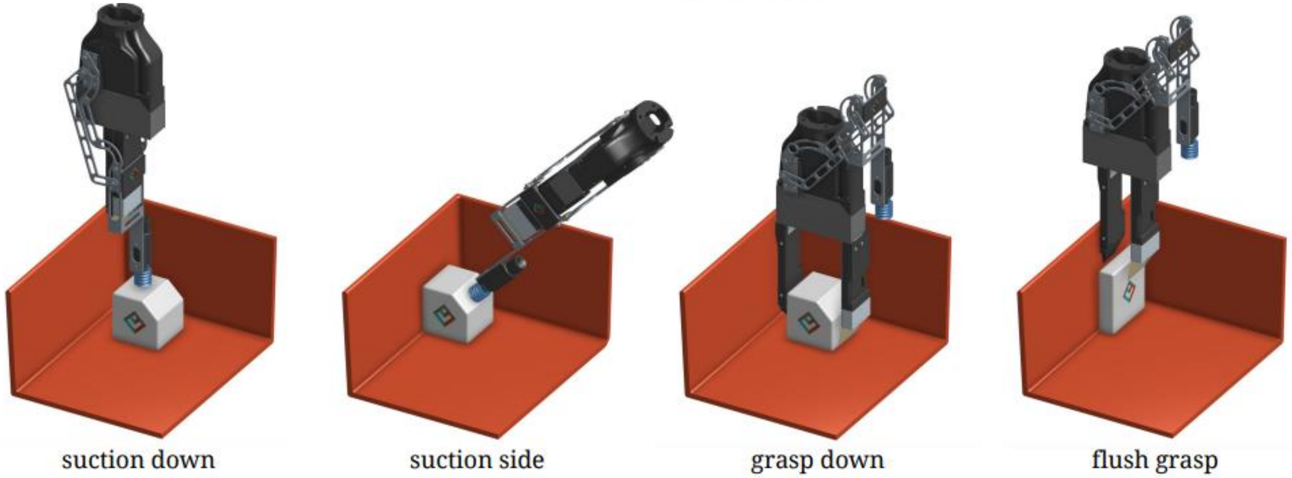


Figure 4. Multiple motion primitives for suction and grasping to ensure successful picking for a wide variety of objects in any orientation.

Robotic Solutions (Perception)

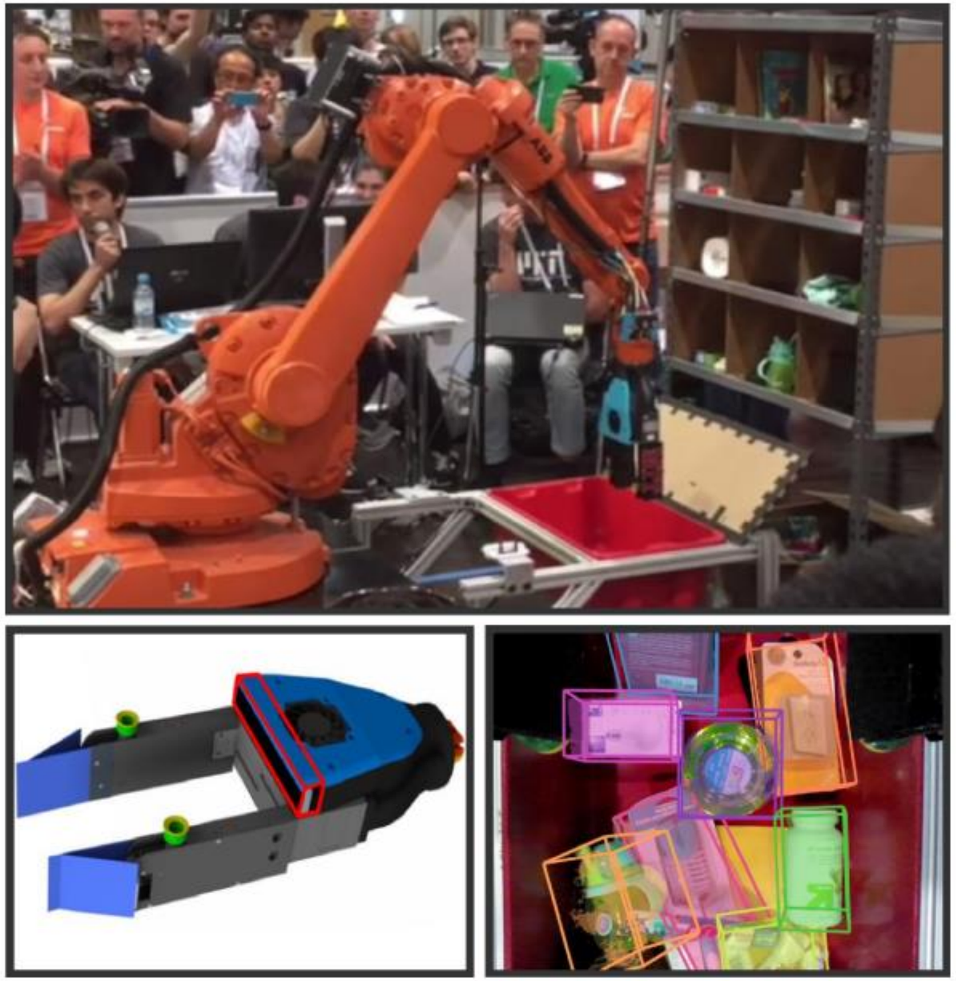


Fig. 1. Top: The MIT-Princeton robotic picking system. Bottom-left: The gripper mounted with an Intel RealSense camera (outlined in red). Bottom-right: Predicted 6D object poses from our vision system during the stow-task finals of the APC 2016. Each prediction is highlighted with a colored 3D bounding box.

Cluttered environments: shelves and totes may have multiple objects and could be arranged as to deceive vision algorithms (e.g., objects on top of one another).

Self-occlusion: due to limited camera positions, the system only sees a partial view of an object.

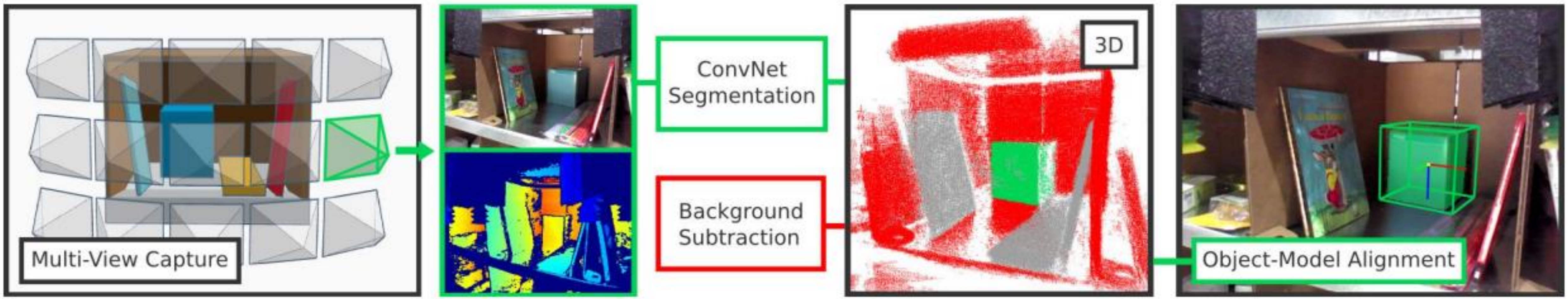
Missing data: commercial depth sensors are unreliable at capturing reflective, transparent, or meshed surfaces, all common in product packaging.

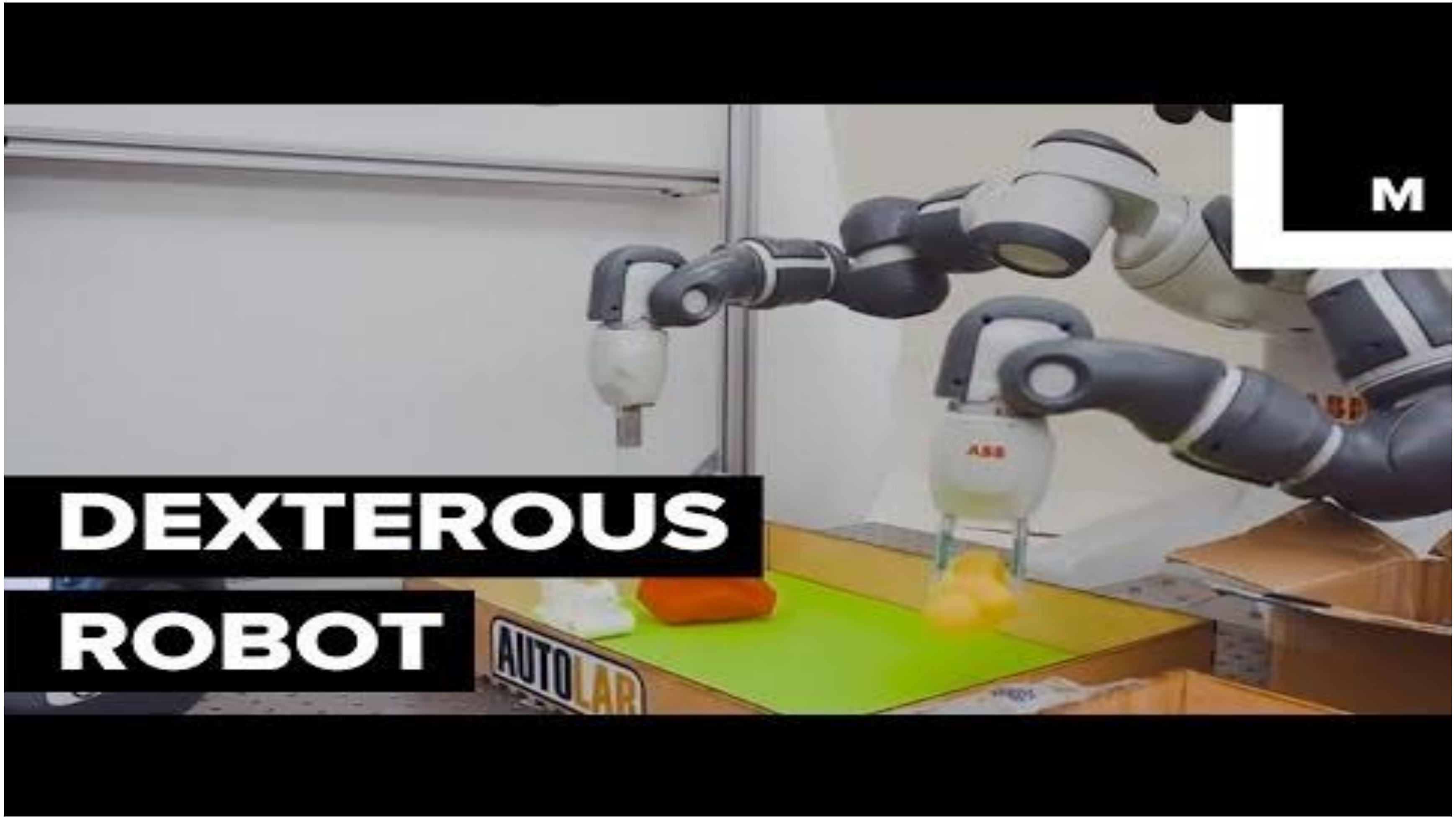
Small or deformable objects: small objects provide fewer data points, while deformable objects are difficult to align to prior models

Speed: the total time dedicated to capturing and processing visual information should be under 20 seconds.

Robotic Solutions (Perception)

- System localise the object, geometry and the pose of each item
- Decide on manipulation behaviours
- Can be used for a wide range and classes of objects without prior learning
- Important factors (enabling safe contact, Force control, avoid obstacles)
- To design an effective robotic system with a common modular architecture requires Hardware, Perception, Manipulation/task planning, Motion planning and control).





https://www.youtube.com/watch?v=PMkA8HjZf2w

Amazon Warehouse Order Picking Robots

A fully autonomous warehouse pick-and-place system requires robust vision that reliably recognizes and locates objects amid cluttered environments, self-occlusions, sensor noise, and a large variety of objects.

https://www.youtube.com/watch?v=Ox05Bks2Q3s

In-class assessment

Will be discussed in class

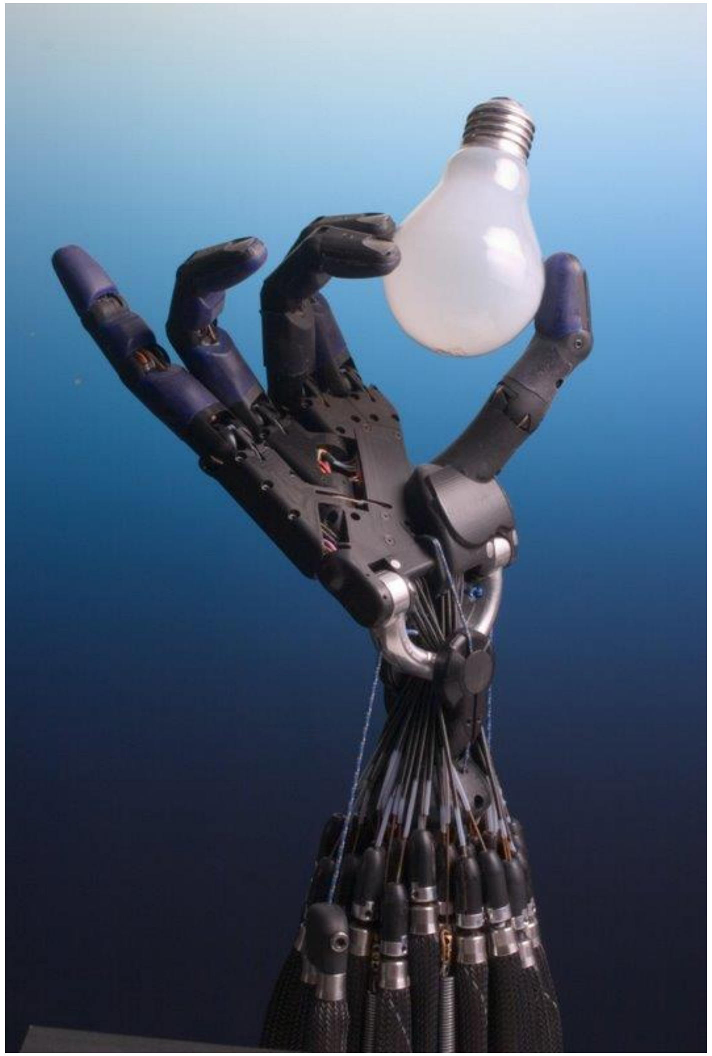
Design and development of robots

SENSORS

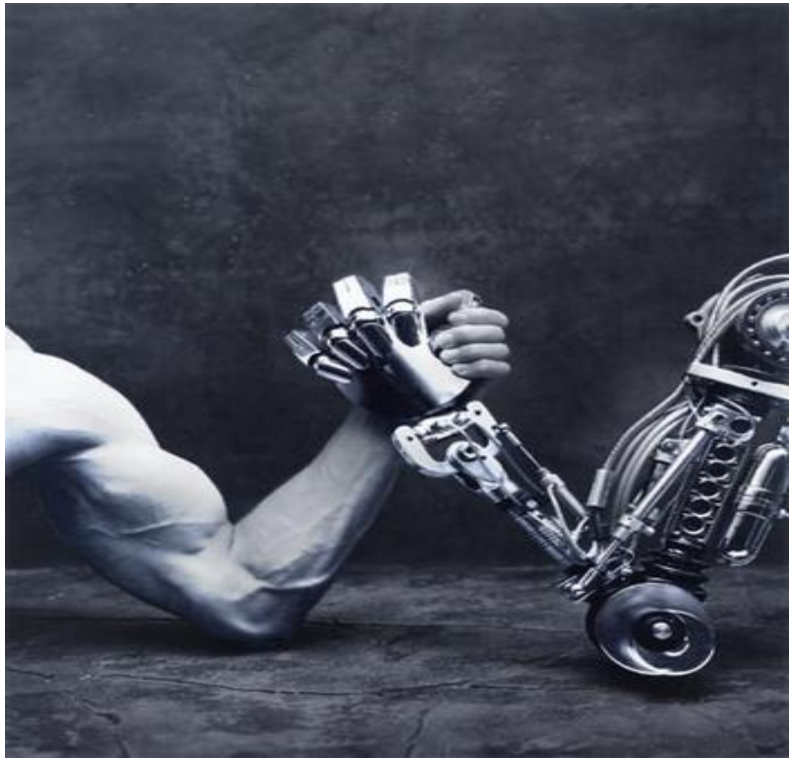
- **Haptic Sensors**
- **Vision Sensors**

ACTUATORS

- **Integrated robot hardware**
  - Grippers
  - Arm manipulator
  - Mobility platform
- **Low-level motors**



Haptic Sensors



Haptics refers to sensing and manipulation through touch

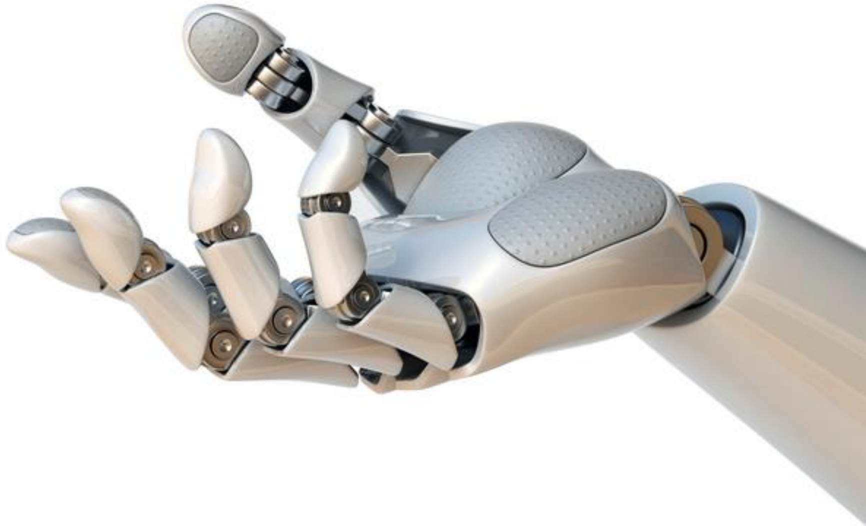
- 'Haptics' - derived from the greek word meaning 'haptein' which means 'hold'
- Analogous to optics
- Measure small deformations of high-strength structures using resistance strain gauge, inferring the applied loads
- Tend to experience a lot of noise due to the sensitivity of resistance strain gauges to temperature fluctuations and vibrations
- Tactile sensors are categorised in haptic sensors

Haptic Sensors

Sensory information can be

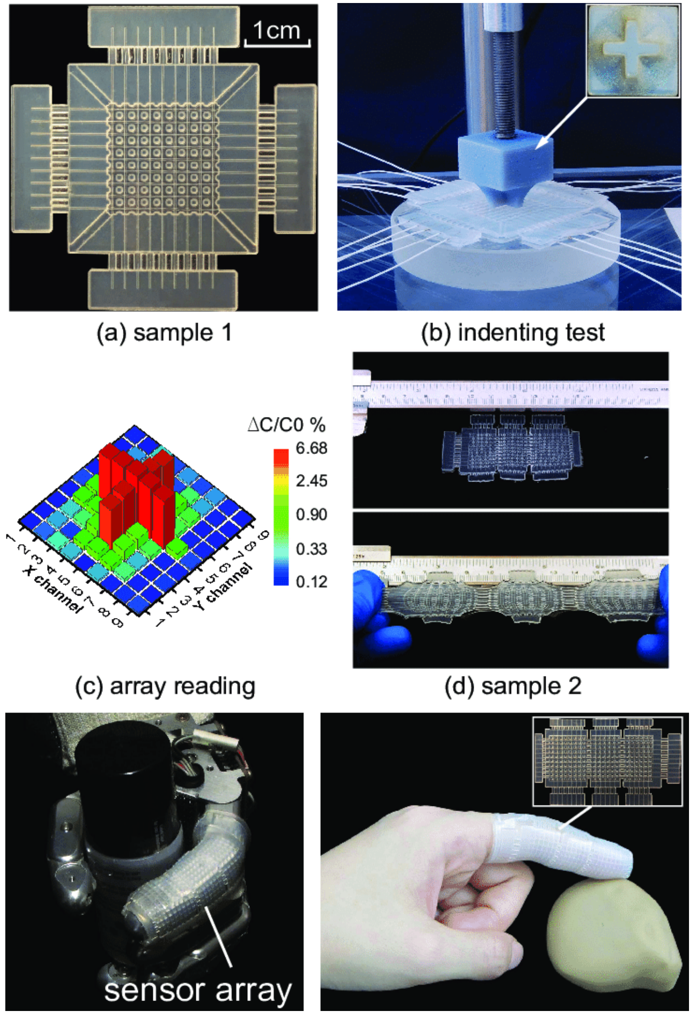
- Tactile : presence of heat, pressure and texture.
- Kinesthetic :position, body movements and the forces which act on it

- Measure small deformation or mechanical stress applied to structures often using resistance, piezoelectric, or capacitance concepts
- Are engaged within robot articulations such as wrists or other joints, and provide high-frequency feedback on joint torques
- Tend to experience a lot of noise due to the sensitivity of resistance strain gauge to temperature, wire shaking, environmental noise and vibration



Haptic Sensors (tactile sensors)

Thin tactile arrays

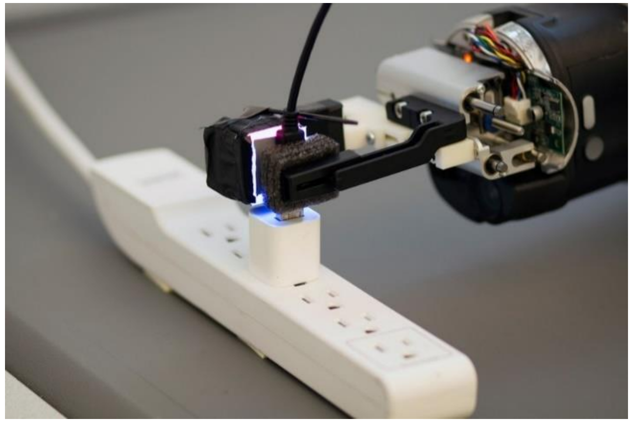


BioTac

Sense texture
Multi-modal sensing (pressure, temperature, vibration)

http://www.robaid.com/bionics/biotac-biomimetic-tactile-sensor.htm

Fingertip sensors



Vision based tactile sensors that capture tactile feedback at a very high spatial resolution

https://news.mit.edu/2014/fingertip-sensor-gives-robot-dexterity-0919

BioTac

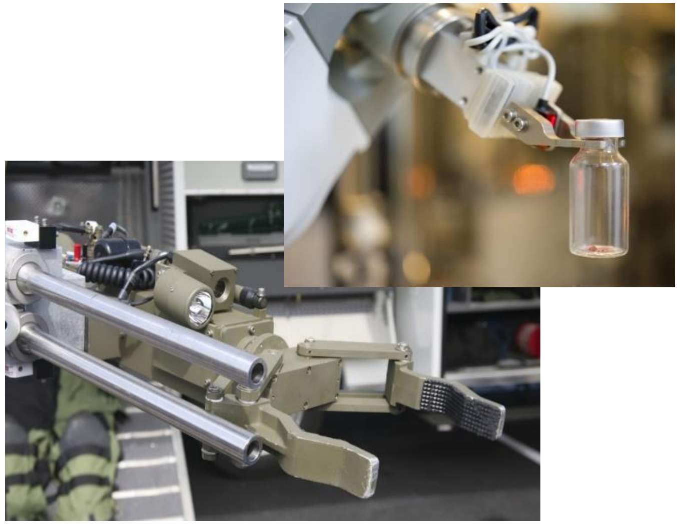
https://www.youtube.com/watch?v=ksTlfklav-k

Actuators

Parallel-jaw gripper

- Parallel Grippers most popular type of gripper where opposing jaws travel in parallel to hold a workpiece

- Parallel-jaw grippers have two phalanges that close on an object with a friction grasp

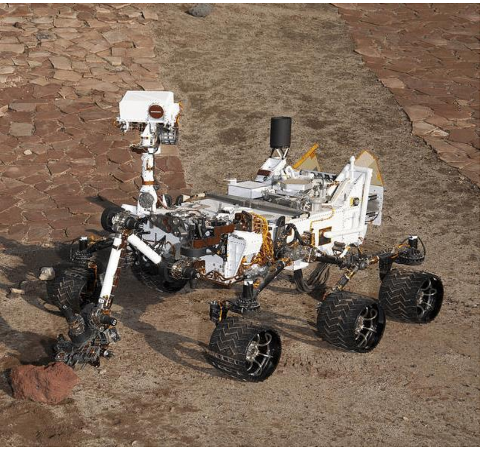


Task Driven Grippers

Designed for a special task

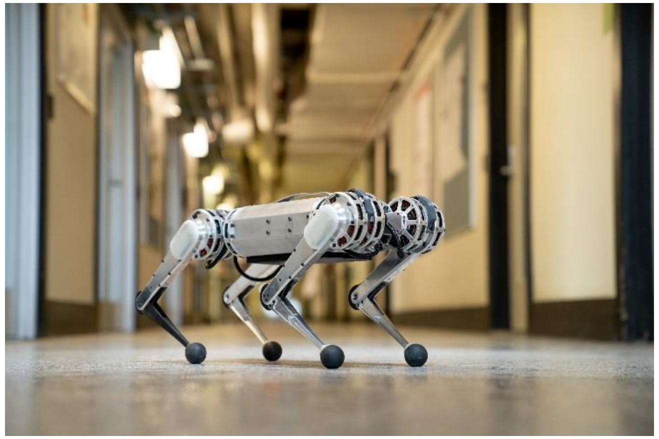
Mobility platforms

Wheeled platforms



Flying platforms

Legged platforms



Group Activity

It’s time to clean up the robotics workshop. Your task: Drag each hardware image into the correct category.

Motors and Actuators	Computers (Microcontrollers, GPUs and more)	Sensors	Commercial Robotic Systems

Items:

- ABB YuMi
- Boston Dynamic Spot
- Piezoresistive tactile sensor
- Depth Camera
- Force Torque Sensor
- Franka Emika Panda
- Graphics Processing Unit (GPU)
- Quadcopter

Graphic Card
Kinetic RGB-D sensor
Lidar
Servo motor
Solenoid
Weiss Gripper
Stepper Motor
Softbank Robotics Pepper

Design and development of Robots

Curiosity rover

Roomba

Plan

Act

Sense

Can you tell the difference?

End of Week 2