Introduction to Robotics

Overview

- Introduction
- A Bit of History
- Robotics Market Outlook
- Elements of Robotics
  - Sensors & Actuators
- Basic concepts
  - Odometry, localization, mapping etc.
- Robotics Projects / Research Problems
- Summary

Sources / Credits

- Elements of Robotics by Mordechai Ben-Ari, Francesco Mondada. Springer
  URL: https://link.springer.com/book/10.1007%2F978-3-319-62533-1

- Information available on Public Domain made available by Google.

Robots - An introduction

- Machines/Artificial Agents that exhibit some aspect of sentient behaviour:
  - Autonomous operation
  - Ability to adapt to changes
  - Ability to learn
  - Ability to interact with environment and with other agents.
  - Programmable by a computer

- Repeatability / Accuracy may not necessarily be an important behaviour for a robot.

- Robots come in various shapes, sizes, functionalities. Software programs (such as spam filter, virus programs) are also called bots.

- Robotics: Study of Robots - Inter-disciplinary

Robot Classification

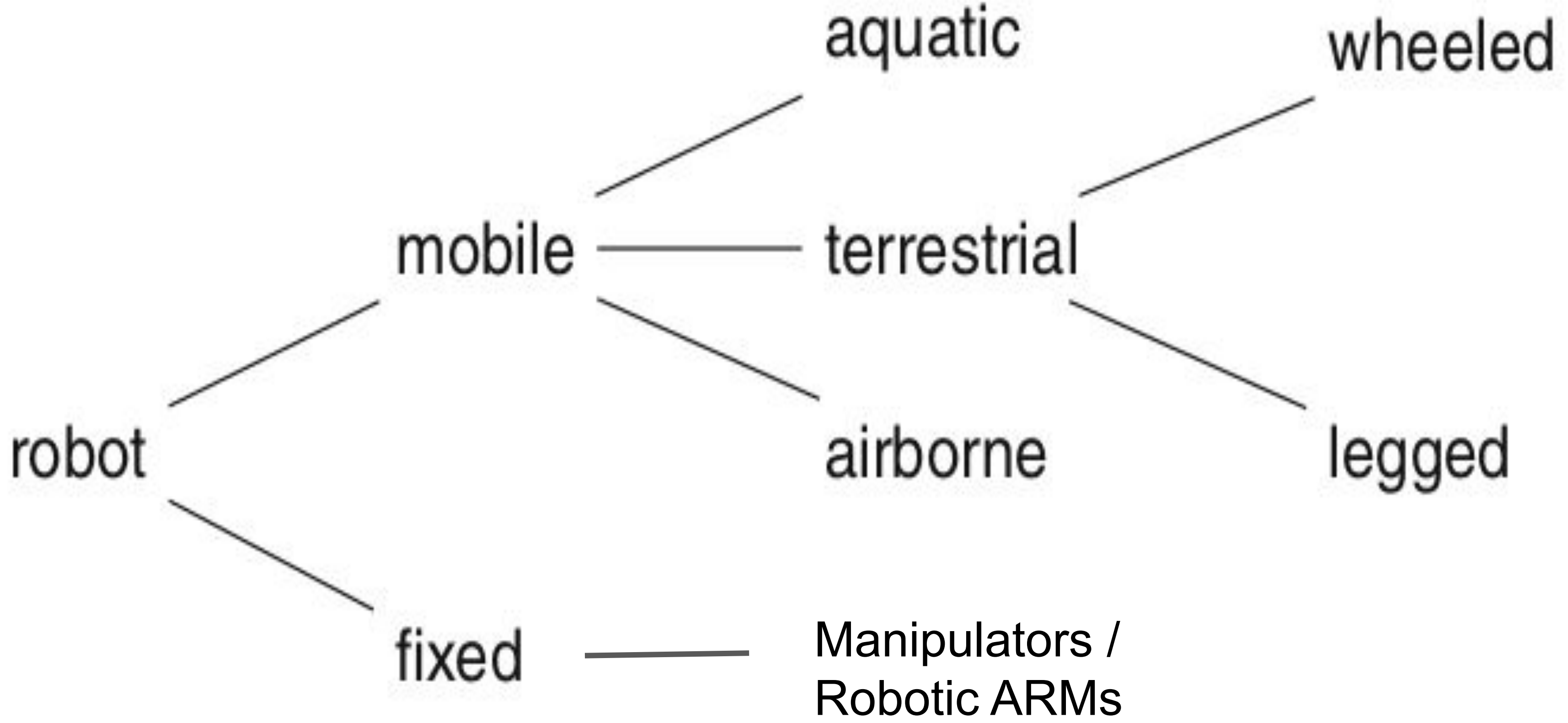
Classification of Robots

- Based on Shape / Size / Appearance
  - Physical robots: Having physical embodiment with hardware and software
  - No physical shape / size: Software bots. E.g., spam filter or a virus / anti-virus program etc.

- Classification of robots by environment and mechanism of interaction

- Classification of robots by application field.

Classification of Robots by environment or the mode of interaction

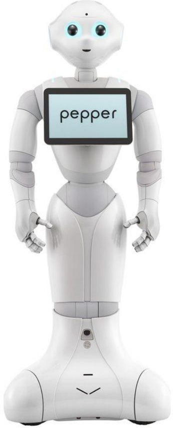








Classification of Robots by Application Field



- robot
  - industrial
    - logistics
    - manufacturing
  - service
    - medical
    - home
    - educational
    - defense
    - Agriculture

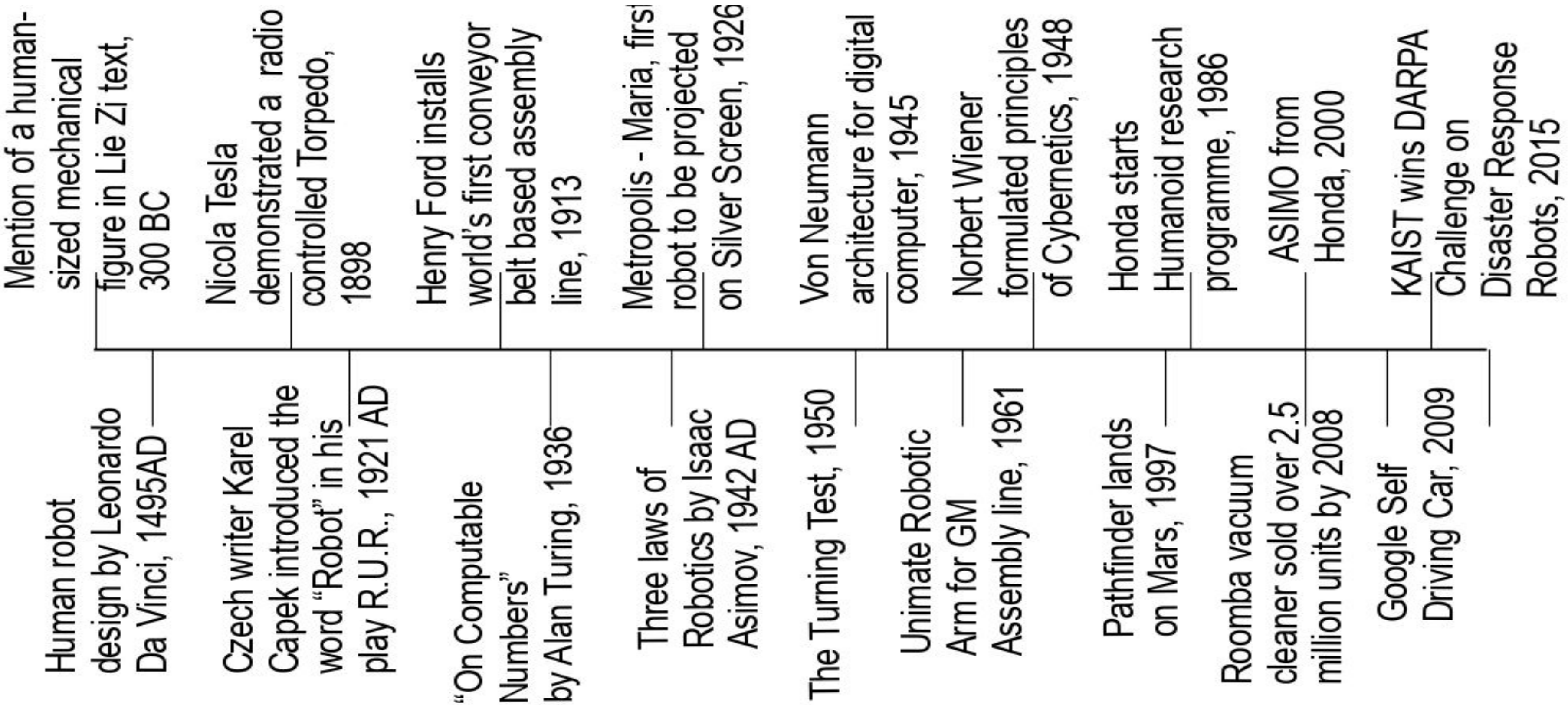
Industrial Vs Service Robots

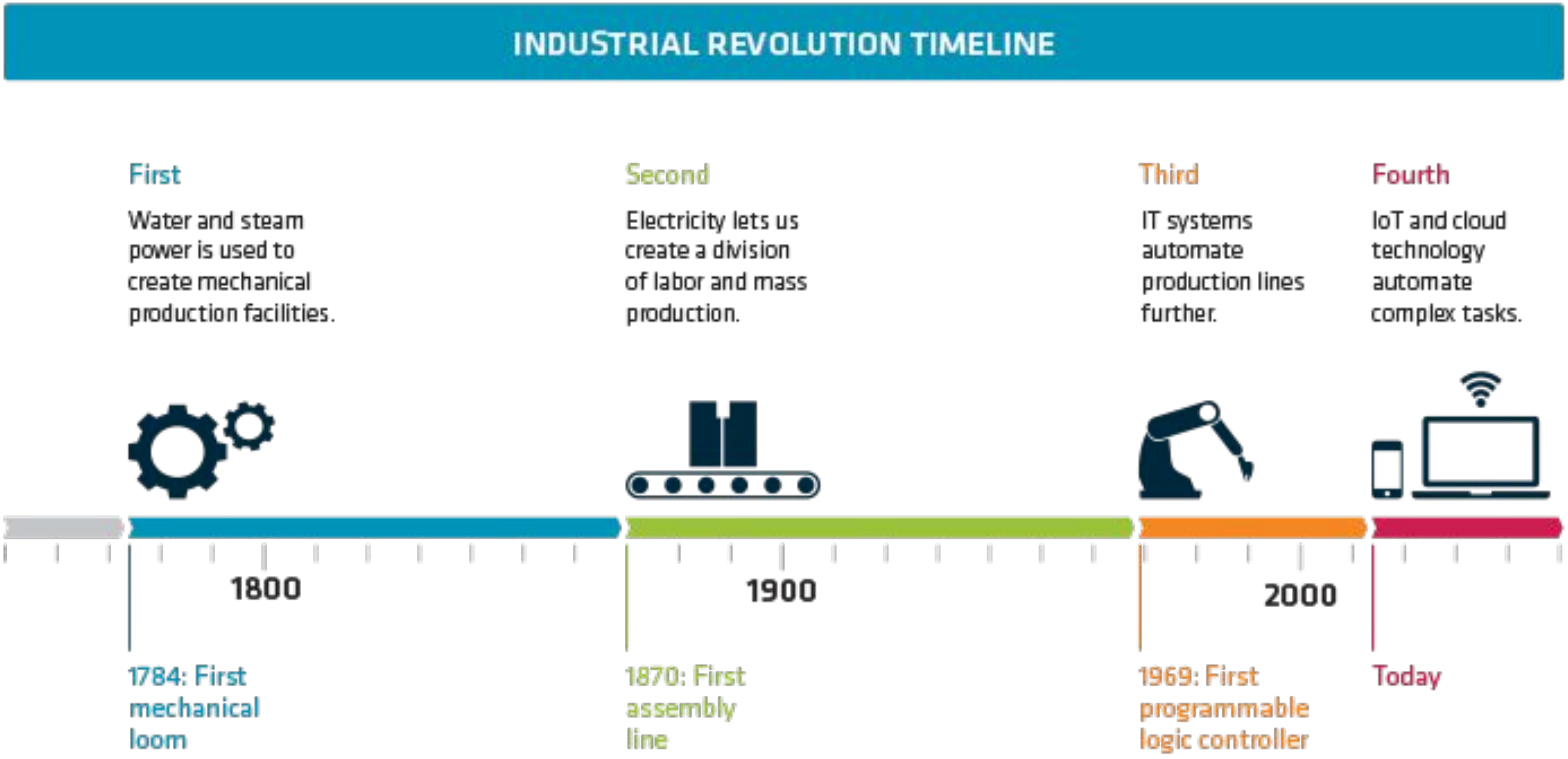
- Fixed and structured Workspace
- Confined in cages to ensure safety of humans
- High speed operations.
- Robots have high precision and repeatability.

- Unstructured workspace without fences
- They can work in close proximity with human operators while sharing each other’s workspace.
- These robots may not have higher speed or precision as their industrial counterparts.

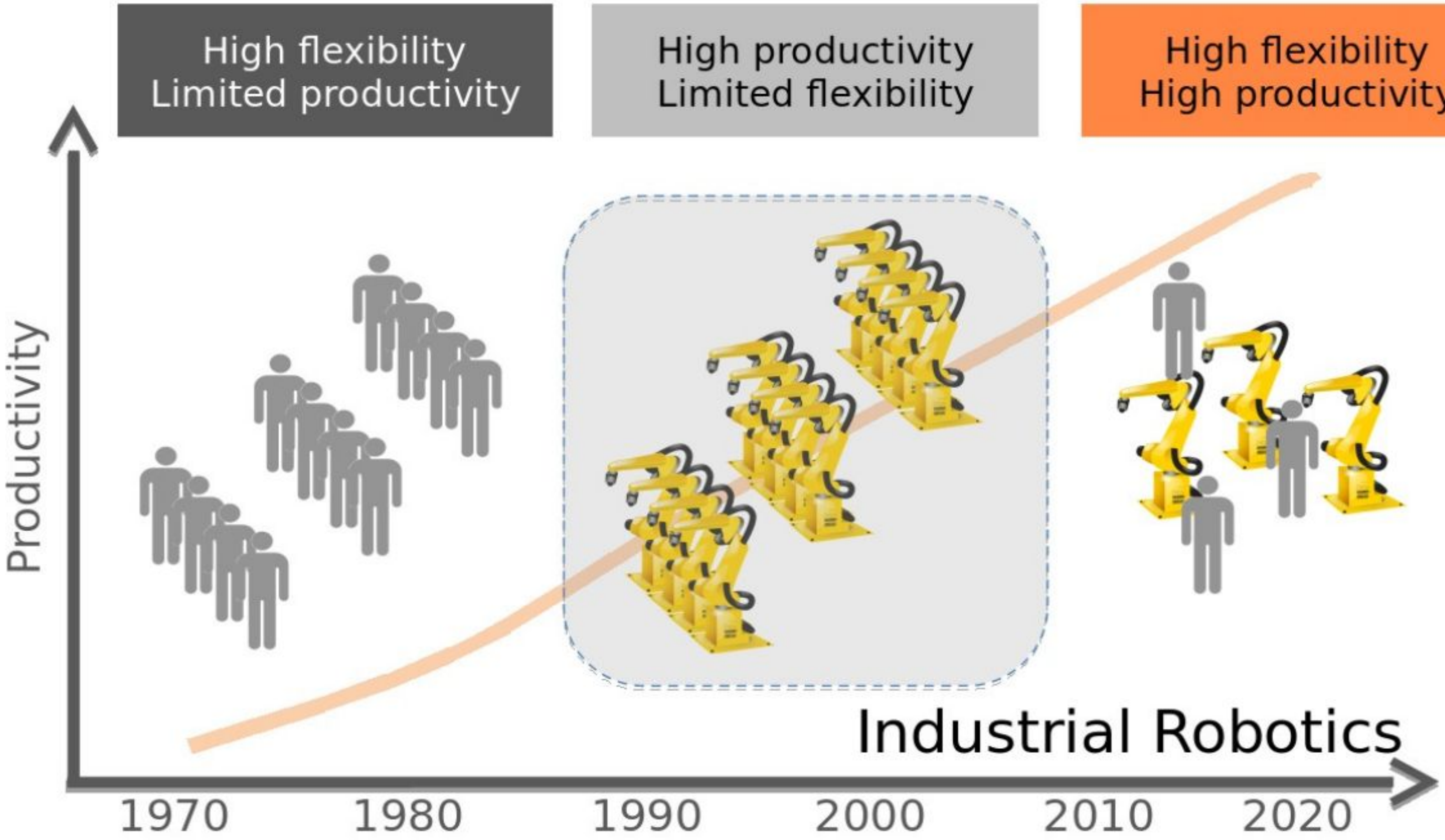
A Bit of History

History of Robots/Robotics

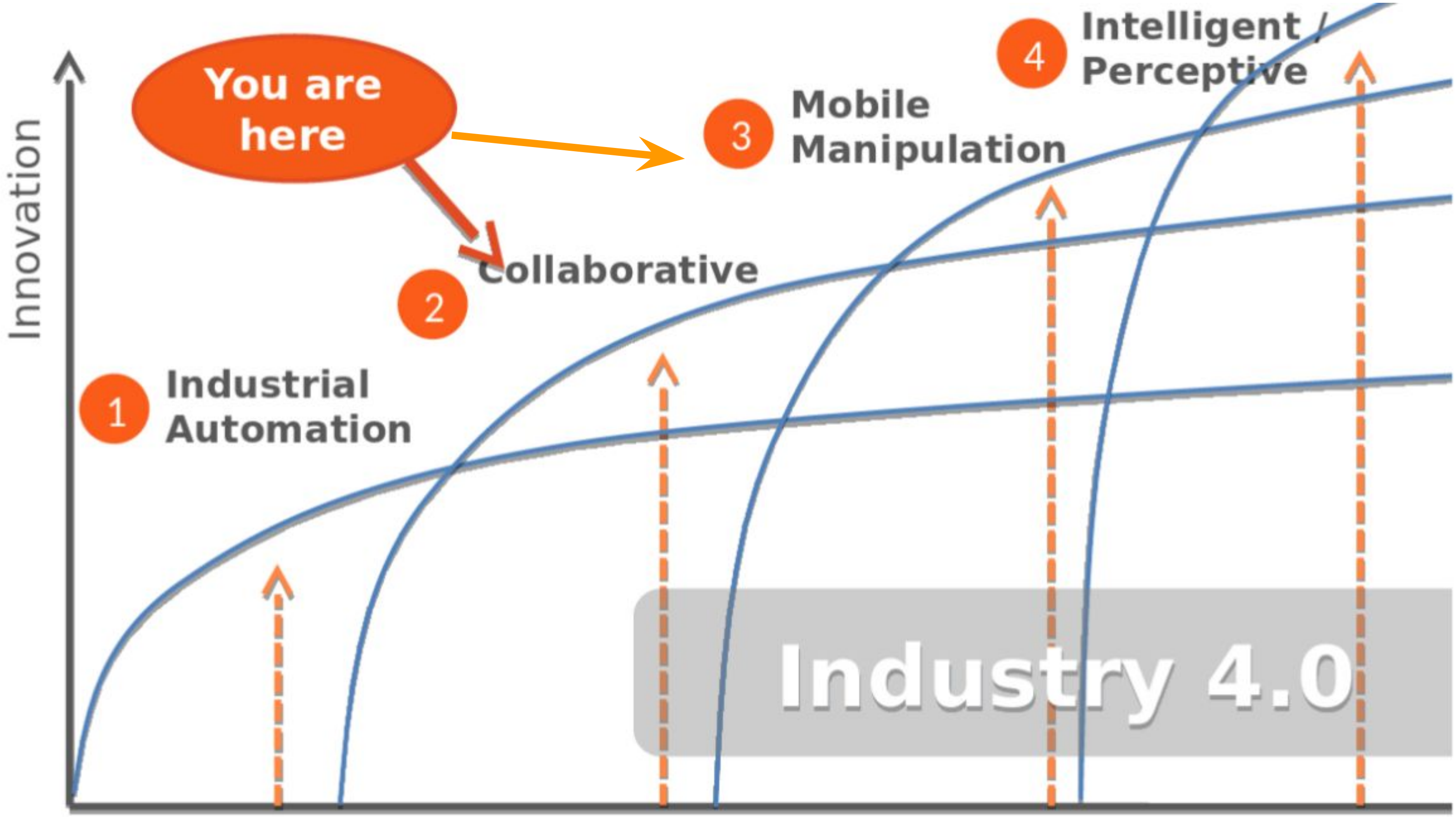



INDUSTRIAL REVOLUTION TIMELINE
First
Water and steam power is used to create mechanical production facilities.
Second
Electricity lets us create a division of labor and mass production.
Third
IT systems automate production lines further.
Fourth
IoT and cloud technology automate complex tasks.
1800
1900
2000
1784: First mechanical loom
1870: First assembly line
1969: First programmable logic controller
Today

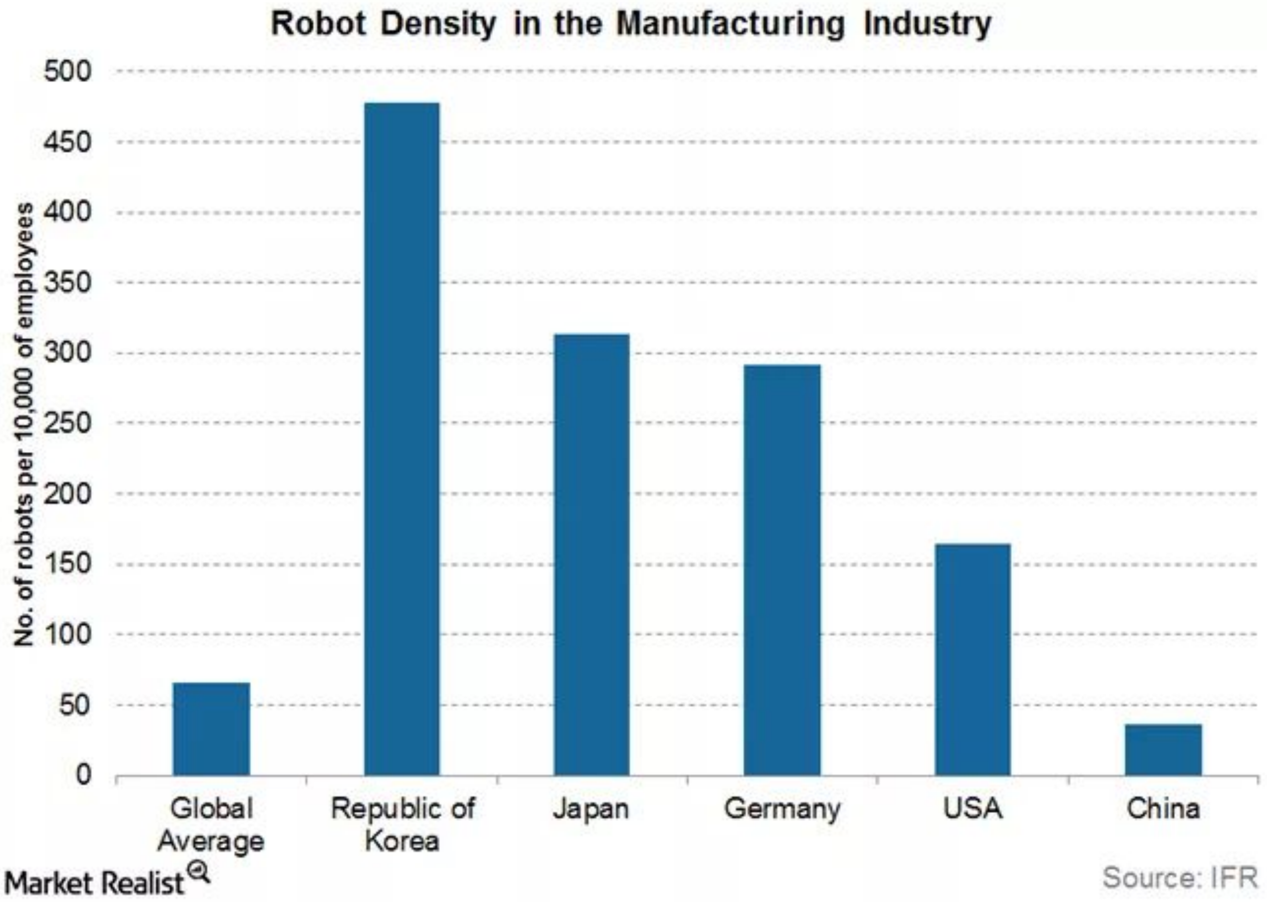
Transitions in the Industry



Robotics Innovation in Industries

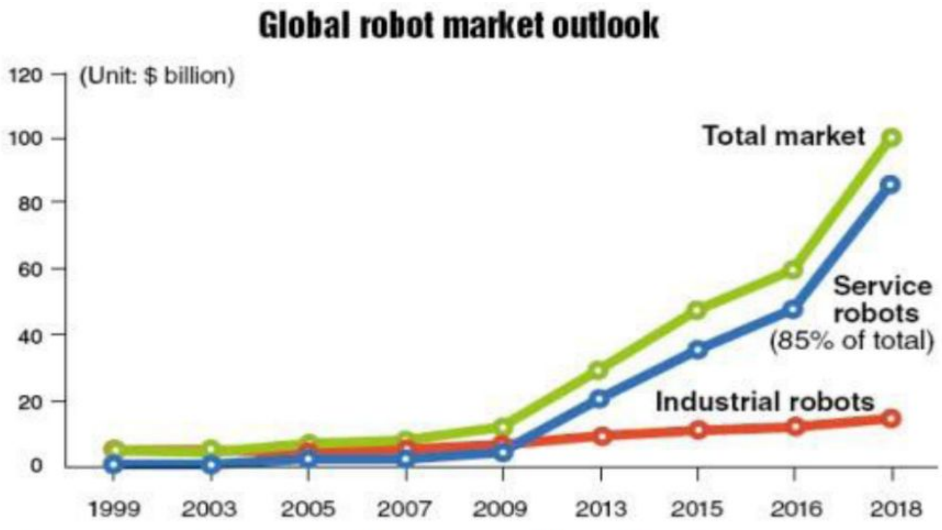


Overview of Global Robotics Market

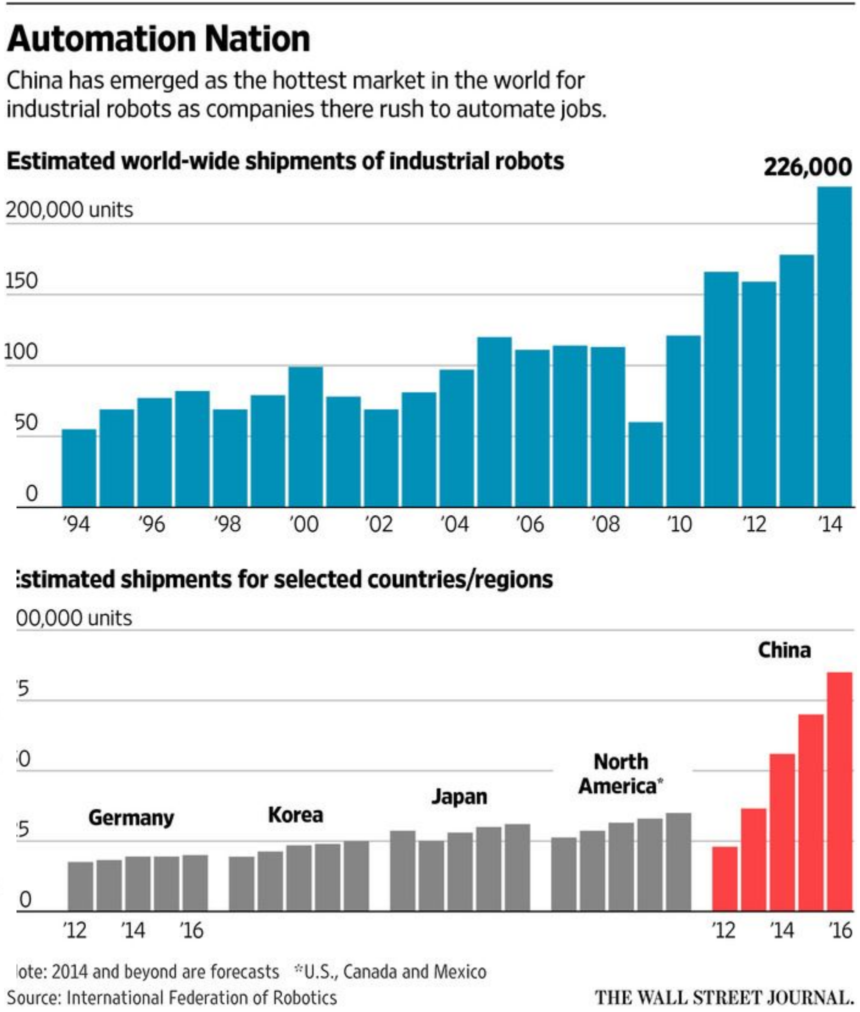

Robot Density in the Manufacturing Industry
No. of robots per 10,000 of employees
500
450
400
350
300
250
200
150
100
50
0
Global Average
Republic of Korea
Japan
Germany
USA
China
Market Realist
Source: IFR

Market Trends

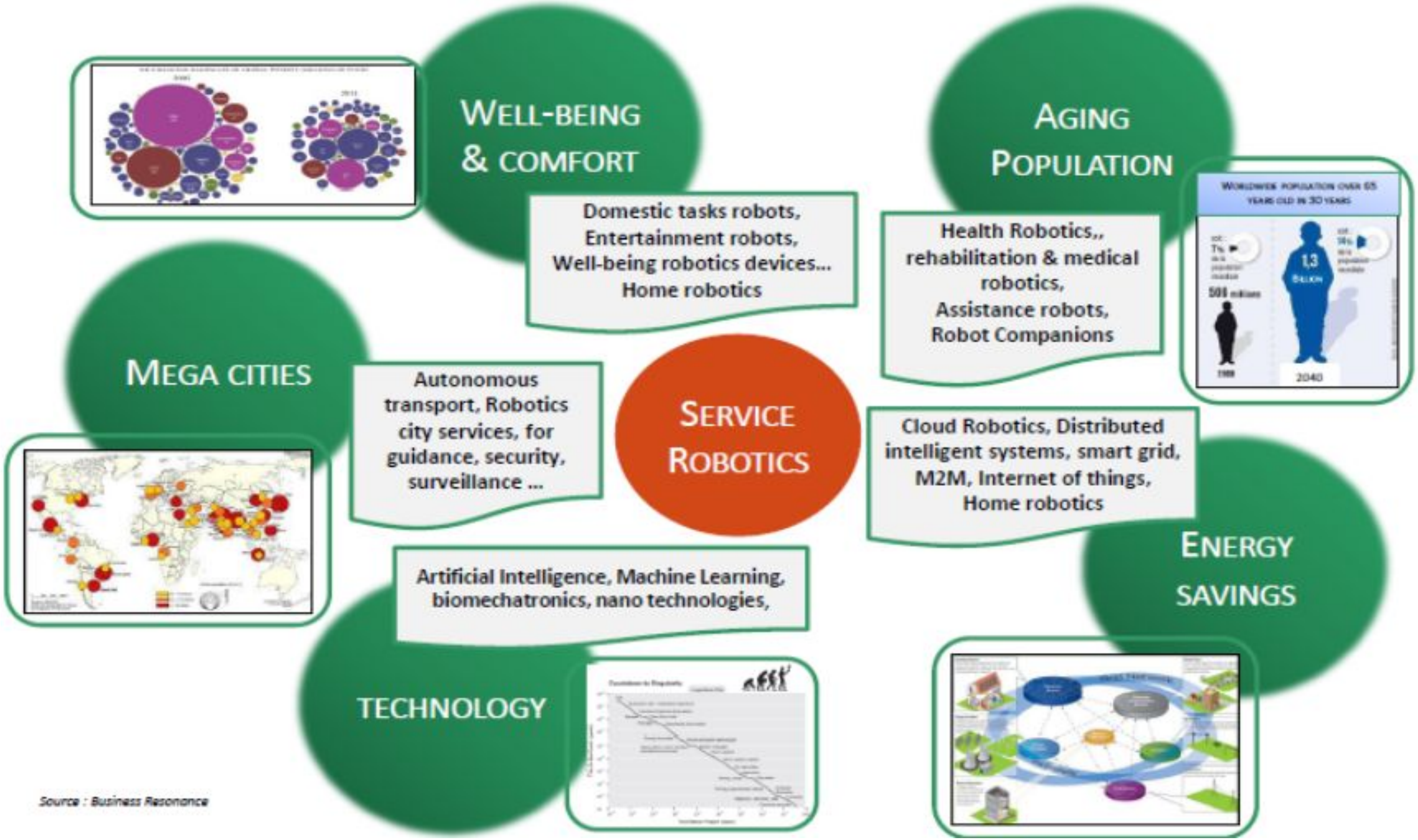
Worldwide robotics markets will witness a double digit growth in the coming decade.



Source Ministry of Knowledge & Economy – South Korea, Jan. 2011



Societal Trends will boost the adoption of Service Robots



Challenges & Opportunities

- Challenges:
    - Robot Cognition is still far inferior to human capabilities.
    - Hardware cost is a determining factor against automation.
    - Lack of uniform standards for robot design and development
    - Lack of skilled manpower.

- Opportunities:
    - Rapid Advancement in Machine Learning and Artificial Intelligence
    - Declining cost of sensors and actuators.
    - Cloud platforms can lead to lower cost for Robot-based services.
    - Open Source and Open Technology platforms.
    - Situations like War (WI, WII), Pandemic (e.g. COVID) situations, Natural or man-made disasters (e.g. Fukushima disaster) expedite the adoption of robots.

Components of a Physical Robotic System

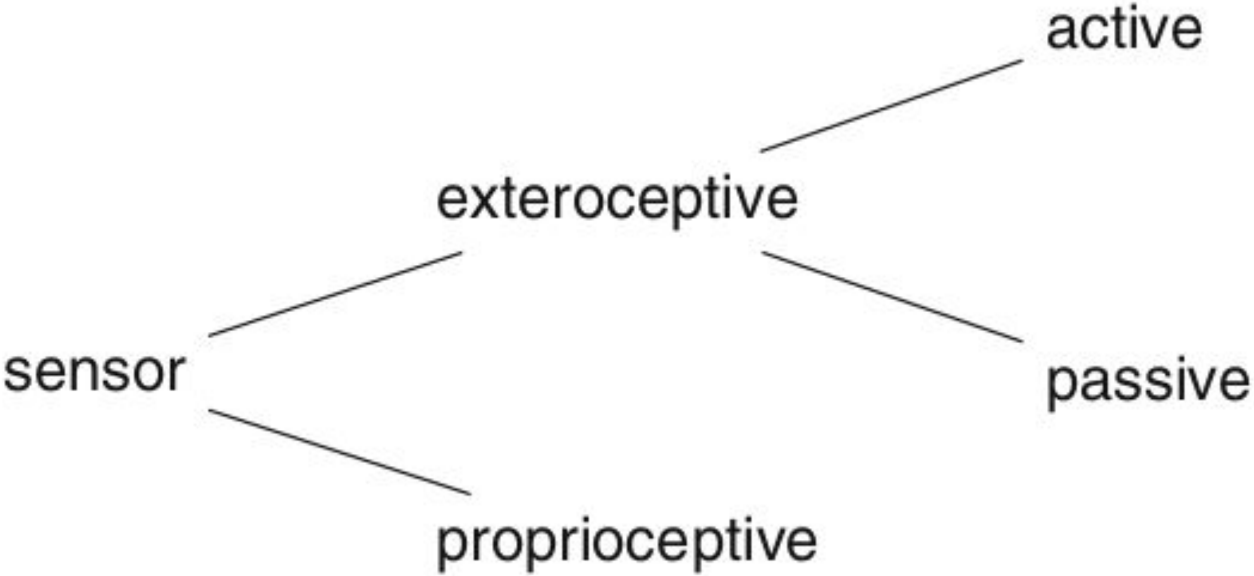
- **Sensors**: Required for measuring its own state as well as the state of the environment.
    - Examples: Camera, Laser Sensor, proximity sensors, IMU etc.

- **Actuators**: Required for generating motion for the robot.
    - Motors are primarily used as actuators.

- **Mechanical Frame**
    - Mechanical structures when used with suitable actuators generate different kind of motion. The same motor can be used for generating rotational motion for a mobile robot as well as bipedal gait of a humanoid robot.

- **Software Program**
    - Computer programs are written to process the sensor information, make intelligent decisions and generate necessary motion commands.

Sensors



- A **proprioceptive** sensor measures something internal to the robot itself. For example: speedometer of a car measures car’s speed.

- An **exteroceptive** sensor measures something external to the robot such as the distance to an object.

- An **active** sensor affects the environment usually by emitting energy: a sonar range finder on a submarine emits sound waves and uses the reflected sound to determine range.

- A **passive** sensor does not affect the environment: a camera simply records the light reflected off an object.

- Examples: Distance Sensors, Cameras, Touch Sensor, Thermal Sensor, Light Sensor, Microphone, Accelerometer, IMU, GPS sensor etc.

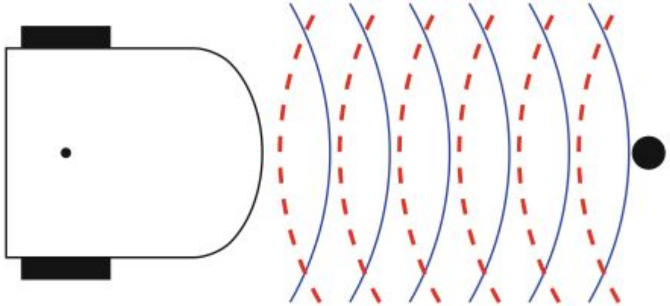
Distance Sensor

- Distance sensors are usually active: they transmit a signal and then receive its reflection (if any) from an object.

- One way of determining distance is to measure the time that elapses between sending a signal and receiving it - ***time-of-flight*** method.

- Low-cost distance sensor measure the intensity of reflected light which decreases with distance.

- Examples: Ultrasonic sound sensor, infrared proximity sensors, optical distance sensors, lasers.



$$s = \frac{1}{2}vt$$

- S is the distance
- V is velocity of signal
- T is the elapsed time between sending and receiving the signal.

Infra-Red Proximity Sensor: measures the distance by measuring the intensity of reflected light.

Ultrasonic Distance Measurement Sensor. Emits Ultrasonic sound (> 20KHz) and receives its echo and computes the distance from time elapsed between the two events.

A single laser sensor is mounted on a rotating shaft to horizontally sweep the area. DIstance is computed either by time of flight method or triangular method.

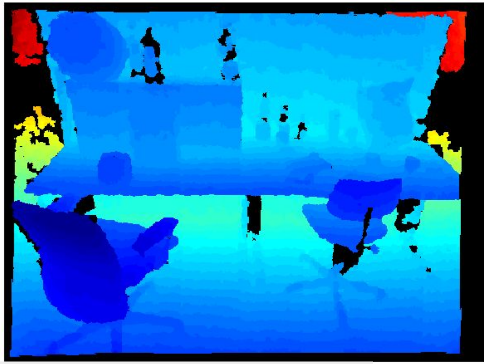
Cameras

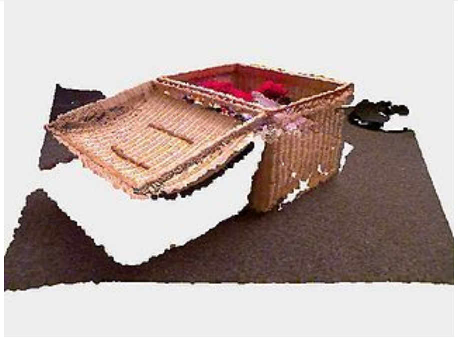
- RGB Cameras
  - Only RGB frames

- RGBD Cameras: RGB + Depth
  - Kinect
  - Intel realsense

- Stereo-Cameras
  - Zed Cameras

(a) Texture map





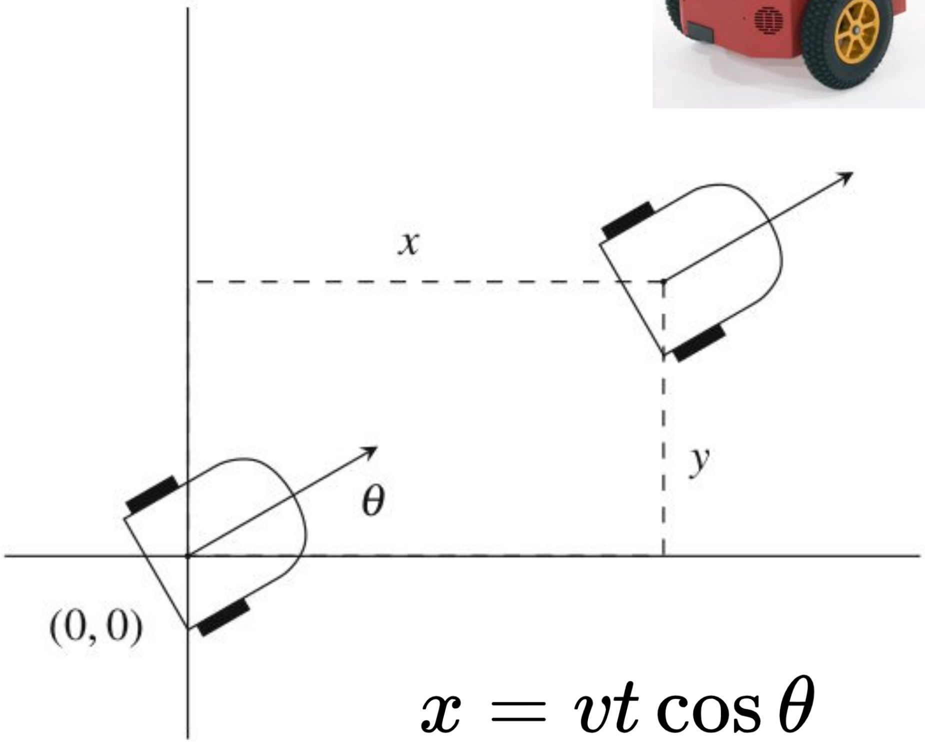
Robotic Motion and Odometry

- A mobile robot has two kinds of motion:
  - Linear Motion
  - Angular motion

- Odometry - the measurement of robot position over time.

- Robot position is given by the vector: (x, y, θ) where \theta is the heading angle.

- Input command: Linear velocity and angular velocity



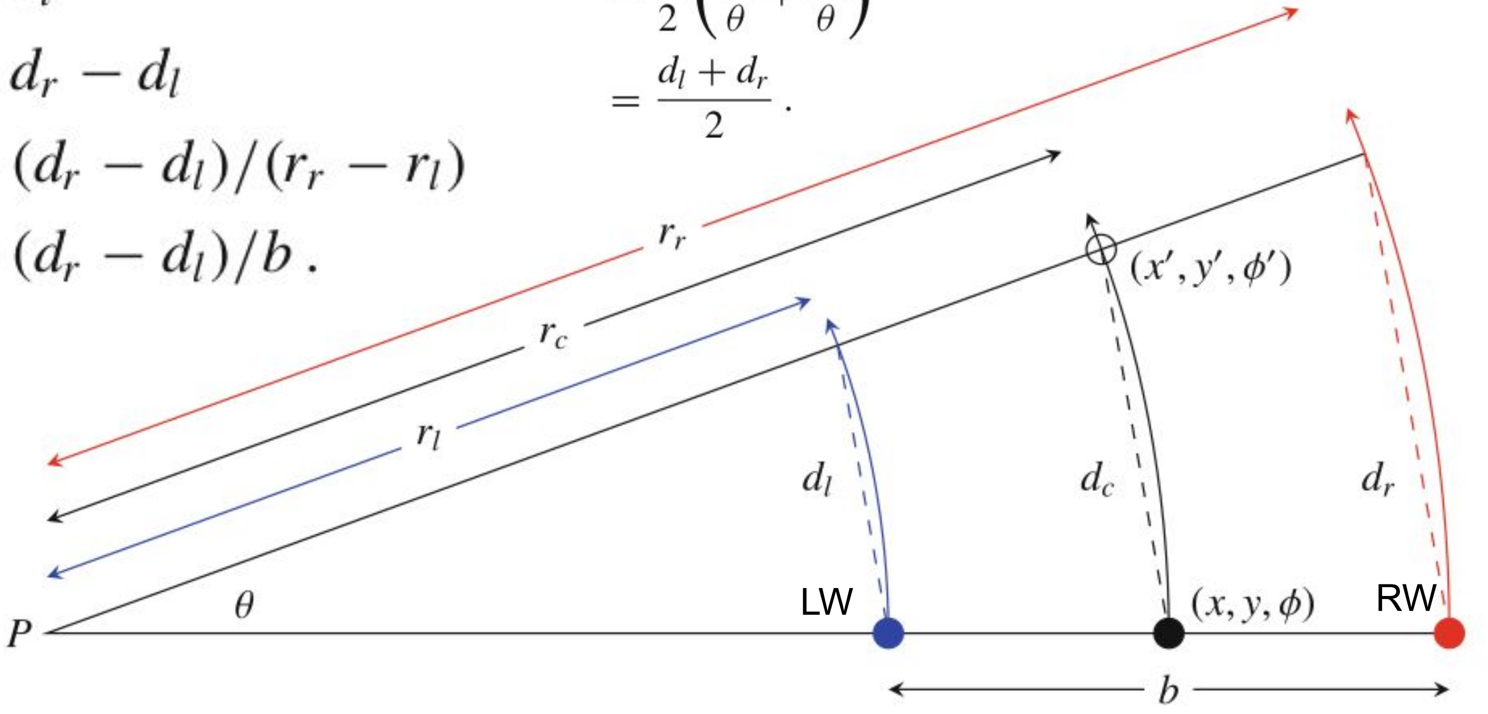
$$x = vt\cos\theta$$

$$y = vt\sin\theta$$

Displacement During a Turn

$$\begin{aligned} d_c &= \theta r_c \\ &= \theta \left(\frac{r_l + r_r}{2} \right) \\ &= \frac{\theta}{2} \left(\frac{d_l}{\theta} + \frac{d_r}{\theta} \right) \\ &= \frac{d_l + d_r}{2} \,. \end{aligned}$$

$$\begin{aligned} \theta r_r &= d_r \\ \theta r_l &= d_l \\ \theta r_r - \theta r_l &= d_r - d_l \\ \theta &= (d_r - d_l)/(r_r - r_l) \\ \theta &= (d_r - d_l)/b \,. \end{aligned}$$

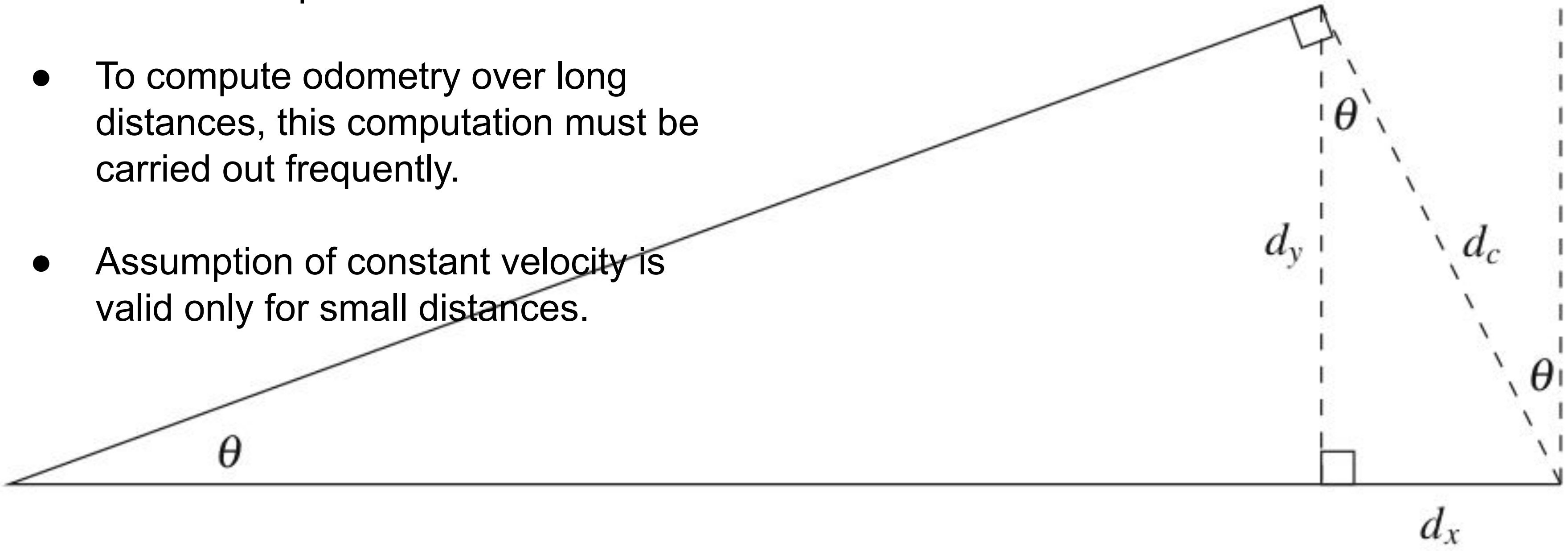


Pose of the robot after the turn:

$$(x', y', \phi') = (-d_c \sin\theta, d_c \cos\theta, \phi + \theta)$$

$$dx = -d_c \sin\theta$$
$$dy = d_c \cos\theta \ ,$$

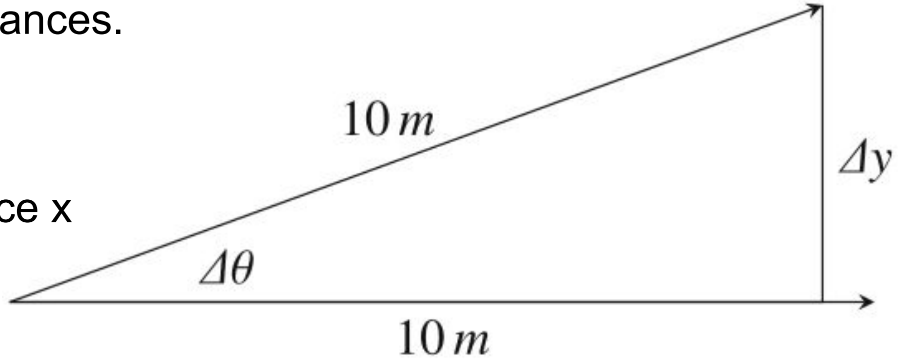
- These approximations are only valid for small displacements.
- To compute odometry over long distances, this computation must be carried out frequently.
- Assumption of constant velocity is valid only for small distances.



Odometric errors

$$x(t+\Delta t) = x(t) + \Delta x$$
$$y(t+\Delta t) = y(t) + \Delta y$$

Error in computing displacement gets accumulated over time leading to large positioning error over longer distances.



Assume p% error in measuring linear distance x and p% error in measuring heading angle.

$$\Delta x \leq \pm 10 \cdot \frac{p}{100} = \pm \frac{p}{10}\ \text{m}$$

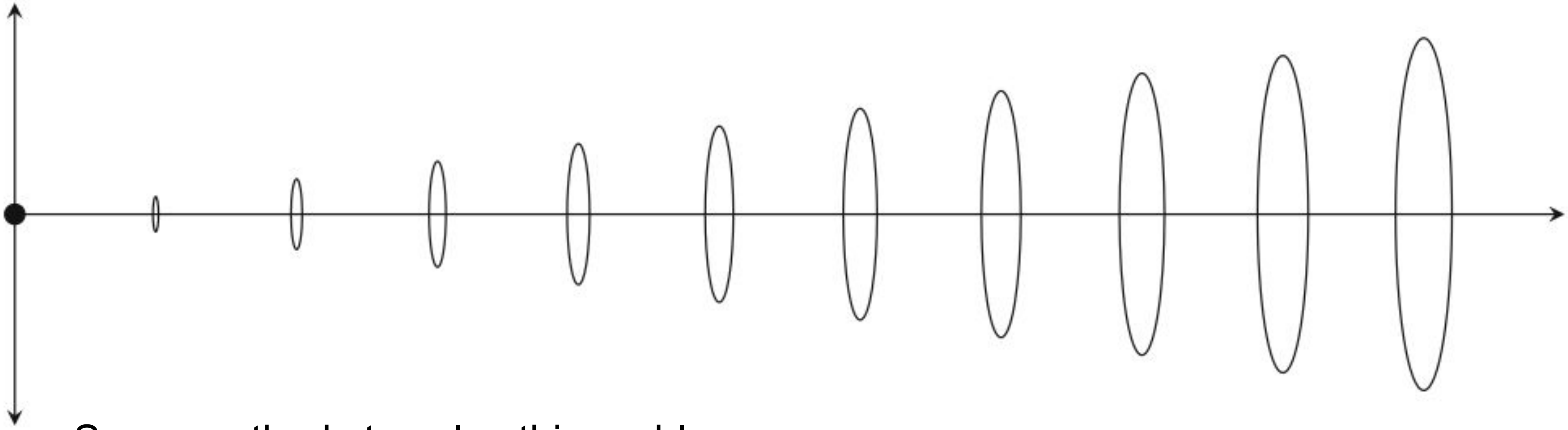
$$\Delta\theta = 360 \cdot \frac{p}{100} = (3.6p)^\circ$$

$$\Delta y \leq \pm 10 \sin(3.6p)$$

$p\%$	Δx (m)
1	0.1
2	0.2
5	0.5
10	1.00

$p\%$	$\Delta\theta$ (°)	$\sin \Delta\theta$	Δy (m)
1	3.6	0.063	0.63
2	7.2	0.125	1.25
5	18.0	0.309	3.09
10	36.0	0.588	5.88

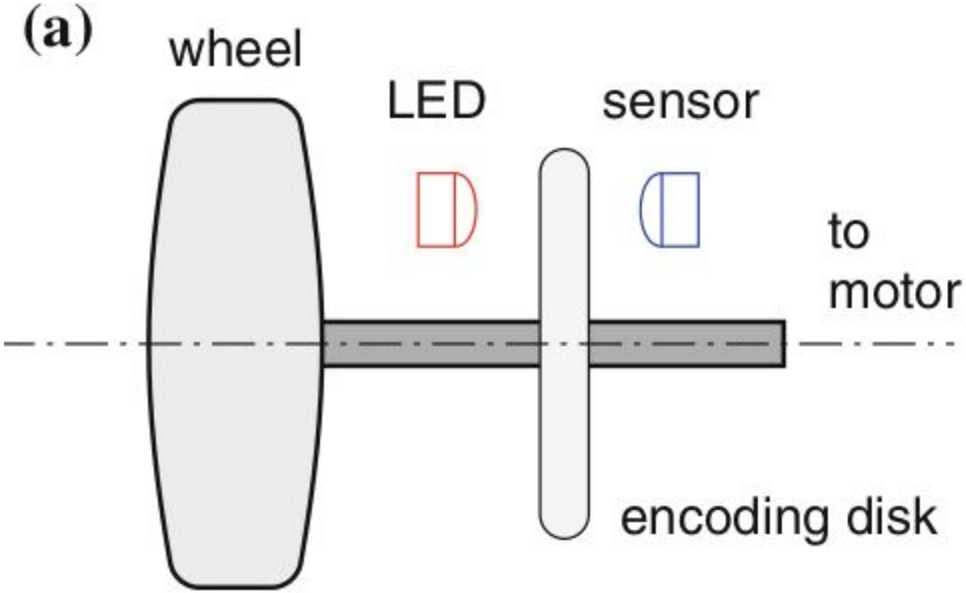
Odometric errors accumulate over time and distance, otherwise known as the **dead-reckoning problem**.

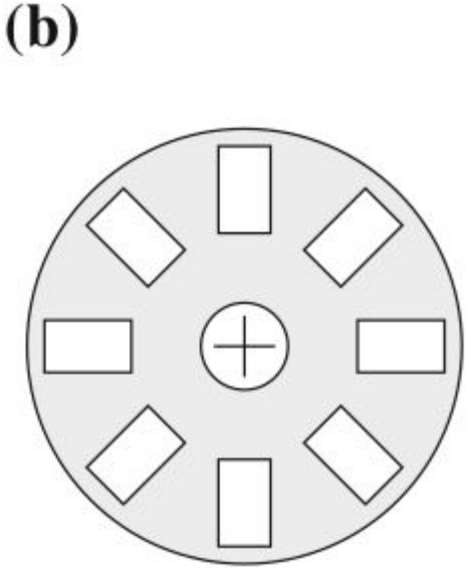


Some methods to solve this problem:

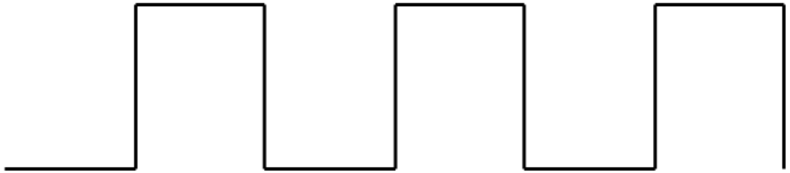
- Use external landmarks to localize its position in the map - SLAM.
- Use multiple sensors to compare and correct each other: Wheel encoders, Gyroscopes, accelerometer, IMU and/or GPS.

Wheel Encoders: to measure speed





a Optical wheel encoder. **b** Encoding disk



Inertial Navigation System (INS)

- An inertial navigation system (INS) directly measures linear acceleration and angular velocity and uses them to calculate the pose of a vehicle.

- It is also known as Inertial Measurement Unit (IMU)

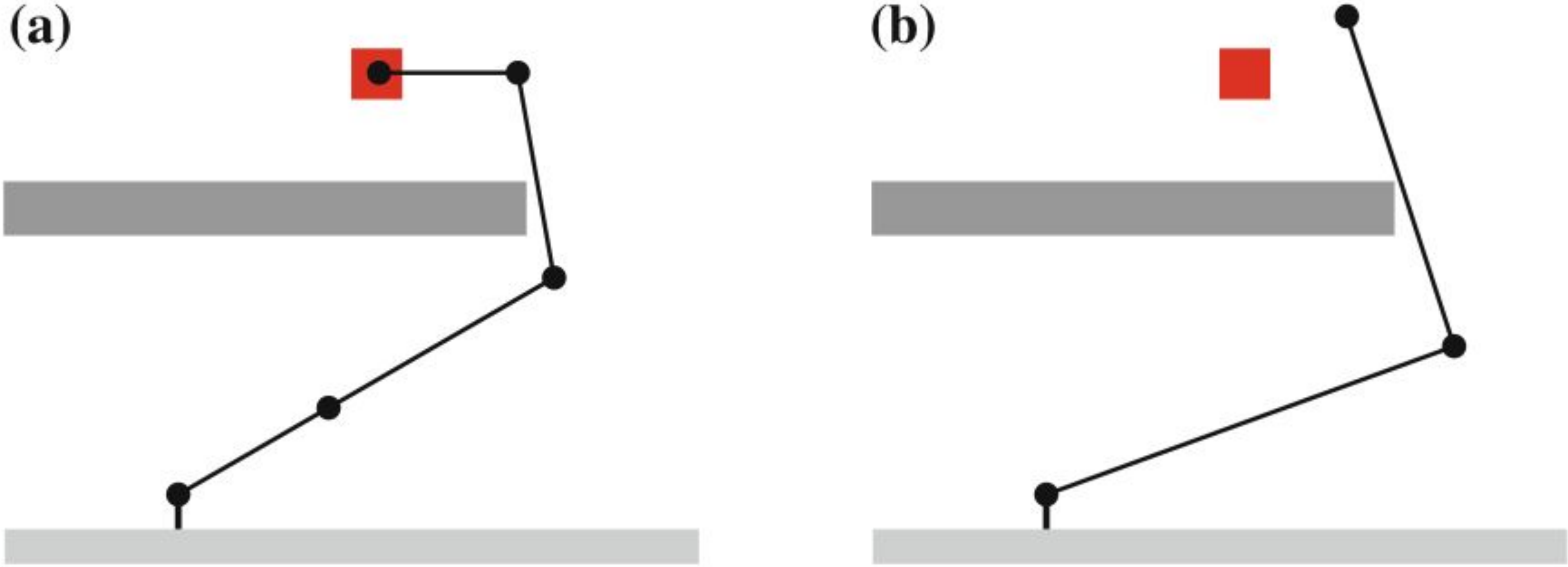
$$v = \int_0^{\tau} a(t)\,dt \qquad \theta = \int_0^{\tau} \omega(t)\,dt \qquad v_n = \sum_{i=0}^{n} a_n \Delta t, \quad \theta_n = \sum_{i=0}^{n} \omega_n \Delta t$$

- Inertial measurement is often combined with GPS to update the position with an absolute location.

- Gyroscopes measure angular velocity by using the principle of Coriolis Force

Degrees of Freedom (DoF)

- It is the dimensionality of coordinate space required to describe the pose of a system.
- A mobile robot has only 3 DOF: (x, y, \theta)
- A helicopter has 6 DOF: (x, y, z, \theta, \phi, \psi)
- Three kinds of systems
  - **Fully-actuated systems:** Number of actuators are same as DoF:
    - Relatively easy to control
    - Example: A 2 or 3-DOF robotic arm
  - **Underactuated Systems:** Number of actuators are less than DoF:
    - Relatively difficult to control. Require greater planning and complex algorithms to control.
    - Example: Mobile Robot
  - **Over-actuated Systems (Redundant Systems):** Number of actuators are greater than DoF
    - Provide redundant solutions - higher dexterity (more ways to do same task)
    - Example: Robotic arm with 7 or higher DoF, Mobile manipulators

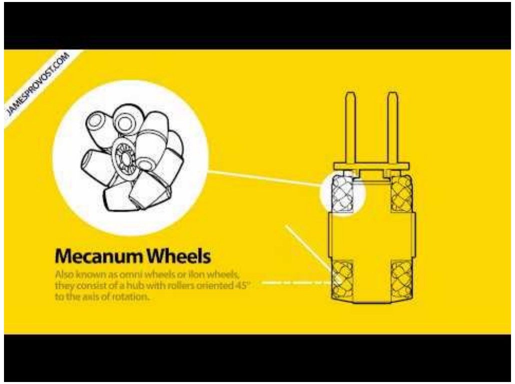


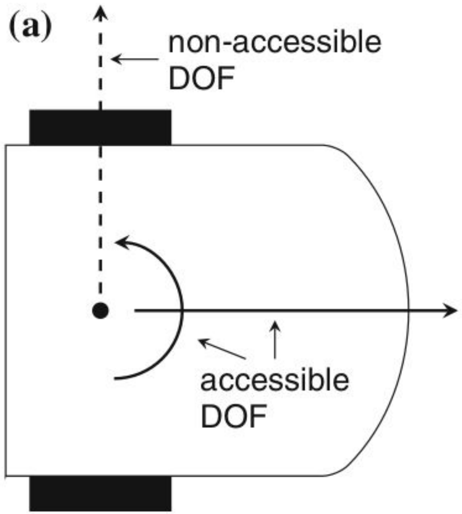
Higher number of actuators provide higher dexterity - ability to do more complex tasks. For example: Obstacle avoidance

Holonomic and Non-holonomic Systems

- **Degree of Mobility (DoM)** is the number of degrees of freedom that can be directly accessed by the actuators.
  - Example: A train has 1 DOF and 1 DoM
  - A mobile robot has 3 DOF but only 2 DoM.

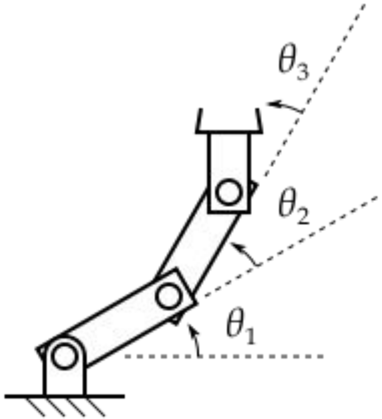
- A robot is **holonomic** if #DoM = #DoF. It is **non-holonomic** if #DoM < #DoF
- **Mechannum Wheels** provide holonomic motion

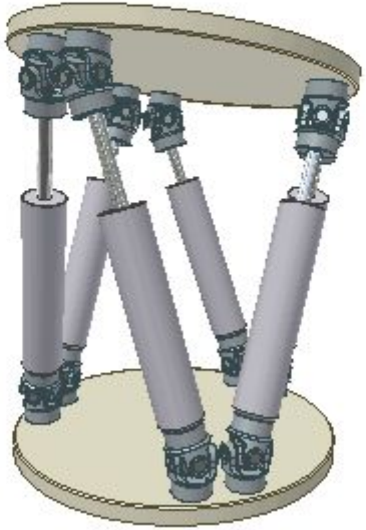


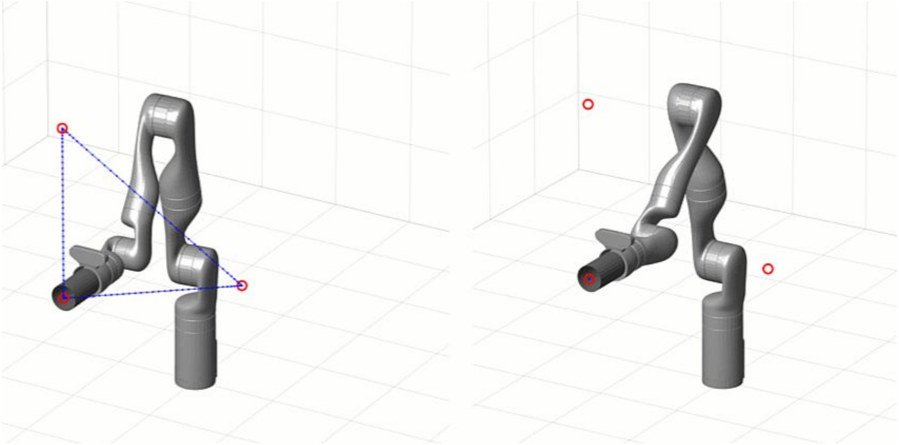


Manipulators

- Serial Manipulators
- Parallel Manipulators







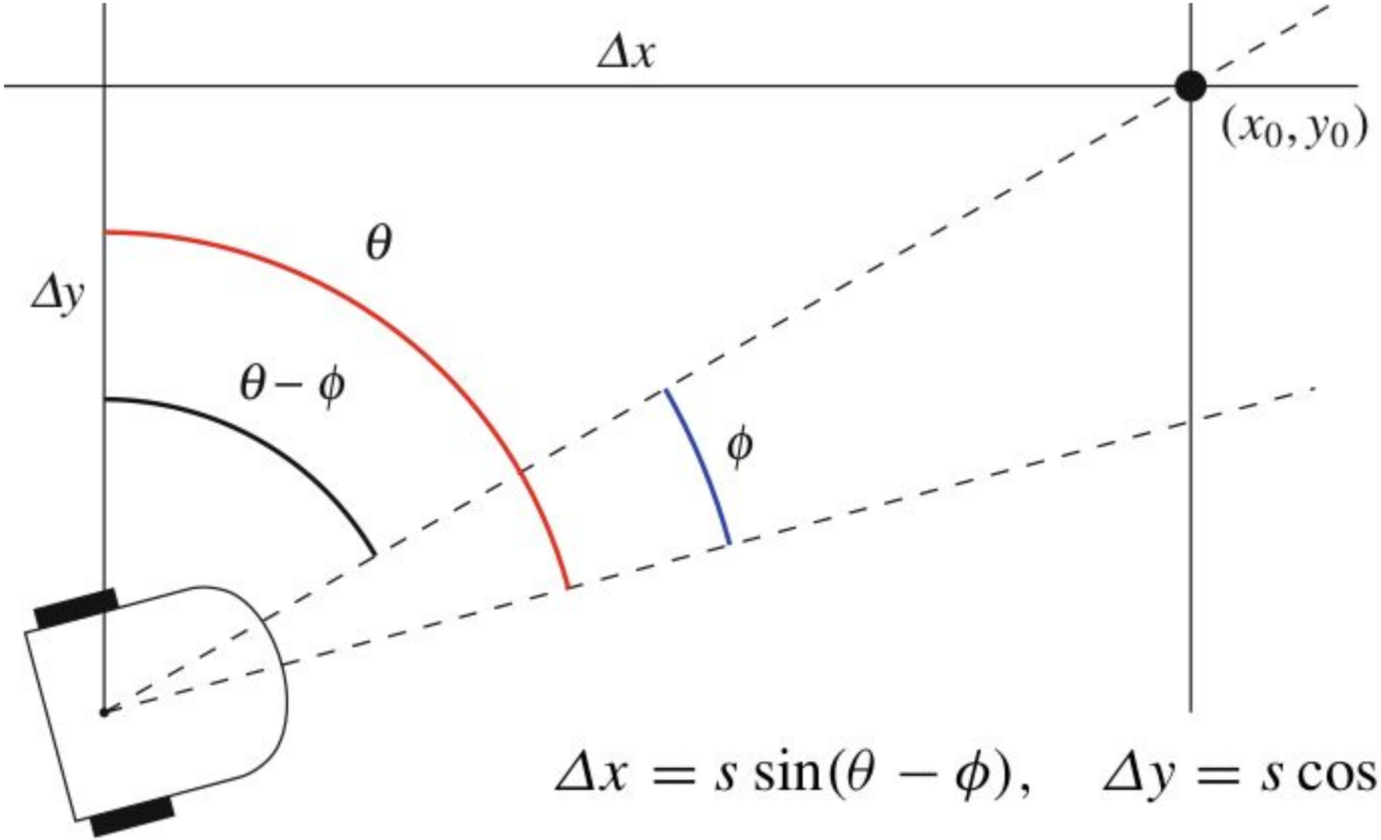
$$\text{FK: } \mathbf{x} = \mathbf{f}(\theta)$$

$$\text{IK: } \theta = \mathbf{f}^{-1}(\mathbf{x})$$

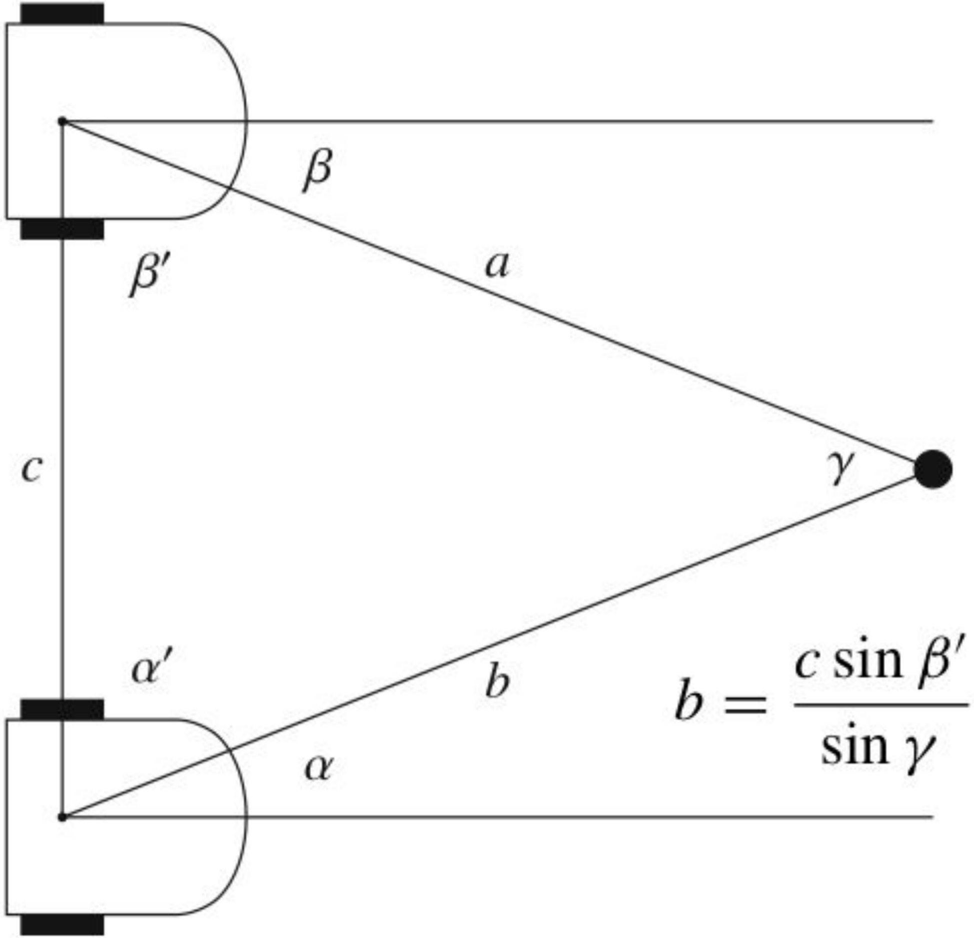
Localization

- Navigation by odometry is prone to errors. Hence, it is preferred to use external references to localizing the robot.
- Finding the position of the robot with reference to external landmarks is called ***Localization***.
- By knowing the distance and angle of the landmark from the robot (say, using a laser), it is possible to find the relative position of the robot.
- Robot position can also be calculated by triangulation if the distance can not be measured.
- A GPS receiver can be used for finding the global coordinates of a system. The positioning error is about 10m. More suitable for outdoor applications.

Determining robot position by knowing the angle distance of the landmark.



$$\Delta x = s \sin(\theta - \phi), \quad \Delta y = s \cos(\theta - \phi)$$



Triangulation is used for determining coordinates when it is difficult or impossible to measure distances.

$$\frac{a}{\sin \alpha'} = \frac{b}{\sin \beta'} = \frac{c}{\sin \gamma}$$

$$b = \frac{c \sin \beta'}{\sin \gamma} = \frac{c \sin(90^\circ - \beta)}{\sin(\alpha + \beta)} = \frac{c \cos \beta}{\sin(\alpha + \beta)}$$

Mapping

- A map is a collection of landmarks positions with respect to a fixed origin.

- It is not possible to provide a pre-built map to a robot for navigation.

- So, it is more practical to have the robot build its own map for a given environment.

- Building map requires localization (knowing robot’s own position), but localization needs a map (position of landmarks) - Its a chicken-and-egg problem.

- Robots use ***simultaneous localization and mapping (SLAM)*** algorithm to solve this problem.

Occupancy Grid Maps

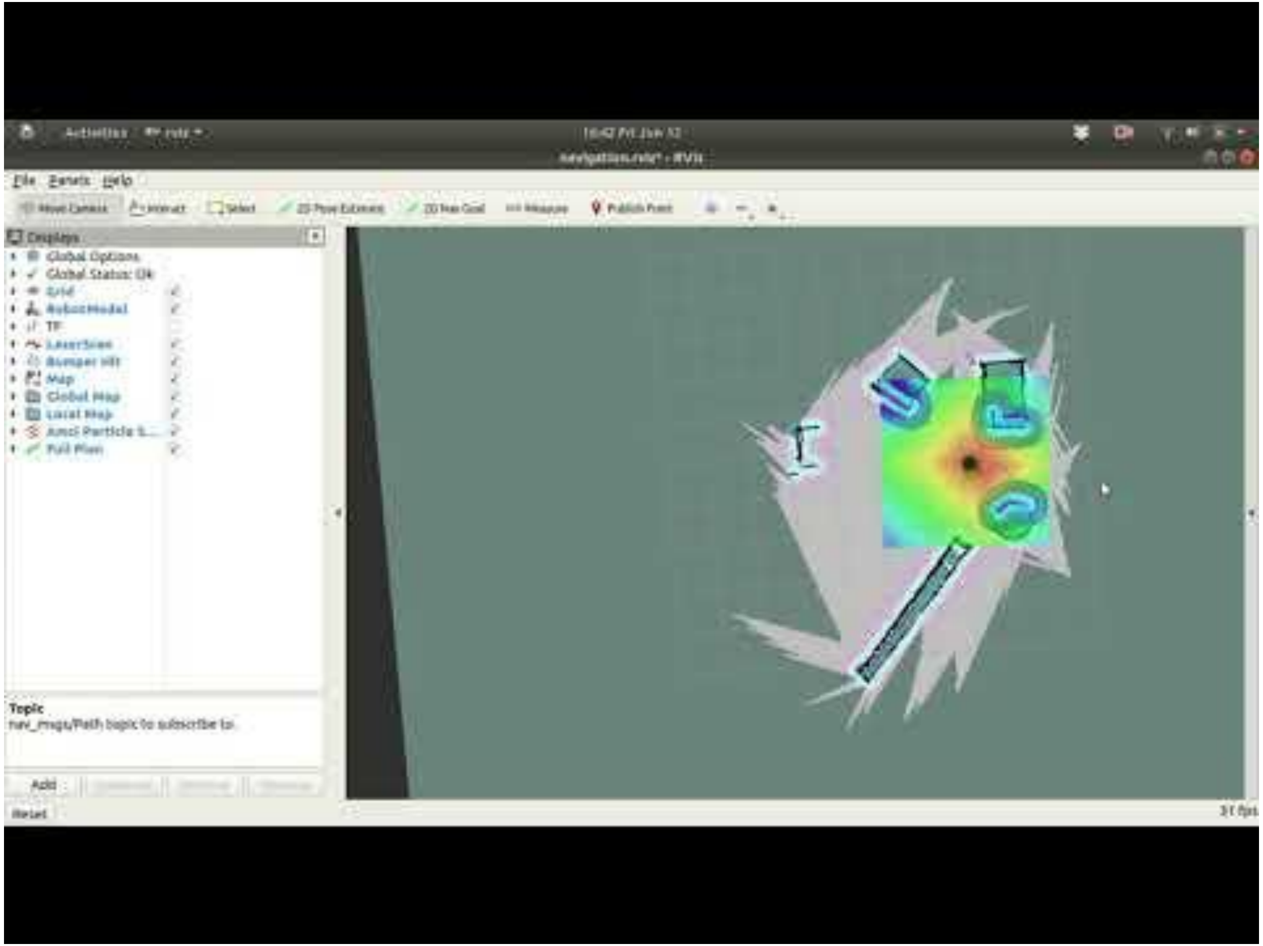
- The map of the environment is represented as grid cells. Whenever an obstacle is detected by the robot sensor, the cell is filled with value ‘1’ with certain probability, otherwise the cell is filled with ‘0’ denoting empty space.

- Robot’s odometry and the map occupancy probabilities are corrected whenever an old place is revisited by the robot - These places are called ***Loop Closures***.

- Map creation can be improved using sensors that can identified regular features such as lines, sharp corners etc.

	0	1	2	3	4	5	6	7
0								
1								
2						.4	.6	.3
3			.1	.2	.4	.6	.9	.5
4			.3	.6	.5	.7	.8	.6
5			.4	.8	1.0	1.0	.9	.5
6			.2	.3	.2	.3	.3	.1
7								

The built maps could then be used for autonomous navigation.


Activities
File
Panels
Help
Move Camera
Interact
Select
2D Pose Estimate
2D Nav Goal
Measure
Publish Point
Displays
Global Options
Global Status: Ok
Grid
RobotModel
TF
LaserScan
Bumper Hit
Map
Global Map
Local Map
Full Plan
Topic
nav_msgs/Path topic to subscribe to.
Add
Reset

Some Robotics Projects

Visual Servoing

- Controlling robot arm motion through visual feedback.

- Relationship between image pixels and robot joint angles is unknown, nonlinear and complex. Hence it is a challenging research problem.

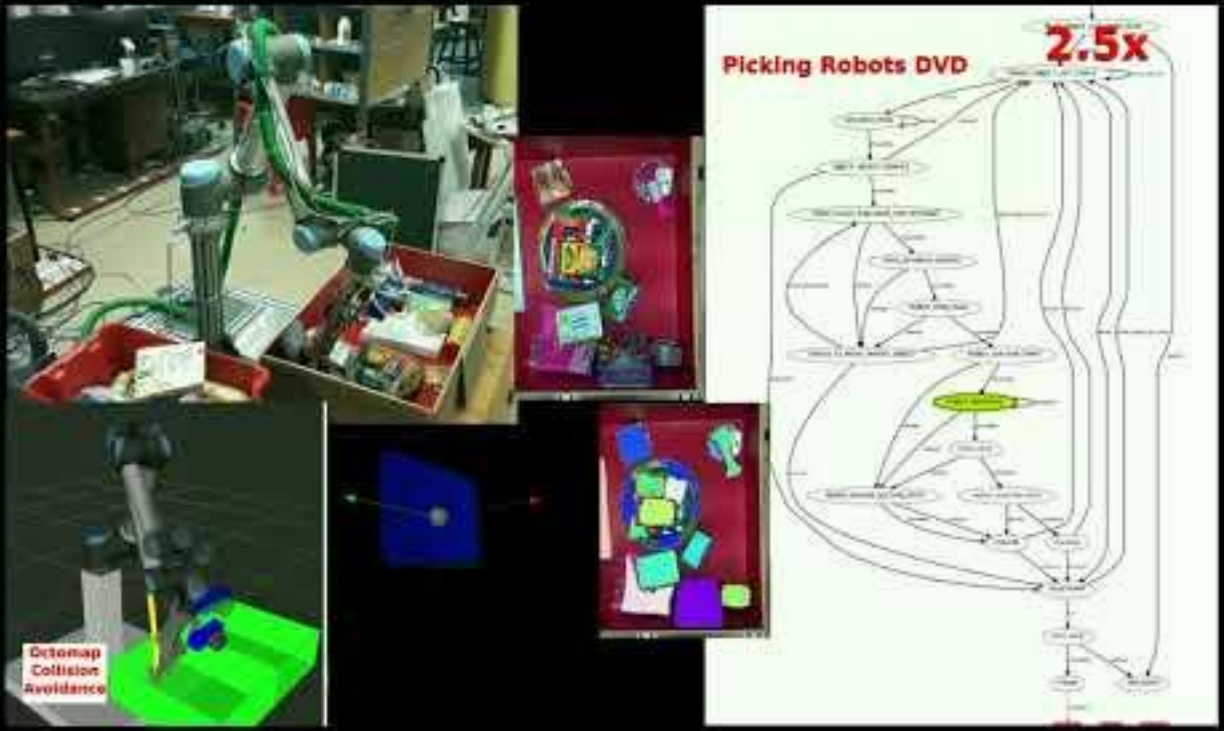
- Conventional methods relied on accurate robot as well as camera models and extraction of suitable visual features.

- Recent methods are exploring Deep Reinforcement Learning to solve this problem.

Manipulation & Grasping

- Computing Grasping handles from RGBD images is a difficult problem.

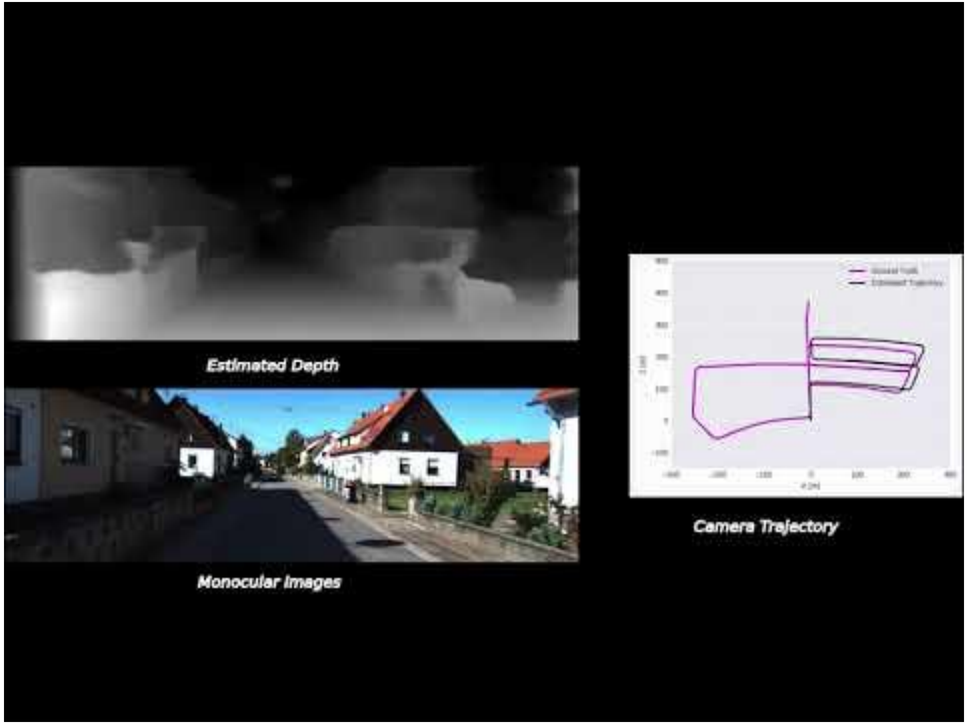
- Widely used for Pick & Place applications in warehouses.



Picking Robots DVD
2.5x
Octomap
Collision
Avoidance

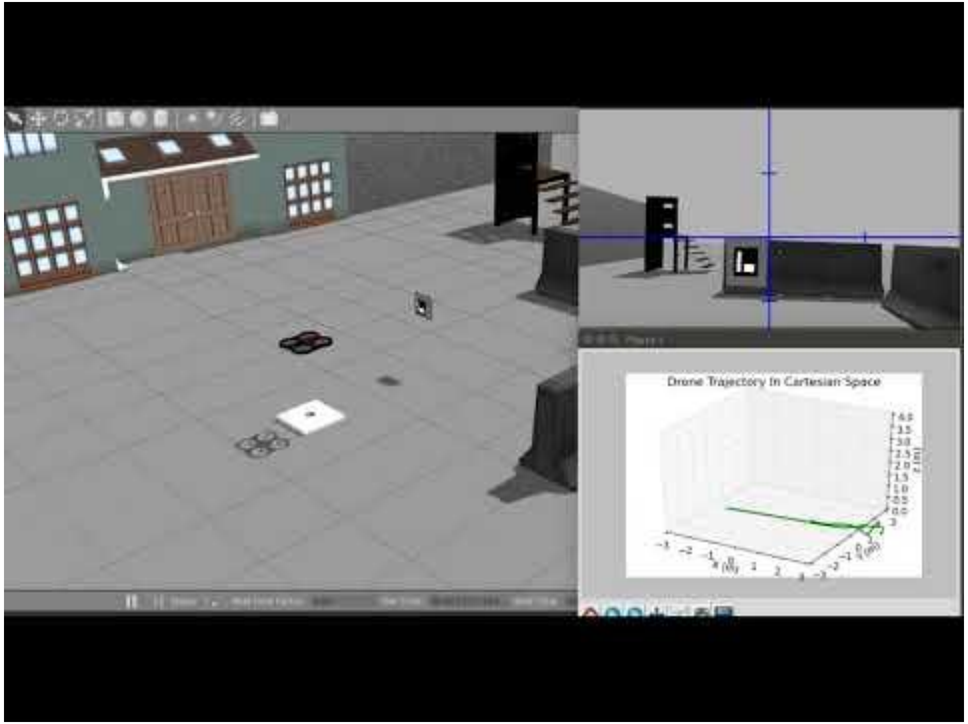
Depth and Pose Estimation from Images

- We are estimating depth and pose information from monocular images without requiring Lasers or LiDARs.
- State-of-the-art Deep Learning Algorithm has been developed for this.



Drone motion Control

- Here we develop a Reinforcement Learning algorithm to make the drone learn the motion profile for Landing.



Summary

- Robots are required to replace human beings from Dull, Dirty and Dangerous (D3) works, leaving them free for more creative pursuits.

- Robotics is an interdisciplinary field requiring skills in multiple domains - Mechanical / Electrical / Computer Science Engineering, biological or neuroscience, chemical engineering etc.

- There is a growing demand for robots which will only increase in future.

- Events like the ongoing COVID Pandemic will accelerate the adoption of robots.

- The aim of this presentation is to provide you an overview of the field of robotics and motivate you to explore further.