



# MODULE 3: TECHNICAL FUNDAMENTALS – AUTONOMOUS VEHICLES & ROBOTICS TECHNOLOGY

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# Contents



1. Understanding the general architecture of Autonomous Systems
2. Challenges faced while designing or developing Autonomous Systems
3. Other aspects of Autonomous Systems Design
4. Understanding the concept of technologies and system architectures that are involved in Autonomous Vehicles and Robots
5. Workshop: Develop basic autonomous robot arm



# **CHAPTER 1:** **UNDERSTANDING THE GENERAL ARCHITECTURE OF AUTONOMOUS SYSTEMS**





# Concept of Autonomy



- **Autonomy = Ability to make one's own decisions**
- **Key to the IoT vision** promising increasing integration of smart systems to achieve goals such as optimal resource management and enhanced quality of life, with **minimal human intervention**
- **Very important questions for autonomous systems engineering:**
  1. Is there a **general reference model** that could provide a basis for evaluating system autonomy?
  2. What are the **technical solutions** for enhancing a system's autonomy?
  3. For each enhancement, is it possible to **estimate the implied technical difficulties and risks?**



## Discussion Question:

**Are autonomous systems ALL about AI  
and learning techniques?**

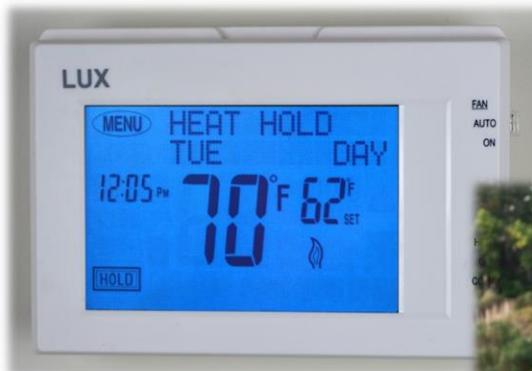




# Concept of Autonomy



## Any differences among the following?

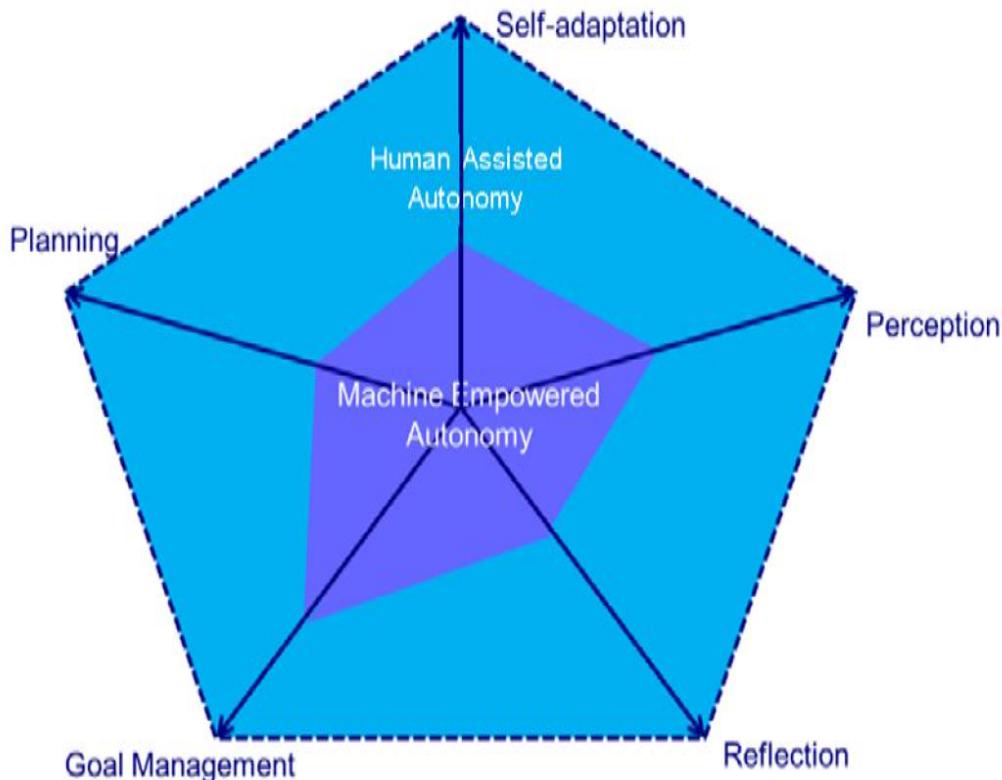


**Hint: 3 Main Differences**





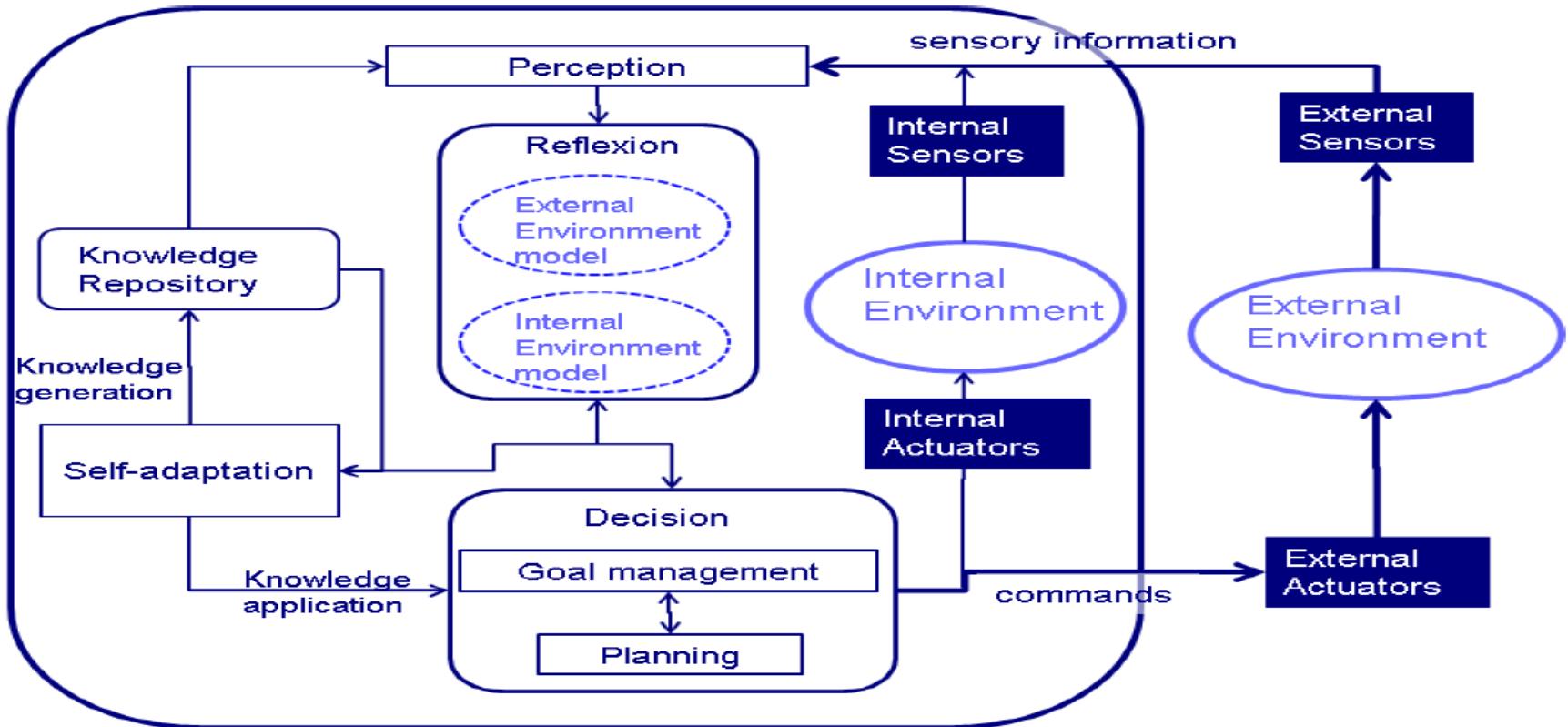
# Main Aspects of Autonomy



1. **Perception** e.g. interpretation of stimuli, removing ambiguity/vagueness from complex input data and determining relevant information
2. **Reflection** e.g. building/updating a faithful environment run-time model
3. **Goal management** e.g. choosing among possible goals the most appropriate ones for a given configuration of the environment model
4. **Planning** to achieve chosen goals
5. **Self-adaptation** e.g. the ability to adjust behavior through learning and reasoning and to change dynamically the goal management and planning processes

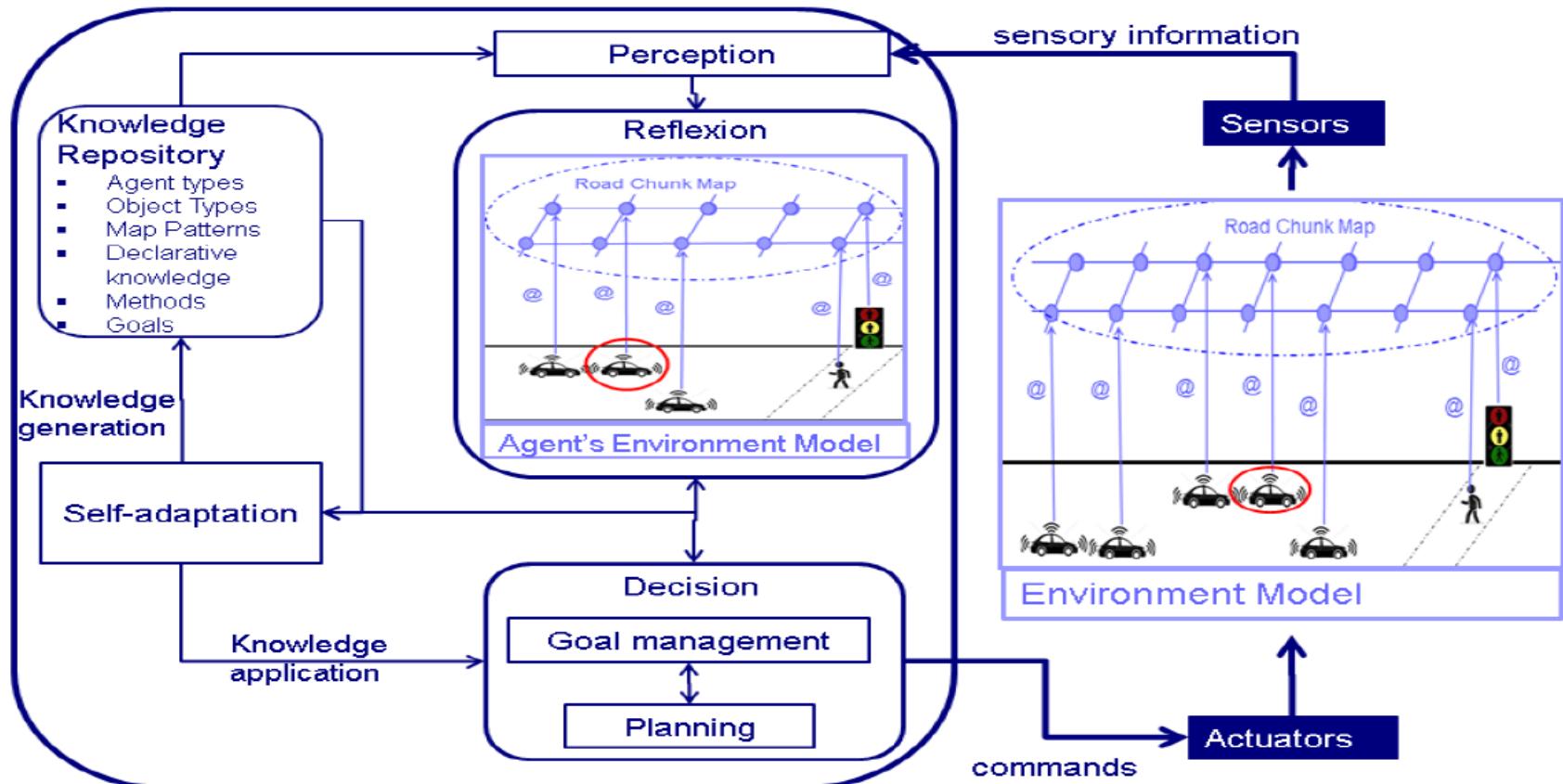


# General Architecture of Autonomous Systems





# General Architecture of Autonomous Systems



Applied to Autonomous Vehicles Case;  
Autonomous Systems Category is broader!



# General Architecture of Autonomous Systems



Component	Description	Examples
<b>Knowledge Repository</b>	Stores static and dynamic knowledge for interpreting sensory information, environment modeling, and goal management.	Static: Agent types, maps, goals. Dynamic: Agent properties, monitor data, learned knowledge.
<b>Perception Module</b>	Extracts and links relevant information from sensors to the knowledge repository, using learning or recognition processes.	Identifies components in the environment, e.g., a self-driving car identifying nearby objects.
<b>Reflection Module</b>	Builds/updates environment models using perception information, crucial for dynamic environments.	Updates the environmental model in real-time, e.g., self-driving cars tracking dynamic changes.
<b>Decision Module</b>	Manages goals and generates action plans, solving optimization problems and translating goals into actions.	Plans actions based on goals and environment, e.g., navigating a car through traffic.
<b>Self-adaption Module</b>	Supervises and coordinates modules, reassesses information coherency, and adapts using reasoning, analysis, and learning techniques.	Monitors environment, detects issues, adapts goals and parameters using learning, e.g., adjusting to new traffic conditions by learning from past experiences.



# General Architecture of Autonomous Systems



## 1. The Knowledge Repository

- **Contains various types of knowledge** used by the other modules for:
  - a) the interpretation of sensory information;
  - b) building the environment model of the agent;
  - c) goal management and subsequent goal planning
- **Some is developed at design time (static), and some is produced and stored at run time (dynamic)**



# General Architecture of Autonomous Systems



## 1. The Knowledge Repository (Cont)

- **Examples of design time knowledge:**
  - a) list of all the relevant types of agents and objects and their corresponding behaviors
  - b) list of predefined maps and coordination patterns
  - c) list of the goals
  - d) monitoring and learning techniques
- **Examples of run time knowledge:**
  - a) Properties of the agent model
  - b) Knowledge produced by monitors of the agent's behavior
  - c) Knowledge produced by application of learning techniques



# General Architecture of Autonomous Systems



## 2. The Perception Module

- **Extracts relevant information from the various stimuli provided by sensors;** extracted information is linked to the knowledge repository
- Makes use of learning techniques or of analysis and recognition processes
- **It concerns:**
  - a) the type and identity of each sensed agent or object
  - b) the state of the identified components
  - c) the type of the external environment
- **Example:** Perception module of a self-driving car provides the types of the components in the vicinity with their associated attributes



# General Architecture of Autonomous Systems



## 3. The Reflection Module

- **Uses information provided by the Perception module to build/update the environment models** (i.e. external and internal)
- **Very important for agents with dynamically changing environment** (e.g. self-driving cars)
- Extensively uses design time knowledge of the Repository to build a complete behavioral model of its perceived environment
- **Performance of this module is critical for mobile agents subject to real-time constraints;** How fast the agent's environment model can track changes of the real environment?



# General Architecture of Autonomous Systems



## 4. The Decision Module

- **Two cooperating submodules:**
  - a) Goal Manager that handles the actual agent's goals
  - b) Planner that generates plans that implement particular goals
- **Assigns higher priority to critical goals according to their importance**
- **Goal management = Solving an optimization problem**
  - ❖ translates goals into utility function policies: a goal is characterized as the desired set of feasible states for which the objective function is optimized subject to a set of constraints
- **For a selected goal, the Planner computes from the environment model a corresponding plan (involves commands for interaction with other agents or reconfiguration of their environment )**



# General Architecture of Autonomous Systems



## 5. The Self-adaption Module

- **Supervises and coordinates all the other modules**
- **Continuously reassesses the coherency of the exchanged information, creates new knowledge and provides directives to the Goal manager**
- **Combines reasoning and run-time analysis techniques; examples:**
  - a) monitoring or analysis techniques to the environment model to detect critical situations
  - b) learning techniques to estimate parameters or detect abnormal situations
- **Directives to the Goal Manager include:**
  - a) Change of parameters
  - b) Change of the set of the managed goals



# CHAPTER 2: CHALLENGES FACED WHILE DESIGNING OR DEVELOPING AUTONOMOUS SYSTEMS





# Possible Challenges



- 1. Design Complexity**
- 2. Autonomy Complexity**
- 3. Implementation Complexity**
- 4. Chaotic environments (limitless scenarios)**
- 5. Challenging conditions (e.g. rain, snow, low sunlight, mist)**
- 6. Miscommunications between the system and human user**



# 1. DESIGN COMPLEXITY



# Design Complexity of Autonomous Systems



Fast response required



Highly dynamic situations



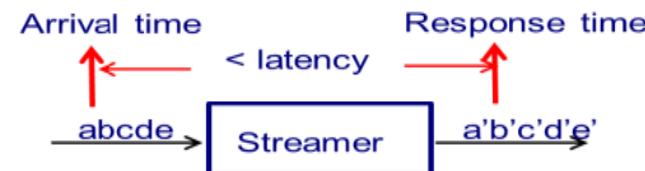
# Reactive Complexity



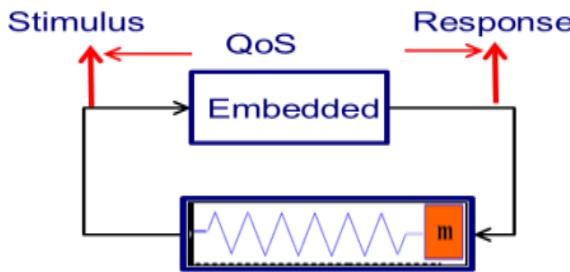
- Characterizes the **complexity of the interaction between an agent and its environment**



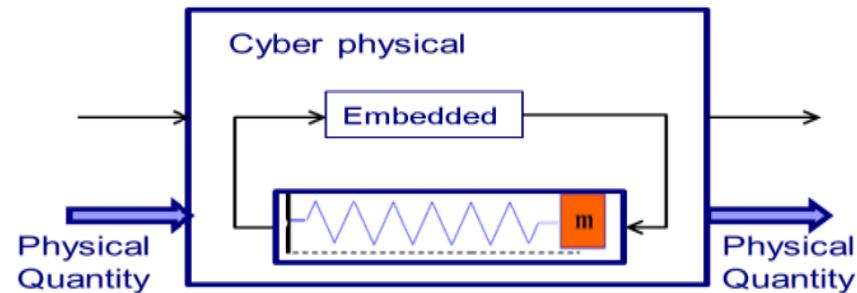
Transformational agent e.g.  
Intelligent Personal Assistant



Streaming Agent  
e.g. Encoder, Signal processor



Embedded Agent  
e.g. Flight controller



Cyber physical agent  
e.g. Self-driving car



# Architecture Complexity



Characterizes the **complexity of coordination between agent(s) and object(s)**; type of architectures with increasing complexity:

- a) **Static:** A given number of agents and objects, with fixed coordinates
- b) **Parametric:** Arbitrary initially known numbers of “pluggable” components for fixed coordination patterns
- c) **Dynamic:** Parametric architectures with dynamic creation/deletion of agents or objects
- d) **Mobile:** Dynamic architectures where also the coordinates of objects and agents can change dynamically (e.g. swarm robotic system). May involve dynamic change of maps when mobile agents explore a space and progressively build a model of their environment.
- e) **Self-organizing:** Mobile architectures with many dynamically changing motifs (e.g. for robocars, soccer playing robots). Able to adapt coordination rules to changing system dynamics.

P.S. Objects are physical dynamic systems without computation capability



## 2. AUTONOMY COMPLEXITY



# Autonomy Complexity



1. **Complexity of perception:** Difficulty to interpret stimuli provided by the environment and to timely generate inputs for the agent environment model. Caused by stimuli ambiguity (admitting different interpretations), vagueness (fuzzy or noisy stimuli), high volume of stimuli data
2. **Lack of observability/controllability:** Partial knowledge of the agent's environment. Affects the ability to build plans and act on the environment
3. **Complexity of goal management:** Complexity of the process of choosing the most compatible set of goals. Utilization of prioritization and optimization models
4. **Complexity of planning:** Directly depends on the type of goals and the complexity of the environment; goals can be simple or complicated
5. **Complexity of adaptation:** Directly related to uncertainty about the environment



# 3. IMPLEMENTATION COMPLEXITY





# Implementation Complexity



## 1. Choosing the Most Suitable Architecture Type to Implement

- Centralized, Decentralized, Distributed

## 2. Accuracy of Dynamic Model of the System

- Challenging to design a **reliable controller**
- Hence, challenging to properly control the system

## 3. Issues of having Multiple Agents

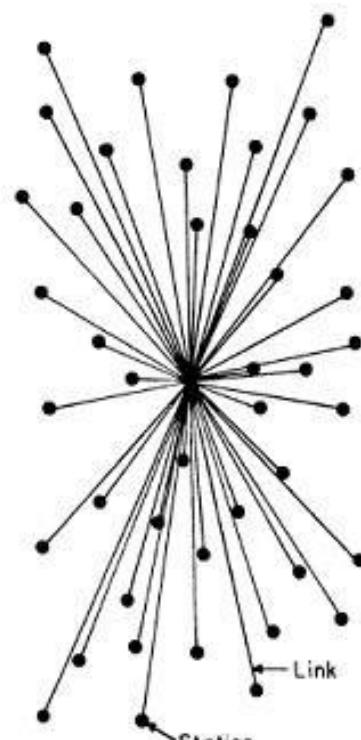
- Coordination issues
- Conflicting objectives



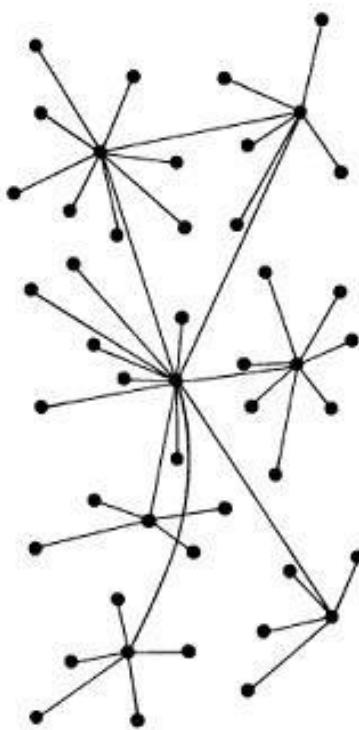
# Implementation Complexity



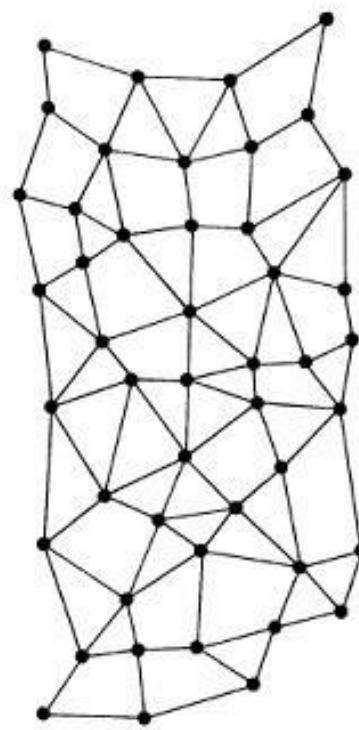
## Centralized vs Decentralized vs Distributed



CENTRALIZED  
(A)



DECENTRALIZED  
(B)



DISTRIBUTED  
(C)



## 4. CHAOTIC ENVIRONMENTS

## 5. CHALLENGING CONDITIONS



# Chaotic Environments



To be continued in HRSE course .....



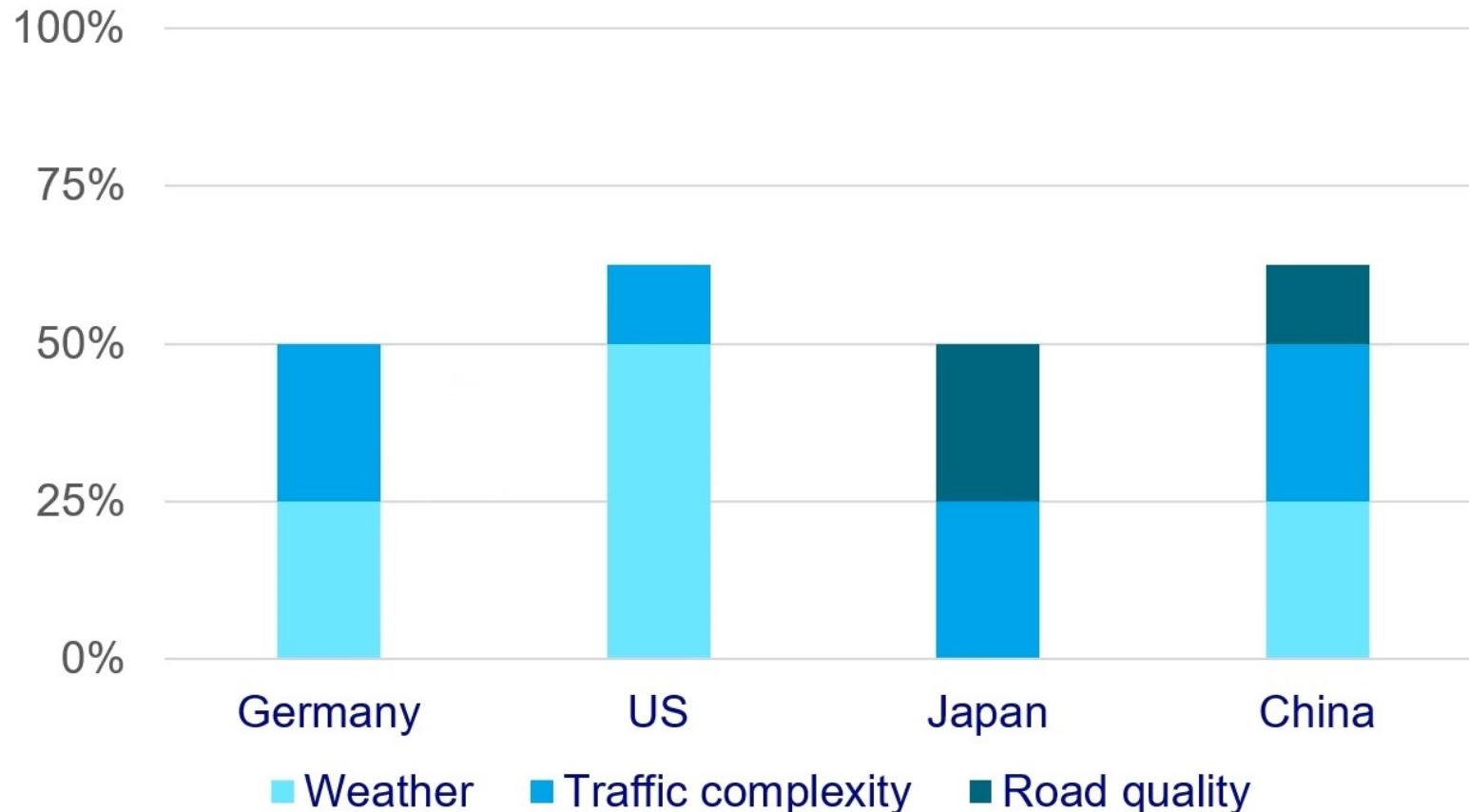
# Challenging Conditions



**Conditions that impaired view of system;  
possible risk of safety compromise**



# System limitation for highly autonomous driving



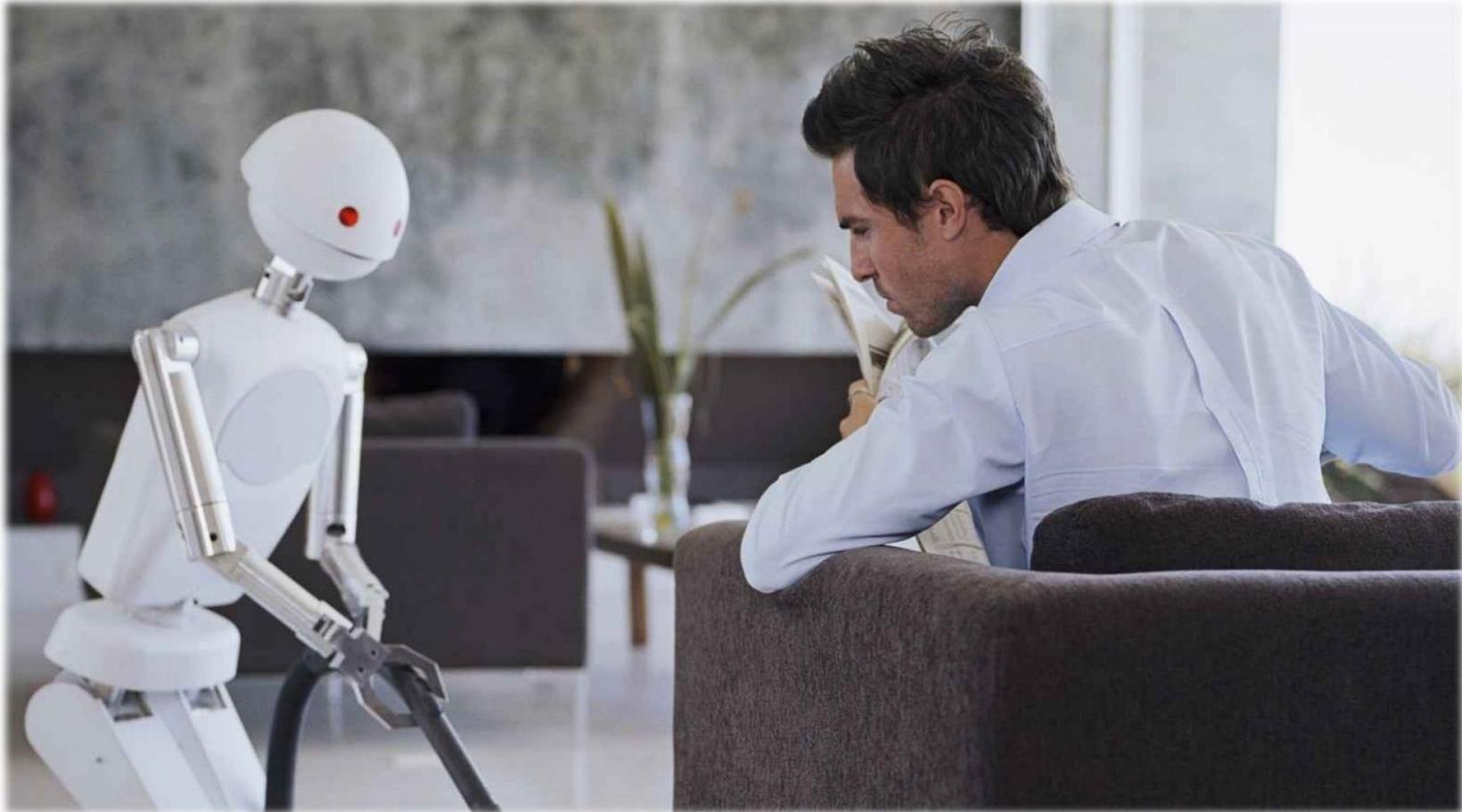


## 6. MISCOMMUNICATIONS BETWEEN THE SYSTEM AND HUMAN USER





# Miscommunications



**E.g. Clearing rubbish in your house**



# CHAPTER 3: OTHER ASPECTS OF AUTONOMOUS SYSTEMS DESIGN





# Funny Self-Driving Car Commercial



Source: <https://www.youtube.com/watch?v=iRIn4-5TmUM>



# Other Aspects of AS Design



- 1. Systems Safety**
- 2. Cyber Security**
- 3. Reliability**
- 4. Responsibility & Accountability**



# 1. SYSTEMS SAFETY



# System Safety



- **Most basic requirement** of autonomous systems
- **Questions to ask:**
  1. How should the system be tested?
  2. What guidelines should be fulfilled to ensure that it is safe to use? E.g. standards and/or technical regulations
  3. For AV case, should a self-driving car require a driver license?
- **Economic considerations might compromise the safety of the system** (e.g. cheap equipment, negligence to maintain software)



# System Safety



## Possible Solutions:

### 1. Failure Mode, Effects & Criticality Analysis (FMECA)

- Used to chart the probability of failure modes against the severity of their consequences; performed at either the functional or piece-part level
- Result highlights failure modes with relatively high probability and severity of consequences

### 2. Fault Tree Analysis

- Utilized to perform risk estimation because of its capability to provide the shortest path to reach the top-level failure from a single component failure

### 3. Dependent Failure Analysis (DFA)

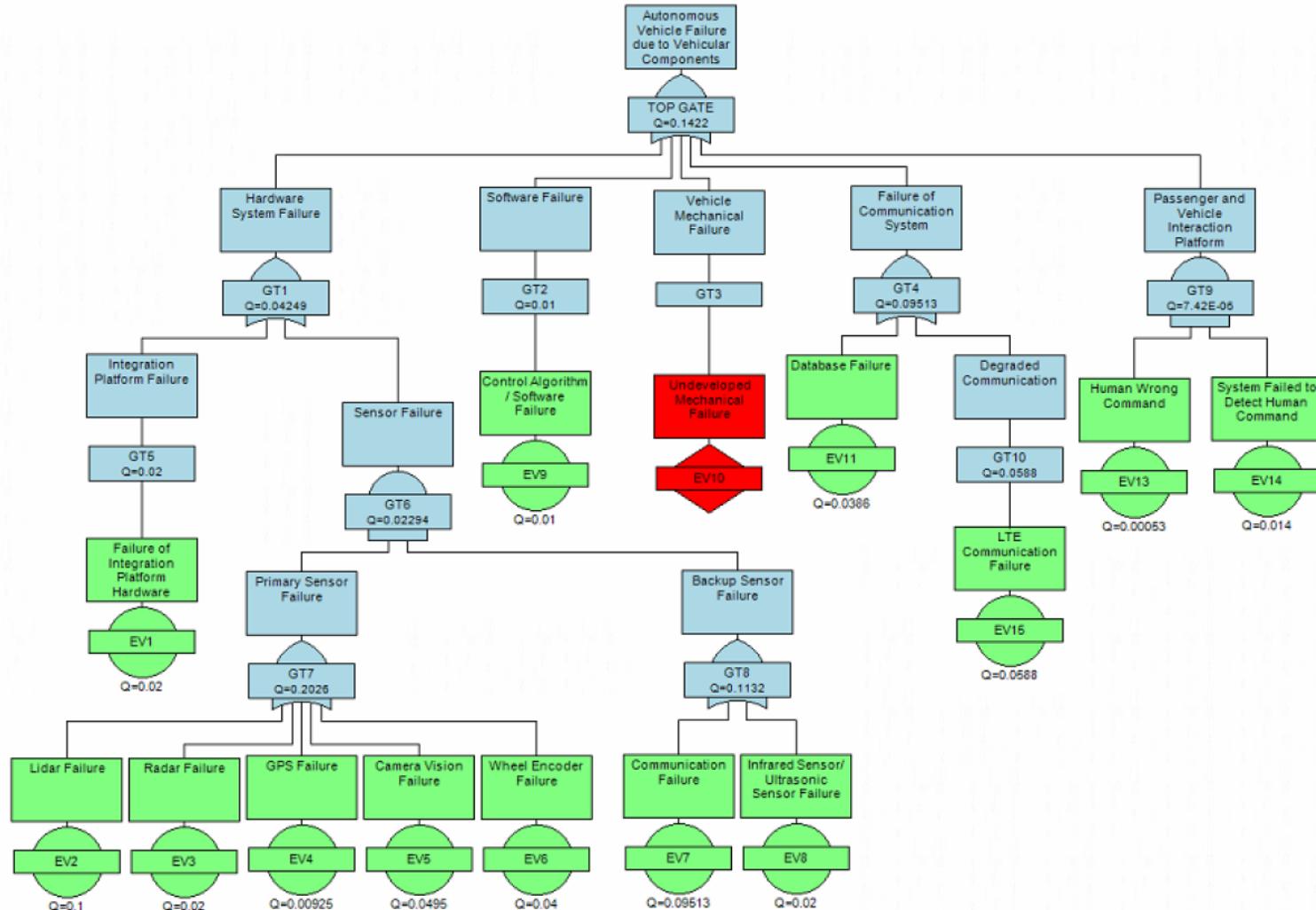
- Aims at identifying failures that may hamper the required independence from interference between given elements (hardware/software/firmware) which can compromise system safety



# System Safety

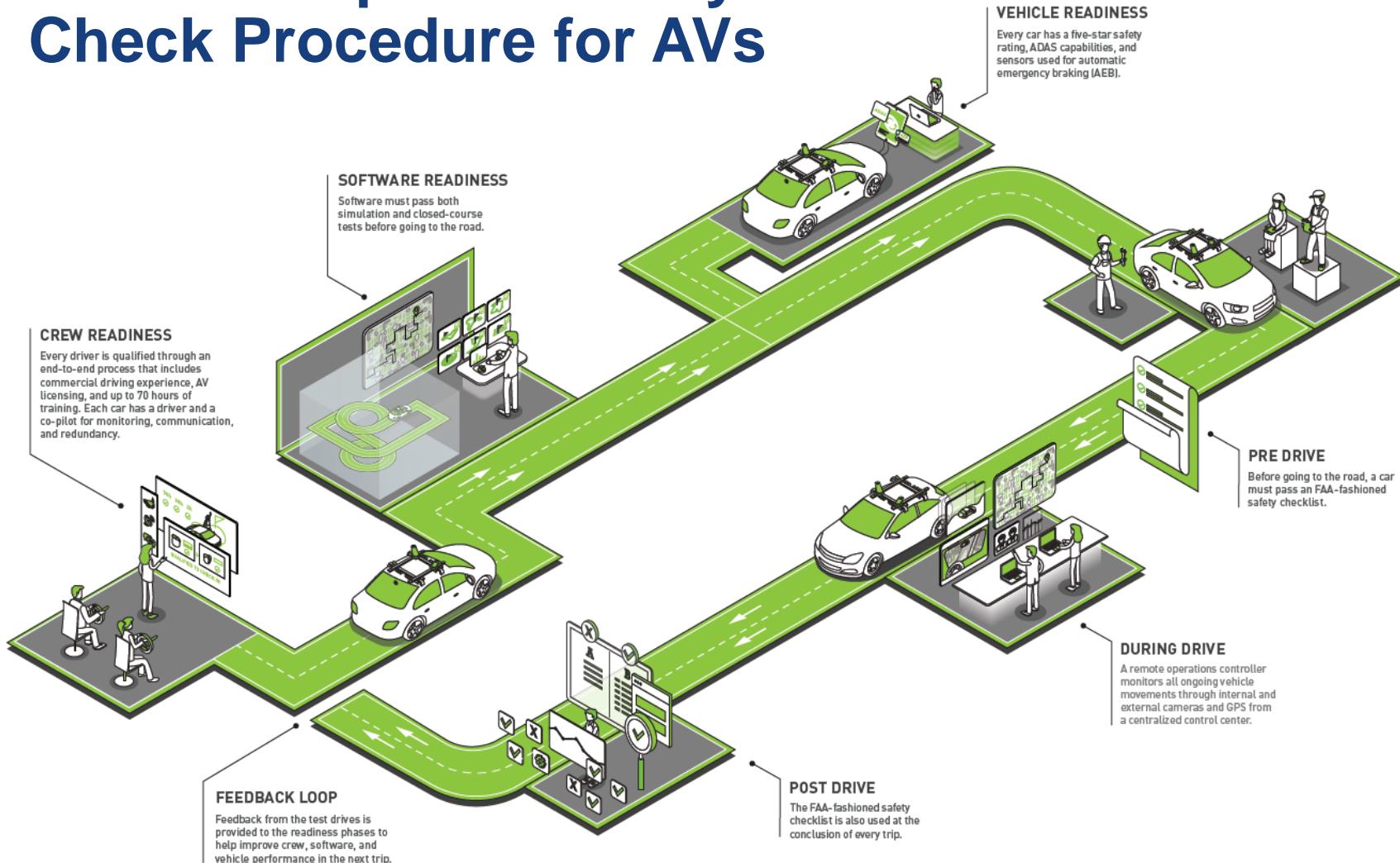


## Fault Tree Analysis Example for AV:





# System Safety: NVIDIA Proposed Safety Check Procedure for AVs





## 2. CYBER SECURITY



# Cyber Security



WIRED

Hackers Remotely Kill a Jeep on the Highway—With Me in It

ANDY GREENBERG SECURITY 07.21.15 6:00 AM

## HACKERS REMOTELY KILL A JEEP ON THE HIGHWAY—WITH ME IN IT

Technology iPhone Android

**BMW ConnectedDrive has been found to expose millions of cars exposed to remote update attacks.**

**Hackers can control 11 functions of a car including heating and access doors.**

Weakness in communication between electronics creates opportunities for hackers



Home News World Business Fintech Politics Technology Science Sport Entertainment

Tesla Patches Vulnerabilities that International Business



ANDY GREENBERG SECURITY 09.10.15 7:00 AM

**Hackers disable Corvette brakes via a dongle meant to lower insurance rates.**



By Alistair Charlton

August 12, 2015 10:03 BST



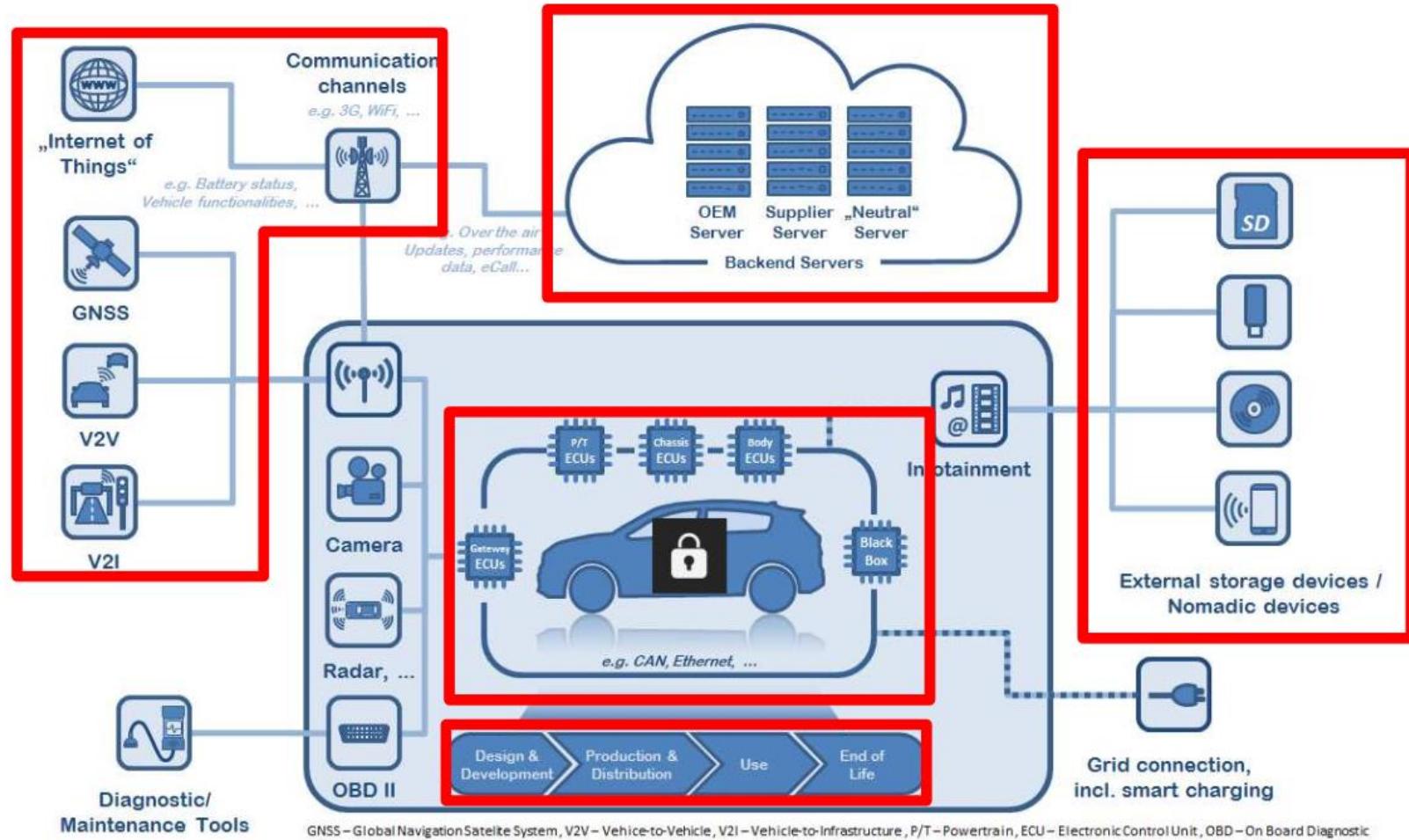
ANDY GREENBERG SECURITY 09.27.15 7:00 AM

**TESLA RESPONDS TO CHINESE HACK WITH A MAJOR SECURITY UPGRADE**





# Cyber Security (Many Considerations)





# Cyber Security



- **Important consideration for designing AS**
- Have been **a number of attacks at car systems and sensors (e.g. LIDAR and GPS) that were used to manipulate the cars behavior**
- **Questions to ask:**
  1. Should there be a minimum security threshold to allow the system to be used?
  2. How secure must the systems and the connections be?
  3. Necessary to involve black boxes (for AV case)?
  4. Constant software updates to ensure cyber security?
  5. Necessary for connectivity functionalities?



## Possible Solutions:

### 1. DREAD (Risk Assessment Model)

- Damage – how bad would an attack be?
- Reproducibility – how easy is it to reproduce the attack?
- Exploitability – how much work is it to launch the attack?
- Affected users – how many people will be impacted?
- Discoverability – how easy is it to discover the threat?

### 2. STRIDE (Security Checklist)

	Threat	Property Violated	Threat Definition
S	Spoofing identify	Authentication	Pretending to be something or someone other than yourself
T	Tampering with data	Integrity	Modifying something on disk, network, memory, or elsewhere
R	Repudiation	Non-repudiation	Claiming that you didn't do something or were not responsible; can be honest or false
I	Information disclosure	Confidentiality	Providing information to someone not authorized to access it
D	Denial of service	Availability	Exhausting resources needed to provide service
E	Elevation of privilege	Authorization	Allowing someone to do something they are not authorized to do



## 3. RELIABILITY



# Reliability



- **Questions to ask:**
  1. How reliable is the cell network?
  2. What if there is no mobile network available?
  3. What if sensor(s) fail?
  4. Should there be **redundancy** for everything?
  5. Is there a threshold that determines when the system is reliable (e.g. when two out of four sensors fail)?
- **Different levels that should be considered for reliability:**
  1. Firstly, the **diagnostic of the system** that might be subject to failures
  2. Then, the **system's sensors** that enable the system to sense its surrounding environment
  3. Lastly, the **data coming from external entities**, like other vehicles and road infrastructures for AV case



## 4. RESPONSIBILITY & ACCOUNTABILITY



# Responsibility & Accountability



- How will responsibility be defined in case of incidents and accidents?
- Should the **designer and/or manufacturer and/or operator be held responsible?**
- Responsible design to **strictly adhere to standards or beyond standard requirements**
- Responsible design of embedded AI systems to **prevent user abuse of Autonomous Systems** (e.g. drone attacks in Saudi Arabia)
- If the system is meant for weapon usage, responsible design to account for the **possibility of malfunction or rebellion** (e.g. Terminator, Matrix, I-Robot pop references)



# CHAPTER 4:

## UNDERSTANDING THE CONCEPT OF TECHNOLOGIES AND SYSTEM ARCHITECTURES THAT ARE INVOLVED IN AV & AR

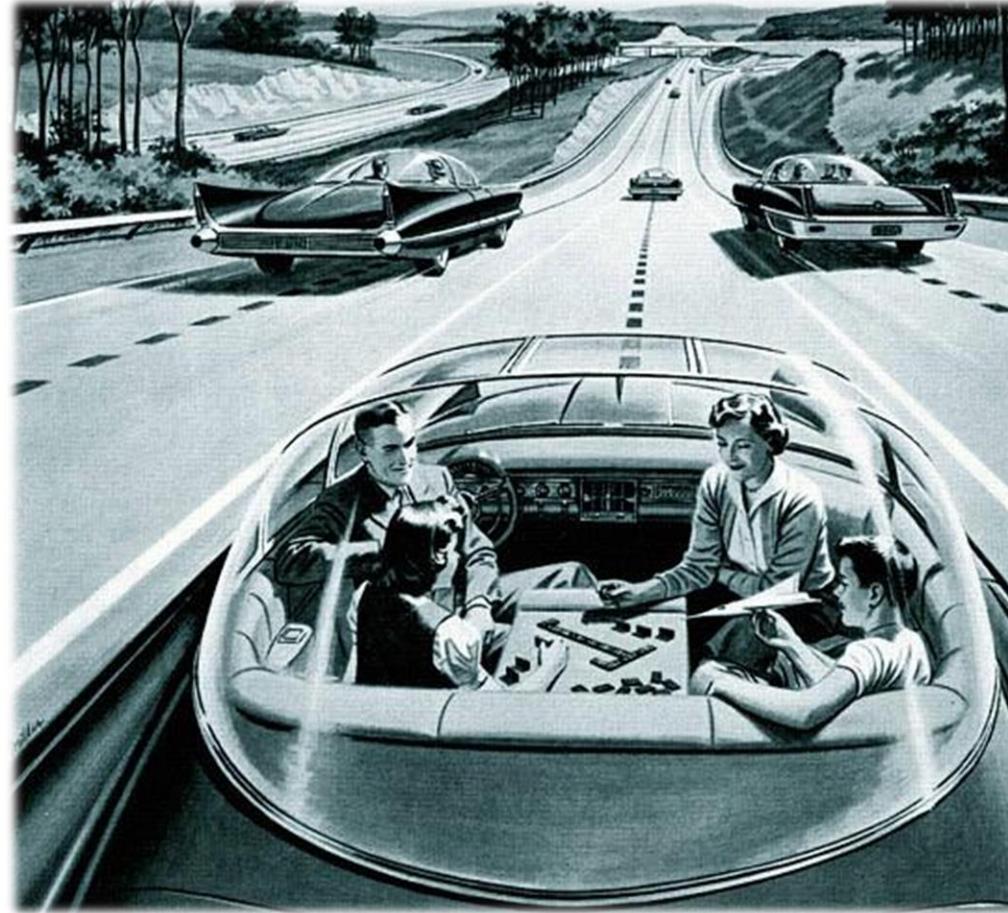




# 1. AUTONOMOUS VEHICLES



# Concept of AV arise in 1956



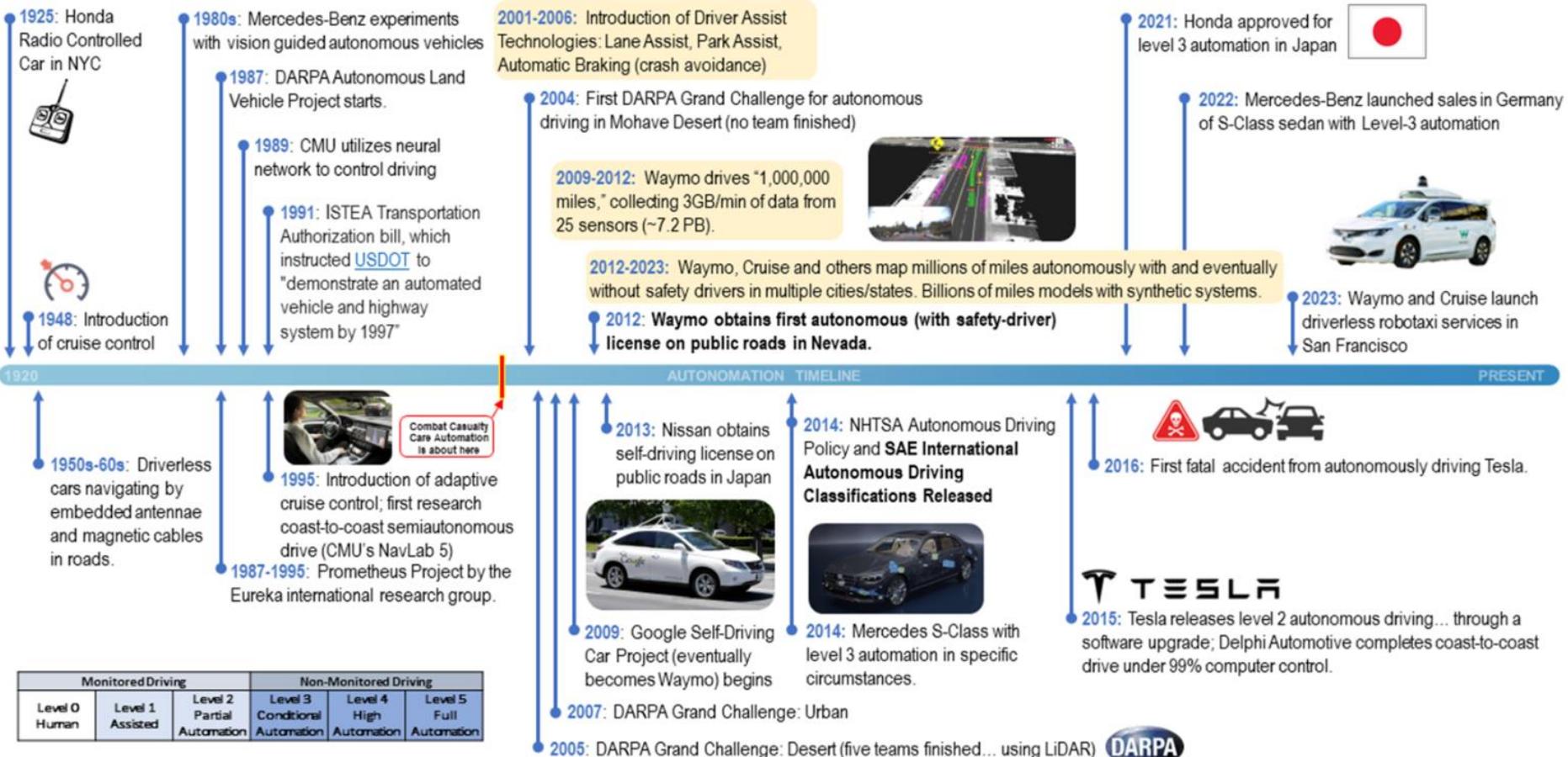
America's Power Companies' advertisement from 1956  
depicting a future with autonomous cars



# AV History



NUS  
National University  
of Singapore





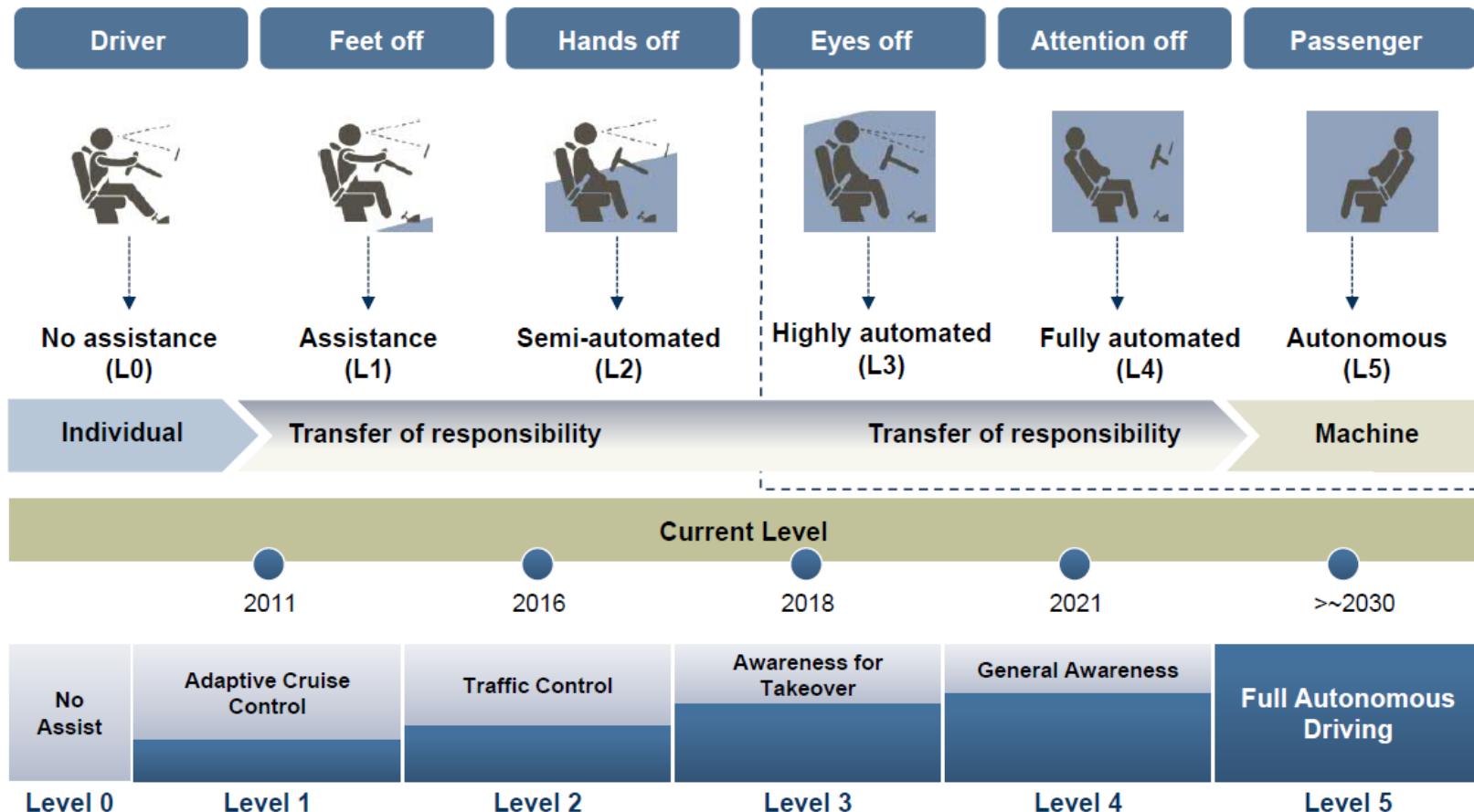
# Driverless Waymo rides



Source: <https://www.youtube.com/watch?v=x4jg4E7LrZE>



# The 5 Levels of Autonomous Driving



Source: BMW Group



# L5 Autonomous Driving Example:





# AV Technology – Are we there yet?

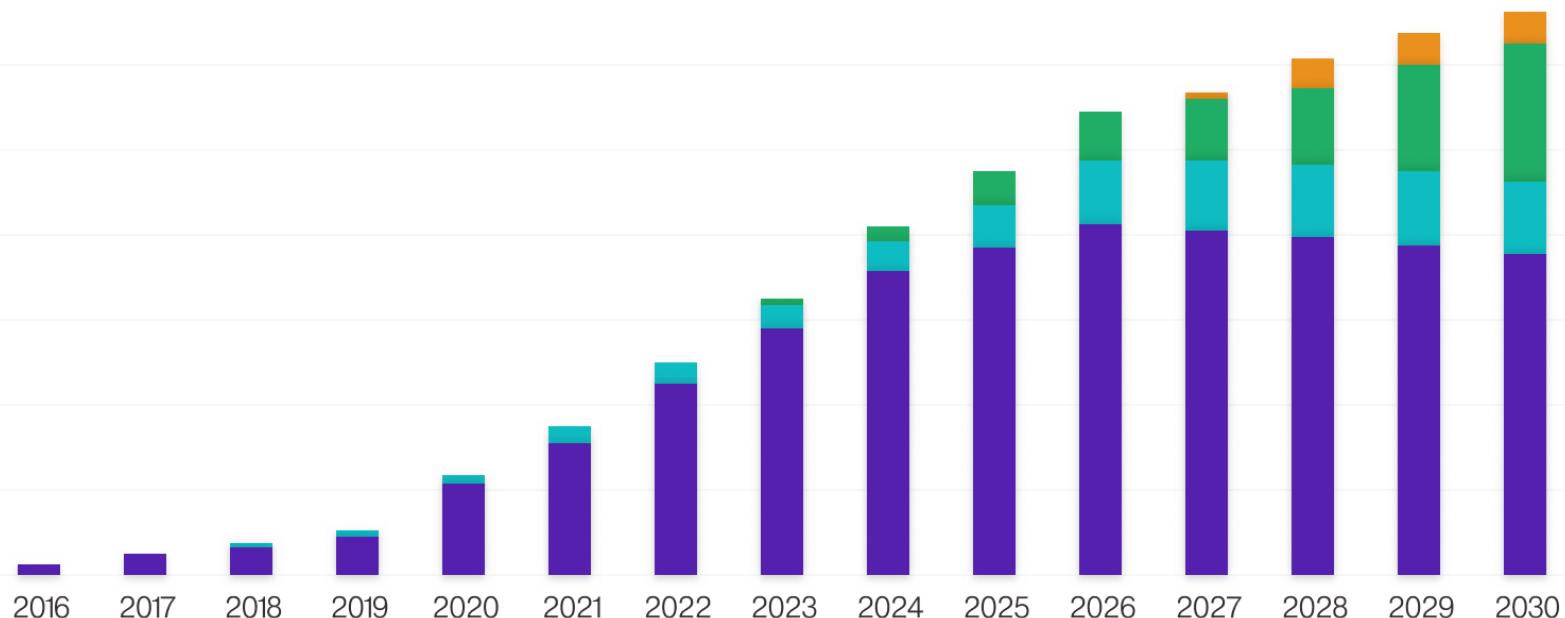


## AUTONOMOUS VEHICLE SHIPMENTS BY SAE LEVEL

itransition

Forecast: North America

■ Level 2 ■ Level 3 ■ Level 4 ■ Level 5

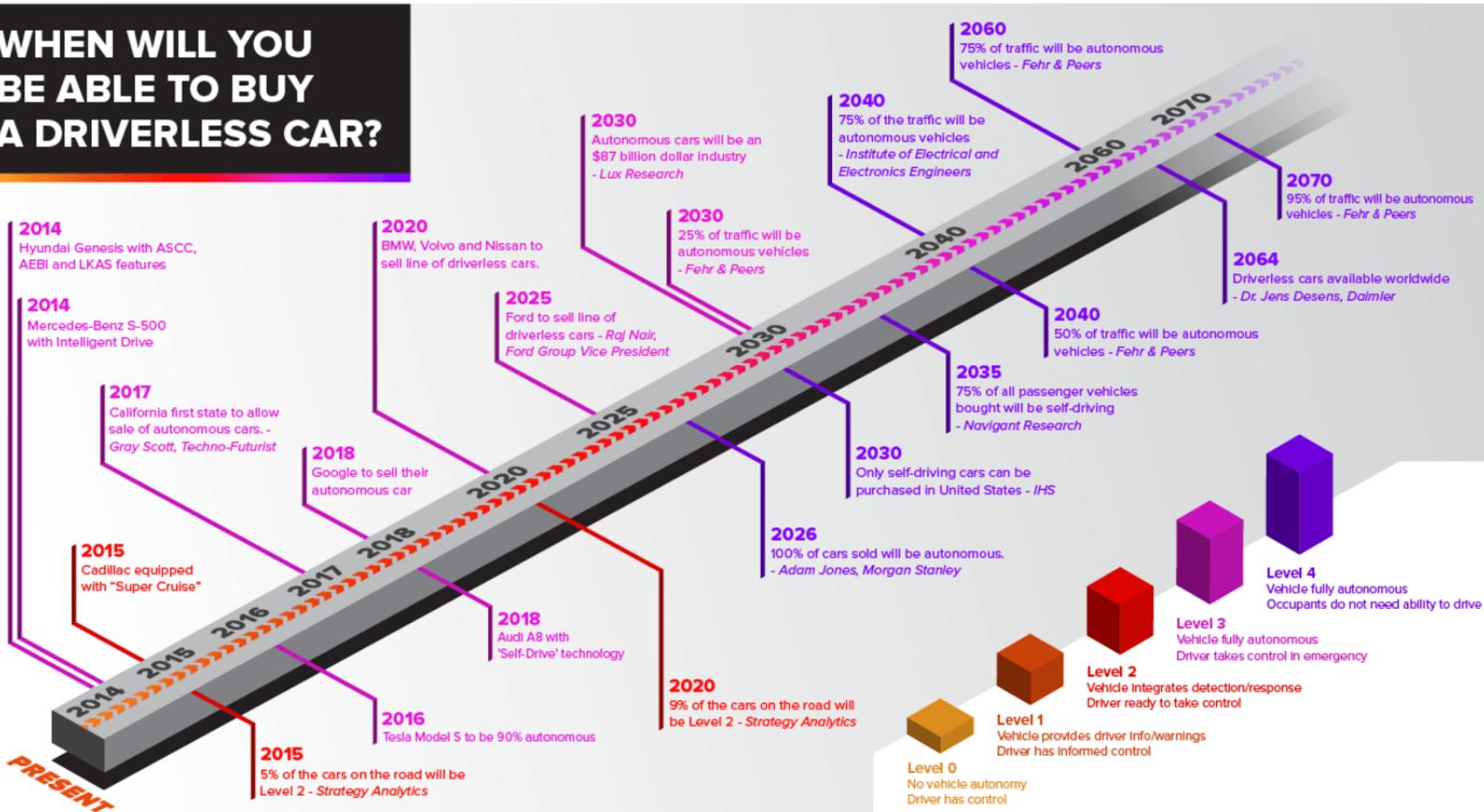




# AV Projected Timeline



## WHEN WILL YOU BE ABLE TO BUY A DRIVERLESS CAR?

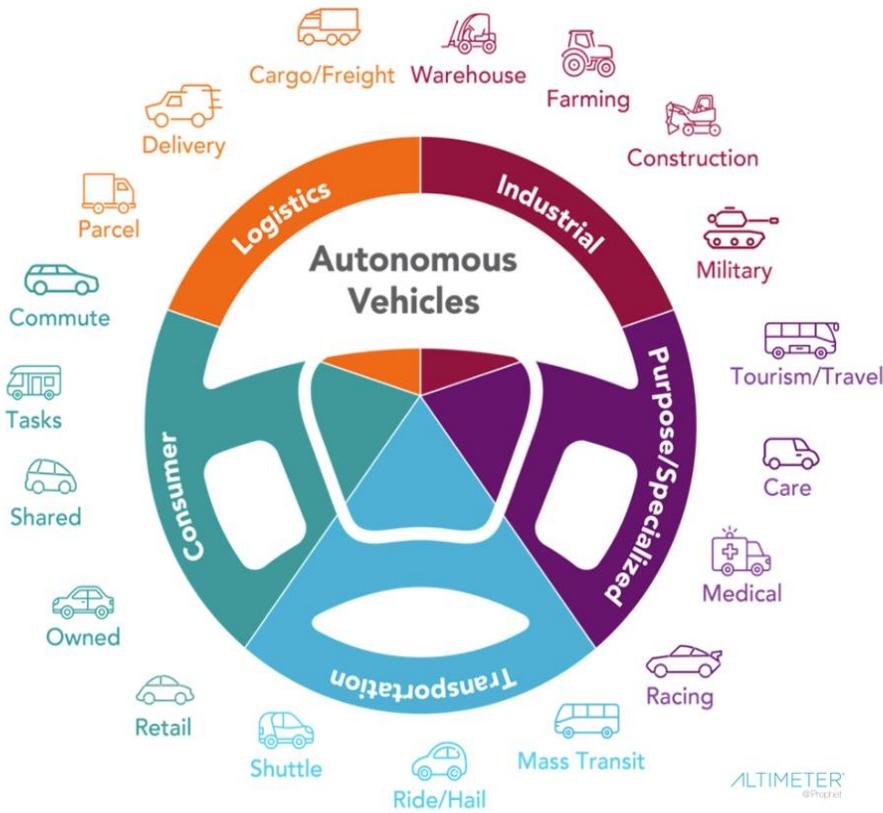


Sources: Mercedes-Benz, GM News, Strategy Analytics, Automotive News, Nissan News, Navigant Research, Volvo News, Fehr & Peers, Lux Research, IHS





# AV Applications



<https://venturebeat.com/2017/02/24/the-state-of-your-self-driving-car/>



# Potential Effects within various industries due to AV



## Automotive

- Less personally owned vehicles, more fleet vehicles
- Value shifts from asset ownership and driving

## Finance

- Growth in fleet financing
- Decrease in auto loans and leasing

## Insurance

- Experience-based insurance product
- Shift from human failure to technical failure

## Energy

- More miles driven, but more efficient
- Shift to alternative fuels



# Potential Effects within various industries due to AV



## Media

- Time freed from driving used for media consumption
- New advertising and subscription models

## Telecom

- Increased demand for connectivity and availability

## Technology

- Emergence of autonomous drive operating system players
- Rise of mobility management providers

## Retail

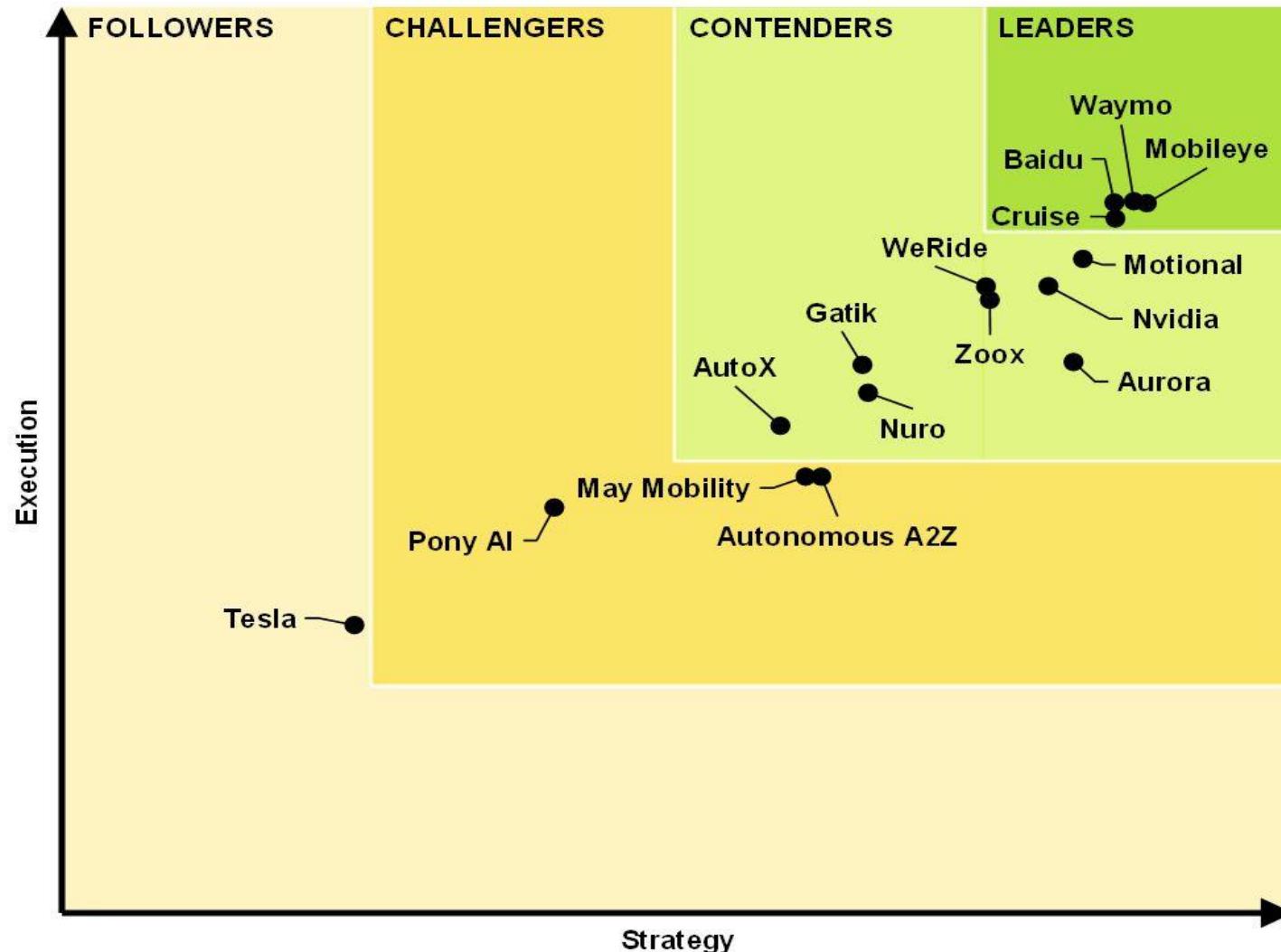
- Change retail landscape in response to city demographics shift
- Expands home delivery options

## Transportation

- Robotaxis substitute, taxis, limos and rental vehicles
- New business models for long-haul trucking and movement of goods



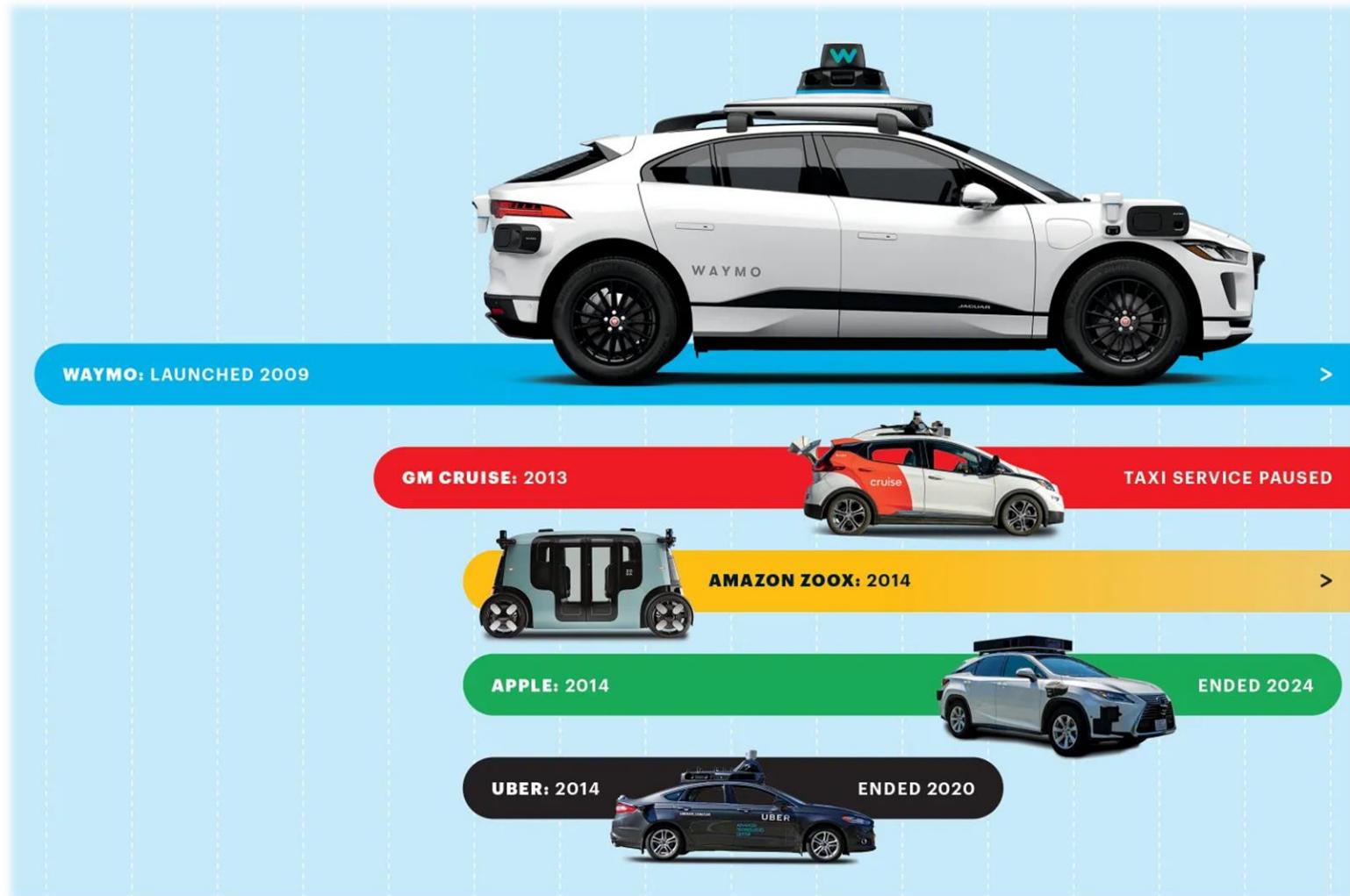
# Current AV Players



Source: <https://guidehouseinsights.com/reports/guidehouse-insights-leaderboard-automated-driving-systems>



# Current AV Players



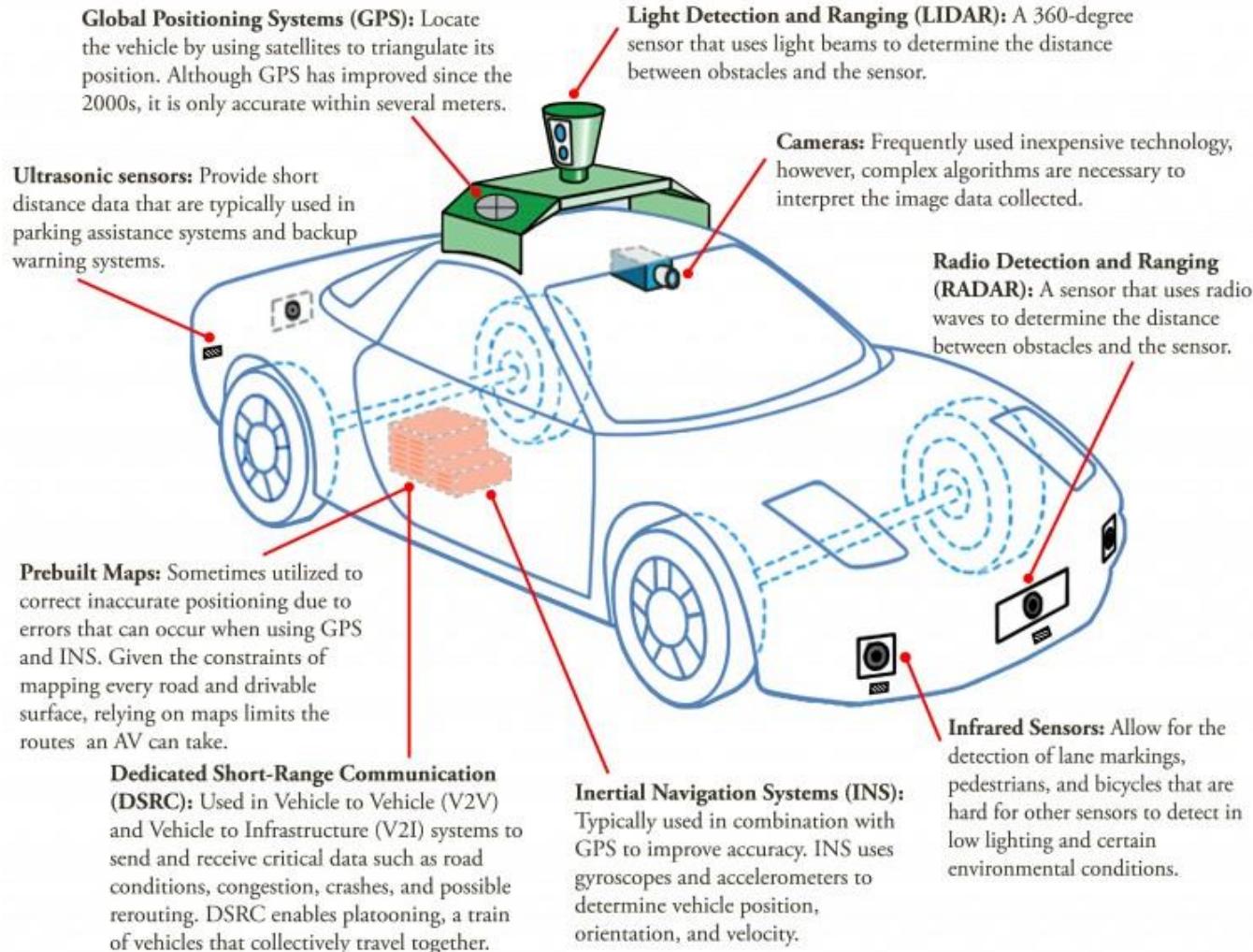
Source: <https://fortune.com/2024/05/29/waymo-self-driving-robo-taxi-uber-tesla-alphabet/>



# AV Technologies

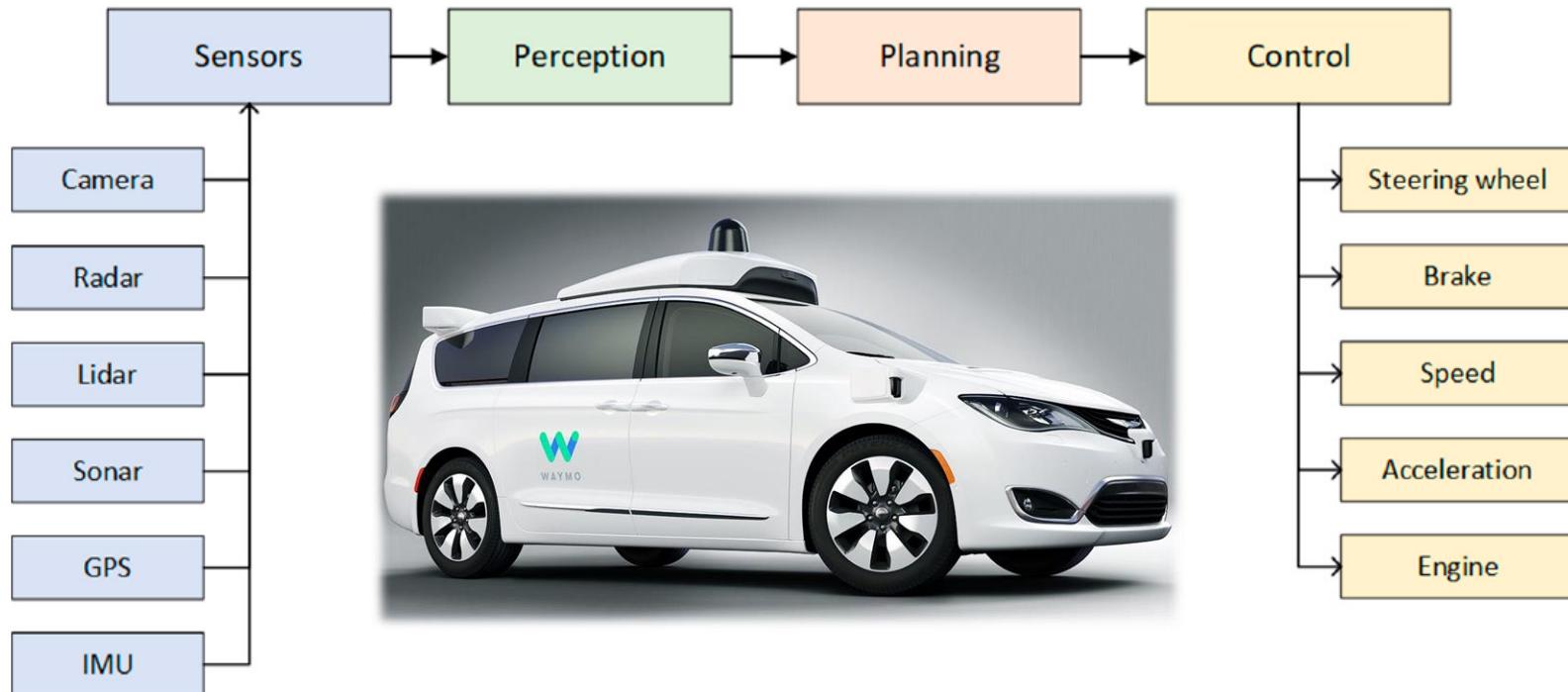


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National University  
of Singapore



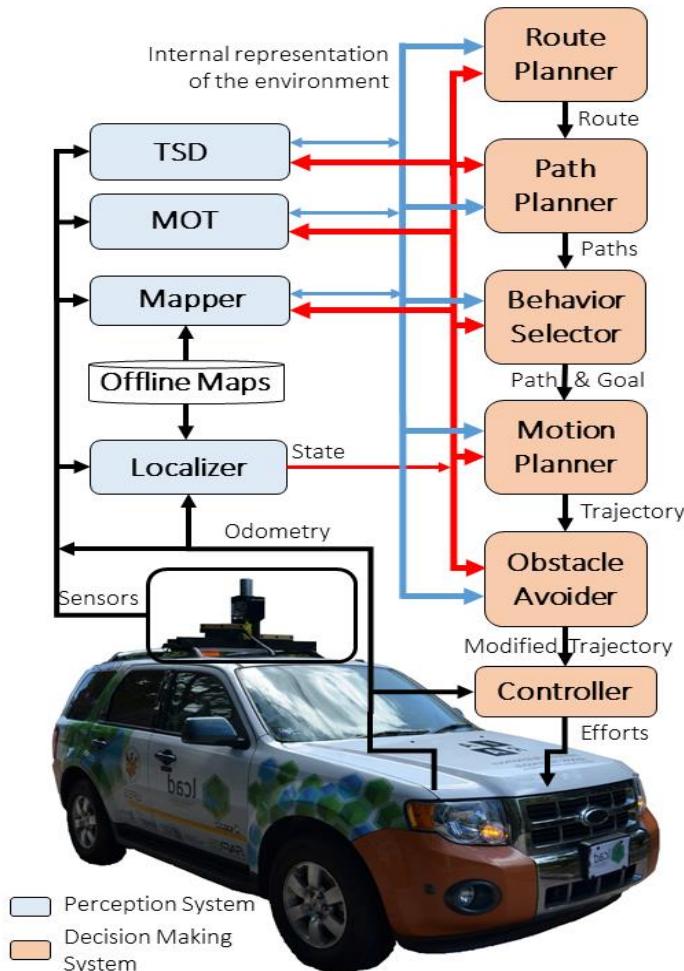


# AV System Block Diagram



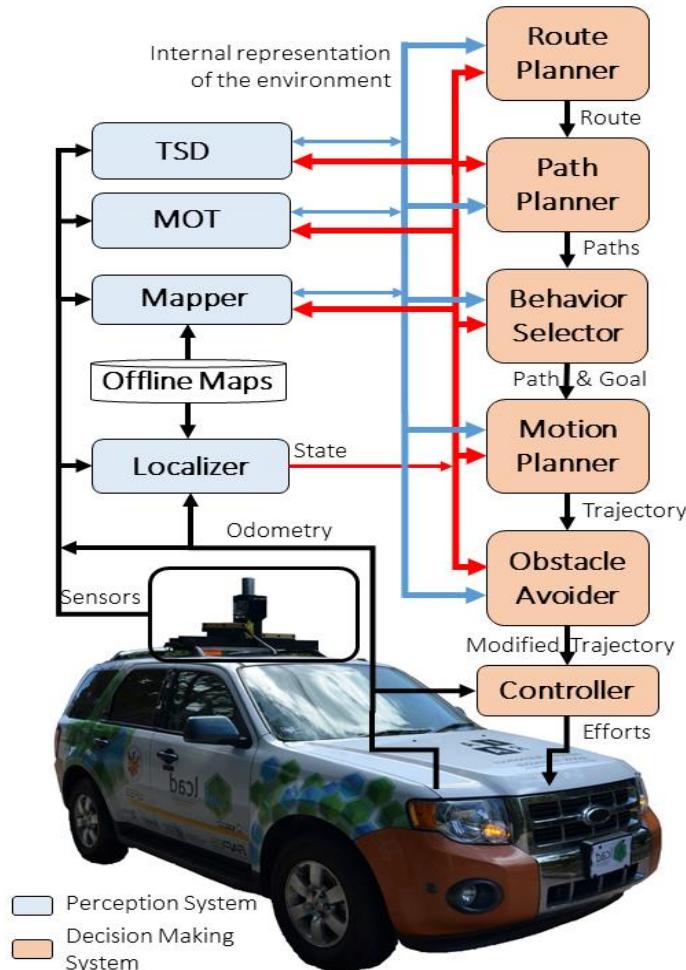


# Typical Architecture of Self-Driving Cars



- **Mainly Perception & Decision-Making Systems**
- **Perception system** is responsible for:
  - **Estimating the State of the car**
  - **Creating an internal (to the self-driving system) representation of the environment,**
  - **Using data captured by on-board sensors**
    - ❖ E.g. Light Detection and Ranging (LIDAR), Radio Detection and Ranging (RADAR), camera, Global Positioning System (GPS), Inertial Measurement Unit (IMU), odometer
- **And prior information about the sensors' models, road network, traffic rules, car dynamics**

# Typical Architecture of Self-Driving Cars



- **Decision-Making system** is responsible for **navigating the car from its initial position to the final goal defined by the user**,
- The current car's State and the internal representation of the environment, as well as traffic rules and passengers' safety and comfort are considered during this process
- This system needs to know where the car is in which location within the environment → State Data from Localizer



# Singapore's Progress: Autonomous Vehicles





# Singapore's Progress: Autonomous Vehicles



Venti Technologies'  
AVs @ Singapore's  
Air/Sea ports





# Singapore's Progress: CETRAN



## Singapore's first Autonomous Vehicle Test Centre





# Singapore's Progress: Autonomous Road Sweepers

Driverless road sweepers put to test again, targeted for Marina coastal area by end-2024



The driverless road sweepers can operate round-the-clock while being monitored remotely by an operator, to enhance safety. ST PHOTOS: NG SOR LUAN

<https://www.straitstimes.com/singapore/autonomous-road-sweepers-put-to-test-again-targeted-for-marina-coastal-area-by-end-2024>



# Singapore's Progress: Singapore a potential hub for AV production



## Hyundai, Motional to Build Self-Driving Taxis in Singapore

The autonomous vehicles will be built at the Hyundai Motor Group Innovation Center Singapore and deployed in the U.S. next year



Graham Hope

November 22, 2023

⌚ 3 Min Read



MOTIONAL



<https://www.iotworldtoday.com/transportation-logistics/hyundai-motional-to-build-self-driving-taxis-in-singapore#close-modal>



# Singapore's Progress: WeRide AVs awarded Level 1 License



## WeRide gets Singapore M1 & T1 autonomous vehicle licenses



Kavipriya · December 12, 2023 · 2 minutes read



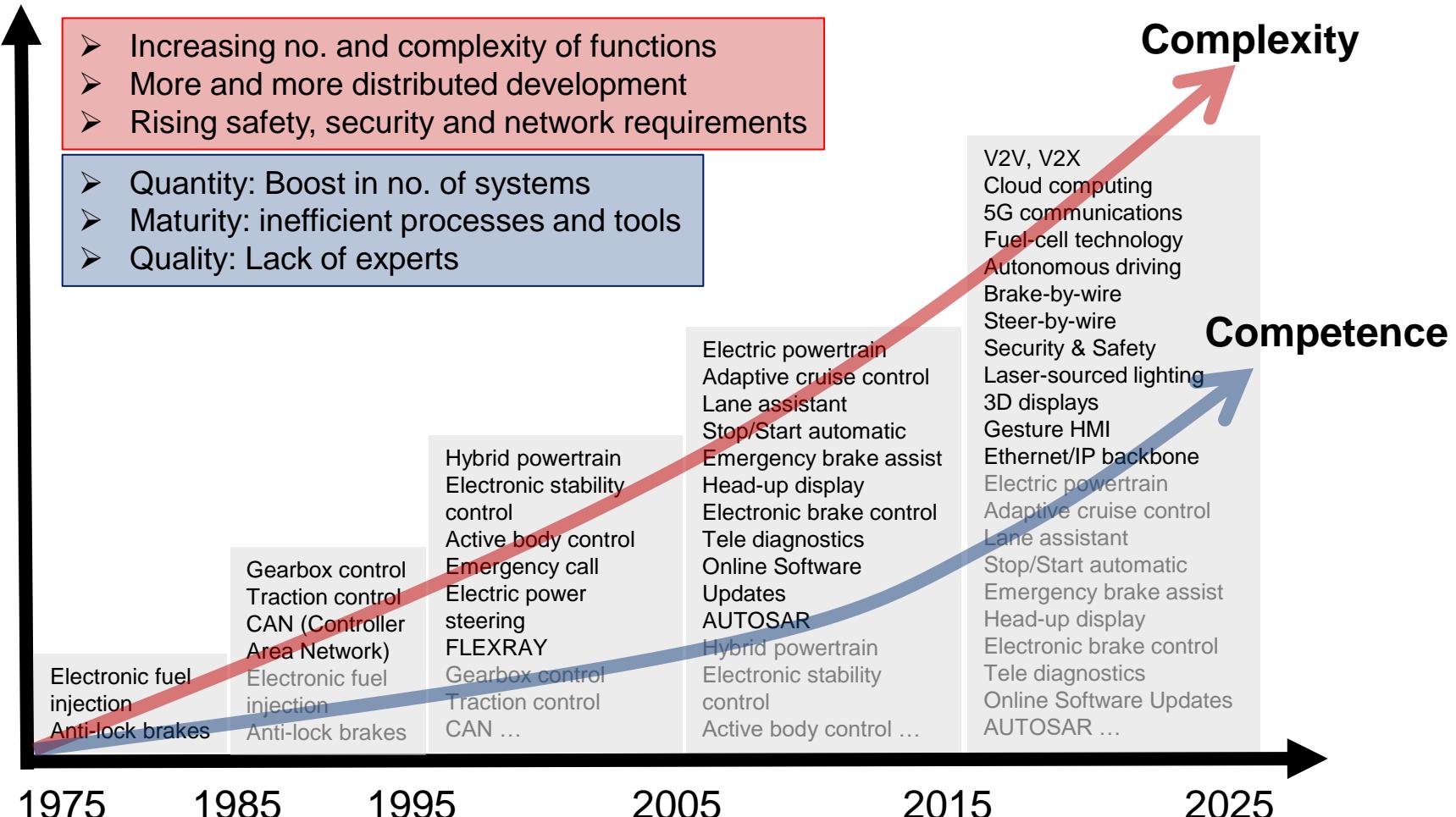
WeRide achieves Singapore M1&T1 autonomous vehicle licenses, Photo Source: Press Release, WeRide

<https://www.telematicswire.net/we-ride-gets-singapore-m1-t1-autonomous-vehicle-licenses/>

Singapore, 11th Dec, 2023 — [WeRide](#) has announced that it has obtained the Milestone Testing Regime Level 1 License for Autonomous Vehicles (AV) on Public Roads (referred to as "M1 License") and the T1 Assessment License for AVs on Public Paths (referred to as "T1 License") from the Land Transport Authority (LTA) of Singapore. **With these licenses, WeRide's Robobus will be able to conduct tests on a larger scale on public roads in Singapore.** This includes covering important areas such as One North and the National University of Singapore.



# Exploding complexity of AVs





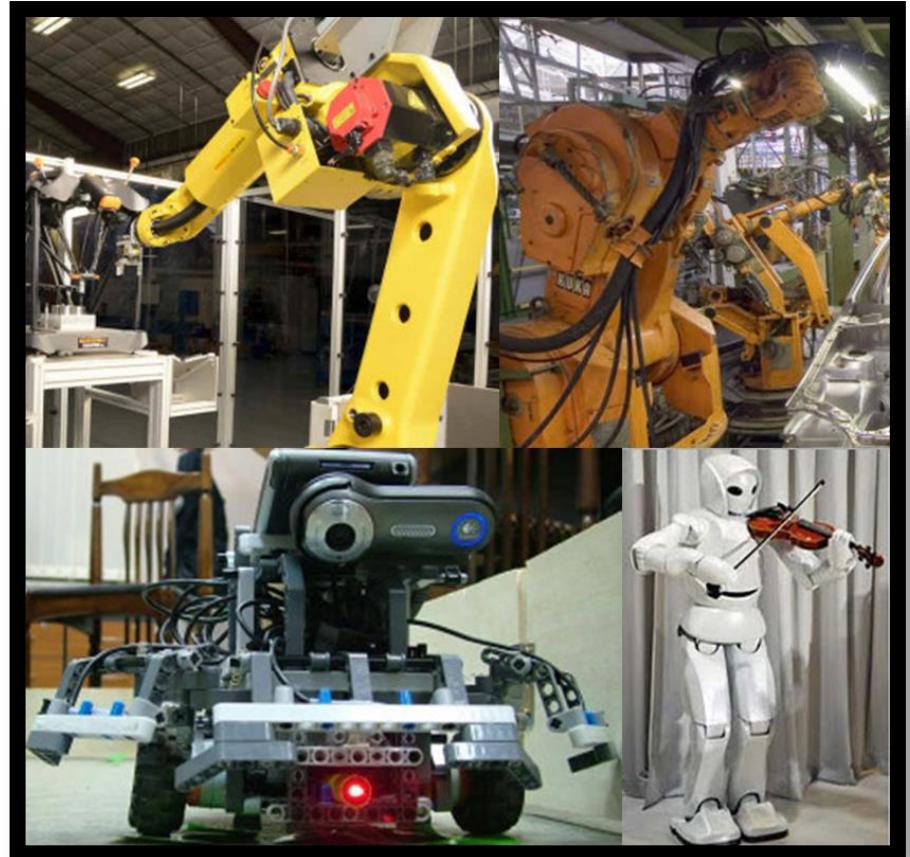
## 2. AUTONOMOUS ROBOTS



# Types of Autonomous Robots



- 1. Non-programmable**
- 2. Programmable**
- 3. Adaptive**
- 4. Intelligent**





# Types of Autonomous Robots

## 1. Non-programmable AR

- Basic type of robot
- An exploiter lacking reprogrammable controlling device
- Non-versatile; unable to change function and application
- Mostly used in industries for mass production purposes
- E.g. Industrial automation systems, toy robots, early-gen vacuum cleaner robots



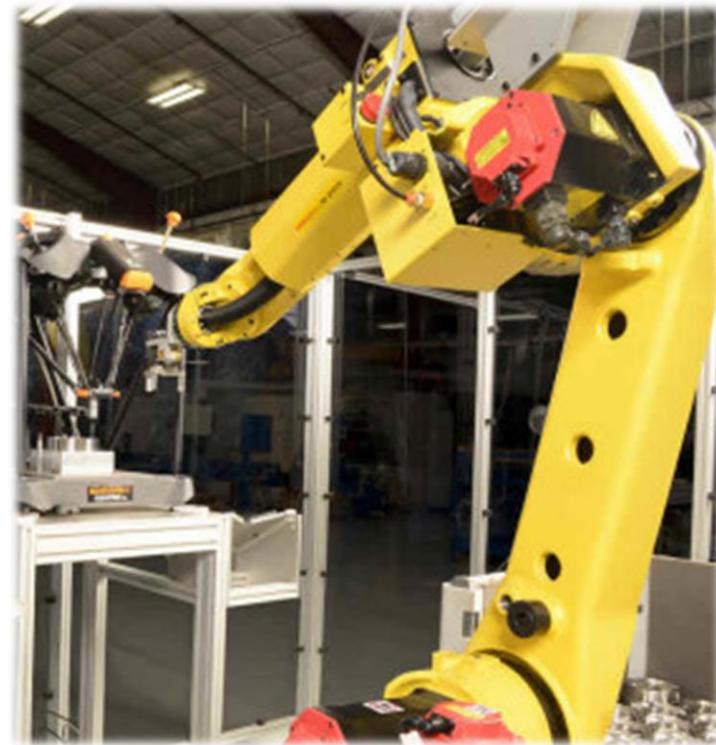


# Types of Autonomous Robots



## 2. Programmable AR

- Reprogrammable and versatile
- Function and application can be changed
- Perform function in the given pattern and fixed sequence
- Drawback: Once programmed it persists operation even if there is a need to change its task (e.g. in the event of emergency)
- E.g. Industrial robotic arms, LEGO Mindstorms, CNC machines



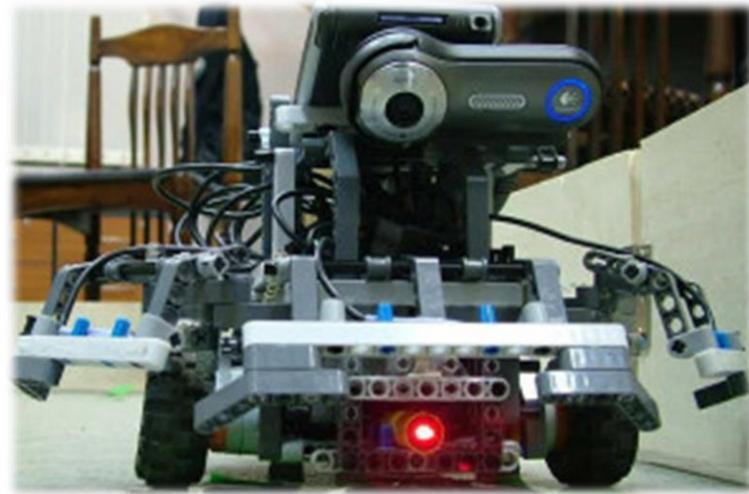


# Types of Autonomous Robots



## 3. Adaptive AR

- Can be adapted independently to various environments
- More sophisticated than programmable robots
- Can be adapted up to a certain extent
- Utilize sensors and control systems
- E.g. Advanced vacuum cleaner robots (Roomba, Xiaomi), warehouse robots (Amazon robots)





# Types of Autonomous Robots



## 4. Intelligent AR

- Most intelligent out of all
- Utilize sensors and microprocessors
- Utilize AI algorithms (e.g. Knowledge reasoning, planning, deep learning, machine vision)
- Highly efficient because of their situation-based analyzing and task performing abilities
- E.g. AVs, robotic surgeons, search & rescue drones, customer service robots





# AR Technologies

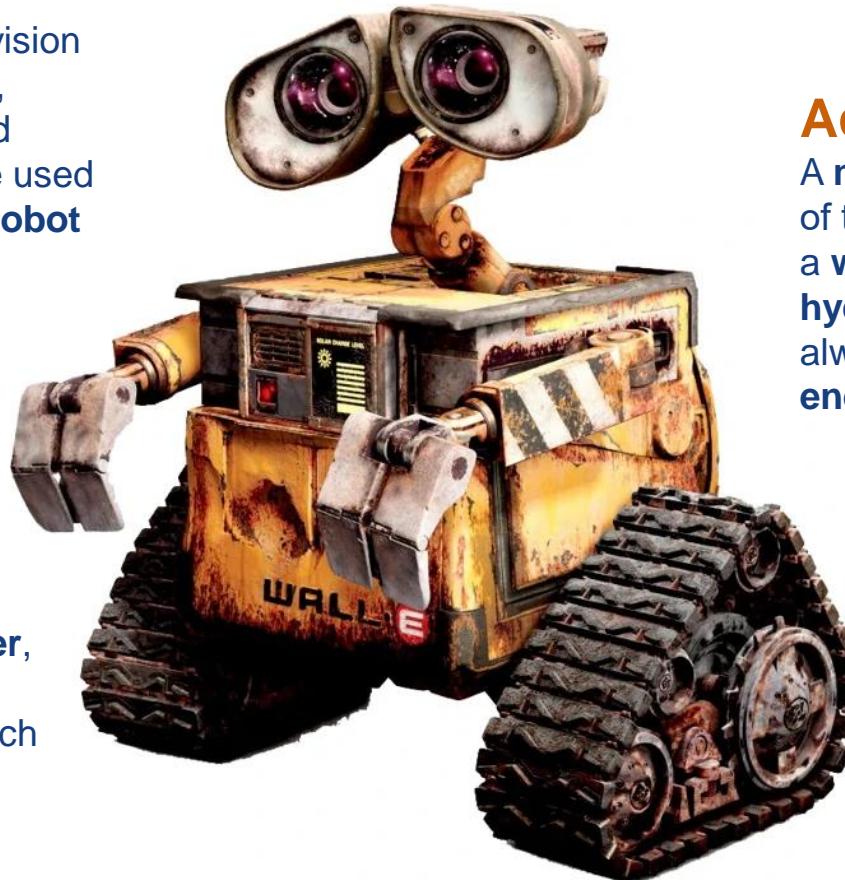


## Perception

Laser scanners, stereo vision cameras, bump sensors, force-torque sensors and spectrometers can all be used as **input devices for a robot**

## Decision

In addition to a **computer**, the robot utilizes an **embedded system**, which operates faster and with higher authority than the computer

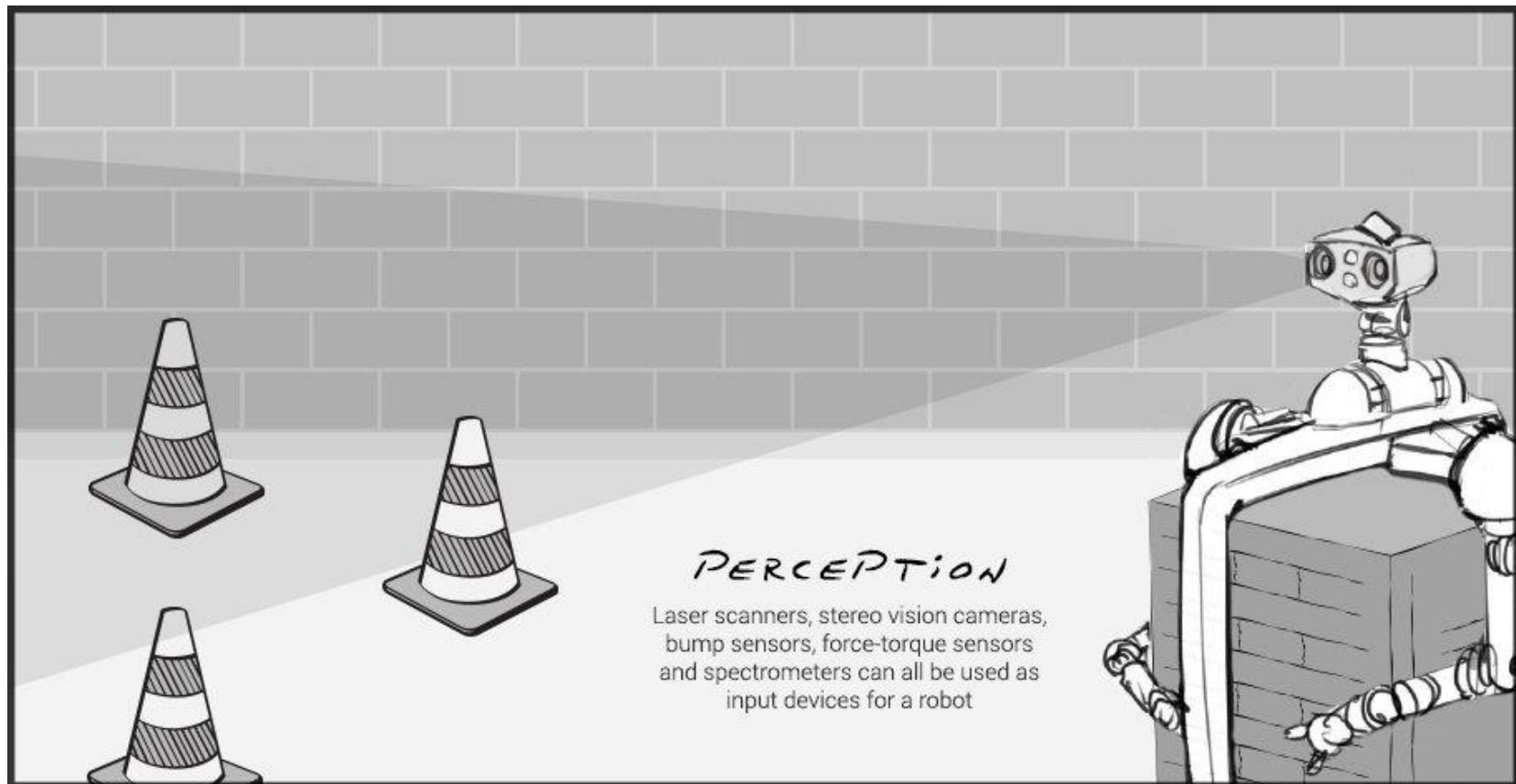


## Actuation

A **motor** is usually the heart of the actuator. Whether it's a **wheel, linear actuator or hydraulic ram**, there's always a motor **converting energy into movement**

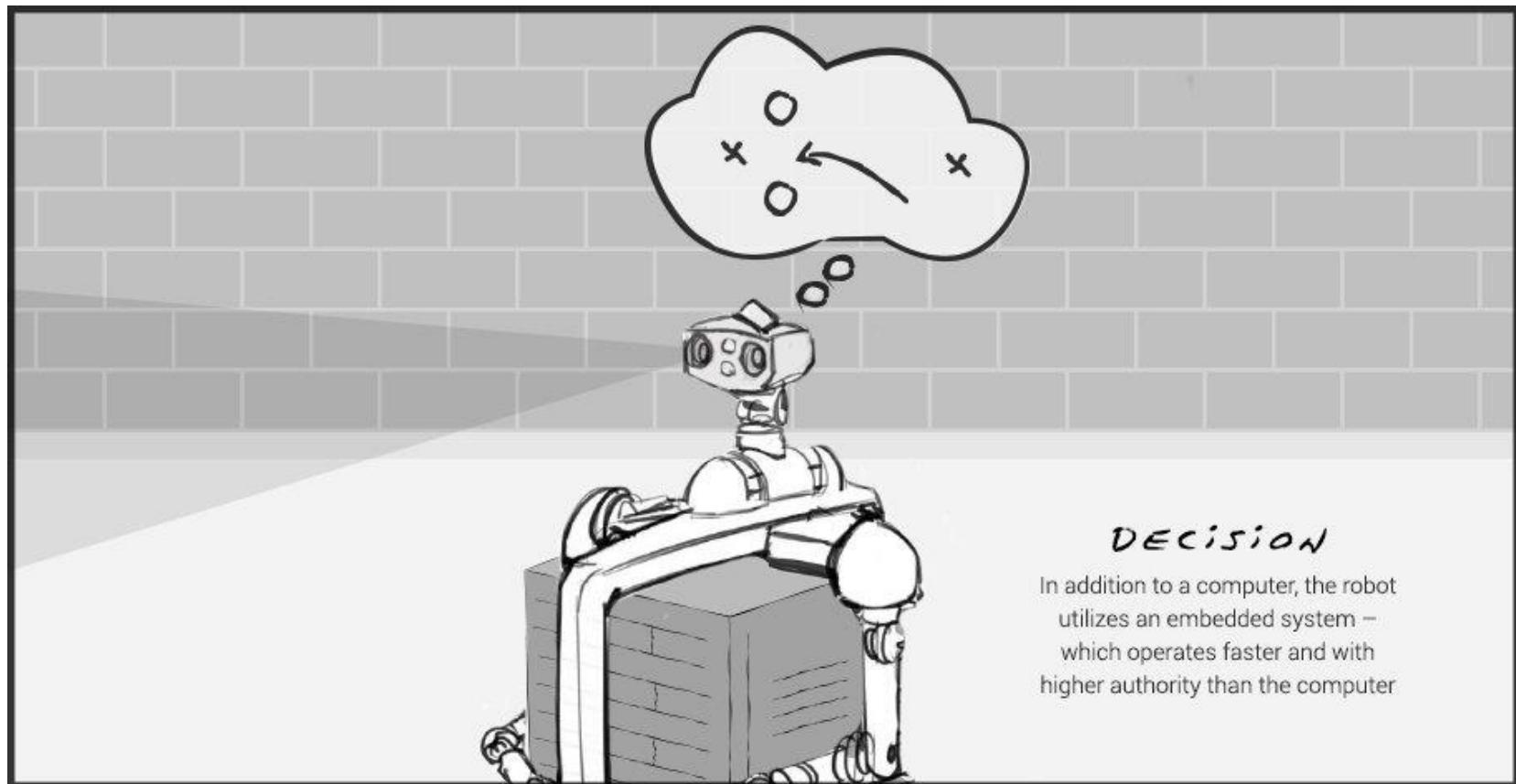


# Robotic Perception



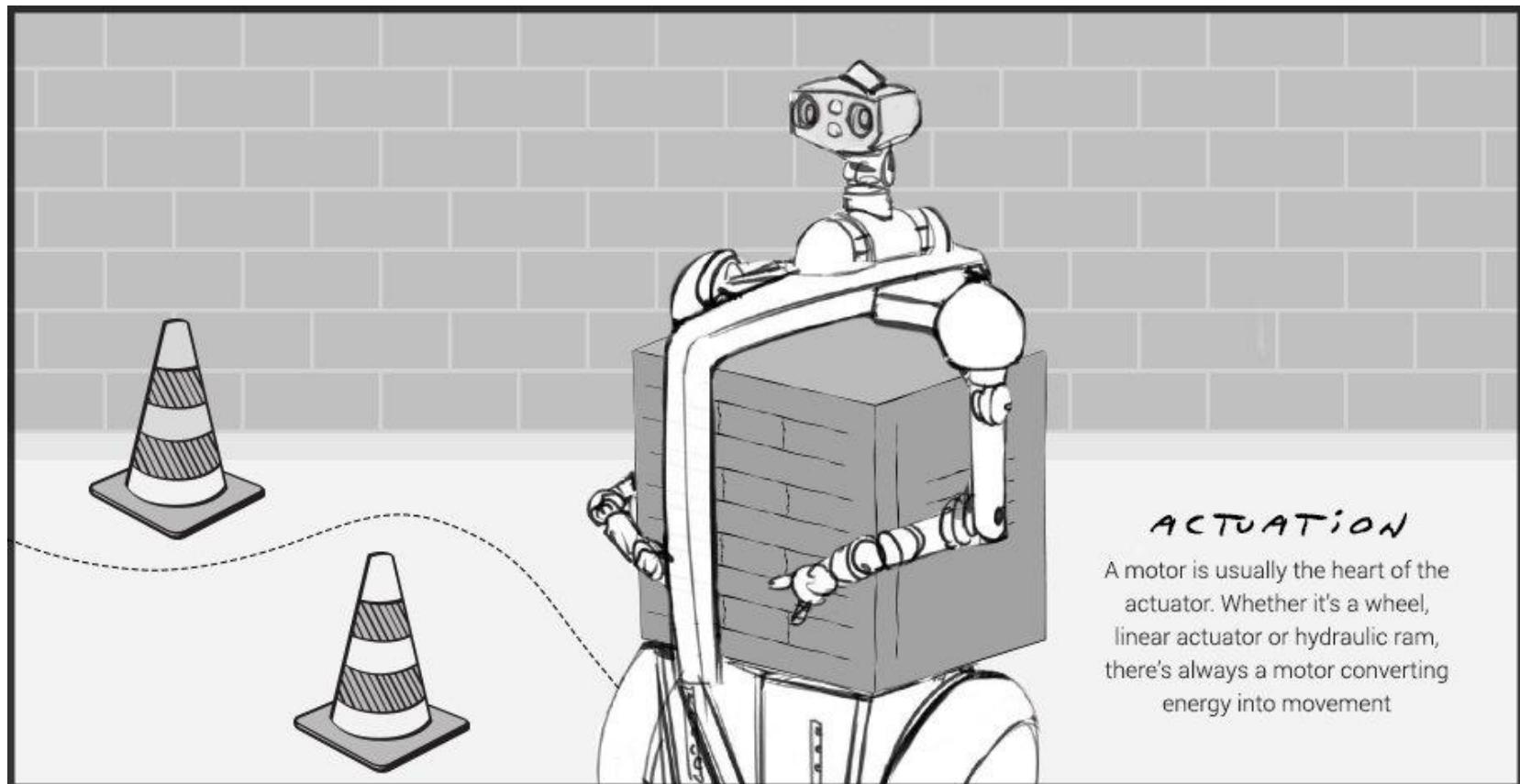


# Robotic Decision



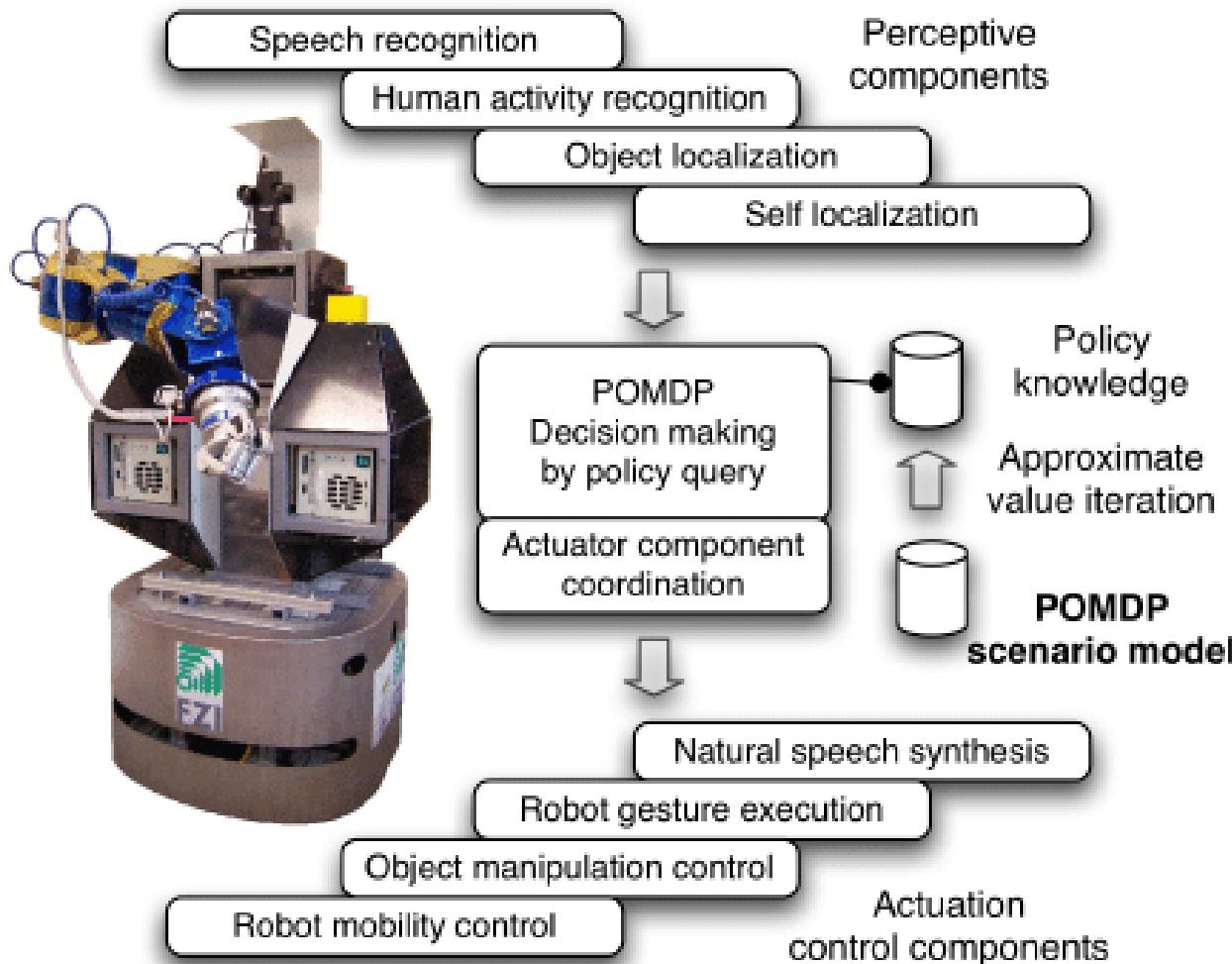


# Robotic Actuation





# Typical Architecture of Autonomous Robots





# Autonomous Robots Applications





# RoboCup Competition (2019):



Source: [https://youtu.be/\\_PC-V5GJP6Q](https://youtu.be/_PC-V5GJP6Q)



# DeepMind's recent “Learning Agile Soccer Skills for a Bipedal Robot with Deep Reinforcement Learning” project (2023):



Source: <https://www.youtube.com/watch?v=xm-juw7r8cQ>



# **WORKSHOP: DEVELOP BASIC** **AUTONOMOUS ROBOT ARM**



# 1. INTRODUCTION TO ROS, TURTLEBOT3 & OPEN MANIPULATOR-X

**For Non-MTech students, we will now switch to the supplementary materials on “Introduction to ROS”**



# Download & Install Autonomous ROS Package



## Steps:

1. Change to the source space directory of the catkin workspace:

```
$ cd ~/catkin_ws/src
```

2. Git Clone the Autonomous package:

```
$ git clone  
https://github.com/nicholashojunhui/autonomous.git
```

3. Build the packages in the catkin workspace:

```
$ cd ~/catkin_ws && catkin_make
```

4. Go to *catkin\_ws/src/autonomous/src* and make all python files executable



# Creating a new ROS Package (Optional)



## Steps:

1. Change to the source space directory of the catkin workspace:

```
$ cd ~/catkin_ws/src
```

2. Use the catkin\_create\_pkg script to create a new package called '**new\_package**' which depends on std\_msgs, roscpp, and rospy:

```
$ catkin_create_pkg new_package std_msgs rospy roscpp
```

3. Build the packages in the catkin workspace:

```
$ cd ~/catkin_ws
```

```
$ catkin_make
```

4. Add the workspace to your ROS environment by sourcing the generated setup file:

```
$ . ~/catkin_ws/devel/setup.bash
```



# Roslaunch vs Rosrun

## RECAP

- **Rosrun** is a command that runs only one node in the specified package

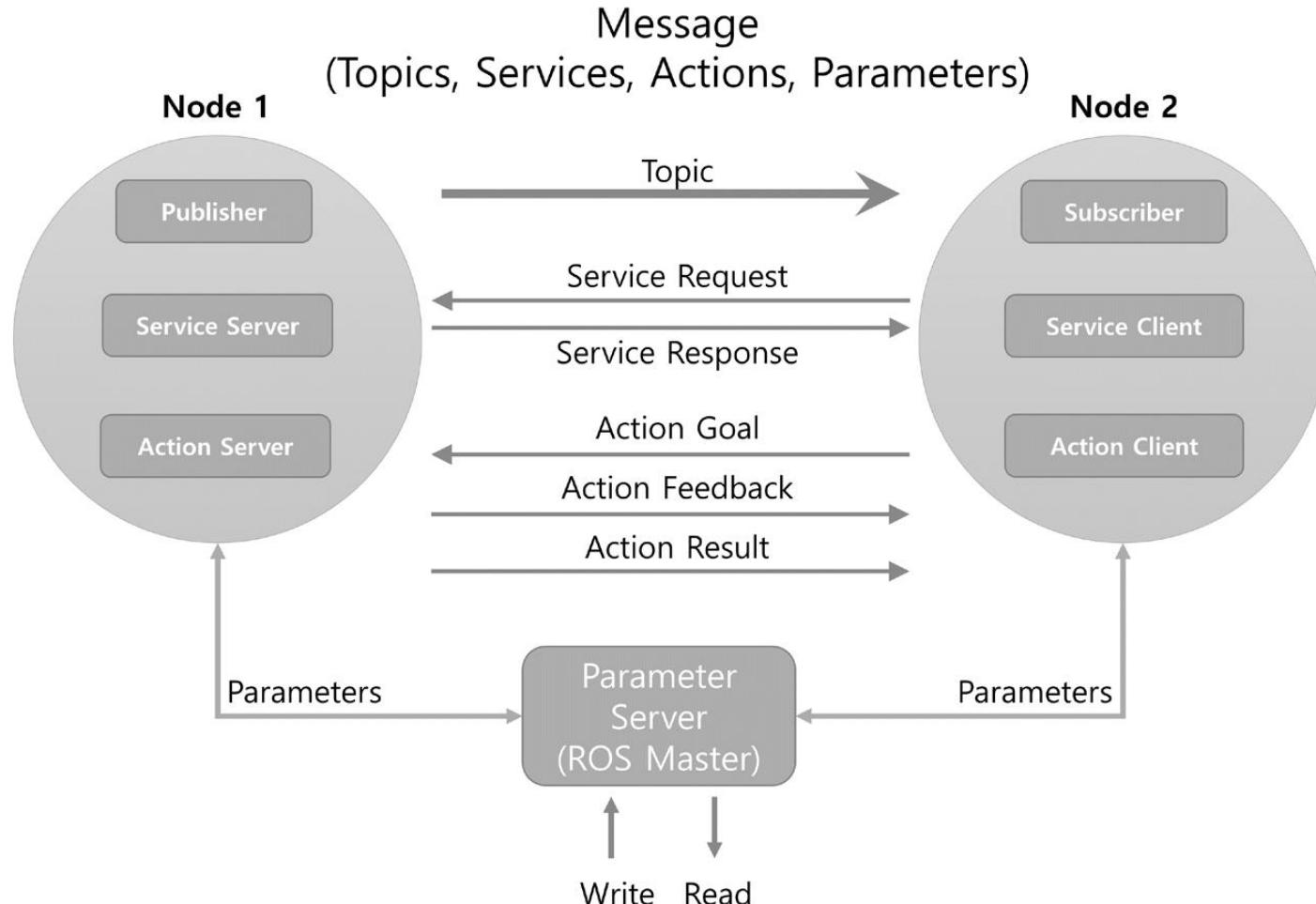
```
rosrun [PACKAGE_NAME] [NODE_NAME]
```

- **Roslaunch** is a command that executes more than one node in the specified package or sets execution options

```
roslaunch [PACKAGE_NAME] [launch_FILE_NAME]
```

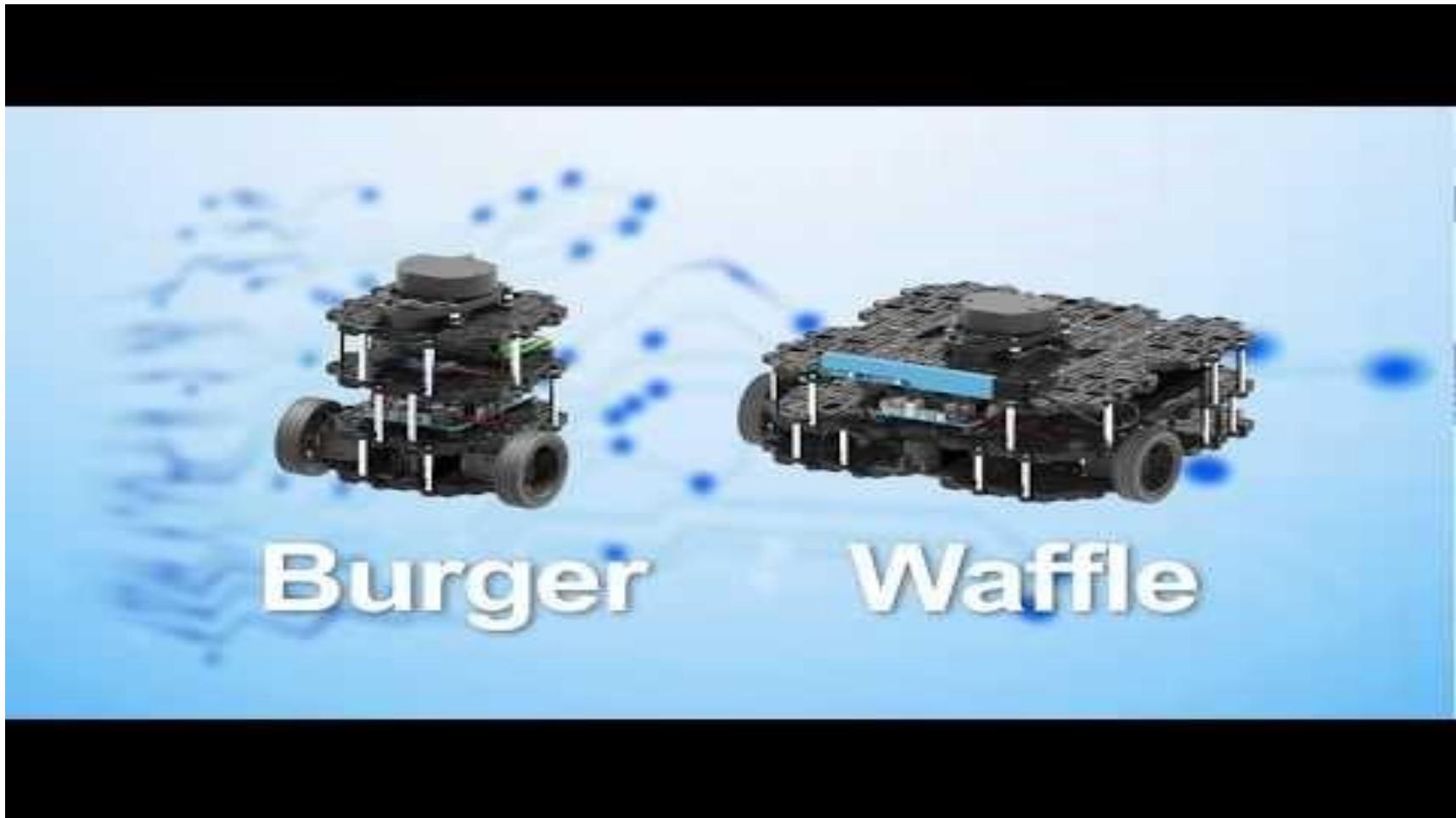


# ROS Communication Block Diagram RECAP:





# Introducing TurtleBot3



Source: <https://youtu.be/9OC3J53RUsk>



# Introducing TurtleBot3



- A **ROS standard platform robot**
- Adopts ROBOTIS smart actuator Dynamixel for driving
- **Small, affordable, programmable** mobile robot
- Evolved with cost-effective and small-sized Single Board Computer (SBC) that is suitable for robust embedded system, 360 degree distance sensor and 3D printing technology
- Core technology is **SLAM** (simultaneous localization and mapping), **Navigation and Manipulation**
- Able to configure **high levels of autonomy**



# Introducing TurtleBot3



## WORLD'S MOST POPULAR ROS PLATFORM



TurtleBot is the world's most popular open source robot for education and research.

## AFFORDABLE COST



TurtleBot is the most affordable platform for educations and prototype research & developments.

## SMALL SIZE



Imagine the TurtleBot in your backpack and bring it anywhere.

## EXTENSIBILITY



Extend ideas beyond imagination with various SBC, sensor, motor and flexible structure.



## MODULAR ACTUATOR

Easy to assemble, maintain, replace and reconfigure.



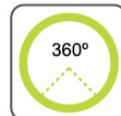
## OPEN SOURCE SOFTWARE

Variety of open source software for the user. You can modify downloaded source code and share it with your friends.



## OPEN SOURCE HARDWARE

Schematics, PCB Gerber, BOM and 3D CAD data are fully opened to the user.



## STRONG SENSOR LINEUPS

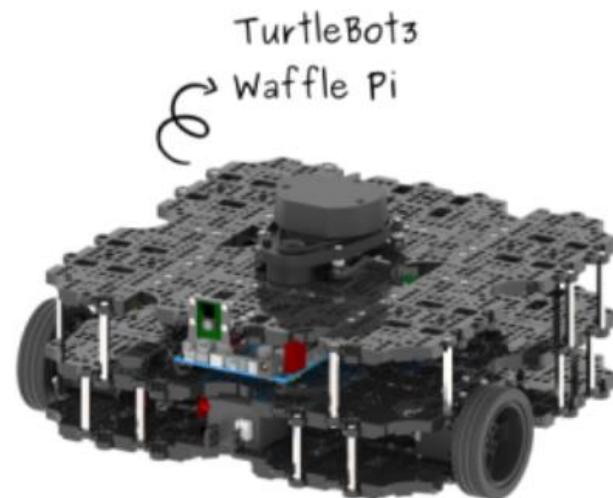
8MP Camera, Enhanced 360° LiDAR, 9-Axis Inertial Measurement Unit and precise encoder for your robot.



# TurtleBot3 Variations



## TURTLEBOT<sup>3</sup>

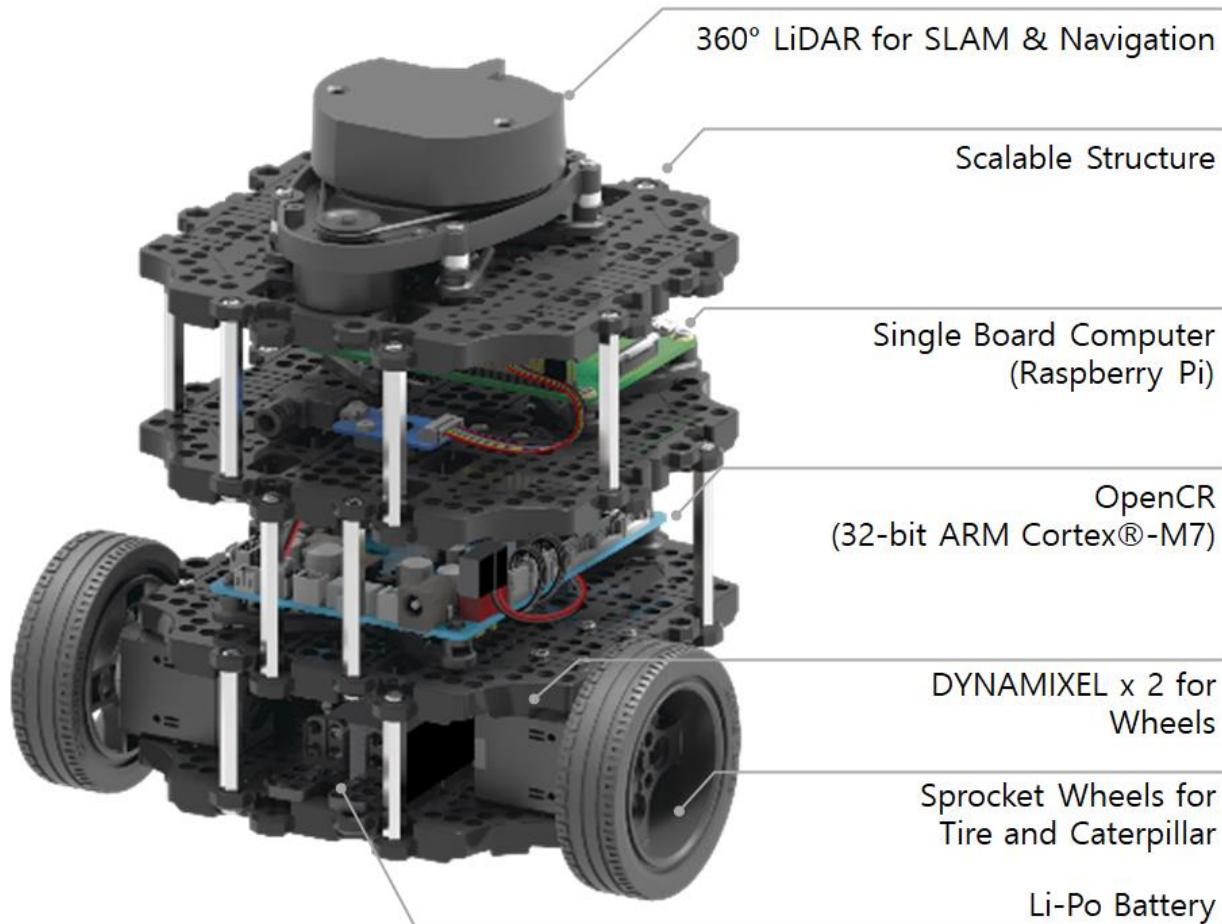




# TurtleBot3 Burger



## TurtleBot3 Burger

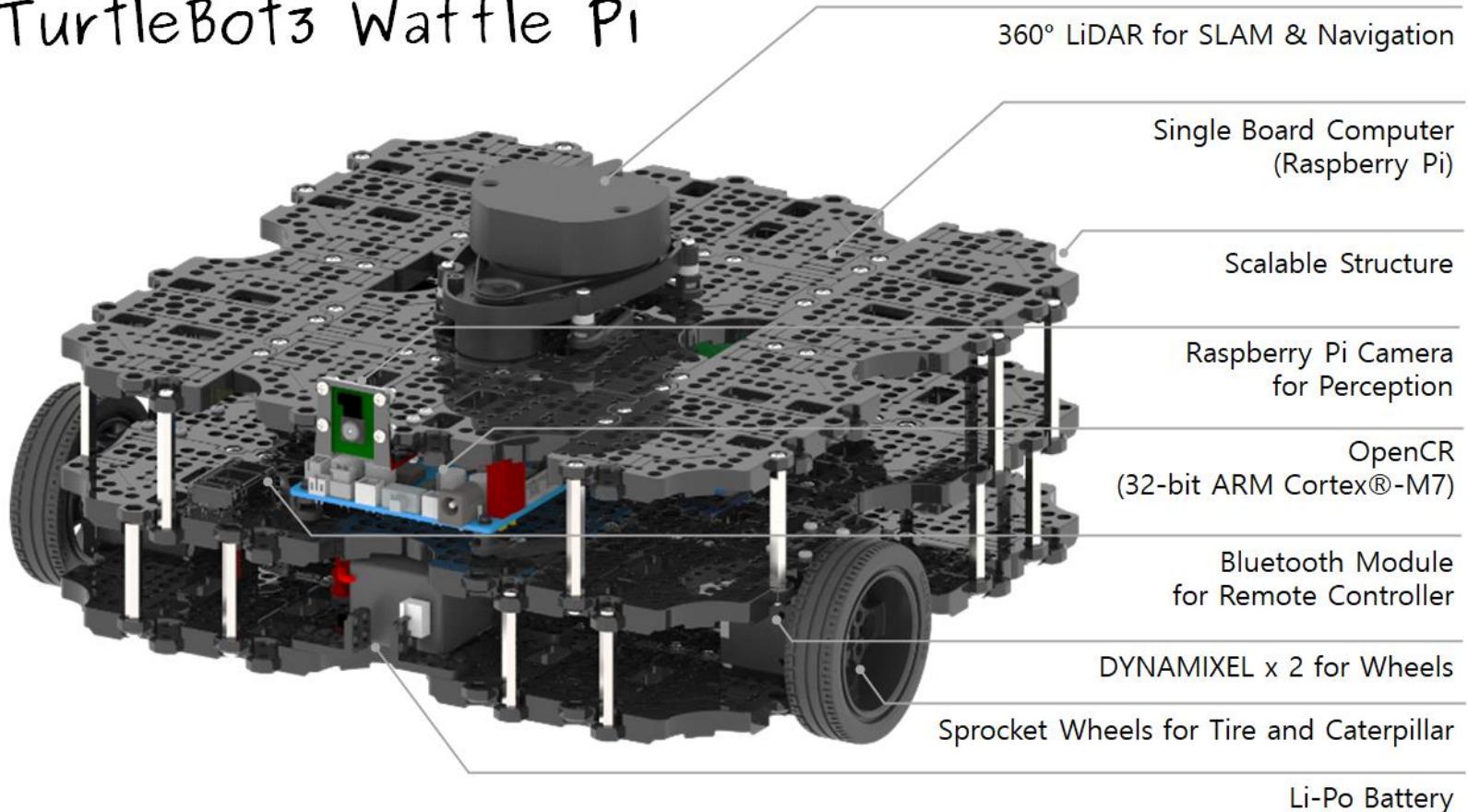




# TurtleBot3 Waffle Pi

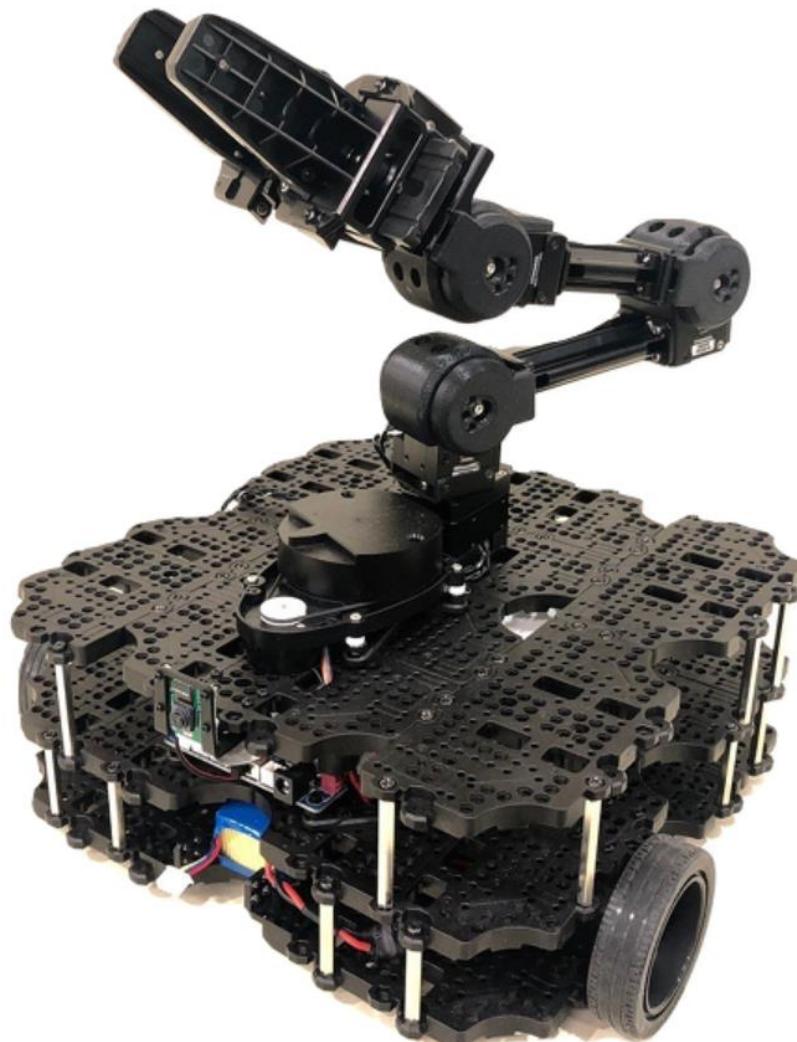


TurtleBot3 Waffle Pi





# TurtleBot3 with OpenManipulator-X





# TurtleBot3 with OpenManipulator-X



## TURTLEBOT3

TurtleBot3  
Burger



TurtleBot3  
Waffle Pi



Source: <https://youtu.be/P82pZsqpBg0>

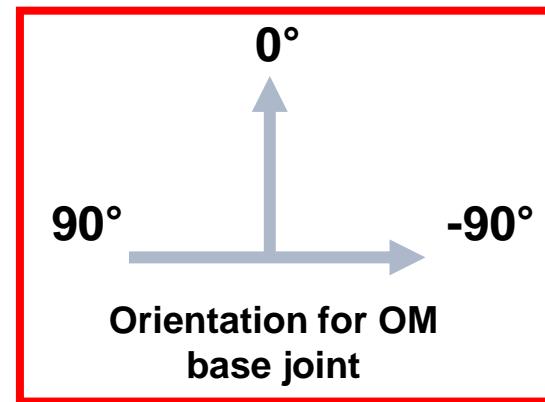
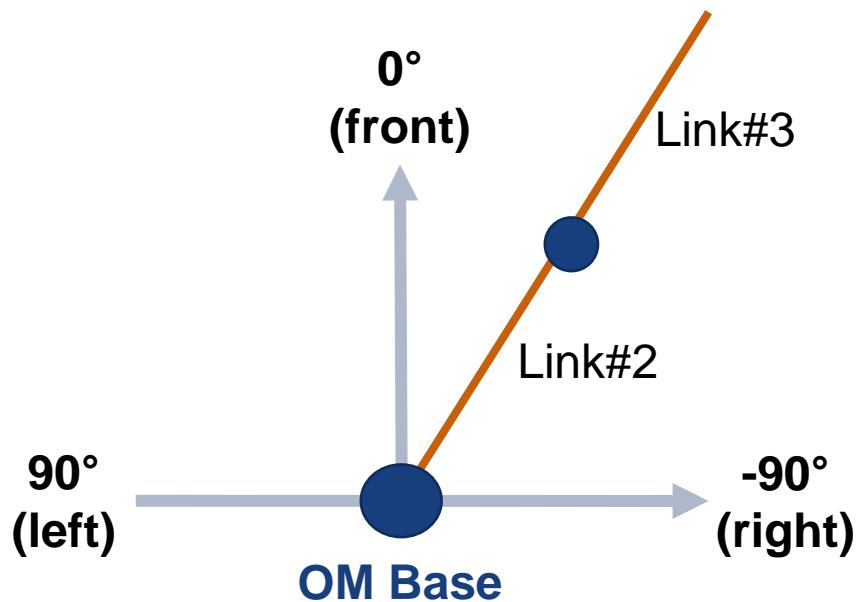


## 2. OPEN MANIPULATOR-X HANDS-ON



# Orientation for OM RECAP

## Top View:

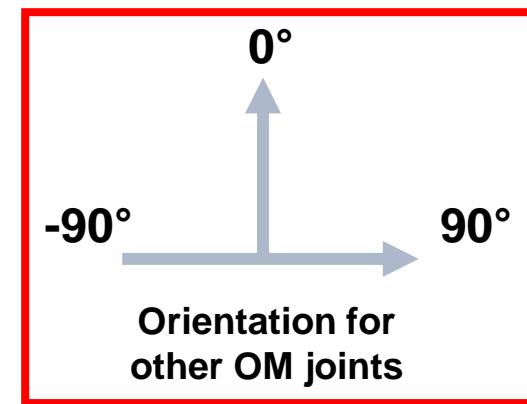
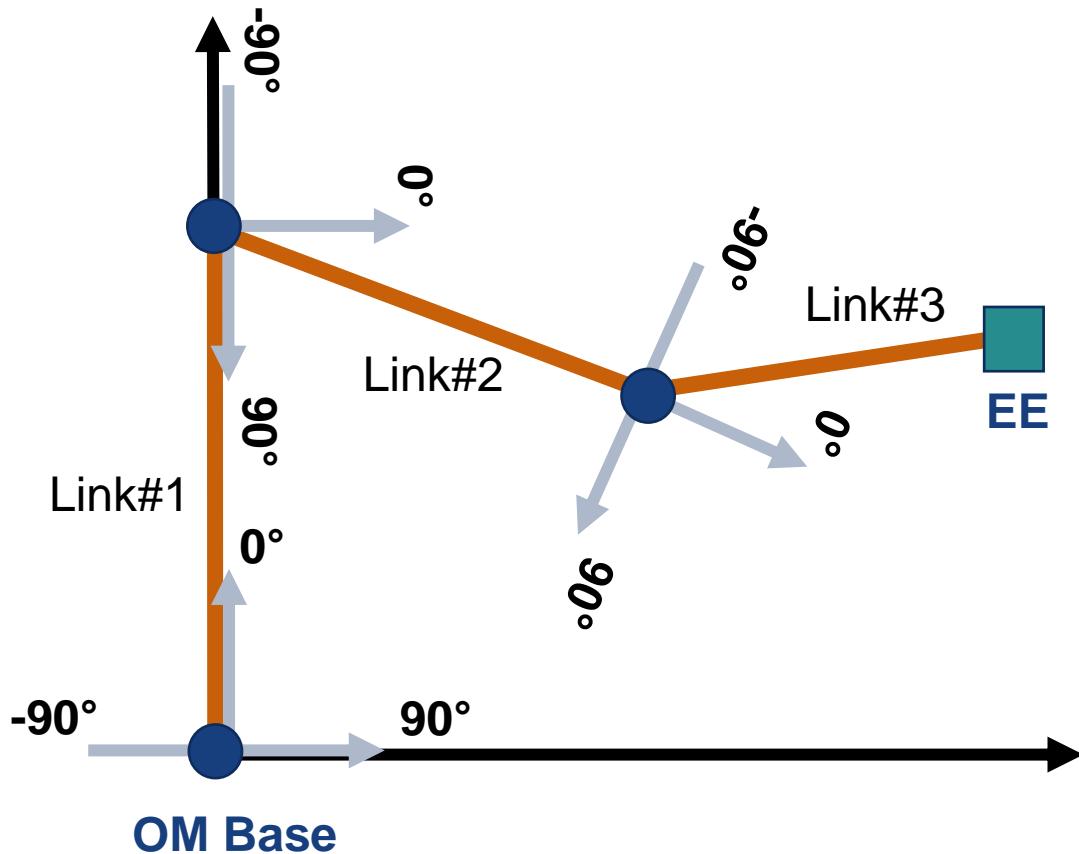




# Orientation for OM RECAP



## Side View:





# RECAP from Robotics System Course



## Steps to control the physical OM:

1. Run `$ roscore` on one terminal
2. Prepare the setup for the OM: Connect the wires, switch on the power, and manually bring up the OM
3. On another terminal, activate the controller; this will lock the motors

```
$ roslaunch open_manipulator_controller  
open_manipulator_controller.launch
```

## 4. ROSRUN your codes

```
$ rosrun robotics control_om.py
```



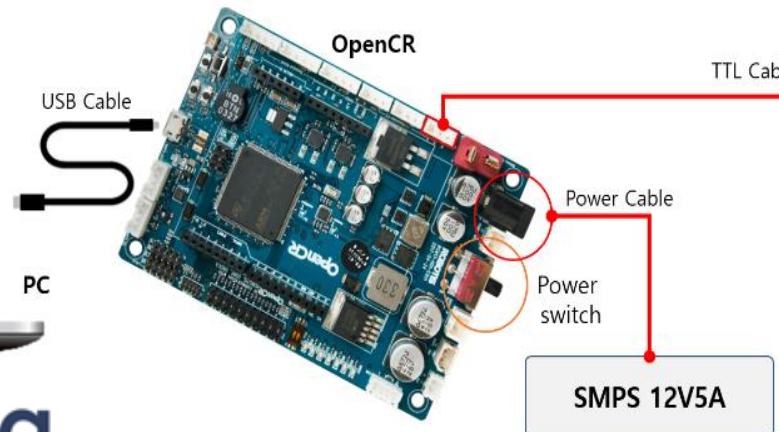
# Using ROS as the Controller



## Setup Configuration:

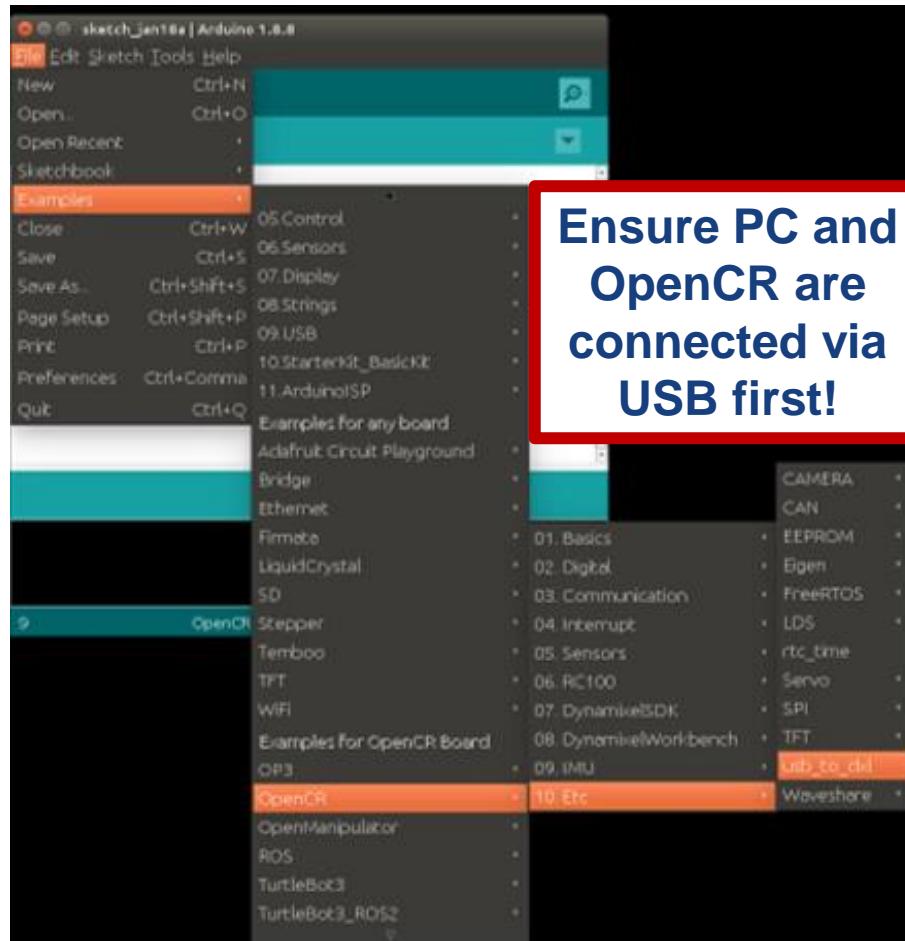


ROS.org



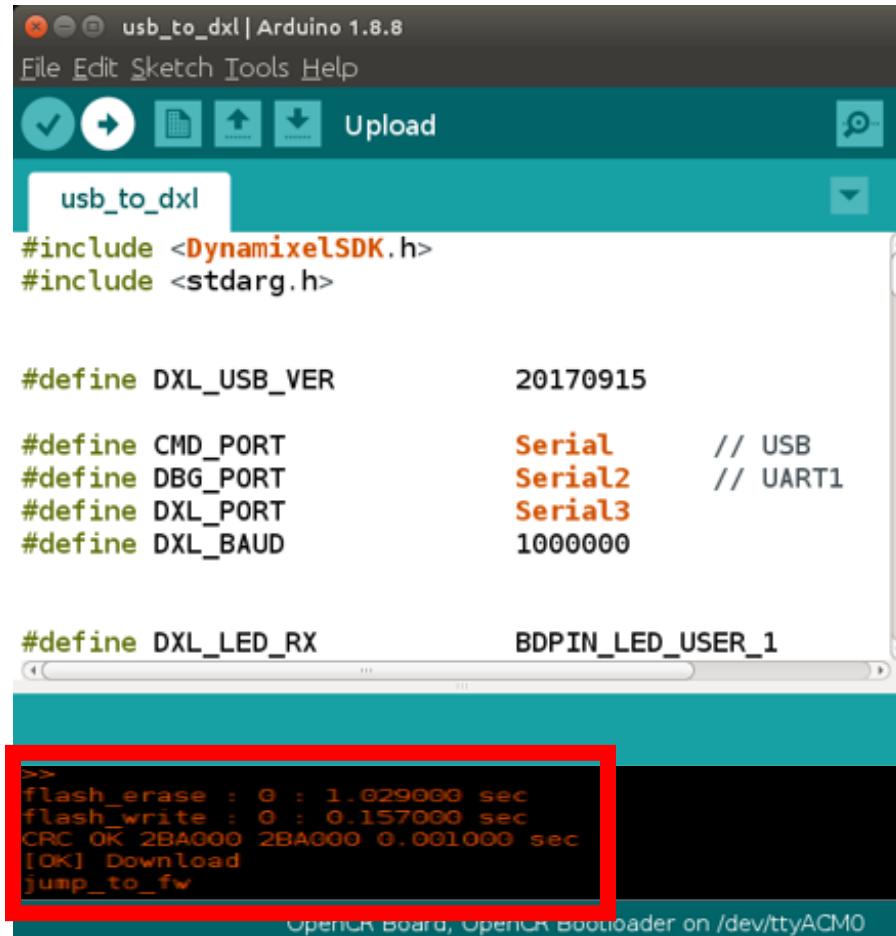


# Using ROS: OpenCR Setup (do it ONCE!):



1. Open Arduino IDE
2. Go to Examples → OpenCR → 10.Etc → usb\_to\_dx1 to open the usb\_to\_dx1 example source code

# Using ROS: OpenCR Setup (do it ONCE!):



The screenshot shows the Arduino IDE interface with the sketch `usb_to_dxl` open. The code includes #includes for `DynamixelSDK.h` and `stdarg.h`. It defines constants for port and baud rates, and a pin for the LED. The terminal window at the bottom shows the output of the OpenCR Board's bootloader, which includes the command `jump_to_fw` at the end of the line.

```
#include <DynamixelSDK.h>
#include <stdarg.h>

#define DXL_USB_VER          20170915
#define CMD_PORT              Serial           // USB
#define DBG_PORT              Serial2         // UART1
#define DXL_PORT              Serial3         1000000
#define DXL_BAUD

#define DXL_LED_RX            BDPIN_LED_USER_1

>>>
flash_erase : 0 : 1.029000 sec
flash_write : 0 : 0.157000 sec
CRC OK 2BA000 2BA000 0.001000 sec
[OK] Download
jump_to_fw
```

3. Click Upload. If launched successfully, the terminal will appear as follows (left)

- `jump_to_fw` will appear at the end of the line



# Using ROS: Launch Controller

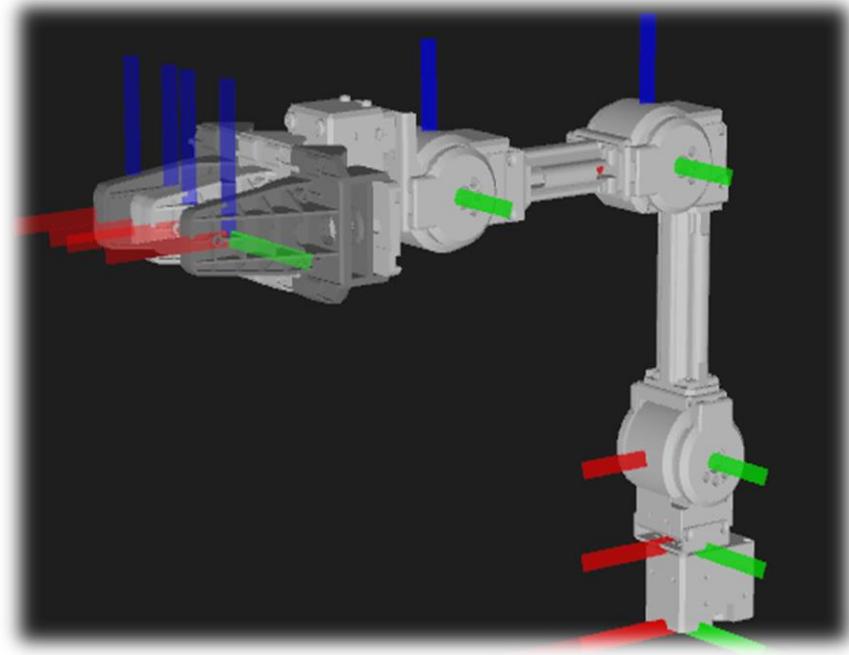


## Important!!!

**Before you launch the controller codes,  
manually lift the arm to  
a “L” position first!!!**

With the end effector  
(i.e. the gripper) facing  
the front

(refer to right image)





# Using ROS: Launch Controller



## Important!!!

**Before you close the terminal with the launched controller codes OR before you switch off the power, manually support the arm first!!! And slowly put it down.**

If not, the arm motors will be switch off, and it will fall and may injure someone or damage the robot/sensors



# Using ROS: Launch Controller

```
SUMMARY
=====
PARAMETERS
  * /open_manipulator/control_period: 0.01
  * /open_manipulator/moveit_sample_duration: 0.05
  * /open_manipulator/planning_group_name: arm
  * /open_manipulator/using_moveit: False
  * /open_manipulator/using_platform: True
  * /rosdistro: kinetic
  * /rosversion: 1.12.14

NODES
  /
    open_manipulator (open_manipulator_controller/open_manipulator_controller)

ROS_MASTER_URI=http://localhost:11311

process[open_manipulator-1]: started with pid [23452]
Joint Dynamixel ID : 11, Model Name : XM430-W350
Joint Dynamixel ID : 12, Model Name : XM430-W350
Joint Dynamixel ID : 13, Model Name : XM430-W350
Joint Dynamixel ID : 14, Model Name : XM430-W350
Gripper Dynamixel ID : 15, Model Name :XM430-W350
[ INFO] [1544509070.096942788]: Succeeded to init /open_manipulator
```

**\*\*\*Ensure the ARM is switched on first**

**Type (in New Terminal):**

- \$ roscore
- \$ roslaunch open\_manipulator\_controller open\_manipulator\_controller.launch
- If launched successfully, the terminal will appear as follows (left)
- You are ready to control your robotic arm



# Using ROS: Launch Controller



**Note that if you can't launch your controller successfully, double check if the USB port in the launch file is defined correctly**

- From Home, search and open  
open\_manipulator\_controller.launch
- Ensure that the following line is as such:  
`<arg name="dynamixel_usb_port"  
default="/dev/ttyACM0"/>`



# Inverse Kinematics (IK)



- Remember Project 1 of the Robotics System course?
- Is it practical to calculate the joint values required like what you did?
- Note that Project 1 is still an important practice to enable you to understand the mechanisms behind IK



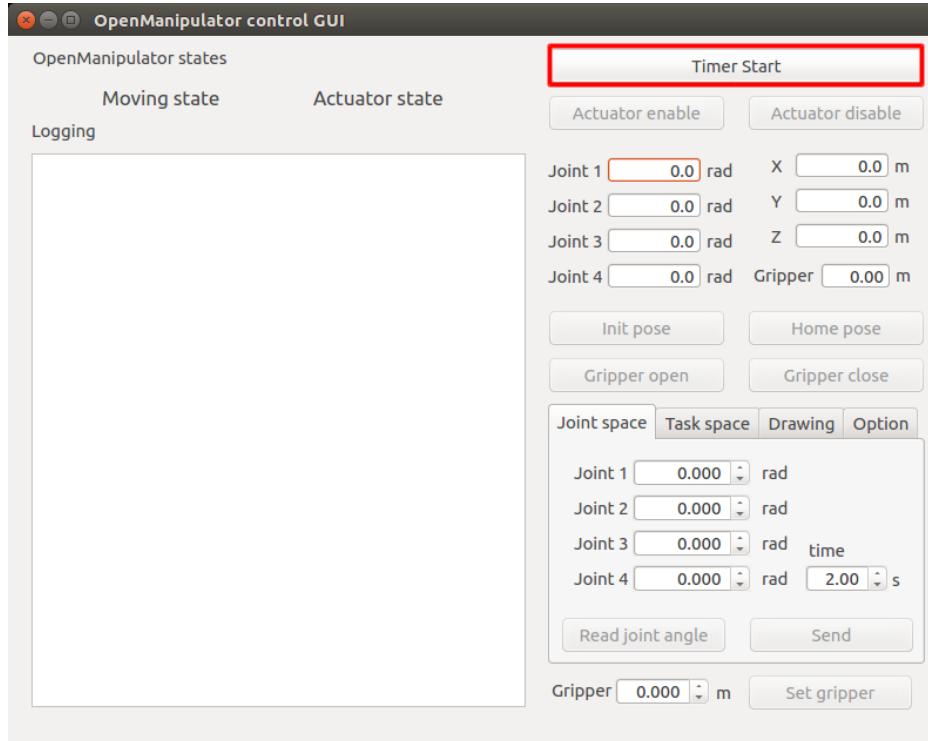
# Practical Ways to Solve IK



- a) Using OM Control GUI
- b) Using rospy (SetKinematicsPose)
- c) Hand Guiding



# (a) Using OM Control GUI to Solve IK



**\*\*\*Ensure the ARM is switched on and the Controller is activated first**

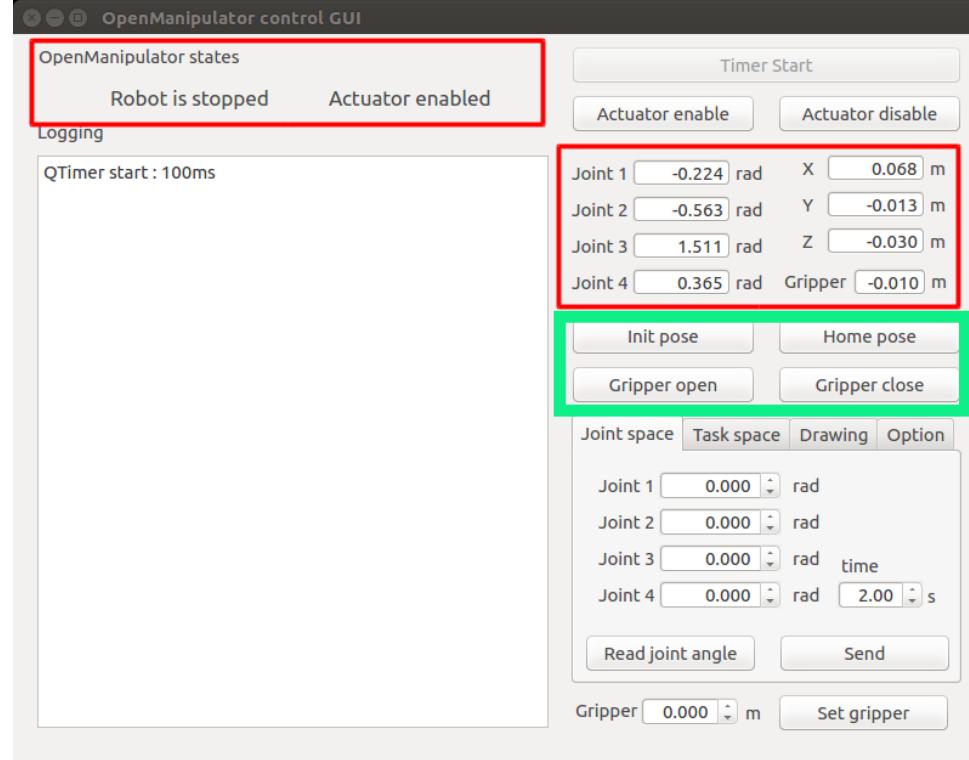
Type (in New Terminal):

- \$ roslaunch open\_manipulator\_control\_gui open\_manipulator\_control\_gui.launch
- This will open the GUI for the arm control
- Click “Timer Start” & “Actuator enable” and you can start controlling the arm; observe the arm for response



# (a) Using OM Control GUI to Solve IK

- You can **check the status of the arm** (i.e. joint states, kinematics pose, end effector position on X-Y-Z)
- To manipulate the arm to get it into **simple poses** (i.e. Init pose, Home pose, gripper open/close), click on the various buttons (in green box) one-by-one

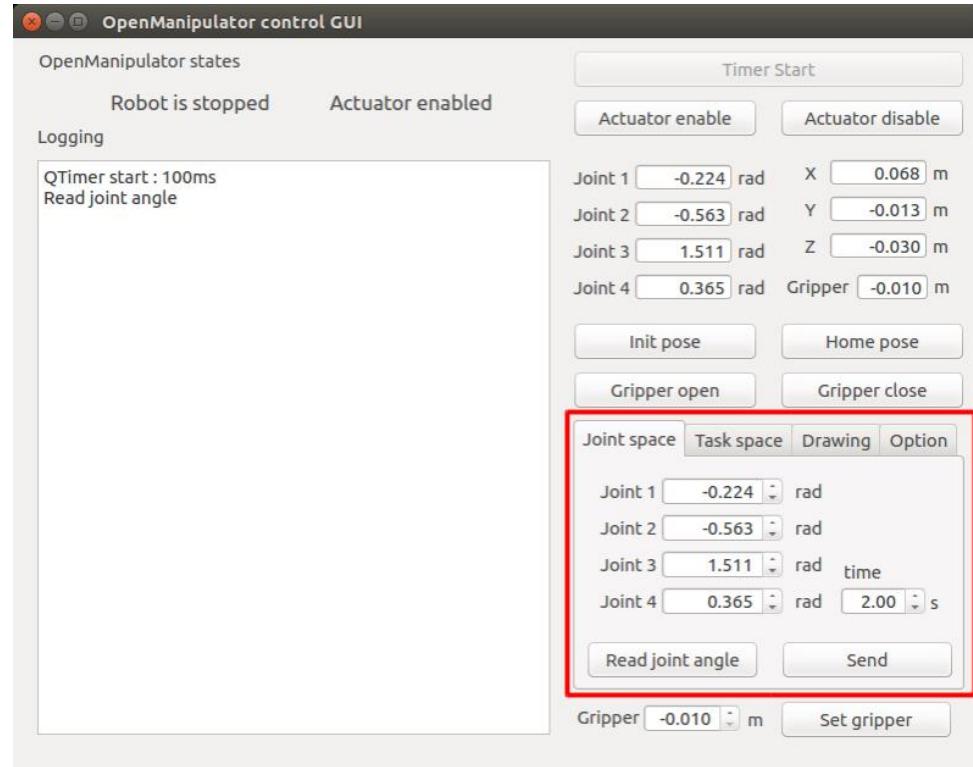




# (a) Using OM Control GUI to Solve IK



To manipulate the arm in the joint space (i.e. **Forward Kinematics**), enter the joint angles and trajectory time; click “Send” when done:

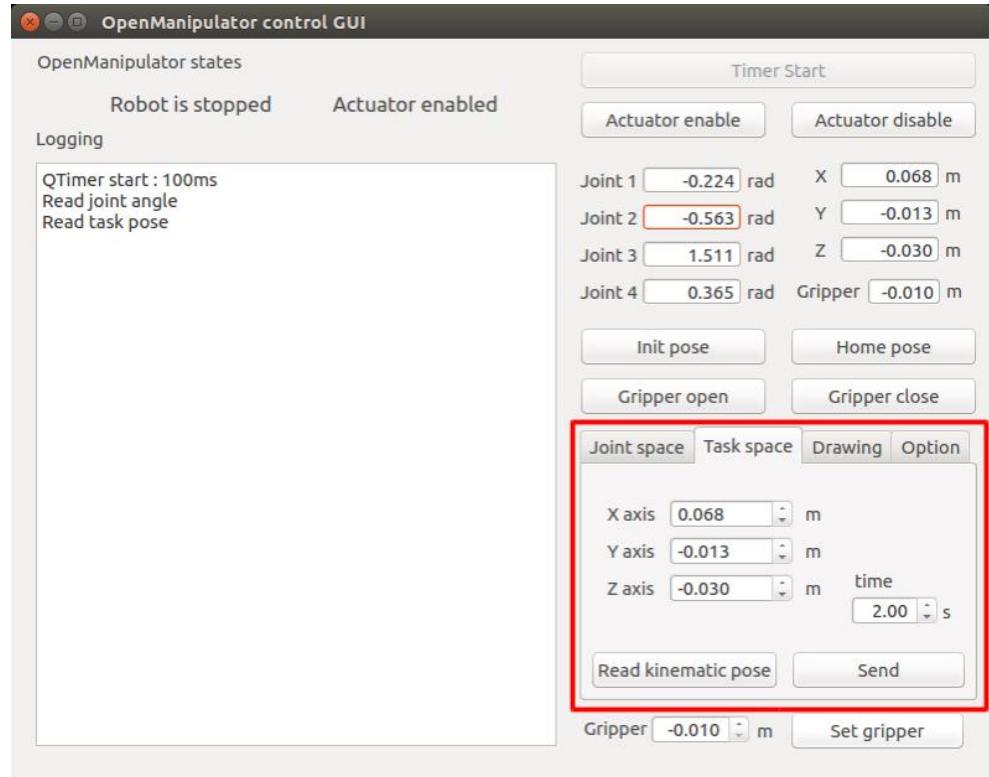




# (a) Using OM Control GUI to Solve IK



To manipulate the arm in the task space (i.e. **Inverse Kinematics**), enter the X-Y-Z values for your end effector's desired position; click "Send" when done:





## (b) Using Python (SetKinematicsPose)



# Important!!!

**Before you close the terminal with the launched controller codes OR before you switch off the power, manually support the arm first!!! And slowly put it down.**

If not, the arm motors will be switch off, and it will fall and may injure someone or damage the robot/sensors



# Using ROS:



## Control via Python (rospy)

**NOTE:** These services are messages to operate OpenMANIPULATOR-X or to change the status of DYNAMIXEL of OpenMANIPULATOR.

**Service Server List :** A list of service servers that open\_manipulator\_controller has.

- `/open_manipulator/goal_joint_space_path` (`open_manipulator_msgs/SetJointPosition`)

The user can use this service to create a trajectory in the joint space. The user inputs the angle of the target joint and the total time of the trajectory.

- `/open_manipulator/goal_joint_space_path_to_kinematics_pose` (`open_manipulator_msgs/SetKinematicsPose`)

The user can use this service to create a trajectory in the joint space. The user inputs the kinematics pose of the OpenMANIPULATOR-X end-effector(tool) in the task space and the total time of the trajectory.

- `/open_manipulator/goal_joint_space_path_to_kinematics_position` (`open_manipulator_msgs/SetKinematicsPose`)

The user can use this service to create a trajectory in the joint space. The user inputs the kinematics pose(position only) of the OpenMANIPULATOR-X end-effector(tool) in the task space and the total time of the trajectory.

- `/open_manipulator/goal_joint_space_path_to_kinematics_orientation` (`open_manipulator_msgs/SetKinematicsPose`)

The user can use this service to create a trajectory in the joint space. The user inputs the kinematics pose(orientation only) of the OpenMANIPULATOR-X end-effector(tool) in the task space and the total time of the trajectory.

- `/open_manipulator/goal_task_space_path` (`open_manipulator_msgs/SetKinematicsPose`)

The user can use this service to create a trajectory in the task space. The user inputs the kinematics pose of the OpenMANIPULATOR-X end-effector(tool) in the task space and the total time of the trajectory.



## (b) Using Python (SetKinematicsPose)

- Open terminal and type:

```
$ rosrun autonomous setkinematicspose.py
```

- The OM will move to a point determined by the X-Y-Z positions. To alter these positions, open the python file, find the following code section and change the positions in it; these angles are in m:

```
kinematics_pose = KinematicsPose()  
kinematics_pose.pose.position.x = 0.0128  
kinematics_pose.pose.position.y = 0.2748  
kinematics_pose.pose.position.z = 0.1938
```



# (b) Using Python (SetKinematicsPose)



```
#!/usr/bin/env python
# works for actual OM ONLY!

import rospy
from open_manipulator_msgs.msg import JointPosition
from open_manipulator_msgs.srv import SetJointPosition
from open_manipulator_msgs.msg import KinematicsPose
from open_manipulator_msgs.srv import SetKinematicsPose
from geometry_msgs.msg import Pose
import math

def talker():
    rospy.init_node('OM_publisher') #Initiate a Node called 'OM_publisher'
    set_kinematics_position = rospy.ServiceProxy('/open_manipulator/goal_joint_space_path_to_kinematics_position', SetKinematicsPose)
    set_gripper_position = rospy.ServiceProxy('/open_manipulator/goal_tool_control', SetJointPosition)

    #while not rospy.is_shutdown():
    kinematics_pose = KinematicsPose()
    kinematics_pose.pose.position.x = 0.287
    kinematics_pose.pose.position.y = 0.0
    kinematics_pose.pose.position.z = 0.194
    resp1 = set_kinematics_position('planning_group', 'gripper', kinematics_pose, 3)

    gripper_position = JointPosition()
    gripper_position.joint_name = ['gripper']
    gripper_position.position = [0.01] # -0.01 for fully close and 0.01 for fully open
    resp2 = set_gripper_position('planning_group', gripper_position, 3)

    rospy.sleep(3)
    kinematics_pose = KinematicsPose()
    kinematics_pose.pose.position.x = 0.0
    kinematics_pose.pose.position.y = 0.276
    kinematics_pose.pose.position.z = 0.192
    resp1 = set_kinematics_position('planning_group', 'gripper', kinematics_pose, 3)

if __name__ == '__main__':
    try:
        talker()
    except rospy.ROSInterruptException:
        pass
```

Note that if you want to use *SetKinematicsPose*, you have to be careful of the coordinates that you select; some of them cannot be solved by the IK solver

WHY so?



## (b) Using Python (SetKinematicsPose)



- Open terminal and type:

```
$ rosrun autonomous  
setkinematicspose_withorientation.py
```

- The OM will move to a point determined by the X-Y-Z positions and its orientations. To alter these positions/orientations, open the python file, find the following code section and change the positions/orientations in it:

```
kinematics_pose = KinematicsPose()  
kinematics_pose.pose.position.x = 0.0128  
kinematics_pose.pose.position.y = 0.2748  
kinematics_pose.pose.position.z = 0.1938  
  
kinematics_pose.pose.orientation.w = 0.707  
kinematics_pose.pose.orientation.x = -0.016  
kinematics_pose.pose.orientation.y = 0.016  
kinematics_pose.pose.orientation.z = 0.7058
```

# (b) Using Python (SetKinematicsPose)

```
#!/usr/bin/env python
# works for actual OM ONLY!

import rospy                                     #import the python library for ROS
from open_manipulator_msgs.msg import JointPosition    #import JointPosition message from the open_manipulator_msgs
package
from open_manipulator_msgs.srv import SetJointPosition
from open_manipulator_msgs.msg import KinematicsPose
from open_manipulator_msgs.srv import SetKinematicsPose
from geometry_msgs.msg import Pose
import math

def talker():
    rospy.init_node('OM_publisher') #Initiate a Node called 'OM_publisher'
    set_kinematics_position = rospy.ServiceProxy('/open_manipulator/goal_joint_space_path_to_kinematics_pose',
SetKinematicsPose)
    set_gripper_position = rospy.ServiceProxy('/open_manipulator/goal_tool_control', SetJointPosition)

    #while not rospy.is_shutdown():
    kinematics_pose = KinematicsPose()
    kinematics_pose.pose.position.x = 0.2867
    kinematics_pose.pose.position.y = 0.0
    kinematics_pose.pose.position.z = 0.194

    kinematics_pose.pose.orientation.w = 0.999
    kinematics_pose.pose.orientation.x = 1.765
    kinematics_pose.pose.orientation.y = 0.023
    kinematics_pose.pose.orientation.z = 0.0

    resp1 = set_kinematics_position('planning_group', 'gripper', kinematics_pose, 3)

    gripper_position = JointPosition()
    gripper_position.joint_name = ['gripper']
    gripper_position.position = [0.01]      # -0.01 for fully close and 0.01 for fully open
    respg2 = set_gripper_position('planning_group', gripper_position, 3)

    rospy.sleep(3)
    kinematics_pose = KinematicsPose()
    kinematics_pose.pose.position.x = 0.0128
    kinematics_pose.pose.position.y = 0.2748
    kinematics_pose.pose.position.z = 0.1938

    kinematics_pose.pose.orientation.w = 0.707
    kinematics_pose.pose.orientation.x = -0.016
    kinematics_pose.pose.orientation.y = 0.016
    kinematics_pose.pose.orientation.z = 0.7058

    resp1 = set_kinematics_position('planning_group', 'gripper', kinematics_pose, 3)
```



## (b) Using Python (SetKinematicsPose)



**Important!!!**

**Before you close the terminal with the launched controller codes OR before you switch off the power, manually support the arm first!!! And slowly put it down.**

If not, the arm motors will be switch off, and it will fall and may injure someone or damage the robot/sensors



## (c) Hand Guiding to solve IK



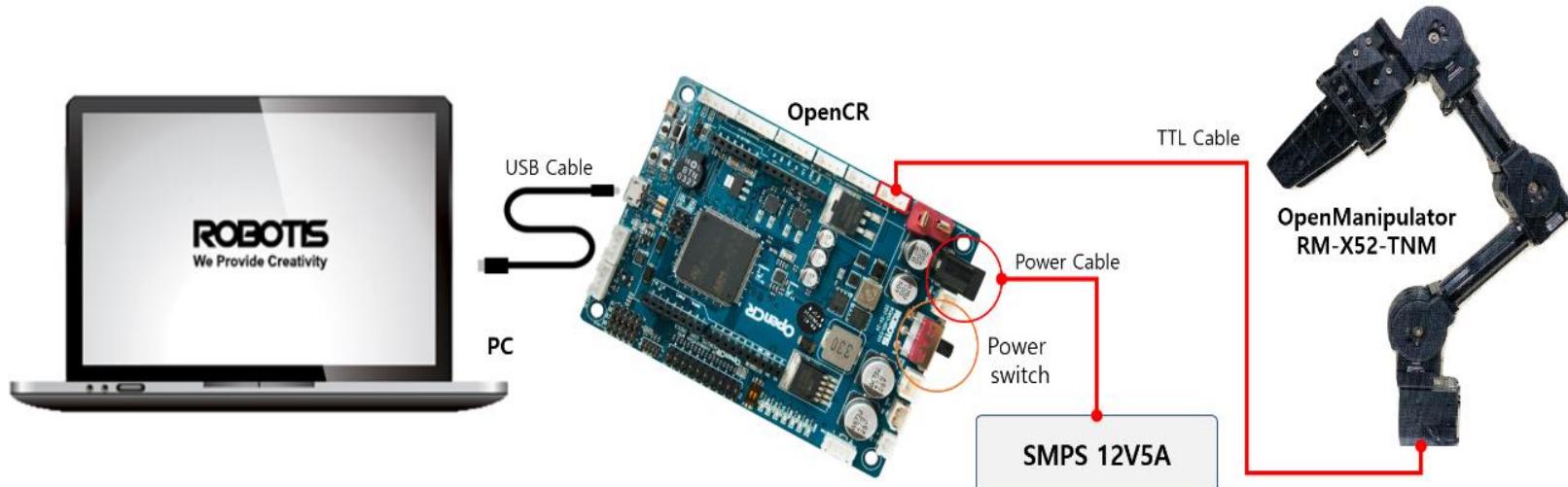
Source: <https://www.youtube.com/watch?v=9mE9QgAro8A>



# Using OpenCR as the Controller



## Setup Configuration (same setup):





# Using OpenCR: Operation



## Upload Controller Program to OpenCR:

1. Open Arduino
2. Go to *File* → *Examples* → *OpenManipulator* → *example* → *Chain* → *open\_manipulator\_chain*
3. Upload the **example source to OpenCR**; upload of firmware is successful if `jump_to_fw` appears at the end of the line (refer to right image)

```
opencr_ld ver 1.0.2
opencr_ld_main
>>
file name : /tmp/arduino_build_193791/Blink.ino.bin
file size : 29 KB
Open port OK
Clear Buffer Start
Clear Buffer End
>>
Board Name : OpenCR R1.0
Board Ver  : 0x16100600
Board Rev  : 0x00000000
>>
flash_erase : 0 : 1.029000 sec
flash_write : 0 : 0.157000 sec
CRC OK 2BA000 2BA000 0.001000 sec
[OK] Download
jump_to_fw
```



# Using OpenCR: Operation



## Launch Processing (GUI):

1. First remove the USB cable, Connect the power supply to OpenCR (do not switch on power yet)
2. Manually lift the OM to a “L” position
3. Hold the OM in that position and switch on the OpenCR switch
4. Check if the motors of OM are torque enabled (i.e. the motors are locked in and prevent you from moving the OM); you may let go the OM once the motors are torque enabled
5. Connect the OpenCR and PC with a USB cable



# Using OpenCR: Operation



## Launch Processing (GUI):

6. Open the Processing application
7. Click *File* → *Open*
8. Search downloaded processing file from  
~/*catkin\_ws/src/* → *open\_manipulator\_processing* →  
*Chain* → *Chain.pde* and **open it on Processing IDE**
9. **Note: If there is error with the OpenGL, find the “settings” function [Line ~64] and change to the following:**

```
System.setProperty("jogl.disable.openglcore", "false");  
size (900, 900, P3D);
```



# Using OpenCR: Operation



## Example of Chain code file in the Processing application:

```
Chain | Processing 3.3.7
File Edit Sketch Debug Tools Help
Run
Chain
1 /*****
2 * Copyright 2018 ROBOTIS CO., LTD.
3 *
4 * Licensed under the Apache License, Version 2.0 (the "License");
5 * you may not use this file except in compliance with the License.
6 * You may obtain a copy of the License at
7 *
8 *      http://www.apache.org/licenses/LICENSE-2.0
9 *
10 * Unless required by applicable law or agreed to in writing, software
11 * distributed under the License is distributed on an "AS IS" BASIS,
12 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
13 * See the License for the specific language governing permissions and
14 * limitations under the License.
15 *****/
16
17 /* Authors: Darby Lim, Hye-Jong KIM, Ryan Shim, Yong-Ho Na */
18
19
```

Console Errors

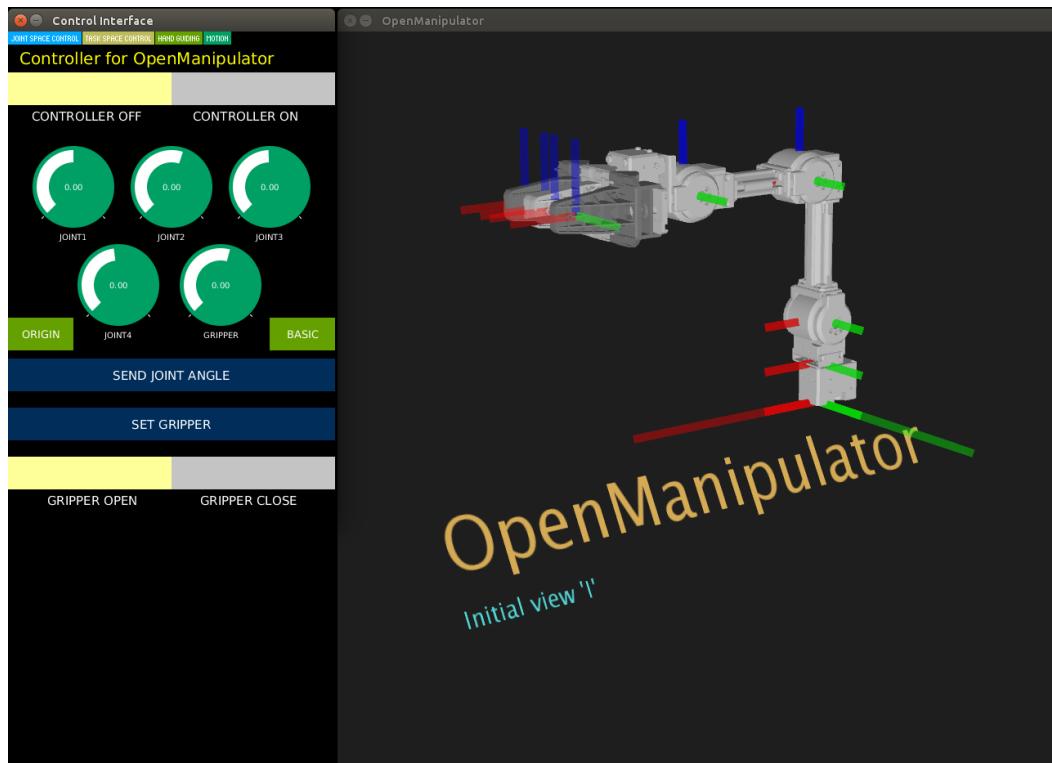


# Using OpenCR: Operation



## Launch Processing (GUI):

9. Run the processing source code, and the following graphical GUI will be displayed

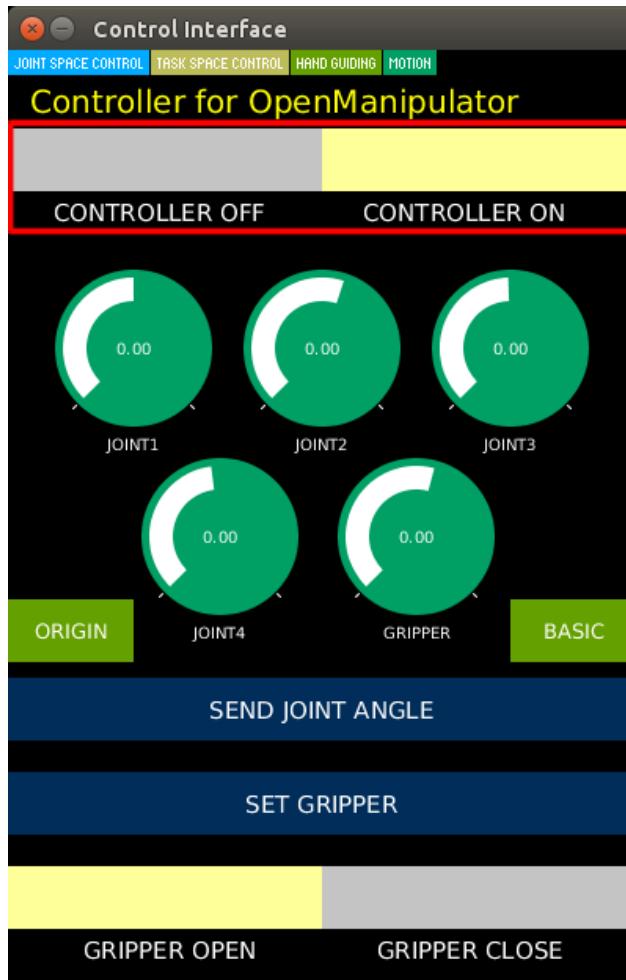




# Using OpenCR: Operation



## Using Control Interface to control arm:



To start manipulating the arm, click the virtual toggle button to **CONTROLLER ON**



# Using OpenCR: Operation



## Important!!!

**If you want to set the CONTROLLER to OFF,  
manually support the arm first!!! And slowly  
put it down.**

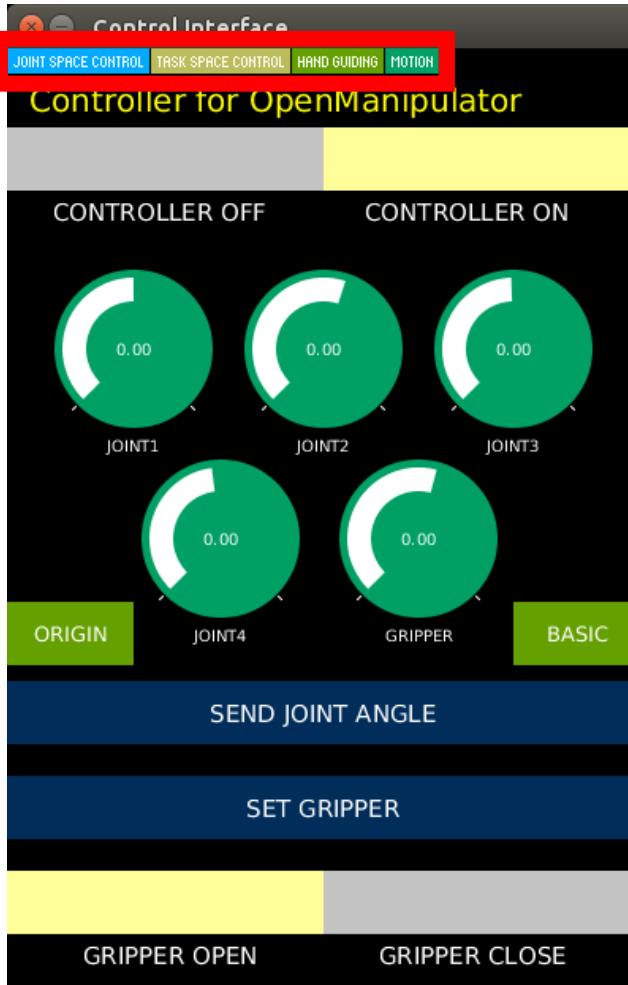
**If not, the arm motors will be switch off, and  
it will fall and may injure someone or  
damage the robot/sensors**



# Using OpenCR: Operation



Using Control Interface to control arm:



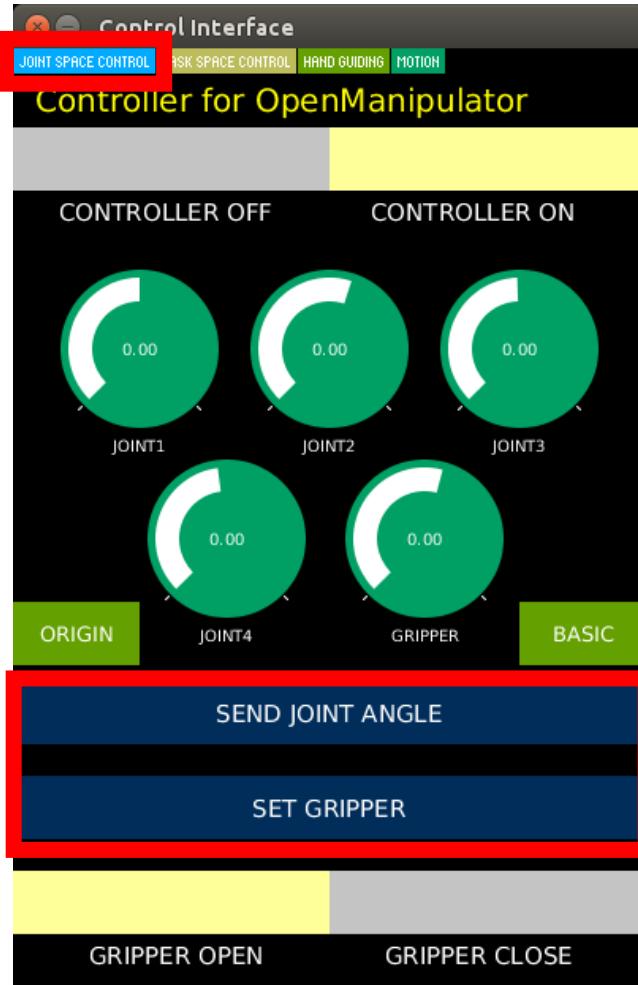
**3 Main Modes of Control:**

- 1. Joint space**
- 2. Task space**
- 3. Hand guiding**



# Using OpenCR: Operation

## (A) Joint space control



- Set the joint angles and click the SEND JOINT ANGLE button
- Set the gripper parameter and click the SET GRIPPER button

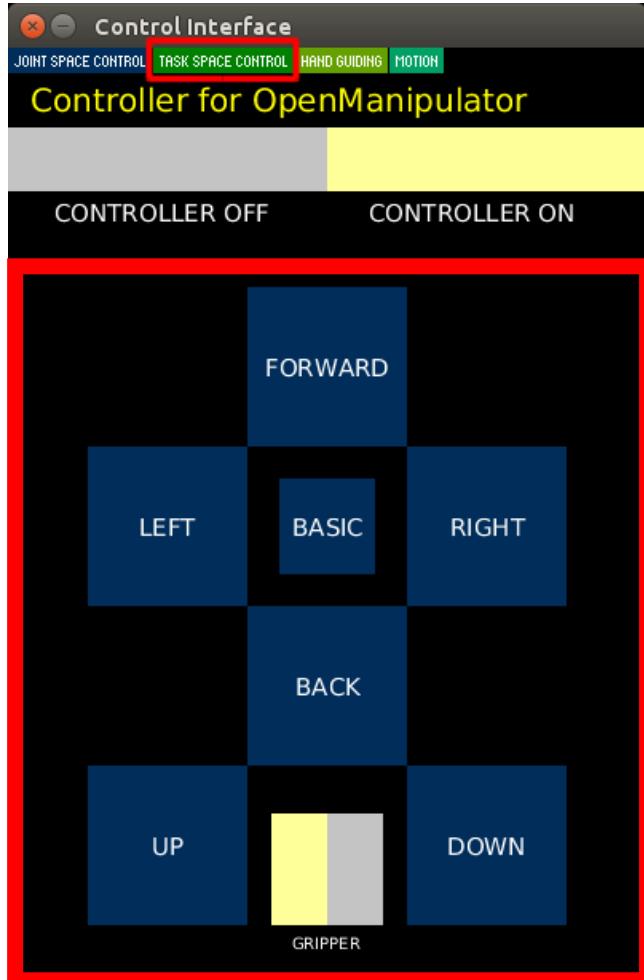




# Using OpenCR: Operation



## (B) Task space control



- Click the desired direction buttons to manipulate the ARM



# Using OpenCR: Operation



## (C) Hand Guiding

**Important!!!**

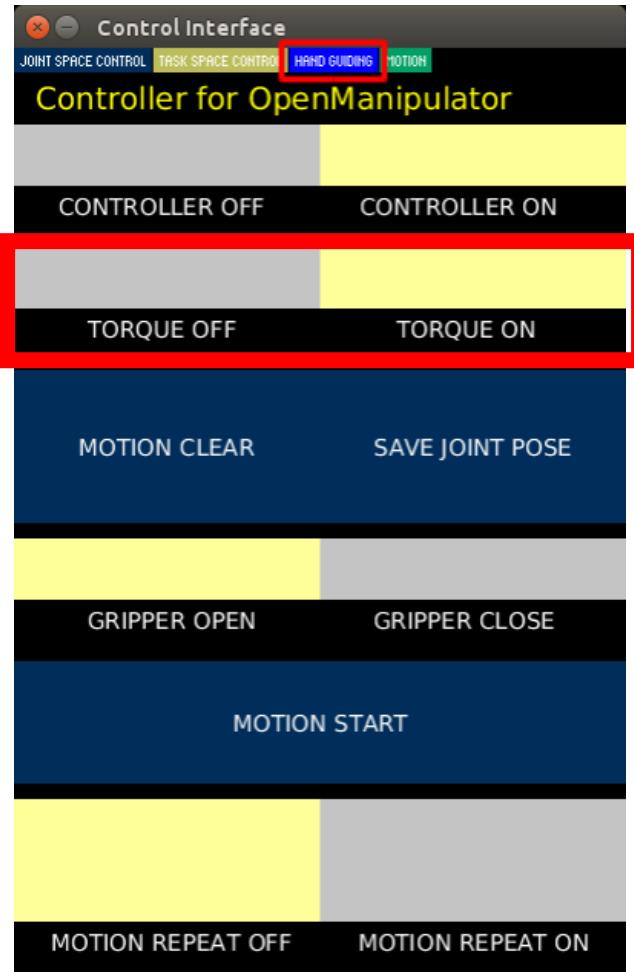
**Before you switch off the torque during the hand guiding session, manually support the arm first!!! And you can start follow the instructions in the following slides.**

**If not, the arm motors will be switch off, and it will fall and may injure someone or damage the robot/sensors**



# Using OpenCR: Operation

## (C) Hand Guiding



## Steps:

- 1. Hold the ARM by your hand (to prevent it from falling) and click the toggle button to TORQUE OFF**
- 2. Move the ARM to the desired pose using your hand**



# Using OpenCR: Operation

## (C) Hand Guiding



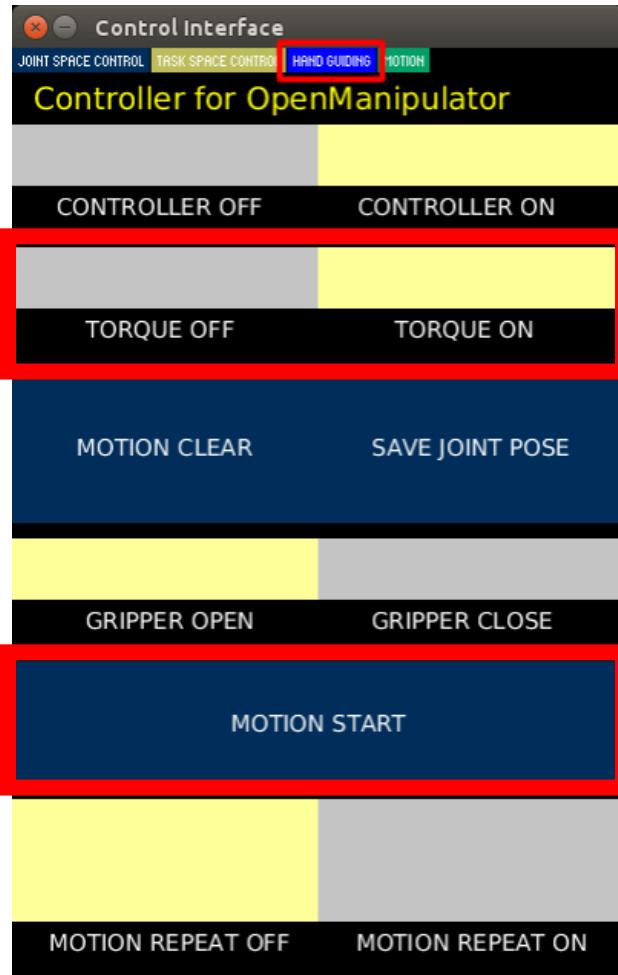
### Steps:

3. Click the **SAVE JOINT POSE** to save the present pose
4. Repeat step 2 & 3 to create the demonstration



# Using OpenCR: Operation

## (C) Hand Guiding



## Steps:

5. Once done, click the toggle button to TORQUE ON
6. Click the MOTION START button to start the saved poses



# Using OpenCR: Operation

## (C) Hand Guiding



## Other considerations:

- **Use the GRIPPER OPEN/CLOSE button to control the gripper**
- **Click MOTION CLEAR if you want to delete memory of the old motion paths in order to create new ones**
- **Click MOTION REPEAT ON if you want to repeat the demonstration**



# Using OpenCR: Operation



**Important!!! Do the following Steps before you start using the RC-100 Controller:**

1. **Remove USB connection to the PC;** you will not be able to use RC-100 to control the OM if the OpenCR and PC are connected via the USB
2. **Connect the power supply to OpenCR (do not switch on power yet)**
3. **Manually lift the OM to a “L” position with the gripper facing the front**
4. **Hold the OM in that position and switch on the OpenCR power switch**
5. Check if the motors of OM are torque enabled; you can let go the OM once the motors are torque enabled
6. **Switch on the RC-100 Controller** and you can start using it to control the OM



# Using OpenCR: Operation



## Using RC-100 Controller (Bluetooth):



**The settings for this controller is included in the OpenCR firmware for the ARM**



# Group Project 2



There are various types of autonomous robots out there in the world. One of the popular type involves the Hand-Guiding method, which rapidly and intuitively program a robotic arm by teaching it the desired trajectories (and hence the respective joint angles) it has to execute in order to achieve its goal(s). One popular application of this method is at manufacturing lines whereby repetitive tasks are common and frequent reprogramming activities are required.

For this project, we will **compare the pros/cons among:**

- a) **Manual-based robots (using the RC100 controller),**
- b) **Programmable autonomous robots (Python-controlled method), and**
- c) **Adaptive autonomous robots (precise Hand-Guiding teaching method)**



# Group Project 2



In groups, you are to:

1. Achieve 2 main goals
  - a) Transfer the BIG item from Position A to B (**use the same A & B positions as the RBS WS1 or “Introduction to ROS” WS**)
  - b) Repeat this task 3 times (you can reuse the item and put it back to Position A each time each task is completed)
  - c) Change Positions A and B to random new positions, and do (a) and (b) again
  - d) Take the SMALL item and do (a) and (b) again; use the same positions from (c)
2. Firstly, try using the **RC100 controller** to remotely control the OM to achieve the goals. Reflect on the pros/cons of this method
3. Secondly, write a **Python code(s) (i.e. rospy)** to control the OM to achieve the goals. **Note that you have already practised this in the RBS WS1 or “Introduction to ROS” WS, hence you can skip this practice.** Reflect on the pros/cons of this method
4. Thirdly, using the **Hand-Guiding teaching method** that we practiced previously, **configure an adaptive autonomous robot** that will automatically achieve the goals. Reflect on the pros/cons of this method



# Group Project 2



## Note:

- **For Manual Control**, use the current **OpenCR configuration**. Use the RC100 controller as explained in the previous slides
- **For Hand Guiding**, use the current **OpenCR configuration**. Refer to the explanations in the previous slides and/or the README instructions
- **For FK/IK Techniques**, use the **ROS configuration**. Remember to reconfigure and upload the correct firmware using Arduino. You can use the given Project2.py file as a reference template for this part



# Group Project 2



## RECAP on procedures to rosrun:

1. Run \$ roscore on one terminal
2. Prepare the setup for the OM: Connect the wires, switch on the power, and manually bring up the OM
3. On another terminal, activate the controller; this will lock the motors

```
$ roslaunch open_manipulator_controller  
open_manipulator_controller.launch
```

4. On another terminal, ROSRUN your codes

```
$ rosrun autonomous Project2.py
```



# Group Project 2



**Fill in the comparison table below:**

	<b>Manual-based robots (using RC100 controller)</b>	<b>Programmable autonomous robots (using Python codes)</b>	<b>Adaptive autonomous robots (using hand-guiding)</b>
<b>Pros</b>			
<b>Cons</b>			



# Group Project 2



## Improving autonomous level of system:

- Upgrade the hand guiding system into an intelligent autonomous robot by **suggesting a newly improved robotic arm system with higher autonomy by drafting out a system architecture design** that represents this system
- Assume that:
  - There is no budget limitation for your system
  - The base equipment (i.e. the OM itself, openCR board and PC) remains the same. You are allowed to suggest additional devices/technologies to improve the system



# Group Project 2



## 2 Items to Submit (can zip all in one file):

1. The filled comparison table (Word/PDF formats are all accepted)
2. System Architecture Design of an improved robotic arm system with a higher autonomous level



**Please upload all your works in**  
**CANVAS → Assignments →**  
**ARV Workshop 2 Submission**

**(Each representative per group to submit)**



# End of Module 3



**THANK YOU  
for your kind  
attention!**