

{Learn, Create, Innovate};

Open Loop Control

*From zero to a
functional robot.*

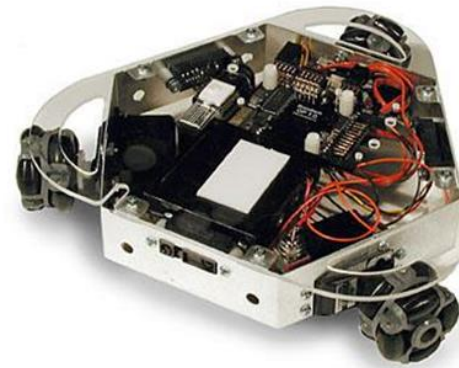




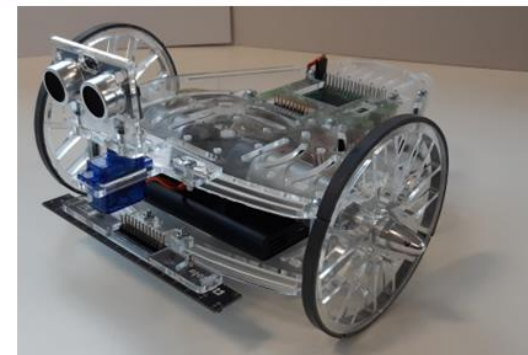
Mobile Robots



- There exists many types of wheeled robotic platforms
 - Differential-Drive robots
 - Omnidirectional robots
 - Ackermann-steering robots
 - and many others...
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- In this course we will focus on differential drive robots, also known as “differential wheeled robots”.



Holonomic Robot
Acroname ©.



Differential-drive
Puzzlebot ©.

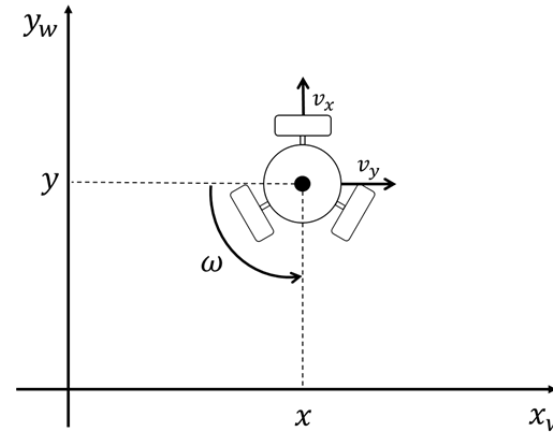


Holonomic vs. Nonholonomic Systems

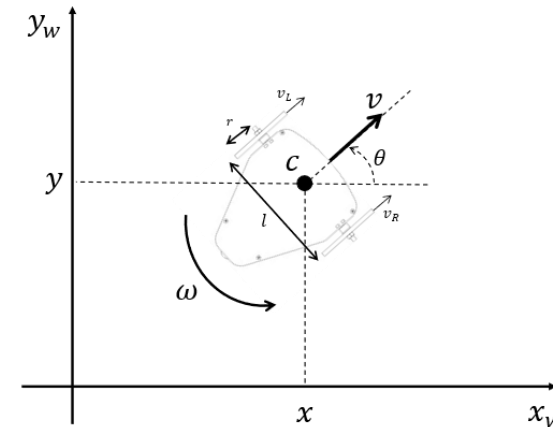


Mobile robots can be classified as "Holonomic" or "Nonholonomic".

- This classification depends on the relationship between controllable and total degrees of freedom of a robot.
- **Holonomic Robots:** If the controllable degree of freedom is equal to total degrees of freedom, then the robot
- **Nonholonomic Robots:** If the controllable degree of freedom is less than the total degrees of freedom. Such systems are therefore called underactuated. Differential Drive Systems fall into this category.



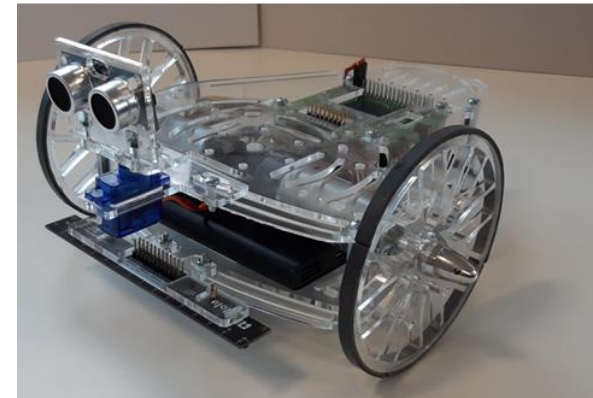
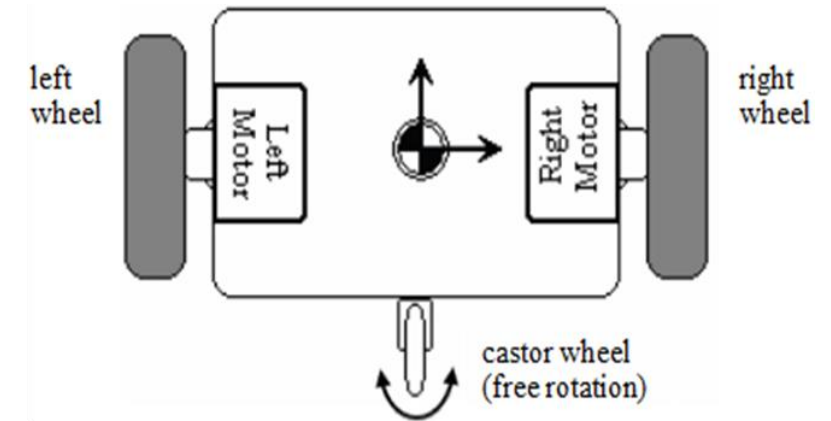
**Holonomic
Robot**



**Nonholonomic
Robot**

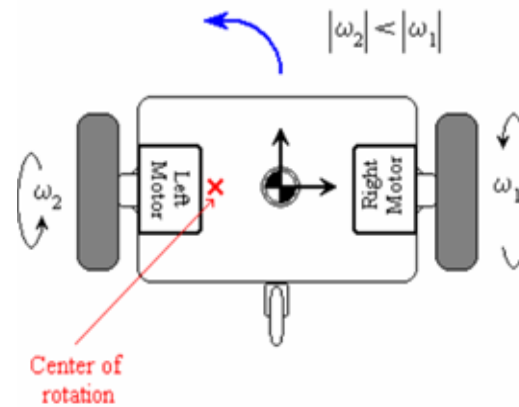
Differential Drive

- These are mobile robots whose movement is based on two separately driven wheels placed on either side of the robot body.
- Two active wheels and one caster wheel (most common configuration)
- It can thus change its direction by varying the relative rate of rotation of its wheels, thereby requiring no additional steering motion.

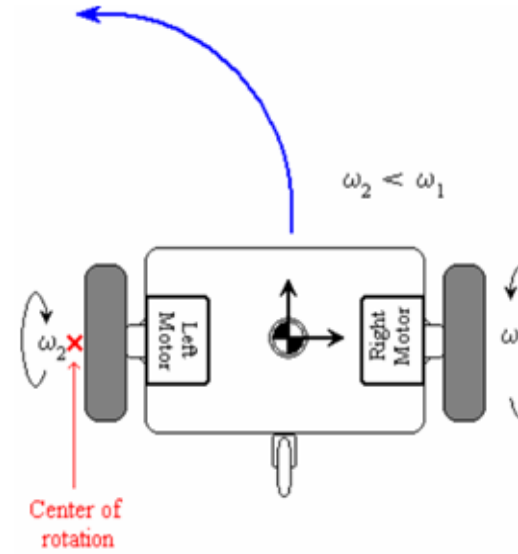
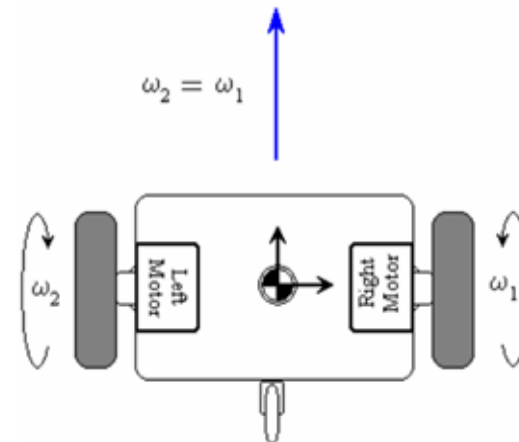


**Differential drive
robots**

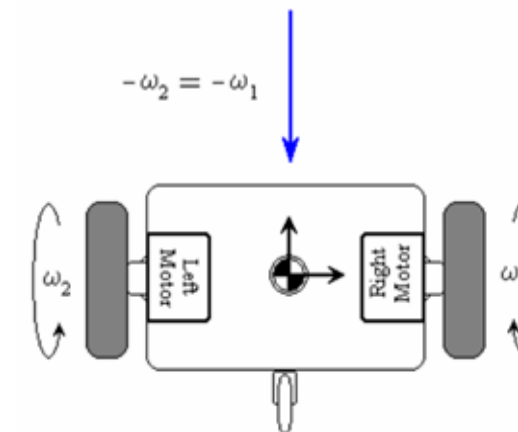
Differential Drive



Forward Turn (1)



Forward Turn (2)

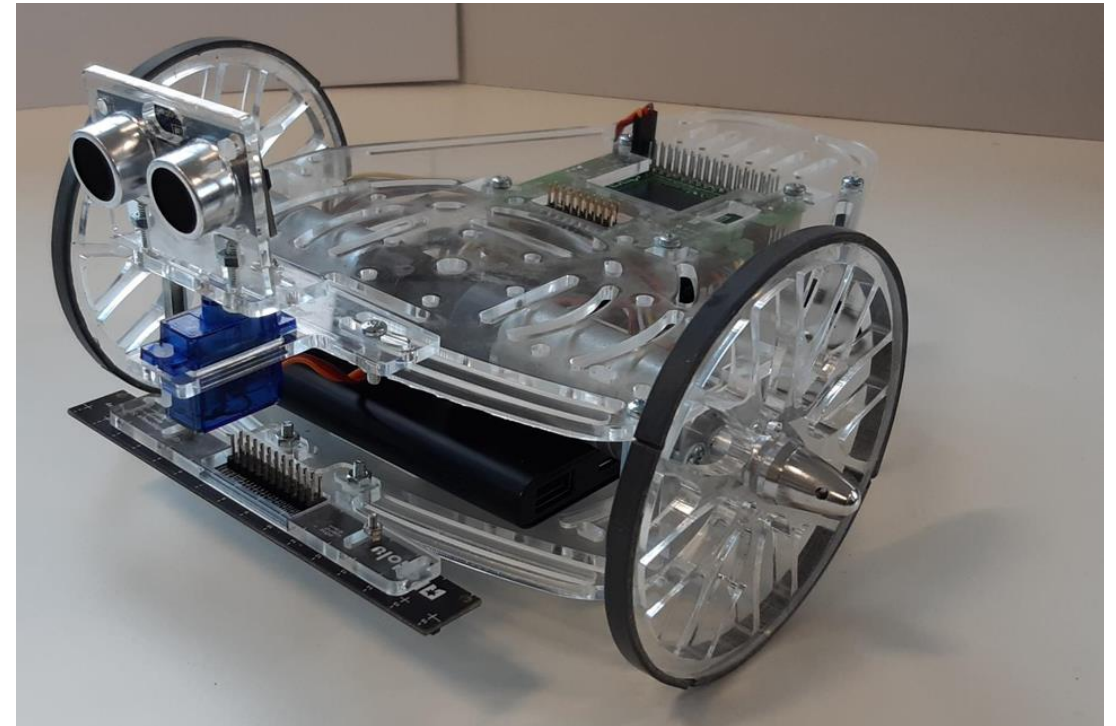




Sensors and Actuators for Differential Drive Robots



- Differential drive robots can perform different tasks autonomously.
- Each task requires a set of sensors and actuators that can be added to the robot to increase its level of autonomy.
- The minimum required sensors and actuators (motors, encoders, etc.), are the ones that allow us to control mobile robot movement and be localised (obtain its position and orientation), to correctly perform its functions.



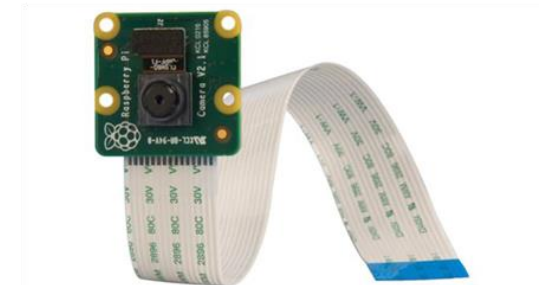
Differential Drive Robot Sensors and Actuators.



Differential Drive Sensors and Actuators

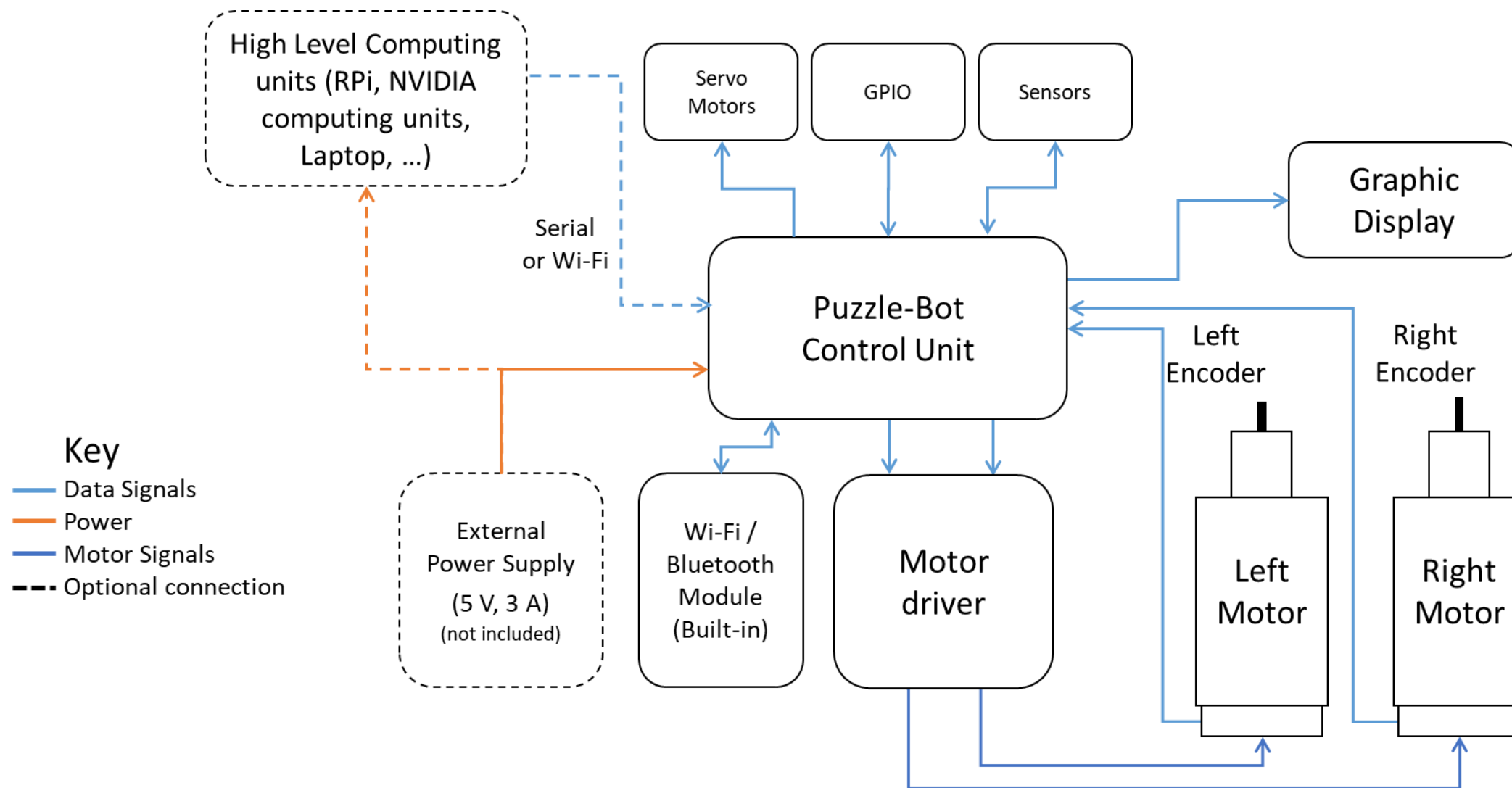


- For the case of the sensors, they can be classified as Exteroceptive and Proprioceptive.
- **Exteroceptive:** Used to measure the environment or the state of the environment, topology of the environment, temperature, etc. Some examples are Sonar, LiDAR, Light sensors, bumper sensors, magnetometers.
- **Proprioceptive:** Used to measure the state of the robot such as wheel position, velocity, acceleration, battery charge, etc. Some examples include, encoders, battery level, gyrometers, accelerometers.

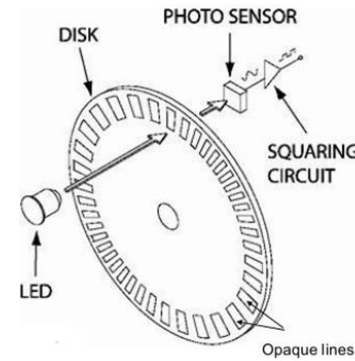


Sensors and Actuators.

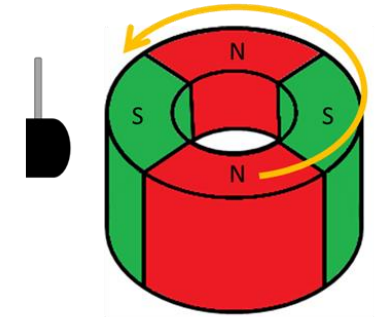
Differential Drive Sensors and Actuators



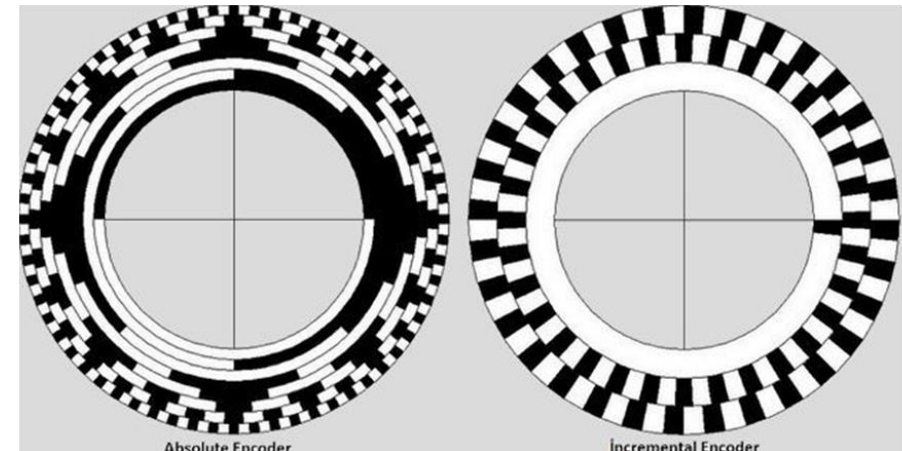
- Device that converts the angular position of a shaft (motor shaft) to an analogue or digital signal.
 - **Absolute:** Indicates the position of the shaft at all times, by producing a unique digital code for each angle (Angle transducers).
 - **Incremental:** Record the changes in position of the motor shaft with no indication or relation to any fixed position of the shaft.
- Encoders in mobile robots are considered proprioceptive sensors because they only acquire information about the robot itself, not the structure of the environment.



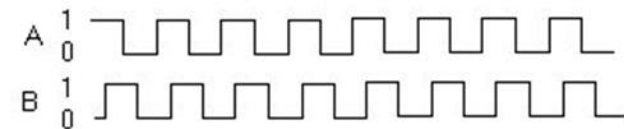
Optical Rotary Encoder



Magnetic Rotary Encoder

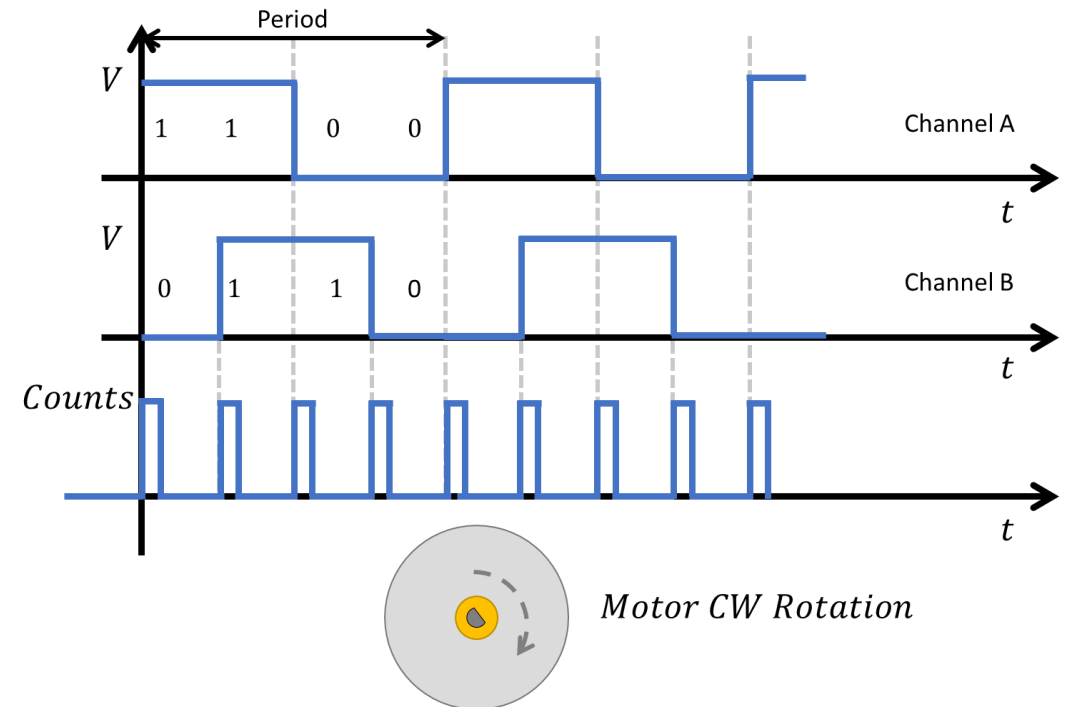


- Incremental encoders, produce a series of electrical high-low pulses. These pulses, allows to obtain information such as the angular rotation of the shaft or the angular speed of the motor by counting the number of pulses that occur in a certain period (Δt).
- In robotics, when an encoder is attached to the axle of each wheel in a differential-drive robot, it is possible to convert the number of pulses into useful information, such as the velocity or distance travelled by each wheel.
- With a single set of pulses (single channel / Channel A), it is impossible to know if the motor is rotating clockwise (CW) or counterclockwise (CCW).
- Therefore, a second line (dual channel / channel B) is attached, having its signal shifted by 90 electrical degrees ($^{\circ}e$) with respect to channel A.

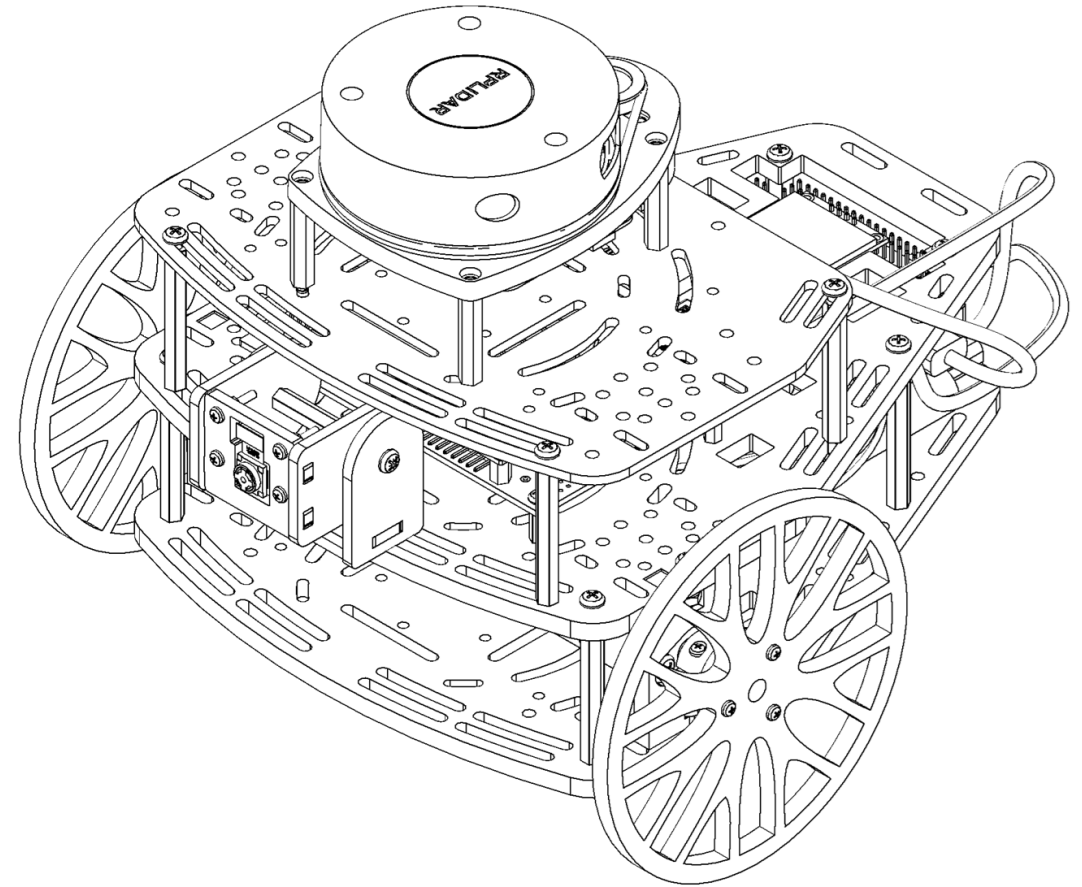


Quadrature Encoder Output

- This phase shift allows to determine the direction of rotation.
- Depending on direction of rotation the signal of channel A is preceding channel B or vice versa.
- A simple estimation of the direction would be to verify the previous inputs (Channels A and B) and compare it with the actual inputs, the “code” will change dependant on the rotation direction.
- Counting the pulses of both channels, also leads to a more accurate angular velocity estimation.
- To count the pulses using a MCU, the most common methodology is to use interrupts so that no information is lost.



- Puzzlebot motors use an incremental dual channel, quadrature encoders with 13 pulses per revolution, attached to the motor shafts before the reduction (35:1).
- The encoder is used to estimate the speed of the motors.
- Since the encoders can have a lot of noise, it is recommended to use a filter (low pass or band pass) to avoid having a noisy signal that affects the controller.



Introduction

- A direct current (DC) motor is a type of electric machine that converts electrical energy into mechanical energy.
- DC motors take electrical power through direct current and convert this energy into mechanical rotation.
- This is done by using generated magnetic fields from the electrical currents, powering the movement of a rotor fixed within the output shaft.
- The output torque and speed depends upon both the electrical input and the design of the motor.

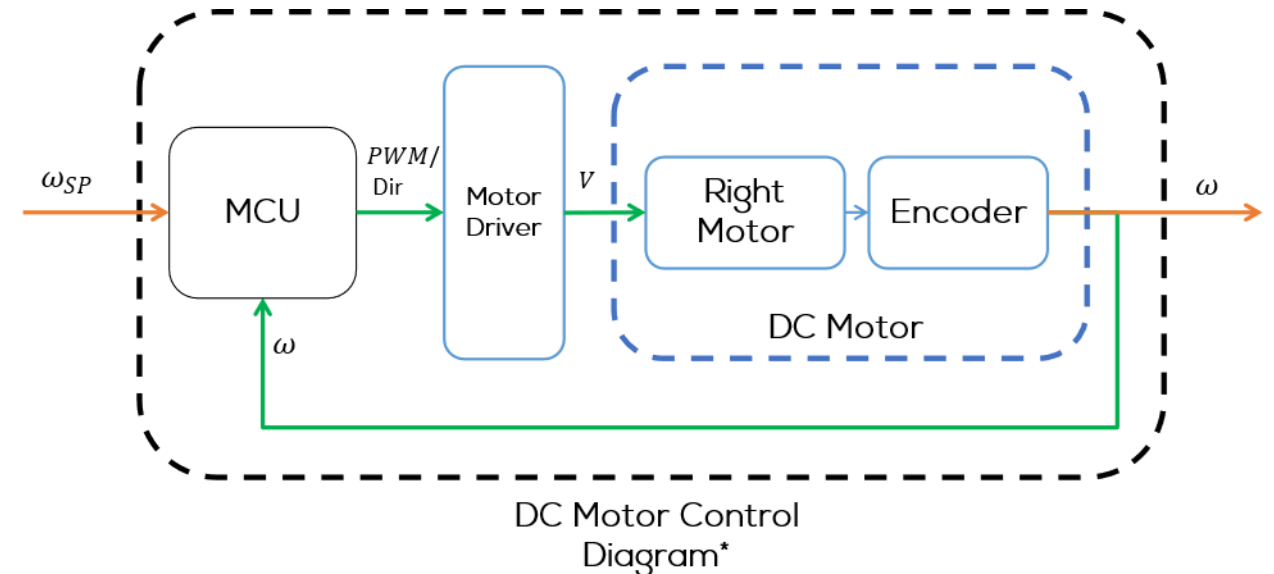
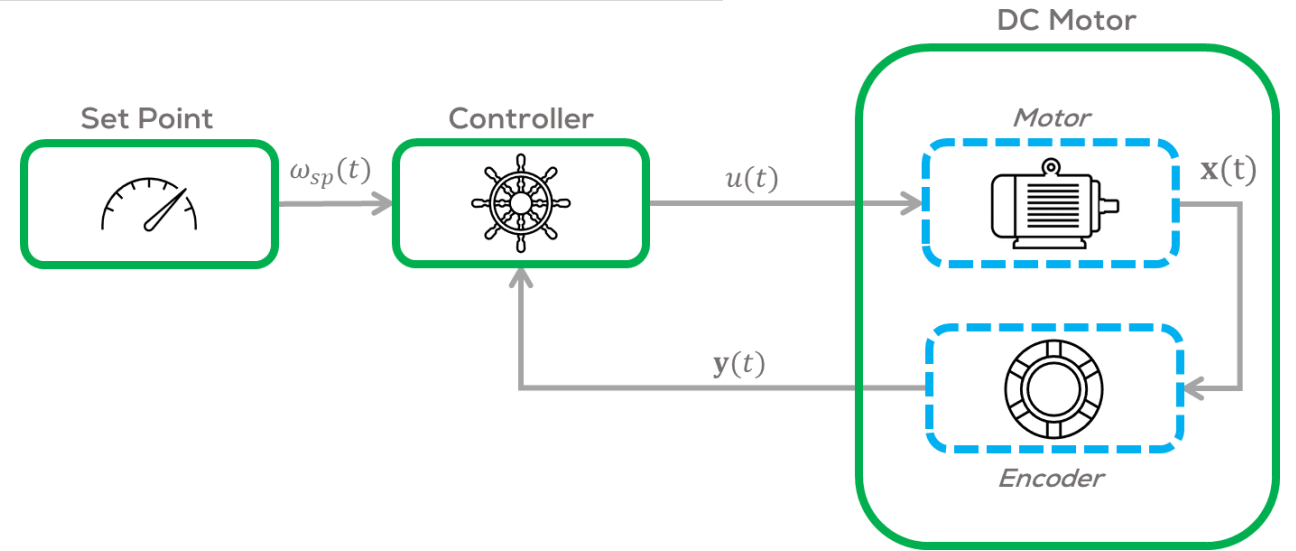


DC Brushed Motor with Encoder.



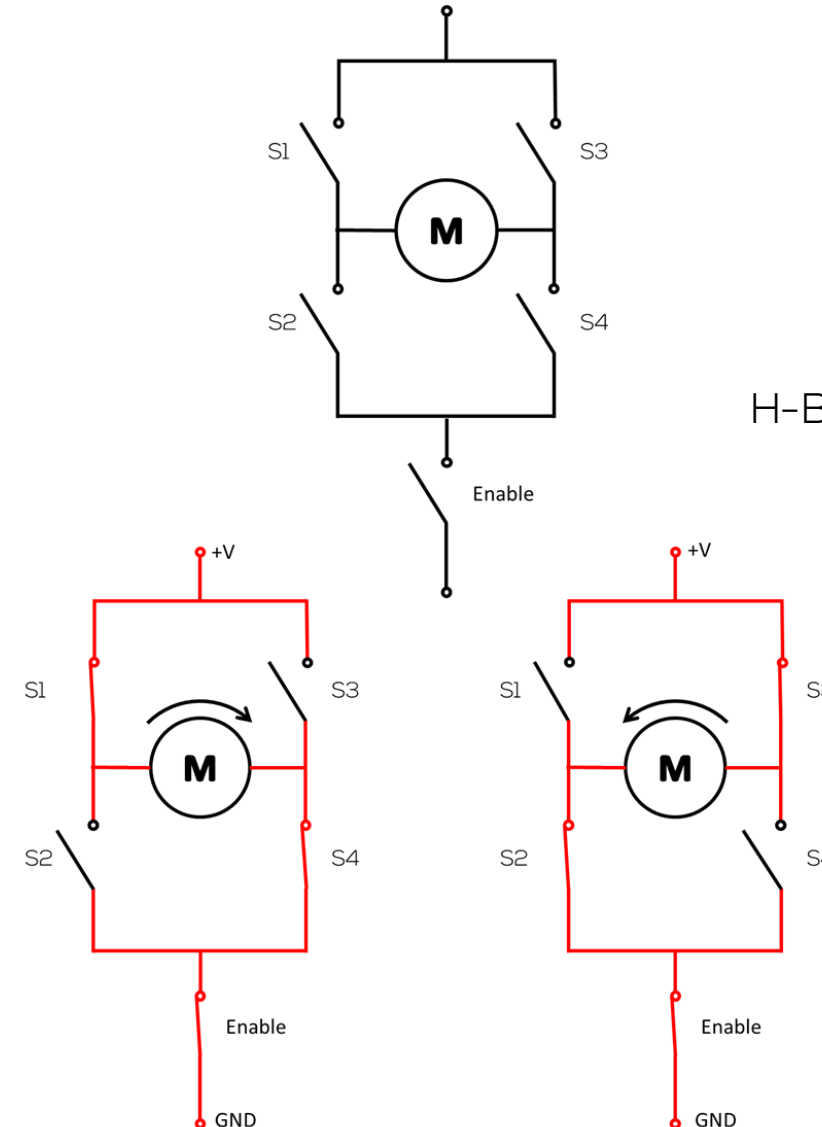
DC Motor Model Representation.

- In robotics, controllers are used to regulate the rotational speed, angular position or torque, required by the application.
- In robotics this is called low level control.
- For the case of a wheeled mobile robot is a common practice to implement a PID control to regulate the angular speed of the DC motors.
- The regulation of the angular speed or position of a motor, requires different stages.
 - Controller Stage
 - Power Stage (Driver)
 - Plant
 - Sensor Stage



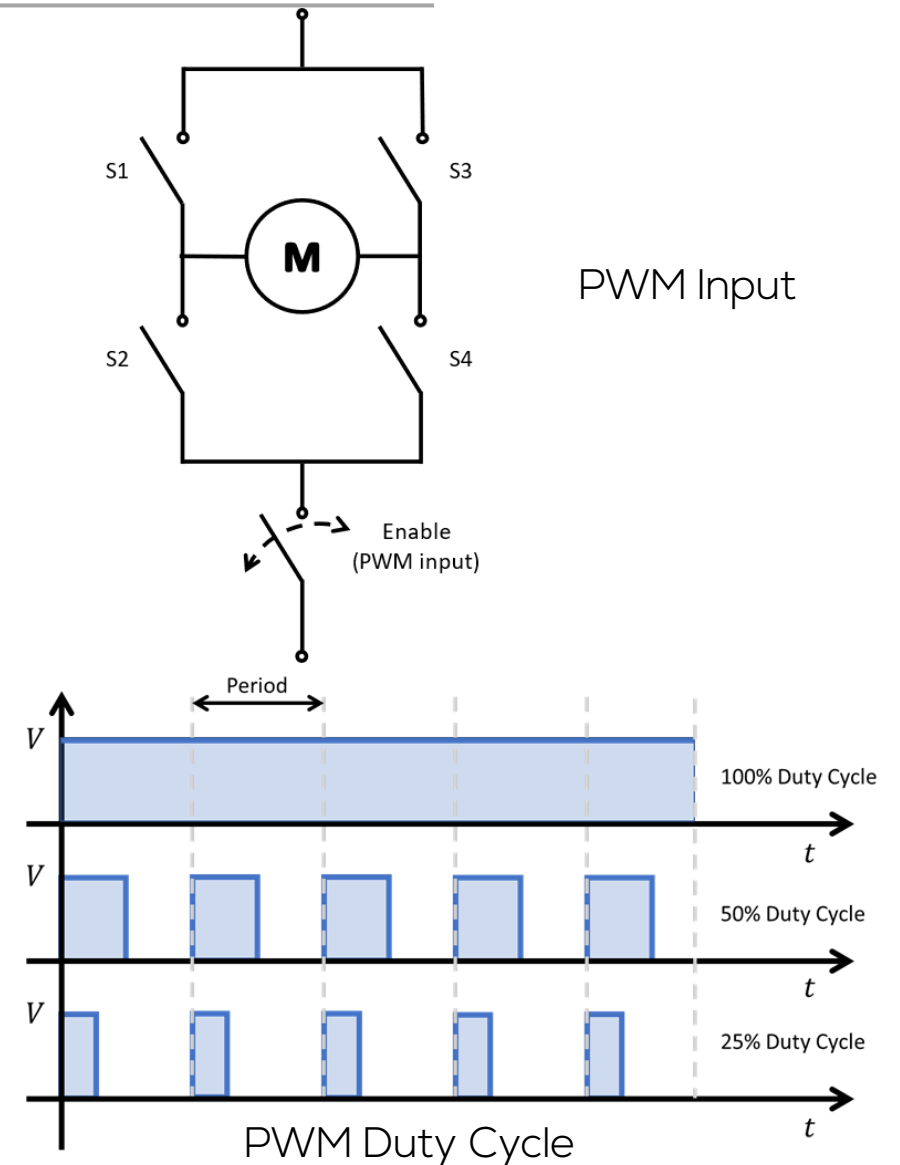
- H-bridge is an electronic circuit that switches the polarity of a voltage applied to a load.
- They work using a combination of switching components (mechanical switches, transistors, etc.), as shown in the diagram, to change the polarity to the load.
- H-Bridge Drivers are some of the most common motor drivers used in the control DC motors to run forwards or backwards.

S1	S2	S3	S4	Motor
0	0	0	0	Motor Off
1	0	0	1	Right Turn
0	1	1	0	Left Turn
1	1	0	0	Short Circuit
0	0	1	1	Short Circuit

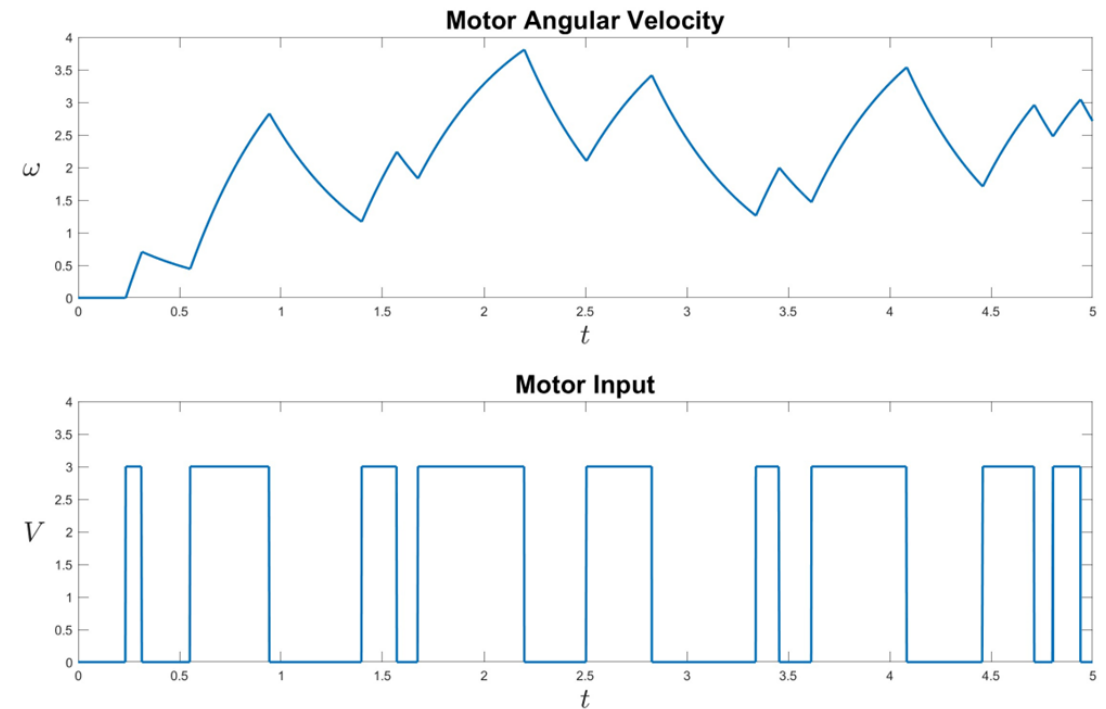


H-Bridge motor Driver Diagram

- Another capability of the motor driver is to regulate the angular speed of the motor.
- There are many ways to obtain this result, one of the most common one is to send a PWM (Pulse width modulated signal) to the enable pin of the H-Bridge.
- PWM (Pulse Width Modulation): Is a technique used in engineering to control the average power delivered by an electrical signal, by dividing it into discrete parts.
- In practice this is accomplished by rapidly turning the switch between the load and the source (enable switch), ON and OFF.



- Given that the motor can be modelled as a second order systems, when applying a PWM voltage as an input, it is possible to observe the output behaviour as in the figure.
- This behaviour, can be used to control the power give to the motor and therefore controlling the motor angular speed.



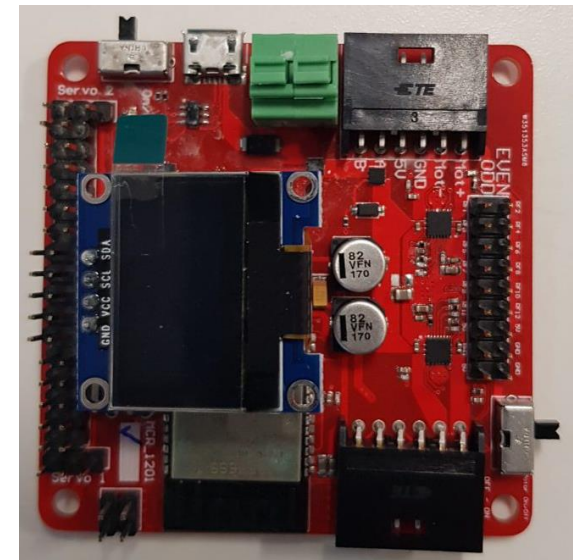
Motor Output/Input



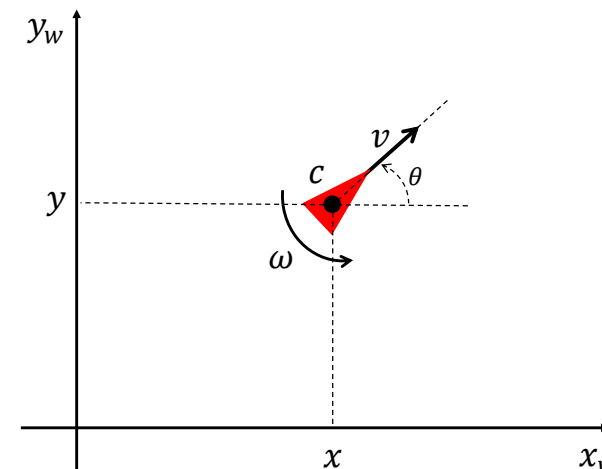
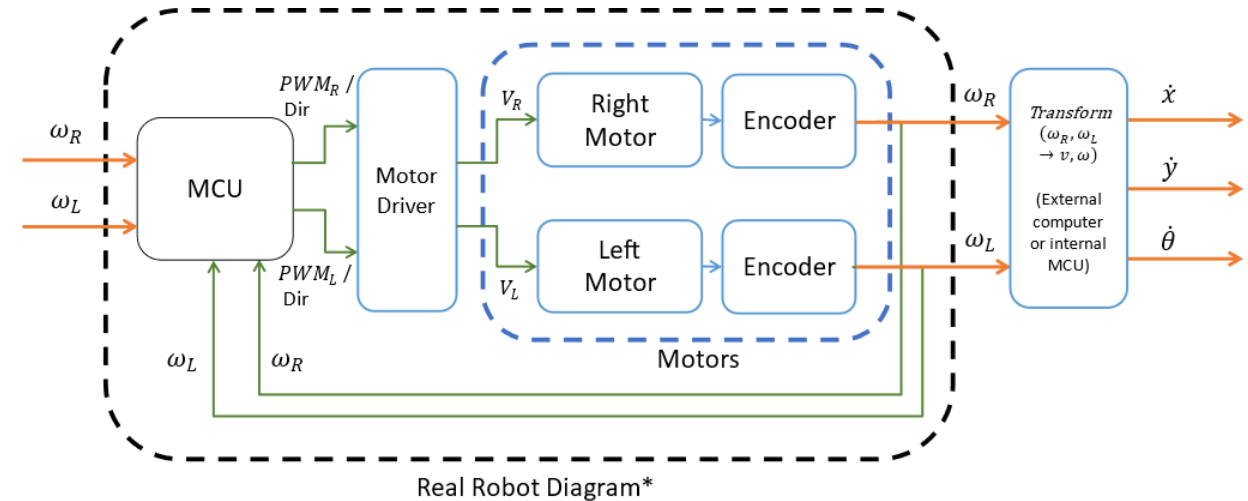
MCU



- A microcontroller is a compact integrated circuit. They are made to perform a specific operation in an embedded system.
- In robotics they are usually in charge of the low-level control of the robot, such as motors, and sensors or actuators that require a dedicated and fast controller to work.
- A typical microcontroller includes a processor, memory and input/output (I/O) peripherals on a single chip.
- For the case of the PuzzleBot:
 - ESP32-based Microcontroller
 - Xtensa dual-core 32-bit LX6 microprocessor
 - 520 KB of SRAM
 - WiFi & Bluetooth
 - DC-DC Converter
 - Motor Driver
 - 0.96" I2C LCD Display

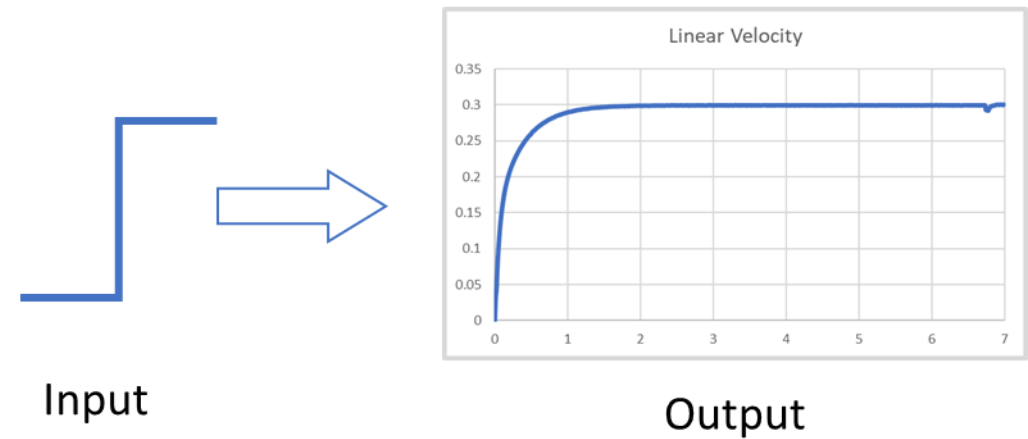
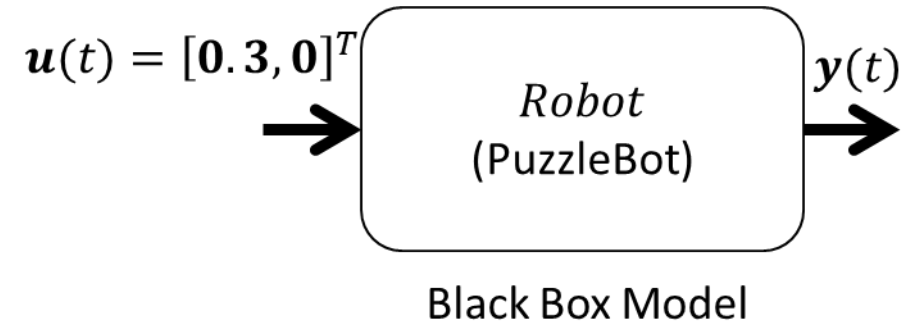


- The real robot, requires the combination and usage of the previously shown sensors and actuators to work.
- For the real robot, a closed control loop for each of the motors is required, in order to reach the required velocities, set by the user.
- In robotics this is called low level control. For the case of a wheeled mobile robot is a common practice to implement a PID control.
- It can be observed that the inputs to the robot are the speed of the wheels $u(t) = [\omega_r, \omega_l]$, and the outputs are the wheel velocities that can be transformed into robot velocities $y(t) = [V, \omega]$.
- The inner loop controller and actuators will determine the behavior of the robot.



Differential Drive Robot Representation.

- Let the system (in this case the robot) to be represented as a black box and let only constant linear velocity of $v = 0.3 \frac{m}{s}$ to be the input to the system (step input).
- It can be observed that the output of the system matches the input reference at steady state. Therefore, the gain of the system is said to be 1. **This gain is only for the robot system for any other system the system's gain must be estimated.*
- A more in-depth analysis of this situation reveals that this is due to the inner controllers of the robot, allows the robot to follow the reference after some transient. The same thing happens with the angular speed.



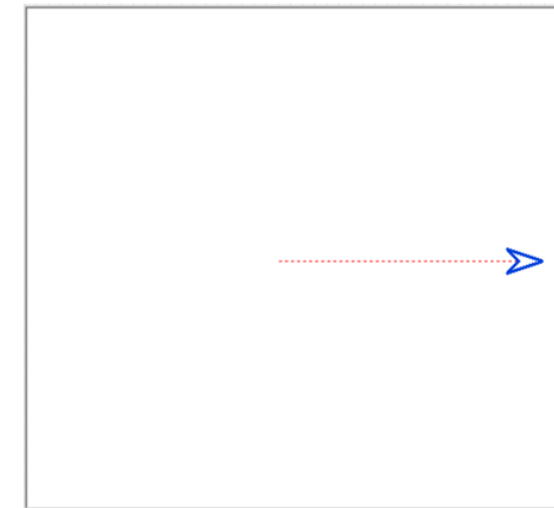
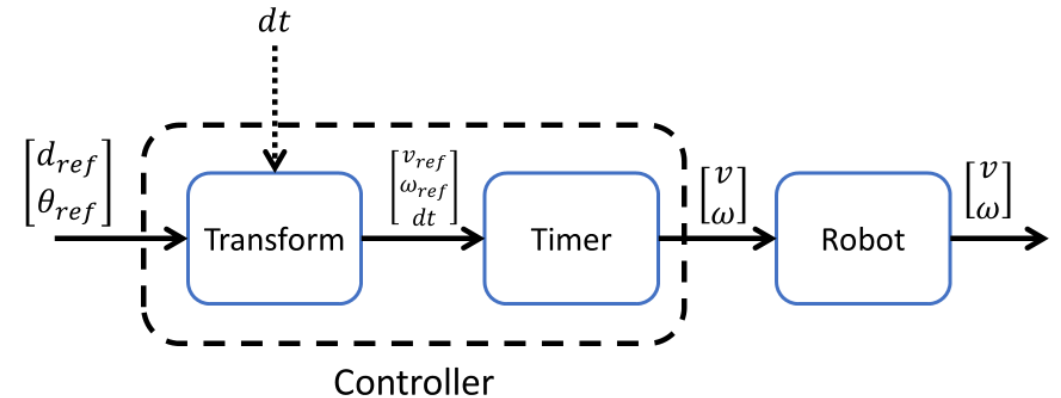
- Knowing that the system's output will follow the input after a transient, a question arises. Can we use this information to move the robot a certain distance?
- Since we know that the output follows the input, it is possible to approximate the distance and angle traveled by using the following formula.

$$d = v \cdot dt = r \left(\frac{\omega_r + \omega_l}{2} \right) \cdot dt$$

$$\theta = \omega \cdot dt = r \left(\frac{\omega_r - \omega_l}{l} \right) \cdot dt$$

where dt is the time since the input was applied.

- Therefore, it is possible to use a timer to control the distance and angle travelled by the robot.
- This is called open loop control.



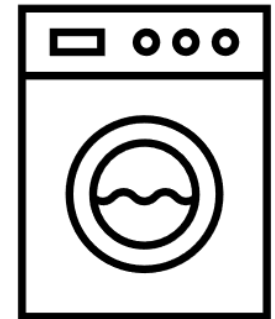
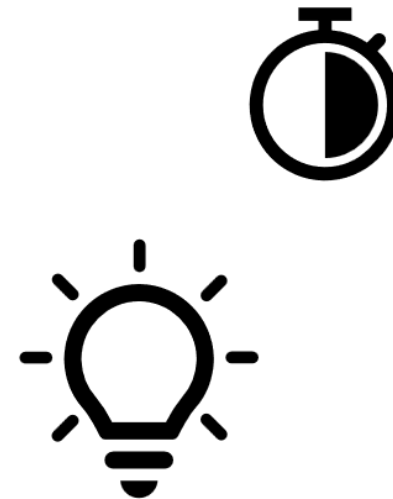
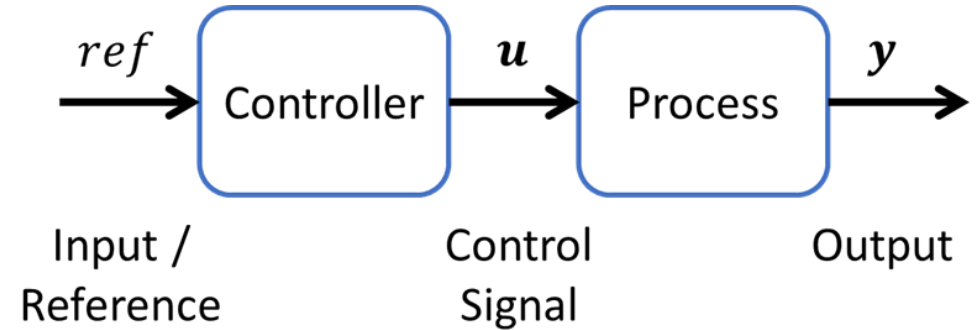
Open Loop Control



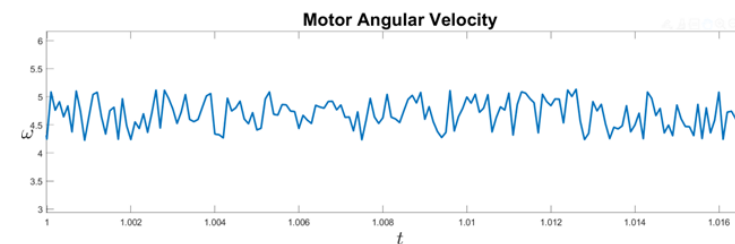
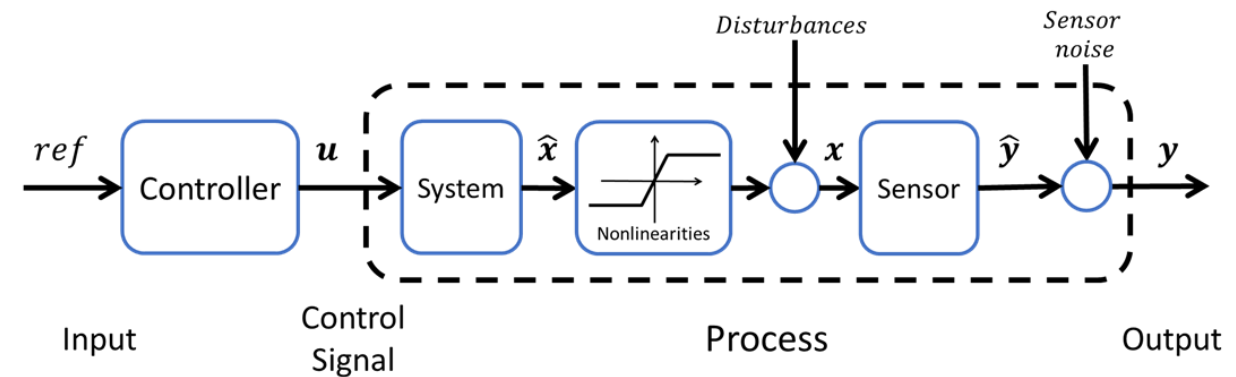
Open Loop Control



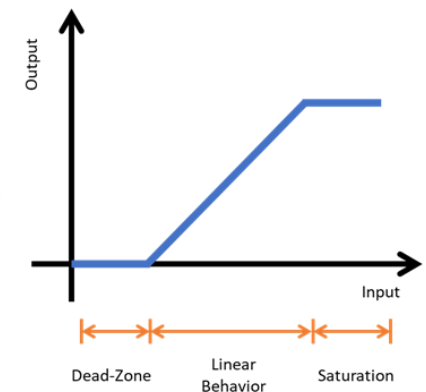
- Open Loop Control System is a system in which the control action is independent of the output of the system.
- In this type of control, the output is regulated by varying the input or reference.
- The output of the system is determined by the current state of the system and the inputs that are received from the controller.
- Some examples of this type of control systems are Windows, window blinds, washing machines, microwave ovens, hair drier, bread toaster, Door Lock System, some stepper motors, turning on/off lights, some remote-controlled applications, etc.



- Every process, present disturbances, nonlinearities and noise.
- Disturbances and noise come from the environment that surrounds the system.
 - On the differential drive robot, some disturbances can come from wheels slipping, obstacles on the environment, different types of terrain, etc.
 - On the other hand, the noise is present when reading the values of the motor encoders (Sensors).
- Nonlinearities are an intrinsic characteristic of a system in which the output does not linearly follow the input (output not proportional to the input).
 - For the case of the robot, the nonlinear behavior can be seen as a saturation and dead-zone in the motors and the robot itself.



Noisy Signal (Angular velocity)



Nonlinear behavior

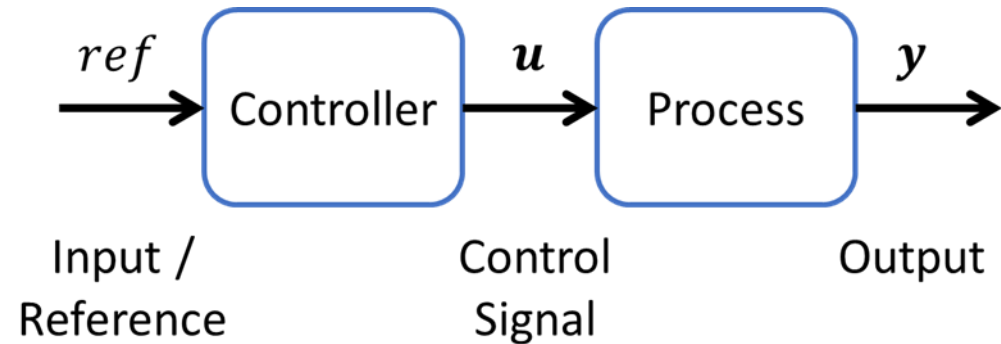


Open Loop Control



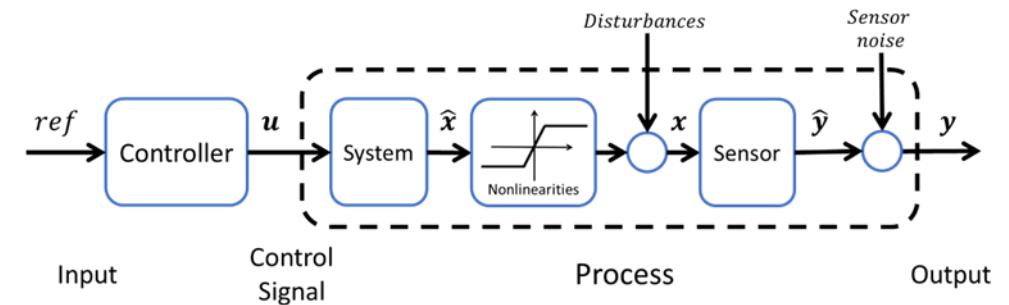
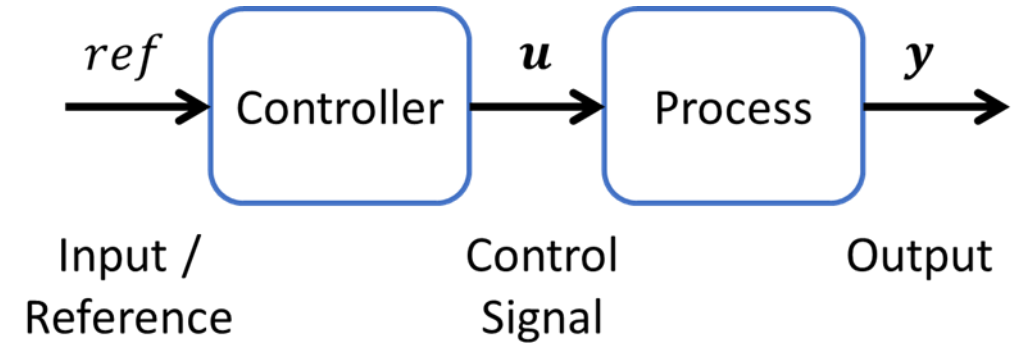
Open Loop Advantages:

- Simple to design and implement, provided that the user has some experience with the system.
- The cost for design, implement and maintain is relatively low compared with other controllers.
- Maintenance is considered simple, no high technical level required (for most of the controllers).
- The behavior of the controller is quite stable, provided that the system is in a controlled environment, such that the process does not present big disturbances, or the process is not dangerous when unsupervised.



- Open Loop Disadvantages:

- This type of control is not robust against disturbances (cannot correct the output in the presence of a disturbance).
- An open-loop system has no self-regulation or control action over the output value.
- Not reliable
- The input depends on the experience of the user.
- Each input determines a fixed operating point of the system.
- Controller must be altered manually in case of an output disturbance or uncalibrated controller.
- Requires re-calibration often.
- Prone to errors in the output and control signal
- Does not take into consideration changes on the process over time.
- Also, there is no chance to correct the transition errors in open loop systems so there is more chance to occur errors.

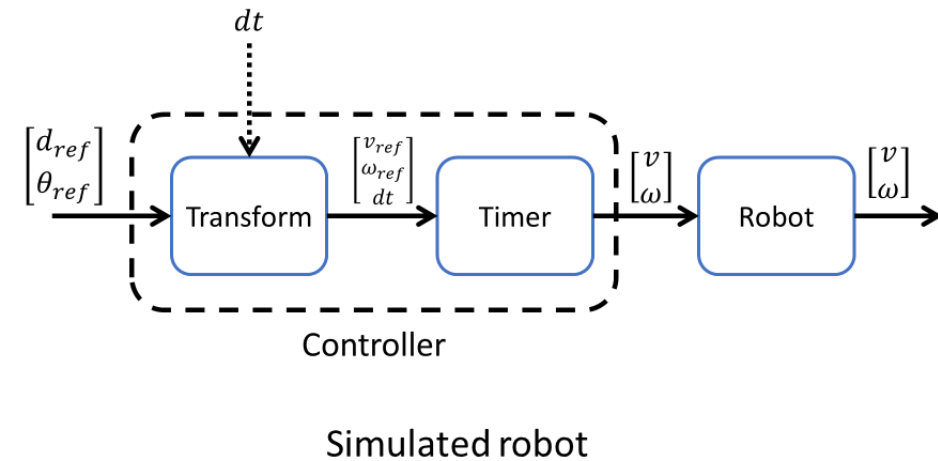
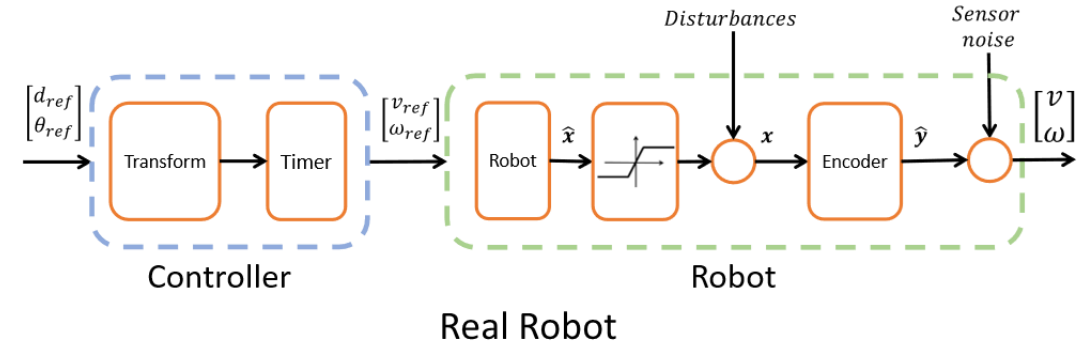




Open Loop Control: Mobile Robot



- As stated before, open loop control can be used to control the position of the robot.
- When designing this controller, the nonlinear behavior, perturbations and noise should be taken into consideration to make the controller work on the linear part of the robot and make it as robust as possible.
- In this case, the real mobile robot is a nonlinear system, due to the maximum and minimum velocities of the motors therefore it presents saturation and dead-zone.
*Other nonlinear behaviours are present, but they are not relevant in this case.
- The linear behaviour is present within a region in which the actuators (motors) output are proportional to the input.

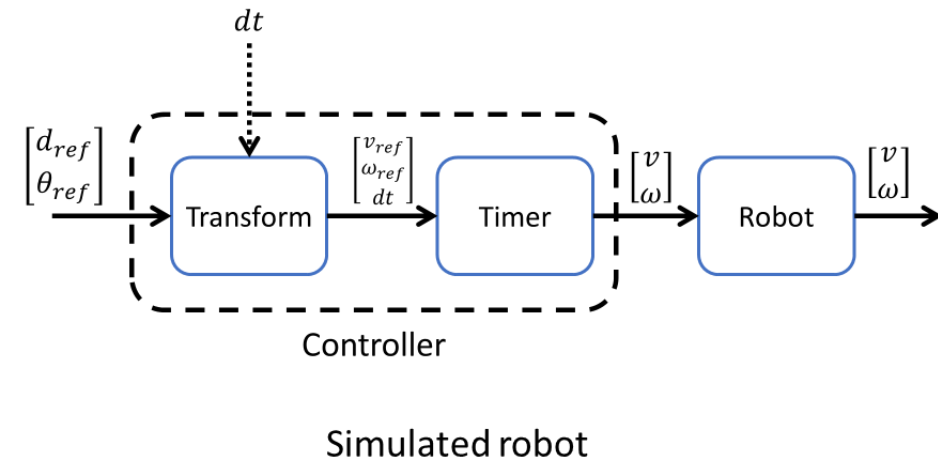
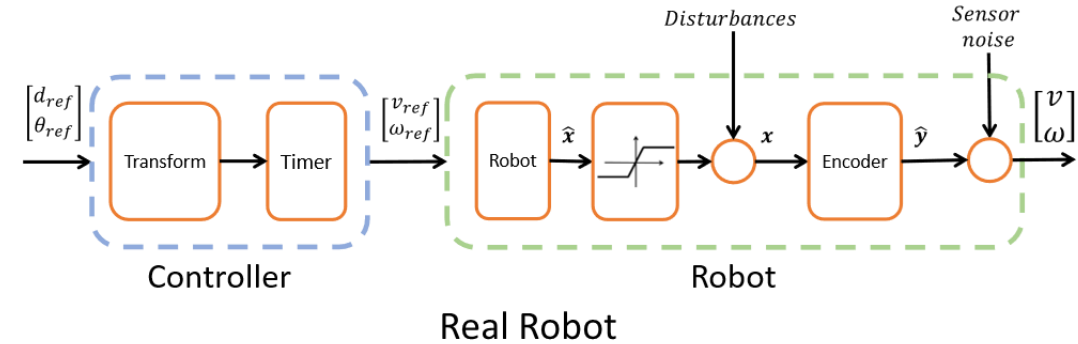




Open Loop Control: Mobile Robot



- Noise and perturbations can also be found in the robot.
- As said before, noise can be found in the encoder reading, the noise can be due to electromagnetic noise or radiation, mechanical unbalance of encoders, etc.
- Disturbances are due to the mechanical unbalance of the wheels, wheel slippage with the floor, defects of productions, changes in the environment, etc.
- Depending on the simulator, the dynamical behavior of the robot can be linear or nonlinear and can consider the noise and disturbances.





Now is your turn...

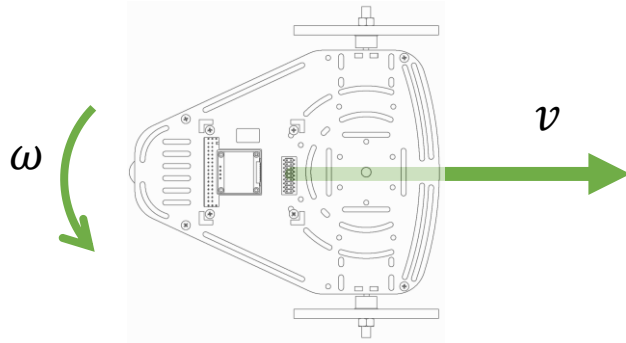


- The following activity will help you build an open loop controller for the Puzzlebot and the Gazebo simulation.
- Activity 1: Create a node that sends commands to the real robot and the gazebo simulation and move in a straight line for a period of time.



Activity 1: Moving a Puzzlebot

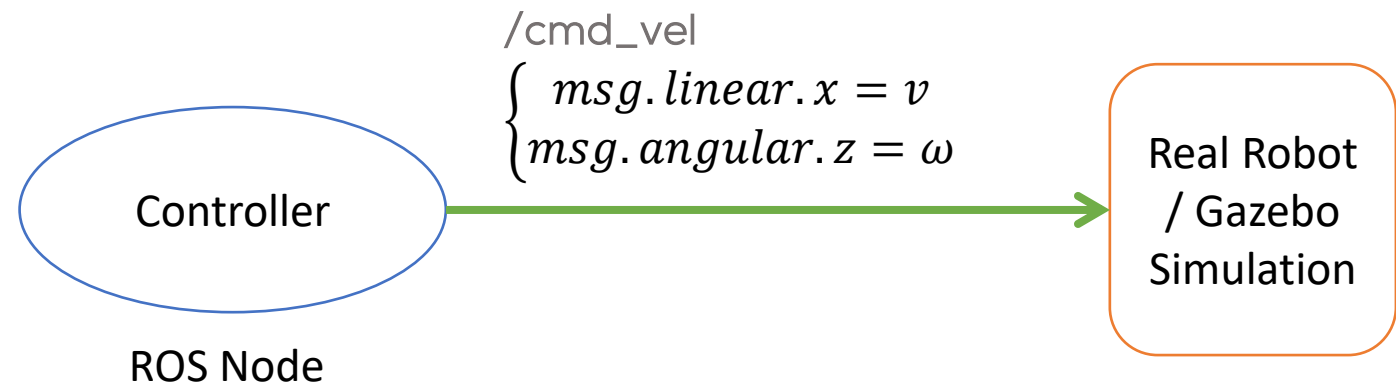
Straight line



Drive the robot 2 meters in a straight line.

- Objectives:

- Create an open loop control as a ROS node that sends commands to the robot gazebo simulation and move in a straight line for 2 meters.





Activity

Some tips and tricks



- One publisher `cmd_vel`
- `cmd_vel` – from `geometry_msgs.msg` import `Twist` – 3 linear and 3 angular velocities.
 - `msg.linear.x`, `msg.linear.y`, `msg.linear.z`
 - `msg.angular.x`, `msg.angular.y`, `msg.angular.z`
- Use the equations below to compute the distance moved and the angle turned by the robot

$$d = v \cdot dt = r \left(\frac{\omega_r + \omega_l}{2} \right) \cdot dt$$

$$\theta = \omega \cdot dt = r \left(\frac{\omega_r - \omega_l}{l} \right) \cdot dt$$

where r is the radius of the wheels (0.05 m) and l is the distance between the wheels (0.18 m)

- Use `rospy.get_time()` to measure the time dt between each loop
- If the robot is not moving, check your topics with `rostopic echo` and `rostopic pub`
- Ensure your python file is executable: `sudo chmod +x <path_to_file>.py`
- Ensure you source your file: `source devel/setup.bash`

