{Learn, Create, Innovate};

Mobile Robots

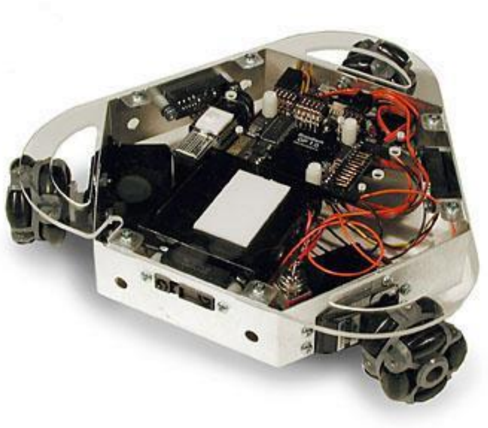
Introduction

MCR2

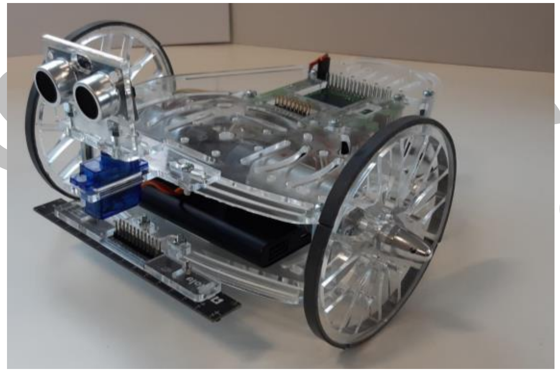
Manchester **Robotics**

Mobile Robots

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



Holonomic Robot
Acroname ©.



Differential-drive
Puzzlebot ©.

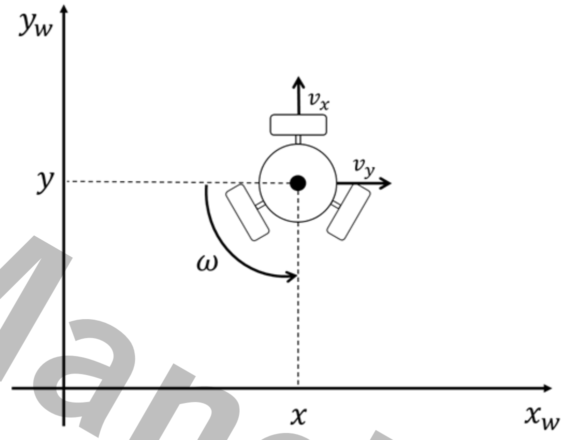
Mobile Robots

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

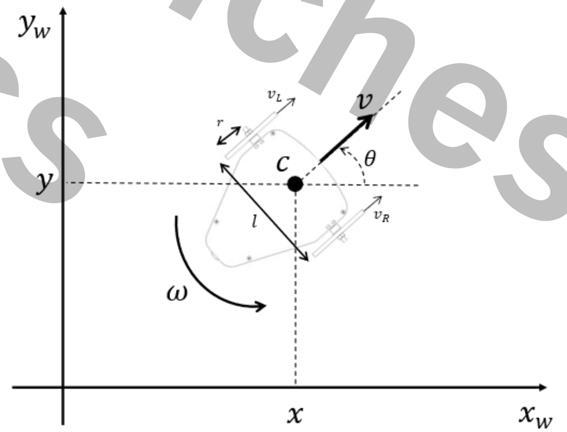
- This classification depends on the relationship between controllable and total degrees of freedom of a robot.

- **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.



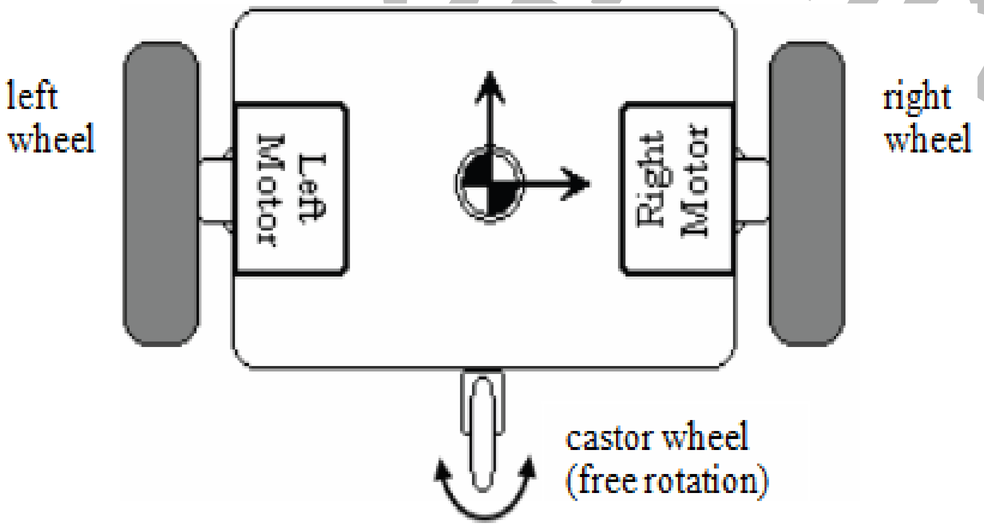
Holonomic Robot



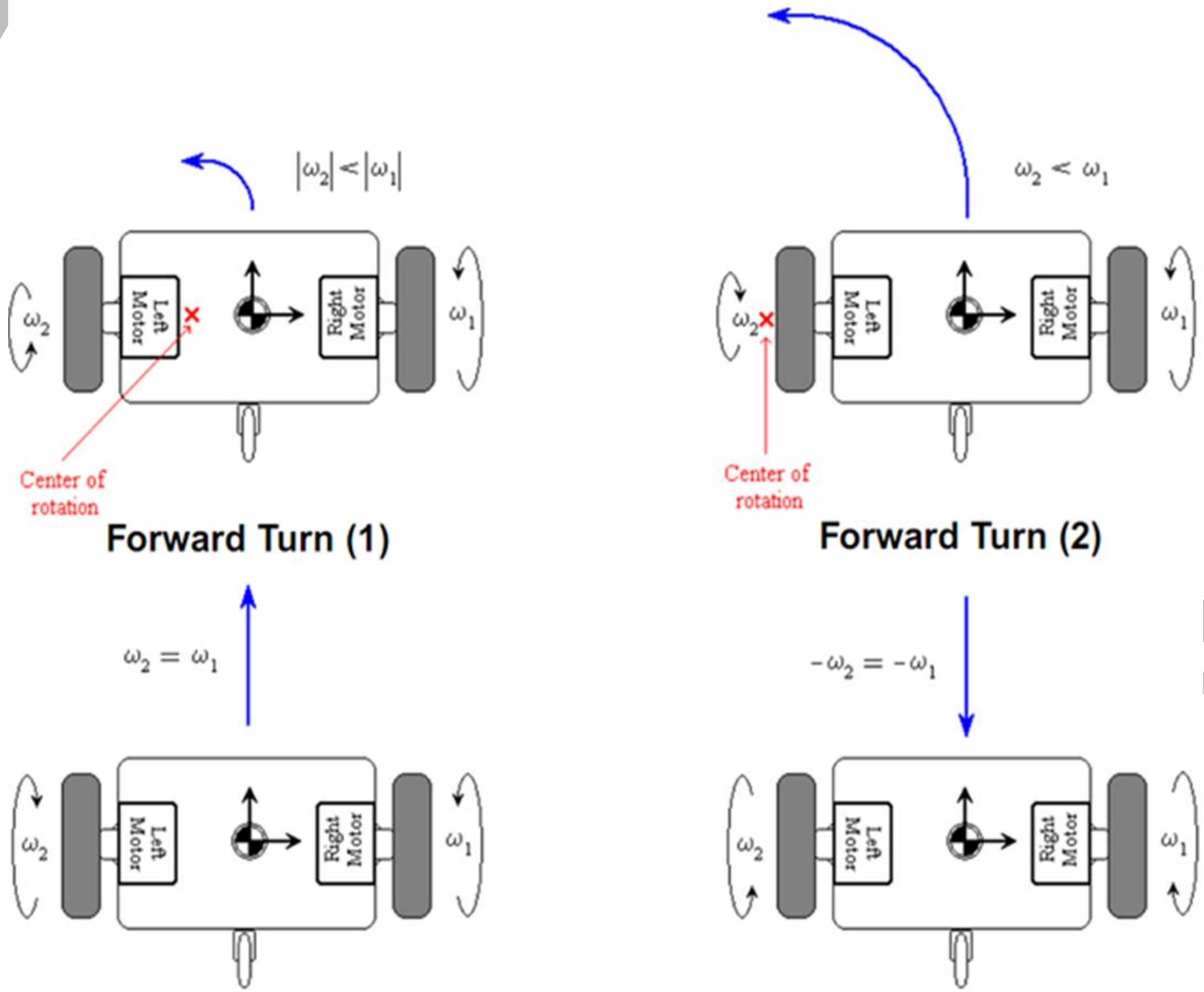
Nonholonomic Robot

Differential drive robots

- Also known as differential wheeled robots, these are mobile robots whose movement is based on two separately driven wheels placed on either side of the robot body. It can thus change its direction by varying the relative rate of rotation of its wheels, thereby requiring no additional steering motion.



Differential drive kinematics



Robot Modelling (Kinematics)

- In engineering, a System is an entity that consists of interconnected components, built with a desired purpose. For this case, the system is said to be the differential drive robot.
- Systems can be modelled depending on their dynamical behavior. This models describe the behavior of a system using mathematical concepts and language.
  - Outputs depend on the present and past values of the inputs.
  - Changes over time.
  - Sometimes called dynamic systems or sequential systems.
  - Mathematically described with differential or difference equations.
- **Dynamic Modelling:** Considers different time varying phenomena and the interaction between motions, forces and material properties.
- **Kinematic modelling**: Studies the motion of a robot or mechanism under a set of constraints, regardless of the forces that cause it. Represent the relationship between the robot motor speeds (inputs) and the robot state.

DC Brushed Motor with encoder

$$In \rightarrow \boxed{\frac{K}{s^2 + 2\zeta\omega_n s + \omega_n^2}} \rightarrow Out$$

2nd Order System

The Unicycle

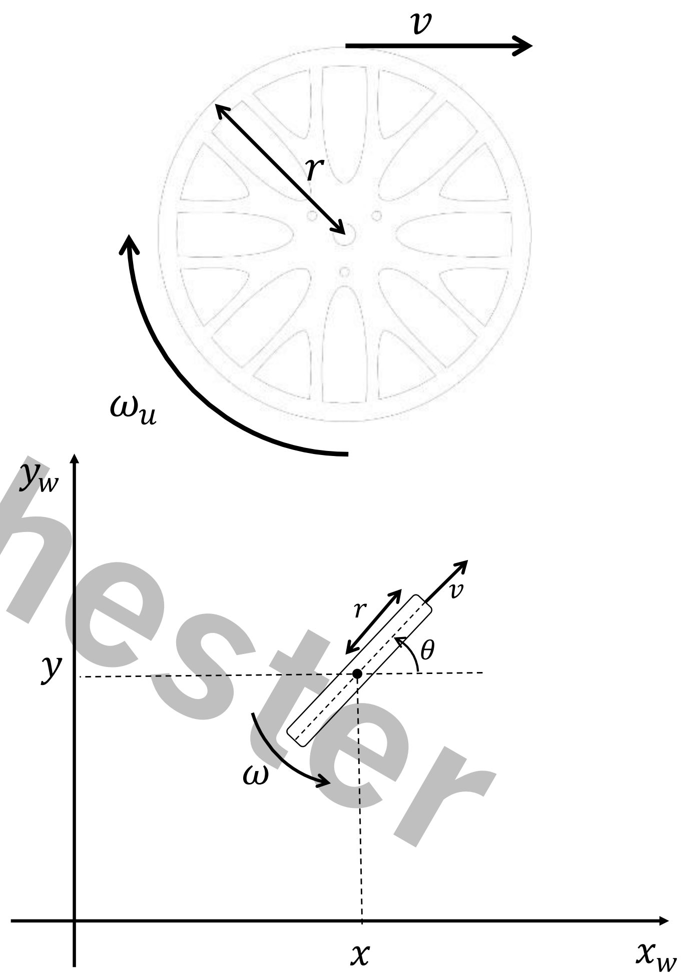
- In order to derive the kinematics of a differential drive robot, it is instructive to first consider a simpler system; the unicycle.
- Ignoring balancing concerns, there are two action variables, i.e., direct inputs to the system in the x_w, y_w plane.

$$\begin{cases} \dot{x} = v \cdot \cos\theta \\ \dot{y} = v \cdot \sin\theta \\ \dot{\theta} = \omega \end{cases}$$

where $v = \omega_u\, r$ is the linear velocity of the unicycle, ω_u is the wheel angular velocity, r is wheel radius whereas the second one is the steering velocity denoted by ω.

- It can be seen, that velocity component in the direction perpendicular to the direction of movement is always zero this is known as the non-slip condition

$$\dot{x} \cdot sin\theta - \dot{y} \cdot cos\theta = 0$$



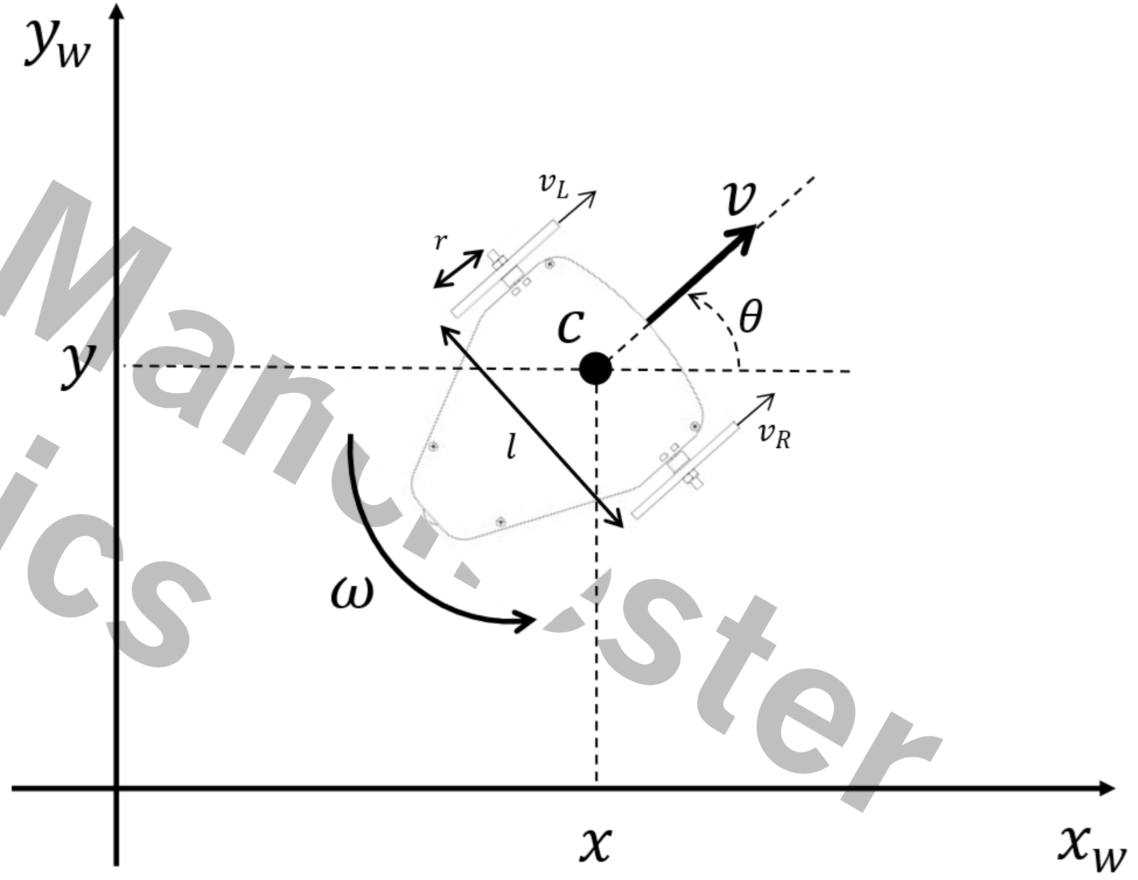
Unicycle side and top views

Differential Drive Kinematics

- For the case of a differential drive system, we can extend the idea of the Unicycle.
- To do this it is necessary to estimate the forward velocity v and the angular velocity ω.
- For this case, the resultant forward velocity v through C (centre of mass) may be reasoned as an average of the two forward wheel velocities given by

$$v = \left(\frac{v_R + v_L}{2}\right) = r\left(\frac{\omega_R + \omega_L}{2}\right)$$

where r is the radius of the wheel and ω_R, ω_L are the angular velocities of the left and right wheels, respectively.



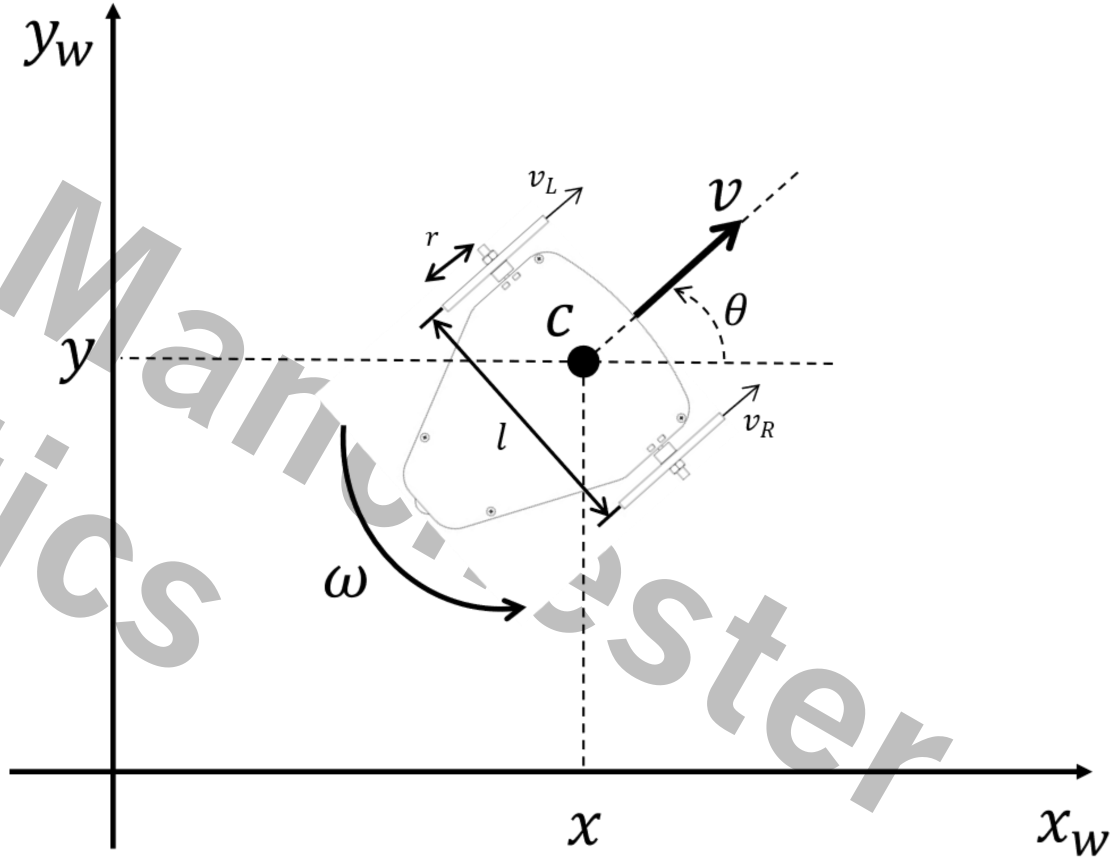
Differential Drive Robot
Puzzlebot ©.

Differential Drive Kinematics

- The resultant angular velocity ω (steering velocity), may also be reasoned as proportional to the difference between wheel velocities but inversely proportional to distance between the wheels, i.e.,

$$\omega = \left(\frac{v_R - v_L}{l}\right) = r \cdot \left(\frac{\omega_R - \omega_L}{l}\right)$$

  where r is the radius of the wheel, l is the distance between wheels (wheelbase) and ω_R, ω_L are the angular velocities of the left and right wheels, respectively.



Differential Drive Robot
Puzzlebot ©.

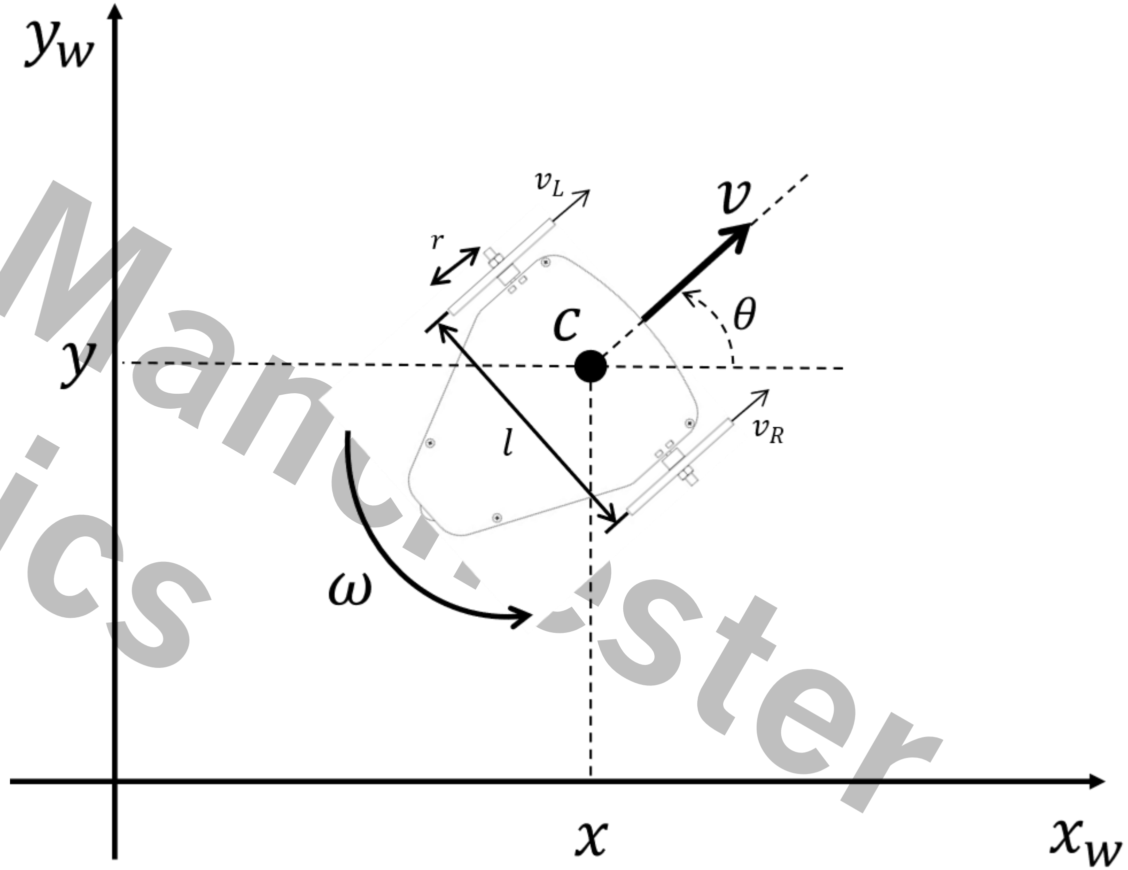
Differential Drive Kinematics

- Thus, just like the unicycle, the configuration transition equations may be given as

$$\begin{cases} \dot{x} = v \cdot cos\theta \\ \dot{y} = v \cdot sin\theta \\ \dot{\theta} = \omega \end{cases}$$

- Replacing v and ω we obtain

$$\begin{cases} \dot{x} = r\left(\dfrac{\omega_R + \omega_L}{2}\right) \cdot \cos\theta \\ \dot{y} = r\left(\dfrac{\omega_R + \omega_L}{2}\right) \cdot \sin\theta \\ \dot{\theta} = r\left(\dfrac{\omega_R - \omega_L}{l}\right) \end{cases}$$



Differential Drive Robot
Puzzlebot ©.

Differential Drive Kinematics

- In general, in the mobile robotic community, the state of a robot is denoted by s, namely the *pose* or *posture*, for this case it consists of the robot position and orientation with respect to a frame of reference (world frame).

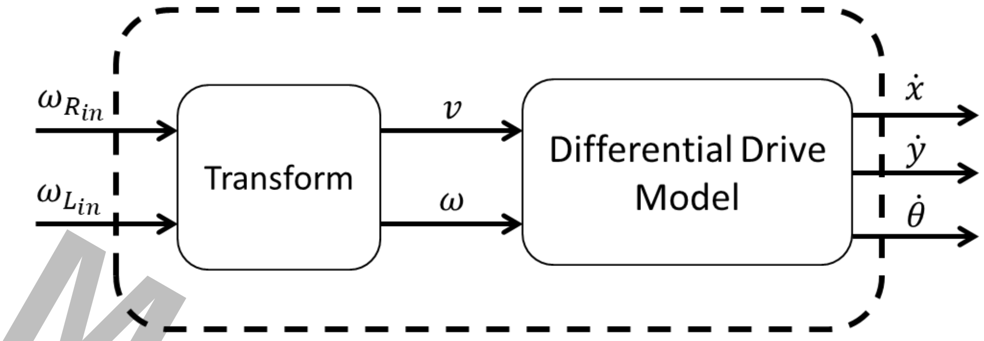
$$\mathbf{s} = [s_x \quad s_y \quad s_\theta]^T$$

- The kinematic model of a differential drive robot can then be stated in terms of the robot *pose* ($\mathbf{s}$), as follows

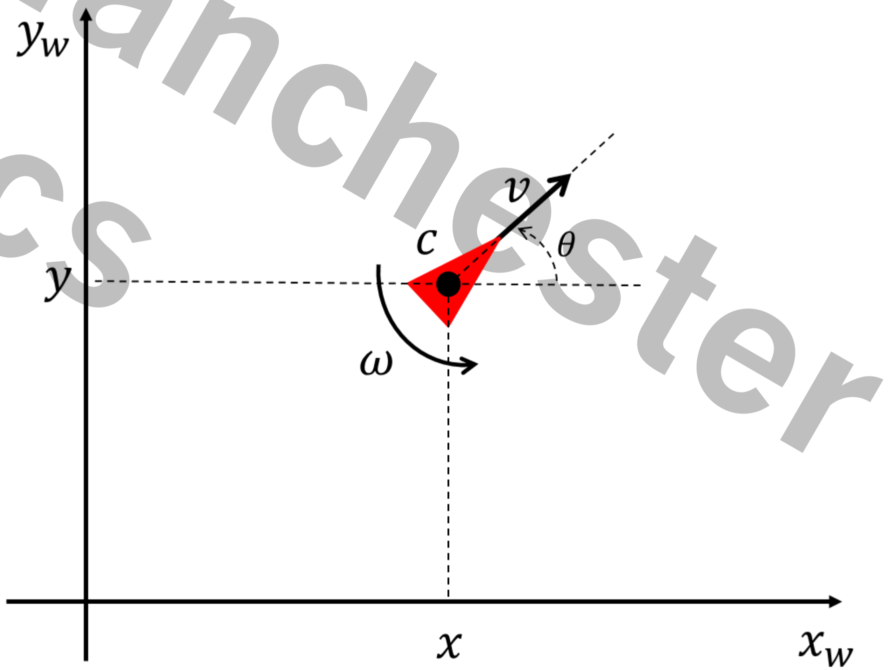
$$\frac{d}{dt}\begin{bmatrix} s_x \\ s_y \\ s_\theta \end{bmatrix} = \begin{bmatrix} \cos(s_\theta) & 0 \\ \sin(s_\theta) & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} v \\ \omega \end{bmatrix}$$

- where, the inputs to the system $\mathbf{u} = [v \quad \omega]^T$, are given by

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{l} & -\frac{r}{l} \end{bmatrix}\begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix}$$

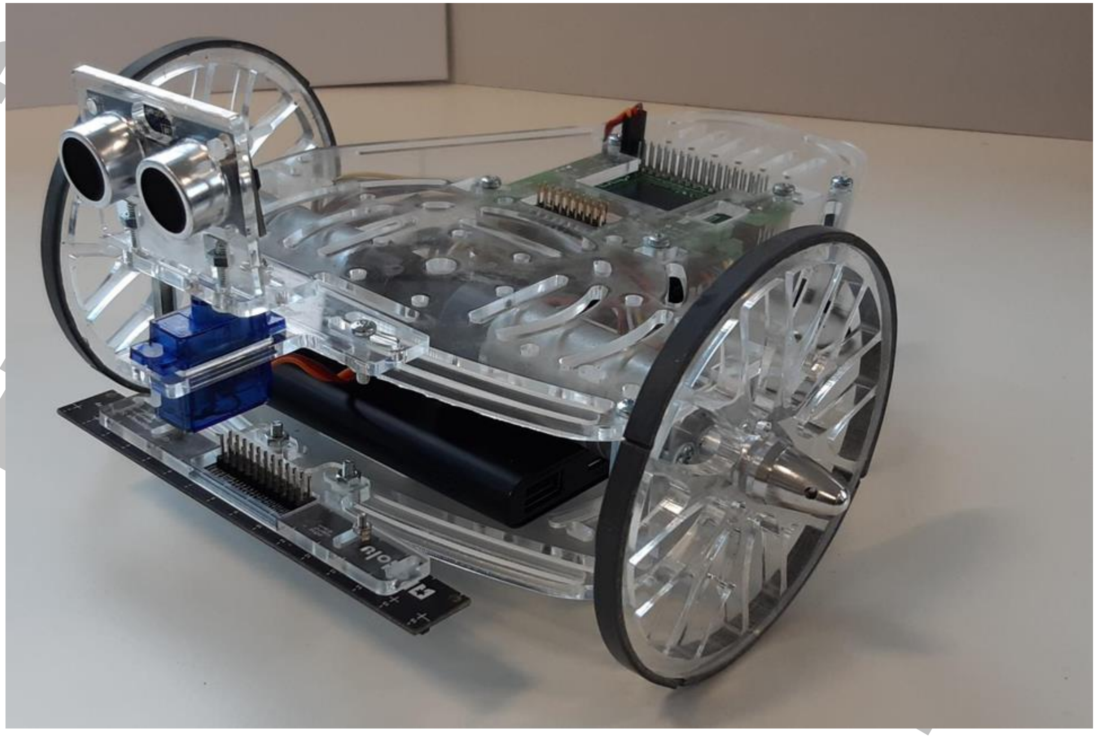


Kinematic Model



Sensors and Actuators for Differential Drive Robots

- As stated before, the kinematic model of a differential drive does not consider the physical characteristics and forces of the robot.
- This type of model is used when testing high level robotic algorithms (control) such as path planning, dead reckoning localization, trajectory tracking, AI, etc.
- Differential drive robots in reality, have sensors and actuators (motors, encoders, etc.) that allow us to control them to reach the correct speed required to correctly perform its functions.



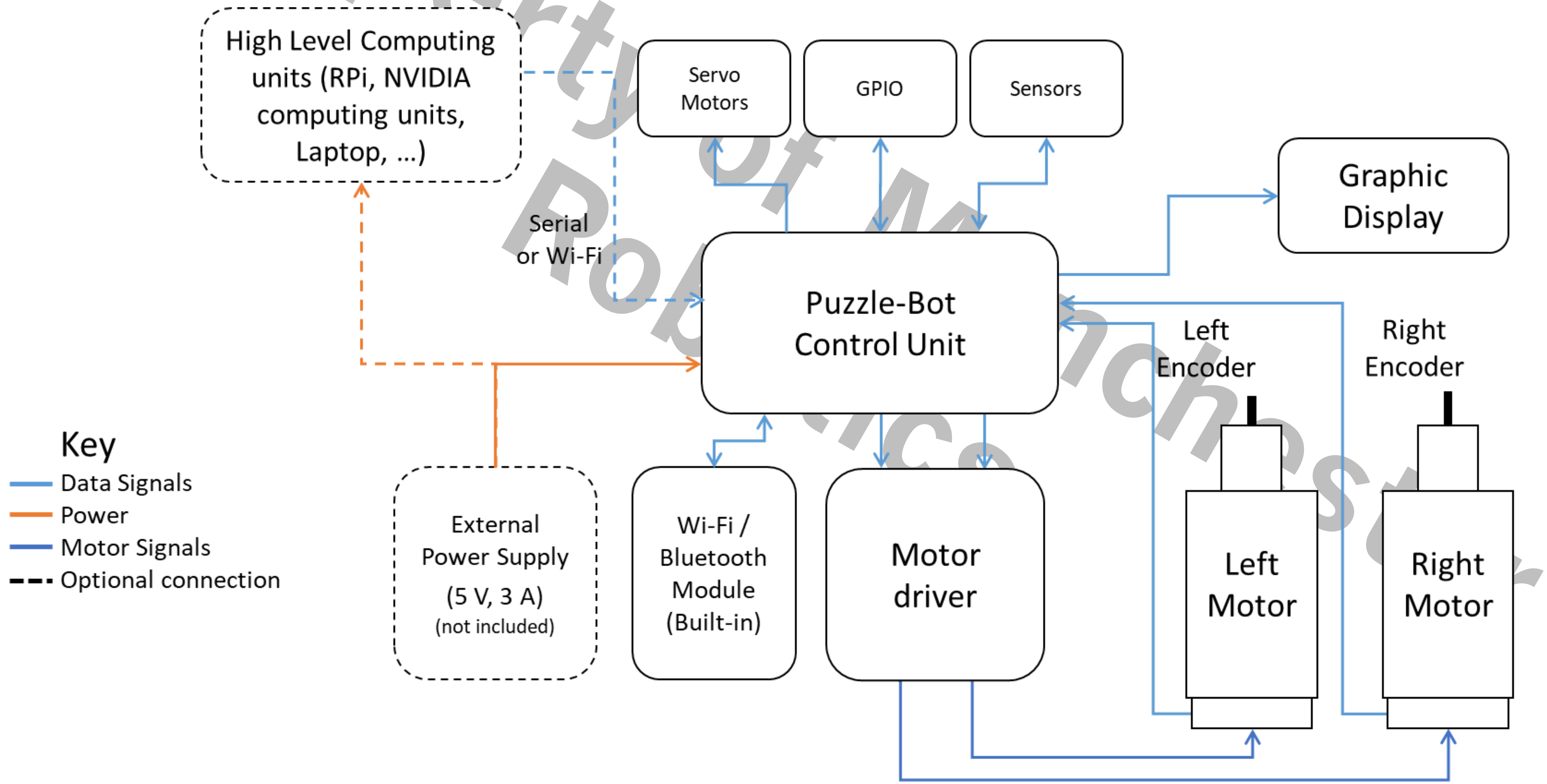
Differential Drive Robot Sensors and Actuators.

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.

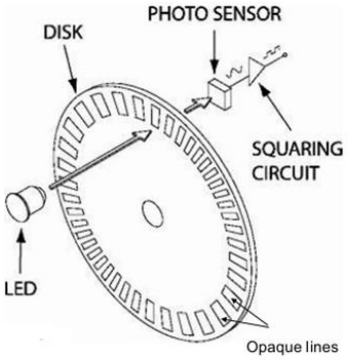
Sensors and Actuators.

Differential Drive Sensors and Actuators

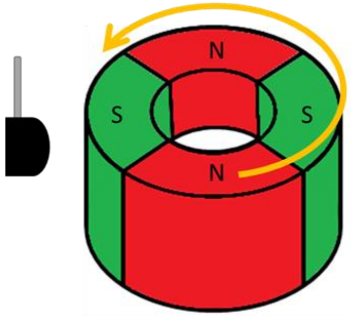


Encoders

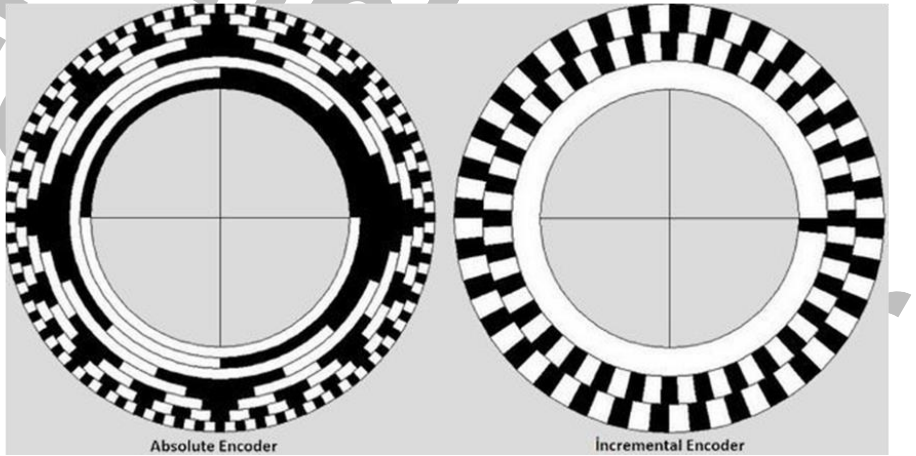
- Device that converts the angular position of a shaft (motor shaft) to an analogue or digital signal.
    - **Absolute:** Indicates the position of the shaft at all times, by producing a unique digital code for each angle (Angle transducers).
    - **Incremental:** Record the changes in position of 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



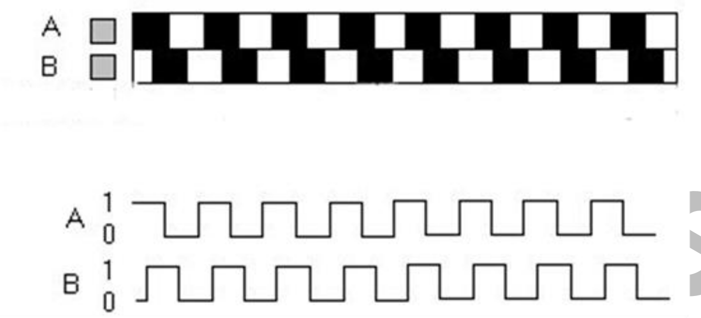
Encoders

- 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).

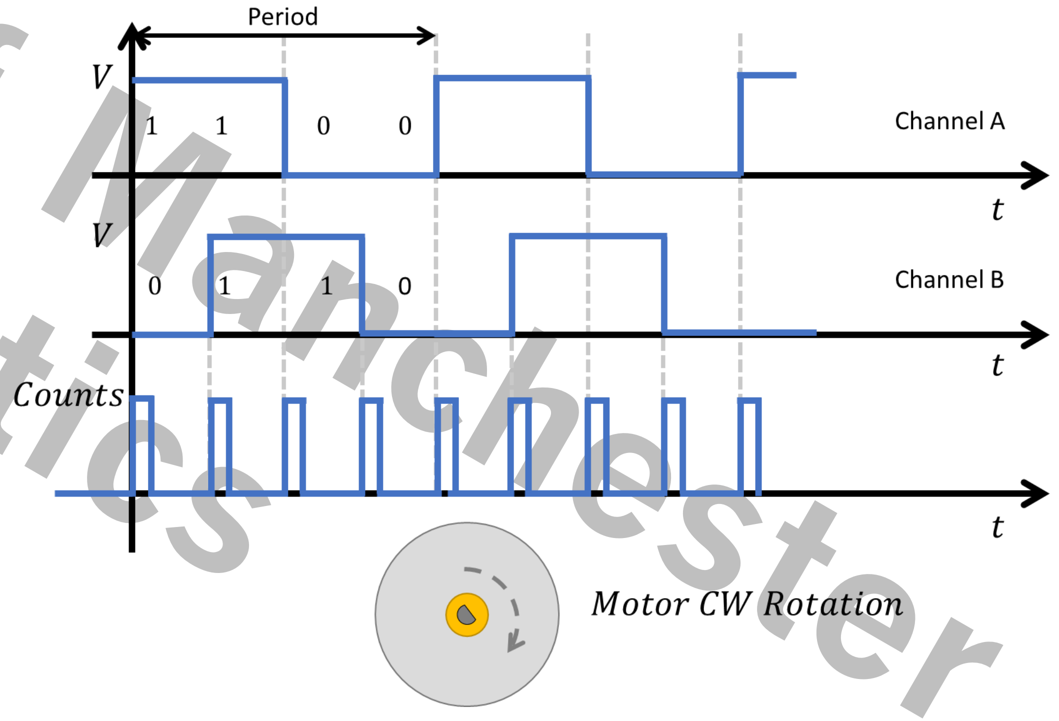
- Therefore, a second line (dual channel / channel B) is attached, having its signal shifted by 90 electrical degrees (°e) with respect to channel A.



Quadrature Encoder Output

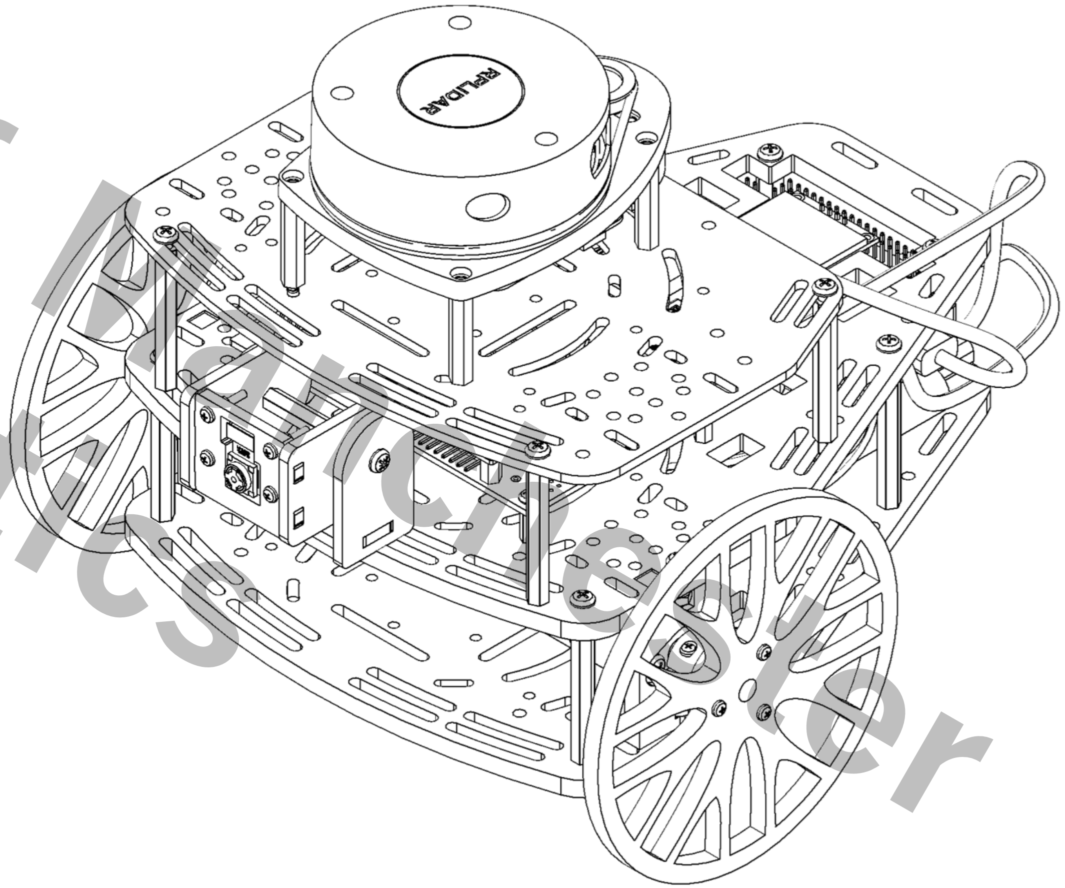
Encoders

- 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.



Encoders

- **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.

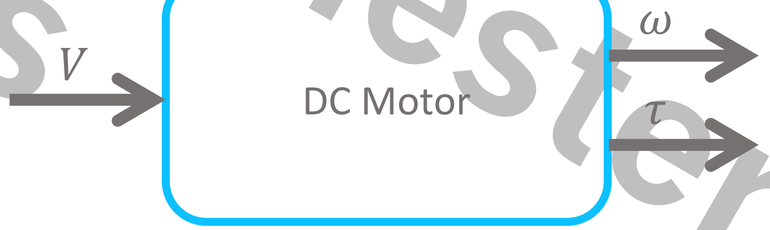


DC Motors

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.

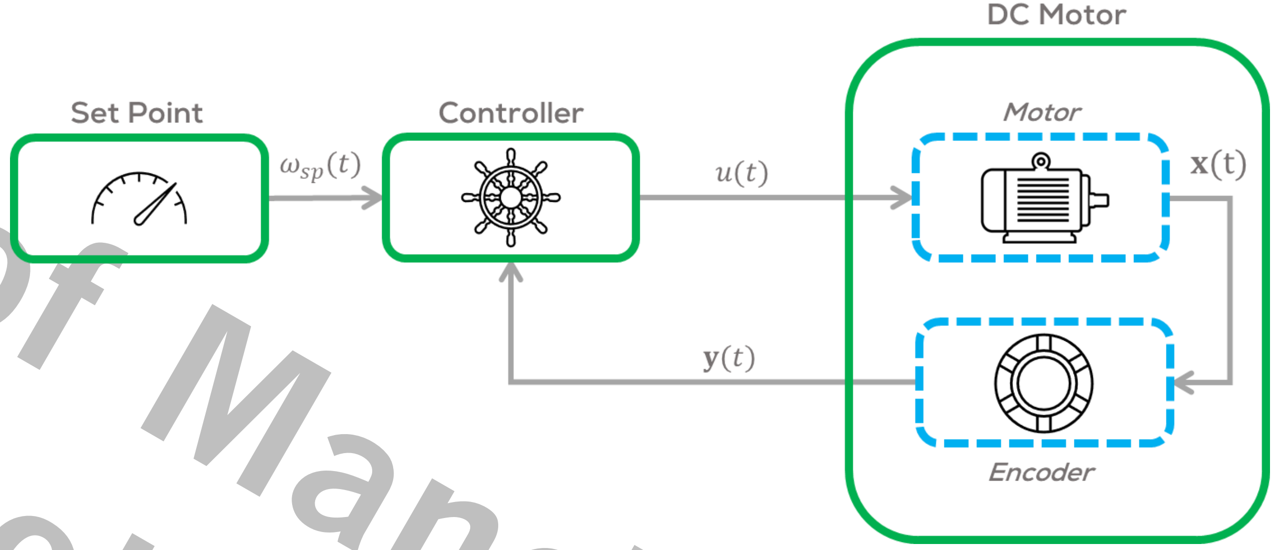
DC Brushed Motor with Encoder.

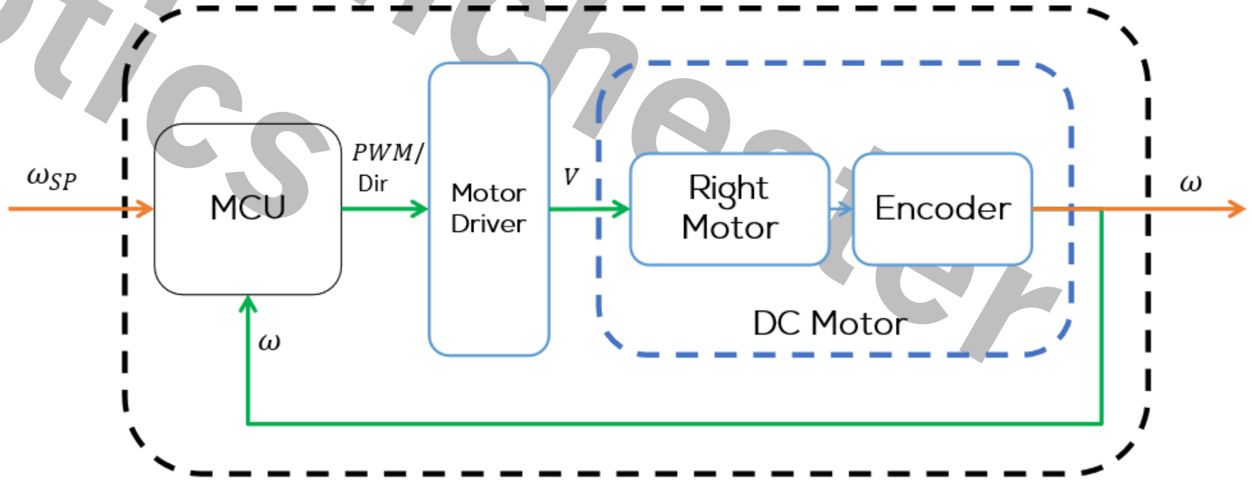


DC Motor Model Representation.

DC Motors

- 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

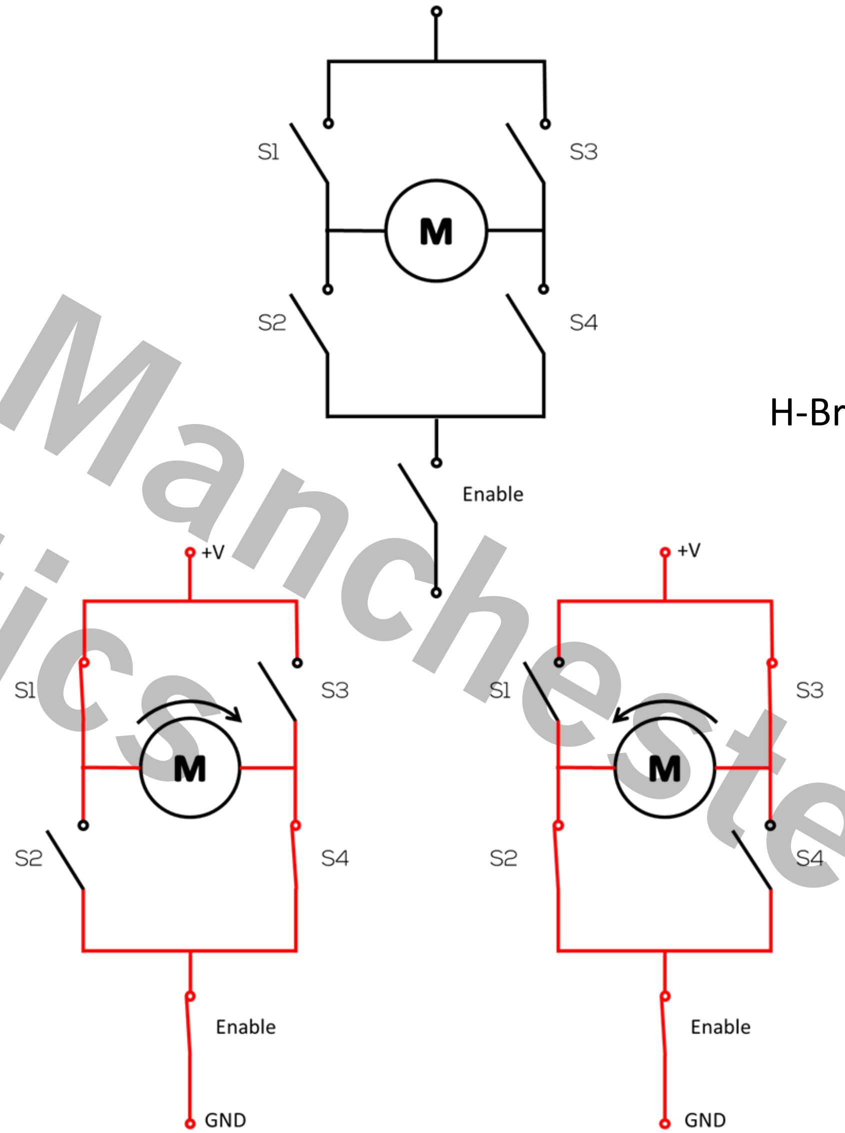




DC Motor Control Diagram*

Motor Driver

- 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.

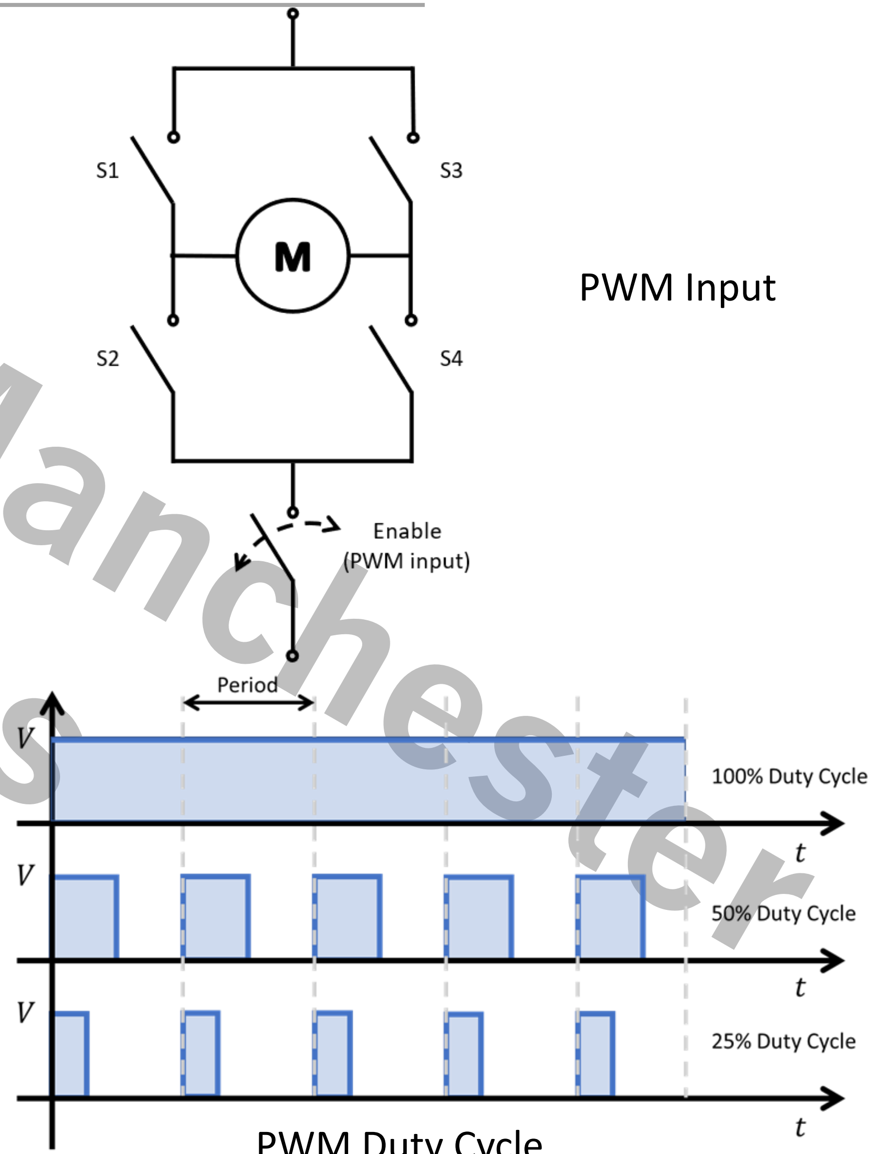


H-Bridge motor Driver Diagram

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

Motor Driver

- 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.

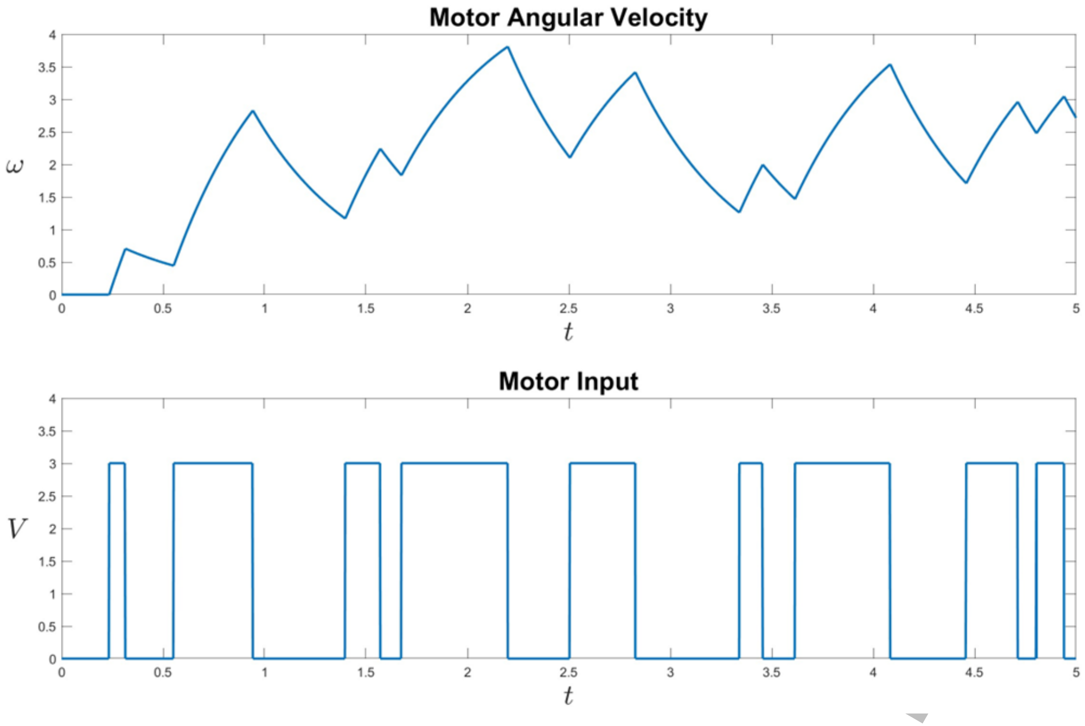


PWM Duty Cycle

Motor Driver

- 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.

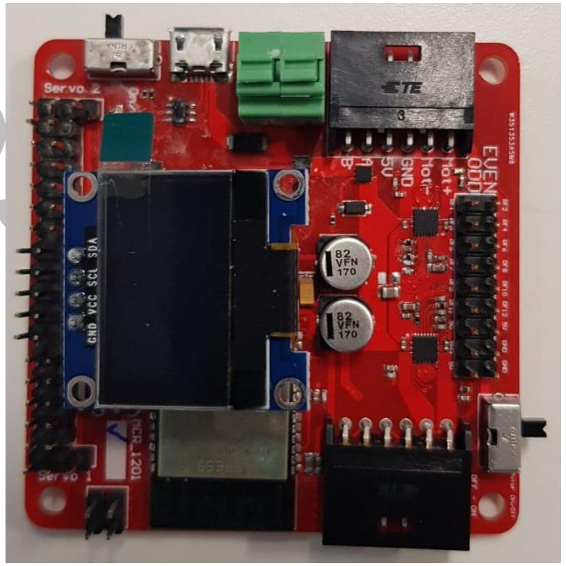


Motor Output/Input

MCU

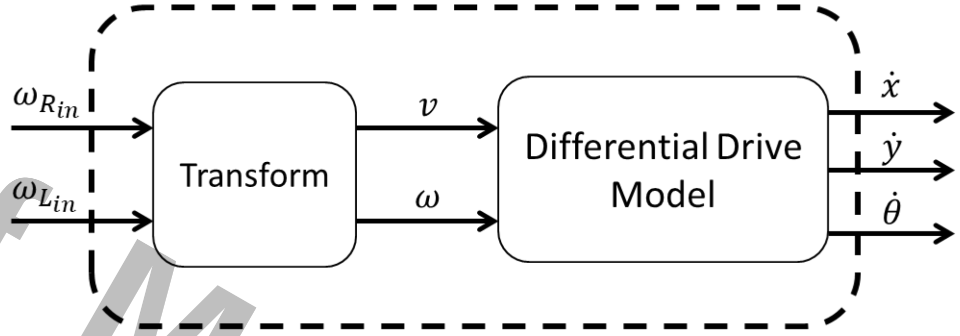
- A microcontroller is a compact integrated circuit. They are made to perform a specific operation in an embedded system.
- In robotics they are usually in charge of the low-level control of the robot, such as motors, and sensors or actuators that require a dedicated and fast controller to work.
- A 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

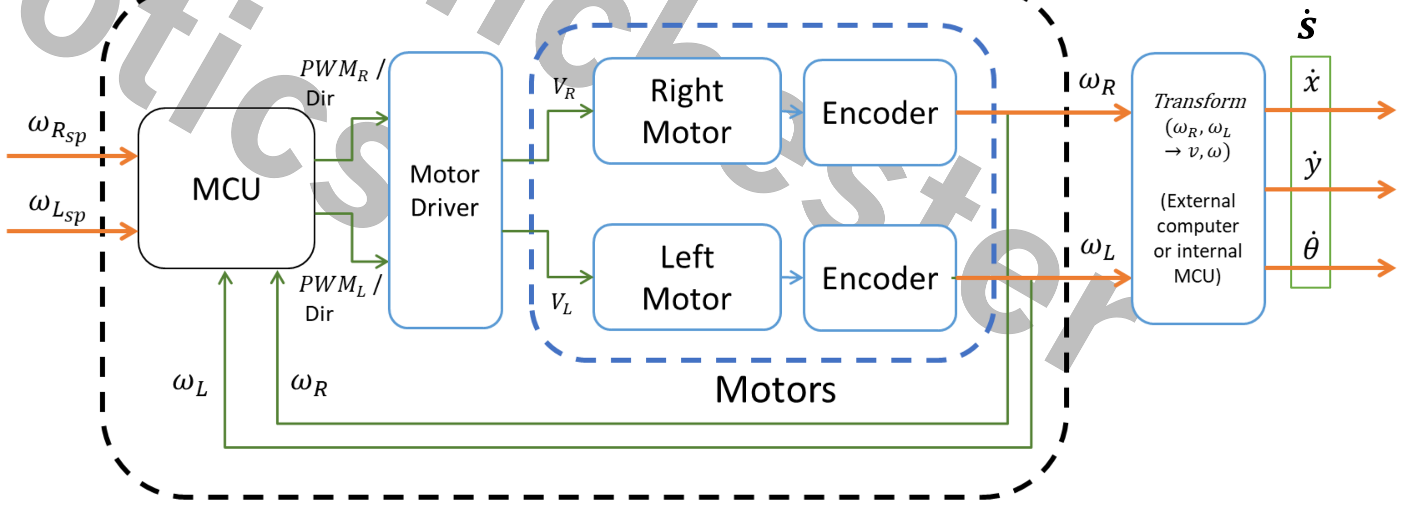


The Mobile Robot

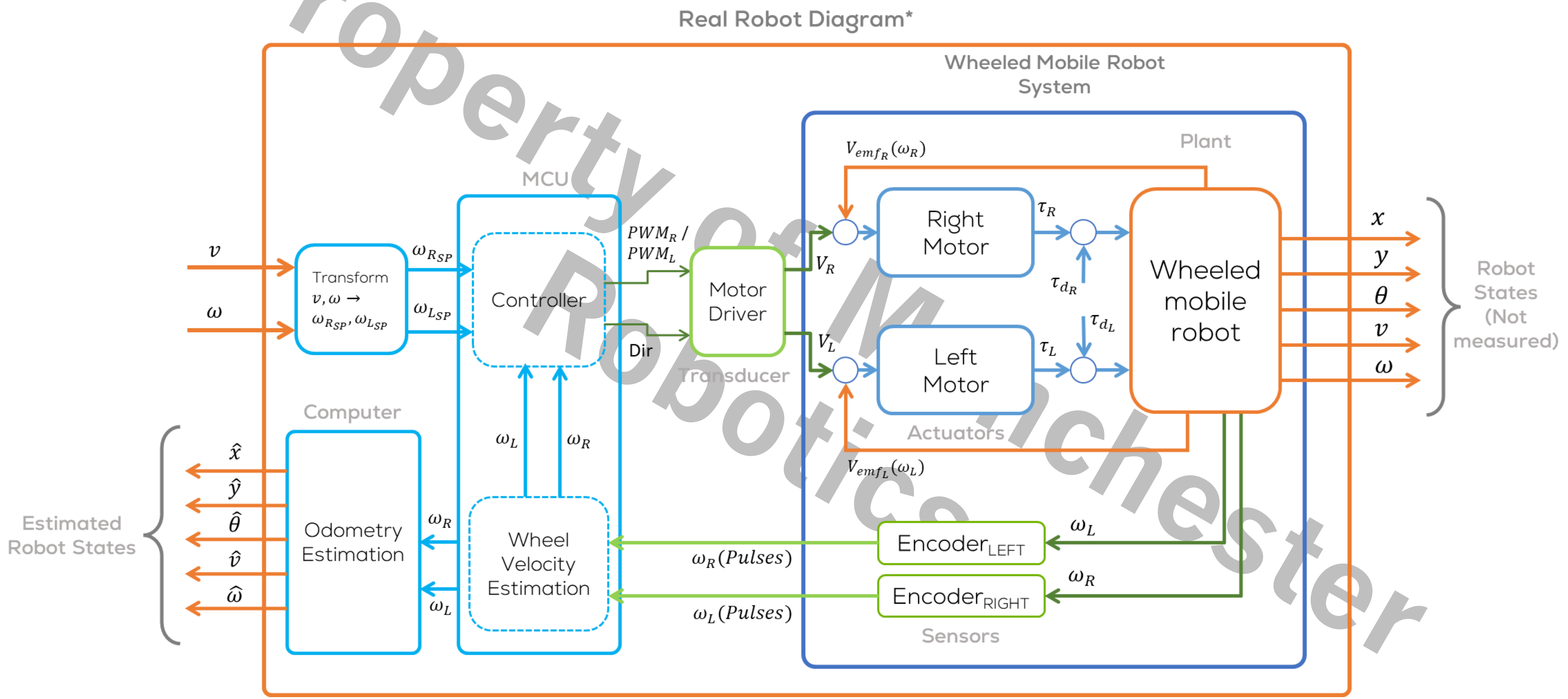
- The real robot, in comparison with the kinematic model, requires the usage of sensors and actuators to work.
- For the real robot, a closed control loop for each of the motors is required, in order to reach the required velocities, set by the user.
- In robotics this is called low level control. For the case of a wheeled mobile robot is a common practice to implement a PID control.
- It can be observed that the inputs and outputs are the same, but the inner loop controller and actuators will determine how close the Real Robot will resemble the Kinematic Model.



Kinematic Model



Real Robot Diagram*



Real Robot Diagram*
Wheeled Mobile Robot System
Plant
MCU
Transform $v, \omega \rightarrow \omega_{R_{SP}}, \omega_{L_{SP}}$
v
ω
$\omega_{R_{SP}}$
$\omega_{L_{SP}}$
Controller
PWM_R / PWM_L
Dir
Motor Driver
Transducer
V_R
V_L
$V_{emf_R}(\omega_R)$
$V_{emf_L}(\omega_L)$
Right Motor
Left Motor
Actuators
τ_R
τ_{d_R}
τ_L
τ_{d_L}
Wheeled mobile robot
x
y
θ
v
ω
Robot States (Not measured)
ω_L
ω_R
Wheel Velocity Estimation
Computer
Odometry Estimation
$\hat{x}$
$\hat{y}$
$\hat{\theta}$
$\hat{v}$
$\hat{\omega}$
Estimated Robot States
$\omega_R(Pulses)$
$\omega_L(Pulses)$
$\text{Encoder}_{\text{LEFT}}$
$\text{Encoder}_{\text{RIGHT}}$
Sensors

Thank you

{Learn, Create, Innovate};

T&C

Terms and conditions

{Learn, Create, Innovate};

Manchester Robotics

Terms and conditions

- *THE PIECES, IMAGES, VIDEOS, DOCUMENTATION, ETC. SHOWN HERE ARE FOR INFORMATIVE PURPOSES ONLY. THE DESIGN IS PROPRIETARY AND CONFIDENTIAL TO MANCHESTER ROBOTICS LTD. (MCR2). THE INFORMATION, CODE, SIMULATORS, DRAWINGS, VIDEOS PRESENTATIONS ETC. CONTAINED IN THIS PRESENTATION IS THE SOLE PROPERTY OF MANCHESTER ROBOTICS LTD. ANY REPRODUCTION, RESELL, REDISTRIBUTION OR USAGE IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF MANCHESTER ROBOTICS LTD. IS STRICTLY PROHIBITED.*
- *THIS PRESENTATION MAY CONTAIN LINKS TO OTHER WEBSITES OR CONTENT BELONGING TO OR ORIGINATING FROM THIRD PARTIES OR LINKS TO WEBSITES AND FEATURES IN BANNERS OR OTHER ADVERTISING. SUCH EXTERNAL LINKS ARE NOT INVESTIGATED, MONITORED, OR CHECKED FOR ACCURACY, ADEQUACY, VALIDITY, RELIABILITY, AVAILABILITY OR COMPLETENESS BY US.*
- *WE DO NOT WARRANT, ENDORSE, GUARANTEE, OR ASSUME RESPONSIBILITY FOR THE ACCURACY OR RELIABILITY OF ANY INFORMATION OFFERED BY THIRD-PARTY WEBSITES LINKED THROUGH THE SITE OR ANY WEBSITE OR FEATURE LINKED IN ANY BANNER OR OTHER ADVERTISING.*