SCUTTLE Software Guide

Last revised: 2022.08.08

- Software Architecture
- Software best practices
- Sensor Communication
- Obstacle Avoidance

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Software Architecture

CONTENTS

This guide covers

- The parts of each software file
- How the programs interact with each other
- How the programs interact with hardware
- Sensor software vs actuator software

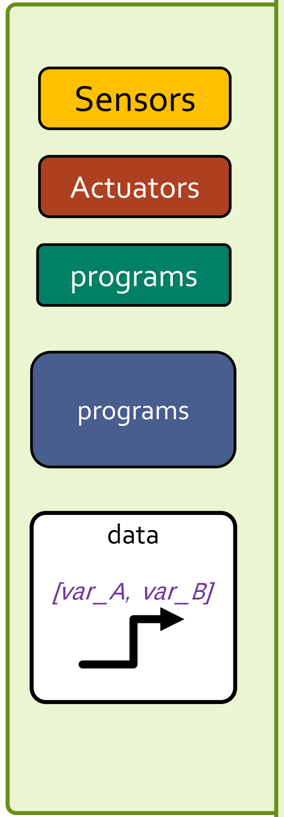
LANGUAGE

The SCUTTLE robot software has been programmed in Python3 on an embedded Linux platform. Both Beaglebone Blue and Raspberry Pi have been tested successfully. The software has been architected to make a robust starting point for students to create their own autonomous missions.

FUTURE OUTLOOK

Next Steps: Robotic Operating System 2 (ROS2) is quickly becoming a reliable, versatile software platform for mobile robots. During 2022 the SCUTTLE team will release demos utilizing simultaneous localization and mapping (SLAM), aim to create a new ROS2 version of the software. Find a sneak peak of our python library intended for using in ROS, called scuttlepy.

Software Architecture – Introduction

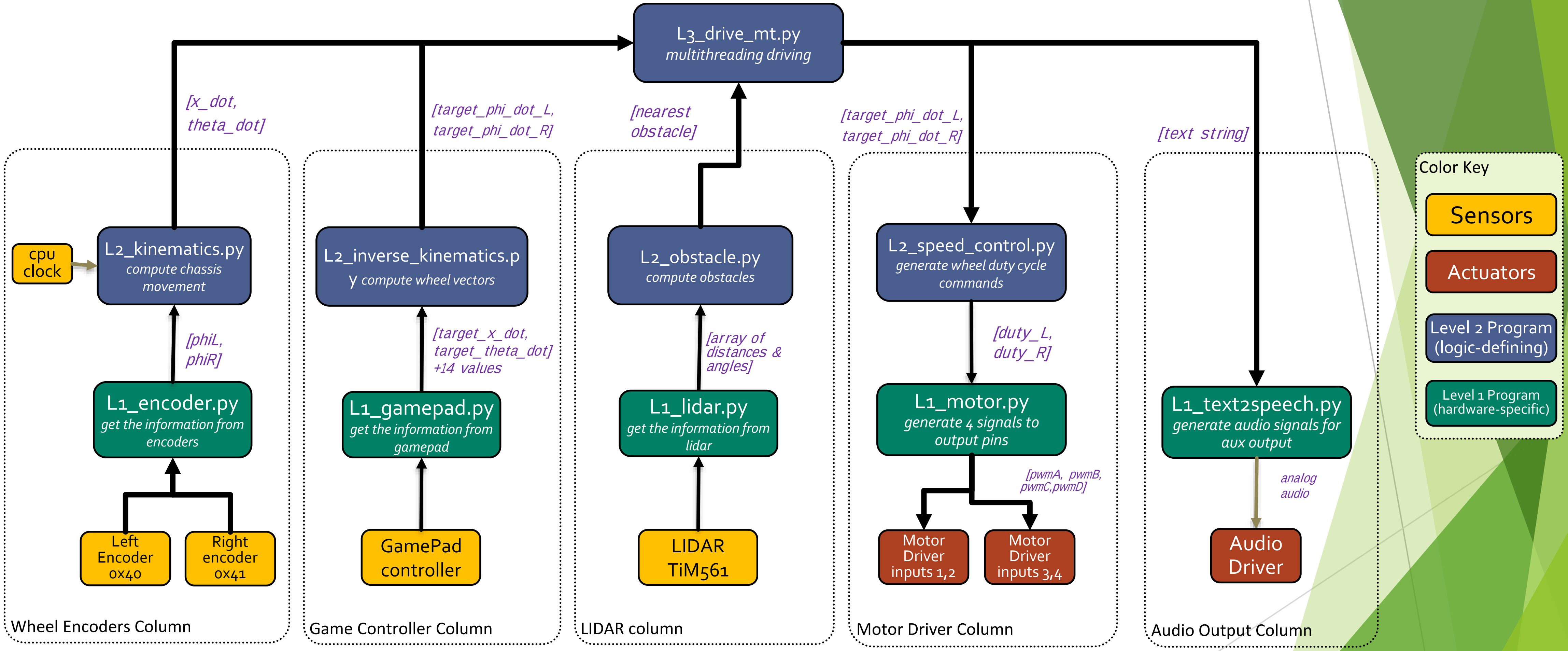


The ***__blocks in yellow__*** are sensors, and the items in orange are actuators or other outputs. The level-2 ***__blocks in teal__*** are specific to the hardware platform (beagle, pi, etc) and perform communication with the low level devices. The ***__blocks of level2 and above__*** are non-hardware specific.

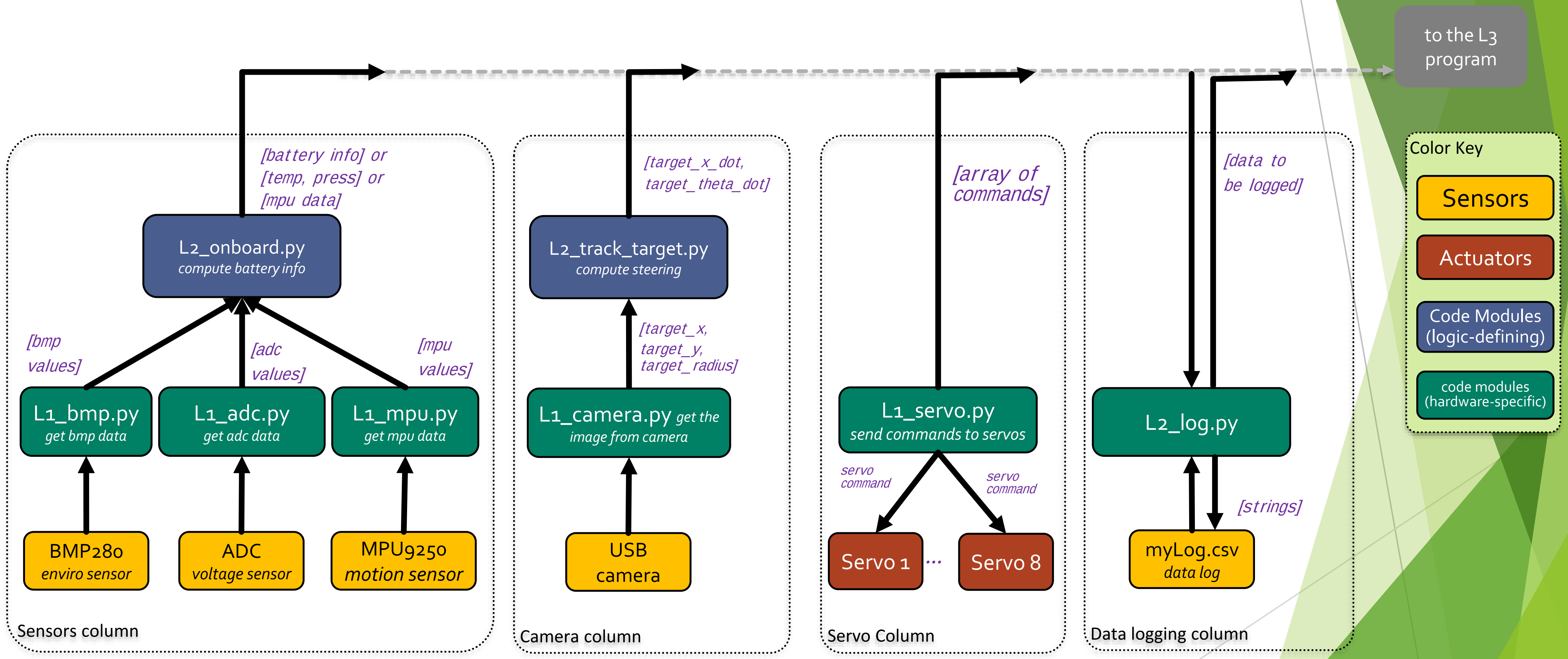
Each block aside from sensors and actuators represent an individual python program. The purple text indicates what important information is passed between programs and the black arrows indicate (for the most part) what direction the data is flowing. If a level 3 program needs information from another, it must receive the information from the top-level program, in order to maintain the structure of independence in program functions.

This software structure is preferred in order to perform subsystem testing. The data flowing through the top level is minimal and can be replaced with artificial data in the even that a sensor is unavailable.

Software Architecture - Overview



Software Architecture – Overview (continued)



Libraries in use:

Python importing guidelines:

1. Each file should import the files below it in hierarchy, and not the files above it.
2. Each file may import non-scuttle libraries as needed (import NumPy, import time, etc.)
3. If the Level-1 file has imported an external library, it does not need to be imported by the Level-2 file

Libraries Utilized:

BeagleBone Blue Integration:

- RCPY for communicating with MPU9250 & commanding motor drivers
- Adafruit GPIO for I2C Communication
- BMP280 for communicating with the onboard bmp280 sensor.

Raspberry Pi integration:

- pysicktim for accessing LIDAR data
- gpiozero for controlling GPIO pins.

Common Libraries

- os for making shell commands via python code.
- time for keeping track of time
- threading for performing multithreading
- NumPy for performing math operations
- Fastlogging for generating log files
- pygame for accessing gamepad controller data
- cayenne.client for sending MQTT messages
- smbus2 for accessing i2c bus through python commands

Libraries Matrix

Lib	Beaglebone Blue	Raspberry Pi 3B+ and 4	Jetson Nano [Under development]
Time	✓	✓	✓
Threading	✓	✓	✓
numpy	✓	✓	✓
pygame	✓	✓	
fastlogging	✓	✓	✓
Cayenne.client	✓	✓	
PySICKtim		✓	
GPIOZERO		✓	
RCPY	✓		
ADAFRUIT GPIO	✓		
BMP280	✓		

Outline of an L1 Program

All files follow this outline when possible. The level-1 programs are most suited to this outline.

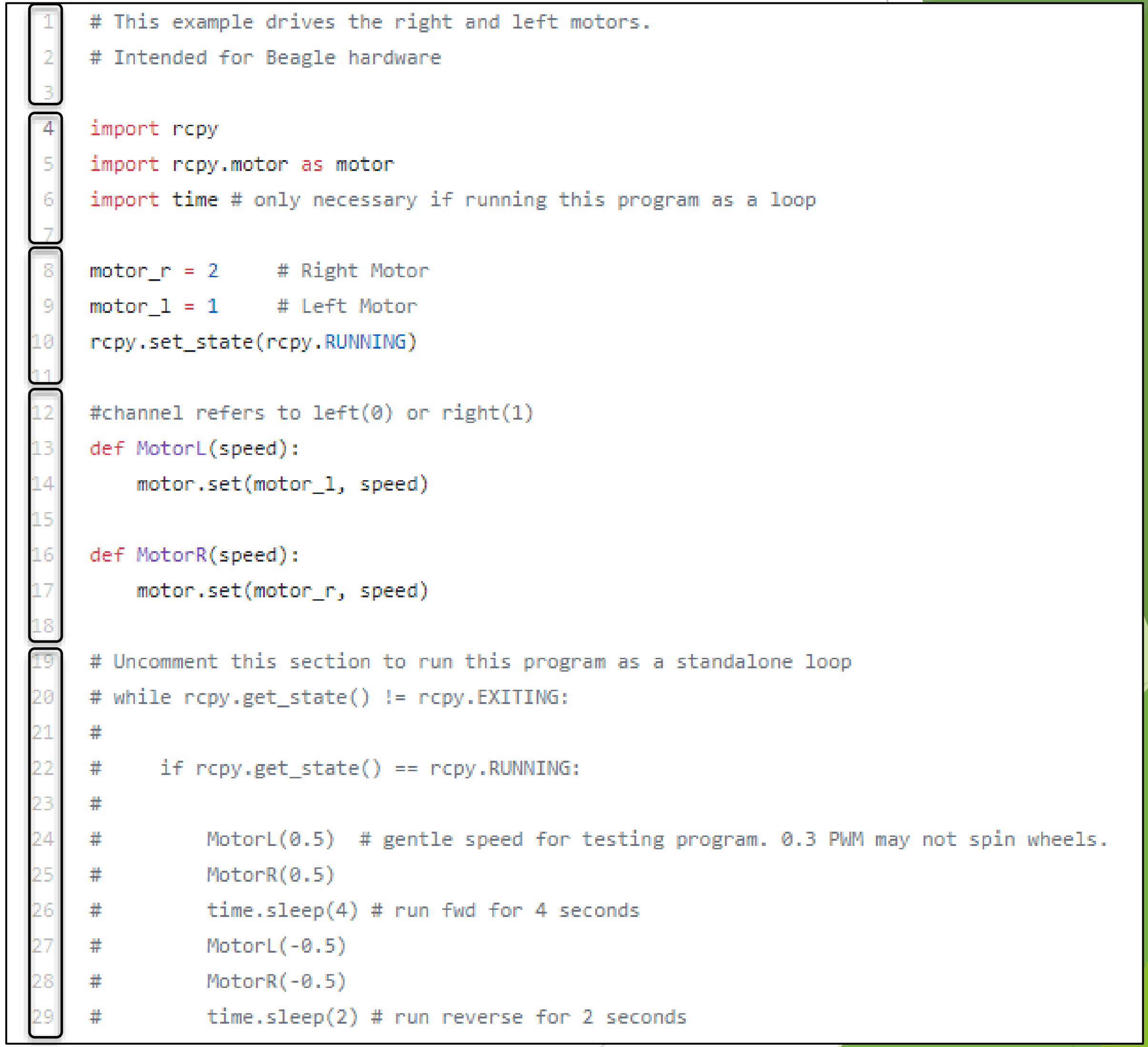
Explanation of the purpose

Import internal programs (if applicable)

Import external programs (aka libraries). Take actions for initializations of objects or global variables.

Define functions. In some cases, make functions that combine other functions in sequence.

Offer a simplified, minimal loop for testing the code.



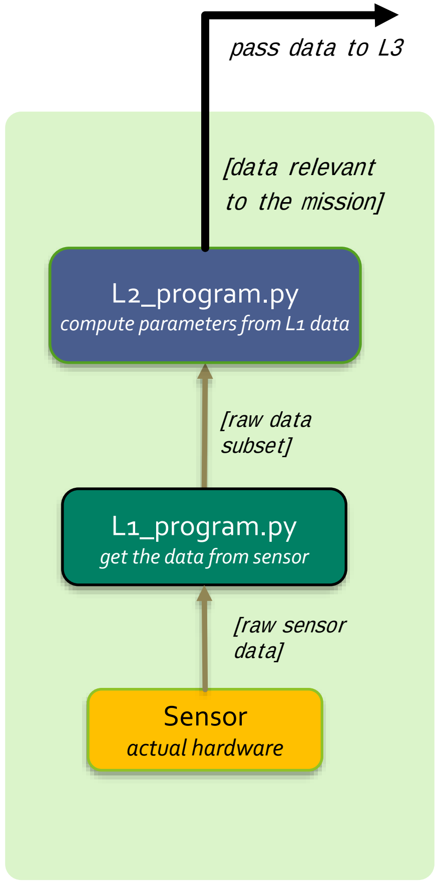
```
# This example drives the right and left motors.
# Intended for Beagle hardware

import rcpy
import rcpy.motor as motor
import time # only necessary if running this program as a loop

motor_r = 2     # Right Motor
motor_l = 1     # Left Motor
rcpy.set_state(rcpy.RUNNING)

#channel refers to left(0) or right(1)
def MotorL(speed):
    motor.set(motor_l, speed)

def MotorR(speed):
    motor.set(motor_r, speed)

# Uncomment this section to run this program as a standalone loop
# while rcpy.get_state() != rcpy.EXITING:
#
#     if rcpy.get_state() == rcpy.RUNNING:
#
#         MotorL(0.5)  # gentle speed for testing program. 0.3 PWM may not spin wheels.
#         MotorR(0.5)
#         time.sleep(4) # run fwd for 4 seconds
#         MotorL(-0.5)
#         MotorR(-0.5)
#         time.sleep(2) # run reverse for 2 seconds
```

Guidelines for Levels

Importing
Files & Libraries

Only import L1 programs directly below. Do not import L3 program. As needed, import external libraries.

Do not import L2 or L3 programs. As needed, import external libraries.



Testing
Code and Hardware

This file has a loop to test the whole group (L1 + L2 + sensor).

This file has a loop to test sensor function.

Multi-threading Purpose

- Threading offers better control over **timing of code execution**.
- Each thread should contain **actions that are related** and that should be executed within a specific time window.
- The user should avoid passing data between threads because it reduces robustness. Instead, **call the level 2 program as needed in each thread**, even if you need to communicate with the same device (ie, retrieve gamepad commands for driving and retrieve in parallel for speaking commands)

	Thread 1 (driving)	Thread 2 (obstacle detect)	Thread 3 (speaking)
Do What?	Drive the robot AND Log the speed	Indicate obstacles using speaker	speak via speaker
When?	After sampling the controller / After sending drive command	when obstacle is detected by lidar	user presses button
	20ms cylcle	10ms cylcle	5ms cylcle

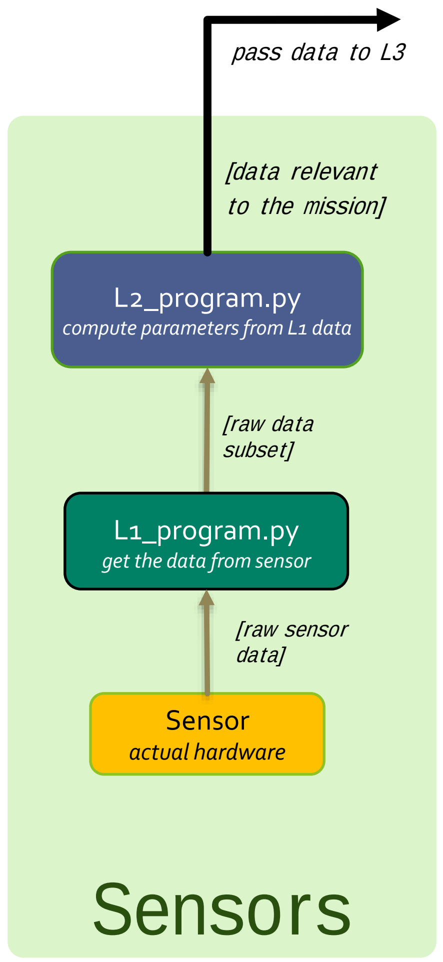
Software Architecture: Sensors vs Actuators

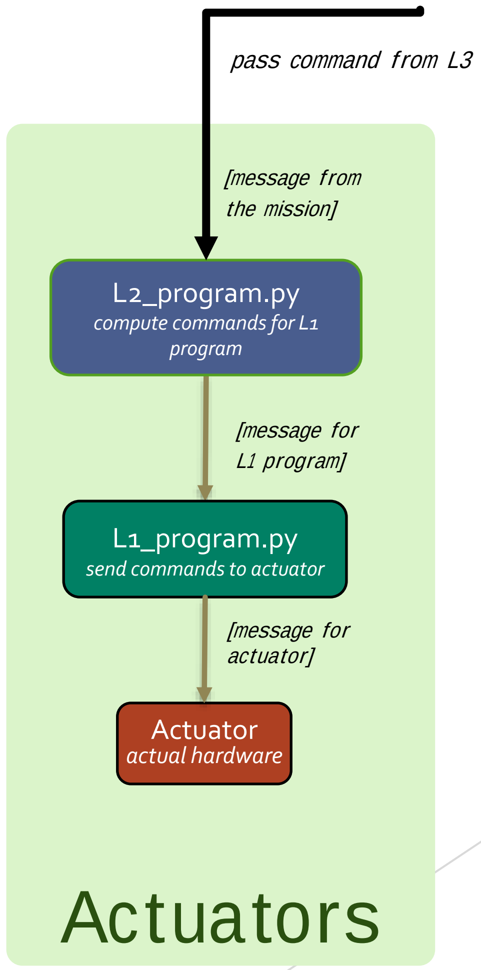
Sensor and Actuators have the same architecture except for **data direction**.

For **sensors**, the data is generated at the hardware and sent UP.

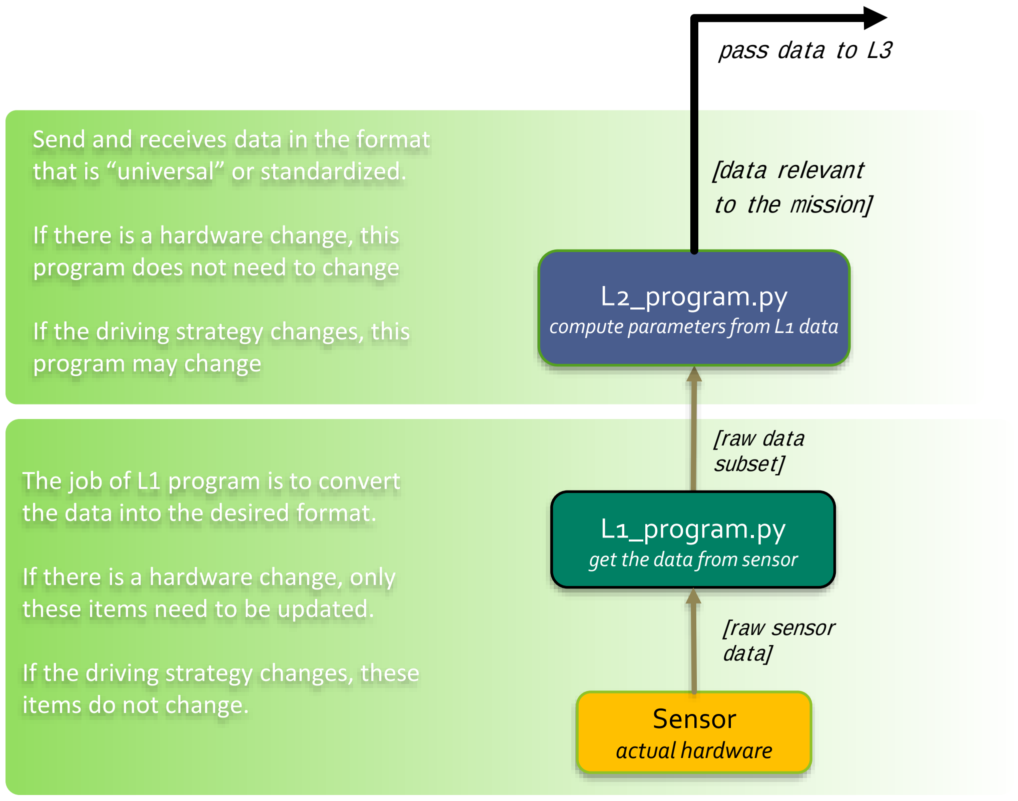
For **actuators**, the data is generated at the top and sent DOWN to hardware.

Some sensors and actuators have feedback and preset commands, so data may flow **both ways**.





Software Architecture: Modularity & Robustness



Send and receives data in the format that is "universal" or standardized.

If there is a hardware change, this program does not need to change

If the driving strategy changes, this program may change

The job of L1 program is to convert the data into the desired format.

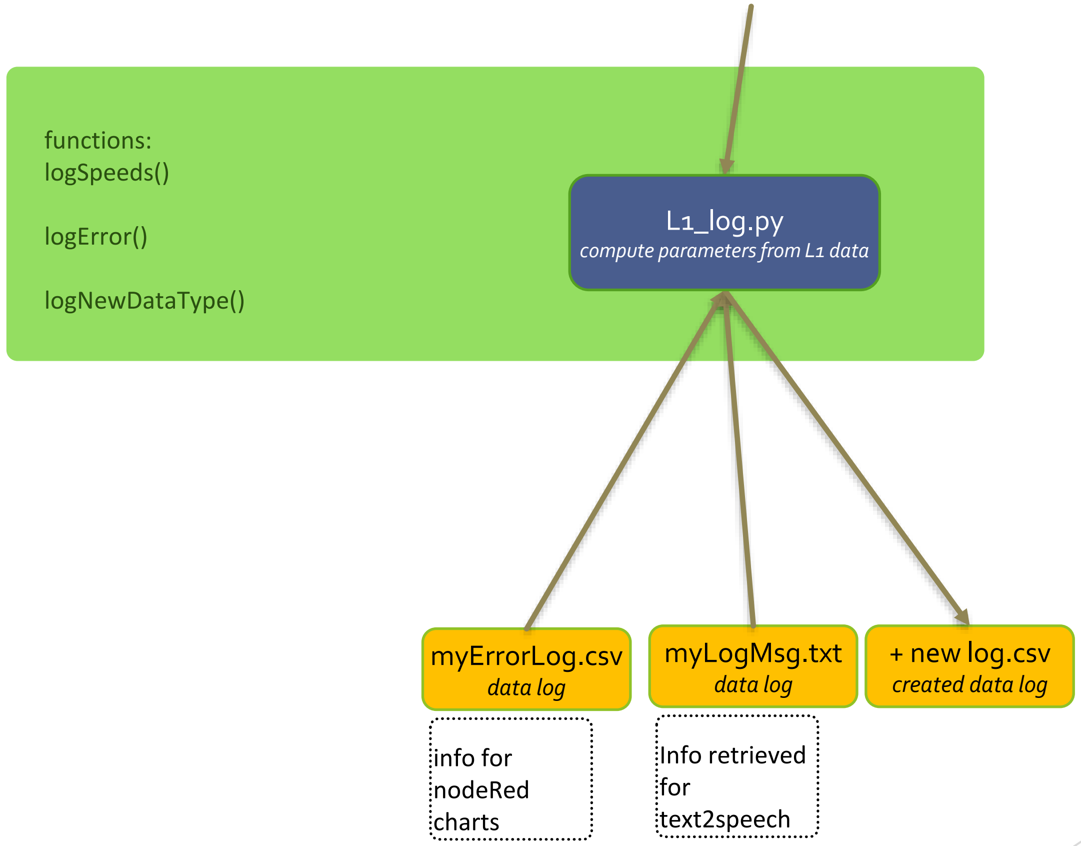
If there is a hardware change, only these items need to be updated.

If the driving strategy changes, these items do not change.

Level 1: logging

Rather than interacting with hardware, the L1_log program interacts with other python files. It **acts as a sensor** in that it retrieves recorded data and it **acts as an actuator** in that it can receive data and perform an action with it (store it in a file).

L1_log.py program was initially designated as level2, but is being set as L1 going forward (2020.11)



Function Explained: Duty Compression

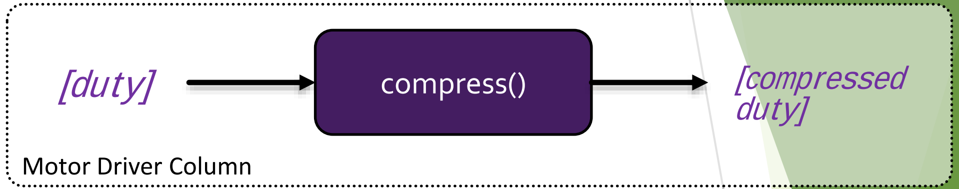
Duty compression, or motor signal scaling, helps reduce the dead band where the wheels don't turn. Sometimes, small commands of duty cycle give insufficient voltage to overcome friction.

Based on an earlier experiment, in forwards and backwards directions, duty cycles below 22% may result in some noise but no movement.

This deadband region can be difficult for a driver to handle and even more difficult for a control system. We could chop this section out entirely to solve the static condition, but in transient conditions we would exacerbate the nonlinearity that takes place crossing the deadband.

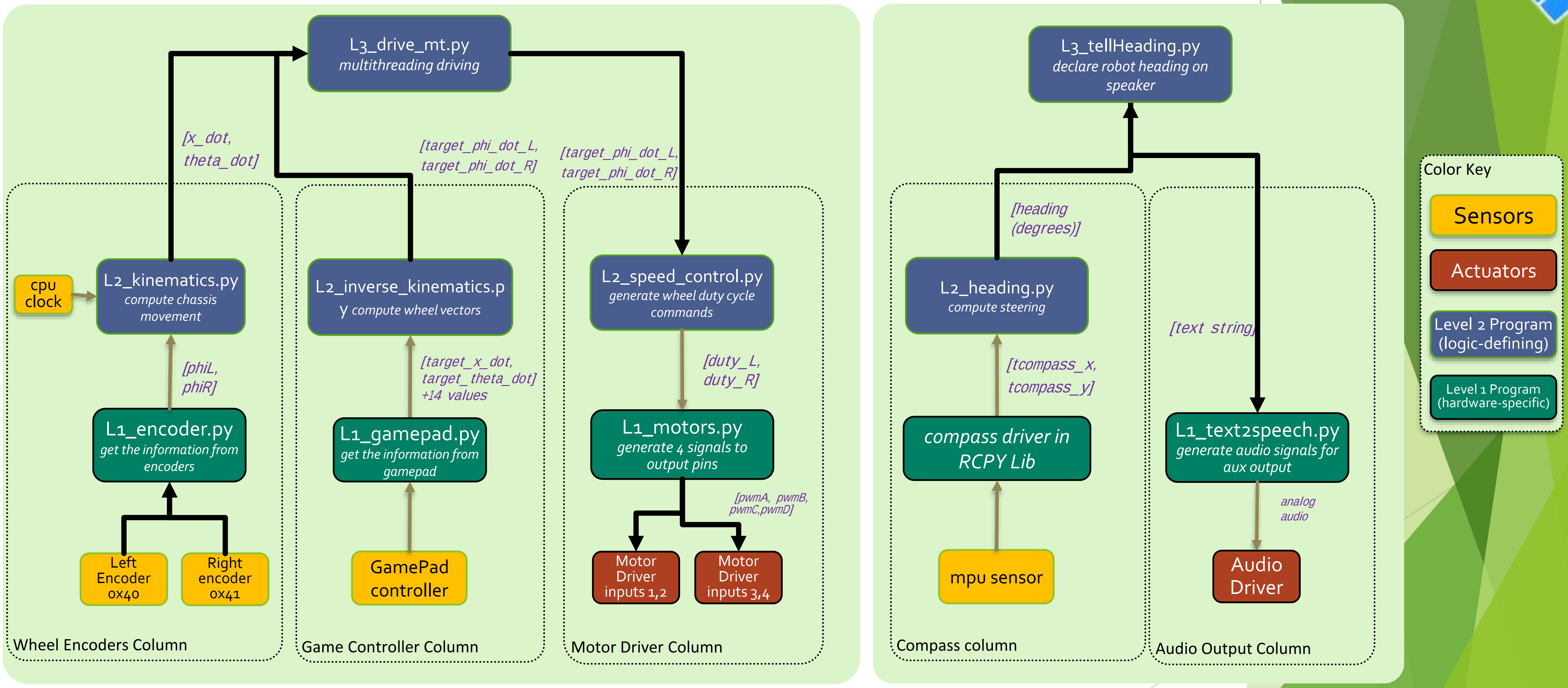
The Compression function "compresses" the deadband and spreads the range where the duty cycle maps to a nonzero wheelspeed.

To define the function, we basically just manipulate the initial slope, and the inflection point for the output, y.

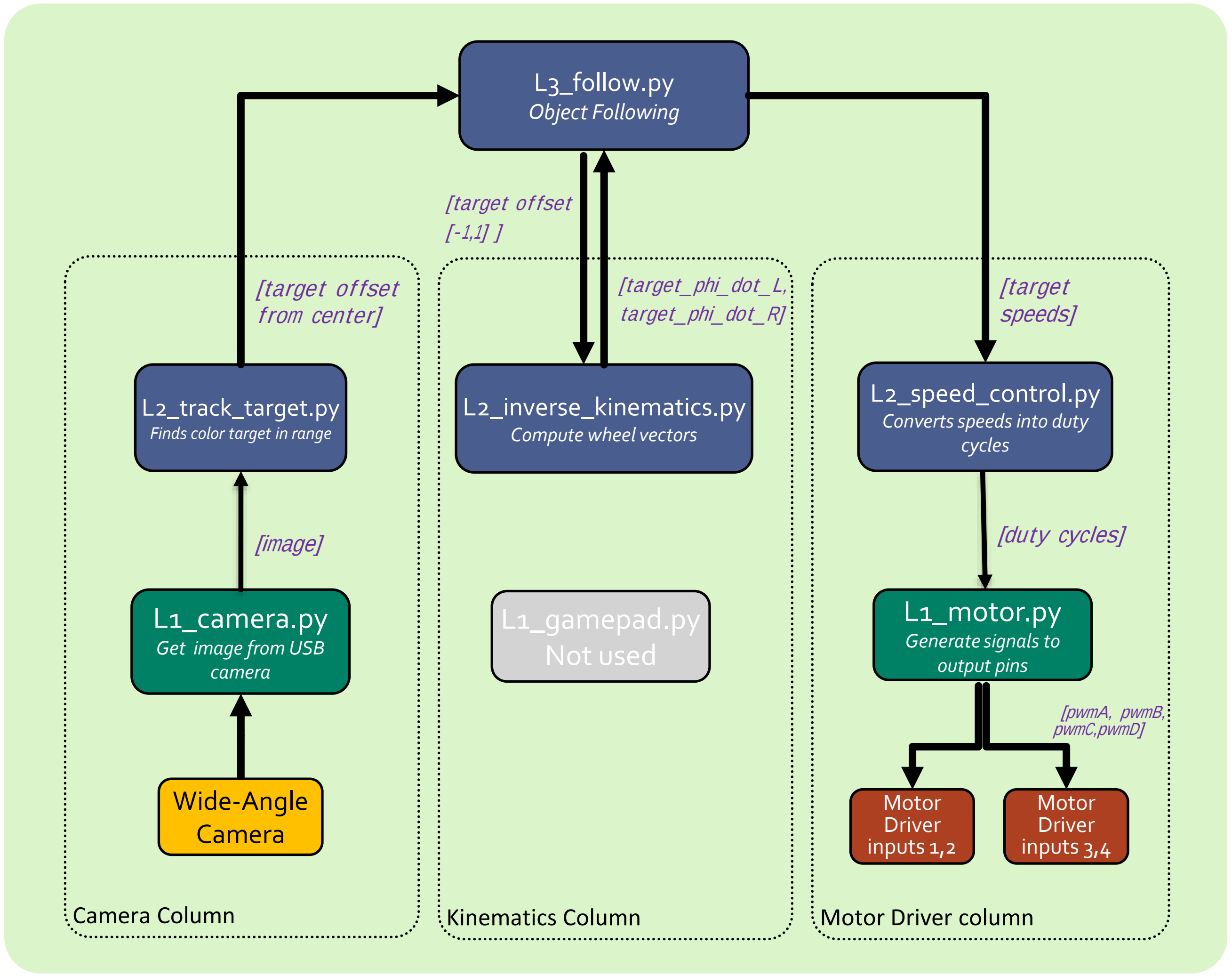


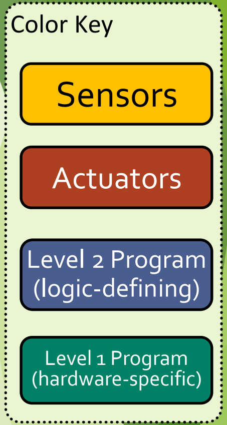
<u>variables & their definitions:</u>
slope1 = input by user
y_inflection = input by user
x_inflection = slope1 / inflection_y
slope2 = (1-inflection_y)/(1-inflection_x)
x_trim = x – x_inflection
y = inflection_y + x_trim*slope2

Multithreading example



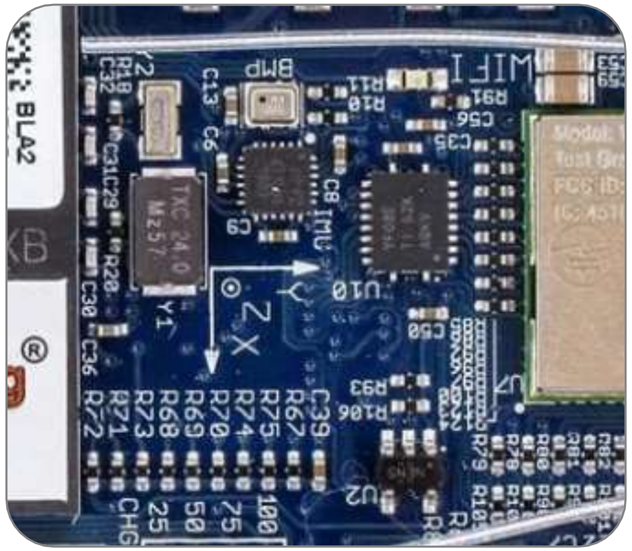
Color Tracking Example



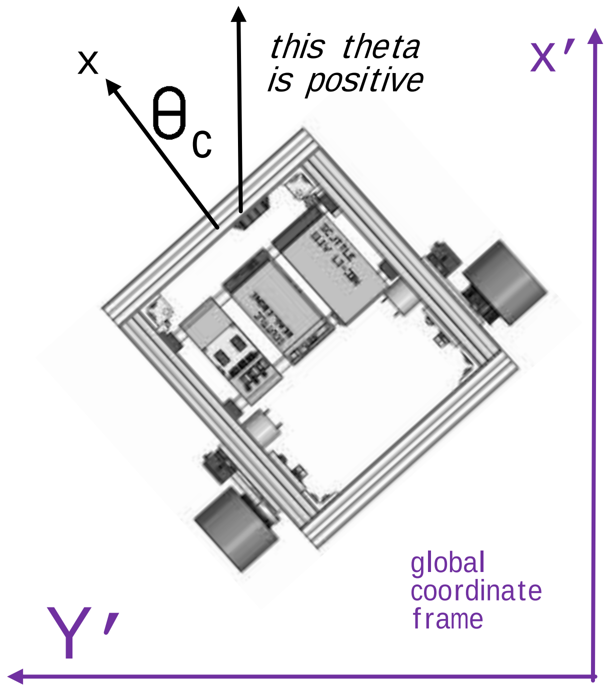

Color Key
Sensors
Actuators
Level 2 Program (logic-defining)
Level 1 Program (hardware-specific)

Absolute Orientation

- SCUTTLE has a compass for orientation
  - The compass is nothing but a 3-axis magnetometer
  - Encoders can provide *relative* orientation
  - Compass is required for *global* orientation
- The compass is embedded in the IMU (MPU-9250)
  - It has 3 sensors oriented in the indicated directions
  - L1_mpu.py accesses the magnetometer
  - Each magnetometer requires calibration



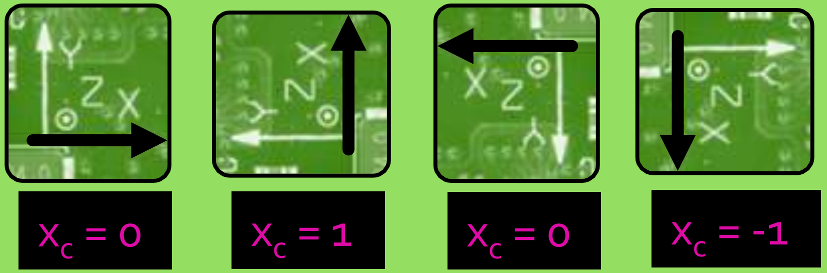
Remember: Theta is defined as scuttle's chassis x-vector minus the global x-vector



Magnetometer Behavior

- An axis is at its MAXIMUM when it is **aligned** NORTH
- The axis is at its MINIMUM when it is **opposing** NORTH
- After calibration, we can achieve the behavior below

Values Desired by Direction
Using X axis for example:



(magnetic north)

1) Discover the maximum and minimum values by rotating sensor in a full circle.

Permanent magnets influence the sensor, so calibration must be done on the robot, in position near the motors.

Before Calibration	Min (microtesla)	max (microtesla)
X	-15	38
Y	-22	20

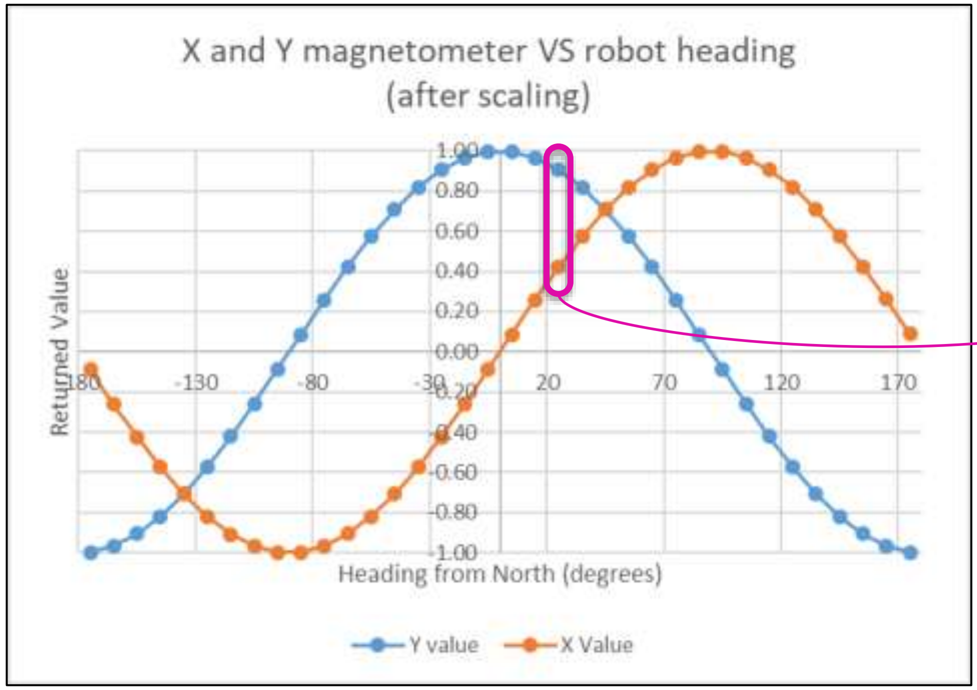
2) Using the following equation, re-scale each axis

$$x_{\text{scaled}} = \frac{2(x - x_{min})}{(x_{max} - x_{min})} - (1)$$

AfterCalibration	Min (ratio to max)	max (ratio to max)
X	-1	1
Y	-1	1

Determining Absolute Orientation

- X and Y axes are sufficient information to give heading.
  - Z axis returns zero if scuttle sits flat
- Theta is defined as rotation of SCUTTLE from the global coordinate frame, or y-prime
  - positive theta means SCUTTLE is turned left from north
  - We can define NORTH as the y-axis of the global coordinate frame



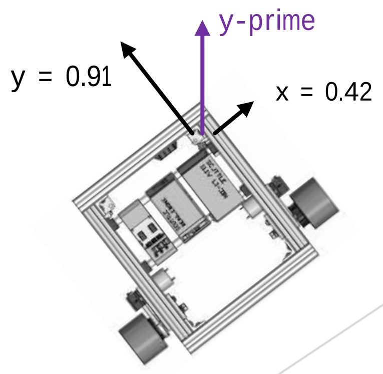
Theta is positive when scuttle points west
Theta is negative when scuttle points east

Use arctan2(y, x) to return a heading

arctan2 is the "element-wise arc tangent of y/x choosing the quadrant correctly."

Example:

ATAN2(0.91, 0.42) returns 25 degrees



y is pointed strongly north
X is pointed weakly north
both axes return positive values

Speeds Tuning

These are general performance characteristics you can expect when using the standard SCUTTLE hardware:

<u>Nominal conditions:</u>

Battery: 11.5 volts OC

Motors: equipped with standard 200 rpm gearbox

Wheels: 83mm diameter urethane wheels

Pulleys: motor = 15 teeth, wheel = 30 teeth

Wheelbase: 405mm

- V_{max} = 0.4m/s (measured by wheel speed)

$$v = \omega * r$$

- $\omega_{max,\ motor\ pulley} = 19.5$ rad/s
- $\omega_{max,\ wheel} = 9.75$ rad/s
- With 1 wheel stopped and 1 wheel moving:

$$\dot{\theta} = \frac{v}{L}$$

(where L = wheelbase)

- $\dot{\theta}_{max,\ chassis} = 1.98$ rad/s (0.32 turns/sec)

Speed Control

This slide is dedicated to describing the wheel speed measurements and calculation of variables for speed control.

<u>Nominal conditions:</u>

Battery: 11.5 volts, open circuit

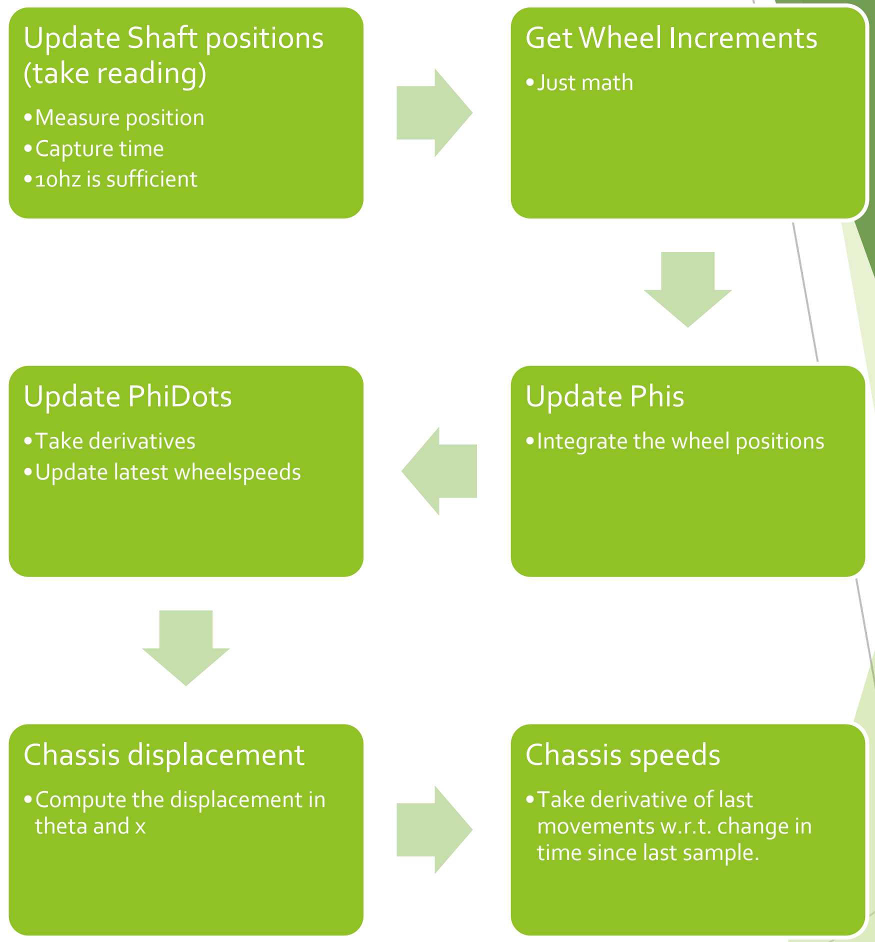
Motors: equipped with standard 200 rpm gearbox

Wheels: 83mm diameter urethane wheels

Pulleys: motor = 15 teeth, wheel = 30 teeth

Wheelbase: 405mm

Closed-loop frequency: 10hz minimum



Update Shaft positions (take reading)
- Measure position
- Capture time
- 10hz is sufficient

Get Wheel Increments
- Just math

Update Phis
- Integrate the wheel positions

Update PhiDots
- Take derivatives
- Update latest wheelspeeds

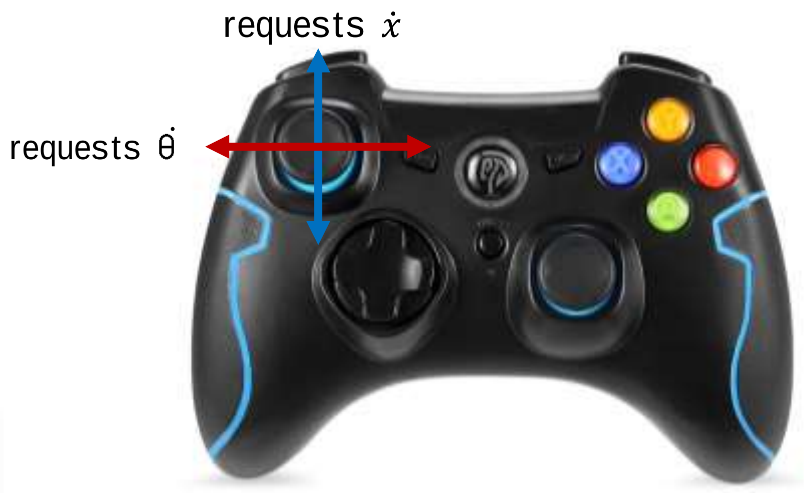
Chassis displacement
- Compute the displacement in theta and x

Chassis speeds
- Take derivative of last movements w.r.t. change in time since last sample.

The variables used to command (closed or open loop) movement on the SCUTTLE are x_dot and theta_dot. Send these variables by any means to the controller (such as Pi) and then controller can produce signals to motor driver.

SCUTTLE Driving

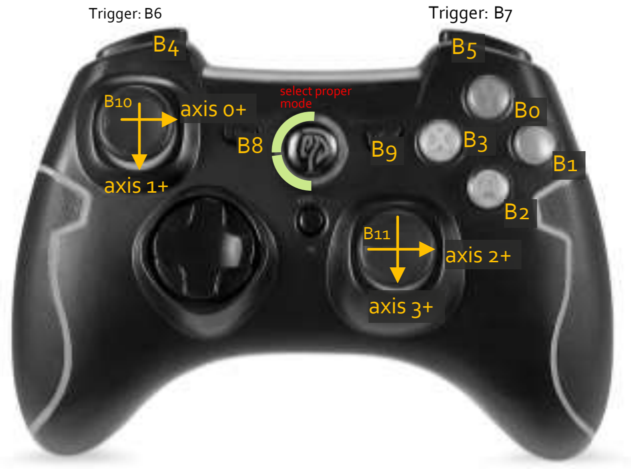
- The left joystick operates the robot wheels
- The forward/backward axis will request a speed
  - (A.K.A movement in x)
- The left/right axis will request an angular velocity
  - (A.K.A movement in theta)



Given a measured max forward velocity of 0.4m/s, the other maximums are calculated.

Move	Theta_dot (rad/s)	X_dot (m/s)	Phi_dot
max	1.99	0.4	9.75

Gamepad Controls Mapping



```
axes_status = np.array([axis_0, axis_1, axis_2, axis_3])
button_status = np.array([B0, B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11])
```

SCUTTLE Movement Example

USER SAYS — right turn on joystick

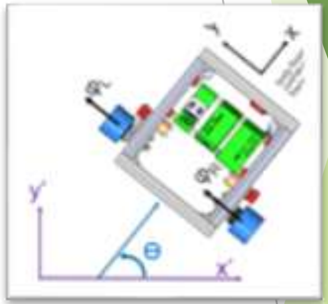
GAMEPAD SAYS — outputs positive value on axis_1

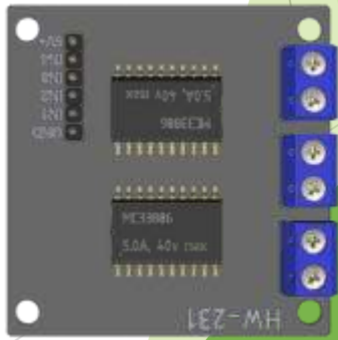
KINEMATICS SAYS — interpret as negative theta movement

KINEMATICS SAYS — performs POSTIVE phi_dot_l and NEGATIVE phi_dot_R

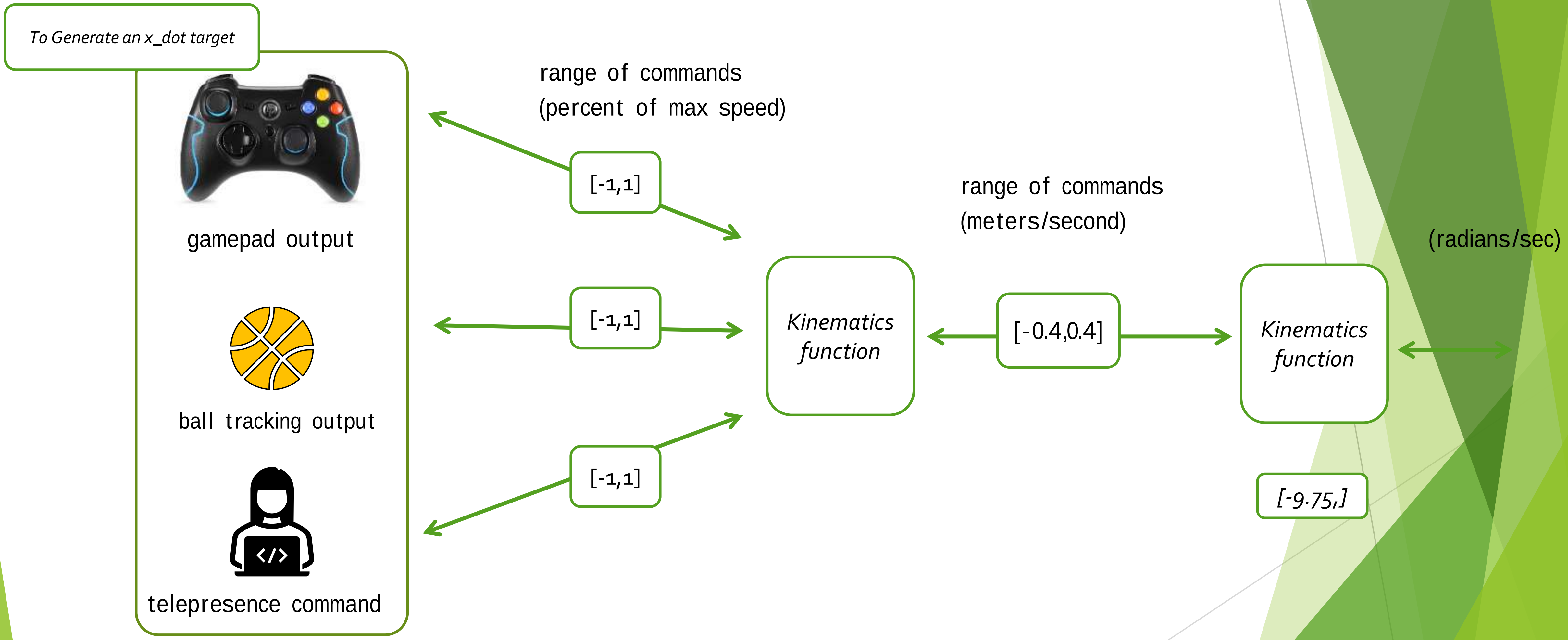
MOTOR PROGRAM SAYS — performs POSTIVE differential on NEGATIVE phi_dot_R

Move	Theta_dot	X_dot	Duty_r	Duty_l
Fwd	0	1	1	1
Rev	0	-1	-1	-1
right	-1	0	-1	1
left	+1	0	1	-1



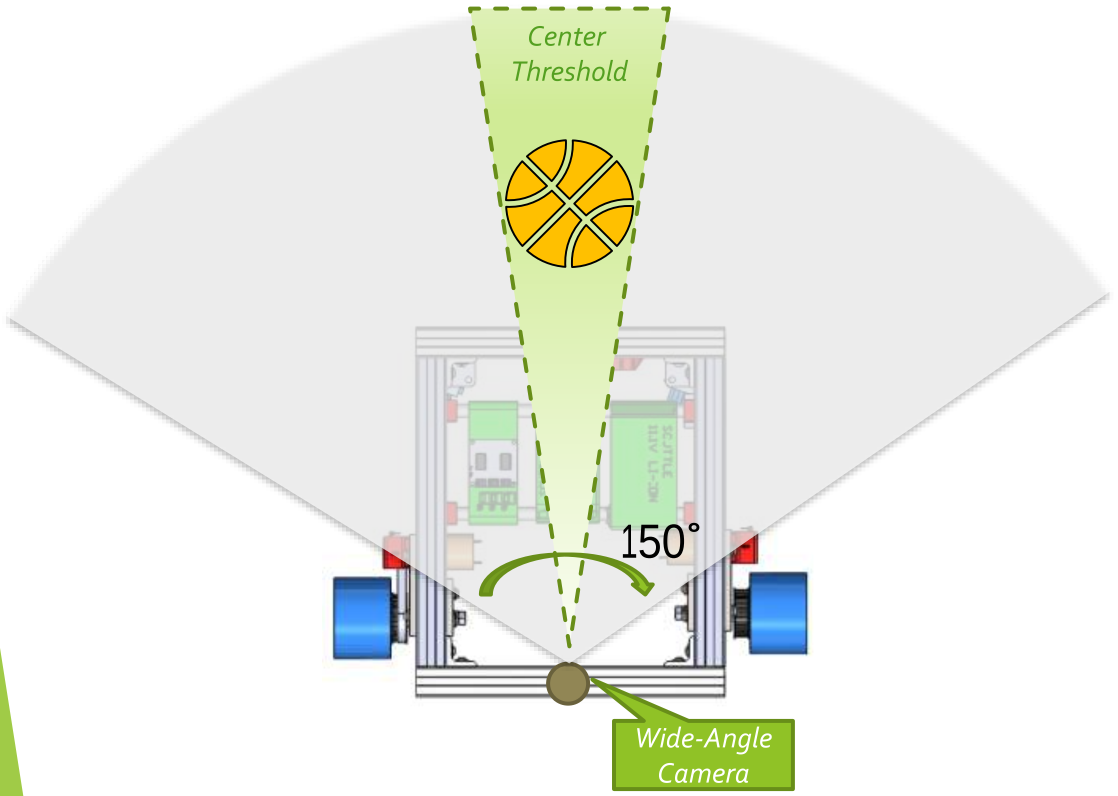


SCUTTLE Movement Options

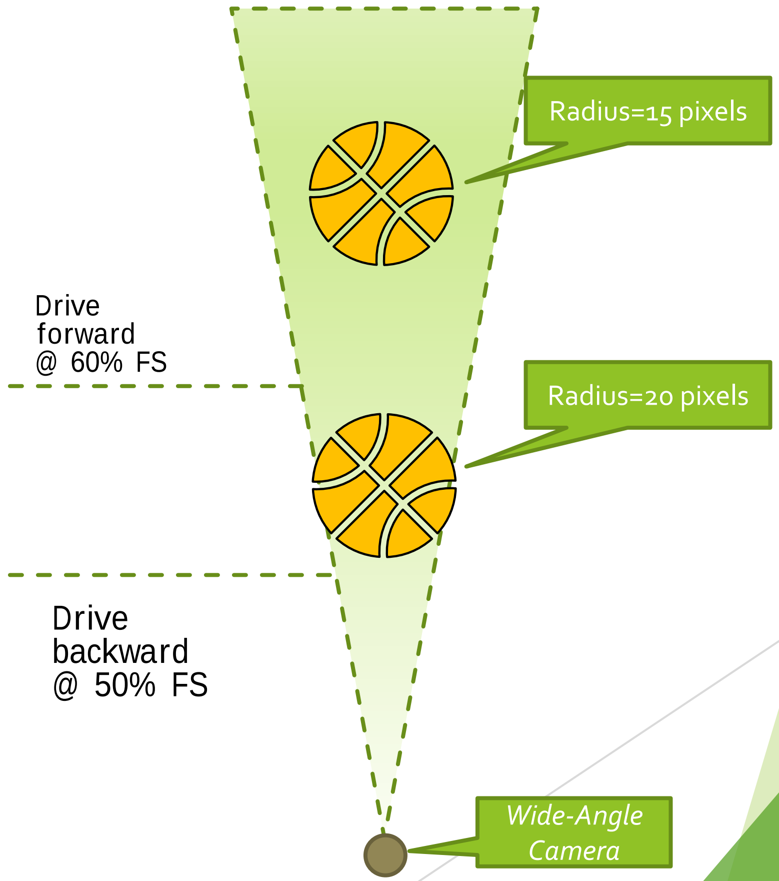


SCUTTLE Color Tracking

1) SCUTTLE turns until the target is detected within the threshold



2) After the target is in the center range, SCUTTLE drives forward or backwards to reach a target radius, in pixels.

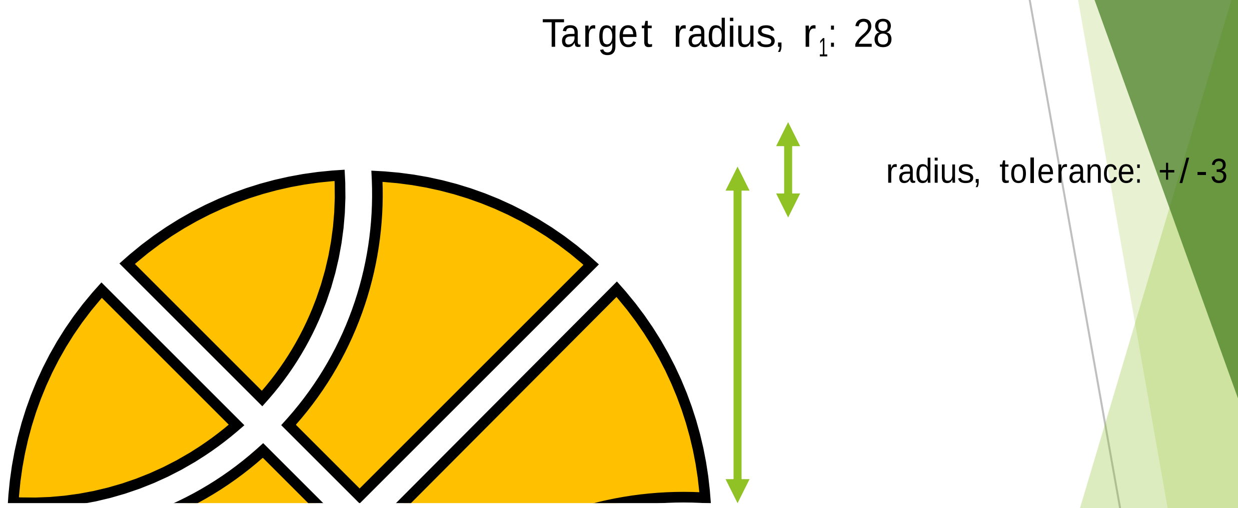


Color Tracking: Radius

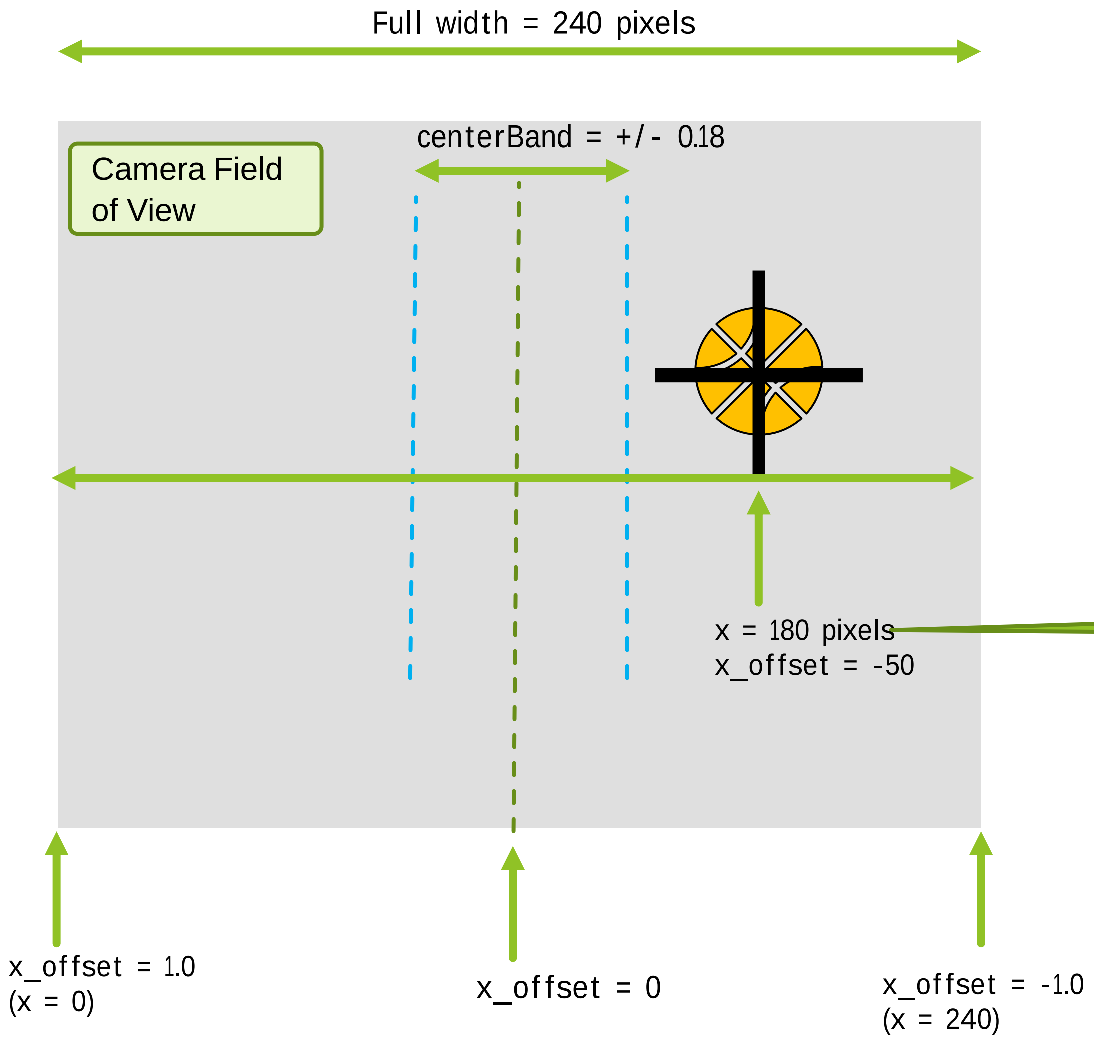
To control x_dot motion, we evaluate the size of the ball in the camera view.

If the ball radius is too large, we make a Reverse command.

If the ball raidus is too small, we make a Forward command.



SCUTTLE Color Tracking



3) The intensity of the turning request is computed, proportional to the offset of the detected object from center.

The requested **angular speed** for SCUTTLE is the x_offset (as a fraction of max) times the maximum turning velocity possible.

In this case, the requested turning velocity is **negative** 0.5 * max speed (2 radians/second). This gives a 1 radian/second *right hand* turn.

LIDAR Concept of Operation

ANATOMY
Lidar systems have a rotating sensor collecting multiple measurements to measure in a 2D plane. (Some have 3D, by other methods).

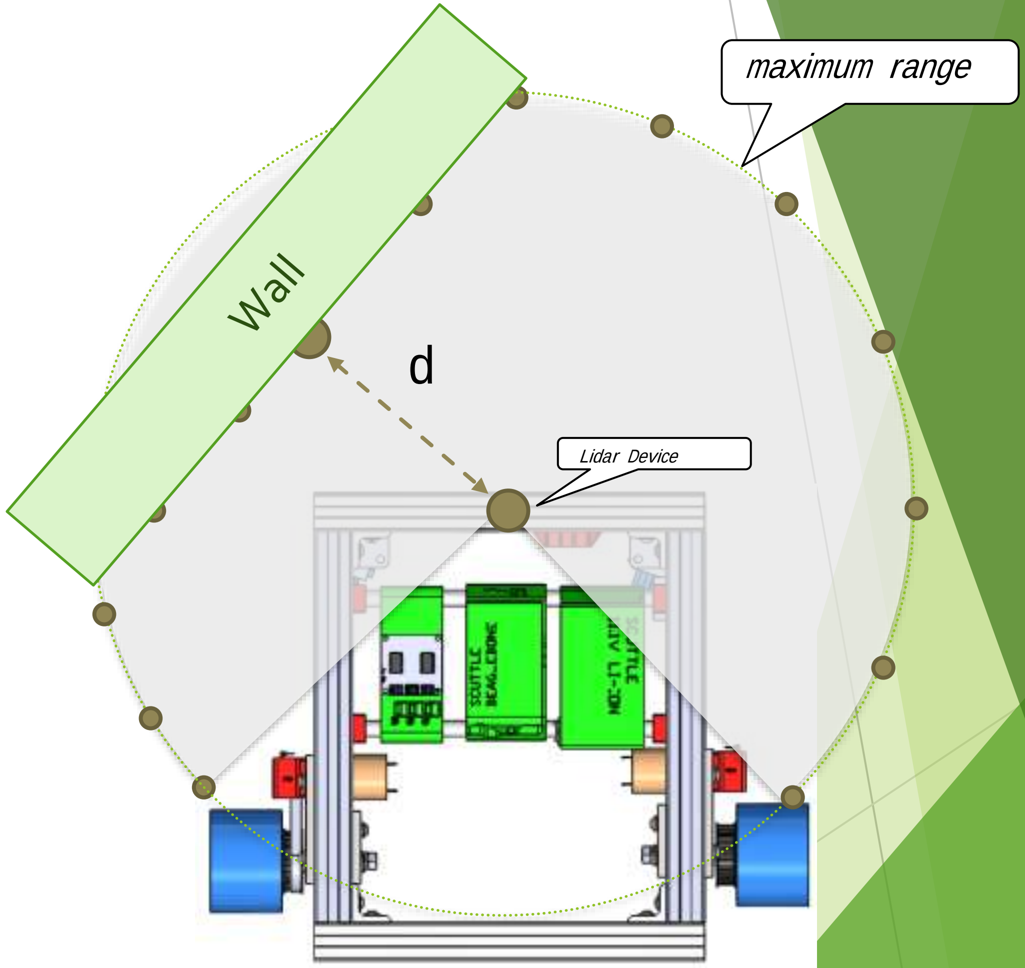
METHOD
Lidar emits a beam of light and receives the reflection. distance is based on Time of Flight concept.

POWER
TiM561 uses about 2.1 watts during operation, mainly due to driving the motor and driving a strong IR emitter diode.

FAILURE MODES
Just like light, a Lidar beam can be absorbed by very dark objects and can be mis-directed by highly reflective objects which are non-perpendicular to the beam.

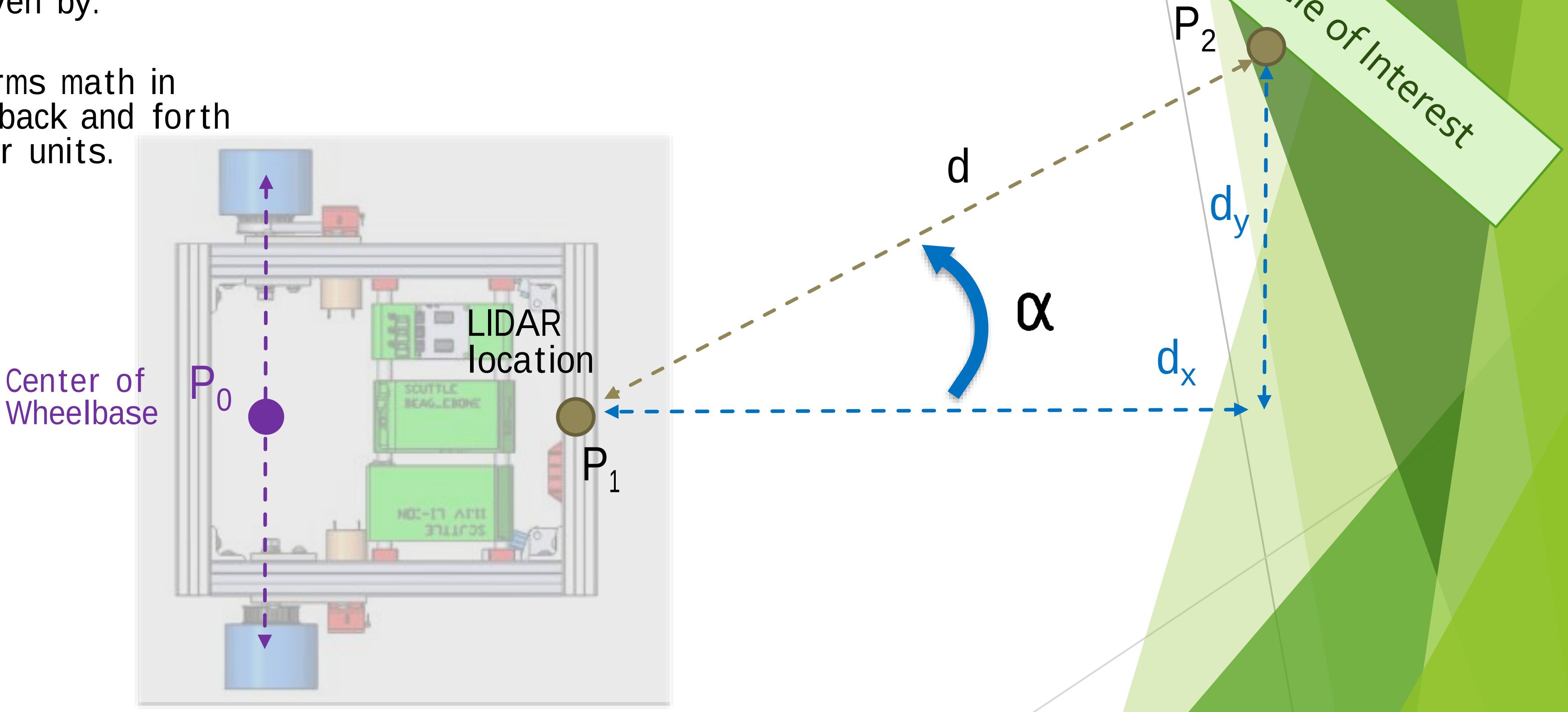
DATA QUALITY
The lidar has *variable resolution* in a sense! 0.33 degrees offers 5mm point spacing at a 1m distance, and at 10 meters, 50mm point spacing.

APPROPRIATE USE
To be successful in using the device, you need to see the datasheet to understand the parameters of your device.



LIDAR – measuring a point

- P_1 is the location of the lidar.
- The points will be initially measured from lidar and returned as pairs given by:
- [d (mm), α (degrees)]
- Python's numpy library performs math in radians. It is easy to convert back and forth but you must be aware of your units.



Software For LIDAR

Key Points:

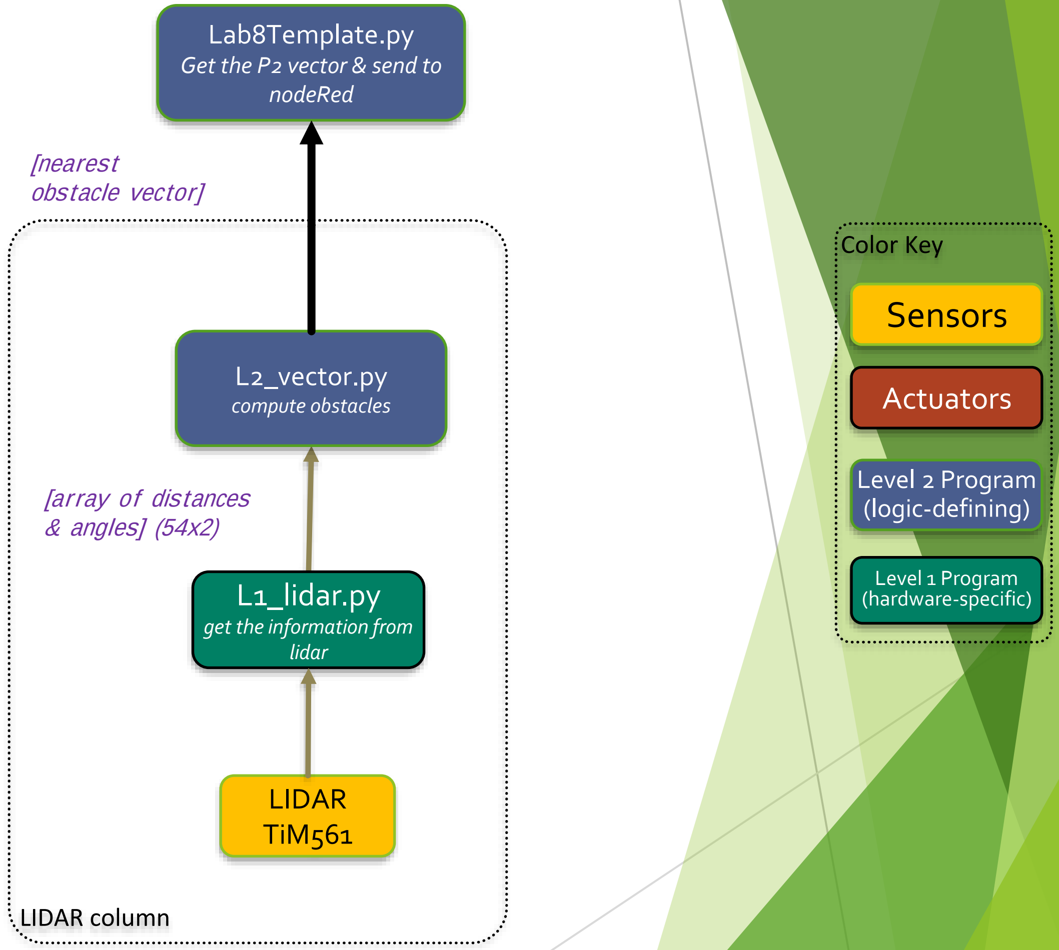
Software is using the numPy library to handle vectors and matrices. numPy computation is faster than raw python and requires proper syntax.

Lidar scan frequency: 15hz, so you cannot get new measurements faster than 66ms.

L1_lidar.py returns 54 measurements by default and can return over 800 single points if desired, for more resolution.

TiM561 LIDAR returns distances in meters. Distances under 16mm are returned as error codes in case of poor reflection or other problem for a given measurement.

L2_vector.py can manipulate measurements, with functions such as returning the nearest point, combining cartesian vectors, and converting vectors from polar to Cartesian coordinates.



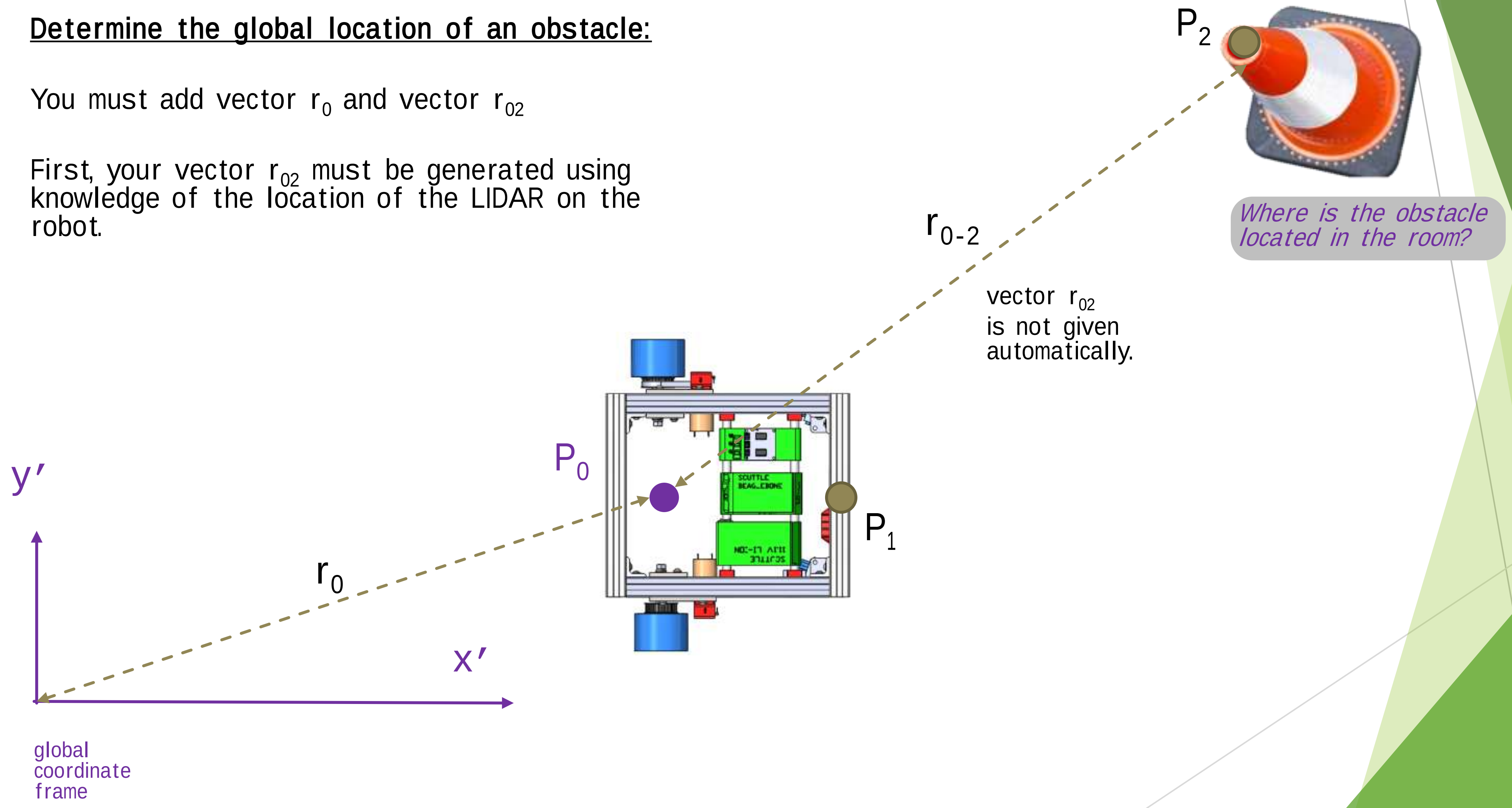
Lab8Template.py
Get the P2 vector & send to nodeRed
[nearest obstacle vector]
L2_vector.py
compute obstacles
[array of distances & angles] (54x2)
L1_lidar.py
get the information from lidar
LIDAR TiM561
LIDAR column
Color Key
Sensors
Actuators
Level 2 Program (logic-defining)
Level 1 Program (hardware-specific)

Global Location of Obstacle

Determine the global location of an obstacle:

You must add vector r_0 and vector r_{02}

First, your vector r_{02} must be generated using knowledge of the location of the LIDAR on the robot.



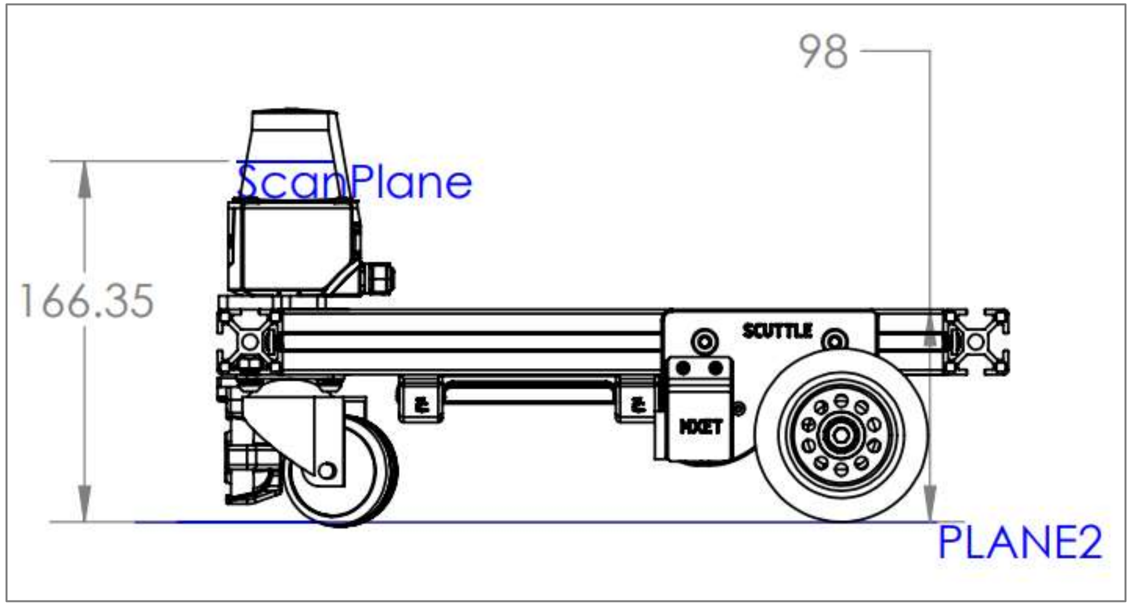
P_2
Where is the obstacle located in the room?
r_{0-2}
vector r_{02} is not given automatically.
P_0
P_1
y'
r_0
x'
global coordinate frame

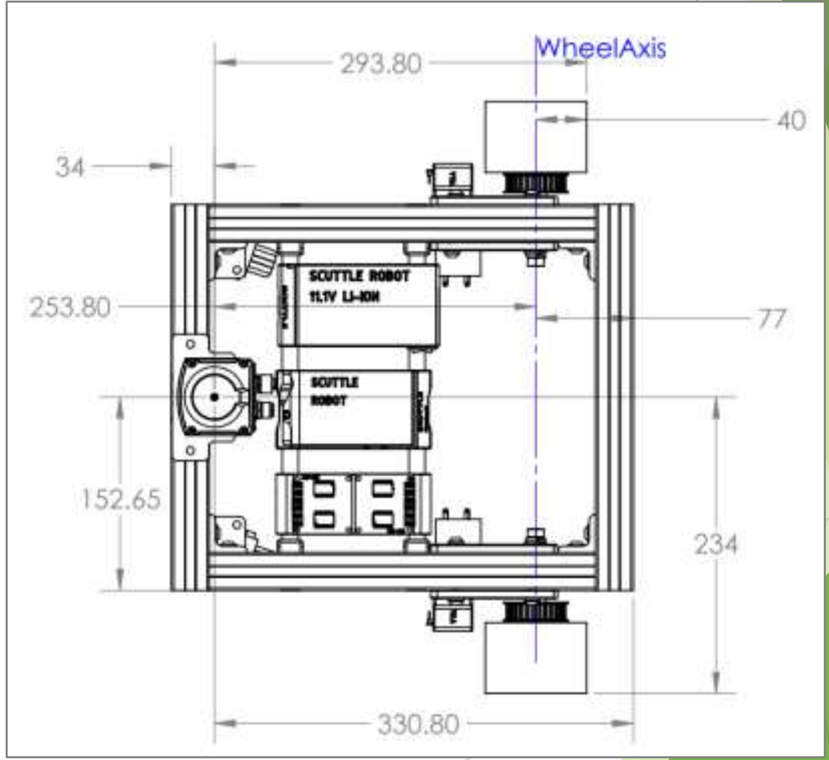
Global Location of Obstacle

Determine the global location of an obstacle:

Lidar is located at positive 254mm in the x-direction on the robot.

The lidar beam is 166 mm above the floor.



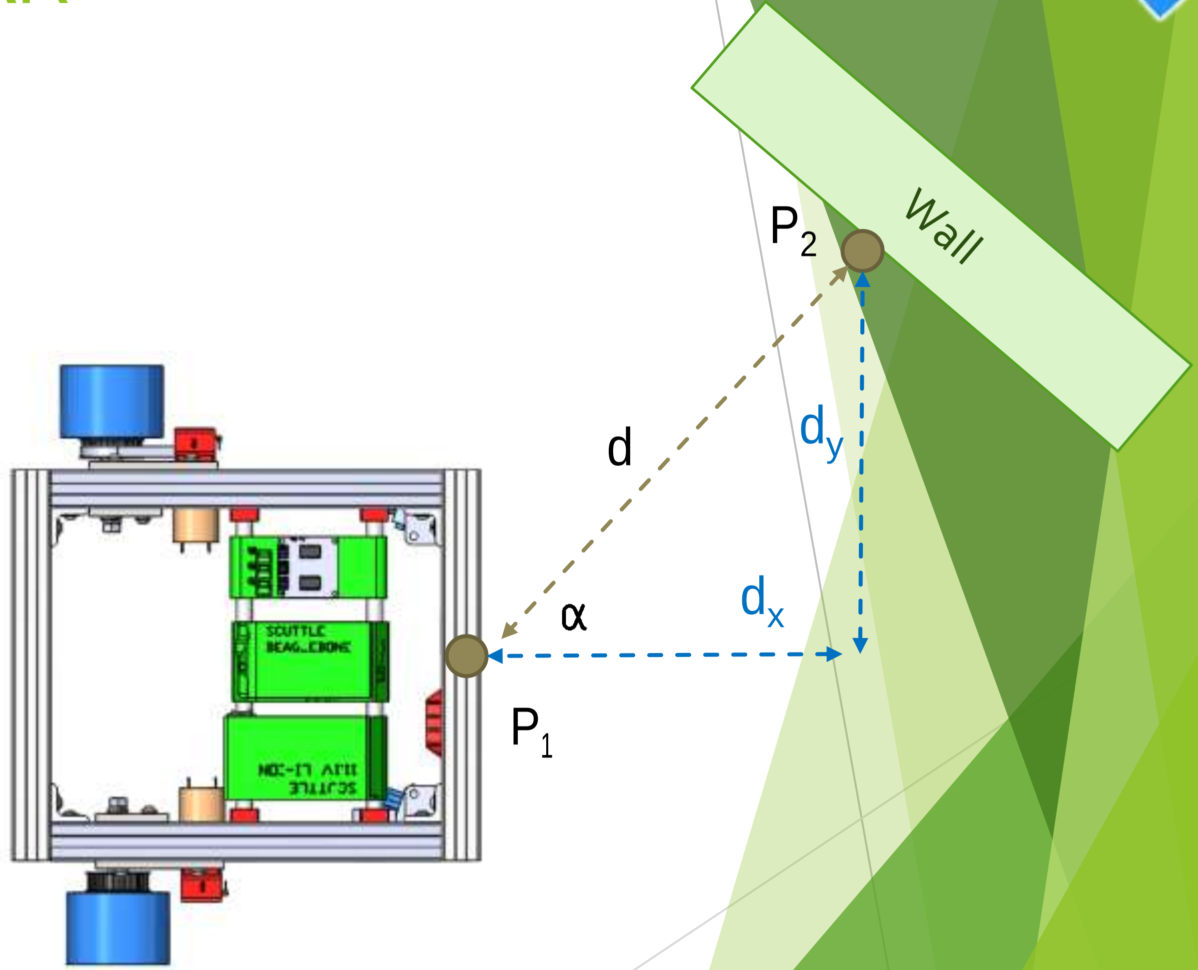


Obstacle Avoidance by LIDAR

One method to avoid obstacles is to generate an imaginary spring which pushes on your robot and depends on the nearest obstacle.

D_y is the y-component of distance d

D_x is the x-component of distance d

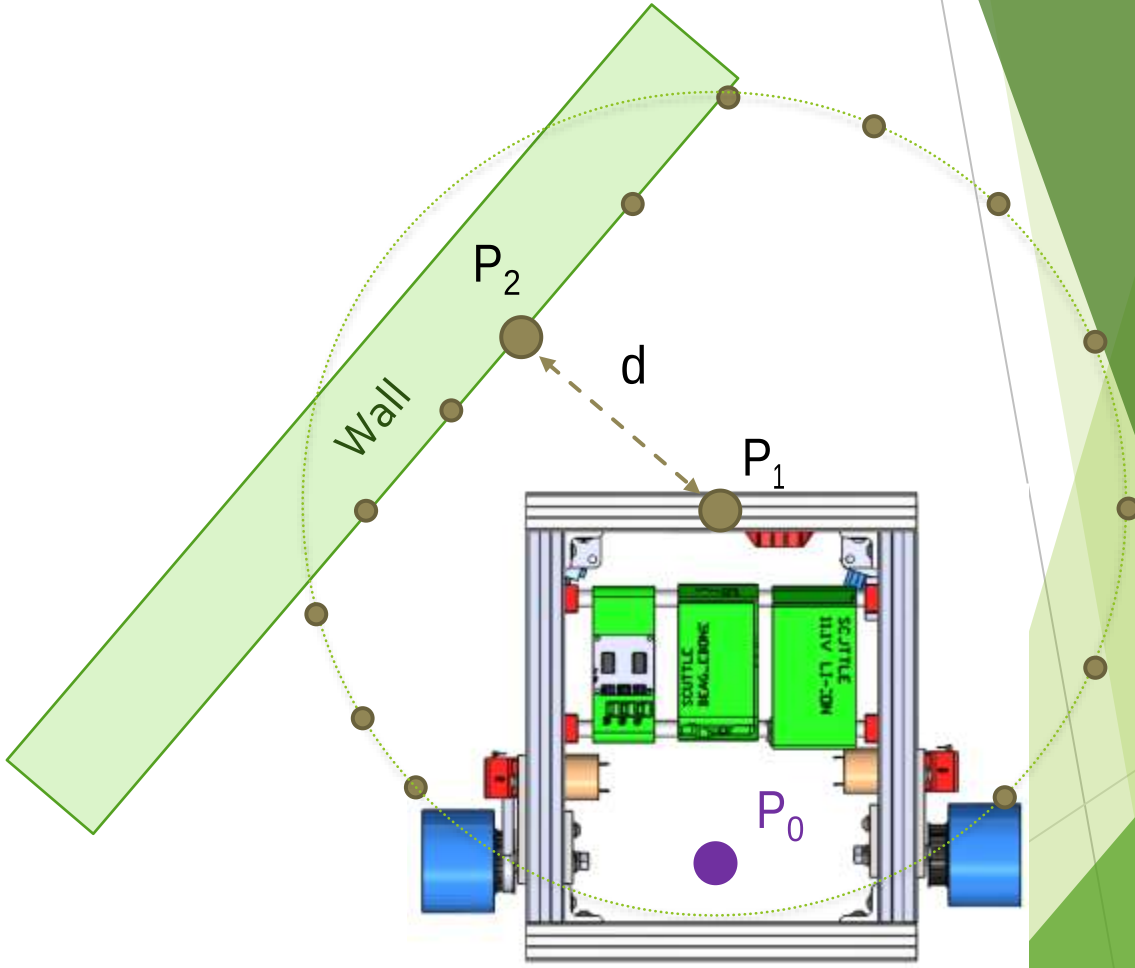


Obstacle Avoidance by LIDAR

Strategy:
The obstacle avoidance feature will try to detect the nearest objects to the robot and apply an "invisible force" to prevent the robot from crashing. The force is intended to act like a spring which is anchored to the nearest obstacle and pushes the robot at a point on the body, referred to as P1.

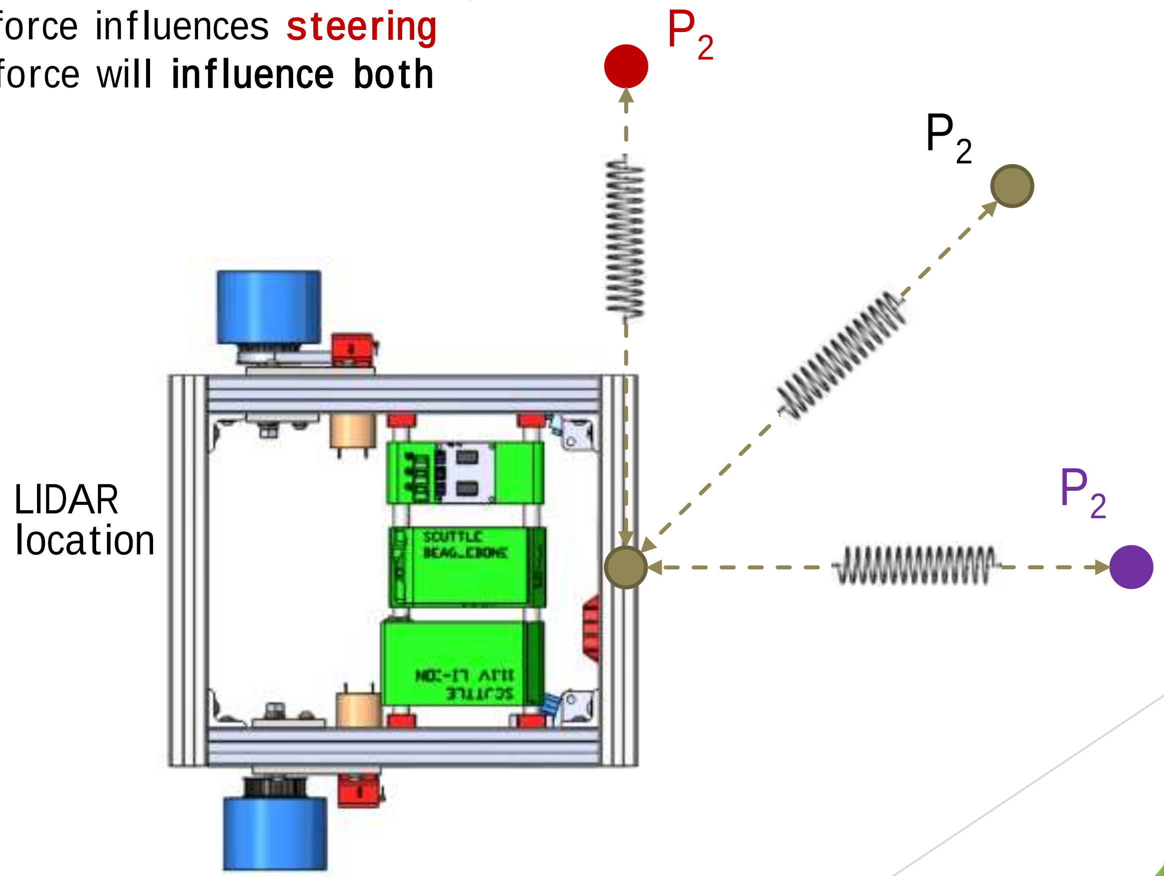
The obstacle avoidance only deals with the body-fixed frame

- Define P_1 as a point of interest on our robot.
- P_2 is assigned to the nearest point detected by the LIDAR scan.
- d is the distance between point 1 and point 2
- We would like to handle all of these variables in:
  - body-fixed frame
  - Cartesian coordinates



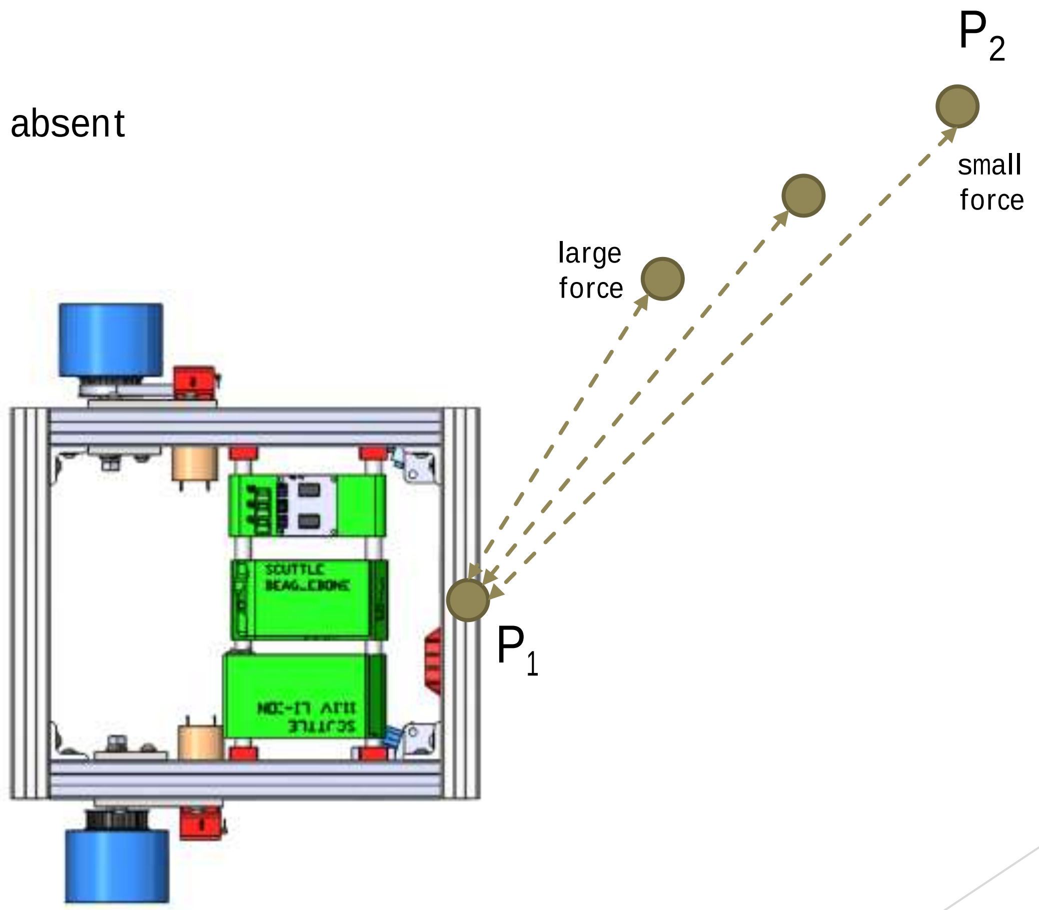
Obstacle Avoidance – influence on velocity (translational and angular)

- If P2 is detected straight ahead, the force influences **velocity**
- If P2 is detected at the side, the force influences **steering**
- If P2 is detected at an angle, the force will **influence both**



Obstacle Avoidance – Variable Force

- If d is large, the force is low
- If d is small, the force is high
- If d is larger than d_{max}, the force is absent



Quick Dive – Barometric Pressure

COLLEGE STATION 4-DAY CHANGE

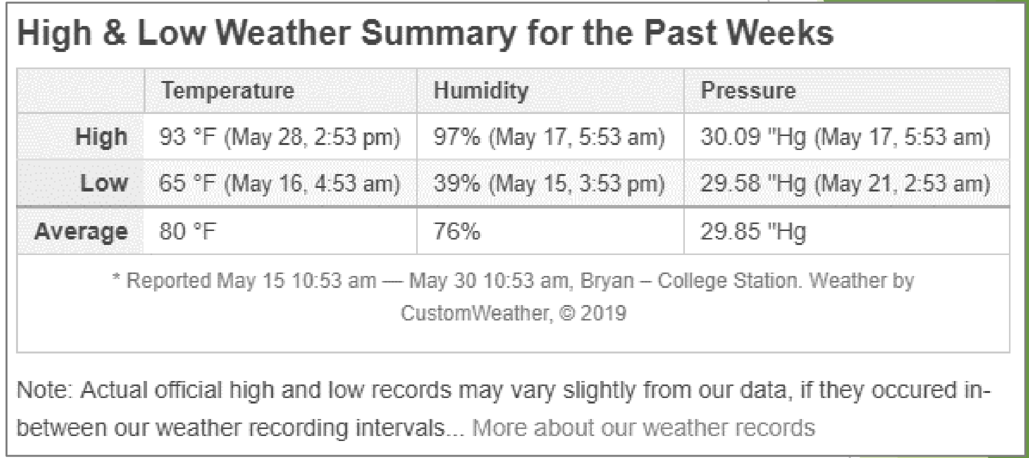
delta in pressure is 30.09-29.58 "Hg ➔ 0.51" Hg
delta pressure = 1.73kPa

STANDARD PRESSURE CALCULATIONS

sea level std pressure: 101.3kPa
pressure at 1000ft: 97.7kPa
delta pressure = 3.6kPa
elevation change represented by 1kPa = 278ft

What the Barometric pressure will tell you:

1.73kPa change in pressure will represent 480ft altitude change.



High & Low Weather Summary for the Past Weeks

	Temperature	Humidity	Pressure
High	93 °F (May 28, 2:53 pm)	97% (May 17, 5:53 am)	30.09 "Hg (May 17, 5:53 am)
Low	65 °F (May 16, 4:53 am)	39% (May 15, 3:53 pm)	29.58 "Hg (May 21, 2:53 am)
Average	80 °F	76%	29.85 "Hg

* Reported May 15 10:53 am — May 30 10:53 am, Bryan – College Station. Weather by CustomWeather, © 2019

Note: Actual official high and low records may vary slightly from our data, if they occured in-between our weather recording intervals... More about our weather records

Historic weather at timeanddate.com

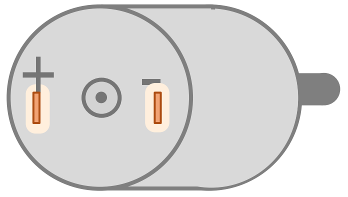
Driving FORWARD in Full Detail:

Controller Board

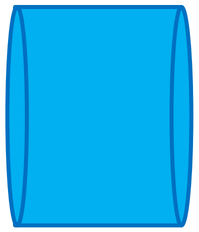
PWM	chA	chB	chA	chB
Pin on Pi	11	12	15	16
Duty	100	0	100	0

Motor Driver

Terminals	in1	in2	in3	in4
Incoming (v)	3.3	0	3.3	0
terminal	out1	out2	out3	out4
outgoing (v)	12	0	12	0

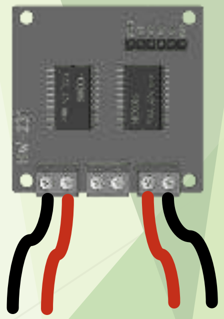

Motor

	LEFT HAND		RIGHT HAND	
outgoing (v) @ motor terminals	+	-	+	-
	12	0	0	12
(facing shaft)	counter-clockwise		clockwise	


wheel

	LEFT HAND	RIGHT HAND
Direction (driver's perspective)	FWD	FWD
Phi Dot	+	+

Where lies the difference between left and right?
A: Where we plug in the terminals.



Further Reading

- https://en.wikipedia.org/wiki/Holonomic_(robotics)
- Connector types
- http://dangerousprototypes.com/blog/2017/06/22/dirty-cables-whats-in-that-pile/