UNIVERSITY OF PADOVA

Embedded Real–Time Control

Laboratory report

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Contents

0 Abstract

During this course we worked on a mobile robotics platform equipped with motors, sensors, interfaces, and different processing units. In the following report it will be referenced as TurtleBot shown in Figure 1. The main processing unit is the STM32F767 microcontroller, it is connected directly or indirectly to all inputs and outputs via GPIOs.

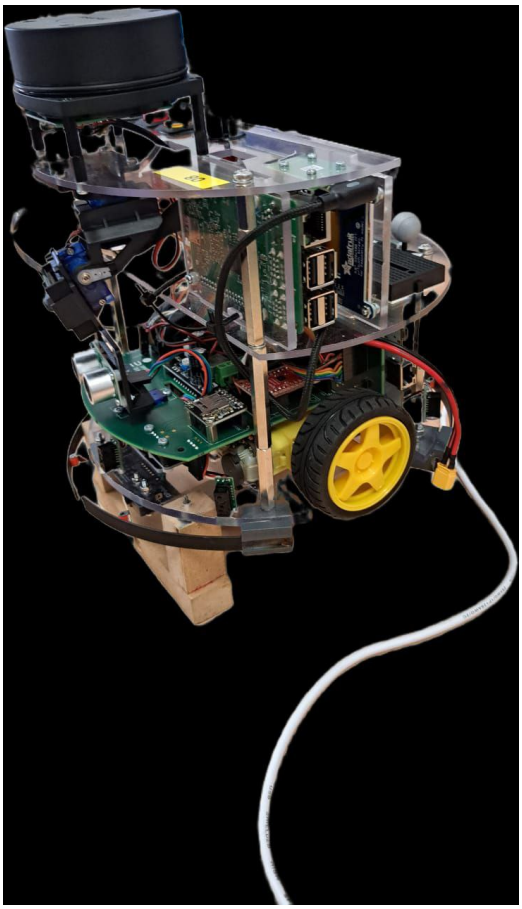


Figure 1: The TurtleBot

1 Laboratory 1: I2C

The purpose of this lab can be categorized as follows:

- Inter-Integrated Circuit (I2C)
- SX1509 I/O Expander
- APIs

1.1 Description

This laboratory aims to explore and gain practical experience with some fundamental concepts in Embedded Systems. In particular, we will focus on working with the I2C protocol and the SX1509 module, as well as understanding and utilizing interrupts in the STM32F767 microcontroller. Throughout this laboratory, we will delve into several exercises that will provide us with hands-on experience in applying these concepts.

1.1.1 Inter-Integrated Circuit (I2C)

The I2C bus is a standard bidirectional interface that uses a controller, known as the master, to communicate with slave devices, Shown in Figure 2.

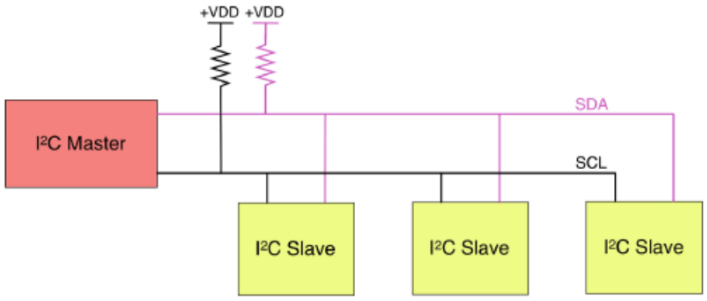
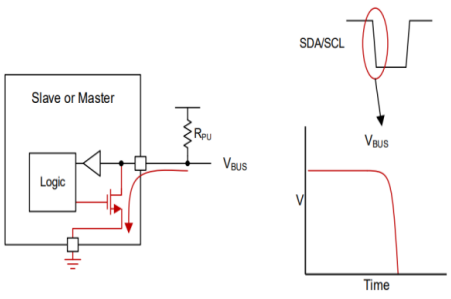
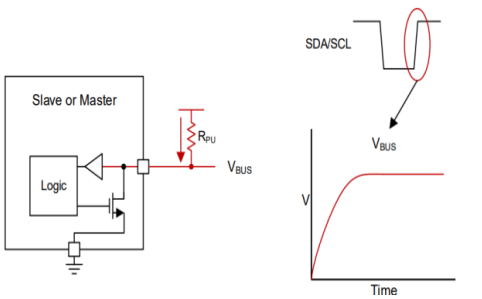


Figure 2: I2C Connection Scheme

A slave may not transmit data unless it has been addressed by the master. Each device on the I2C bus has a specific device address to differentiate between other devices that are on the same I2C bus. Many slave devices will require configuration upon startup to set the behavior of the device. This is typically done when the master accesses the slave's internal register maps, which have unique register addresses. A device can have one or multiple registers where data is stored, written, or read. The physical I2C interface consists of the serial clock (SCL) and serial data (SDA) lines. Both SDA and SCL lines must be connected to VCC through a pull-up resistor. The size of the pull-up resistor is determined by the amount of capacitance on the I2C lines. Shown in Figure (3a) and Figure (3b)



(a) Pulling the Bus Low with an open-drain Interface



(b) Releasing the bus with an open-drain interface

Figure 3

The protocol transmits messages composed by a 9 bit packet. Each message begins with the μC generation of a start signal and ends with a stop signal from the microcontroller, Shown in Figure 4.

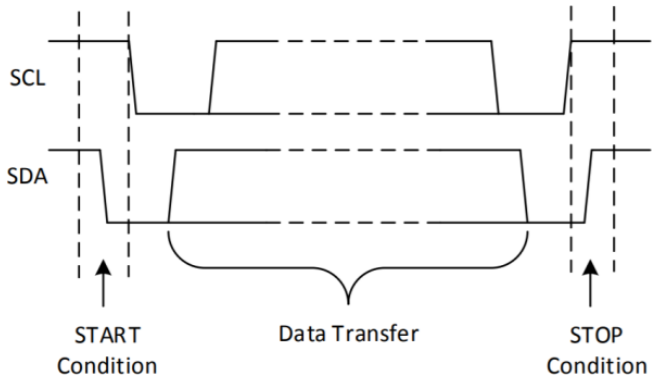


Figure 4: Example of Start and Stop condition

The start and stop conditions are characterized by the data line that moves towards low (start) or high (stop) during the clock high phase. Any other bit is set during the low clock phase. This ensures that the start and stop condition can be discriminated from any other data transmission.

In this communication protocol, each packet consists of 9 bits. The first 8 bits are transmitted by the sending unit, while the 9th bit is set by the receiving unit. The order of the bits within each byte follows a "Most Significant Bit" (MSB) format. The 9th bit serves as an reply, indicating whether the receiver acknowledges the data. To acknowledge, the receiver sets the data line to a low state at the 9th bit position. Example of Single Byte data transfer in Figure 5.

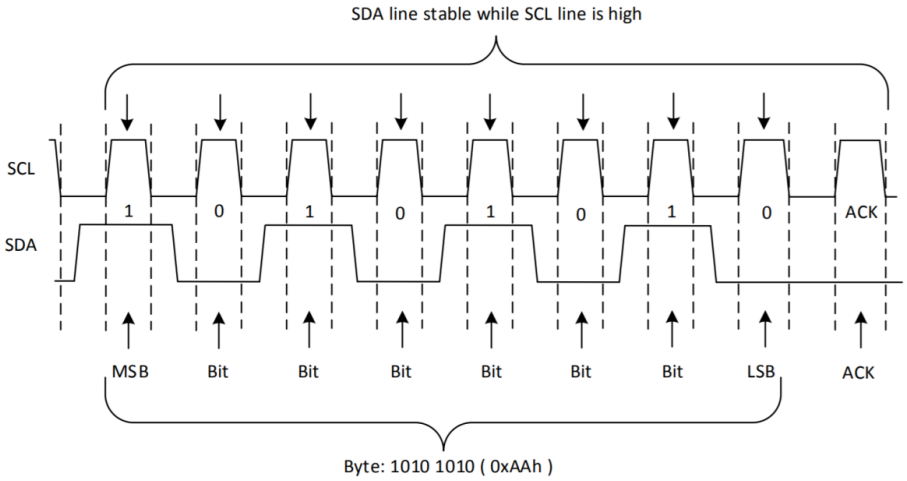


Figure 5: Example of Single Byte Data Transfer

1.1.2 SX1509 I/O Expander

The SX1509 is a general purpose GPIO expander board, able to parallel handle several inputs and outputs. It has ultra-low voltage capabilities of 1.2 to 3.6 V, ideal for battery powered equipment. This family of GPIOs comes in 4-, 8-, 16-channel configuration and allows easy serial expansion of I/O through a standard 400kHz I2C interface. GPIO devices can provide additional control and monitoring when the microcontroller or chipset has insufficient I/O ports, or in systems where serial communication and control from a remote location is advantageous. Keypad application is also supported with the on-chip scanning engine. It enables continuous keypad monitoring up to 64 keys without any additional host interaction, keeping the bus activity low. The SX1509 has the ability to generate mask-programmable interrupts based on falling/rising edge of any of its GPIO lines.

In this setup, two SX1509 modules are connected to the microcontroller using the I2C bus. Both devices share the same I2C line, specifically I2C1. To differentiate between the two modules, we assign a specific slave address to each. The first SX1509, referred to as sx1509_1, is assigned the slave address 0x3E, while the second module, known as sx1509_2, is associated with the slave address 0x3F.
Allocated addresses of slaves implemented in Listing 1

Listing 1: I2C Addresses

```
1 #define SX1509_I2C_ADDR1 0x3E          //SX1509 Proxy Sensors I2C address
2 #define SX1509_I2C_ADDR2 0x3F          //SX1509 Keypad I2C address
```

The two lines of Listing 2 are addressing of SX1509 registes for Keypad.

Listing 2: Keypad Data registers

```
1 #define REG_KEY_DATA_1  0x27          //RegKeyData1 Key value (column) 1111 1111
2 #define REG_KEY_DATA_2  0x28          //RegKeyData2 Key value (row) 1111 1111
```

This addressing scheme allows the microcontroller to communicate with each SX1509 module individually over the shared I2C bus, Figure 6

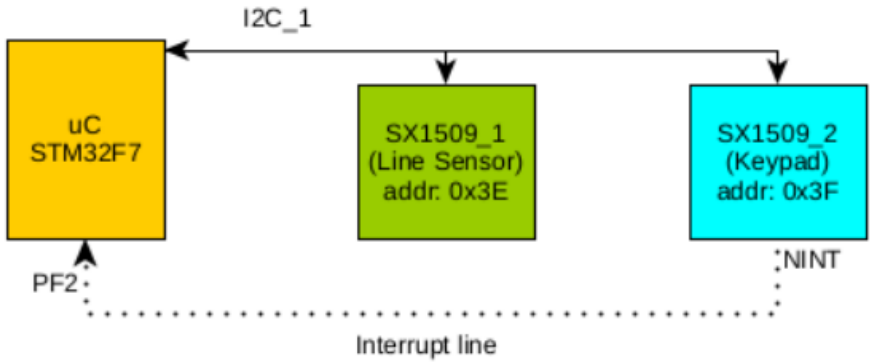


Figure 6: SX1509 connected to Keypad and Line sensor

1.1.3 APIs

The HAL (Hardware Abstraction Layer) API (Application Programming Interface) is a software layer provided by STM32 microcontrollers that abstracts the underlying hardware functionalities and provides a standardized interface for developers to interact with the microcontroller's peripherals and features. The HAL API serves as a bridge between the application software and the hardware, allowing developers to access and control the microcontroller's peripherals, such as GPIO (General Purpose Input/Output), UART (Universal Asynchronous Receiver-Transmitter), SPI (Serial Peripheral Interface), I2C (Inter-Integrated Circuit), timers, and more. It provides a higher-level programming interface, hiding the low-level hardware details and offering a set of functions that encapsulate complex hardware operations.
Listing 3 are useful HAL functions that we used during this Laboratory.

Listing 3: Reading Register values

```
1 HAL_StatusTypeDef HAL_I2C_Mem_Read(I2C_HandleTypeDef *hi2c, uint16_t
2     DevAddress, uint16_t MemAddress, uint16_t MemAddSize, uint8_t *pData,
3     uint16_t Size, uint32_t Timeout);
```

Read an amount of data in blocking mode from a specific memory address

- **hi2c** Pointer to a I2C_HandleTypeDef structure that contains the configuration information for the specified I2C.
- **DevAddress** Target device address: The device 7 bits address value in datasheet must be shifted to the left before calling the interface.
- **MemAddress** Internal memory address

- **MemAddSize** Size of internal memory address
- **pData** Pointer to data buffer
- **Size** Amount of data to be sent
- **Timeout** Timeout duration
- **return value** HAL status

Listing 4: Writing Register values

```
1 HAL_StatusTypeDef HAL_I2C_Mem_Write(I2C_HandleTypeDef *hi2c, uint16_t
2     DevAddress, uint16_t MemAddress, uint16_t MemAddSize, uint8_t *pData,
3     uint16_t Size, uint32_t Timeout)
```

Write an amount of data in blocking mode to a specific memory address

- **hi2c** Pointer to a I2C_HandleTypeDef structure that contains the configuration information for the specified I2C.
- **DevAddress** Target device address: The device 7 bits address value in datasheet must be shifted to the left before calling the interface.
- **MemAddress** Internal memory address
- **MemAddSize** Size of internal memory address
- **pData** Pointer to data buffer
- **Size** Amount of data to be sent
- **Timeout** Timeout duration
- **return value** HAL status

1.2 Exercises

1.2.1 Exercise 1:

In this exercise we are asked to write an ISR that recognize and correctly handles the keypad interrupts. We properly implemented the void HAL_GPIO_EXTI_Callback(uint16_t pin) function, which is used in conjunction with the EXTI (External Interrupt) peripheral to handle interrupts generated by GPIO pins. Then the triggered interrupt is printed i.e. the pin. To be able to receive another interrupt from the keypad, we read the registers REG_KEY_DATA_1 and REG_KEY_DATA_2 inside the ISR.

Listing 5: Interrupt Callback

```
1  void HAL_GPIO_EXTI_Callback(uint16_t GPIO_Pin){
2      /*Reading Data From SX1509_I2C_ADDR2 Device Address and REG_KEY_DATA_1 and
3      REG_KEY_DATA_2 Memory Addresses */
4      HAL_StatusTypeDef status;
5      status = HAL_I2C_Mem_Read(
6          &hi2c1,
7          SX1509_I2C_ADDR2 << 1,
8          REG_KEY_DATA_1,
9          1,
10         &colum,
11         1,
12         I2C_TIMEOUT
13     );
14     if (status != HAL_OK) {
15         printf("Error occurred during reading I2C, REG_KEY_DATA_1\n");
16     }
17     status = HAL_I2C_Mem_Read(
18         &hi2c1,
19         SX1509_I2C_ADDR2 << 1,
20         REG_KEY_DATA_2, 1,&row,
21         1,
22         I2C_TIMEOUT
23     );
24     if (status != HAL_OK) {
25         printf("Error occurred during reading I2C, REG_KEY_DATA_2\n");
26     }
27     printf("Interrupt on pin (%d).\n", GPIO_Pin);
28 }
```

The provided code is an ISR (HAL_GPIO_EXTI_Callback) that handles GPIO interrupts generated by a keypad. It uses I2C communication to read data from an SX1509 device. The code reads the values from REG_KEY_DATA_1 and REG_KEY_DATA_2 registers in the SX1509 device to retrieve information about the keypad input. The colum and row variables store the read data, representing the column and row information of the pressed key, respectively. If any errors occur during the I2C read operations, corresponding error messages are printed. Finally, the code prints a message indicating the GPIO pin that triggered the interrupt.

1.2.2 Exercise 2:

In this exercise the previous code was extended to handle the keypad interrupts. Using mapping the pressed keypad button can be printed.

Listing 6: Pressed Keypad Button

```
const char keypadLayout[4][4] = {
    {'*', '0', '#', 'D'},
    {'7', '8', '9', 'C'},
    {'4', '5', '6', 'B'},
    {'1', '2', '3', 'A'}
};
int colum, row;
char triggeredChar;
int columDir [4]= { 3, 2 ,1 ,0};
int getIndex(int value);

void HAL_GPIO_EXTI_Callback(uint16_t GPIO_Pin){

    HAL_StatusTypeDef status;
    status = HAL_I2C_Mem_Read(
        &hi2c1,
        SX1509_I2C_ADDR2 << 1,
        REG_KEY_DATA_1,
        1,
        &colum,
        1,
        I2C_TIMEOUT
    );
    if (status != HAL_OK) {
        printf("Error occurred during reading I2C, REG_KEY_DATA_1\n");
    }
    status = HAL_I2C_Mem_Read(
        &hi2c1,
        SX1509_I2C_ADDR2 << 1,
        REG_KEY_DATA_2, 1,&row,
        1,
        I2C_TIMEOUT
    );
    if (status != HAL_OK) {
        printf("Error occurred during reading I2C, REG_KEY_DATA_2\n");
    }
    printf("Interrupt on pin (%d).\n", GPIO_Pin);
    printf("colum.raw (%d)    row.raw (%d).\n", colum, row);
    colum = getIndex (colum);
    row = getIndex(row);
    printf("colum (%d)    row (%d).\n", colum, row);
    triggeredChar = keypadLayout[row][colum];
} //End of Interrupt Callback function
int getIndex(int value){
  switch (value){
    case 247:
      return 3;
    case 251:
      return 2;
    case 253:
      return 1;
    case 254:
      return 0;
    default:
      return 99;
```

```
56     }
57 }
```

In this exercise, the code has been extended to handle keypad interrupts. The ‘HAL_GPIO_EXTI_Callback‘ function is responsible for handling GPIO interrupts triggered by the keypad. The code reads the values from ‘REG_KEY_DATA_1‘ and ‘REG_KEY_DATA_2‘ registers in the SX1509 device using I2C communication. After reading the values, the code prints the GPIO pin that triggered the interrupt, as well as the raw values of ‘colum‘ and ‘row‘. These raw values are then processed using the ‘getIndex‘ function to obtain the corresponding column and row indices in the keypad layout. The ‘getIndex‘ function takes a value as an input, which represents the raw value of ‘colum‘ or ‘row‘. It compares the value with predefined values and returns the corresponding index. If the value doesn’t match any of the predefined values, it returns a default value of 99. Finally, the code uses the obtained column and row indices to access the ‘keypadLayout‘ array and assigns the corresponding character to the ‘triggeredChar‘ variable, representing the keypad button that has been pressed. Overall, the extended code reads the state of the keypad from the SX1509 device, converts the raw values to column and row indices, and determines the specific keypad button that has been pressed based on the indices.

1.2.3 Exercise 3:

In this exercise a routine was written, which reads the status of the line sensor and prints it. The routine checks the status with a polling period of 100ms.

Listing 7: Reading Line Data

```
int findBinary(int decimal){
    int base = 1;
    int binary = 0;
   while(decimal > 0){
       int rem = decimal % 2;
       binary = binary + rem*base;
       decimal = decimal / 2;
       base = base * 10;
   }
   printf("Binary: %d\n\r", binary);
}//End of findBinary Function
int lineData;
while (1){
    HAL_I2C_Mem_Read(
        &hi2c1,
        SX1509_I2C_ADDR1 << 1,
        REG_DATA_B,
        1,
        &lineData,
        1,
        I2C_TIMEOUT
        );
      findBinary(lineData);
      printf("Decimal is: %d \n\r", lineData);
      HAL_Delay(100);
}//End of While loop
```

1.2.4 Exercise 4 - Bonus:

In this exercise the LED should change its blinking frequency. By using LEDs connected to PE5 or PE6, it is necessary to check the *.ioc to make sure that those pins are set as GPIO_output. The blinking frequency should be set by the user through the keypad. The frequency can be set "dynamically" by the user. For example, if the user press 125# the LED should blink with a frequency of 125Hz. If the user press 250# the LED should blink with a frequency of 250Hz, and so on.

Listing 8: C code using listings

```
1  //These are Global Variables//
2  int inputUser = 0;
3  int counter = 0;
4  int flag=0;
5  int freq;
6
7  //This part of code has implemented in the Interrupt Callback Function
8  triggeredChar = keypadLayout[row][colum];
9  if(flag == 1){
10     freq = inputUser;
11     inputUser = 0;
12     counter = 0;
13     flag = 0;
14 }
15 if((triggeredChar <= '9') && (triggeredChar >= '0')){
16     keypadFreq = (int)(triggeredChar - '0');
17     inputUser = inputUser*(10^counter) + keypadFreq;
18     counter++;
19 }
20   printf("Triggered Char: %c \n\r ", triggeredChar);
21 //End of Interrupt Callback function
22
23
24 //Start infinit loop
25 while (1){
26     if(triggeredChar == '#'){
27     flag = 1;
28     HAL_GPIO_TogglePin(GPIOE, GPIO_PIN_5);
29         if(inputUser != 0){
30          HAL_Delay((1.0/inputUser)*1000);
31         }
32         else{
33          HAL_Delay(1000);
34         }
35     }//End of if(triggerChar ..)
36     else{
37          HAL_GPIO_TogglePin(GPIOE, GPIO_PIN_5);
38          if(freq != 0){
39          HAL_Delay((1.0/freq)*1000);
40          }
41          else{
42              HAL_Delay(1000);
43          }
44     }
45 }//End of While loop
```

The Code is designed to control the blinking of an LED using a keypad for user input. It utilizes an interrupt callback function to capture keypad button presses and extract the frequency values entered by the user. When the user presses a button on the keypad, the callback function is triggered, and the character associated with the button press is obtained. The code checks if the user has completed entering the frequency by using a flag variable. If the flag is set, it means the user has finished entering the frequency, and the value is stored in the 'inputUser' variable. If the triggered character is a digit, it is converted to an integer and accumulated to form the complete frequency value. The 'counter' variable keeps track of the number of digits entered, allowing

multi-digit frequencies to be entered. The main loop continuously toggles the LED pin based on the entered frequency. If the user has pressed the '#' button to complete the frequency input, the LED is toggled with a delay based on the calculated frequency. If a valid frequency is entered (‘inputUser‘ is not zero), the delay is calculated as the inverse of the frequency. Otherwise, a default delay of 1 second (corresponding to a frequency of 1Hz) is used. It is important to note that the code provided assumes the availability of a keypad layout and initialization code, as well as the necessary configuration for GPIO pins and interrupts. Additionally, some aspects such as resetting the variables after completing the LED blinking are missing and need to be added. Overall, this code enables users to dynamically set the blinking frequency of the LED using the keypad.

2 Laboratory 2: Open loop control (camera stabilizer)

In this lab an open loop stabilizer was implemented using the IMU and servo motors.

2.1 Description

2.1.1 IMU

IMU stands for Inertial Measurement Unit. It is a device that is used to measure and report an object's specific force, angular rate, and sometimes the magnetic field surrounding it. IMUs are commonly used in various applications, including robotics, navigation systems, virtual reality, augmented reality, and motion capture.

An IMU typically consists of several sensors that work together to provide information about an object's motion and orientation:

- **Accelerometer**: Measures linear acceleration along different axes (typically three axes: X, Y, and Z). It detects changes in velocity and orientation, allowing the IMU to determine the object's acceleration and tilt. Figure (7)
- **Gyroscope**: Measures angular velocity or rate of rotation around different axes. It provides information about the object's rotational motion and helps track changes in orientation.
- **Magnetometer**: Measures the strength and direction of the magnetic field around the object. It is often included in IMUs to provide additional information for orientation estimation, especially when used in combination with accelerometers and gyroscopes.

By combining the data from these sensors, an IMU can estimate the object's orientation, position, and velocity relative to its initial state.

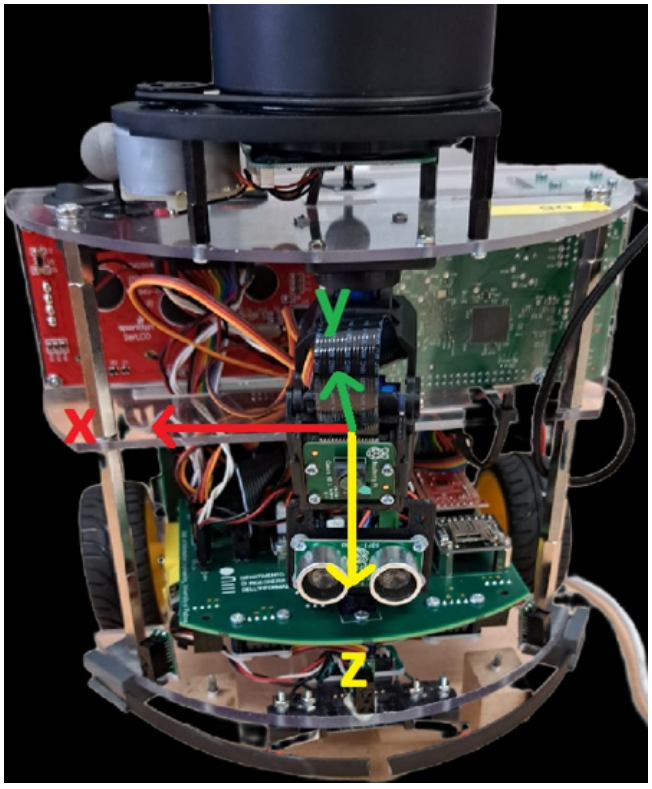


Figure 7: The axis of the accelerometer

- **Tilt** refers to the vertical movement of the camera, where the camera is moved up or down.
- **Pan** refers to the horizontal movement of the camera, where the camera is rotated around its vertical axis to the left or right.

2.1.2 Servo Motor

A servo motor is a type of motor that is widely used in various applications, particularly in robotics, automation, and control systems. It is designed to provide precise control over angular or rotational movement.

The distinguishing feature of a servo motor is its ability to maintain a specific position or follow a desired trajectory with great accuracy. It achieves this through a closed-loop control system, which continuously compares the actual position of the motor shaft with the desired position and adjusts the motor's output accordingly.

Here are some key components and characteristics of servo motors:

- **DC Motor**: Most servo motors are based on a DC motor as the primary driving mechanism. The DC motor converts electrical energy into rotational motion.
- **Gear Train**: Servo motors often include a gear train that reduces the motor's high-speed, low-torque output to a lower speed with higher torque. This gearing mechanism enables the servo motor to generate more precise and controlled movements.
- **Position Feedback Sensor**: A servo motor typically incorporates a position feedback sensor, such as an encoder or a potentiometer. This sensor provides information about the current position and velocity of the motor shaft. The feedback data is used by the control system to determine if the motor needs to adjust its position.
- **Control Circuitry**: The control circuitry of a servo motor includes a microcontroller or a dedicated servo controller. It receives the control signal or command from an external device, such as a microcontroller or a computer, and generates the appropriate electrical signals to drive the motor.
- **Pulse Width Modulation (PWM) Signal**: Servo motors commonly utilize a PWM signal to control their position and speed. The control signal consists of a series of pulses with varying widths, where the width of each pulse determines the desired position. The control circuitry interprets the pulse width and adjusts the motor's position accordingly. Figure (8)

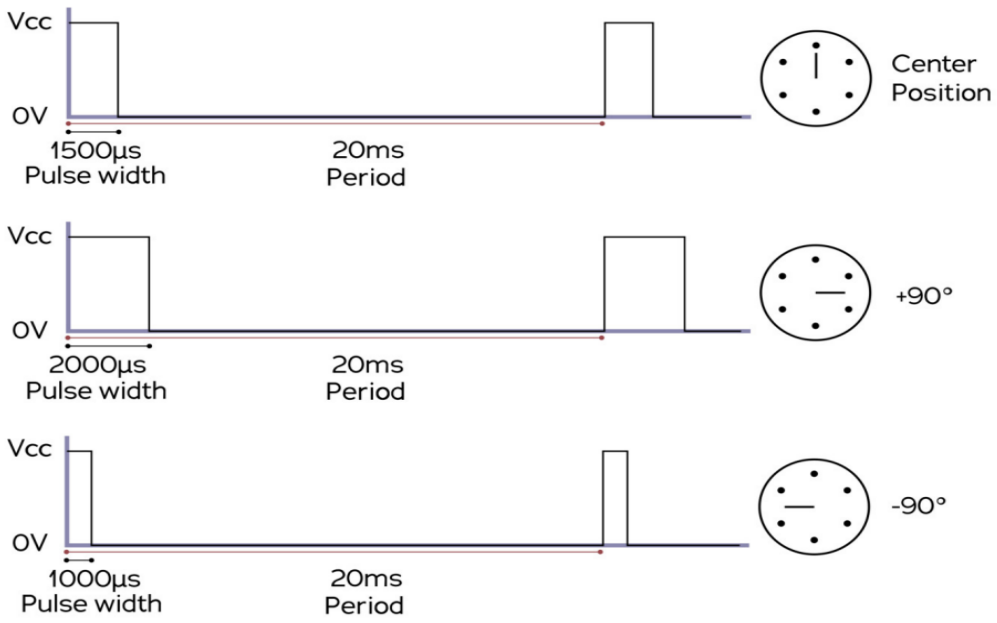


Figure 8: PWM signal and comtroling the position of the motor

On the TurtleBot there are two servos that control the tilt and pan of the camera, as shown in Figure (9).

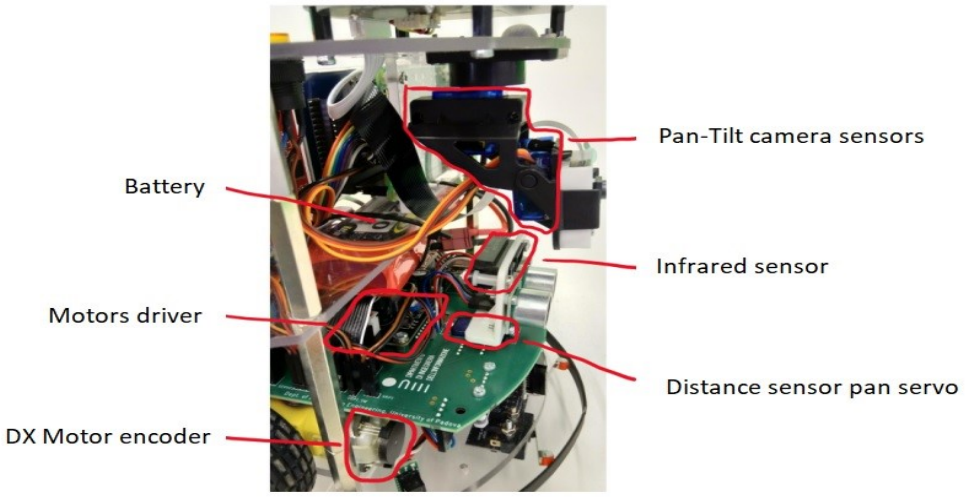


Figure 9: PWM signal and comtroling the position of the motor

2.2 Exercises

2.2.1 Exercise1:

Develop a control law to stabilize the camera's tilt by utilizing data from an IMU.
First of all, we have to keep the camera aligned (0 degree) with the horizon. For this purpose, we should obtain the accelerometer and gyroscope data from the robot.

Listing 9: C code using listings

```
1
2       int8_t tilt = 0;
3       float angle = 0;
4   while (1) {
5
6       HAL_Delay(20);
7       bno055_convert_double_accel_xyz_msq(&d_accel_xyz);
8       angle = (asin(d_accel_xyz.y/ 9.81)) * 180 / 3.14;
9       tilt = -angle;
10      logger_data.u1 = tilt;
11      logger_data.u2 = d_accel_xyz.y;
12      ertc_dlog_send(&logger, &logger_data, sizeof(logger_data));
13      ertc_dlog_update(&logger);
14
15      __HAL_TIM_SET_COMPARE(&htim1,
16            TIM_CHANNEL_3,
17            (uint32_t)saturate((150+tilt*(50.0/5.0)),
18             SERVO_MIN_VALUE,
19             SERVO_MAX_VALUE));
20
21    }
```

As you see, first we defined tilt and angle globally. To obtain the accelerometer data we use "bno055_convert_double _accel_xyz_msq" and "d_accel_xyz" as a pointer to a structure as input.

The formula for calculating the tilt angle of the TurtleBot is: $\theta = \sin^{-1}\left(\frac{a_y}{g}\right)$, θ is the tilt angle, a_y is the acceleration measured on the y axis and g is gravity acceleration g = 9.81 $\frac{m}{s^2}$. To convert θ from radiant the equation should be multiplied by $\frac{180}{\pi}$. As we want to keep the camera aligned the tilt angle of the camera needs to be equal to -θ .
For moving the camera the "__HAL_TIM_SET_COMPARE" is used. It is a HAL library macro used for setting the compare value of a specific channel of a hardware timer on the microcontroller.

To record sensor values a data logger is used. For this a structure is defined, which takes the necessary values.

```
struct ertc_dlog logger;

struct datalog {
    float u1, u2;
} logger_data;
```

Then we use logger_data.u1 as the tilt data and logger_data.u2 as the acceleration measured on the y axis data in the while loop.

To plot the data we use Matlab and the serial datalogger is invoked using serial_datalog() function as below:

```
data = serial_datalog('COM9',{'2*single','2*single'}, 'baudrate', 115200)
```

"COM9" is the port of the serial datalogger. "single,single" specifies the data format to be logged. It indicates that two data values will be logged in each iteration of the logging process. In this case, the logged data is expected to be of type single (a single-precision floating-point number).
"baudrate", "115200" sets the baud rate of the serial communication. The baud rate determines the speed at which data is transferred over the serial port. In this case, the baud rate is set to 115200 bits per second.

2.2.2 Bonus:

Implement a control algorithm that implement a "smooth pan" control (i.e. a control system that compensate sharp horizontal rotations of the TBot) using data from the gyroscope.
Process is like exercise 1:

```
    int8_t pan = 0;

    float angle = 0;
while (1) {
    HAL_Delay(20);
    bno055_convert_double_gyro_xyz_rps(&d_gyro_xyz);
    angle = d_gyro_xyz.z * 180 / 3.14;
    pan = -angle/8;
    logger_data.u1 = pan;
    logger_data.u2 = d_gyro_xyz.z;
    ertc_dlog_send(&logger, &logger_data, sizeof(logger_data));
    ertc_dlog_update(&logger);
    __HAL_TIM_SET_COMPARE(&htim1,TIM_CHANNEL_3,
    (uint32_t)saturate((150+pan*(50.0/55.0)),
     SERVO_MIN_VALUE,
    SERVO_MAX_VALUE));
}
```

To compensate the pan motion of the camera the gyroscope angle around the z axis is measured. converted to degrees and negated the angle can be feed directly to the servo controlling for the pan motion. The result is a camera, which moves very jerky in the opposite direction of the TurleBots pan angle. To degrees the jerk of this motions a fraction of $\frac{1}{8}$ is used. The servo motor is set on "TIM_CHANNEL_3".

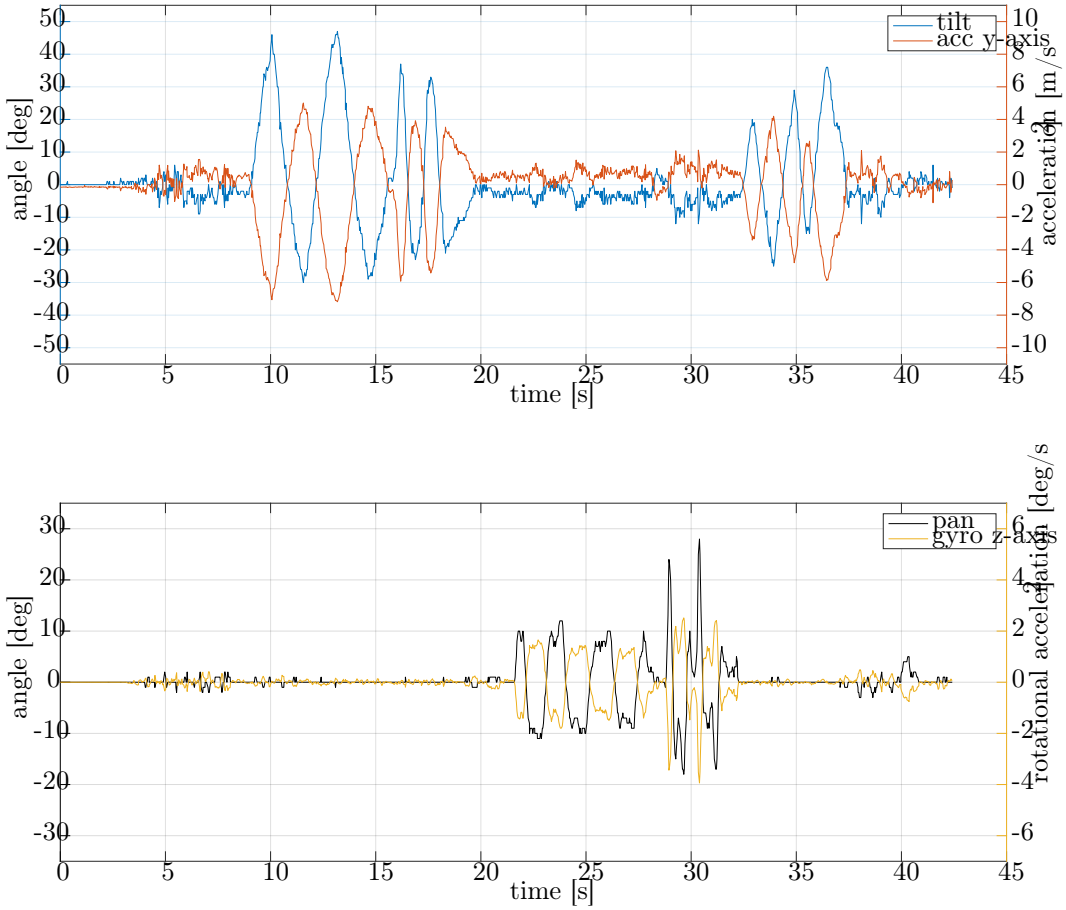


Figure 10: Data captured while tilting and panning the TurtleBot

3 Laboratory 3: Motor Control

3.1 Description

The goal of this laboratory is to implement a controller to drive and control the DC motors of the TurtleBot. To reach that goal a PI controller is designed. The current angular speed is measured through an encoder on the motors. The reference input for the controller is angular speed , measured in rotation's per minute [rpm].

3.1.1 DC Motor

A DC motor is a class of rotary electrical motor that converts direct current (DC) electrical energy into mechanical energy. There are three common parts in all types of DC motors:

- a stator, which can be implemented as a permanent magnet;
- a rotor winding or a coil, which can be simply a wire;
- a commutator is connected to the rotor winding and its purpose is to force the direction of the current flowing into the rotor to be always the same;

However, the DC motor which is used in the Turtle-Bot uses Brushed implementation. Brushes are used to feed current to the commutator and each brush is connected to one pole of the power supply.

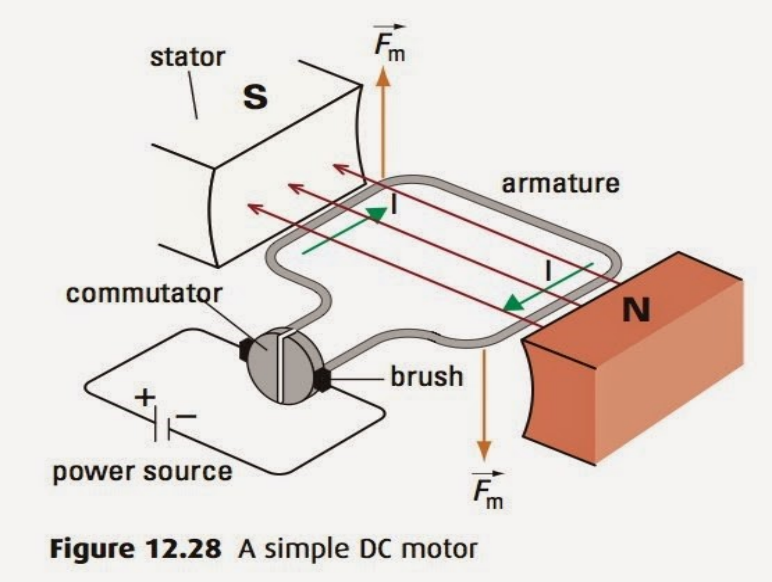


Figure 11: DC Motor simplified scheme

The stator generates a magnetic field and the rotor winding, which is positioned within the field generated by the stator, when a current flow through it, is subjected to a magnetic force perpendicular to the direction of the stator field. The commutator has a ring-like shape and present gaps, so that each part of the commutator is connected to power source of opposite polarity, ensuring the current flows in the proper direction.

Inverting the power source polarity, invert the direction of the current, allowing the motor to rotate in both directions.

3.1.2 DRV8871

Since we want to use a PWM as a control signal for the motor, we use a chip that can convert a PWM input into a proper output, both in terms of voltage and current, to drive the motor. For such purpose, the chosen chip is a DRV8871, which is a brushed DC motor driver. The motor can be controlled bidirectionally by implementing an H-bridge.

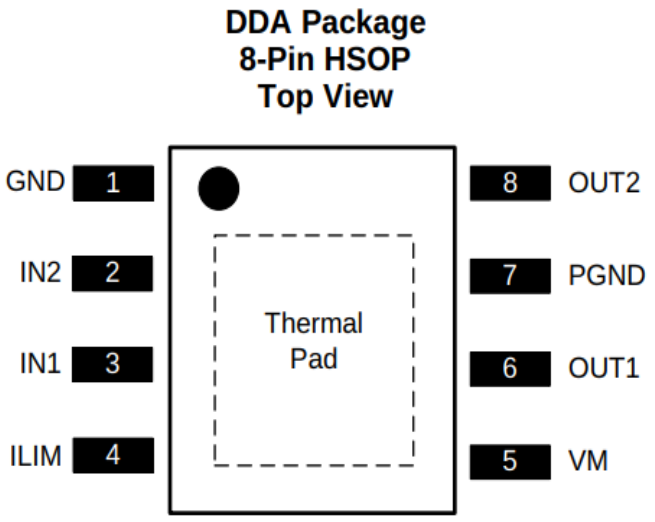


Figure 12: DRV8871 pinout

Below a description of some pins important to our case can be found.

Pin Name	Pin Number	Pin Type	Description
IN1	3	Input	Input of the chips that allow to control the output of the h-bridge. These pins receive the PWM signal from the microcontroller.
IN2	2	Input	""
OUT1	6	Output	H-bridge output that goes to the motor
OUT2	8	Output	""

The table below describes how the input signals can be used to control the output.

Mode Name	IN1	IN2	OUT1	OUT2
Coast	0	0	Hiz	Hiz
Reverse	0	1	L	H
Forward	1	0	H	L
Brake	1	1	L	L

Coast mode allows the motor to coast to a stop, which means that the motor is not driven and will move by inertia. On the other hand, Brake mode will stop the motor faster. When used to drive the motor with PWM control signal with a duty cycle $< 100\%$ and, for example, in forward mode, it is possible to alternate between forward and brake mode or between forward and coast mode.

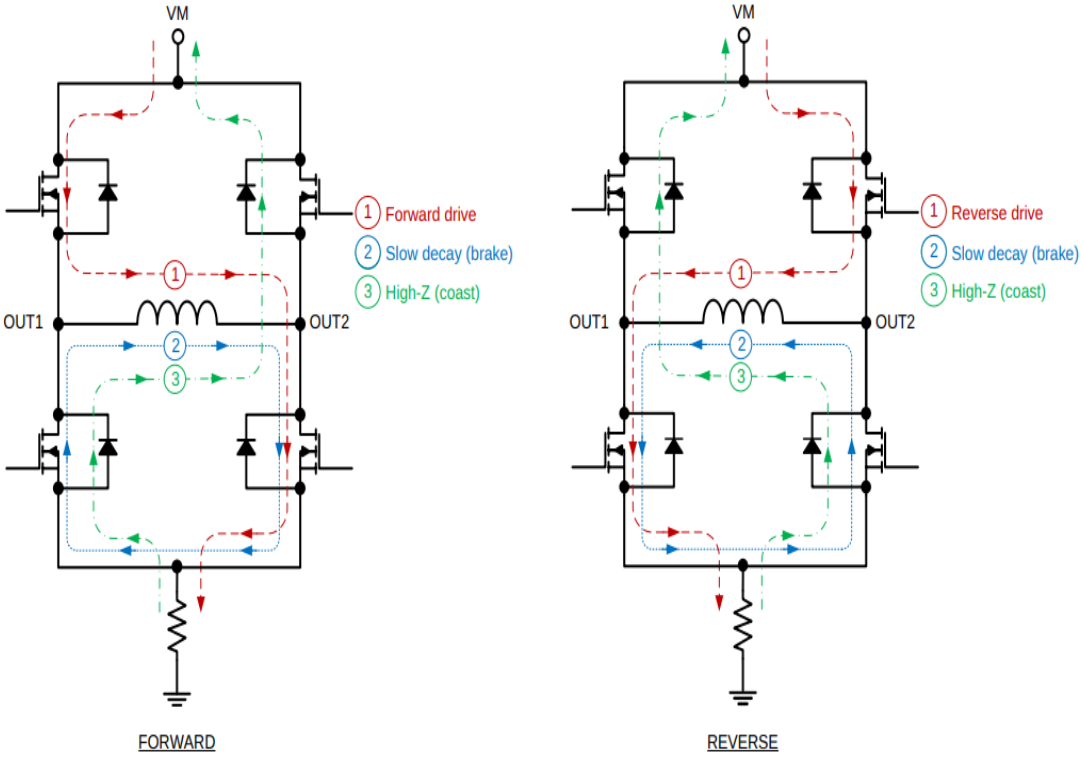


Figure 13: H-Bridge Current Paths

3.1.3 PWM Setting

The voltages applied to the inputs should have at least 800[ns] of pulse width to ensure detection. If the PWM frequency is 200[kHz], the usable duty cycle range is 16% to 84%.

3.1.4 Position Encoder

The position encoder is a sensor that transform a position information into an electrical signal. A quadrature encoder employs two outputs A and B which are called quadrature outputs, as they are 90 degrees out of phase; the direction of the motor depends on which phase's signal lead over the other;

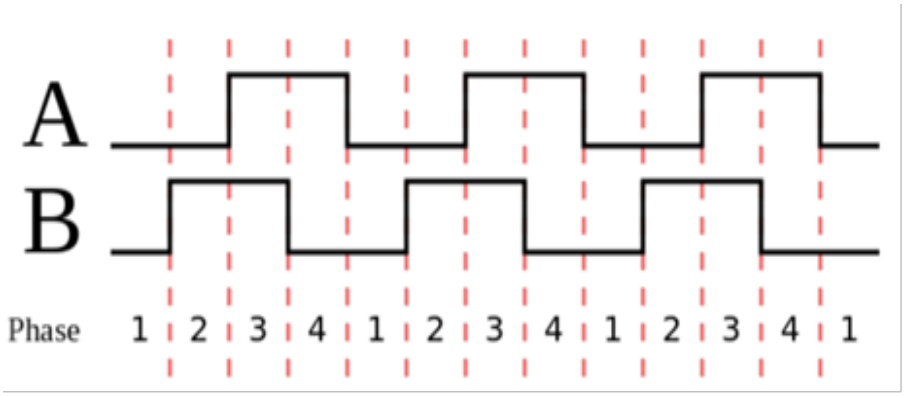


Figure 14: Signals generated by a quadrature encoder with B leading over A

A counter can be used to measure the number of pulses (a pulse can be counted when an edge happens).

3.1.5 PID Controller:

PID (Proportional Integral Derivative) controllers use a control loop feedback mechanism to control process variables and are the most accurate and stable controller. Using the derivative control mode is a bad idea when

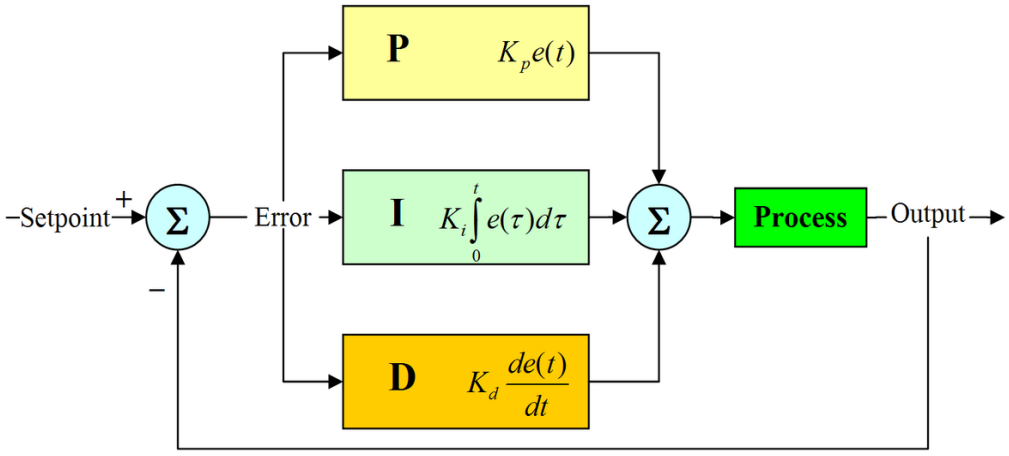


Figure 15: PID Controller diagram

the process variable has a lot of noise on it. 'Noise' is small, random, rapid changes in the process variable, and consequently rapid changes in the error. Because the derivative mode extrapolates the current slope of the error, it is highly affected by noise. Therefore, we only need to design and implement PI controller for this lab.

3.1.6 Anti-Windup feature

Integral windup refers to the situation in a PID controller where a large change in setpoint occurs (say a positive change) and the integral term accumulates a significant error during the rise (windup), thus overshooting and continuing to increase as this accumulated error is unwound (offset by errors in the other direction). The specific problem is the excess overshooting.

Integral windup can come from derivative action or a large reference. In case of the TurtleBot, since no derivative control mode is used in the controller, only the reference may cause the overshooting.

In order to solve the problem, an Anti-windup architecture is necessary. It is basically a saturation over the control output of the integrator, that keeps the error caused by the integral term of the controller in a desired range. This prevents accumulation of the error and consequently the overshooting. The figure below illustrates a common Anti-windup architecture.

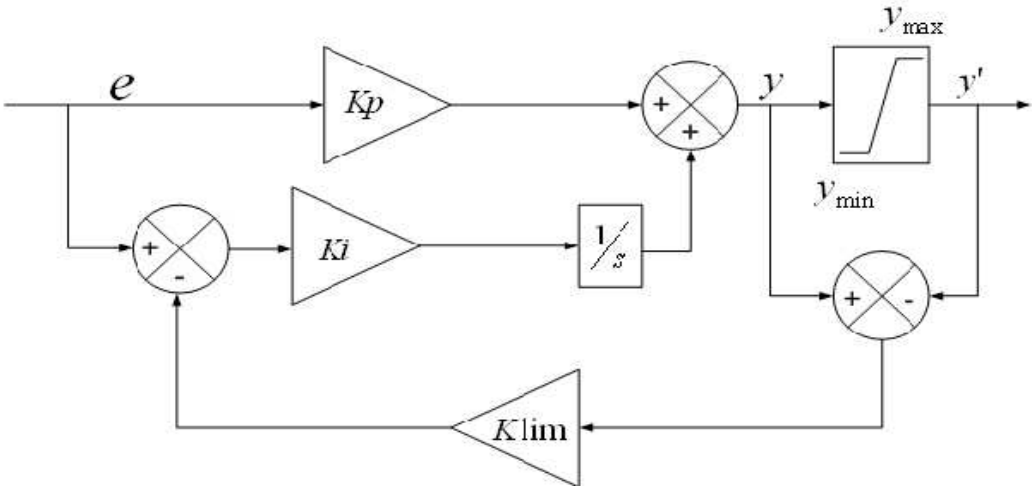


Figure 16: Anti-windup architecture

3.2 Implementation details

3.2.1 Hardware setup and peripheral list

- TIM3 (16-bit, general-purpose timer), channel 1 and channel 2: Encoder for motor 1
- TIM4 (16-bit, general-purpose timer), channel 1 and channel 2: Encoder for motor 2
- TIM6 (16-bit, basic timer): Provide the clock for the controller
- TIM8 (16-bit, advanced timer), channel 1 and channel 2: PWM for motor 1
- TIM8 (16-bit, advanced timer), channel 3 and channel 4: PWM for motor 2

3.2.2 Motor and Encoder

The module encompasses a gearbox with a 120:1 ratio, which means that for every round performed by the wheel, the motor rotates 120 times.

The encoder provides 16 pulses per round. This means that the number of pulses per round from the wheel-side is 1920, assuming to use encoder mode 2X; this number is doubled when considering encoder mode 4X. Notice that this mode halves the quantization error, when compared with the 2X mode.

The selected timer needs to be configured in encoder mode. Also, the counter period which can be setup to be equal to the number of pulses counted in one round (in this case 3840 since a 4X encoder mode is used) has to be taken into account.

Listing 10: encoder code in order to have the current speed of each motor

```
1  void HAL_TIM_PeriodElapsedCallback(TIM_HandleTypeDef *htim)
2  {
3  /* Speed ctrl routine */
4  if(htim->Instance == TIM6)
5  {
6      uint32_t TIM3_CurrentCount , TIM4_CurrentCount;
7              int32_t TIM3_DiffCount , TIM4_DiffCount;
8              static uint32_t TIM3_PreviousCount = 0, TIM4_PreviousCount = 0;
9
10         // read the counter value from the encoder
11             TIM3_CurrentCount = __HAL_TIM_GET_COUNTER(&htim3);
```

```
12              TIM4_CurrentCount = __HAL_TIM_GET_COUNTER(&htim4);
13
14          //compute the difference between the current value and the old value
15              /*  evaluate increment of TIM3 counter from previous count  */
16              if (__HAL_TIM_IS_TIM_COUNTING_DOWN(&htim3)) // right motor
17              {
18                  /* check for counter underflow */
19                  if (TIM3_CurrentCount <= TIM3_PreviousCount)
20                      TIM3_DiffCount = TIM3_CurrentCount - TIM3_PreviousCount;
21                  else
22                      TIM3_DiffCount = -((TIM3_ARR_VALUE+1) - TIM3_CurrentCount)
23                          - TIM3_PreviousCount;
24              }
25              else
26              {
27                  /* check for counter overflow */
28                  if (TIM3_CurrentCount >= TIM3_PreviousCount)
29                      TIM3_DiffCount = TIM3_CurrentCount - TIM3_PreviousCount;
30                  else
31                      TIM3_DiffCount = ((TIM3_ARR_VALUE+1) - TIM3_PreviousCount)
32                          + TIM3_CurrentCount;
33              }
34
35              TIM3_PreviousCount = TIM3_CurrentCount;
36              if (__HAL_TIM_IS_TIM_COUNTING_DOWN(&htim4)) // left motor
37                  {
38                      /* check for counter underflow */
39                      if (TIM4_CurrentCount <= TIM4_PreviousCount)
40                          TIM4_DiffCount = TIM4_CurrentCount - TIM4_PreviousCount;
41                      else
42                          TIM4_DiffCount = -((TIM4_ARR_VALUE+1) - TIM4_CurrentCount)
43                              - TIM4_PreviousCount;
44                  }
45                  else
46                  {
47                  /* check for counter overflow */
48                      if (TIM4_CurrentCount >= TIM4_PreviousCount)
49                          TIM4_DiffCount = TIM4_CurrentCount - TIM4_PreviousCount;
50                      else
51                          TIM4_DiffCount = ((TIM4_ARR_VALUE+1) - TIM4_PreviousCount)
52                              + TIM4_CurrentCount;
53                  }
54
55                  TIM4_PreviousCount = TIM4_CurrentCount;
```

3.2.3 PWM

Configuration for the timer generating the PWM signal (TIM8):

- Clock source: APB1-Timer_clocks at 96[MHz];
- Prescaler (PSC): 959 -> $f_T = 96 * (\frac{106}{96}) * 10 = 105[Hz]$
- Counter period (Auto Reload Register): 399 -> $T_{PWM} = 4 * 102 * 10[s]$

3.3 Exercises

3.3.1 Exercise1

In order to control the DC motors, a PI Controller is used.

By using the encoders (TIM3, TIM4), implemented in the way that has been explained in section 3.2.2, the number of pulses for each wheel is available. Considering that the counter period is the number of pulses per

round from each wheel-side (in this case 3840 since a 4X encoder mode is used), the speed of the motors can be evaluate in round per minutes as follow:

$$\textbf{speed[rpm]} = \frac{\textbf{number of pulses}}{\textbf{3840}} * \frac{60}{T_s}$$

Which T_s is the sampling time. Also the reference for the speed of each motor in rpm is defined, which are hard coded. Therefore, the tracking error can be calculated, which will be considered as the input of the function PI_controller. The output of the function is the control signal (in rpm) used to control the DC motors.

Listing 11: calculating the control signal for DC motors in rpm

```
// compute the motor speed in [rpm]
float current_rpm_R = ((float)TIM3_DiffCount/(2.0*1920.0))*(60.0/TS );
tracking_error_R = reference_rpm_R - current_rpm_R;

float current_rpm_L = ((float)TIM4_DiffCount/(2.0*1920.0))*(60.0/TS );
tracking_error_L = reference_rpm_L - current_rpm_L;

// compute the tracking error via PI controller
controller_return_R = PI_controller(tracking_error_R);
controller_return_L = PI_controller(tracking_error_L);

motor_V_R = controller_return_R;
motor_V_L = controller_return_L;
```

A closed loop is established according to the following logic: The input of the function PI_controller is the tracking error. The error signal is multiplied in parallel by two parameters, the first is proportional gain K_P producing the proportional term, and the second is the product of integral gain K_I and the sampling period T_s, producing the integral term.

To avoid overshooting in the response, caused by accumulation of the integrator error, an Anti-windup scheme is set up. It is a saturation over E_I. The threshold of the error which is 10 has been selected by trial and error. The optimal values of the K_P and K_I are found by trial and error.

Listing 12: PI Controller

```
float Kp = 0.34;
float KI = 0.2;

float PI_controller (float error){
    float P = Kp * error;
    static float I = 0;
    I = I + error * KI * TS;
    if(I>10){ // anti windup
        I=10;
    }
    return P + I;
}
```

After summing up the proportional and integral term and producing the output of the function (control signal in rpm), it will be fed to the DC motors through TIM8 as PWM signals. Notice that TIM6 is acting as a clock in the system. All the steps needed to accomplish the goal, should be executed from inside the HAL_TIM_PeriodElapsedCallback function, which is a callback function called when a timer's period is elapsed.

A linear relationship between the duty cycle and the voltage applied to the motor is assumed. The supply voltage $[o, V_{PowerSupply}]$. $V_{PowerSupply}$,depending on the power supply source, is assumed equal to $V_{BAT} = 8[v]$.

Listing 13: calculating duty cycle

```
#define VBATT    8.0
#define V2DUTY   ((float)(TIM8_ARR_VALUE+1)/VBATT)
#define DUTY2V   ((float)VBATT/(TIM8_ARR_VALUE+1))

// calculate duty cycle for motor

int32_t duty_R = V2DUTY*motor_V_R;

int32_t duty_L = V2DUTY*motor_V_L;
```

According to the Counter Period of TIM6, generating the PWM signal, a saturation of 399 is set over each duty cycle to prevent over driving the motors.

Listing 14: calculating duty cycle and command the motors

```
// calculate duty cycle for motor
int32_t duty_R = V2DUTY*motor_V_R;
int32_t duty_L = V2DUTY*motor_V_L;

if (duty_R > 399)
duty_R = 399;

/* calculate duty properly */
if (duty_R >= 0) { // rotate forward
    // alternate between forward and coast
    //__HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_1, (uint32_t)duty_R);
    //__HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_2, 0);

    // alternate between forward and brake, TIM8_ARR_VALUE is a define
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_1,
          (uint32_t)TIM8_ARR_VALUE);
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_2,
          (uint32_t)(TIM8_ARR_VALUE - duty_R));
} else { // rotate backward
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_1, 0);
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_2, (uint32_t)-duty_R);
}

if (duty_L > 399)
    duty_L = 399;

/* calculate duty properly */
if (duty_L >= 0) { // rotate forward
    // alternate between forward and coast
    //__HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_3, (uint32_t)duty_L);
//__HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_4, 0);

    // alternate between forward and brake, TIM8_ARR_VALUE is a define
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_3,
          (uint32_t)TIM8_ARR_VALUE);
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_4,
          (uint32_t)(TIM8_ARR_VALUE - duty_L));
} else { // rotate backward
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_3, 0);
    __HAL_TIM_SET_COMPARE(&htim8, TIM_CHANNEL_4, (uint32_t)-duty_L);
}
```

Since the control is implemented using the Forward/Break technique in Exercise 1, the commands to the motors are setup in the way that is shown in Listing 14 To collect the sensor values the data logger is setup to save and plot all relevant information. The set up is as follows:

Listing 15: setting up data logger

```
1  data.w1 = reference_rpm_R;
2  data.w2 = current_rpm_R;
3  data.u1 = tracking_error_R;
4  data.u2 = controller_return_R;
5
6
7  data.x1 = reference_rpm_L;
8  data.x2 = current_rpm_L;
9  data.y1 = tracking_error_L;
10 data.y2 = controller_return_L;
11
12 ertc_dlog_send(&logger, &data, sizeof(data));
```

The results are plotted as shown below:

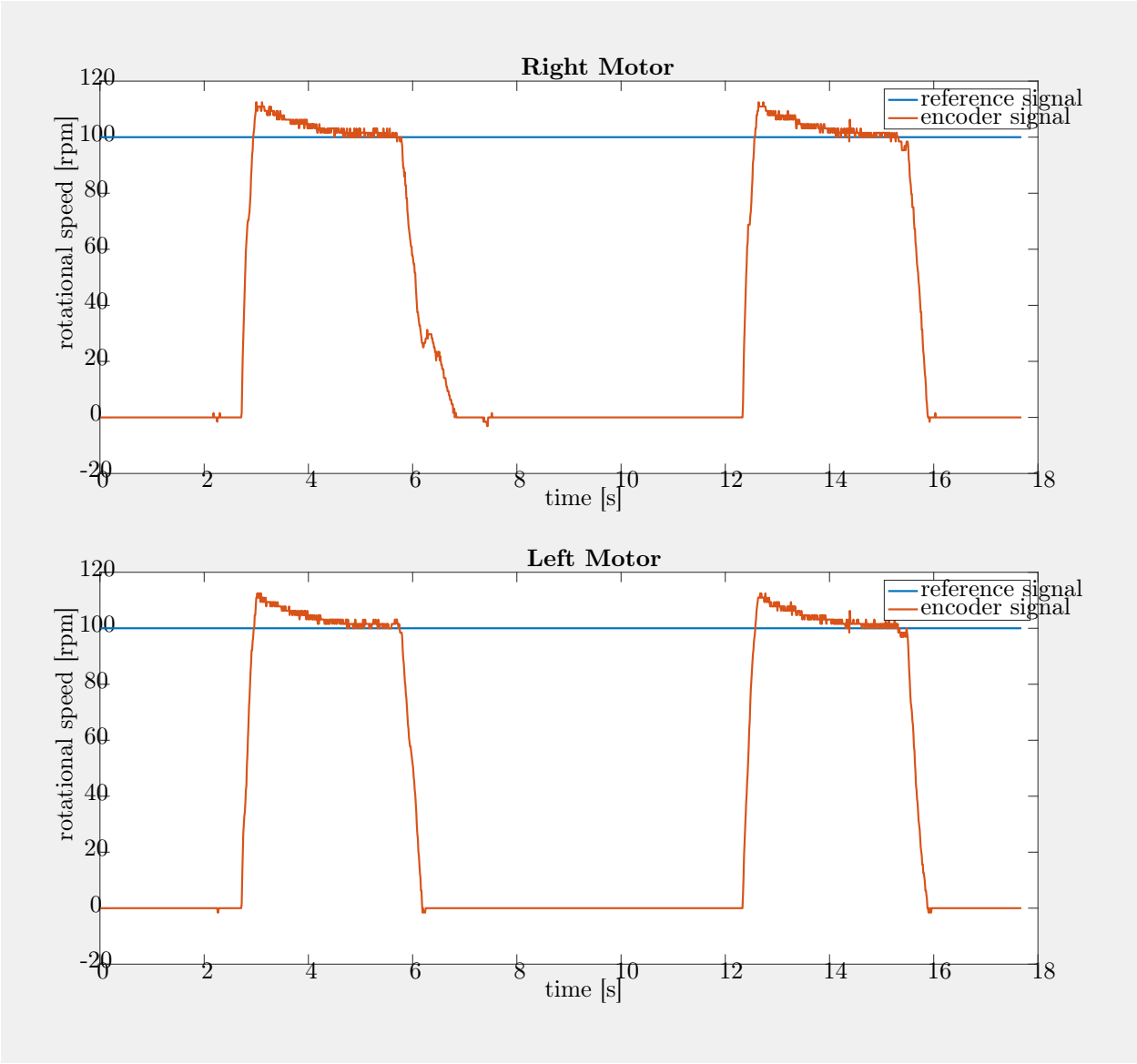


Figure 17: The results of the control using the Forward/Brake technique

To conclude, the results show that after turning on the motors, it takes a few milliseconds for motors to reach desired speed (acceptable rise time); even after being turned off for a while, the over-shoot does not go higher than a certain and reasonable level of speed (effect of the Anti-windup scheme). Lastly, the step response is settled at the reference value in few seconds. Notice that the noise in the response is because of the nature of the system and the digital controller.

3.3.2 Exercise2

In order to implement the controller with the Forward/Coast technique, the alternative piece of code is changed, shown in Listing 14.

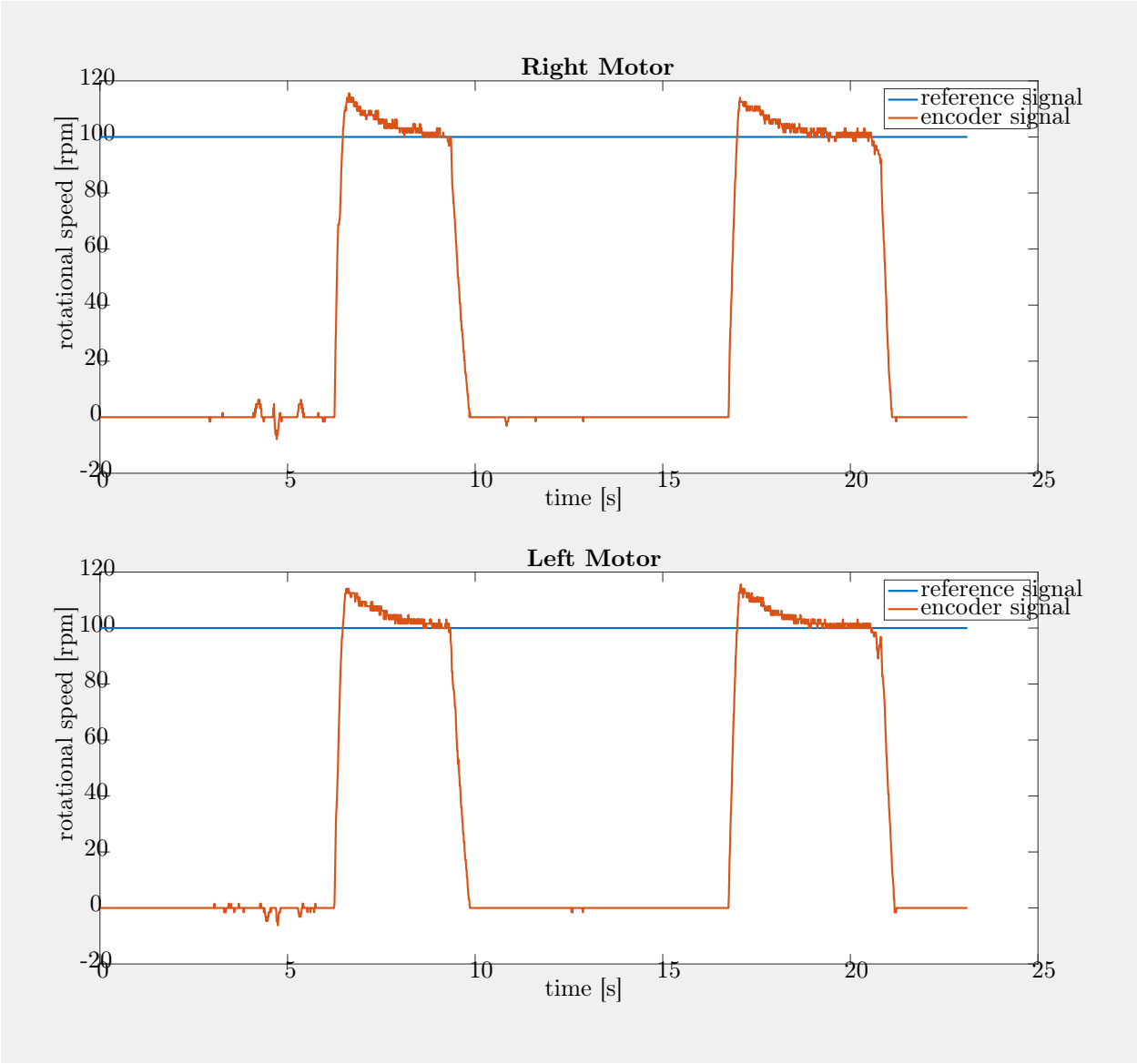


Figure 18: The results of the control using the Forward/Coast technique

Coast mode allows the motor to coast to a stop, which means that the motor is not driven and will move by inertia. On the other hand, brake mode will stop the motor faster. Therefore, the step response of motor implemented by Forward/Coast technique has more noises (even when the motor is set to be off) which can be interpreted as the inertia.

3.3.3 Exercise Bonus

The Anti-windup is implemented in the way that has been explained in section 3.3.1, particularly in Listing 12. As mentioned before the threshold for the saturation has been chosen by trial and error. However, the first Anti-windup method used was to set directly a saturation over the voltages fed to the motors. After saturating the voltage directly by changing the threshold to different values (for example, 4 in Listing 16), the overshoot

problem was still unsolved. Hence, the Anti-windup method had to saturate only the integral term of the control signal, shown in Listing 12.

Listing 16: wrong Anti-windup method

```
1  if (motor_V_R > 4)
2        motor_V_R = 4;
3  if (motor_V_R < -4)
4        motor_V_R = -4;
5
6  if (motor_V_L > 4)
7        motor_V_L = 4;
8  if (motor_V_L < -4)
9        motor_V_L = -4;
```

The step response of the motors using both Forward/Break and Forward/Coast techniques, when the Anti-windup implementation is not used are shown in Figure 19 and Figure 20. To conclude, the step response of the system (no matter implemented by which technique), without implementing an Anti-windup feature, has a large overshoot due to the accumulation of the error caused by integral term. Adding an Anti-windup feature enhances the overall performance and reduced the overshoot in the system, as expected (Figure 17 and Figure 18).

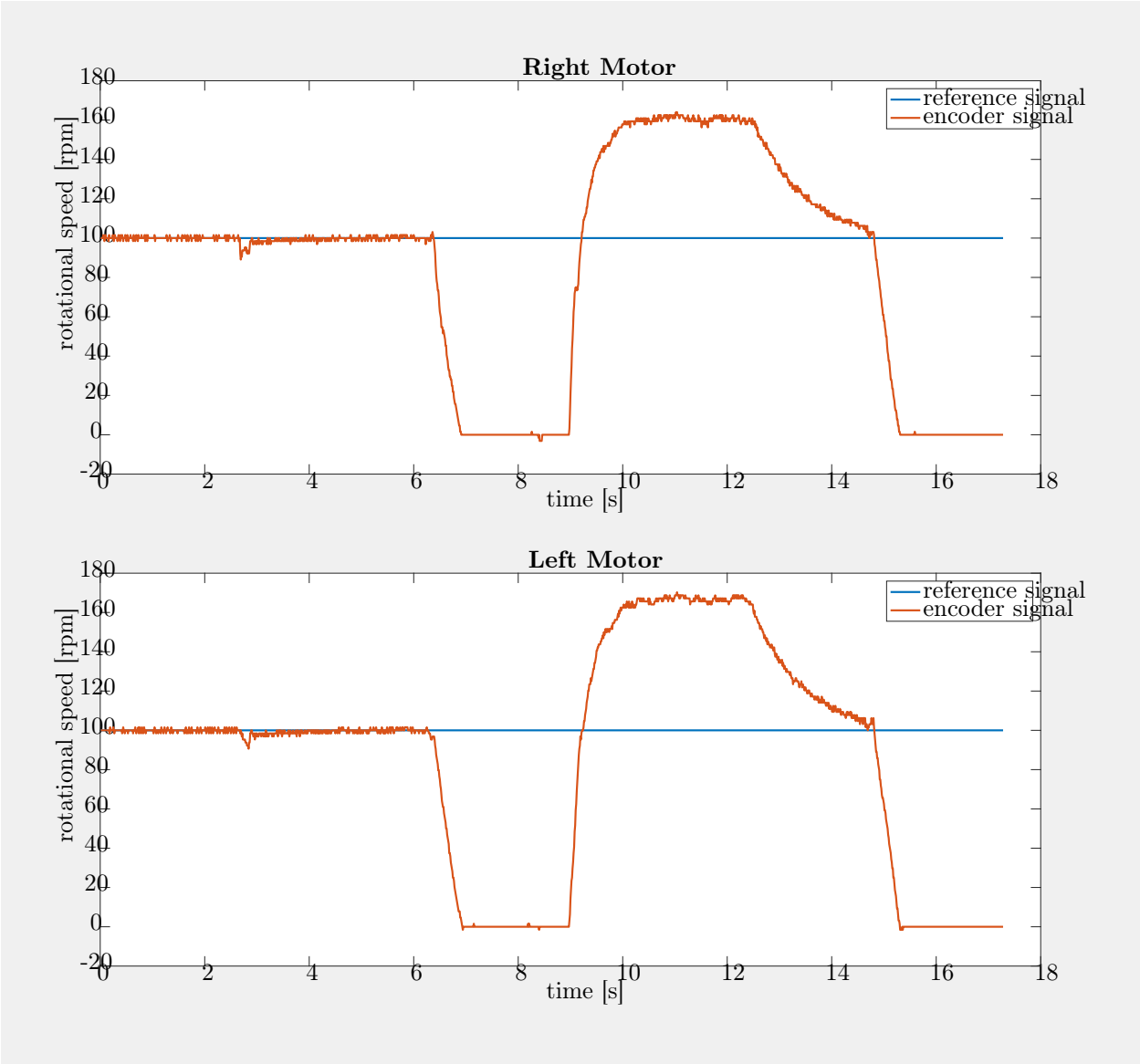


Figure 19: The results of the control using the Forward/Break technique without Anti-windup

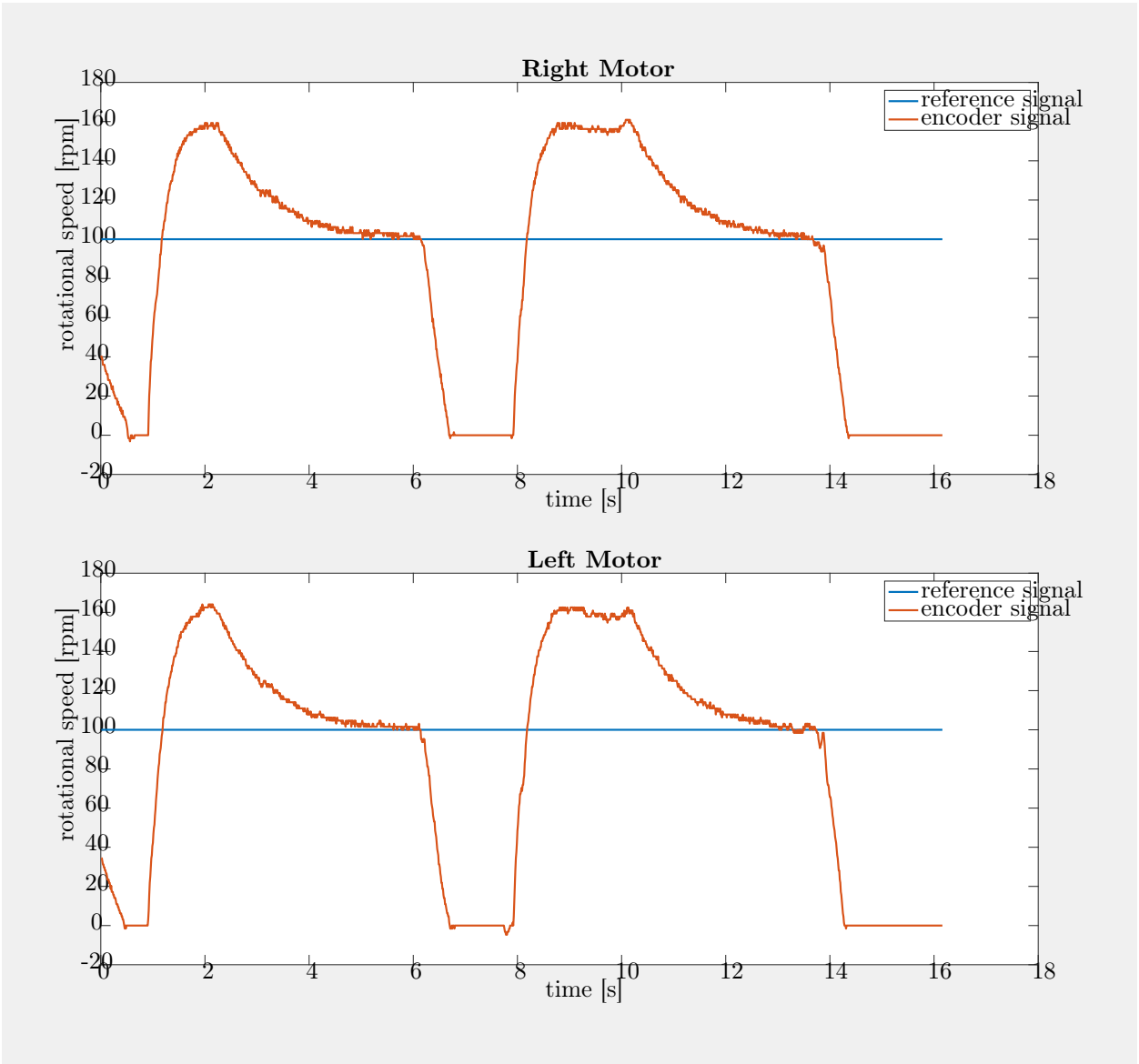


Figure 20: The results of the control using the Forward/Coast technique without Anti-windup

4 Laboratory 4: Line Following

4.1 Description

The goal of this laboratory was to combine the line sensor from Lab 1 and the motor controller from Lab 3 to make the TurtleBot follow a given line autonomously.

4.1.1 The infrared line sensor

A Pololu QTR reflectance sensor is used, which can detect how much infrared light has been reflected from a surface. With a certain threshold the difference between dark and light surfaces can be determent. The installed sensor is located on the lower front of the robot. It is about 10 cm wide and consists of an array of 8 photo diodes with each one photo transistor. The distance between every sensor is 8 mm. This gives a total of 8 individual sensors that can differentiate between dark and light areas. This data is retrieved by the controller MCU through a port expander board using a I2C connection. The sensor data encoded in a binary format and received as an integer. To retrieve the original data, it is necessary to convert the integer back to a binary number. This binary number has 8 bits, each storing the value of one sensor.

4.1.2 Properties of the line

The line is assumed to be wide enough to trigger at least one of the infrared sensors and at most two at the same time. The goal is to create a controller algorithm that keeps the line between the two middle sensors 3 and 4. A tracking error is implemented and center position is defined as tracking error 0. The tracking error is defined to be greater than zero when the line is on the left side of the sensor. If the tracking error is less than zero, the line is on the right side of the sensor. Figure 21

Figure 21: Spacing of the infrared sensors

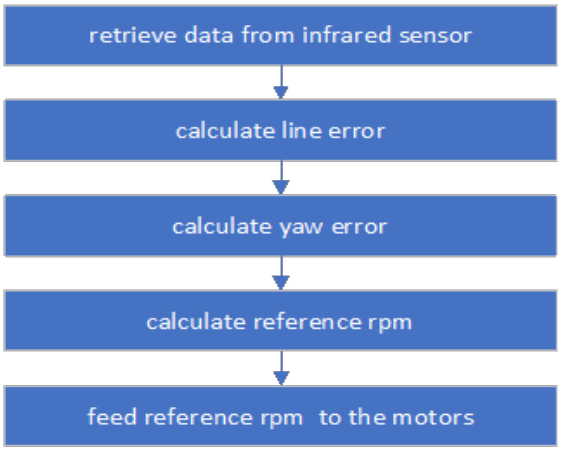


Figure 22: Main structure of the line following code

In LAB1 a function was already created to get the binary values of the integer received by the line sensor. However, this function would output an integer again, with all the bits in a single number. This was not a very useful implementation. It was necessary to get the bits in an array. For that an empty array is defined in the callback function (Listing 18) and the pointer is given to the findBinary function. The basic decimal to binary converter in form of a while function would then store every bit in this array, Listing 17.

Listing 17: converts integer to a binary array

```
void findBinary(int decimal, int * binary){
    int i =0;
    while(decimal > 0){
        int rem = decimal % 2;
        binary[i] = rem;
        i++;
        decimal = decimal / 2;
       }
}
```

Listing 18: Top part of the timer callback function

```
    void HAL_TIM_PeriodElapsedCallback(TIM_HandleTypeDef *htim)
{
    /* Speed ctrl routine */
    if(htim->Instance == TIM6) // check if interrupt came from timer
    {
        // get the line sensor data
        status = HAL_I2C_Mem_Read(&hi2c1,
                    SX1509_I2C_ADDR1 << 1,
                    REG_DATA_B, 1,
                    &lineData, 1,
                    I2C_TIMEOUT);
    int binary[8] = {0};
    findBinary(lineData, binary); // converts int to binary array
```

The calc_error_line function shown in Listing 19 does the calculation of the line error. The input of this function is an 8-dimensional array, containing the state of each infrared sensor coded in binary. A logical one means, that the corresponding sensor has detected a dark spot. The for loop iterates through every value in the binary[] array, ergo through all sensors data. The sum of the binary[] array is calculated to get the total number of triggered sensors. Furthermore, the "distance_from_middle" array is filled with the opposing distance of every sensor from the middle. The distance between every sensor is 4mm. These values get negative to indicate a distance to the left and positive to indicate a distance to the right. The sum_dist value is the sum of every distance from the center if the sensor was activated. Calculating the line_error by dividing the sum of the distance of each activated sensor with the total number of activated sensors. This line_error represents the

offset of the black line from the center, regardless of how wide the line is. Even if only one sensor is not activated, a useful line error value is calculated.

Listing 19: Function to calculate the line error based on a binary array

```
int calc_error_line (int binary[]){
    float distance_from_middle[8]={0};
    float sum_dist = 0;
    int sum_binary = 0;
    for(int n=0;n<8;n++){
        sum_binary += binary[n];
        distance_from_middle[n]=((7.0/2.0)-n)*4;
        sum_dist += binary[n]*distance_from_middle[n];
    }
    float line_error = sum_dist / sum_binary;
    return line_error;
}
```

Listing 20: Conversion from line error to yaw error

```
float calc_yaw_error(float line_error){
    float phi_err = line_error/85;
    float yaw_err = phi_err * (165/2);
    return yaw_err;
}
```

The calc_yaw_error function in Listing 20 calculates a much stabler result for the error value. It includes the wheelbase dimension (D) and the distance between the line sensor and wheels (H). This determines the position of the turning point of the bot, which is between the two wheels, shown in Figure (23)

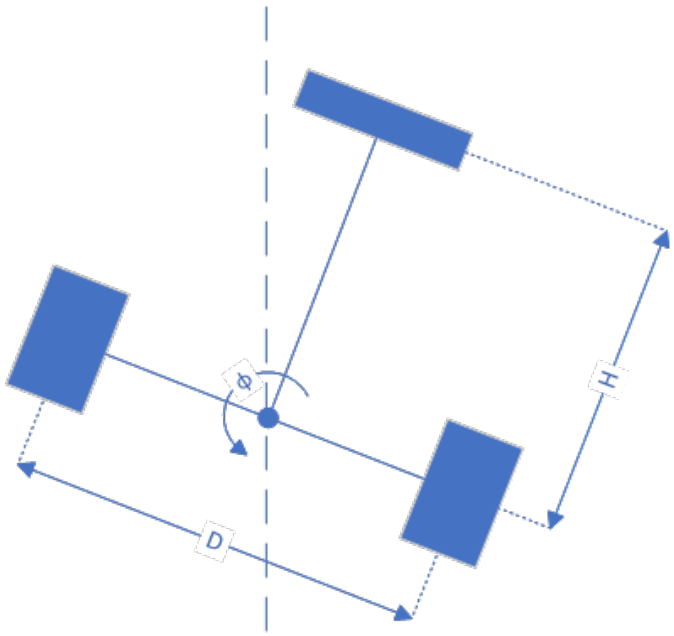


Figure 23: Schematic of the wheelbase and line sensor placement
D=165 mm, H=85 mm

4.1.3 Calculating the reference for the motors

Based on the yaw error the reference for the two motors is calculated. Since the motor controller is designed to compute rotations per minute, a base speed of 100 rpm is set and depending on the direction of the motor the yaw error add or subtract. To give the yaw error more effect on the base speed, an additional gain is incorporated. Testing different gains, a reliable solution with a base speed of 100 rpm +- yaw_error * 12 was found. By Increasing the gain, the performance in sharper corners got better. The drawback was increased instability on the straight segments. Small changes in the yaw error multiplied with a high gain gave the bot a very shaky ride in straight segments. To furthermore improve the performance a linear or even an exponential gain was necessary. This would increase the impact of the yaw error in tighter corners and make sure to decrease the gain when the line is going straight. The robot would be very stable on straight lines and keep its agile performance in sharp corners. One solution was to implement different "if" statements to check if the yaw error was in a certain range. Then different gains could be set accordingly. This worked, but needed a lot of tuning of all the values. The settled values for each section of the if statements where very similar to the yaw error itself. A very simple solution was to square the yaw error. This would increase the gain linearly. To keep the sign of the yaw error, the absolute value of the yaw error was multiplied by itself, see Listing 21. For tuning this setup to use different base speeds it is possible to also add a gain to increase the impact of the squared yaw error.

Listing 21: Calculating the reference signals for the motors

```
reference_rpm_L = 100 - yaw_err*ABS(yaw_err); // workes great
reference_rpm_R = 100 + yaw_err*ABS(yaw_err);
```

The plot of Figure 24 shows the signals of the left and right motor. There is also shown the line and yaw error calculated from the data collected by the line sensor. The reference signal for each motor is then set by the functions shown in Listing 21. It is clear to see that the encoder value of each motor is tracing the reference signal great. It is also clear to see the limitations of the motors. When the reference exceeds a given speed of around 150 rpm, the motors are limited by the duty cycle implemented in LAB 3. The solution for this would be to set a limit to the reference signal when calculated. Because of the geometry of the robot, calculating the yaw error results in a very similar value of the line error. This is because the ratio between wheelbase (D) to distance of line (H) sensor to wheels is almost one half, shown in Figure 23.

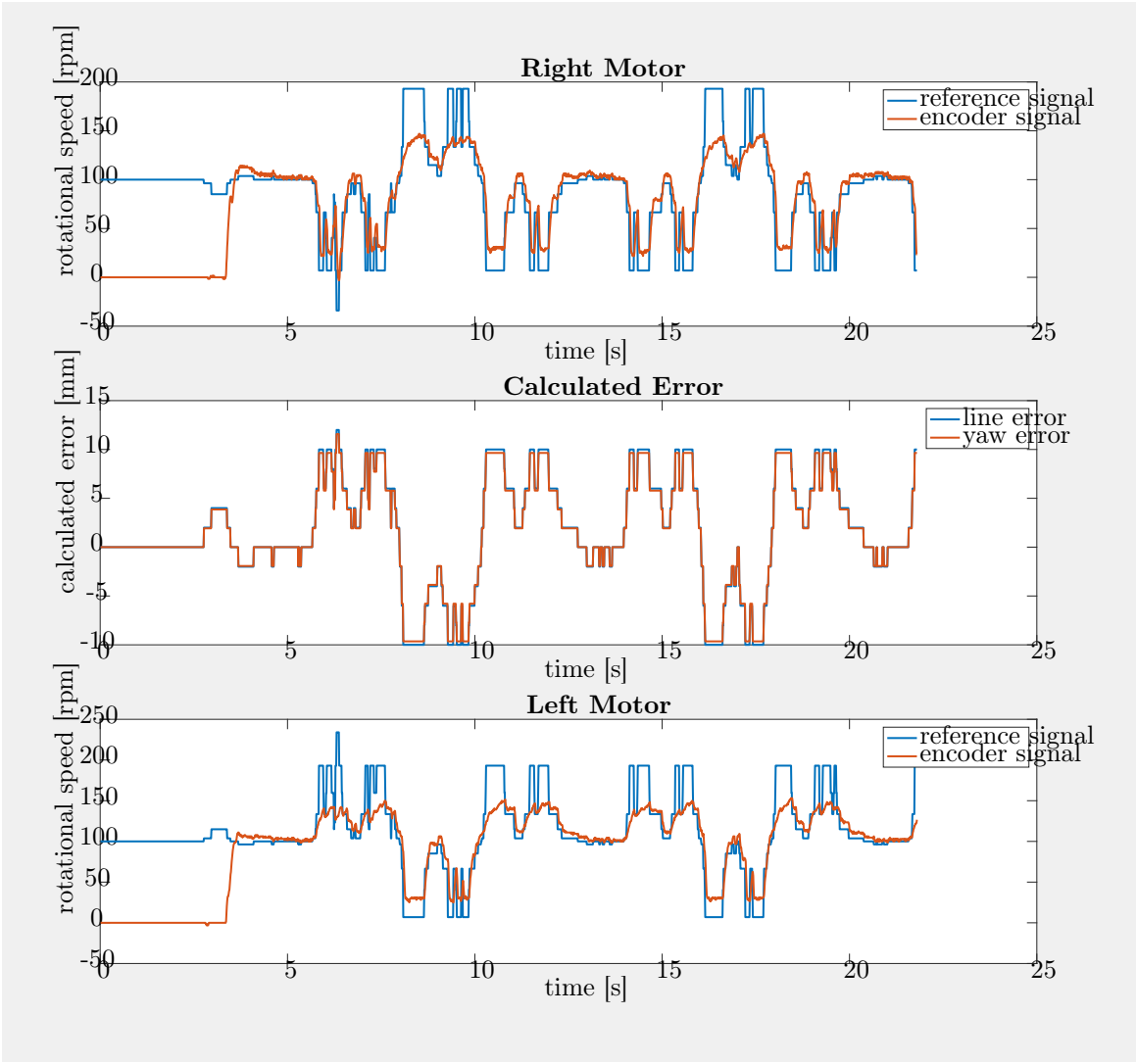


Figure 24: Motor Level Plot

A Section in the Appendix

A.1 Subsection in the Appendix

Additional relevant information...