VIENA

Veículo Inteligente Elétrico de Navegação Autónoma

Documentation Guide

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Revision: 2

September 2018

Acknowledgments

The group VIENA would like to acknowledge all past and present contributors that are making this project alive and growing. Following is a list of them in no particular order.

IST For allowing the creation of this project and providing a variety of tools and of course the facilities.

FST Lisboa Contributtor with main parts that made possible the powertrain. Among them are two essential parts, the battery pack and inverter.

Dr. João Fernandes Co-supervisor of project.

Dr. João Sequeira Co-supervisor of project.

Dr. Paulo Branco Co-supervisor of project.

Pedro Costa Former FST leader. Valuable knowledge contributor to get us started with parts supplied by FST team as well as many suggestions to problems that arise or can arise in future. His experience as former FST leader, saved us may time in problems.

André Agostinho FST member. Provided us help and information specially with battery pack.

André Antunes Former FST member. Enlightened us in the very beginning of CAN connection with inverter.

AEIST/ BPI In partnership, provided funding for the project as one of the winners in an open competition fundings.

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Nomenclature

σ_P	Standart deviation associated to a position reading provided by a GNSS receiver.
σ_V	Standart deviation associated to a velocity reading provided by a GNSS receiver.
$\Omega_\times$	Skew symmetric matrix of angular velocities used to represent cross products as matrix multiplications.
$\hat{q}$	Normalized quaternion.
$\otimes$	Quaternion product operation generally described as Hamilton product.
q^*	Quaternion conjugate.
q	Quaternion.
${}^bA$	Physical quantity defined in superscript frame (in this case b, body frame).
${}^b_wR_{2D}$	A rotation matrix reduced to only two dimensions.
${}^b_wR$	Rotation matrix that maps physical quantities defined in subscript frame (in this case w, world frame) to superscript frame (in this case b, body frame).
a posteriori	Latin expression denoting, in this case, an estimate after performing correction using recent information.
a priori	Latin expression denoting, in this case, an estimate before atually having information about it and before possible correction.
intrinsic	Intrinsic rotation means that rotation is applied about an axis of the moving frame .
lever arm	A distance correction for the point of application of a physical quantity or to describe the same quantity in a specific location.
polyfit	Polynomial fit function available in Matlab®.
pure quaternion	Pure quaternion is a quaternion with real part equal to zero.

Acronyms

9DOF	Nine Degrees of Freedom.
A-GNSS	Assisted GNSS.
ADC	Analog to Digital Converter.
AHRS	Attitude and Heading Reference System.
AP	Access Point.
CAN	Controller Area Network.
CEP	Circular error probable.
DC	Direct Current.
DHCP	Dynamic Host Configuration Protocol.
DIY	Do It Yourself.
DNS	Domain Name System.
DOF	Degrees of Freedom.
ECEF	Earth Centered, Earth Fixed.
EEPROM	Electrically-Erasable Programmable Read-Only Memory.
EKF	Extended Kalman Filter.
ENU	East North Up.
EPOS	Easy Positioning System.
FS	Full Scale.
FST Lisboa	Formula Student Team Lisboa.
GNSS	Global Navigation Satellite System.
GPS	Global Position System.
I^2C	Inter-Integrated Circuit bus.
IC	Integrated Circuit.
IMU	Inertial Measurement Unity.
INS	Inertial Navigation System.
IST	Instituto Superior Técnico.
LSB	Least signigicant bit.
MAC	Media Access Control.
MARG	Magnetic Angular Rate and Gravity.

MCU	Microcontroller Unit.
MEMS	Microelectromechanical systems.
MQTT	Message Queue Telemetry Transport.
OS	Operating System.
PCB	Printed Circuit Board.
rms	root mean square.
Rpi	Raspberry PI.
SBC	Single Board Computer.
SoC	System on Chip.
SPI	Serial Peripheral Interface bus.
UART	Universal Asynchronous Receiver/Transmitter.
VIENA	Veiculo Inteligente Elétrico de Navegação Autónoma.
WGS84	World Geodetic System.
ZVU	Zero Velocity Update.

Chapter 1

Introduction

Instituto Superior Técnico (IST) is currently developing research in autonomous electrical vehicles, namely converting from commercial vehicles with upgraded power management. This provides a motivating/attracting setup for new students and a testbed for industry solutions and it is the main motivation for this work.

The main goal of the project is a conversion of an electrical car (Fiat Elettra) property of IST into an autonomous vehicle as framework for future projects or research in this field and also energy efficiency. Within the conversion, researchers, student and collaborators knowledge acquired during academic cycle is put into test and evaluated in a real situation.

With environmental issues and technological waste in mind, this project has also been focused on the reuse of parts and material from other IST projects by the simple fact that they have been replaced by improved versions or will no longer serve the current goals of those projects. Not only it is given a new propose for those parts but it will also allow the cost reduction.

This guide aims to be auxiliary documentation and future memory source as part of the IST project named Veiculo Inteligente Elétrico de Navegação Autónoma (VIENA) and as well as final report for fellowship BL43/2018.

Although all the instructions are given based on Linux operating system, they should be similar to any other Operating System (OS) and the majority of code developed is made in Python, intending to be as much cross-platform as possible.

1.1 Guide Outline

This documentation guide is organized in five main chapters, Code guidelines, server, main sensors, controllers, miscellaneous. In chapter code guidelines is described suggested and used assumption especially focused in code structuring and tools used in development. In the server is provided information about the used hardware, designed pieces, software configuration needed to get started and connections. In main sensors will be discussed the work done with the current available sensors. New sensor additions should be documented under this chapter. In controllers will be reported mainly hardware controllers and software necessary to connect, configure or communicate with it. Miscellaneous contain other parts that do not fit particularly inside any of those chapters but are necessary or may help in the project.

1.2 Contributions

During the fellowship BL43/2018, it was made the main contributions:

1. Development of 3D printed parts for allowing the control of steering wheel without disassembling or violating the integrity of steering shaft column
2. Development of a library in Python based on CAN bus protocol to enable interconnection between software and hardware to control the steering wheel.
3. Development of prototype circuit to add CAN communication for main computer
4. Development and design of PCB for future CAN communication to replace the protoboard for main computer
5. Identification of the function that relates the steering wheel position with angle of the front wheel in a bicycle model of the car.
6. Mounting of available sensors (two GNSS unities and one IMU 9DOF)
7. Calibration of the inertial sensor.
8. Updated code related with MARG sensor.
9. Updated code related with GNSS unities.

Although not initially planned, but because the change of hardware and/or adversities found during the fellowship, following additional work was also contributed:

1. Study of interconnection of the main battery pack
2. Study of software used for management of main battery pack
3. Study of hardware necessary for management of main battery pack
4. Study and initial software development for inverter received from FST Lisboa
5. Creation of an headless structure and an AP station based on Rpi to communicate with vehicle
6. Initial development of an MQTT based design to control the vehicle or check its status.
7. Development of library to interact with Schneider Altivar 71 (abandoned due to change of inverter)

Main code contributions are available under Github repository in https://github.com/brtiberio/VIENA and will be kept up to date as soon as possible. The developed 3D pieces are also present in that repository and the companion drawings are shown in this guide also. The developed PCB schematics and board layouts are also presented in this guide.

Chapter 2

Code Guidelines

In this chapter is described the main guidelines used for coding and documentation as well as relevant suggestions. Since the majority of code is developed in Python, the guidelines are provided for that language. However similar suggestion may apply for the other languages cases. Here follows a list of sugestions:

Git

The first suggestion is the code version control system, Git. It has a lot integrations with majority of IDE's and have lot of free tools to manage it. It allows easy contributions from multiple users. Documentation and guides to become familiar with it can be found at try.github.io

Python3

Since Python core team is dropping support for python 2.7.x in 2020 [1] and some of important package developers are also dropping support for it [2], the chosen **version is the 3.X.**

Use virtual environment

Typically, every Linux distribution uses python to run critical routines. Perturbing the main ecosystem of python packages should be avoided, at least during development phase. Raspbian is no exception, so it is suggested to use virtual environments. It is used to create a isolated local installation in the directory you are working. Since version 3.5 the official recommended tool for creating virtual environments is the venv [3]. To create a virtual environment use the following console command `python3 -m venv /path/to/new/virtual/environment` or assuming the user is currently in desired local path, simplify to `python3 -m venv .` To activate/deactivate the local environment follow the specification accordingly to used OS as present in table 2.1, using the same assumption as before. After activation, the shell prefix will change from the default to `(<path of venv>)` which is a easy away to check if environment is active or not.

Requirements files (requirements.txt)

Requirement files are an easy away to install all the requisites necessary to run the code and ensure repeatability of installations. Unless any particular reason, a restriction of any package version should be avoided. Requirements file can be as simple as a list of necessary packages or more complex struture, if needed [4]. Installation of requirements is done by running the following command `pip install -r requirements.txt`

Google style docstrings

A good documentation is a key point for keeping good readability of a project. Docstrings format from Google Style Guide [5] is adopted. Many projects can fail from bad documentation.

Sphinx with automation

Similar to previous point, sphinx will allow the auto documentation generation from code. Is a popular tool for creating documentation and is used also in readthedocs.org, that allows to integrate documentation update with commits in the three main git repository management services, GitHub, Bitbucket, and GitLab. Using autodoc and napoleon extension allow an easy maintenance of code documentation.

Argparse

Use argparse to create clean and readable argument handling if necessary. It auto generates help, description and handles unknown options.

Logging

Since the main intention is to run programs in a headless computer, the logging module should be used instead of typical print() function. Not only it helps keep tracking of events defined in code, but also keeps track of other modules events. It also allows the creation of multiple destinations using the handlers and each handler can have its own format. Typical handlers used in project are files, console and websockets (currently only in development branchs)

Shell	Activate	Deactivate
	POSIX	
bash/zsh	source ./bin/activate	deactivate
fish	source ./bin/activate.fish	deactivate
csh/tcsh	source ./bin/activate.csh	deactivate
	Windows	
cmd	.\Scripts\activate.bat	deactivate
PowerShell	.\Scripts\Activate.ps1	deactivate

Table 2.1: Activation/deactivation of venv OS specific

Chapter 3

Main Server configuration

In order to control the current features already developed and used in the car it is used a Raspberry PI (currently version 3 model B). The Raspberry PI, from now on denoted as Rpi, is a Single Board Computer (SBC) affordable and low power, widely used among community and developed by Raspberry Pi Foundation. Figure 3.1 show the relevant parts of Rpi and also the pinout labels.

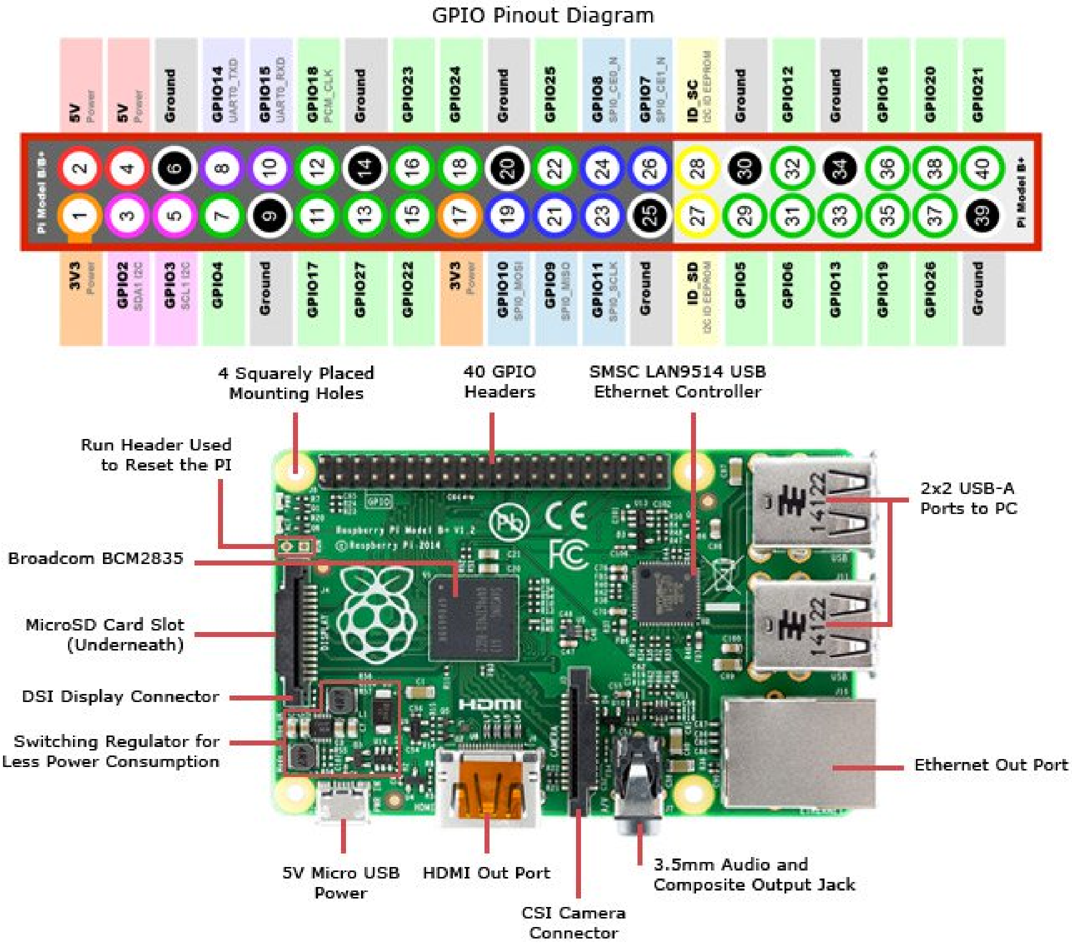


Figure 3.1: Pinout labels for RaspberryPi 3 (source)

3.1 Requirements

For using the SBC it is required the following hardware:

- **Raspberry Pi SBC** Recommended version at least 3 since it has a built in wifi.
- **MicroSD card** Recommended with 8Gb capacity at least.
- **Power Supply** Recommended 2.5 Amps . While developing, it is used as the main power for the SBC.
- **Host computer (any OS)** with internet and ability to read MicroSD cards.
- **Ethernet cable** for connecting to router/switch for internet access. It can also be used an crossover cable connecting directly to PC if it is able to share internet connection.

3.2 Initial Preparation

This preparation will focus on providing instructions to a minimal headless setup. For this reason, the recommended OS image version is the Raspbian Lite.

For this step it is recommended to be used the Etcher software for burning the OS image into microSD card. It is assumed the user is familiar with ssh capable software, for example Putty. The next steps are mainly based in the documentation guide provided by [6].

1. Download the OS image, Raspbian Lite version in here
2. Connect the MicroSD to host computer.
3. Open Etcher and:
   (a) Select OS image or zip file that have been downloaded.
   (b) Select the SD card you wish to write your image to.
   (c) Review your selections and click 'Flash!' to begin writing data to the SD card.
   (d) after successful write, continue to next step.
4. From microSD card, open the boot partition.
5. Create a new blank file with name "ssh" without extension. This will allow to enable the ssh daemon at first boot time.
6. Remove card from host computer and insert on raspberry PI.
7. Plug in the Ethernet cable and connect the Rpi to the same local network as host computer.
8. Plug in the power supply to Rpi.

If everything went as expected, the Rpi will start to boot and prepare the first setup. It will be seen led light blinking indicating activity. After a few minutes, it should be possible to access it remotely via ssh

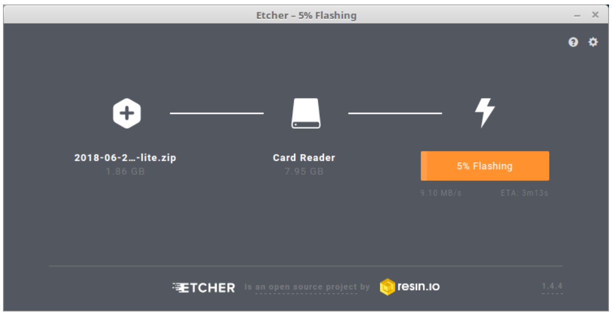


Figure 3.2: Etcher flashing image to microSD card

3.2.1 Remote access

The next step is to find the ip address of the Rpi. For example, in linux terminal type `arp -a`. In figure 3.3 is seen an output example. In red stroke is shown the Media Access Control (MAC) address of a Rpi. Every MAC is unique and the first three bytes are fixed in every Rpi wich correspond to organizationally unique identifier [7] associated to Raspberry Pi Foundation, B8:27:EB [8].

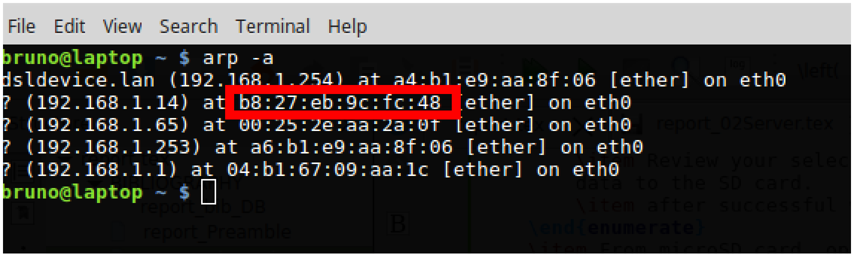


Figure 3.3: arp -a command example output

Perform the first login with using the default login details as shown in table 3.1. Using the discovered ip for the Rpi, in Linux, the first login may be performed using `ssh pi@<ip-of-Rpi>` command and entering the default password.

username:	pi
password:	raspberry

Table 3.1: Default login details for Rpi

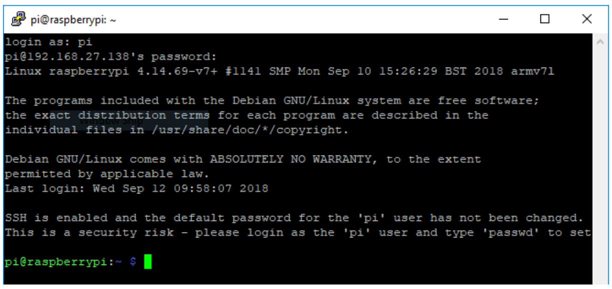


Figure 3.4: SSH sucessfull login

3.2.2 Initial update and configuration

If the user as been granted with permission to login, the next steps are used to perform a few tweaks. To do that user must use the command `sudo raspi-config`. Example output is seen in figure 3.5.

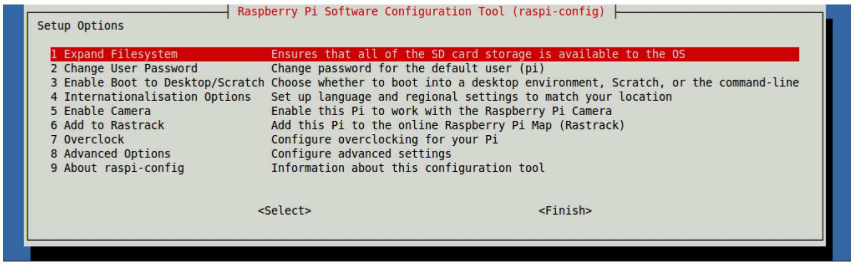


Figure 3.5: Raspi-config example output

It is recommended to configure the following:

- Set Keyboard Layout
- Update to lastest software
- Set Timezone
- Set language [optional]
- Change default login password
- Configure Wifi-zone [if present]

If you are connected directly to a switch via Ethernet cable, skip wifi configuration.

- Enable Serial Peripheral Interface bus (SPI) for Controller Area Network (CAN) controller
- Enable Inter-Integrated Circuit bus (I^2C) for RTC
- Set hostname
- change default password
- change memory for GPU

The current settings are presented in table 3.2.

Username:	pi
Password:	fiatelettra
Hostname:	raspberrypi
wait for network at boot:	no
Language:	en_GB.UTF-8 UTF-8
Timezone:	Europe → Lisbon
Keyboard layout:	pt_PT
WIFI country:	PT_Portugal
SPI:	on
I2C:	on
Memory split:	16 (minimum since is running headless)

Table 3.2: Suggested details for Rpi

After successfully changed the settings, perform a full update and upgrade by running:

```
sudo apt update && sudo apt upgrade -y
```

3.3 Prepare CAN interface

The current protoboard uses the Integrated Circuit (IC) MCP2515 as CAN network controller and MCP2551 as CAN transceiver. Figure 3.7 shows the used protoboard with highlighted connections names and parts.

The schematic circuit implemented in the protoboard is present in figure 3.6. Current raspbian kernel, automatically support the can interaction via SPI to IC MCP2515, making it available via SocketCAN. To enable that, it is necessaries to configure MCP2515 driver on device tree overlay and install the can-utils package.

- Install can-utils using `sudo apt install can-utils`
- Enable MCP2515 overlay by using `sudo nano /boot/config.txt` and append at end:

```
#CAN bus controllers
dtoverlay=mcp2515-can0,oscillator=16000000,interrupt=25
dtoverlay=spi-bcm2835
```

- To enable the interface at boot time, use `sudo nano /etc/network/interfaces` and append at end:

```
auto can0
iface can0 inet manual
  pre-up /sbin/ip link set can0 type can bitrate 1000000 \
  triple-sampling on restart-ms 10
  up /sbin/ifconfig can0 up
  down /sbin/ifconfig can0 down
```

This will enable the CAN interface at boot time with the setting present in table 3.3.

The protoboard is considered temporary and new board as been designed and projected to include not only a CAN controller but also a Real Time Clock (RTC) chip, a battery holder for RTC chip and a DC-DC converter to power Rpi from 12V battery pack. In figure 3.8 is show the proposed and developed circuit for replacing the protoboard. The respective schematic is present in appendix D. Suggested board was designed in Eagle Software and files are also included in the Github repository.

For connecting the protoboard please refer to figure 3.1 to see the respective pins in the Rpi side.

3.4 Additional packages installation

The following list describes additional package installation that are currently used or are planned to be used.

python3-pip

Required to enable pip manager.

python3-venv

To enable the creation of virtual environments.

libatlas-base-dev

Required to install numpy package.

mosquitto

Local Message Queue Telemetry Transport (MQTT) broker used currently in development branch. It might be useful to install also the `mosquitto-clients`.

build-essential

Required if needed to compile anything.

git Add git support to raspbian.

nginx

Local lightweight web server application used to control or see current status of vehicle (in development)

ufw Firewall interface to improve security.

dnsmasq

Provides network infrastructure for small networks as Domain Name System (DNS), Dynamic Host Configuration Protocol (DHCP). Will be used to configure Rpi as an Access Point (AP).

hostapd

Daemon for configuring and enabling the AP

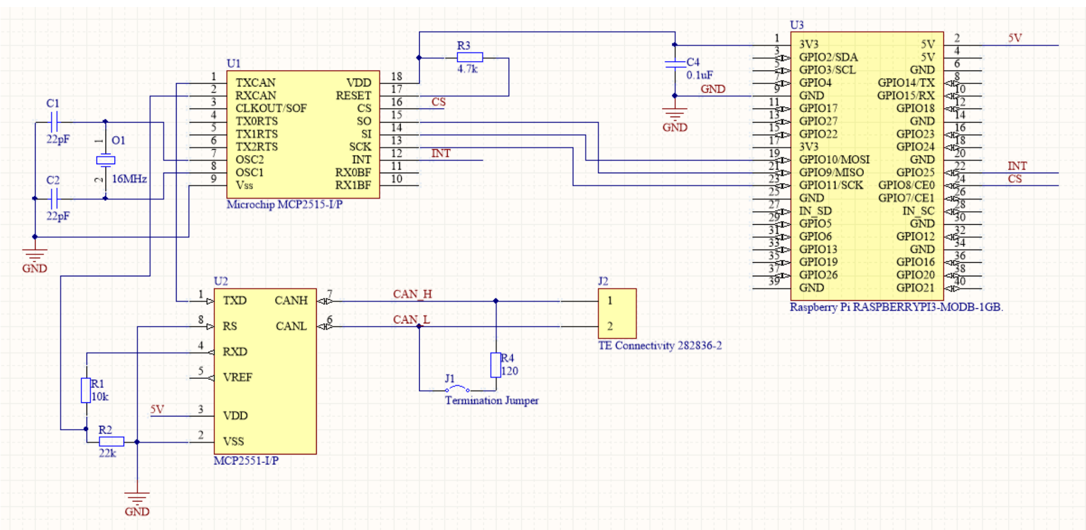


Figure 3.6: CAN protoboard schematic

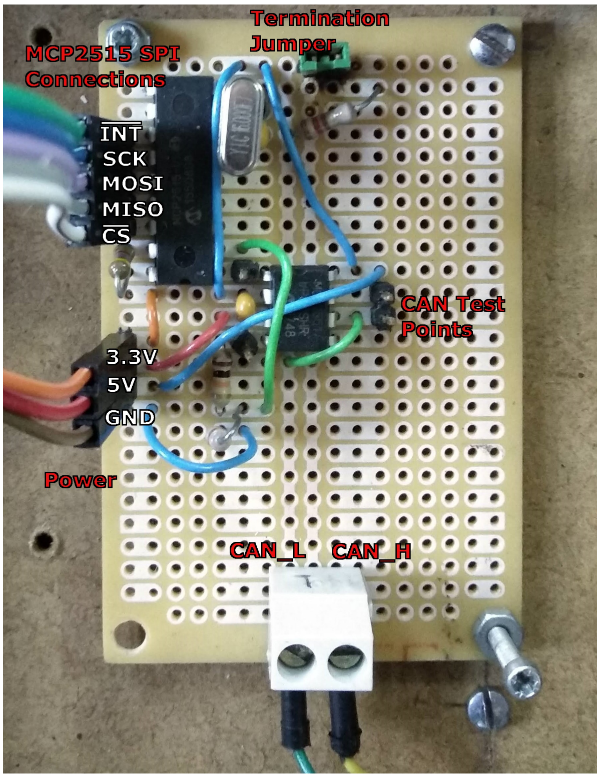


Figure 3.7: Protoboard designed for CAN interface

Parameter	Value
Bitrate	1Mbps
Triple Sampling	on
Sampling point	0.75
Restart	10ms

Table 3.3: CAN used settings

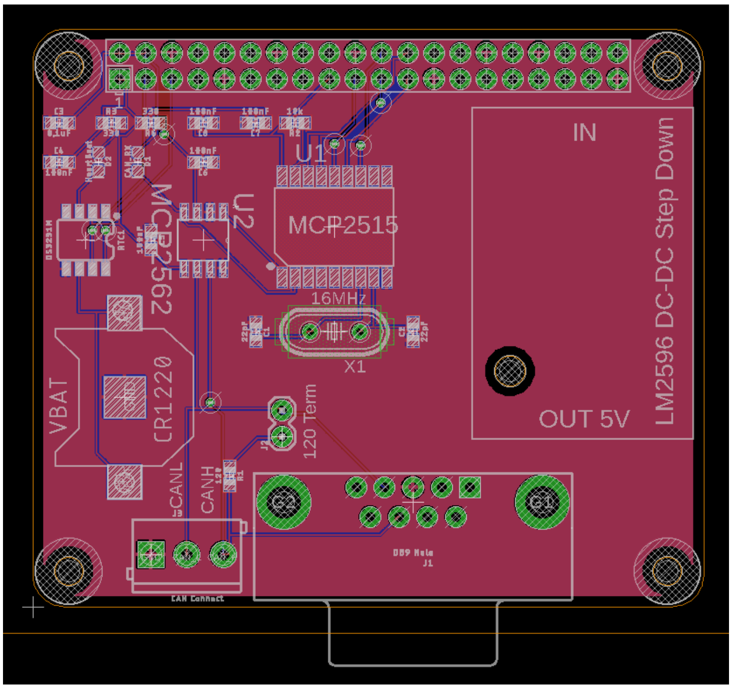


Figure 3.8: Proposed CAN interface board for future use

3.5 Post-Installation Procedures

After installing the recommended packages, user should perform several configurations. In this section is described each of them.

3.5.1 Adding user to groups

After adding user to any group, **a logout must be performed to changes take effect**. Changes can be confirmed by using the command `groups` that prints the groups current user is in.

www-data

Grant user ability to perform changes on /var/www. Run `sudo adduser pi www-data`

dialout

Grant user ablility to use ports. Run `sudo adduser pi dialout`

3.5.2 Configuring MQTT Broker

Current and planned development roadmap use MQTT brocker to change messages between user or high level software and hardware interface. It is also used websockets and in this section will be shown how to enable it. The current used broker is mosquitto. If not already installed, use:
`sudo apt install mosquitto`
After installation edit mosquitto.conf by using `sudo nano /etc/mosquitto/mosquitto.conf` and add an additional port for websockets protocol. If advanced configuration is need refer to [9]. In order to use mosquitto with Quality of Service (QoS) of 1 or 2 and accept large queues, it was increase maximum queued messages to 10000. Also, since it is not required, persistence file was disabled.

```
pid_file /var/run/mosquitto.pid
persistence false
persistence_location /var/lib/mosquitto/

log_dest file /var/log/mosquitto/mosquitto.log

include_dir /etc/mosquitto/conf.d

port 1883
listener 8080
protocol websockets

# max_inflight_messages 0
max_queued_messages 10000
```

Since official repository did not have the latest release of mosquitto, it was necessary to manually update it using:

```
wget http://repo.mosquitto.org/debian/mosquitto-repo.gpg.key
```

```
sudo apt-key add mosquitto-repo.gpg.key
cd /etc/apt/sources.list.d/
sudo wget http://repo.mosquitto.org/debian/mosquitto-stretch.list
sudo apt update
sudo apt upgrade
```

In order to discuss future implementations it was tested the ability of using the MQTT interface for fast rate messages. For that, in table 3.4 are shown different approaches using local vs online brokers and implementation on Rpi vs local laptop (Lenovo T480).

As summary, test conditions are as follow:

- 1000 messages sent, using an Int32 with the number of message as payload.
- Same QoS in both ends.
- Using same PC to run the sender and receiver clients (Lenovo T480)
- Comparison between local MQTT broker (mosquitto), running in RaspberryPI 3 and Laptop, as well as online servers.
- Mean of 5 consecutive tests.
- Transport used is websockets in both clients.

Scripts used for testing can be seen in VIENA-IST/HighLevelCommBenchMarks repository.

3.5.3 Configuring Rpi as AP

Use only if necessary and not working with an external router.

While in development user is advised to use ethernet connection between development PC and Rpi, it is useful to configure Rpi as an AP so users can connect to it using wifi in field environment. Here will be assumed that internet connection is provided via ethernet cable during development phase, for example via host PC, and during normal operation Rpi will not be connected to internet. This section follows the main instructions given in [10].

- Turn off hostapd and dnsmasq. Perform this using systemctl with:

  ```
  sudo systemctl stop dnsmasq
  sudo systemctl stop hostapd
  ```

- Configuring a static IP. Edit `/etc/dhcpcd.conf` with nano and change the file as shown below, assuming the user wants to assign the server IP address as 192.168.4.1, using wlan0 as interface.

  ```
  # static ip address for wlan0 to be used as AP
  interface wlan0
      static ip_address=192.168.4.1/24
      nohook wpa_supplicant
  ```

Receiving Results						
Server	**Is local?**	**QoS**	**Mean**	**std**	**min.**	**max.**
mosquitto	Yes	0	9754.14	1735.97	7316.35	11653.73
mosquitto	Yes	1	4917.01	172.89	4680.69	5125.19
mosquitto	Yes	2	3663.86	234.97	3339.15	3999.98
mosquitto (Rpi)	Yes	0	820.48	36.45	781.01	860.08
mosquitto (Rpi)	Yes	1	780.07	73.96	650.22	835.46
mosquitto (Rpi)	Yes	2	390.70	30.80	356.01	426.96
mosquitto.org	No	0	103.71	4.47	96.85	108.64
mosquitto.org	No	1	107.87	9.85	90.55	113.12
mosquitto.org	No	2	57.69	0.65	56.89	58.44
broker.hivemq.com	No	0	3209.51	2631.14	555.91	6589.80
broker.hivemq.com	No	1	4917.01	172.89	4680.69	5125.19
broker.hivemq.com	No	2	3663.86	234.97	3339.15	3999.98
Transmitting Results						
Server	**Is local?**	**QoS**	**Mean**	**std**	**min.**	**max.**
mosquitto	Yes	0	20855.58	6606.65	13611.86	29385.87
mosquitto	Yes	1	6370.67	343.24	5797.45	6627.05
mosquitto	Yes	2	4653.94	189.67	4374.28	4883.84
mosquitto (Rpi)	Yes	0	5969.37	570.65	5100.85	6436.20
mosquitto (Rpi)	Yes	1	818.21	25.51	784.16	850.88
mosquitto (Rpi)	Yes	2	409.12	22.39	372.51	430.22
mosquitto.org	No	0	6863.24	1031.36	5768.09	8451.10
mosquitto.org	No	1	106.53	8.66	91.23	111.90
mosquitto.org	No	2	57.64	0.59	56.92	58.43
broker.hivemq.com	No	0	6382.99	905.09	4832.09	7004.41
broker.hivemq.com	No	1	6370.67	343.24	5797.45	6627.05
broker.hivemq.com	No	2	4653.94	189.67	4374.28	4883.84

Table 3.4: Benchmark results for MQTT

- Restart dhcpd using `sudo service dhcpcd restart`
- Configuring the DHCP server (dnsmasq). Perform a copy of original file and create a new one

```
sudo mv /etc/dnsmasq.conf /etc/dnsmasq.conf.orig
sudo nano /etc/dnsmasq.conf
```

On new opened configuration file place that will allow dhcp on interface wlan0 giving ip addresses to clients from 192.168.4.2 to 192.168.4.20 with a lease time of 24h:

```
interface=wlan0
dhcp-range=192.168.4.2,192.168.4.20,255.255.255.0,24h
```

- Configuring the access point host software (hostapd). Table 3.5 show the suggested SSID and password. Edit file /etc/hostapd/hostapd.conf and add:

```
interface=wlan0
driver=nl80211
ssid=VIENA
hw_mode=g
channel=7
wmm_enabled=0
macaddr_acl=0
auth_algs=1
ignore_broadcast_ssid=0
wpa=2
wpa_passphrase=fiatelettra
wpa_key_mgmt=WPA-PSK
wpa_pairwise=TKIP
rsn_pairwise=CCMP
```

Now edit file `sudo nano /etc/default/hostapd` and add to it:
`DAEMON_CONF="/etc/hostapd/hostapd.conf"`

- Restart services:

```
sudo systemctl start hostapd
sudo systemctl start dnsmasq
```

- Edit /etc/sysctl.conf and uncomment line `net.ipv4.ip_forward=1`
- Add a masquerade for outbound traffic on ehternet port:

```
sudo iptables -t nat -A  POSTROUTING -o eth0 -j MASQUERADE
sudo sh -c "iptables-save > /etc/iptables.ipv4.nat"
```

- Edit /etc/rc.local and add this just above `exit 0` to install these rules on boot:

```
iptables-restore < /etc/iptables.ipv4.nat
```

- Reboot. After it user should be able to connect to configured network and current user authentication settings.

SSID	VIENA
password	fiatelettra

Table 3.5: Suggested AP login settings

3.5.4 Configure Nginx

The configuration of nginx will be minimally changed from default values and will follow mainly [11]. For more advanced uses, please refer for example to [12] and [13]. The use of web server is intended for current in development branch of MQTT web interface. A user can connect to local network of Rpi and see current information displayed in dashboard webpage.

If not already, do `sudo apt install nginx`. Test installation by starting the webserver with

```
systemctl status nginx.service
sudo systemctl start nginx.service
```

Change user permissions for `/var/www/html` and clone the current repository of webpage interface using the following commands:

```
sudo rm -R /var/www/html/*
sudo chown -R pi:pi /var/www/html
git clone https://github.com/brtiberio/VIENA_interface.git /var/www/html
```

Use a browser using the ip of Rpi or the defined hostname.local to confirm it is working (see figure 3.9).

3.5.5 Configure firewall

First enable firewall by using `sudo ufw enable`. After use the following console command to enable the previously configured ports for ssh connection, mqtt connections and http server configured in nginx:

```
sudo ufw allow 22
sudo ufw allow 80
sudo ufw allow 1883
sudo ufw allow 8080
```

If needed, confirm status with `sudo ufw status`. For more advanced use run `man ufw`.

3.6 Troubleshooting

The command arp -a do not show my Rpi

In that case, try use the sudo nmap -sS 192.168.1.0/24, assuming the 192.168.1.0/24 is your local network. This is a time consuming command!

Cannot find my Rpi IP. Is it even running?

Maybe there is some problem with boot or bad microSD reading. The easiest solution is to connect a monitor and keyboard. Check messages at boot time. If nothing seems strange, manually login and then check if ehternet connection is ok using ifconfig

CAN seems to not be working

First see if MCP2515 is successfully connected.

1. Use dmesg |grep mcp2515*. If it says successfull configured, go to next step. If not, recheck connections and restart. Also make sure the oscilator frequency match the used on boot configuration file settings as seen here.
2. Check if can is detected as a socketcan interface. Use ifconfig. If CAN is available, it should show a section for can0. If not, re-check if can-utils is installed.
3. View details about CAN connection. use ip -details -statistics link show can0 to get more information. If current state is BUS-OFF, manually restart the CAN by using the following:

```
sudo ip link set can0 down
sudo ip link set can0 up
```

webpage is nginx default

Restart nginx service by using sudo systemctl restart nginx.service. If it still shows a different page, confirm the enabled sites are correct. Use:

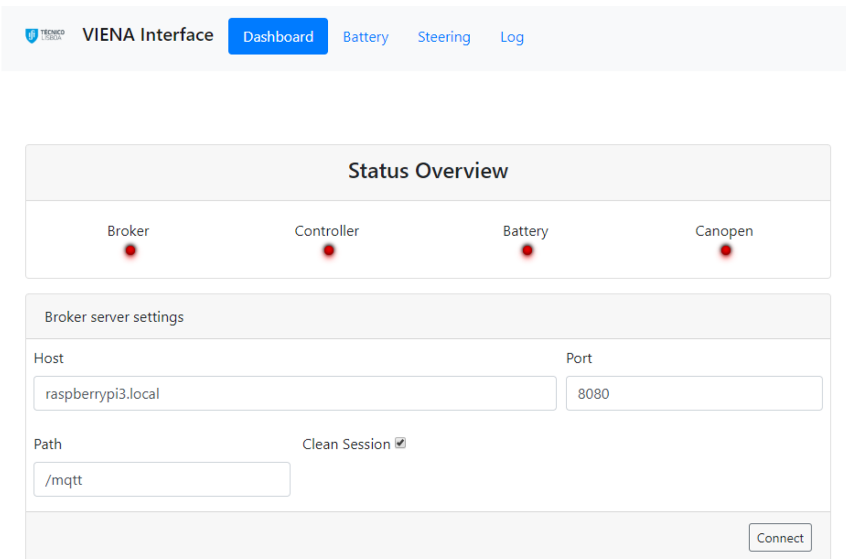


Figure 3.9: Current interface webpage

```
nano /etc/nginx/sites-enabled/default
```

The default values for listen setting and root should be:

```
listen 80 default_server;
listen [::]:80 default_server;
...
root /var/www/html;

# Add index.php to the list if you are using PHP
index index.html index.htm index.nginx-debian.html;
```

If they are different, change it accordingly to meet desired configuration, by editing:

```
sudo nano /etc/nginx/sites-available/default
```

If still show different then expected, try clear browser cache files.

Chapter 4

Batteries

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4.1 Main battery packs

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4.1.1 Connections

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4.1.2 Power requirements

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4.1.3 Enabling power

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4.1.4 List of CAN messages

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4.2 Auxiliary battery pack

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Chapter 5

Sensors

In this chapter will is briefly explained several notations used along the report and important definitions that help the reader to walk through the work. Many parts of the text presented here are extracted from [14] where full description is available and user should refer to it, if necessary. The notation system of leading superscripts and subscripts is used to denote relative frames orientation or general physical quantities (vectors, points). For frames orientations, leading subscript refers to the frame being represented with respect to the frame in leading superscript. For example let R be a rotation matrix. Using the notations stated before, ${}^{a}_{b}R$ describes orientation of frame b with respect to frame a. For physical quantities, a vector is represented in the frame defined by is leading superscript, ${}^{a}v$ and in similar way points follow the same rule, ${}^{a}P = [{}^{a}x, {}^{a}y, {}^{a}z]$.

5.1 Definition of frames

The frames cited are Earth Centered, Earth Fixed (ECEF), World Geodetic System (WGS84), East North Up (ENU) and body frame. The ECEF, WGS84 are just auxiliary frames used to define the ENU frame which will be considered the world frame.

5.1.1 ECEF and ENU Frame

ECEF coordinate system defines a referential axis where the origin is defined as the center of Earth, X axis is defined through the intersection of the plan defined by zero latitude line (Equator) and plan defined by zero longitude line (prime meridian). The X-axis orientation is considered positive from center towards the point defined by zero latitude and zero longitude. Z axis is defined by line intersecting origin and both Poles, being positive towards North Pole. Y axis is perpendicular to the plan defined by X and Z axis and it positive direction is defined by right hand rule.

ENU coordinate system is a local coordinate system where the origin is located at a user defined point in ECEF coordinate system, with Y axis pointing towards North Pole and X axis pointing towards East. The plan defined by X and Y axis is tangent to the WGS84 frame on the origin of ENU. Z axis

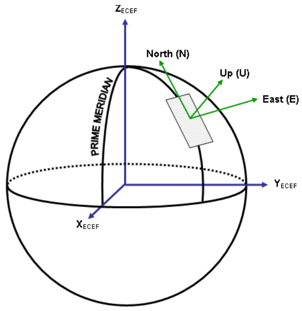


Figure 5.1: ECEF frame and Local ENU frame (source:wikipedia)

.

express the altitude from defined local plane (see figure 5.1). The ENU frame is considered in this work as the reference frame and will be denoted with superscript or subscript w.

Given a point of reference in ECEF frame, it is necessary to find the corresponding latitude and longitude of reference point (X_r, Y_r, Z_r). To do it is necessary to use the parameters of WGS84 presented in the table 5.1

WGS 84 Defining Parameters[15]		
Parameter	**Notation**	**Value**
Semi-major axis	a	6 378 137.0 m
Reciprocal of flattening	$1/f$	298.257 223 563
Semi-minor axis	b	6 356 752.3142 m
First eccentricity squared	e^2	6.694 379 990 14x10^{-3}
Second eccentricity squared	e'^2	6.739 496 742 28x10^{-3}

Table 5.1: WGS84 parameters necessary to transform ECEF coordinates into ENU

Using set of equations (5.1) to estimate the latitude (λ_r) and longitude (φ_r) for the reference coordinate point. The final transformation results in applying (5.2) to ECEF physical quantities [16].

$$p = \sqrt{{X_r}^2 + {Y_r}^2} \tag{5.1a}$$

$$\theta = \arctan\left(Z_r \frac{a}{pb}\right) \tag{5.1b}$$

$$\lambda_r = \operatorname{arctan2}(Y_r, X_r) \tag{5.1c}$$

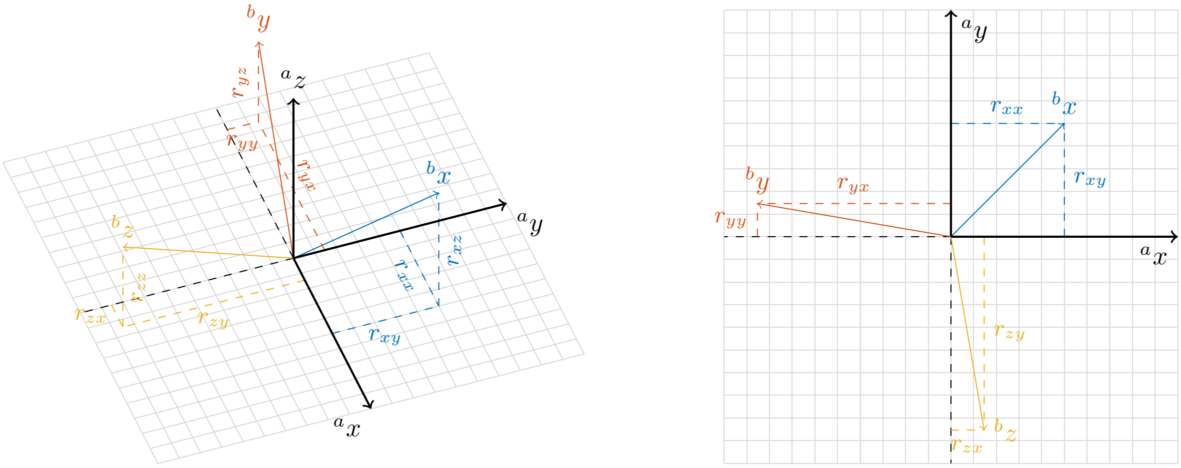
$$\varphi_r = \arctan\left(\frac{Z_r + e^2 b \sin^3(\theta)}{p - e'^2 a \cos^3(\theta)}\right) \tag{5.1d}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ENU} = \begin{bmatrix} -\sin(\lambda_r) & \cos(\varphi_r) & 0 \\ -\sin(\varphi_r)\cos(\lambda_r) & -\sin(\varphi_r)\sin(\lambda_r) & \cos(\varphi_r) \\ \cos(\varphi_r)\cos(\lambda_r) & \cos(\varphi_r)\sin(\lambda_r) & \sin(\varphi_r) \end{bmatrix} \begin{bmatrix} X - X_r \\ Y - Y_r \\ Z - Z_r \end{bmatrix}_{ECEF} \tag{5.2}$$

5.1.2 Body frame, *b*

Each sensor present in the razor board is aligned to match the sensor axes printed in the board as seen in figure 5.5. For simplicity, the razor sensor is placed as possible near the middle point of the bisector segment between the two wheel axes in such a away that YY axis as marked in the figure 5.5 is pointing towards the front of vehicle, XX axis is pointing to the right side of the car and ZZ axis is pointing to the top. This way, if the Euler angles describing the orientation of body frame related to world frame are all equal to zero, it means the axes in each frame are coincident apart from an offset in origin. Rotation angles are considered positive following the right hand rule in each axis. The origin of body frame is equal to intersection of rear wheel axis with the bisector defined above.

5.2 Euler angles and Rotation Matrix



(a) 3D view of axes frames example

(b) XY plane of axes frame example

Figure 5.2: Two frames axes example

The rotation matrix is a tool used to describe transformation of coordinates from one frame to another and this also describe orientation of one frame relative to another frame. The convention used in this work is represented by (5.3) and maps quantities described in frame b to frame a. Comparing the structure of (5.3) with figure 5.2 it is seen that columns of ${}^{a}_{b}R$ represent each unity vector defining all axes of frame b.

$$
{}^{a}_{b}R = \begin{bmatrix} {}^{a}r_{xx} & {}^{a}r_{yx} & {}^{a}r_{zx} \\ {}^{a}r_{xy} & {}^{a}r_{yy} & {}^{a}r_{zy} \\ {}^{a}r_{xz} & {}^{a}r_{yz} & {}^{a}r_{zz} \end{bmatrix} \tag{5.3}
$$

Rotation matrices belong to the orthonormal group and one important property is that ${}^{a}_{b}R{}^{a}_{b}R^{T} = I$ meaning ${}^{a}_{b}R^{T} = {}^{a}_{b}R^{-1}$. Also ${}^{a}_{b}R^{T}$ is equal to ${}^{b}_{a}R$ [17][18].

Euler angles are another form to describe orientation of one frame relative to another by defining three angles. The Euler angles convention adopted in this work is the Tait–Bryan intrinsic rotation sequence Z-Y-X, meaning referential a axes, represented in figure 5.2, can be mapped into referential b by performing sequential rotations, first along ZZ axis by an angle ψ, second along the resulting YY axis by an angle θ and final rotation along the resulting XX axis by an angle ϕ. In figure 5.3 is represented the sequence necessary to rotate frame a into frame b with the respective Euler angles to achieve the same orientation as expressed in figure 5.2. It is also represented the intermediary axes resulting from each sequential rotation and it positive direction. Each individual rotation is expressed by is own rotation matrix using the respective Euler angle associated and the final orientation is the result of successive matrices multiplications as shown in equation 5.4 where the intermediary axes sequence is denoted as expressed in the figure 5.3.

$$
\begin{aligned}
{}^{b}_{a}R &= {}^{b}_{2}R_x(\phi){}^{2}_{1}R_y(\theta){}^{1}_{a}R_z(\psi) \\
&= \begin{bmatrix} \cos(\psi)\cos(\theta) & \sin(\psi)\cos(\theta) & -\sin(\theta) \\ \cos(\psi)\sin(\theta)\sin(\phi)-\sin(\psi)\cos(\phi) & \cos(\psi)\cos(\phi)+\sin(\psi)\sin(\theta)\sin(\phi) & \cos(\theta)\sin(\phi) \\ \sin(\psi)sin(\phi)+\cos(\psi)\sin(\theta)\cos(\phi) & \sin(\psi)\sin(\theta)\cos(\phi)-\cos(\psi)\sin(\phi) & \cos(\theta)\cos(\phi) \end{bmatrix}
\end{aligned} \tag{5.4}
$$

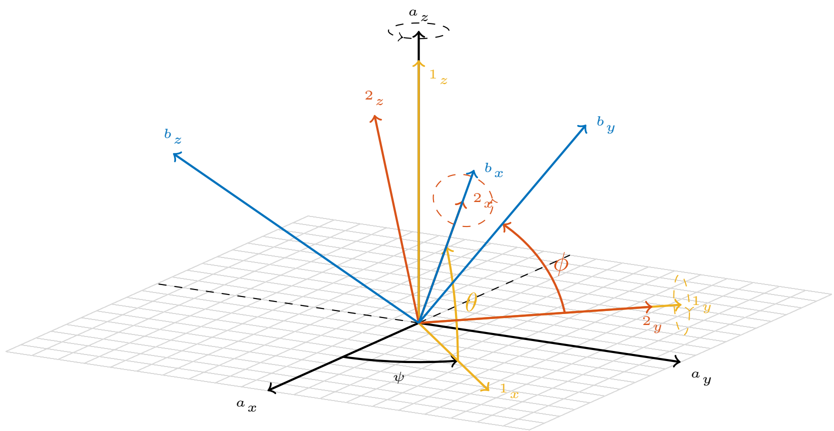


Figure 5.3: Two frames axes example - Euler angles. In this case, the angles are $\psi = 45^o, \theta = -45^o, \phi = 45^o$

5.3 Quaternion

During the work an Attitude and Heading Reference System (AHRS) algorithm based on [19] and derived in [14] is implemented and it uses quaternions. Basic definitions for understanding the filter terminology are explained in this section following the same notation as present by [14] in case the user as no notion of quaternions at all.

Quaternion is a complex number in four dimension that can be used, similar to rotation matrices and Euler angles, to represent orientation of frames with respect to others. The Euler rotation theorem and the Rodriguez formula are the basis for quaternion representation of rotations but will not be discussed. The theorem states it is possible to describe an orientation of frame relative to other by performing a rotation of α along an axis r that is defined by the points that remain static relative to the original frame. [20] quickly resumes the main idea about quaternions, why they can be used to express orientations and relation between them and Euler and Rodriguez formulations.

A quaternion can be represented by (5.5) where q_1 is the norm of it, q_2, q_3 and q_4 are complex coordinates with *i, j, k* being the axis versors. If a quaternion is normalized, it is denoted with a circumflex accent as shown in (5.6).

$$q = q_1 + q_2 i + q_3 j + q_4 k$$
$$q = [q_1 \; q_2 \; q_3 \; q_4] \tag{5.5}$$

$$\hat{q} \implies \|q\| = 1 \tag{5.6}$$

Using the same notation as stated before, ${}^w_b q$ represent the orientation of body frame with respect to world frame. With (5.5) in mind, the following list of properties/operations are summarized in this list:

Identities All quaternions multiplications must obey to the following set of properties described in equation 5.7.

$$i^2 = j^2 = k^2 = ijk = -1 \tag{5.7a}$$

$$ij = -ji = k \tag{5.7b}$$

$$jk = -kj = i \tag{5.7c}$$

$$ki = -ik = j \tag{5.7d}$$

Quaternion multiplication The quaternions multiplication, denoted by $\otimes$, is defined by the Hamilton product as in equation 5.8

$$\begin{aligned} a \otimes b &= [a_1 \; a_2 \; a_3 \; a_4] \otimes [b_1 \; b_2 \; b_3 \; b_4] \\ &= \begin{bmatrix} a_1 b_1 - a_2 b_2 - a_3 b_3 - a_4 b_4 \\ a_1 b_2 + a_2 b_1 + a_3 b_4 - a_4 b_3 \\ a_1 b_3 - a_2 b_4 + a_3 b_1 + a_4 b_2 \\ a_1 b_4 + a_2 b_3 - a_3 b_2 + a_4 b_1 \end{bmatrix}^T \end{aligned} \tag{5.8}$$

Quaternion conjugate The quaternion conjugate describes the inverse rotation and is defined as equation 5.9.

$${}^w_b q^* = {}^b_w q = [q_1 \; -q_2 \; -q_3 \; -q_4] \tag{5.9}$$

Vector rotation Let's define the following quaternion representation of the same vector but in each referential by using is pure quaternion as ${}^w v = [0 \, {}^w x \, {}^w y \, {}^w z]$ and ${}^b v = [0 \, {}^b x \, {}^b y \, {}^b z]$. The rotation of vector v from one frame to other, using a quaternion, is performed by equation 5.10.

$${}^b v = {}^w_b \hat{q} \otimes {}^w v \otimes {}^w_b \hat{q}^* \tag{5.10}$$

Composed rotations The composition of rotations can be described in quaternions as the product between quaternions. For example the sequence ${}^a_b \hat{q} \rightarrow {}^b_c \hat{q}$ is equal to ${}^a_c \hat{q}$ and is defined as equation 5.11.

$${}^a_c \hat{q} = {}^b_c \hat{q} \otimes {}^a_b \hat{q} \tag{5.11}$$

5.4 Novatel OEM4-G2L FlexPak

(a) Novatel OEM4-G2L FlexPak receiver. (b) Novatel GPS-701-GG antenna

Figure 5.4: Novatel GNSS devices used (source:NovAtel)

Each Novatel GPS sensor is composed with Novatel OEM4-G2L FlexPak receiver and Novatel high performance GPS-701-GG antenna. The Novatel OEM4-G2L FlexPak receiver provides position and velocity estimations using GPS broadcasted satellites radio signals. It has two communications ports that can be configured independently. Additional to common GPS protocols, it has support for custom Novatel protocols (which will be used) providing the best possible estimation the receiver can do making it as simple as possible from the point of view of user. The receiver can handle both L1 and L2 signals provided by satellites [21], however, antenna module only can handle L1 frequency signal (1575.42MHz)[22]. Power supply to FlexPak enclosure should range from 6 to 18 volts DC with typical consumption of 5W. Without differential GPS methods, the Novatel receiver can achieve up to 1.8 meters precision Circular error probable (CEP) with single point operation. Output logs data rate is up to 20Hz in binary mode and 10Hz in ASCII format.

Since the receivers used are industrial grade, no particular effort is made to modeling any error source or trying to improve the solution given by it. However is important to have minimal knowledge the limitations of those types of receivers. It is trusted that the reported position and velocity information is the best the sensor could possibly estimate.

The developed library interface full documentation is present in the attach appendix A, however is advised to use the online version for granting the most recent updated documentation.

5.4.1 GNSS main errors

The main cause of Global Navigation Satellite System (GNSS) calculations errors are presented in table 5.2. While some can't be controlled by user (satellite clocks, orbit clocks), others can be mitigated using differential GNSS techniques, multi-frequency (currently civilians have access to more than one), satellite based augmentations system and multi-constellation or using modeling the error source. Multipath is probably the most user dependent but in some situations hard to avoid for example in streets surround with high buildings general denoted as urban canyons.

Source	Value (up to)
Satellite clocks	± 2m
Orbit Errors	± 2.5m
Inospheric Delays	± 5m
Tropospheric Delays	± 0.5m
Receiver Noise	± 0.3m
Multipath	± 1m

Table 5.2: Main source of errors in calculations using GNSS [23]

5.5 Sparkfun Razor IMU 9DOF

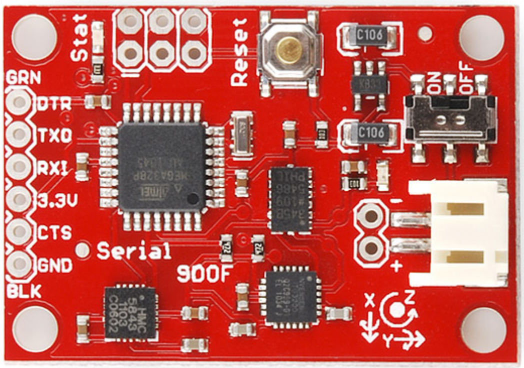


Figure 5.5: Razor 9DOF IMU.

Razor IMU 9DOF is an electronics board, developed by Sparkfun Electronics, which includes an accelerometer, a gyroscope and a magnetometer, each one with three axis of sensibility. Since this board is based on the Arduino project, the chip sensors are interconnected by an Atmel® ATmega328p Microcontroller Unit (MCU) which allows the configuration of sensors, handles the readings and processing of their respective outputs.

5.5.1 ADXL345 Digital Accelerometer

The ADXL345 is a Microelectromechanical systems (MEMS) sensor with three axis accelerometer made by Analog Devices . It has an adjustable acceleration scale range value up to $\pm 16g$. It is possible to measure both dynamic accelerations resulting from motion and shock or measure static accelerations such as gravity, which allows this device to be used as a tilt sensor also. Acceleration deflects the a proof mass attached to one differential capacitor plate and unbalances it, resulting in a sensor output whose amplitude is proportional to acceleration [24].Conversion of outputs is made through 10 to 13 bit Analog to Digital Converter (ADC) according to selected range to maintain the same scale of 4mg/LSB.

5.5.1.1 Accelerometer sensor model

The output of accelerometer is proportional to the sum of acceleration in each axis. However the accelerometer is not capable of distinguish if the acceleration is caused by a true acceleration produced by motion or produced by a static force, generally gravity force. As so, equation (5.12) describes the general output of accelerometer [25] where, ${}^{b}A_{ext}$ is the sum of real external acceleration due to linear or rotational dynamics in the body frame, ${}^{b}_{w}R$ is the rotation matrix mapping quantities in world frame into sensor frame, ${}^{w}g$ represents the fictitious acceleration due to gravity in the world frame, ${}^{b}A_0$ is an offset and δA_ϵ describes addictive gaussian noise. Ideally, G should be equal to identity matrix but in fact it represents the product of two matrices, one describing the cross-axis influence and the other a scale factor for each axis [25].

$$ {}^{b}A_s = G[{}^{b}A_{ext} + {}^{b}_{w}R\,{}^{w}g] + {}^{b}A_0 + \delta A_\epsilon \tag{5.12} $$

5.5.1.2 Accelerometer calibration

The suggested calibration method by the manufacturer [26] assumes that cross-axis influence is small enough and can be neglected, this way, G should only be represented by a diagonal matrix with the scale factors for each axis. However, if more precision for the application is needed, calibration using the ellipsoid fitting approach should be made [27].

For this application it will be used the suggested calibration by manufacturer resulting in exposing the sensor to six position combination while resting. This means the ${}^{b}A_{ext}$ will be zero and accelerometer will be only influenced by the gravity force, 1g.

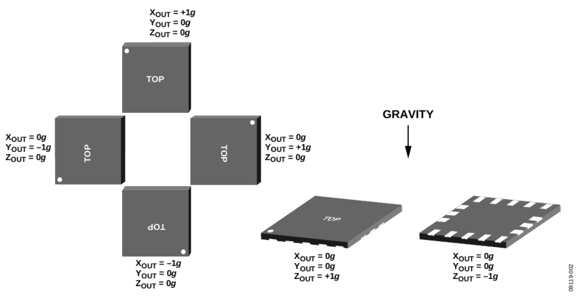


Figure 5.6: ADXL345 calibration poses and expected output [26].

Gains and offset [LSB]	Razor
Z gain	253.66
Z offset	-3.47
Y gain	266.27
Y offset	-3.18
X gain	266.04
X offset	13.83

Table 5.3: Summary of values extracted and calculated for each axis of accelerometer in both sensors

Aligning one axis at a time with gravity vector, as seen in figure 5.6, the mean value of several samples is calculated. Using these means for each axis and the known acceleration values($\pm$1g), it is calculated the slope and offset of the respective line passing through the two points. Calculated values (see table 5.3) will be stored in the internal EEPROM memory of MCU to be loaded at boot time of each razor. The conversion between LSB and g unities is given by the relation $254LSB/g$ or $3.9mg/LSB$ [24]

5.5.2 ITG3200 Digital Gyroscope

The ITG-3200 is a microelectronic mechanical integrated circuit chip with three axis independent gyroscopes, built by Invensense able of measuring angular velocities up to $\pm 2000^{\circ}/s$. When the gyroscopes are rotated about any of the sensor axes, the Coriolis effect causes a deflection that is detected by a capacitive pick-off circuit proportional to angular velocity. The measured signal is filtered and converted using internal ADC. The scale factor that allow to convert the output values to angular velocities in degrees per second is, according to its datasheet [28], factory calibrated and equal to $14.375 LSB/^{\circ}.s^{-1}$.

5.5.2.1 Gyroscope sensor model

For a given axis, the gyroscope output is proportional the angular velocity sensed of that axis and is given by equation (5.13) where ${}^{b}\omega_{s}$ represents the vector output of the sensor in body frame at instant t, ${}^{b}\omega_{real}$ is the real angular velocity vector applied to sensor in body frame, ${}^{b}\omega_{0}$ is the bias vector term and $\delta\omega_{\epsilon}$ addictive gaussian noise. Since the sensor is described in [28] as factory calibrated, G which represent a scaled factor correction, is expected to be equal to identity matrix. Note that the equation model (5.13) is in fact a simplified version of a more accurate model described in [25]. As stated in [25] cross-axis misalignment and linear acceleration sensitivity are expected to be small for the application purpose so they are considered irrelevant.

In general, the offset value depends on the temperature value inside chip. Once internal stability is reached, offset values tends to be constant [29]. Electrical temperature stability can be achieved after a few minutes of operation. At the beginning of initialization of Razor, several samples are acquired internally in the microprocessor and mean value is calculated for each axis, defining this way the offset constant for each axis.

$$ {}^{b}\omega_{s} = G\,{}^{b}\omega_{real} + {}^{b}\omega_{0} + \delta\omega_{\epsilon} \tag{5.13} $$

5.5.3 HMC5843 Digital compass

The HCM5843 sensor is a digital compass chip designed by Honeywell, designed for low field magnetic sensing. This sensor uses anisotropic magnetic resistor technology, making it immune to vibration noises, and the use of Wheatstone bridge makes it more robust to noise. A material with anisotropic magnetic resistor properties changes its resistance according to absolute value and direction of magnetic field.

5.5.3.1 Magnetometer model

The magnetometer sensor model follows a similar structure as two previous sensors and is given by equation (5.14). The ${}^{b}H_{s}$ is the value sensed by the sensor in body frame. C is a matrix resulting from the multiplication of matrices containing influence of cross-axis, gain scale factor and soft-iron interference [30]. ${}^{w}h_{e}$ represent the geomagnetic vector of Earth, ${}^{b}h_{offset}$ is an offset vector which describes the influence of zero-field offset and the ferromagnetic masses fixed relative to body frame usually denoted as hard-iron. δh_ϵ represents gaussian additive noise.

$$^{b}H_s = C\,{}^{b}_{w}R^{w}h_e \; + {}^{b}h_{offset} + \delta h_\epsilon \tag{5.14}$$

5.5.3.2 Geomagnetic field

The geomagnetic field can be described as 3D vector in each point as seen in [31]. As previous defined, ${}^{w}h_e$ represent the geomagnetic vector of Earth. Let us define now, ${}^{w}h_0$ as the horizontal projection of ${}^{w}h_e$. The angle between ${}^{w}h_0$ and ${}^{w}h_e$ is denominated as inclination, I. As stated in [31], the horizontal projection of the geomagnetic vector points to the magnetic north which may not be aligned with the north axis of reference frame, ${}^{w}Y$. This defines the magnetic declination angle, D, as the angle between horizontal projection and the ${}^{w}Y$ axis.

For Lisbon, the magnetic declination angle, in January 2017, defined in the reference frame is equal to 2.48° , inclination angle is equal to 52.77° and the ${}^{w}h_e$ is equal to $[-1121.5, 26479.8, -34884.7]^T$ nanoteslas [32]

5.5.3.3 Hard and soft-iron compensation

The compensation for hard and soft-iron effects can be done using a geometric approach as described by [30] [33] [34]. If the geomagnetic vector is known and sensor perfect calibrated, free of any type ambient distortion, points collected are expected to belong a surface of an origin centered sphere with radius equal to the magnitude of geomagnetic field ${}^{w}h_e$. Distortions, cross-axis influence, scale-factor inequalities between axis, causes the expected sphere to be deformed into a ellipsoid. Collecting points in 3D space by performing rotations of the sensor frame, allow us to fit the data to an ellipsoid surface and after determinate the matrix C and offset vector ${}^{b}h_{offset}$.

However since the body frame is a vehicle, it is not physically possible to collect points based in rotations of YY and XX axis. Only ZZ axis rotations are available and the data instead of belonging to an ellipsoid surfaces, will belong to an ellipse in Z-plane as a result from that plan cutting the ellipsoid in some undetermined z coordinate. Because of restriction stated before it will be considered that the influence in ZZ axis is zero and the scale factor is equal to one. Offset in ZZ axis will also be considered zero. In [14] is shown that this assumption is not relevant. (5.14) will be rearranged to equation (5.15) form.

$$\begin{aligned} {}^{b}H_s &= C\,{}^{b}_{w}R^{w}h_e \; + {}^{b}h_{offset} + \delta h_\epsilon \\ {}^{b}_{w}R^{w}h_e &= C^{-1}[{}^{b}H_s - {}^{b}h_{offset} - \delta h_\epsilon] \end{aligned} \tag{5.15}$$

Without loss of generality, $C^{-1}\delta h_\epsilon$ will result also in a gaussian vector so it will be rewritten as δh_ϵ. Equation (5.15) can take now be arranged into (5.16) where ${}^{b}H_c$ is the corrected value after calibration process.

$$
\begin{aligned}
{}^b_wR(t)^wh_e &= C^{-1}[^bH_s - {}^bh_{offset} - \delta h_\epsilon] \\
{}^bH_c &= C^{-1}[^bH_s - {}^bh_{offset}] + \delta h_\epsilon
\end{aligned} \tag{5.16}
$$

The matrix C^{-1} and ${}^bh_{offset}$ is obtained as described by [33] using the *ellipse_fit*[1]. The function *ellipse_fit* returns the least square estimate that best fits the data collected from sensor and the parameters that define the estimated ellipse as described in this list:

- **semi-major** - The length of major semi axis of ellipse.
- **semi-minor** - The length of minor semi axis of ellipse.
- x_0 - The offset in the XX axis of ellipse.
- y_0 - The offset in the YY axis of ellipse.
- α - Rotation angle between semi-major axis and XX axis in reference frame.

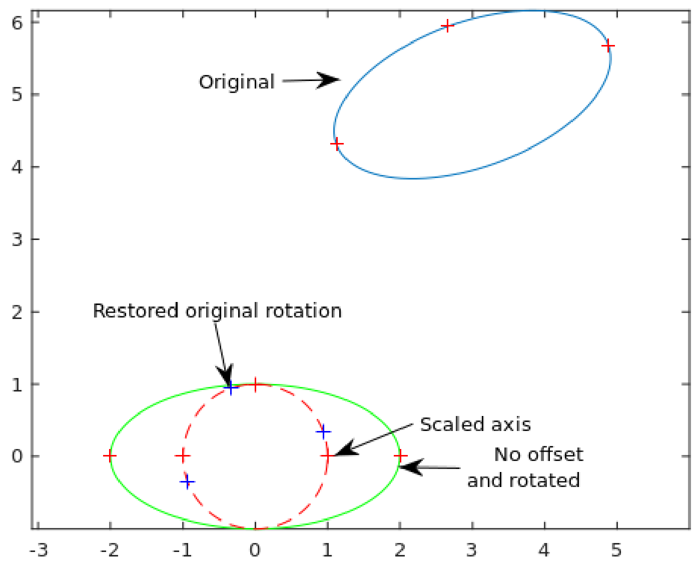


Figure 5.7: Simulation of the calibration steps applied to hypothetical ellipse data.

Take note the fact that since is not physically possible to perform rotations in 3D space, the calibration will only be reflect the XX and YY axis. Using the values returned, the calibration process consists in the following sequential steps:

1 Remove offset by using equation (5.17) with ${}^bh_{offset} = [{}^bx_0, {}^by_0, 0]^T$

$$
{}^bH_s = {}^bH_s - {}^bh_{offset} \tag{5.17}
$$

2 Align semi-major axis of ellipse with the XX axis of reference frame using a rotation of $-\alpha$ by using equation (5.18)

[1] https://www.mathworks.com/matlabcentral/fileexchange/22423-ellipse-fit

$$
\begin{aligned}
{}^{b}H_s &= R_{cal}\,{}^{b}H_s \Leftrightarrow \\
\Leftrightarrow {}^{b}H_s &= \begin{bmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix} {}^{b}H_s
\end{aligned} \tag{5.18}
$$

(3) Apply a scaling matrix S to make semi-major axis the same length as semi-minor axis using (5.19)

$$
\begin{aligned}
{}^{b}H_s &= S\,{}^{b}H_s \Leftrightarrow \\
\Leftrightarrow {}^{b}H_s &= \begin{bmatrix} \frac{semi-minor}{semi-major} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} {}^{b}H_s
\end{aligned} \tag{5.19}
$$

(4) Restore the initial rotation α to the scaled data using the transpose of R_{cal} as seen in (5.20)

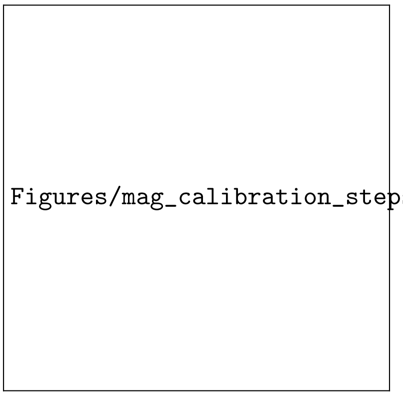
$$
\begin{aligned}
{}^{b}H_s &= R_{cal}^{T}\,{}^{b}H_s \Leftrightarrow \\
\Leftrightarrow {}^{b}H_s &= \begin{bmatrix} \cos(\alpha) & \sin(\alpha) & 0 \\ -\sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix} {}^{b}H_s
\end{aligned} \tag{5.20}
$$

The ${}^{b}H_s$ resulting from step four is in fact the expected corrected reading of sensor, ${}^{b}H_c$. In figure 5.7 visually represented the steps applied to a hypothetical ellipse. Resuming, all sequential steps in one equation results in (5.21).

$$
{}^{b}H_c = R_{cal}\,S\,R_{cal}^{T}[{}^{b}H_s - {}^{b}h_{offset}] \tag{5.21}
$$

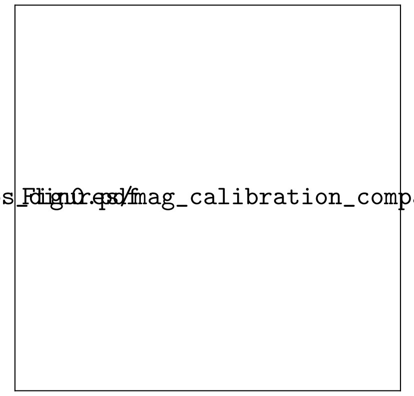
Comparing the structure of (5.21) with (5.16) this implies that C^{-1} is equal to $R_{cal}\,S\,R_{cal}^{T}$.

The results of calibration are presented for one of the devices in figure 5.8 and the obtained are expressed in the table 5.4. The trajectory used is not important as long as it is able perform one or more rotation of the vehicle in the horizontal plan. In figure 5.8c is shown the results before and after calibration for the estimation of Euler ψ angle. It is also present the estimation of the same angle using the the one of the gps unities as a reference for the comparison.



(a) Trajectory used for calibration.

(b) Magnetometer calibration



(c) ψ angle estimation before and after calibration of magnetometers

Figure 5.8: Magnetometer calibration steps applied to real data

	Razor 1
${}^{b}h_{offset}\quad [nT]$	$[-2.5828\ \ -2.1703]^{T}\mathrm{x}10^{4}$
$\alpha\quad [deg]$	107.5238
$\frac{semi-minor}{semi-major}$	0.9567
R_{cal}	$\begin{bmatrix} -0.3011 & -0.9536 & 0 \\ +0.9536 & -0.3011 & 0 \\ 0 & 0 & 1 \end{bmatrix}$
C^{-1}	$\begin{bmatrix} +0.9961 & +0.0124 & 0 \\ +0.0124 & +0.9606 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

Table 5.4: Magnetometers calibration results.

Chapter 6

Steering

The control of steering wheel take advantage of motor for steering assist originally present in the car. The motor is controlled by a positioning controllers designed for brushed DC and brushless DC motors with encoders. denominated Easy Positioning System (EPOS) by many manufactures

6.1 Maxon EPOS 70/10 controller

Figure 6.1: Maxon EPOS 70/10 controller

The controller available to use is the Maxon EPOS 70/10, from now on denoted as EPOS. It includes CAN network interface and a RS-232. The relevant electrical specs can be seen in table 6.1. The full specifications as well as connections layout must be seen in [35]. The controller contains two led in a single package that is used as status reference. Table 6.2 present the status of device based on pattern of leds shown by it. The EPOS will be used as a Proportional Integral Derivative (PID) controller for the steering wheel.

6.2 Steering sensor support

Maxon EPOS 70/10 accepts quadrature sensors to give feedback of position. The used sensor is a quadrature line driver with index (although index is disabled because its track is damaged). The sensor model is HEDR-55L2-BY09 with main characteristics shown in table 6.3 [36]. Table 6.4 show the required configuration to be passed to EPOS device to correctly use the steering controller. See appendix B for further description.

The sensor support is mainly 3D printed in ABS filament. It is composed of the following parts

Description	**Min.**	**Max.**	**Unity**
Power supply voltage V_{CC} (Ripple <10%)	11	70	V_{DC}
Max. output voltage		$0.9 \cdot V_{CC}$	V_{DC}
Max. output current I_{max} (<1sec)		25	A
Continuous output current I_{cont}		10	A
Sample rate PI - current controller	10K	10K	Hz
Sample rate PI - speed controller	1K	1K	Hz
Sample rate PI - positioning controller	1K	1K	Hz
Max. speed (motors with 2 poles)		25K	rpm

Table 6.1: EPOS electric specifications

Description	**Red**	**Green**
The EPOS is in state: • Switch ON Disabled • Ready to Switch ON • Switched ON • The power stage is disabled	OFF	Blinking ($\approx$ 1Hz)
The EPOS is in state: • Operation Enable • Quick Stop Active • The power stage is enabled	OFF	ON
EPOS is in Fault State	ON	OFF
EPOS is in temporary state Fault Reaction Active	ON	ON
There is no valid firmware on the EPOS (due to a failed firmware download)	ON	Flashing

Table 6.2: Maxon EPOS 70/10 Led status

Description	**Value**
Line Driver	Yes
Counts per revolution	3600
Total number of positions	14400
Shaft diameter	8mm

Table 6.3: Main HEDR-55L2_BY09 sensor characteristics

Description	**Value**
Sensor Type	2
Pulse Number	3600
Sensor Polarity	0

Table 6.4: Quadrature sensor settings configured in EPOS

presented in table 6.5. A dimensional sketch of the sensor and bearing used was also designed just for auxiliary purposes and to provide assembly instructions. The drawings with respective dimensions are added in appendix C. The parts were designed in Autodesk Fusion 360 and are available under the Github repository

Part name	**Quantity**	**Reference design**
608 bearing	1	Bearing Diagram
Sensor Case HEDR-55L2_BY09	1	Sensor case
Half Gear 54 teeth	2	Half gear
Sensor gear 32 teeth	1	Sensor gear

Table 6.5: Sensor support parts

6.3 Calibration process

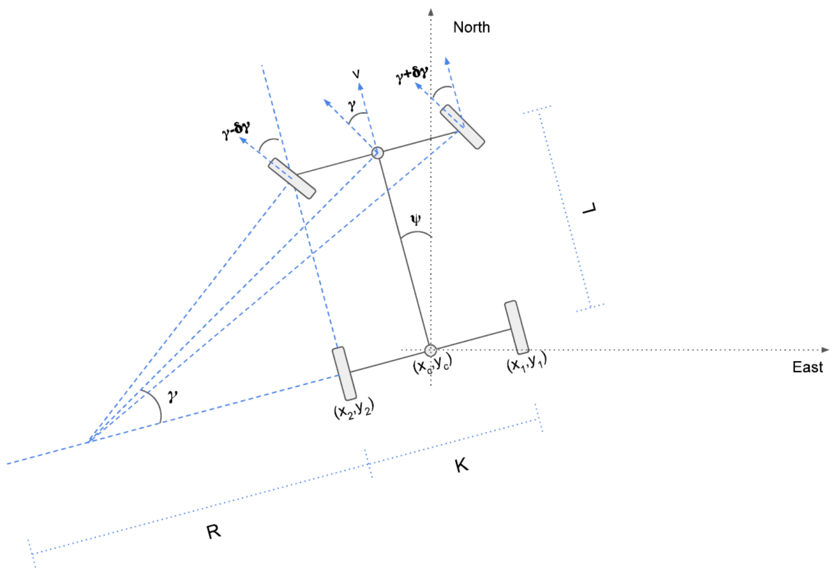
Here is assumed the vehicle follows a model of Ackermann steering model typical valid for low speed which result in the simplified approximation of the single line model or as in general described in literature, as bicycle model[37] [38]. A simplified representation of the model is present in figure 6.2. This model is normally used in control applications and expected to be used in future high level control. As it is necessary to determine the angle of wheel with respect to body frame YY axis (recall subsection 5.1.2), the first calibration process required is to determine the function relating steering wheel position and angle of fictional wheel. A set up was made fixing the car and placing a white duck tape in front of it, perpendicular as physically possible and apart by 1.47 meters in front of the car. The duck tape will serve as a ruler. In each wheel is attached a laser level, pointing to front duck tape. Several measurements are take for different steering position values and using trigonometric relations, the angles of each wheel is estimated.

The other calibration process is taken each time a power up is made. It consists in performing a full rotation of the steering wheel to each extreme points. During this movement, the program is always reading sensor position and updating the maximum and minimum value read. After these quadrature counter values are found, user is requested to end calibration and the offset are calculated and stored along with maximum and minimum position. These values will only change in case of shut down performed on steering controller device.

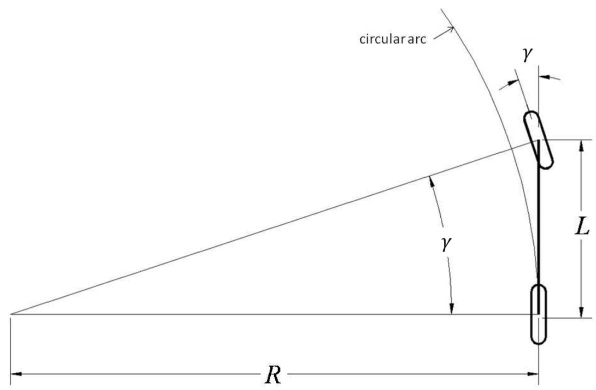
Taking figure 6.3 that represents the calibration set up made, the bold line between points max_L and max_R represent the our ruler. The $d1$ represent the distance between outer of each wheel where the lasers are attached. The relevant distances using in this step up are present in table 6.6.

Comparing figure 6.2 with figure 6.3 results in (6.1). Then is assumed that:

- γ must be a first order function.
- $\delta\gamma$ must be always great or equal to zero and therefore, quadratic.
- β and α should be, at least a second order function with opposite concavities orientation.



(a) Four wheel representation



(b) Bicycle Representation (source [37])

Figure 6.2: Ackermann steering model simplification

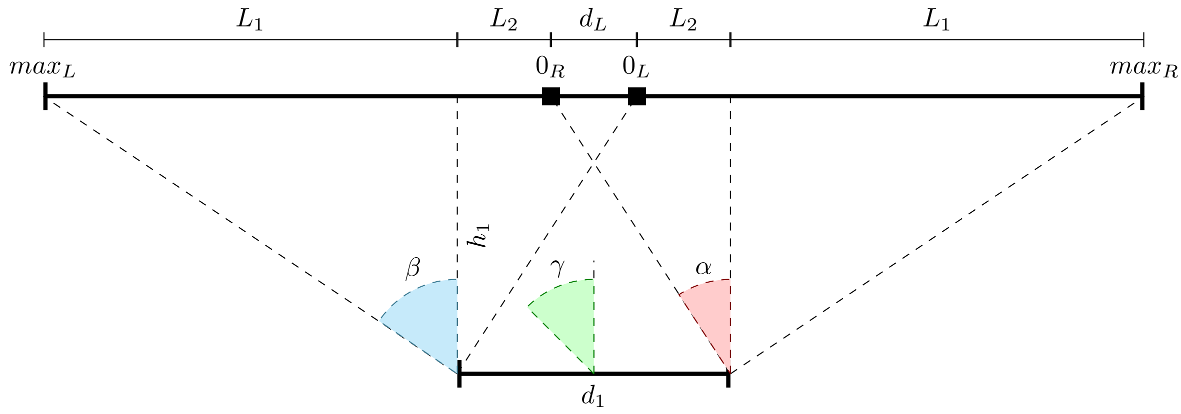


Figure 6.3: Calibration set up scheme

$$\begin{cases} \beta = \gamma + \delta\gamma \\ \alpha = \gamma - \delta\gamma \end{cases} \tag{6.1}$$

Taking several measurements for different values of quadrature counters, is calculated the respective values of α and β. After, for each of those pairs is calculated the estimated values of $\delta\gamma$ and γ. Using least squares approach (polyfit from Matlab®) is estimated the best fitting for each variable with respect to Quadrature counters (qc), assuming the discussed points above. The result of fitting is shown in figure 6.4. It shows the evaluated values of fitted functions in the range of -40000 to 40000 qc. Note the fact that zero value is slightly apart to the right. This is a normal consequence of small misalignment (approximate 1°) of wheels when the EPOS device is initialized, which is assumed the zero of it. This reflects the requirement to perform the full rotation to each side after device power up, to find the offset at origin.

The estimated ration between steering wheel qc and the fictional wheel of bicycle model is then $-7.5014E-04$, translating in the equation (6.2), where the offset is determined at each power up calibration step.

The Matlab™used for calibration is present in appendix E

$$f(qc) = -7.5014E-04 \times qc + offset \tag{6.2}$$

Description	**Measurement [cm]**
d_1	144.5
L_1	124
L_2	49.5
d_L	45.5
h_1	147
max_L	$L_1 + L_2 + d_L =$ 219
max_R	$L_1 + L_2 + d_L =$ 219

Table 6.6: Reference measurements for calibration set up scheme

6.4 interface library

The developed interface library for EPOS is present in the same Github repository. The library is made in python language and using the CAN interface to interact with EPOS. User should note that the library still not cover all the possible interactions and modes of operation of EPOS. It is only designed for position control mode. In the same repository are the firmware manual provided by Maxon and they should be consulted for further information. The respective documentation of the library is present on online version here and also as appendix B. User should always prefer the online documentation to grant is the most updated version.

6.5 Support and controller advices

⚠ **Caution!**

Since the sensor support is 3D printed, care must be taken to avoid abrupt variations of the steering wheel or the sensor gear might brake. User must also be careful to not apply achieve or surpass the extreme positions because it may cause damage to either the structure of car or the motor it self.

The EPOS contains built-in function that disables the operation if difference between the demanded position and current position grows or is higher beyond the predefined maximum following error parameter. These situation can be caused by a badly conditioned reference, if the motor is blocked or if the motor is not able to keep up with the rate of variation requested. A careful reference trajectory generation must be provided by user to avoid damage. During the testing of vehicle in field and development, a series of functions have been developed that can serve as inspiration for future implementations. They are presented in appendix **??** in the form of a Python class. It may serve as future inspiration for high

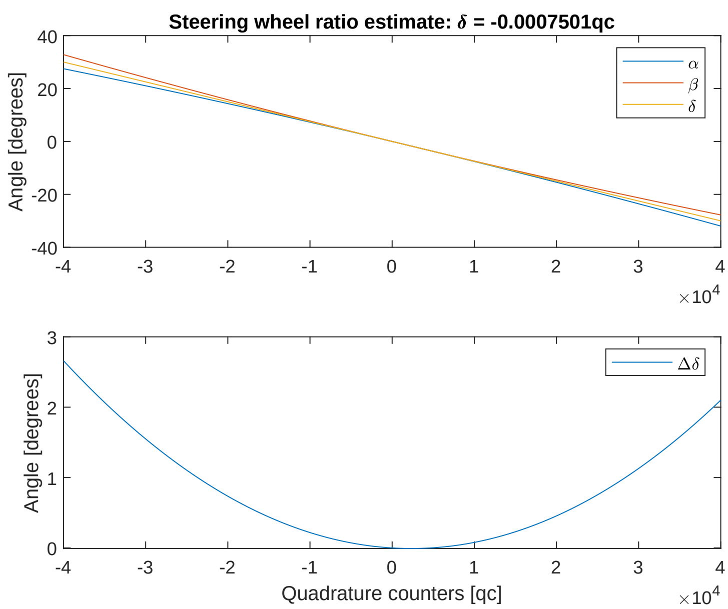


Figure 6.4: Results for Calibration of steering wheel

level design. It contains the following list of base functions:

getQcPosition

test

Chapter 7

Power Train controller

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

7.1 Motor data

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Motor Equivalent Circuit Parameters. (Data from inverter SIEMENS SINAMICS using STARTER. for other Data, check below in Annex). Motor Nameplate Data

Parameter	**Value**	**Units**
Weight	1200	kg
Batteries Weight	400	kg
Autonomy	90	km
Maximum speed	100	km/h
Acceleration (0-50km/h)	8	s
Wheel diameter	60.97	cm
Width	150.8	cm
Height	144.5	cm
Area	2.18	m^2
Drag Coefficient	0.33	-

Table 7.1: Original car parameters

Parameter	Value	Units
Maximum Power	30	kW
Maximum Torque	130	Nm
Maximum speed	10000	rpm
Weight	41.5	kg
Equivalent circuit parameters		
stator resistance	8.56	mOhms
stator leakage inductance	0.06292	mH
Iron Resistance	∞	mOhms
Mutual Inductance	1.0122	mH
rotor resistance	5.10	mOhms
rotor leakage inductance	0.06709	mH

Table 7.2: Motor parameters

U (V)	f (Hz)	I (A)	Torque (Nm)	Speed (rpm)
76	76	157	65	2200
121	220	90	22	6500
121	305	88	16	9000

Table 7.3: Motor Nameplate parameters

7.2 Siemens Sinamics

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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Appendix A

NovatelOEM4 GPS library Documentation

Date 24 Jul 2018

Version 0.4

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CHAPTER 1

Changelog

version 0.4 Moved from optoparse to argparse module. changed Queue to make it compatible with python3 queue. Backwards compatibility is maintained. Restructured default location. Moved from Lib folder to base path. Moved examples to proper folder. This cause backwards compatibility problems. On import, replace `import Lib.NovatelOEM4` with simply `import NovatelOEM4`

version 0.3 logging configuration as moved outside module to enable user to use already configured logging handler. Check multimodule logging docs

version 0.2 data from bestxyz message is now placed into a Queue.Queue() FIFO

version 0.1 initial release

This module contains a few functions to interact with Novatel OEM4 GPS devices. Currently only the most important functions and definitions are configured, but the intention is to make it as much complete as possible.

A simple example can be run by executing the main function wich creates a Gps class object and execute the following commands on gps receiver:

- **begin:** on default port or given port by argv[1].
- **sendUnlogall**
- **setCom(baud=115200):** changes baudrate to 115200bps
- **askLog(trigger=2,period=0.1):** ask for log *bestxyz* with trigger *ONTIME* and period *0.1*
- wait for 10 seconds
- **shutdown:** safely disconnects from gps receiver

Example:

```
$python NovatelOEM4.py
```

Contents:

1.1 Gps Class

class NovatelOEM4.**Gps**(*sensorName='GPS'*)

Novatel OEM4 GPS library class

This class contents is an approach to create a library for Novatel OEM 4 GPS

Parameters **sensorName** (*optional*) – A sensor name if used with multiple devices.

header_keys

all field keys for the headers of messages.

MessageID

A dictionary for the types of messages sent. Not all are implemented yet!

1.1.1 Methods

1.1.1.1 askLog

Gps.**askLog**(*logID='BESTXYZ'*, *port=192*, *trigger=4*, *period=0*, *offset=0*, *hold=0*)

Request a log from receiver.

Parameters

- **logID** – log type to request.
- **port** – port to report log.
- **trigger** – trigger identifier.
- **period** – the period of log.
- **offset** – offset in seconds after period.
- **hold** – mark log with hold flag or not.

Returns True or false if command was sucessfull or not.

The log request command is defined as:

Field	ID	N Bytes	Description
1	Com header	H = 28	Header of message
2	port	ENUM = 4	identification of port
3	message	Ushort = 2	Message ID of log to output
4	messageType	char = 1	Message type (Binary)
5	RESERVED	char = 1	
6	trigger	ENUM = 4	message trigger
7	period	double = 8	Log period (for ONTIME in secs)
8	offset	double = 8	Offset for period (ONTIME in secs
9	hold	ENUM = 4	Hold log
10	crc32	Ulong = 4	crc32 value

Note: Total byte size = header + 32 = 60 bytes

Log trigger Identifiers (field 6):

Binary	ASCII	Description
0	ONNEW	when the message is updated (not necessarily changed)
1	ONCHANGED	Current message and then continue to output when the message is changed
2	ONTIME	Output on a time interval
3	ONNEXT	Output only the next message
4	ONCE	Output only the current message
5	ONMARK	Output when a pulse is detected on the mark 1 input

1.1.1.2 begin

`Gps.begin`(*dataQueue*, *comPort='/dev/ttyUSB0'*, *baudRate=9600*)
Initializes the gps receiver.

This function resets the current port to factory default and setup the gps receiver to be able to acept new commands. If connection to gps is made, it launchs a thread used to parse messages comming from gps.

Parameters

- **comPort** – system port where receiver is connected.
- **dataQueue** – a Queue object to store incoming bestxyz messages.
- **baudRate** – baudrate to configure port. (should always be equal to factory default of receiver).

Returns True or False if the setup has gone as expected or not.

Example

```
Gps.begin(comPort="<port>",
    dataQueue=<your Queue obj>,
    baudRate=9600)
```

Default values

ComPort "/dev/ttyUSB0"

BaudRate 9600

> **Warning:** This class uses module `logging` wich must be configured in your main program using the `basicConfig` method. Check documentation of module logging for more info.

HW info:

Receptor Novatel Flexpak G2L-3151W.

Antenna Novatel Pinwheel.

1.1.1.3 create_header

`Gps.create_header`(*messageID*, *messageLength*, *portAddress=192*)

Creates a header object to be passed to receiver.

Parameters

- **messageID** – the corresponding value of identifying the message body.
- **messageLength** – size of message in bytes excluding CRC-32bit code.
- **portAddress** – port from where message request is sent.

Returns The header of message.

The header is defined as:

Field	Value	N Bytes	Description
1	sync[0]	UChar = 1	Hexadecimal 0xAA.
2	sync[1]	UChar = 1	Hexadecimal 0x44.
3	sync[2]	UChar = 1	Hexadecimal 0x12.
4	header-Length	UChar = 1	Length of the header (should always be 28 unless some firmware update)
5	messageID	UShort = 2	This is the Message ID code
6	mes-sageType	UChar = 1	message type mask (binary and original message)
7	portAd-dress	Uchar = 1	Corresponding value of port
8	message-Length	UShort = 2	Length of message body
9	sequence	UShort = 2	This is used for multiple related logs.
10	idleTime	UChar = 1	The time that the processor is idle in the last second between successive logs with the same Message ID
11	timeStatus	Enum = 1	Indicates the quality of the GPS time
12	week	UShort = 2	GPS week number.
13	ms	int = 4	Milliseconds from the beginning of the GPS week.
14	receiver-Status	Ulong = 4	32 bits representing the status of various hardware and software components of the receiver.
15	reserved	UShort = 2	
16	swVersion	UShort = 2	receiver software build number.

Note: portAddress=192 (equal to thisport)

1.1.1.4 getDebugMessage

`Gps.getDebugMessage(message)`

Create a string which contains all bytes represented as hex values

Auxiliary function for helping with debug. Receives a binary message as input and convert it as a string with the hexdecimal representation.

Parameters **`message`** – message to be represented.

Returns A string of corresponding hex representation of message.

1.1.1.5 parseResponces

`Gps.parseResponces()`

A thread to parse responses from device

1.1.1.6 reset

`Gps.reset(delay=0)`

Performs a hardware reset

Parameters **`delay`** – seconds to wait before resetting. Default to zero.

Returns A boolean if request was sucessful or not

The reset message is defined as:

Field	value	N Bytes	Description
1	header	H = 28	Header of message
2	delay	UL = 4	Seconds to wait before reset
CRC32		UL = 4	

Following a RESET command, the receiver initiates a coldstart boot up. Therefore, the receiver configuration reverts either to the factory default, if no user configuration was saved, or the last SAVECONFIG settings. The optional delay field is used to set the number of seconds the receiver is to wait before resetting.

1.1.1.7 saveconfig

`Gps.saveconfig()`

Save user current configuration

Returns A boolean if request was sucessful or not

Saveconfig message is defined as:

Field	value	N Bytes	Description
1	header	H = 28	Header of message
CRC32		UL = 4	

This command saves the user's present configuration in non-volatile memory. The configuration includes the current log settings, FIX settings, port configurations, and so on. Its output is in the RXCONFIG log.

1.1.1.8 sbascontrol

`Gps.`**`sbascontrol`**(*keywordID=1*, *systemID=1*, *prn=0*, *testmode=0*)

Set SBAS test mode and PRN SBAS

Parameters

- **`keywordID`** – True or false. Control the reception of SBAS corrections Enable = 1, Disable = 0.
- **`systemID`** – SBAS system to be used.
- **`prn`** – PRN corrections to be used.
- **`testmode`** – Interpretation of type 0 messages.

Returns A boolean if request was sucessful or not

sbascontrol message is defined as:

Field	value	N Bytes	Description
1	header	H = 28	Header of message
2	keyword	Enum = 4	Enable = 1 or Disable = 0
3	system	Enum = 4	Choose the SBAS the receiver will use
4	prn	UL = 4	0 - Receiver will use any PRN
			120~138 - Receiver will use SBAS only from this PRN
5	testmode	Enum = 4	Interpretation of type 0 messages
CRC32		UL = 4	

System (Field 2) is defined as:

Binary	ASCII	Description
0	NONE	Don't use any SBAS satellites.
1	AUTO	Automatically determinate satellite system to use (default).
2	ANY	Use any and all SBAS satellites found
3	WAAS	Use only WAAS satellites
4	EGNOS	Use only EGNOS satellites
5	MSAS	Use only MSAS satellites

Testmode (field 5) is defined as:

Binary	ASCII	Description
0	NONE	Interpret Type 0 messages as they are intended (as do not use).(default)
1	ZEROTOTWO	Interpret Type 0 messages as type 2 messages
2	IG-NOREZERO	Ignore the usual interpretation of Type 0 messages (as do not use) and continue

This command allows you to dictate how the receiver handles Satellite Based Augmentation System (SBAS) corrections and replaces the now obsolete WAASCORRECTION command. The receiver automatically switches to Pseudorange Differential (RTCM or RTCA) or RTK if the appropriate corrections are received, regardless of the current setting.

1.1.1.9 sendUnlogall

`Gps.sendUnlogall(port=8, held=1)`
Send command unlogall to gps device.

On sucess clears all logs on all ports even held logs.

Returns True or False if the request has gone as expected or not.

unlogall message is defined as:

Field	value	N Bytes	Description
1	header	H = 28	Header of message
2	port	ENUM = 4	identification of port
3	Held	ENUM = 4	can only be 0 or 1. Clear logs with hold flag or not?
CRC32		UL = 4	

Note: See: OEMStar Firmware Reference Manual Rev 6 page 161

1.1.1.10 setCom

`Gps.setCom(baud, port=6, parity=0, databits=8, stopbits=1, handshake=0, echo=0, breakCond=1)`
Set com configuration.

Parameters

- **baud** – communication baudrate.
- **port** – Novatel serial ports identifier (default 6 = "thisport").
- **parity** – byte parity check (default 0).
- **databits** – Number of data bits (default 8).
- **stopbits** – Number of stop bits (default 1).
- **handshake** – Handshaking (default No handshaking).
- **echo** – echo input back to user (default false)
- **breakCond** – Enable break detection (default true)

Returns True or false if command was sucessfull or not.

The com request command is defined as:

Field	ID	N Bytes	Description
1	Com header	H = 28	Header of message
2	port	ENUM = 4	identification of port
3	baud	Ulong = 4	Communication baud rate (bps)
4	parity	ENUM = 4	Parity
5	databits	Ulong = 4	Number of data bits (default = 8)
6	stopbits	Ulong = 4	Number of stop bits (default = 1)
7	handshake	ENUM = 4	Handshaking
8	echo	ENUM = 4	No echo (default)(must be 0 or 1)
9	break	ENUM = 4	Enable break detection (default 0) ,(must be 0 or 1)

Note: Total byte size = header + 32 = 60 bytes

COM Serial Port Identifiers (field 2):

Binary	ASCII	Description
1	COM1	COM port 1
2	COM2	COM port 2
6	THISPORT	The current COM port
8	ALL	All COM ports
9	XCOM1	Virtual COM1 port
10	XCOM2	Virtual COM2 port
13	USB1	USB port 1
14	USB2	USB port 2
15	USB3	USB port 3
17	XCOM3	Virtual COM3 port

Parity(field 4):

Binary	ASCII	Description
0	N	No parity (default)
1	E	Even parity
2	O	Odd parity

Handshaking (field 7):

Binary	ASCII	Description
0	N	No handshaking (default)
1	XON	XON/XOFF software handshaking
2	CTS	CTS/RTS hardware handshaking

Note: See: OEMStar Firmware Reference Manual Rev 6 page 56

1.1.1.11 setDynamics

`Gps.`**`setDynamics`**(*dynamicID*)

Set Dynamics of receiver.

Parameters **`dynamicID`** – identifier of the type of dynamic.

Returns True or False if the request has gone as expected or not.

dynamics message is defined as:

Field	value	N Bytes	Description
1	header	H = 28	Header of message
2	dynamics	ENUM = 4	identification of dynamics
CRC32		UL = 4	

The dynamics identifiers (field 2) are defined as:

Binary	ASCII	Description
0	AIR	Receiver is in an aircraft or a land vehicle, for example a high speed train, with velocity greater than 110 km/h (30 m/s). This is also the most suitable dynamic for a jittery vehicle at any speed.
1	LAND	Receiver is in a stable land vehicle with velocity less than 110 km/h (30 m/s).
2	FOOT	Receiver is being carried by a person with velocity less than 11 km/h (3 m/s).

This command adjusts the receiver dynamics to that of your environment. It is used to optimally tune receiver parameters. The DYNAMICS command adjusts the Tracking State transition time-out value of the receiver. When the receiver loses the position solution, it attempts to steer the tracking loops for fast reacquisition (5 s time-out by default). The DYNAMICS command allows you to adjust this time-out value, effectively increasing the steering time. The three states 0, 1, and 2 set the time-out to 5, 10, or 20 seconds respectively.

Note:

- The DYNAMICS command should only be used by advanced users of GPS. The default of AIR should not be changed except under very specific conditions.
- The DYNAMICS command affects satellite reacquisition. The constraint of the DYNAMICS filter with FOOT is very tight and is appropriate for a user on foot. A sudden tilted or up and down movement, for example while a tractor is moving slowly along a track, may trip the RTK filter to reset and cause the position to jump. AIR should be used in this case.

1.1.1.12 shutdown

`Gps.shutdown()`

Prepare for exiting program

Returns always returns true after all tasks are done.

Prepare for turn off the program by executing the following tasks:

- unlogall

- reset port settings
- close port

1.1.1.13 CRC32Value

`Gps.CRC32Value(i)`

Calculate the 32bits CRC of message.

See OEMStar Firmware Reference Manual Rev 6 page 24 for more information.

Parameters `i` – message to calculate the crc-32.

Returns The CRC value calculated over the input message.

Appendix B

Maxon EPOS CANopen Library Documentation

Date Sep 11, 2018

Version 0.1

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This documentation describes the class Epos developed in Python using CANopen to control the Maxon Motors EPOS 70/10 device.

CHAPTER 1

Epos Class description

class epos.**Epos**(*_network=None*, *debug=False*)

begin(*nodeID*, *_channel='can0'*, *_bustype='socketcan'*, *objectDictionary=None*)

Initialize Epos device

Configure and setup Epos device.

Parameters

- **nodeID** – Node ID of the device.
- **channel** (*optional*) – Port used for communication. Default can0
- **bustype** (*optional*) – Port type used. Default socketcan.
- **objectDictionary** (*optional*) – Name of EDS file, if any available.

Returns A boolean if all went ok.

Return type bool

changeEposState(*newState*)

Change EPOS state

Change Epos state using controlWord object

To change Epos state, a write to controlWord object is made. The bit change in controlWord is made as shown in the following table:

State	LowByte of Controlword [binary]
shutdown	0xxx x110
switch on	0xxx x111
disable voltage	0xxx xx0x
quick stop	0xxx x01x
disable operation	0xxx 0111
enable operation	0xxx 1111
fault reset	1xxx xxxx

see section 8.1.3 of firmware for more information

Parameters **`newState`** – string with state witch user want to switch.

Returns boolean if all went ok and no error was received.

Return type bool

`checkEposState`()

Check current state of Epos

Ask the StatusWord of EPOS and parse it to return the current state of EPOS.

State	ID	Statusword [binary]
Start	0	x0xx xxx0 x000 0000
Not Ready to Switch On	1	x0xx xxx1 x000 0000
Switch on disabled	2	x0xx xxx1 x100 0000
ready to switch on	3	x0xx xxx1 x010 0001
switched on	4	x0xx xxx1 x010 0011
refresh	5	x1xx xxx1 x010 0011
measure init	6	x1xx xxx1 x011 0011
operation enable	7	x0xx xxx1 x011 0111
quick stop active	8	x0xx xxx1 x001 0111
fault reaction active (disabled)	9	x0xx xxx1 x000 1111
fault reaction active (enabled)	10	x0xx xxx1 x001 1111
Fault	11	x0xx xxx1 x000 1000

see section 8.1.1 of firmware manual for more details.

Returns numeric identification of the state or -1 in case of fail.

Return type int

`loadConfig`()

Load all configurations

`logDebug`(*message=None*)

Log a message

A wrap around logging. The log message will have the following structure: [class name : function name] message

the function name will be the caller function retrieved automatically by using sys._getframe(1).f_code.co_name

Parameters **`message`** – a string with the message.

`logInfo`(*message=None*)

Log a message

A wrap around logging. The log message will have the following structure: [class name : function name] message

Parameters **`message`** – a string with the message.

`printControlWord`(*controlword=None*)

Print the meaning of controlword

Check the meaning of current controlword of device or check the meaning of your own controlword. Usefull to check your own controlword before actually sending it to device.

Parameters **`controlword`** (*`optional`*) – If None, request the controlword of device.

printCurrentControlParameters()
Print the current mode control PI gains

Request current mode control parameter gains from device and print.

printMotorConfig()
Print current motor config

Request current motor config and print it

printOpMode()
Print current operation mode

printPositionControlParameters()
Print position control mode parameters

Request device for the position control mode parameters and prints it.

printSensorConfig()
Print current sensor configuration

printSoftwarePosLimit()
Print current software position limits

readControlWord()
Read ControlWord

Request current controlword from device.

Returns

A tupple containing:

controlword the current controlword or None if any error.

Ok A boolean if all went ok.

Return type tupple

readCurrentControlParameters()
Read the PI gains used in current control mode

Returns

A tupple containing:

gains A dictionary with the current pGain and iGain

OK A boolean if all went as expected or not.

Return type tupple

readCurrentModeSetting()
Read current value setted

Asks EPOS for the current value setted in current control mode.

Returns

A tupple containing:

current value setted.

Ok a boolean if sucessfull or not.

Return type tupple

readCurrentValue()

Read current value

Returns

a tupple containing:

current current in mA.

Ok A boolean if all requests went ok or not.

Return type tupple

readCurrentValueAveraged()

Read current averaged value

Returns

a tupple containing:

current current averaged in mA.

Ok A boolean if all requests went ok or not.

Return type tupple

readFollowingError()

Returns the current following error

Read the current following error value which is the difference between atual value and desired value.

Returns

a tupple containing:

followingError value of actual following error.

OK A boolean if all requests went ok or not.

Return type tupple

readMaxFollowingError()

Read the Max following error

Read the max following error value which is the maximum allowed difference between atual value and desired value in modulus.

Returns

a tupple containing:

maxFollowingError value of max following error.

OK A boolean if all requests went ok or not.

Return type tupple

readMotorConfig()

Read motor configuration

Read the current motor configuration

Requests from EPOS the current motor type and motor data. The motorConfig is a dictionary containing the following information:

- **motorType** describes the type of motor.
- **currentLimit** - describes the maximum continuous current limit.

- **maxCurrentLimit** - describes the maximum allowed current limit. Usually is set as two times the continuous current limit.
- **polePairNumber** - describes the pole pair number of the rotor of the brushless DC motor.
- **maximumSpeed** - describes the maximum allowed speed in current mode.
- **thermalTimeConstant** - describes the thermal time constant of motor winding is used to calculate the time how long the maximal output current is allowed for the connected motor [100 ms].

If unable to request the configuration or unsucessfull, None and false is returned .

Returns

A tupple with:

motorConfig A structure with the current configuration of motor

OK A boolean if all went as expected or not.

Return type tupple

`readObject`(*index*, *subindex*)

Reads an object

Request a read from dictionary object referenced by index and subindex.

Parameters

- `index` – reference of dictionary object index
- `subindex` – reference of dictionary object subindex

Returns message returned by EPOS or empty if unsucessfull

Return type bytes

`readOpMode`()

Read current operation mode

Returns

A tupple containing:

opMode current opMode or None if request fails

Ok A boolean if sucessfull or not

Return type tupple

`readPositionControlParameters`()

Read position mode control parameters

Read position mode control PID gains and and feedfoward and acceleration values

Returns

A tupple containing:

posModeParameters a dictionary containg pGain, iGain, dGain, vFeed and aFeed.

OK A boolean if all went as expected or not.

Return type tupple

`readPositionModeSetting`()

Reads the setted desired Position

Ask Epos device for demand position object. If a correct request is made, the position is placed in answer. If not, an answer will be empty

Returns

A tupple containing:

position the demanded position value.

OK A boolean if all requests went ok or not.

Return type tupple

`readPositionValue()`

Read current position value

Returns

a tupple containing:

position current position in quadrature counts.

Ok A boolean if all requests went ok or not.

Return type tupple

`readPositionWindow()`

Read current position Window value.

Position window is the modulus threashold value in which the output is considerated to be achieved.

Returns

a tupple containing:

postionWindow current position window in quadrature counts.

Ok A boolean if all requests went ok or not.

Return type tupple

`readPositionWindowTime()`

Read current position Window time value.

Position window time is the minimum time in milliseconds in which the output must be inside the position window for the target is considerated to have been reached.

Returns

a tupple containing:

postionWindowTime current position window time in milliseconds.

Ok A boolean if all requests went ok or not.

Return type tupple

`readQuickStopDeceleration()`

Read the quick stop deceleration.

Read deceleration used in fault reaction state.

Returns

A tupple containing:

quickstopDeceleration The value of deceleration in rpm/s.

OK A boolean if all went as expected or not.

Return type tupple

readSensorConfig()

Read sensor configuration

Requests from EPOS the current sensor configuration. The sensorConfig is an struture containing the following information:

- sensorType - describes the type of sensor.
- pulseNumber - describes the number of pulses per revolution in one channel.
- sensorPolarity - describes the of each sensor.

If unable to request the configuration or unsucessfull, an empty structure is returned. Any error inside any field requests are marked with 'error'.

Returns

A tupple containing:

sensorConfig A dictionary with the current configuration of the sensor

OK A boolean if all went as expected or not.

Return type tupple

readSoftwarePosLimit()

Read the software position limit

Returns

A tupple containing:

limits a dictionary containing minPos and maxPos

OK A boolean if all went as expected or not.

Return type tupple

readStatusWord()

Read StatusWord

Request current statusword from device.

Returns

A tupple containing:

statusword the current statusword or None if any error.

Ok A boolean if all went ok.

Return type tupple

readVelocityModeSetting()

Reads the setted desired velocity

Asks EPOS for the desired velocity value in velocity control mode

Returns

A tupple containing:

velocity Value setted or None if any error.

Ok A boolean if sucessfull or not.

Return type tupple

readVelocityValue()

Read current velocity value

Returns

a tupple containing:

velocity current velocity in rpm.

Ok A boolean if all requests went ok or not.

Return type tupple

readVelocityValueAveraged()

Read current velocity averaged value

Returns

a tupple containing:

velocity current velocity in rpm.

Ok A boolean if all requests went ok or not.

Return type tupple

saveConfig()

Save all configurrations

setCurrentControlParameters(*pGain*, *iGain*)

Set the PI gains used in current control mode

Parameters

- **pGain** – Proportional gain.
- **iGain** – Integral gain.

Returns A boolean if all went as expected or not.

Return type bool

setCurrentModeSetting(*current*)

Set desired current

Set the value for desired current in current control mode

Parameters **current** – the value to be set [mA]

Returns a boolean if sucessfull or not

Return type bool

setMaxFollowingError(*maxFollowingError*)

Set the Max following error

The Max Following Error is the maximum permissible difference between demanded and actual position at any time of evaluation. It serves as a safety and motion-supervising feature. If the following error becomes too high, this is a sign of something going wrong. Either the drive cannot reach the required speed or it is even blocked.

Parameters **maxFollowingError** – The value of maximum following error.

Returns A boolean if all requests went ok or not.

Return type bool

setMotorConfig (*motorType*, *currentLimit*, *maximumSpeed*, *polePairNumber*)
Set motor configuration

Sets the configuration of the motor parameters. The valid motor type is:

motorType	value	Description
DC motor	1	brushed DC motor
Sinusoidal PM BL motor	10	EC motor sinus commutated
Trapezoidal PM BL motor	11	EC motor block commutated

The current limit is the current limit is the maximal permissible continuous current of the motor in mA. Minimum value is 0 and max is hardware dependent.

The output current limit is recommended to be 2 times the continuous current limit.

The pole pair number refers to the number of magnetic pole pairs (number of poles / 2) from rotor of a brushless DC motor.

The maximum speed is used to prevent mechanical destroys in current mode. It is possible to limit the velocity [rpm]

Thermal winding not changed, using default 40ms.

Parameters

- **motorType** – value of motor type. see table behind.
- **currentLimit** – max continuous current limit [mA].
- **maximumSpeed** – max allowed speed in current mode [rpm].
- **polePairNumber** – number of pole pairs for brushless DC motors.

Returns A boolean if all requests went ok or not.

Return type bool

setOpMode (*opMode*)
Set Operation mode

Sets the operation mode of Epos. OpMode is described as:

OpMode	Description
6	Homing Mode
3	Profile Velocity Mode
1	Profile Position Mode
-1	Position Mode
-2	Velocity Mode
-3	Current Mode
-4	Diagnostic Mode
-5	MasterEncoder Mode
-6	Step/Direction Mode

Parameters **opMode** – the desired opMode.

Returns A boolean if all requests went ok or not.

Return type bool

setPositionControlParameters(*pGain*, *iGain*, *dGain*, *vFeed=0*, *aFeed=0*)
Set position mode control parameters

Set position control PID gains and feedfoward velocity and acceleration values.

Feedback and Feed Forward

PID feedback amplification

PID stands for Proportional, Integral and Derivative control parameters. They describe how the error signal e is amplified in order to produce an appropriate correction. The goal is to reduce this error, i.e. the deviation between the set (or demand) value and the measured (or actual) value. Low values of control parameters will usually result in a sluggish control behavior. High values will lead to a stiffer control with the risk of overshoot and at too high an amplification, the system may start oscillating.

Feed-forward

With the PID algorithms, corrective action only occurs if there is a deviation between the set and actual values. For positioning systems, this means that there always is â€“ in fact, there has to be a position error while in motion. This is called following error. The objective of the feedforward control is to minimize this following error by taking into account the set value changes in advance. Energy is provided in an open-loop controller set-up to compensate friction and for the purpose of mass inertia acceleration. Generally, there are two parameters available in feed-forward. They have to be determined for the specific application and motion task:

- Speed feed-forward gain: This component is multiplied by the demanded speed and compensates for speed-proportional friction.
- Acceleration feed-forward correction: This component is related to the mass inertia of the system and provides sufficient current to accelerate this inertia.

Incorporating the feed forward features reduces the average following error when accelerating and decelerating. By combining a feed-forward control and PID, the PID controller only has to correct the residual error remaining after feed-forward, thereby improving the system response and allowing very stiff control behavior.

According to Position Regulation with Feed Forward the acceleration and velocity feed forward take effect in Profile Position Mode and Homing Mode. There is no influence to all the other operation modes like Position Mode, Profile Velocity Mode, Velocity Mode and Current Mode

Parameters

- **pGain** – Proportional gain value
- **iGain** – Integral gain value
- **dGain** – Derivative gain value
- **vFeed** – velocity feed foward gain value. Default to 0
- **aFeed** – acceleration feed foward gain value. Default to 0

Returns A boolean if all requests went ok or not

Return type OK

setPositionModeSetting(*position*)
Sets the desired Position

Ask Epos device to define position mode setting object.

Returns A boolean if all requests went ok or not.

Return type bool

`setPositionWindow` (*positionWindow*)
Set position Window value

Position window is the modulos threashold value in which the output is considerated to be achieved.

Parameters **`positionWindow`** – position window in quadrature counts

Returns A boolean if all requests went ok or not.

Return type bool

`setPositionWindowTime` (*positionWindowTime*)
Set position Window Time value

Position window time is the minimum time in milliseconds in which the output must be inside the position window for the target is considerated to have been reached.

Parameters **`positionWindowTime`** – position window time in milliseconds.

Returns A boolean if all requests went ok or not.

Return type bool

`setQuickStopDeceleration` (*quickstopDeceleration*)
Set the quick stop deceleration.

The quick stop deceleration defines the deceleration during a fault reaction.

Parameters **`quicstopDeceleration`** – the value of deceleration in rpm/s

Returns A boolean if all went as expected or not.

Return type bool

`setSensorConfig` (*pulseNumber*, *sensorType*, *sensorPolarity*)
Change sensor configuration

Change the sensor configuration of motor. **Only possible if in disable state** The encoder pulse number should be set to number of counts per revolution of the connected incremental encoder. range : [16 - 7500]

sensor type is described as:

value	description
1	Incremental Encoder with index (3-channel)
2	Incremental Encoder without index (2-channel)
3	Hall Sensors (Remark: consider worse resolution)

sensor polarity is set by setting the corresponding bit from the word:

Bit	description
15-2	Reserved (0)
1	Hall sensors polarity 0: normal / 1: inverted
0	Encoder polarity 0: normal 1: inverted (or encoder mounted on motor shaft side)

Parameters

- **`pulseNumber`** – Number of pulses per revolution.

- **sensorType** – 1,2 or 3 according to the previous table.
- **sensorPolarity** – a value between 0 and 3 describing the polarity of sensors as stated before.

Returns A boolean if all went as expected or not.

Return type bool

setSoftwarePosLimit (*minPos*, *maxPos*)

Set the software position limits

Use encoder readings as limit position for extremes range = [-2147483648 | 2147483647]

Parameters

- **minPos** – minimum possition limit
- **maxPos** – maximum possition limit

Returns A boolean if all went as expected or not.

Return type bool

setVelocityModeSetting (*velocity*)

Set desired velocity

Set the value for desired velocity in velocity control mode.

Parameters **velocity** – value to be setted.

Returns a boolean if sucessfull or not.

Return type bool

writeControlWord (*controlword*)

Send controlword to device

Parameters **controlword** – word to be sent.

Returns a boolean if all went ok.

Return type bool

writeObject (*index*, *subindex*, *data*)

Write an object

Request a write to dictionary object referenced by index and subindex.

Parameters

- **index** – reference of dictionary object index
- **subindex** – reference of dictionary object subindex
- **data** – data to be stored

Returns boolean if all went ok or not

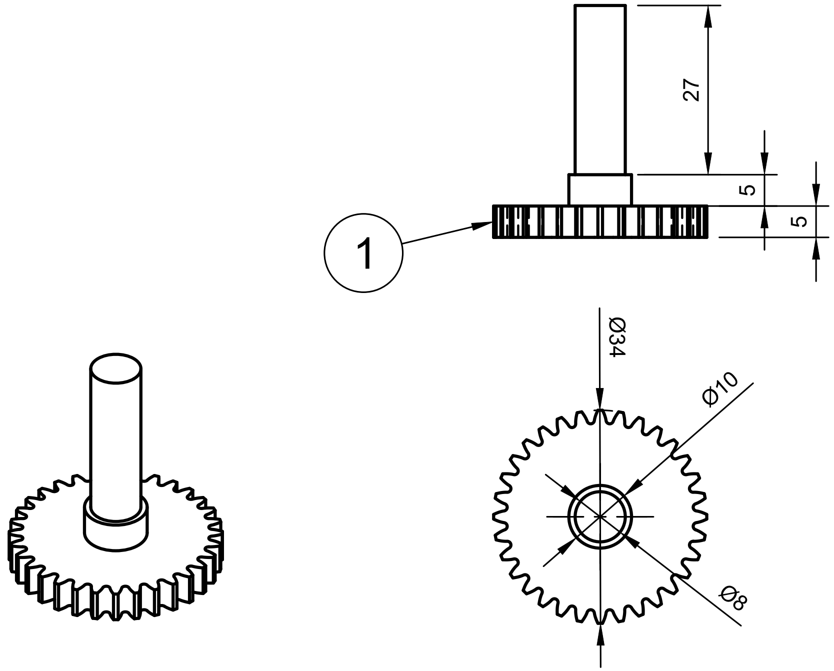
Return type bool

Appendix C

Sensor support Drawings

C.1 Sensor gear 32 teeth

Parts List				
Item	Qty	Part Number	Description	Material
1	1	Sensor gear (32 teeth) 1mm module	Spur Gear; Module: 1.0; Num Teeth: 32; Pressure Angle: 20.0; Backlash: 0.00 mm	ABS Plastic



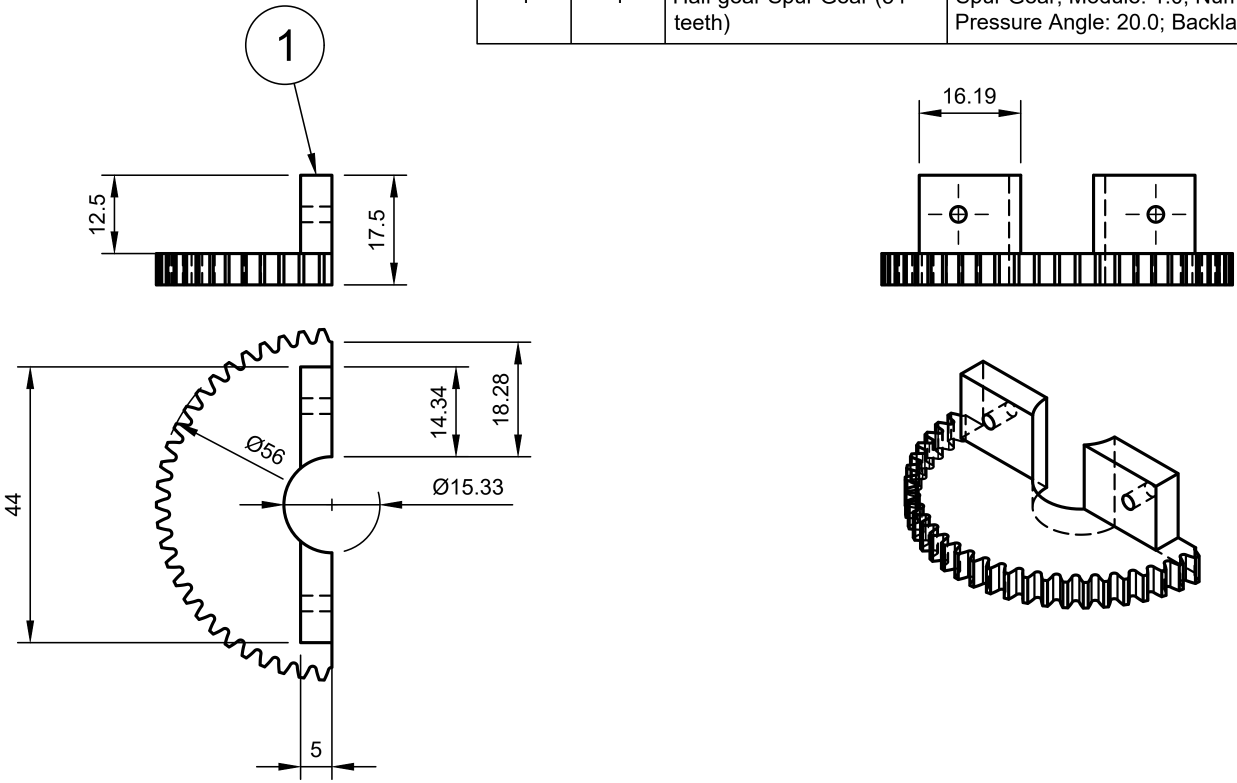
Dept.	Technical reference	Created by Bruno Tibério 13/08/2018	Approved by
		Document type	Document status
		Title sensor gear (32 teeth) 1mm module	DWG No.
			Rev. / Date of issue / Sheet 1/1

C.2

C.2 Half gear 54 teeth

Parts List

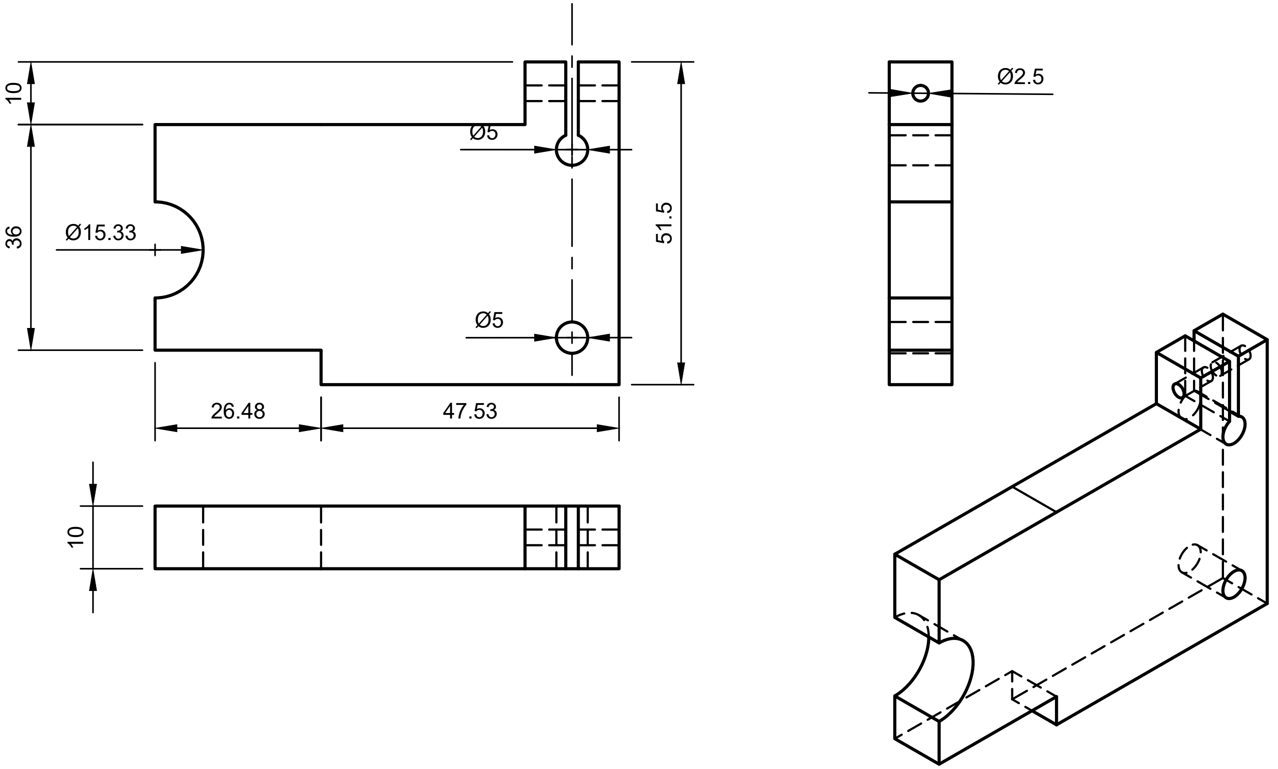
Item	Qty	Part Number	Description	Material
1	1	Half gear Spur Gear (54 teeth)	Spur Gear; Module: 1.0; Num Teeth: 54; Pressure Angle: 20.0; Backlash: 0.00 mm	ABS Plastic



Dept.	Technical reference	Created by Bruno Tibério 13/08/2018	Approved by
		Document type	Document status
		Title: half gear Spur Gear (54 teeth)	DWG No.
			Rev. / Date of issue / Sheet 1/1

C.3

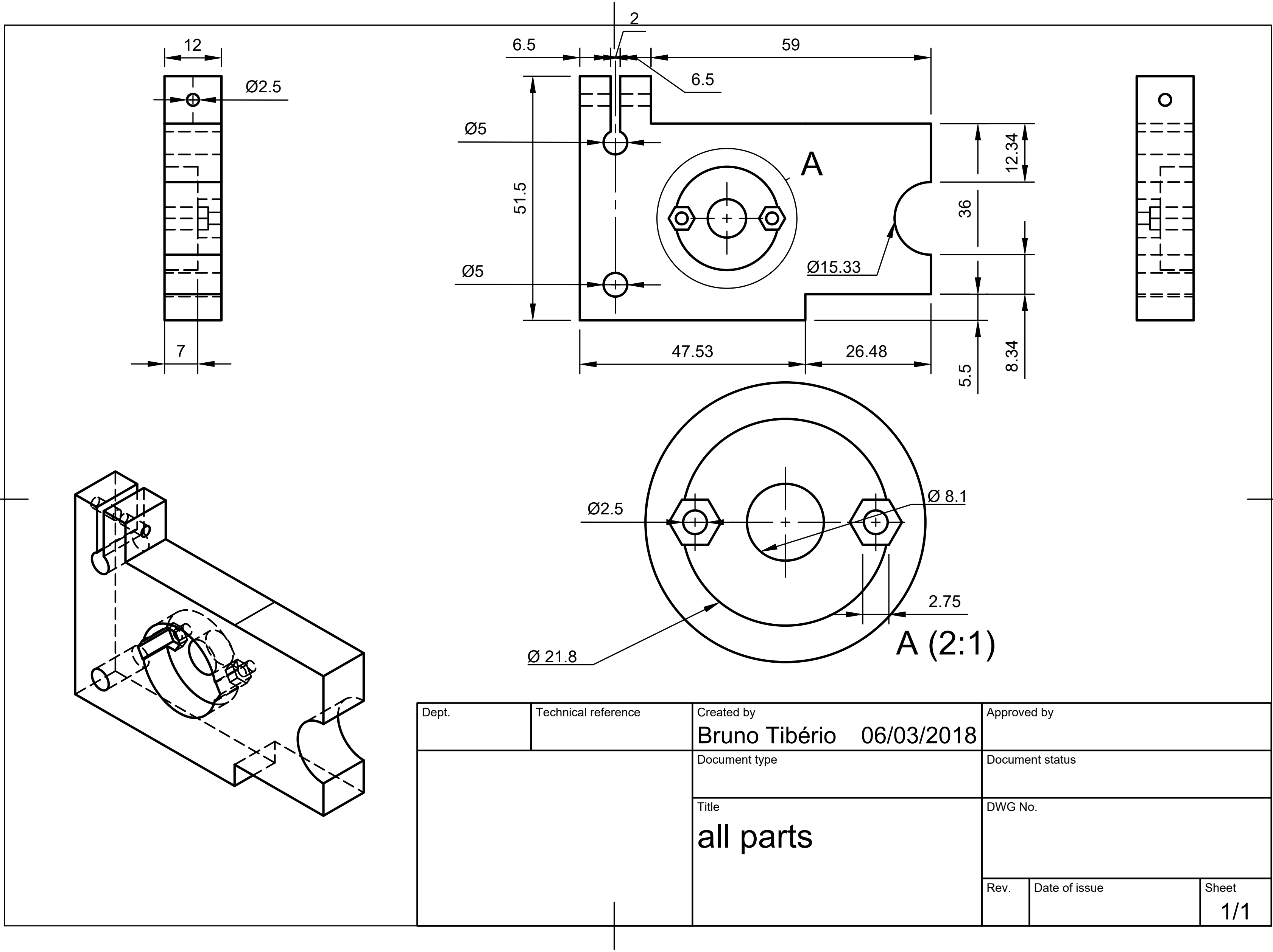
C.3 Sensor back spacer



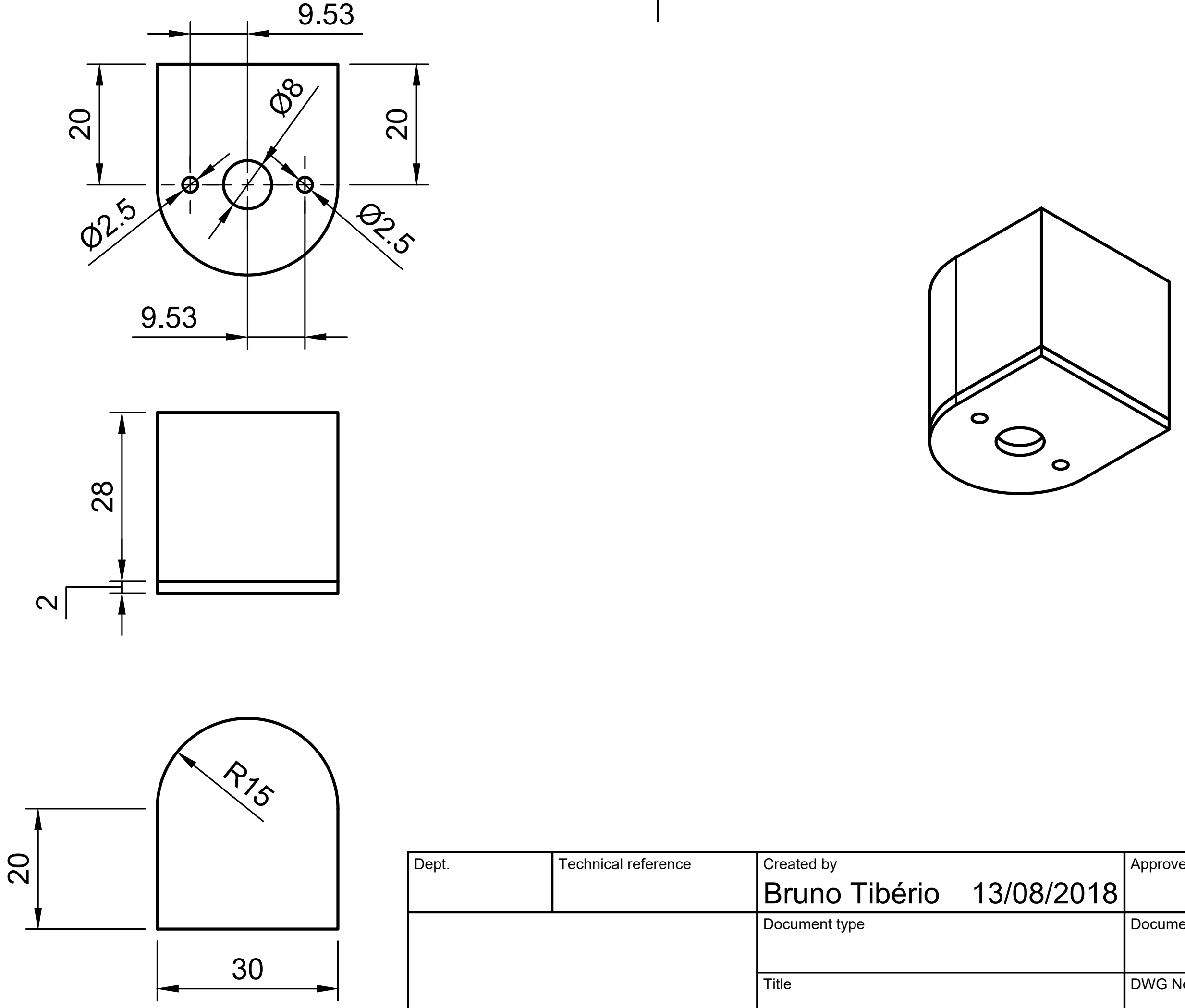
Dept.	Technical reference	Created by Bruno Tibério 06/03/2018	Approved by
		Document type	Document status
		Title HEDR 55xx support Sensor back	DWG No. 1
			Rev. 1 / Date of issue / Sheet 1/1

C.4

C.4 Sensor bearing holder



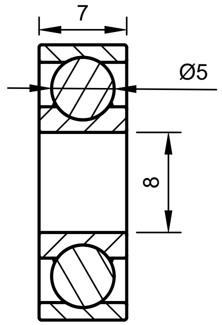
C.5 Sensor case

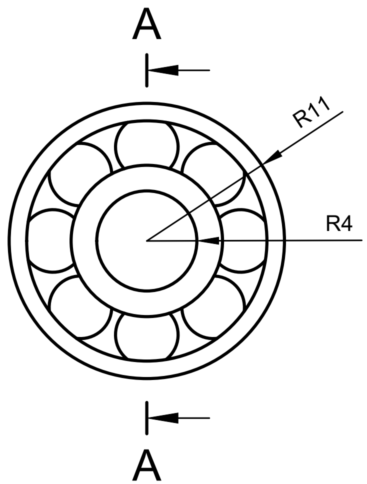


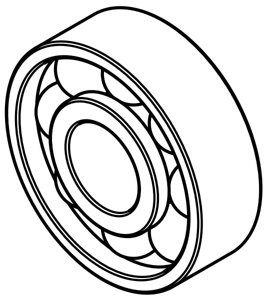
Dept.	Technical reference	Created by	Approved by
		Bruno Tibério 13/08/2018	
		Document type	Document status
		Title: sensor	DWG No.
			Rev. / Date of issue / Sheet: 1/1

Parts List				
Item	Qty	Part Number	Description	Material
1	1	Bearing 608zz		Steel

A-A (2:1)



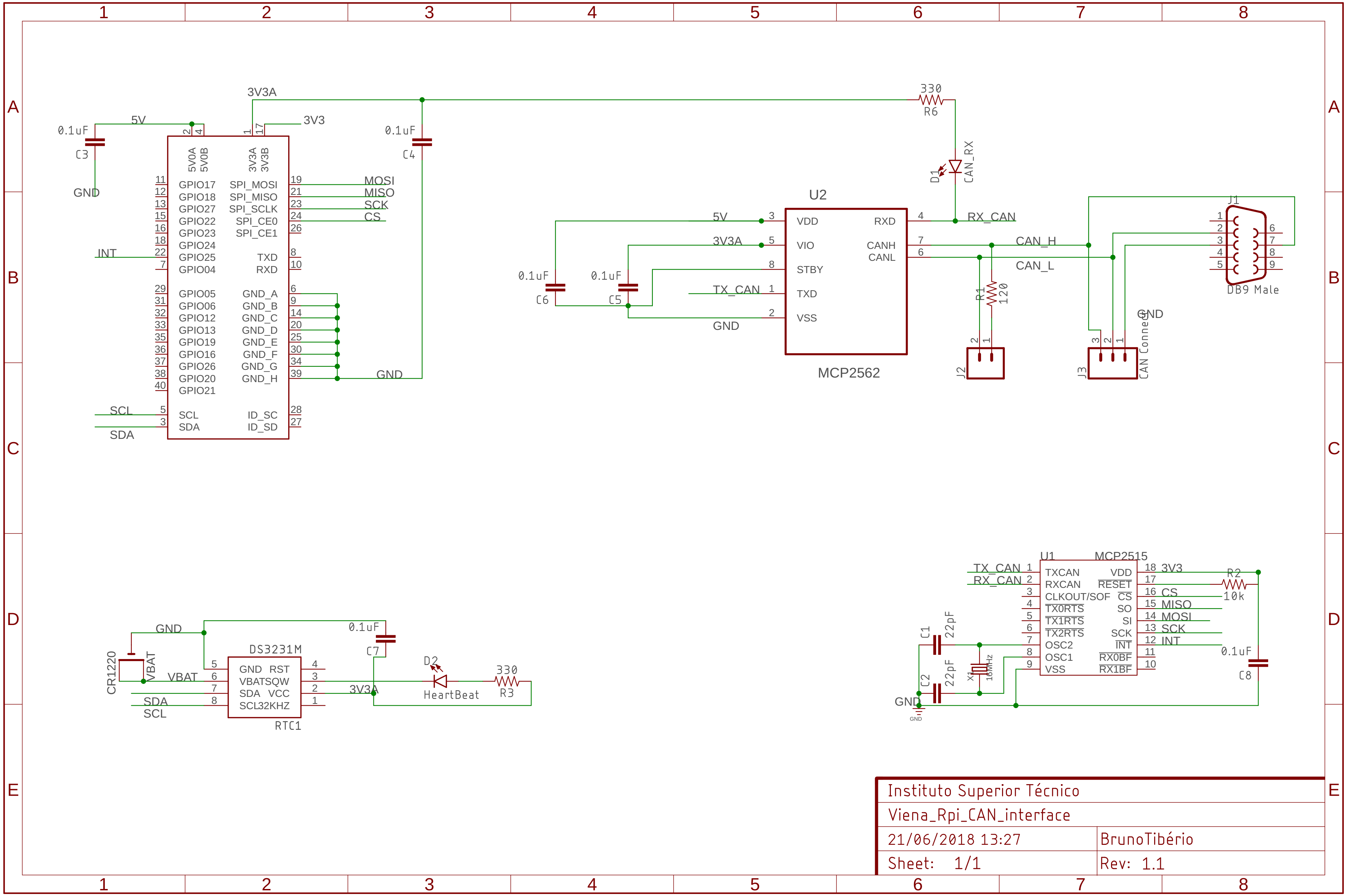




Dept.	Technical reference	Created by	Approved by
		Bruno Tibério 26/09/2018	
		Document type	Document status
		Title bearing 608zz	DWG No.
			Rev. / Date of issue / Sheet 1/1

Appendix D

Development CAN board schematics


3V3A
5V
3V3
0.1uF
C3
C4
GND
INT
SCL
SDA
MOSI
MISO
SCK
CS
5V0A
5V0B
3V3A
3V3B
GPIO17 SPI_MOSI
GPIO18 SPI_MISO
GPIO27 SPI_SCLK
GPIO22 SPI_CE0
GPIO23 SPI_CE1
GPIO24
GPIO25 TXD
GPIO04 RXD
GPIO05 GND_A
GPIO06 GND_B
GPIO12 GND_C
GPIO13 GND_D
GPIO19 GND_E
GPIO16 GND_F
GPIO26 GND_G
GPIO20 GND_H
GPIO21
SCL ID_SC
SDA ID_SD
330
R6
D1
CAN_RX
U2
MCP2562
VDD RXD
VIO CANH
STBY CANL
TXD
VSS
RX_CAN
TX_CAN
CAN_H
CAN_L
C6
C5
R1
120
J2
J3
CAN Connect
J1
DB9 Male
U1
MCP2515
TXCAN VDD
RXCAN RESET
CLKOUT/SOF CS
TX0RTS SO
TX1RTS SI
TX2RTS SCK
OSC2 INT
OSC1 RX0BF
VSS RX1BF
R2
10k
C8
C1
C2
22pF
X1
16MHz
DS3231M
GND RST
VBATSQW
SDA VCC
SCL32KHZ
RTC1
CR1220
VBAT
C7
D2
HeartBeat
R3
Instituto Superior Técnico
Viena_Rpi_CAN_interface
21/06/2018 13:27
BrunoTibério
Sheet: 1/1
Rev: 1.1

Appendix E

Calibration script

```
function find_calibration_parameters()
    %----------------------------------------------------------------------
    % Constants
    %----------------------------------------------------------------------
    % readings at 0 qc.
    % Since it has different values, it means when the EPOS was turned on,
    % the visually estimated position for wheels with zero angle has a
    % small offset. In this case should be near atan2d(0.5*0.05, 1.47) ~ 1
    % degree
    steeringWheelZero=0.01*[92.5, 97.5];
    % dL is distance from OR and OL with steering wheel at center position.
    % qc should be near zero.
    dL = 0.01*45.5;
    % d1 is distance between attached laser position in the outside wheel
    % face
    d1 = 1.445;
    % d0 is distance between center or wheels. Shaft distance.
    d0 = 1.40;
    % h1 is distance from wheel front axis to the "rule" of readings.
    h1 = 1.47;
    % maxR and maxL is maximum distance achievable from poit OR and OL
    % respectivly
    maxR = 2.19;
    maxL = 2.19;
    maxRange = maxR+maxL-dL;

    L1 = 0.5*(maxRange -d1);
    L2 = 0.5*(d1-dL);
    %----------------------------------------------------------------------
```

```
% kept for future improvements!
%-----------------------------------------------------------------------
%    %marked positions of left wheel starting from 0_L to the left side
%    distL =0.01*(0:20:200);
%    % readings of encoder
%    qcL = [47602, 40267, 30764, 20356, 9374, -1643, -11968, -21040,...
%           -29419, -36495, -41506];
%-----------------------------------------------------------------------
% readings right wheel starting from 0_R to the right side
distR =0.01*(0:20:200);
qcR = [ -45178, -37680, -28428, -18063, -6735, 4388, 15110, 24331, ...
    32335, 39414, 44218];
% readings of left wheel from 0L to the left, placing the steering
% wheel in the same quadrature counters as best as possible
distL=[219, 184.5, 158, 133.5, 111, 91, 71.8, 53.8, 37.8, 23, 10];

%-----------------------------------------------------------------------
% Data correction to fit 0 with steering wheel aligned
%-----------------------------------------------------------------------
% adjust measures so \beta = 0 gives a reading of 0 distance.
%distL = distL-(dL+L2);
distL = 0.01*distL-(dL+L2);
% make positive to left side and
% adjust measures so \beta = 0 gives a reading of 0 distance.
distR = -1*(distR-(dL+L2));
%-----------------------------------------------------------------------
% calculate all angles
%-----------------------------------------------------------------------
betaL = zeros(1,length(distL));
alphaR = betaL;
dirac = alphaR;
deltaDirac = dirac;
for I =1: length(distL)
    % betaL(I) = atan2d(distL(I), 1.47);
    betaL(I) = atan2d(distL(I),1.47);
    alphaR(I) = atan2d(distR(I), 1.47);
    dirac(I) = 0.5*(betaL(I)+alphaR(I));
    deltaDirac(I) = 0.5*(betaL(I)-alphaR(I));
end
%-----------------------------------------------------------------------
% plot figures
%-----------------------------------------------------------------------
```

```
    figure();
    plot(qcR,distL,qcR,distR);
    legend('Dist_L','Dist_R');
    ylabel('distance [m]');
    xlabel('Steering wheel position [qc]');

    figure();
    plot(qcR, alphaR, qcR, betaL, qcR, dirac, qcR, deltaDirac);
    xlabel('Steering wheel position [qc]');
    ylabel('angles [degrees]');
    hold on;
    line([qcR(1) qcR(end)],[0, 0],'color', 'red','LineStyle','--');
    limMax = max(max(alphaR),max(betaL));
    limMin = min(min(alphaR),min(betaL));
    line([qcR(1)+0.5*(qcR(end)-qcR(1)) qcR(1)+0.5*(qcR(end)-qcR(1))],...
        [limMin limMax],'color','red','lineStyle','--');
    legend('\alpha_R','\beta_L', '\delta','\Delta\delta','0');

    % change format to show small values in cmd window
    format short e;
    %--------------------------------------------------------------------
    % polyfit of alpha, beta, dirac, deltaDirac
    %--------------------------------------------------------------------
    % alpha and beta must have oposite concavities

    [pAlpha, sAlpha] = polyfit(qcR, alphaR, 2);
    fprintf('Polyfit for alpha:');
    display(pAlpha);
    fprintf('Norm of the residuals:%.4g\n', sAlpha.normr)
    [pBeta, sBeta]  = polyfit(qcR, betaL, 2);
    fprintf('Polyfit for beta:');
    display(pBeta);
    fprintf('Norm of the residuals:%.4g\n', sBeta.normr)
    % delta must be concave up always.
    [pDirac, sDirac] = polyfit(qcR, dirac, 1);
    fprintf('Polyfit for dirac:');
    display(pDirac);
    fprintf('Norm of the residuals:%.4g\n', sDirac.normr)
    [pDelta, sDelta] = polyfit(qcR, deltaDirac, 2);
    fprintf('Polyfit for delta:');
    display(pDelta);
    fprintf('Norm of the residuals:%.4g\n', sDelta.normr)
```

```
    % reset format
    format;
    %----------------------------------------------------------------------
    % evaluate polyfits for range -40000 to 40000
    %----------------------------------------------------------------------
    qc = -40000:100:40000;
    % set zero offset in each polyfit
    % The values for alpha = beta = dirac = deltaDirac must be all zero por
    % a perfect zero alignemt of the steering wheels. This does not happen
    % because the wheels at qc = 0 had a small misalignment.
    pAlpha(end) = 0;
    pBeta(end) = 0;
    pDirac(end) = 0;
    pDelta(end) = 0;
    alpha = polyval(pAlpha, qc);
    beta = polyval(pBeta, qc);
    dirac2 = polyval(pDirac, qc);
    delta = polyval(pDelta, qc);
    figure();
    subplot(2,1,1);
    plot(qc, alpha, qc, beta, qc, dirac2);
    % xlabel('Quadrature counters [qc]');
    ylabel('Angle [degrees]');

    title(['Steering wheel ratio estimate: \delta = ',...
        sprintf('%.4g', pDirac(1)),'qc']);
    legend('\alpha','\beta', '\delta');
    subplot(2,1,2);
    plot(qc, delta);
    xlabel('Quadrature counters [qc]');
    ylabel('Angle [degrees]');
    legend('\Delta\delta');
end
```

appendix/find_calibration_parameters.m