How To Sigi

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1 Introduction

The Sigi is a robot from Pololu(the Balboa 32U4 board) combined with a Raspberry Pi. It is a segway-based robot(inverted pendulum on wheels), so it has two parallel wheels. It is an unstable system, so it is interesting to try the stability of different controllers.

This document is a guide to how to use the Sigi robot. It attempts to be a comprehensive guide to the robot, from the hardware to the software, including various useful resources for understanding the operation of all different parts of the system. It will also include some info on problems caused by the current design of the system and, when possible, details on how to fix them.

If detailed documentation is needed, the Sigi2.0: Documentation is quite complete on anything related to hardware.

2 Hardware

2.1 Different parts overview

2.1.1 Balboa 32U4

The Balboa 32U4 is the main board of the robot. It can be programmed like an Arduino board using the Arduino IDE for example, by plugging the board to a computer using its micro-USB interface. It has a lot of components, but the most important are:

- The two motor drivers, which are used to control the two motors of the robot.
- The IMU, which is used to measure the angle of the robot.
- The encoders, which are used to measure the speed of the motors.

Other notable components are:

- The buzzer, which can be used to make sounds.
- The buttons, which can be used to interact with the robot.

- The LEDs, which can be used to show information to the user.
- The battery monitor, which can be used to measure the battery level.
- The communication interfaces and GPIOs, which can be used to connect the board to other devices.
- A reset button on the side of the board.

2.1.2 Raspberry Pi3B+

The Raspberry Pi are a series of small single-board computers. The Raspberry Pi 3B+ is the one used in the Sigi robot. It is used to run the high-level software of the robot.

The Pi 3B+ in particular features a wi-fi interface which can be used to connect to the robot remotely.

2.2 Sigi power management

The Sigi is intended to be used with cells, but can also be powered by its micro-USB interface, with an USB power bank for example. But the micro-USB interface is not fed into the motors, so a jumper wire has been installed on the Sigi bypass the battery regulator and feed the motors with the micro-USB power when connected. This jumper is located between the VSW and the 5V pins near the micro USB port of the Balboa board.

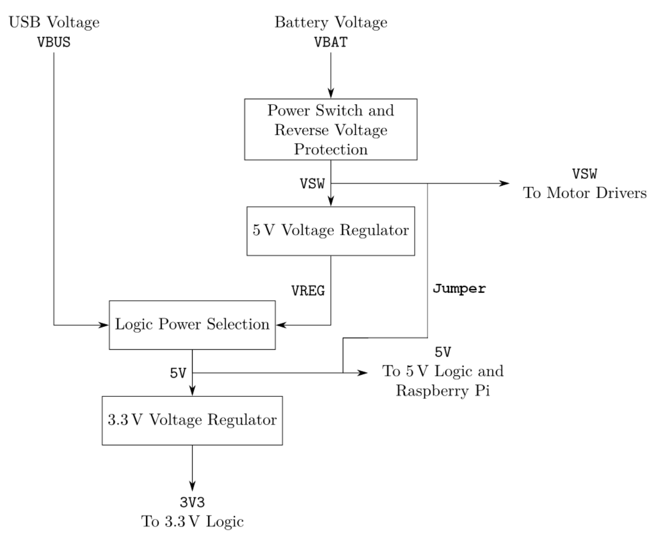


Figure 1: The jumper wire on the Sigi robot voltage lines.

This is fine most of the time, but it can occasionally cause problems. If the current drawn by the system is too high(high speed change in the motors+heavy computations on the Raspberry Pi), the voltage of the 5V logic will drop, causing resets of the Balboa board. Fortunately this reset stops the motors, so the voltage will rise again, so the Raspberry Pi, requiring less voltage, won't reboot. But since the Balboa board resets, the encoders will reset, which may cause the robot to lose its position if it was not saved by the Raspberry Pi.

One solution could be using a battery, but the jumper prevents the battery's voltage from being too high, since it is connected to the 5V logic and the Raspberry Pi. Experimentally, the max voltage was measured around 7.5V, but it was already causing consumption and heating problems on the regulator. In normal conditions, the voltage should be capped at 7V for safer operation. This also implies a minimal voltage. In fact, the voltage protection removes approximately 10% of the voltage, so in order to achieve the 5V logic, the voltage should be at least 5.5V. Some problems have been observed at 5.5V, but their exact cause is unknown. It could be the voltage regulator not having enough power when the motors are running for example. So the optimal voltage of a battery should be between 6 and 7V. A higher voltage battery with a voltage regulator would also be ok.

*note: insert power diagram

Removing the jumper would help if using a battery, but of course it would prevent to go back to using an USB power bank without soldering the jumper back.

Side note: It is what I have done with my Sigi(14), and I alternate between the battery and the USB power for tests and operation.

Another solution could be to use another Raspberry Pi with less current consumption. For example, a Pi Zero W has almost the same wireless capabilities, but consumes less power. However, the computational power is also reduced, so it may not be enough for some applications.

3 Software

The current design of the Sigi is like this:

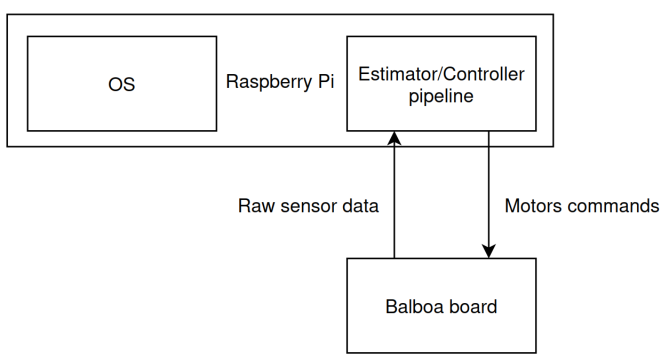


Figure 2: Software overview

The Balboa 32U4 is only used to get the raw sensor data, and the controller is running on the Raspberry Pi. The Balboa board could also be used to run the controller, but using the Raspberry Pi allows for more complex computations and easier debugging. The possibility of using the Python language is also a plus, see 3.3 for more details.

3.1 Interface between the Raspberry Pi and the Balboa board

Communication between the Raspberry Pi and the Balboa board is needed for multiple purposes that cannot be done directly with the Raspberry Pi :

- Reading the state of the robot from the sensors
- Sending commands to the motors, LEDs or other actuators

The communication is done via the I2C interface. Other communication media could possibly be used, but have not been documented by Pololu, using an USB or UART interface for example. The current protocol used is actually a variant of the I2C protocol, the SMBUS protocol. The Raspberry Pi is the master and the Balboa board is a slave. The IMU is also a slave, since it is accessed directly by the Raspberry Pi without going through the Balboa board's micro controller.

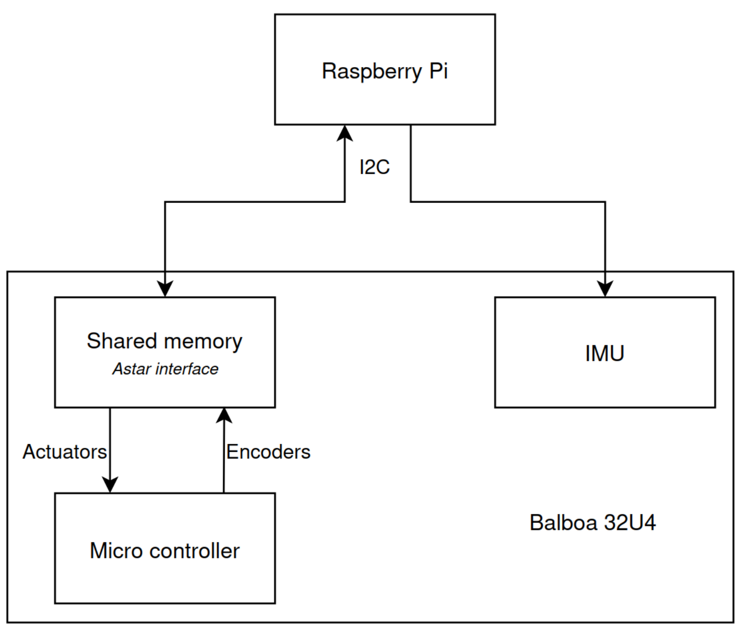


Figure 2: I2C diagram of the Balboa/Pi interface

3.1.1 Balboa board

The Balboa board's micro-controller has to read the shared memory(note: it is called a buffer in the code but it is technically not one) to know the orders from the Raspberry Pi, and update its right fields so that the encoders ticks can be read from the Raspberry Pi. The default example code from Pololu handles these tasks quite well. A notable possible improvement could be improving it to read the last saved value on the buffer after resets to recover more efficiently. It could also be possible to write more information in the buffer, like debugging information.

The default example code can be found in the Pololu's GitHub repository. It can easily be flashed on the Balboa board using the Arduino IDE.

3.1.2 Raspberry Pi

The Raspberry Pi has to access the shared memory to read the encoders ticks and write the orders. The best way to do it is simply using the Raspberry Pi's I2C interface.

Pololu recommends using their Python library to communicate with the Balboa board. It can be found in their Github as well as the example code.

It is possible to use the I2C interface directly, but it is more complicated and error-prone. The exact addresses to read and write are documented here: Sigi2.0: Documentation.

3.2 Operating System of the Raspberry Pi

Since the Raspberry Pi only has to use its I2C interface to communicate with the Balboa board, any OS that supports I2C can be used.

The two main possibilities are the Raspberry Pi OS, a Linux-based OS very similar to Ubuntu (it is derived from Debian), and the Matlab OS form Mathworks.

The Matlab OS would have been very interesting since it allows to run Matlab/Simulink models in real time, but its I2C interface seems to be broken. The previous students have demonstrated that every time the Matlab OS tried to read a value from the shared memory, using the I2C functions of the matlab OS, it started by setting the values of the whole memory array(next 8 addresses) to full 1. This typically caused the robot to start playing the Fugue every time an attempt to read the encoders was made, and would read false values (full 1). This bug could maybe be fixed, but since the matlab OS doesn't let full control over the system, it could be hard and would certainly require a lot of time.

So for now, the Raspberry Pi OS is the best choice. See the section 4 for details on how to install it.

3.3 Programming language

It is possible to use almost any language on the Raspberry Pi, but Matlab would be really hard to install because they do not support ARM processors, and the

RAM of the Pi is way too low (see Matlab on Linux requirements).

Python seems to be the optimal choice, because it has a great support for Raspberry Pi. It is also a great language for prototyping, and it is easy to use. However, it is not the fastest language, it is interpreted, and has an irregular garbage collection system, so it is not precise in terms of time.

It could be possible to use C or C++, but it would be harder to use.

3.4 Software architecture

Now that we know the OS and the programming language, we can focus on the software architecture. The python code is based on ftprci, a Python library developed for this occasion, that can also be used for other projects.

3.4.1 ftprci presentation

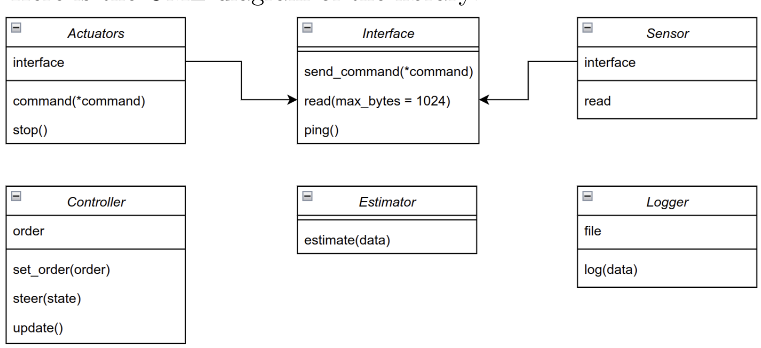
ftprci mean "Fast Time Robot Controller Interface". It is designed to be a fast and easy to use interface to control robots. The goal is to regroup different pieces of code that are often used in robot controllers, like the PID controller, the Kalman filter, the LQR controller, etc. in a single library. It is also designed to be easy to use, with a simple API.

The library is still in development, but it is already usable.

To use the library, the principle is to implement diverse classes needed for the robot, like an estimator, a sensor interface... Some classes are already implemented, like the PID controller, some sensors...

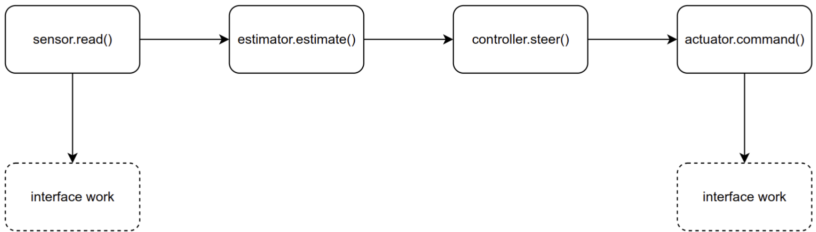
The library also has a low level part to control timings precisely to ensure that the loop runs at the right frequency with as little jitter as possible.

But if you have to implement a new class, you should follow the ftprci interface. Here is the UML diagram of the library:



Controlling the Sigi using ftprci is trivial, because all necessary classes are already implemented. This really simplifies the code, and makes it easier to understand.

When you have your classes ready, you can start to link them. Basically, the normal architecture should be :



This is what the code should look like. Everything else is handled by the library, including the management of the loop, the threading part, and so on. Basically, the library creates a thread for running the loop, and the above diagram is run as the callback in the loop. This means that the code can be controlled from the main thread, while the loop is running in another thread. Any function can be used as a callback, which makes it easy to add new functions. For example, if logging the output of the estimator is needed, it can be added in the middle callback.

Every function added to the callback will be executed, and their output will be sent to the next function. This is a simple way to chain functions.

For the Sigi, the code looks like this:

```
1  import ftprci as fci
2
3  # Create an instance of the LSM6 sensor
4  sensor = fci.LSM6(0x6B)
5
6  estimator = fci.ComplementaryFilter()
7
8  pid = fci.PIDController(10, 0, 3, fci.DiscreteIntegral.Tustin())
9
10 actuators = fci.PololuAstar()
11
12 th = fci.RunnerThread(frequency=100)
13
14 th.callback | sensor.read | estimator.estimate | pid.steer | actuators.command
15
16 while True:
17     pid.set_order(0.1)
18     fci.sleep(0.5)
19     pid.set_order(-0.1)
20     fci.sleep(0.5)
```

The first line imports the library.

The next 4 lines instantiate the classes needed: the LSM6 (with an address of 0x6B), the complementary filter, the PID controller, and the Pololu Astar actuator controller.

The 12th line instantiates the runner thread and starts it, with an empty callback.

Then the next line defines the callback of the loop. You can notice it is exactly the same as the flowchart above. So the functions of the callback will start to get executed.

The while loop only gives orders to the controller to make the Sigi move around.

This simplicity is the advantage of this library: you only have to implement the classes you need, and the library does the rest.

3.4.2 Implementing a custom class in ftprci

To implement a custom class in ftprci, you have to follow the interface of the library. The simplest way to do it is to inherit from the class you want to and re-implement the necessary methods from the UML diagram.

For example, we will implement a simple updating PID controller. We will inherit from the PID controller, and overload the update method.

```
class PIDController(Controller):
    def __init__(self, p, i, d, integrator: DiscreteIntegral = None, update_rate=0.01):
        super().__init__(p, i, d, integrator)
        self.update_rate = update_rate

    def steer(self, state):
        self.last_state = state
        self.update()
        return super().steer(state)

    def update(self):
        self.p -= (self.last_state-self.order)*self.update_rate
```

This is a simple example, but it shows how easy it is to implement a new class in ftprci.

I will write a proper documentation for the library soon, but for now if you have any question, do not hesitate to ask me on the ftprci Github via issues for example.

3.5 Software problems

i2c is slow

4 Starting with the Sigi

Starting to work with the Sigi can be quite hard, primarily because of its age. If the Sigi you have has already been used, you will probably not have to follow this whole section entirely, so I advise you to just do the checks for every subsection.

4.1 Hardware

Let's start by checking the hardware of the Sigi. The first important thing to check is the power source of the Sigi. If you use an USB power bank, is it charged?

If you chose to use an other battery to power the Sigi as I've advised in the power management section, is it correctly connected to the battery input pins of the Balboa board?

It can also be interesting to check if you have the jumper wire on the Sigi, and if it is soldered. It should be on the upper part of the board, between the VSW and the 5V pins, on the side near the Raspberry Pi. If you do not have it, you won't be able to use the power bank to power the motors, but you can continue for now.

4.2 Balboa board's firmware

You can flash the firmware using the Arduino IDE, and the code can be found in the Github of Pololu. The insctructions to flash the firmware are here : Pololu Balboa 32U4 Balancing Robot User's Guide

4.2.1 Check

If you have flashed the firmware, you can check if it is working by turning the Sigi on (connecting the micro USB to the power bank or the battery). If the code is flashed correctly, then a sound will be played.

This sound is played at every reset of the Balboa board. You can disable it if you find it annoying by commenting the line 56 of the example code, but I advise you to keep it for now because it is a good troubleshoot tool. In fact, resetting the Balboa board will reset the encoders, so if you hear the sound, you know that the encoders have been reset.

4.3 Raspberry Pi SD card flashing

We will remove the Raspberry Pi from the Sigi for the next part.

We need to connect the SD card of the Raspberry Pi to a computer to flash the OS.

There are two main possibilities to flash the Raspberry Pi OS: using the Raspberry Pi Imager, or manually with an other software like Etcher.

4.3.1 Using the Raspberry Pi Imager

Raspberry Pi Imager is a software that allows you to flash the Raspberry Pi OS on an SD card easily. It automatically downloads the OS, flashes it on the SD card, and verifies the flashing. It also allows you to setup some settings like the wifi connection, etc.

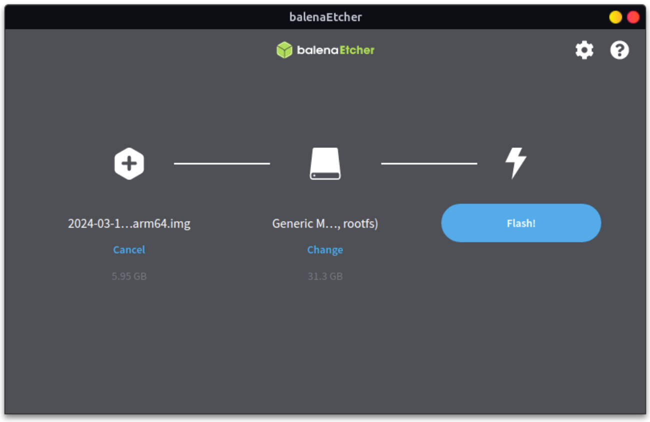
After downloading the imager, the process is quite simple:

- Select Raspberry Pi 3 for the device.
- For the operating system, choose Raspberry Pi OS Lite, 64bits if possible. It may be in the category "Raspberry Pi OS (other)".
- Select your SD card on the list of storages. Warning: it will be formatted, so make sure you have selected the right one. Unplugging it from the computer will remove it from the list, so you can check like this.
- Edit settings : you can set the wifi connection here, it should help later. I also advise you to enable SSH, so you can connect to the Raspberry Pi remotely, and to create a ssh key to login without password. Github has a good tutorial on how to do it. I recommend you to set the username to sigi¡number of your sigi¿ to be able to connect easily.
- Click yes to apply the settings.
- Wait for the flash to finish, it should take a few minutes depending on the size of the SD card and your internet connection if you do it for the first time.

4.3.2 Using BalenaEtcher

It is also possible to flash the Raspberry Pi OS using BalenaEtcher, or any other software that can flash an image on an SD card, like Rufus.

BalenaEtcher is used here as an example, but the process is quite similar with other software.

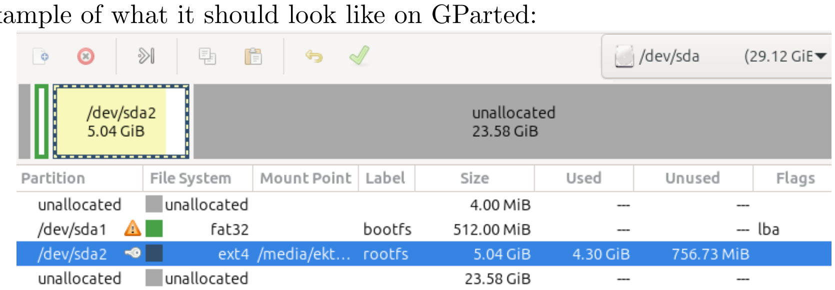


To flash the OS with Etcher:

- Download the right image of the Raspberry Pi OS from the Raspberry Pi website. It should be the Raspberry Pi OS Lite, since we will not use the desktop environment. The 64bits version is recommended. The download is quite big, so it may take some time.
- Choose the image you have just downloaded.
- Choose the SD card you want to flash. Warning: it will be formatted, so make sure you have selected the right one. Unplugging it from the computer will remove it from the list, so you can check like this.
- Click on flash.
- Wait for the flash to finish, it should take a few minutes depending on the size of the SD card.

4.3.3 Check

To check if the flashing is correct, the easiest way is to read it using a computer. Opening the Disk Management on Windows, GParted on Linux, or Disk Utility on MacOS should show you the different partitions of the SD card. There should be at least two partitions: one boot partition, and one root partition, followed by free space. If not, the Raspberry Pi will not be able to boot. Here is an example of what it should look like on GParted:



We can open the root partition on the file browser. The folders should be the typical folders of a Linux system, like `bin`, `boot`, `dev`, `etc`, `home`, `lib` ...

Note: it is better to leave the empty space for now, we will change this later. But if it doesn't work then, you can to expand the root partition using your disk manager.

4.4 Raspberry Pi setup

Now that the Raspberry Pi OS is flashed, we can setup the Raspberry Pi.

We need to insert the SD card in the Raspberry Pi, and power on the Raspberry Pi. The Raspberry Pi should boot, and you should see the leds blinking.

If you have a screen and a keyboard, plug them to the Raspberry Pi, it will be easier to setup the Raspberry Pi. In this case, you can ignore the next section.

It takes some time for the Raspberry Pi to boot for the first time, so be patient.

4.4.1 Setting up SSH connection without a screen(more complex)(Imager required)

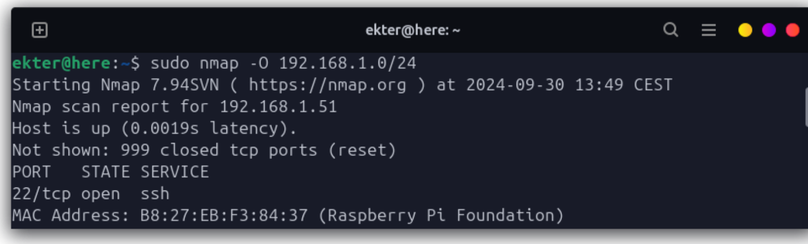
If you have enabled the SSH connection in the Imager, you can connect to the Raspberry Pi using SSH, provided that the Raspberry Pi is connected to the Internet, that you know the IP address of the Raspberry Pi, and that there is no firewall blocking the connection.

If you can connect both the Raspberry Pi and your computer to the same network, you can use a command like nmap to find the IP address of the Raspberry Pi. For example, plugging them both on a switch via Ethernet, or setting the wifi connection on a mobile phone to share the connection with the Raspberry Pi.

The IP address of the Raspberry Pi is written on the screen during boot, but if you don't have one, you will have to find it the hard way.

Then, after getting your IP address, you can find the address of the Raspberry Pi by installing nmap and running the command `nmap -sn <your IP address>/24` on your computer.

This will show you the devices connected to the network, and you should be able to find the Raspberry Pi. If you see too many devices and can't identify the Raspberry Pi, it may be interesting to use the OS detection tool of nmap, using the command `nmap -O <your IP address>/24`, but it is longer. You may also need elevation rights to use it.



To use the ssh command to connect, you also need the username. If you have changed the username in the Imager, you should use it here. Otherwise, the default username is pi, and the default password is raspberry. The command to connect is ssh <username>@<IP address>, and you will be asked for the password if you haven't generated an ssh key.

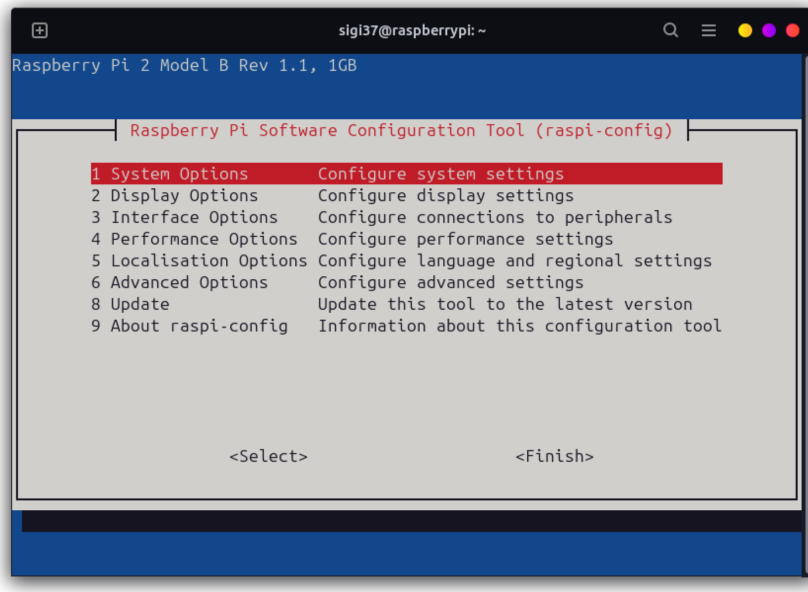
If the command works, you should be connected to the Raspberry Pi. You have access to the terminal so you can run commands. You can skip the next section, and go directly to the next part.

4.4.2 Setting up SSH with a screen

If you have a screen and a keyboard, you can setup the Raspberry Pi easily.

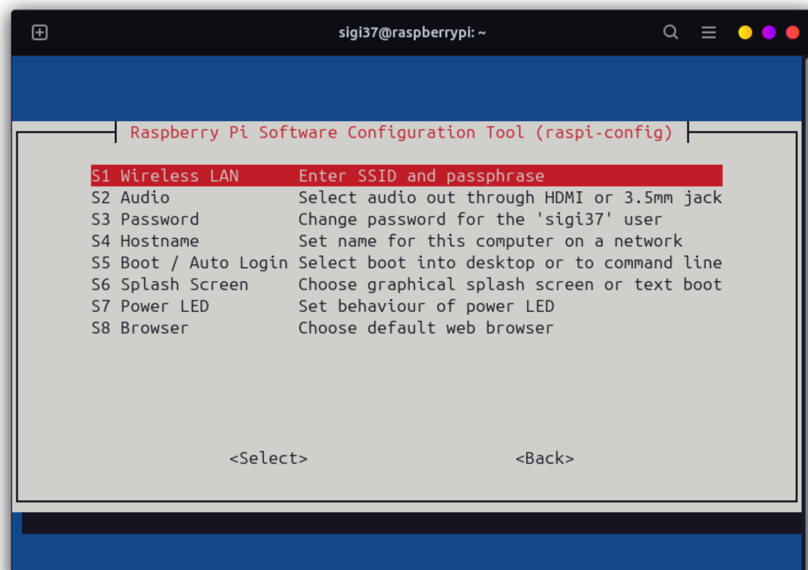
After the Pi has finished booting, you should see a login prompt. The default username is pi, and the default password is raspberry. If you have changed it using the Imager, use the new username and password.

The first thing to do is to connect the Pi to the internet, or at least, to the same network as your computer. You can use the command sudo raspi-config to do this if you haven't done it in the Imager.

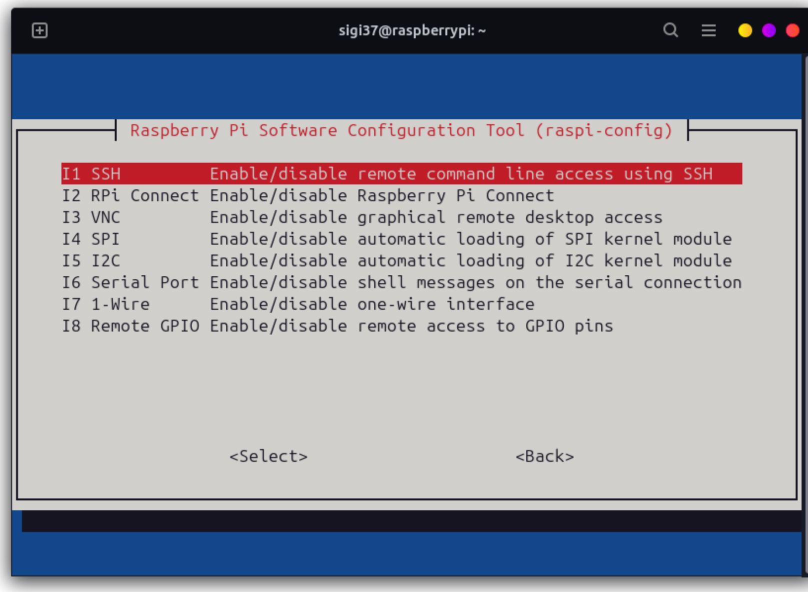


note: this is not the correct Pi model, I don't have the correct one for now.

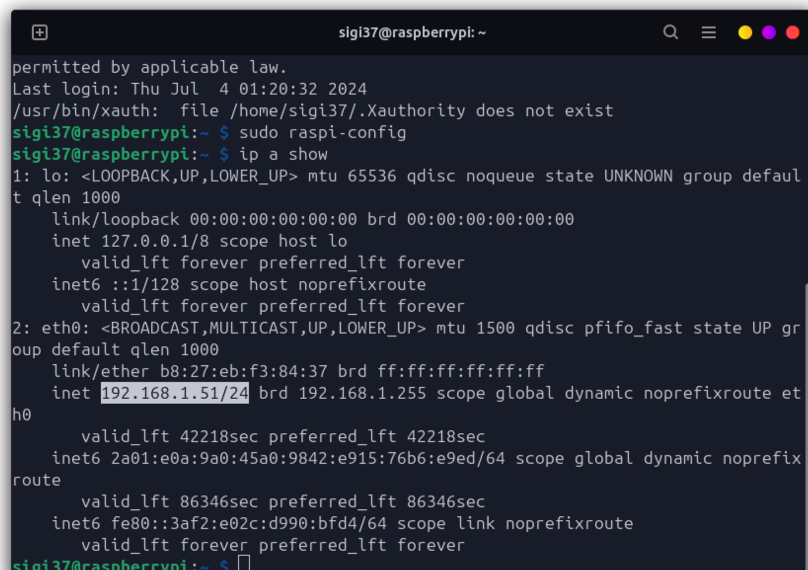
It is the first option in the system panel, and you can follow the instructions to connect to the wifi.



Then, you can enable the SSH connection in the Interface panel from the main menu.



After exiting, you can check the IP address of the Raspberry Pi using the command: `ip a show`



The IP 127.0.0.1 is the loopback, it is not what we are looking for. If you are connected on a normal network, you should see an IP starting with 192.168 or 10.0, but if your network is complex, then your IP address might be entirely different.

In my case, the IP is highlighted. In my case, it is below eth0 because I am connected via Ethernet.

Then, you should be able to connect from your computer using the command:

```
ssh <username>@<IP address>
```

You should be prompted for the password if you haven't generated an ssh key.

4.4.3 Check

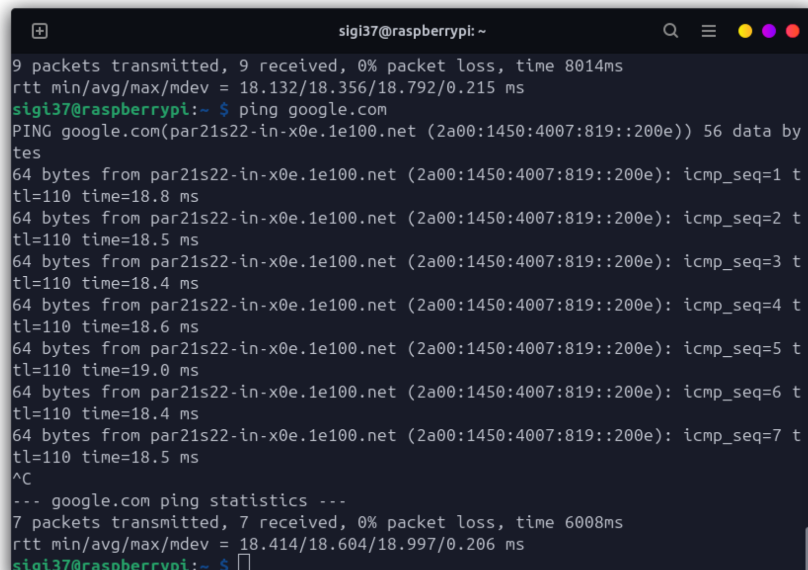
You should be connected to the Raspberry Pi, and you should be able to run commands on it. For the following steps, you will need to type commands on the Raspberry Pi, so if you are connected through SSH, you can copy-paste the commands from your computer to the Raspberry Pi. Note: the copy-paste method on a terminal can be either `Ctrl+Shift+C` or `Ctrl+C`, depending on the terminal and the OS(idem for paste with V).

If you have a keyboard and a screen, you can also type them directly.

Check that the Raspberry Pi is connected to the internet using the command:

```
ping google.com
```

then press `Ctrl+C` to stop the ping after a few seconds.

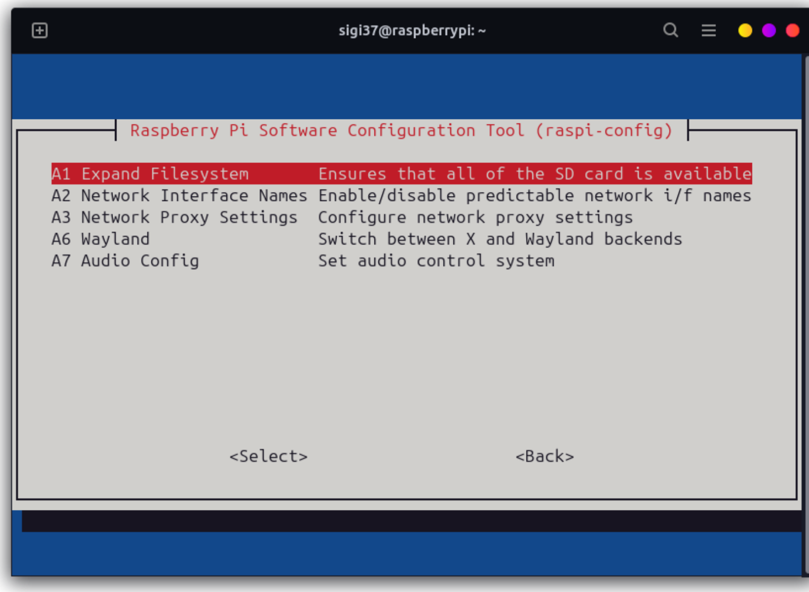


The output should show that the packets are sent and received.

4.4.4 Increasing the size of the root partition and updating the system

The root partition of the Raspberry Pi is small by default, so we will increase it.

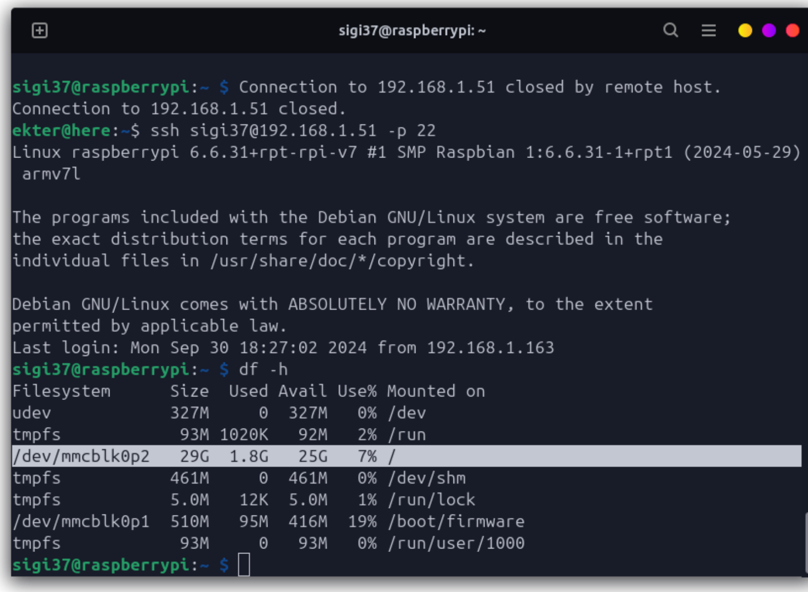
In the `sudo raspi-config` menu, you can find the option to expand the filesystem in the Advanced Options panel. This will expand the root partition to the maximum size of the SD card. Rebooting the Raspberry Pi is required to apply the changes. It should be done automatically after you exit raspi-config.



Then we will refresh the repositories using the command:
`sudo apt update`
If the network is unreachable, the command will fail.
Then update the packages using the command:
`sudo apt upgrade`
It should take some time, the download is quite big.

4.4.5 Check

We will check that the raspberry pi has available space using the command:
`df -h`



```
sigi37@raspberrypi:~ $ Connection to 192.168.1.51 closed by remote host.
Connection to 192.168.1.51 closed.
ekter@here:~$ ssh sigi37@192.168.1.51 -p 22
Linux raspberrypi 6.6.31+rpt-rpi-v7 #1 SMP Raspbian 1:6.6.31-1+rpt1 (2024-05-29)
 armv7l

The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Mon Sep 30 18:27:02 2024 from 192.168.1.163
sigi37@raspberrypi:~ $ df -h
Filesystem      Size  Used Avail Use% Mounted on
udev            327M     0  327M   0% /dev
tmpfs            93M 1020K   92M   2% /run
/dev/mmcblk0p2   29G  1.8G   25G   7% /
tmpfs           461M     0  461M   0% /dev/shm
tmpfs           5.0M   12K  5.0M   1% /run/lock
/dev/mmcblk0p1  510M   95M  416M  19% /boot/firmware
tmpfs            93M     0   93M   0% /run/user/1000
sigi37@raspberrypi:~ $
```

The line with `/` should show a size close to the size of the SD card, and a low usage.

4.4.6 Setting up Python, git, and the I2C interface

Python should already be installed, but just in case:

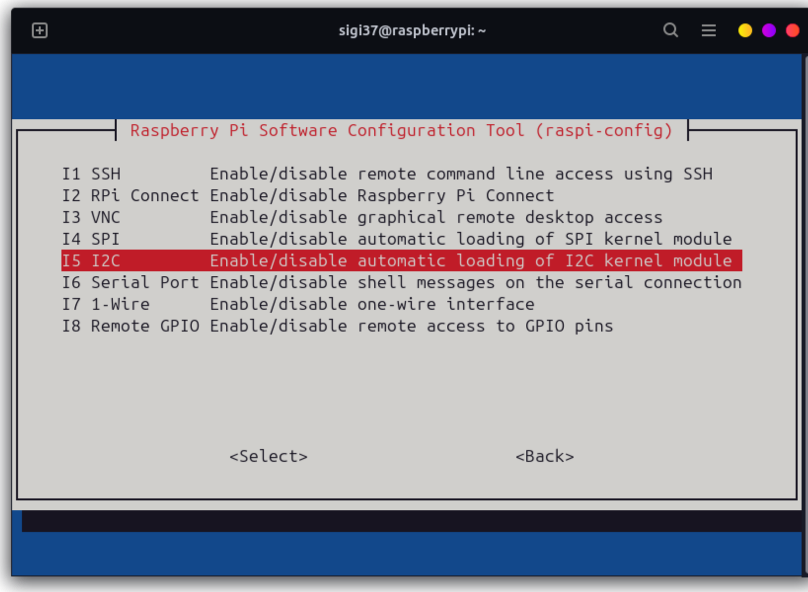
`sudo apt install python3-full python3-venv python3-pip`

If you install pip like this, you can use it with the command `pip`. Sometimes it is referred to as `pip3`, but it is the same command.

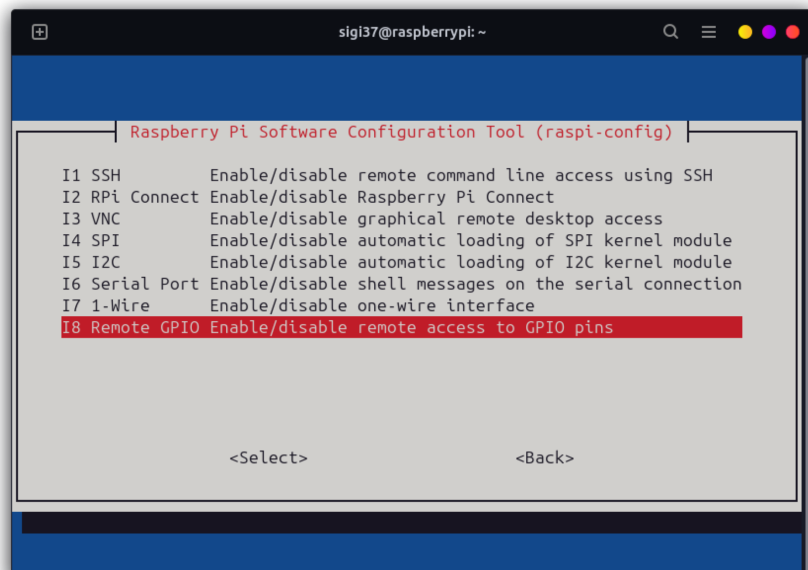
Install git:

`sudo apt install git`

We will also need the I2C interface to communicate with the Balboa board, so let's activate it on rapsi-config.



We will also need to enable the remote GPIO server.



We will then reboot to complete the changes.

```
sudo reboot
```

4.4.7 Check

Check the version of Python using the command:

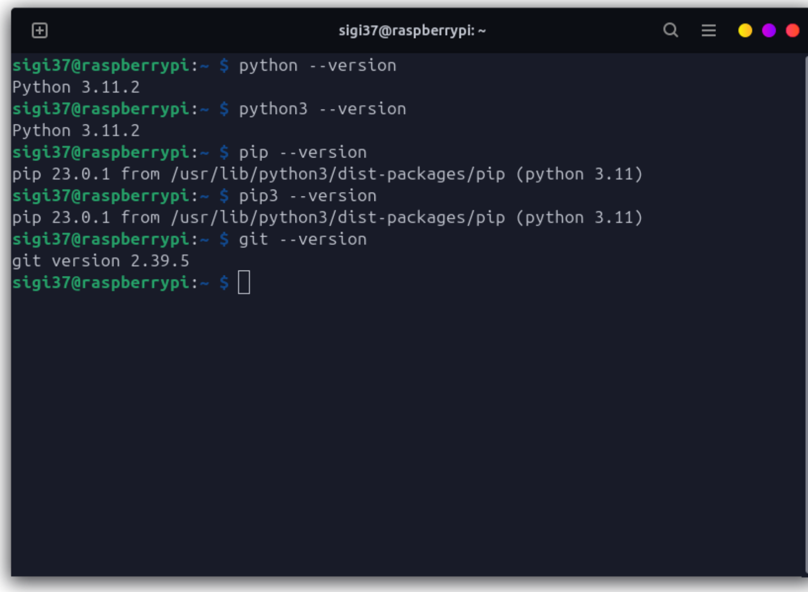
`python3 --version`

The version of pip:

`pip3 --version`

And the version of git:

`git --version`



4.4.8 Cloning the sigi repository

We will now clone this repository to get the code of the Sigi.

If you want to use different code, you can clone it instead, or just create a new repository.

I recommend you to make a fork of this repository and clone it, so you can push your changes directly without having to make a pull request every time, but for now, we will just clone it.

`git clone` will create a folder with the name of the repository in the current directory. Change the directory if needed using the `cd` command.

`git clone https://github.com/Ekter/sigi.git`

Or you can use the ssh version if you have generated an ssh key and added it to your Github account:

`git clone git@github.com:Ekter/sigi.git` (replace by your repository is this case)

If you need advise on how to use git, here is a nice tutorial: Git tutorial by freecodecamp

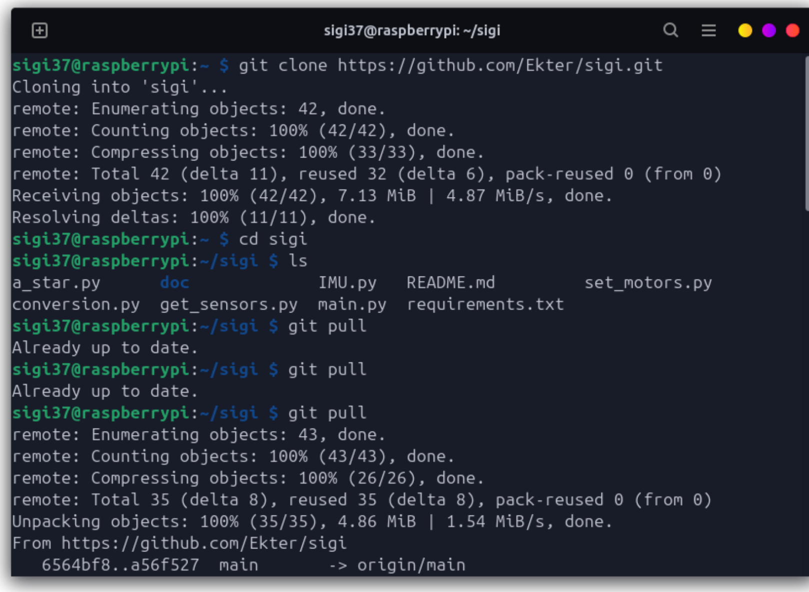
4.4.9 Check

Let's move inside the freshly cloned repository:

`cd sigi`

We should be able to see the files of the repository using the command:

`ls`



```
sigi37@raspberrypi: ~/sigi
sigi37@raspberrypi:~ $ git clone https://github.com/Ekter/sigi.git
Cloning into 'sigi'...
remote: Enumerating objects: 42, done.
remote: Counting objects: 100% (42/42), done.
remote: Compressing objects: 100% (33/33), done.
remote: Total 42 (delta 11), reused 32 (delta 6), pack-reused 0 (from 0)
Receiving objects: 100% (42/42), 7.13 MiB | 4.87 MiB/s, done.
Resolving deltas: 100% (11/11), done.
sigi37@raspberrypi:~ $ cd sigi
sigi37@raspberrypi:~/sigi $ ls
a_star.py      doc             IMU.py   README.md         set_motors.py
conversion.py  get_sensors.py  main.py  requirements.txt
sigi37@raspberrypi:~/sigi $ git pull
Already up to date.
sigi37@raspberrypi:~/sigi $ git pull
Already up to date.
sigi37@raspberrypi:~/sigi $ git pull
remote: Enumerating objects: 43, done.
remote: Counting objects: 100% (43/43), done.
remote: Compressing objects: 100% (26/26), done.
remote: Total 35 (delta 8), reused 35 (delta 8), pack-reused 0 (from 0)
Unpacking objects: 100% (35/35), 4.86 MiB | 1.54 MiB/s, done.
From https://github.com/Ekter/sigi
   6564bf8..a56f527  main       -> origin/main
```