Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

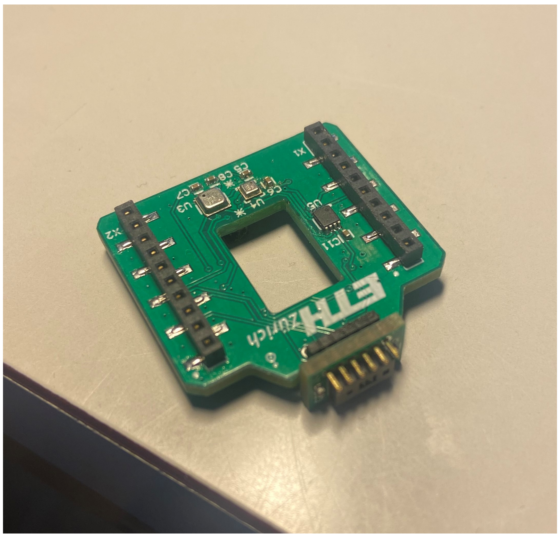
Center for Project-Based Learning

DEPARTMENT OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

Spring Semester 2021

Sensor node shield for PULP based nano-drones

Bachelor Project



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07 June 2021

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Acknowledgements

Thanks to my helpful supervisors.

Abstract

Unmanned Aerial Vehicles(UAVs) are increasing in popularity and are used in all kinds of different regions. They are often used fully autonomous. Regular-sized UAVs have the computational power and energy available to achieve autonomy with vision-based control. Nano-sized UAVs on the other hand do not have these capabilities and are therefore not as autonmous as the bigger ones. Especially cameras and image analysis algorithms are very computationally demanding. Thus new alternative sensors have to be found for the use on nano drones to increase their sensing capabilities and autonomy while not reducing flight time too much. In this project, new sensors were investigated for the use on nano drones. An extension shield for an already existing nano drone was designed and developed using these sensors. The board features 2 Vl53L5 Time-of-Flight laser ranging sensors from ST. The Vl53L5 is able to measure the distance in a 4x4 or 8x8 grid, allowing for basic object detection and localization. In addition the board has a BMP390L high precision pressure sensor and a BME680 gas sensor to do environmental sensing.

Declaration of Originality

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor. For a detailed version of the declaration of originality, please refer to Appendix B

Jonas Martin,
Zurich, 07 June 2021

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Chapter 1

Introduction

Nano-sized unmanned aerial vehicles (UAVs) are a class of small, lightweight drones. They are only a few centimeters big and weigh a few 10 grams. They are useful where bigger-sized drones aren't able to fly, for example, indoors or to help find buried survivors in collapsed buildings. Due to their size, they are limited in terms of computational power, sensing capabilities, flight time, and maximum payload weight. This in turn affects the autonomy of the drone. Regular-sized drones are often fully autonomous with vision-based control. Cameras and the respective algorithms to extract information like depth out of the 2D images are computationally demanding. Regular-sized drones do have the space for big batteries providing the power needed for fast MCUs. Nano-UAVs are limited in the available energy due to their size. Therefore new and improved sensors are required to increase the autonomy of nano drones. Either more precise versions of already used sensors like pressure sensors, but also new sensors for example alternatives to cameras.

The goal of this project is to investigate different sensors to be used on nano drones and to develop an expansion board for existing nano-sized UAVs. The board should increase the sensing capabilities of the drone and help evaluate new possible sensors for the use on nano drones.

Chapter 2

Preliminaries

2.1. Crazyflie

The Crazyflie, shown in Figure 2.1, is an open-source nano-sized Quadrocopter developed by Bitcraze. It is used in research and education due to it's relatively low price and the fact that it is open source. It has a size of 92x92x29mm and weighs only 27g. It can carry a payload of up to 15g with a flight time of up to 7 minutes. On board, it features two micro-controllers. An nRF51822 is used for power and radio management and an STM32F405 is used for controlling and sensing and any other algorithms. The Crazyflie has Bluetooth capabilites and can also communicate to PCs over the Crazyradio, a long range open USB radio dongle.[1] On the Crazyflie installed are a BMI088, which is an inertial measurement unit(IMU), and a BMP388, a high precision pressure sensor. With these two sensors the Crazyflie is able to measure it's acceleration and rotation, as well as getting an estimation for it's height. These sensors alone are not enough for the Crazyflie to fly fully autonomous, as they provide no information about the environment. But the Crazyflie has a standard connector shown in Figure 2.2 to connect expansion decks. There are expansion decks providing additional sensing capabilities like the Flow deck, but also decks providing functionality like an LED-ring, a buzzer, an SD-card slot or wireless charging.[2] The expansion decks can be mounted both on the bottom and top of the Crazyflie. To communicate with the expansion boards UART, SPI or I2C can be used together with 4 free GPIOs.[3] [4]

2.1.1. Flow deck

The Flow deck is an existing expansion board from Bitcraze. It is mounted on the bottom of the drone and is equipped with a VL53L1x Time-of-Flight distance sensor and a PMW3901 optical flow sensor to measure the distance to the ground and the

Figure 2.1.: Crazyflie[5]

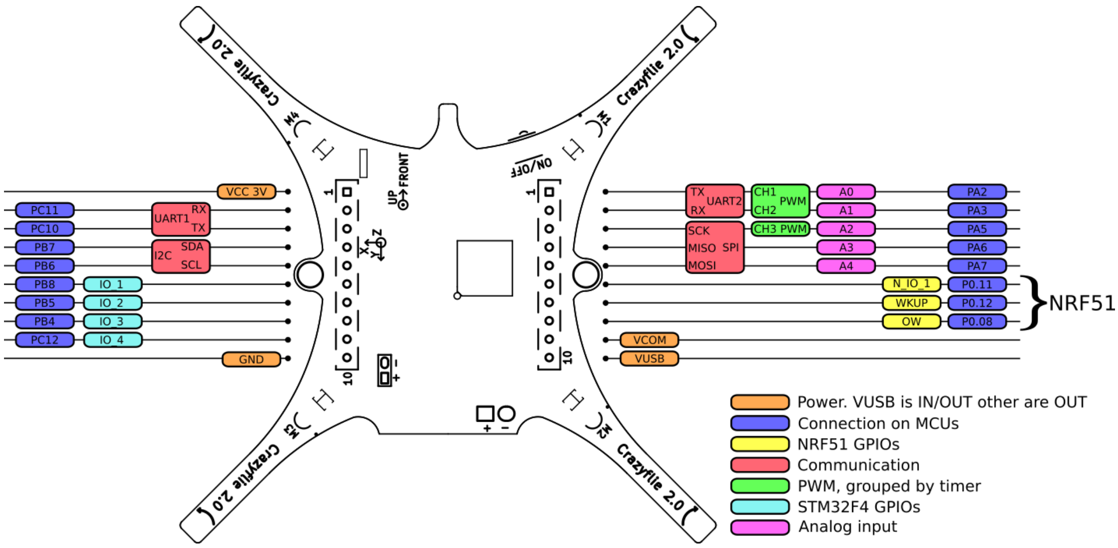


Figure 2.2.: Crazyflie expansion connectors[6]

horizontal movement. This makes the drone able to hover steadily in one place or to fly pre-programmed distances.[7]

2.2. Sensors

2.2.1. ST VL53L5

The Vl53L5 is a not yet publicly released Time-of-Flight(ToF) laser-ranging sensor from ST. Time-of-Flight sensors work by sending out a pulse of light and measuring the time until they receive the reflected pulse. The distance is then calculated using the speed of light. There are ToF sensors that measure the distance to multiple different points, acting as a camera but creating a depth image. These ToF-cameras can be used to create a 3D image around the device. As of now, these sensors are often too big to be mounted on a nano drone. There are ToF sensors small enough for use on drones but they only have 1 single measurement point. They are useful for measuring distances but not for getting an understanding of the area. The VL53L5 combines both of these aspects. With a size of 6.4x3.0x1.5mm it is small enough to be mounted on a nano-sized drone. And its resolution of either 4x4 or 8x8 pixels allows it to be used for scene understanding and object detection. The sensor has a range of 0-400cm with a frame rate of up to 60Hz. [8] For example if you were hovering 50cm above the object in Fig.2.3 a measurement in 4x4 mode could lead to Fig.2.4.

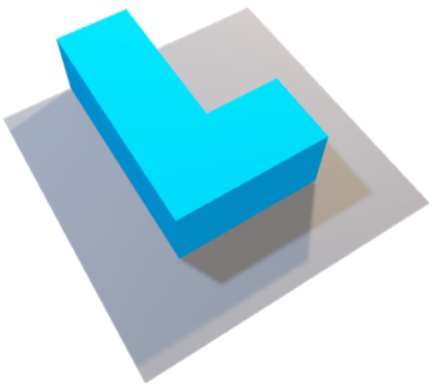


Figure 2.3.: Object

100	50	100	100
100	50	100	100
100	50	50	100
100	100	100	100

Figure 2.4.: Result

2.2.2. Bosch BME680

The BME680 is digital low-power gas, pressure, temperature, and humidity sensor from Bosch. It has a size of 3x3x0.93mm. The different sensors can be individually turned on or off, depending on the use case. Typical applications include air quality measuring or indoor and outdoor navigation. It supports both oversampling and an IIR filter directly inside the sensor. The Gas sensor can be used to detect volatile organic compounds(VOC) like ethanol or exhaled breath. The gas sensor resistance measurement has a typical resolution of 0.08%. The humidity sensor inside the BME680 has an absolute accuracy of ±3%r.H. It has an operating range of 0-65°C and 0-100%r.H. The pressure sensor in the BME680 has a pressure range of 300-1100hPa with a relative accuracy pressure of ±0.12hPa and an absolute accuracy of ±0.6hPa. And the temperature sensor works from -40°C to 85°C with an accuracy of ±0.5°C. The current consumption can be seen in table[9]

Table 2.1.: BME680 Current consumption

Gas sensor: Ultra-low power mode	0.09mA
Gas sensor: Low power mode	0.9mA
Gas sensor: Continuous mode	12mA
Humidity & Temperature at 1Hz	2.1µA
Pressure & Temperature at 1Hz	3.1µA
Temperate at 1Hz	1.0µA

2.2.3. Bosch BMP390L

The BMP390L is a digital pressure sensor from Bosch. This sensor is the more precise version of the BMP388 already on the Crazyflie. It has higher relative accuracy and lower power consumption. The numerical values are shown in table 2.2 The small size of 2x2x0.75mm and the low power consumption make it suitable for battery-driven devices. Like the BME680 it is able to do oversampling and filtering internally.[10] [11]

Table 2.2.: BMP390L compared to BMP388

	BMP390L	**BMP388**
Relative accuracy	$\pm 3Pa \Leftrightarrow \pm 0.25m$	$\pm 8Pa \Leftrightarrow \pm 0.66m$
Absolute accuracy	$\pm 50Pa$	$\pm 50Pa$
Current consumption at 1Hz	3.2µA	3.4µA
Current consumption in sleep mode	1.4µA	2.0µA

Chapter 3

Hardware Implementation

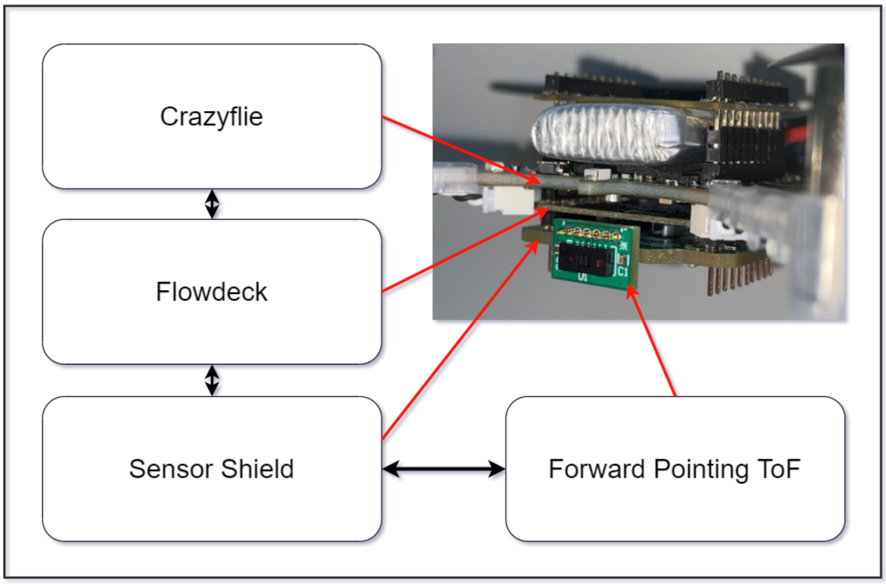
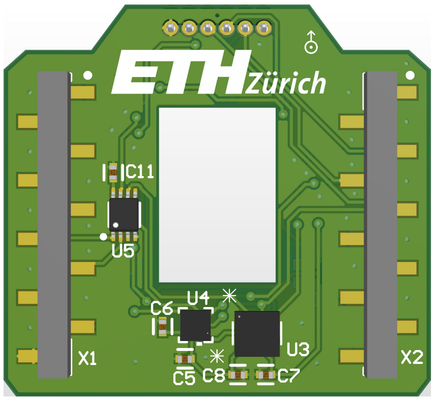


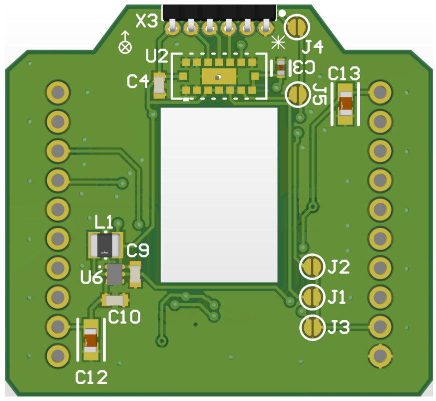
Figure 3.1.: System overview

3.1. Requirements

There are certain requirements the board has to fulfill. Since this board is an expansion deck for the Crazyflie, the interface to the drone and the connector placement have to be exactly the same. To fit onto the drone, the board has to be smaller than 30x30mm. In addition, it has to weigh less than 15g in order for the drone to be able to lift it.



(a) PCB Top View



(b) PCB Bottom View

Figure 3.2.: PCB

To allow for a stable flight, it must be possible to use the board together with the Flow deck.
Most importantly the board has to increase the sensing capabilities of the Crazyflie. The VL53L5's ability to perform range measurements in a grid allows gaining a depth perception of the area. This can then be used to detect and localize objects or get an understanding of the scene. This is required for autonomous flight as the drone needs to know what's around it. The VL53L5 could replace the need for a camera on the nano drone. Cameras require computationally intense algorithms to extract information out of the images they take. The VL53L5 on the other hand directly provides the depth field of the scene, removing the need to compute it.
As the BMP390L is the more precise version of the BMP388 already on the Crazyflie, it is interesting to see how much more useful this sensor is for autonomous navigation and how much can really be gained out of the added precision. These results can then help decide which sensor to use when designing a new drone.
Lastly, the BME680 was chosen because it provides a whole new area of functionality. With it, environmental measurements can be made using nano drones. Maybe it could even be used to detect human presence in a room or in a collapsed building.

3.2. Implementation

The board is designed to be mounted on the bottom of the drone. Because both this board and the flow deck require a direct line of sight to the ground, a 13x8mm big cutout had to be made where the sensors of the flow deck are located. This can be seen in Fig. 3.3. In total 4 sensors are on the board: 2 VL53L5, 1 BME680, and 1 BMP390L. The BMP and the BME are located on the top side to protect them from too much airflow while flying. One of the ToF sensors is mounted directly on the bottom and the other

one is soldered on a small extra board, which is connected via a right-angled connector to the main board.
The final board has a size of 29x30x4mm including the connectors and weighs 2.9g.

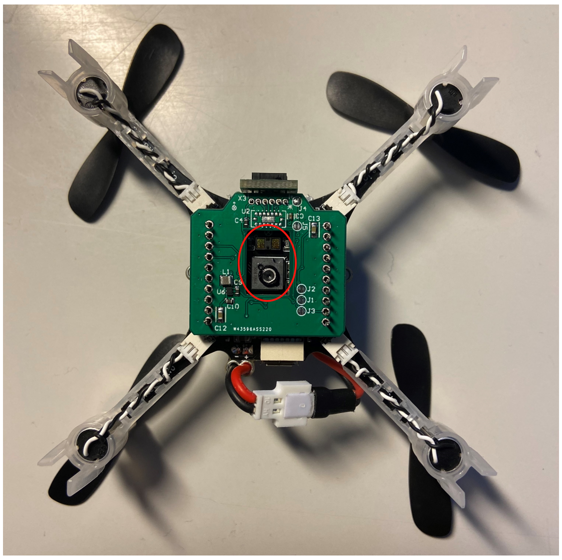


Figure 3.3.: View from bottom with Flow deck

3.2.1. Communication

The communication with the sensors happens over SPI. In theory, I2C would be preferable because it requires no additional GPIOs. A problem with I2C is, that sensors can have the same default device address. For the sensors in this project, this is the case for the ToF sensor on the Flow deck and the VL53L5 as well as the BMP390 and the BME680. These addresses can be changed, but that requires an additional GPIO Pin per sensor. Therefore no GPIOs are saved when using I2C, and SPI was chosen.
The third of the 4 GPIO-pins is already used as chip select for the optical flow sensor on the flow deck and can therefore not be used. Since only 1 Chip select line can be active at any time, it is possible to control 3 sensors with just 2 GPIOs. To achieve this, the first 2 GPIOs are fed into a 2-to-4 Line Decoder(SN74LVC1G139 by TI). The Decoder has active low output signals which is exactly whats needed for the Chip Selects. The resulting encoding is shown in Fig. 3.1.

Selection between the forward or downward-pointing VL53L5 is done via a solder jumper. The fourth GPIO can be connected via solder jumpers to the interrupt pin of the sensors. This is optional but might be useful depending on how the sensors are used.

Table 3.1.: GPIO to Chip select decoder.

GPIO1	GPIO2	active chip select
0	0	VL53L5
0	1	BMP390
1	0	BME680
1	1	None

3.2.2. Power

The sensors and the Crazyflie work at 3V. The Crazyflie has 3 power pins on the expansion connector. VUSB is connected directly to the USB port and can be used both as input and output. VCC is a regulated 3V supply limited to a maximum of 100mA. VCOM is unregulated and directly connected to the battery. The Pin is rated at a maximum of 1A[4]. The 100mA on the VCC pin is not enough for all 3 sensors. Therefore the VCOM is used as the power supply. To convert the 3.7V battery voltage down to 3V, the Step-Down converter TPS62233 from Texas Instruments is used. It has a fixed output voltage of 3V and a maximum current of 500mA. It supports an input voltage range from 2.05 V to 6 V and has an efficiency of up to 94%.[12] Its small size and high efficiency make it optimal for use on a battery-driven device like the drone. The wide input range also makes it possible to use this board on a drone that uses a battery with a different voltage level.

Chapter 4

Verification and Results

Due to the limited availability of the VL53L5, only the forward-pointing one was soldered on. If there would be a problem with the main board, the sensor could be separated easier.

4.1. Verification

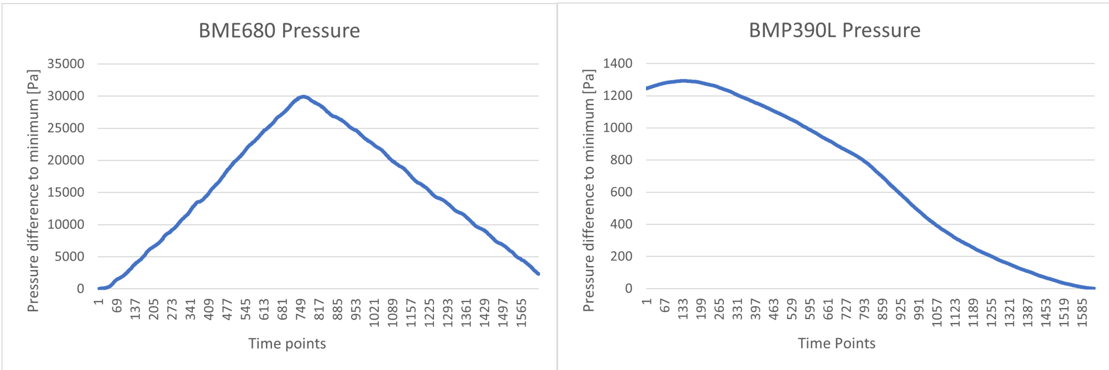
To test the board a short deck driver was made, which initializes the sensors and reads out their respective chip-id. This worked for both the BME680 and the BMP390. The communication with the BMP390L for a part of the initialization is shown in Fig. 4.1. Unfortunately, the VL53L5 did not respond to the communication. It is unclear whether this is the result of a hardware or software error. There might be an error in the PCB design of the deck or in the firmware. Since this sensor is not released yet, it's also possible that there is a hardware bug with the SPI on the sensor itself. Other people have used the sensor over I2C, but as far as we know no one has used it over SPI.

Figure 4.1.: Communication with the BMP during Initialization

4.2. Results

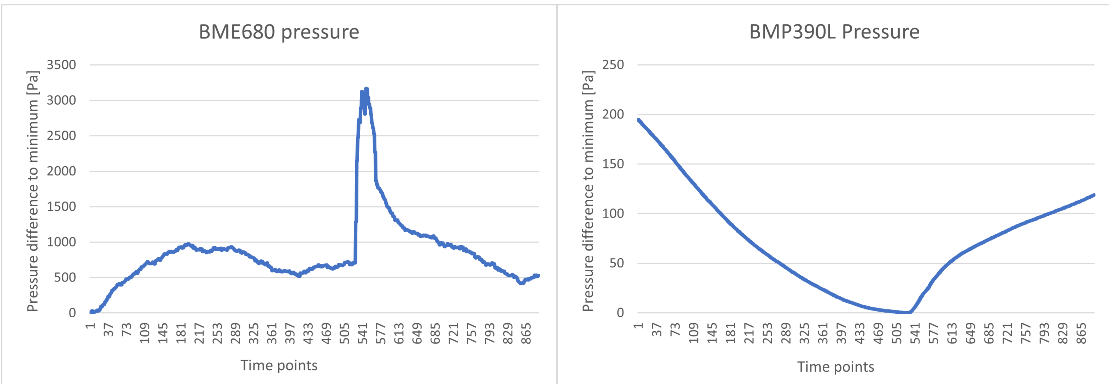
With both the BME680 and the BMP390 the air pressure was measured while going down 7 floors(25 meters) and back up again. The sensors were configured to not do any

oversampling or filtering. The results are shown in Fig. 4.2. In another experiment, the pressure was measured while stationary. At a certain time, point air was blown into the sensors. The results from this are shown in Fig. 4.3. The BME680 successfully shows the expected curve. The BMP390L on the other hand does not show the correct results. Its readings drift and do not show any correlation to the correct curve. In the blowing experiment, the drift changes direction at the moment where the air was blown into it. This might be a coincidence though.
The BMP390L was then unsoldered and another one was soldered back on, but the results were the same. It has to be noted that the BMP390L is currently not available on the market and the ones used on this board are not new. They have been soldered off from another board and were then given to us. So they could already have been damaged when we got them.



(a) BME680 (b) BMP390L

Figure 4.2.: Data from the height experiment



(a) BME680 (b) BMP390L

Figure 4.3.: Data from the blow experiment

Chapter 5

Conclusion and Future Work

In this project, different sensors were evaluated and selected. An expansion board for the Crazyflie was then developed using these sensors and assembled. The board features 2 VL53L5 time-of-flight ranging sensors, a BME390L pressure sensor, and a BME680 gas sensor. In the next step, the boards supporting systems were tested. Finally, the sensor drivers were added and adapted to the Crazyflie firmware. With those in place, the sensors could now be tested.
All the supporting systems work. Unfortunately, the VL53L5 didn't work at all and did not respond to any communication. The BMP390L is working to the extent that communication with it can happen but the actual measurements are wrong. The BME680 seems to be working fine. Future work includes getting the communication with the VL53L5 to work as well as ordering new BMP390L and testing them. Once the sensors are working, this board can be used to test out the function of these sensors for autonomous flight and the use on nano drones.

Appendix A

Task Description

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IIS
Center Project-Based Learning

Bachelor thesis at the
Department of Information Technology and
Electrical Engineering

for

Martin Jonas

Sensor node shield for PULP based nano-drones

Advisors: Tommaso Polonelli
Hanna Müller

Professor: Prof. Luca Benini

Handout Date: 01.03.2021
Due Date: 07.06.2021

1 Project Goals (14 weeks)

Nowadays, the industry is pushing the evolution of autonomous flying vehicles (UAV) toward rapidly decreasing form factors and increasing of computational capabilities. Usually, the development is either in the one direction (adding intelligence, computational and sensing capabilities) or the other (miniaturization). This means that on nano-sized aerial vehicles flight control, navigation, and planning capabilities are either absent or based on monocular low-resolution cameras. In contrast, relatively big-sized drones (i.e., DJI or Matek) have been proven capable of impressive autonomous sense-and-act capabilities, running in real-time complex and computationally intensive multi-sensor and vision-based control systems.

Therefore, this project focuses on this challenging class of Unmanned Autonomous Vehicles, characterized by few centimeters in diameter, tens of grams in weight, and a few Watts total power consumption, of which 85% is to be dedicated to the propellers, leaving a total power budget for onboard sensing, computation, control actuation of only a few hundred mW. Thus, in this project our custom nano-size UAVs is based on an PULP microcontroller, specifically the Mr. Wolf board designed in ETH, which support custom firmware and hardware. This thesis focuses on enhancing the nano-drone capabilities by adding additional sensing capabilities through state-of-the-art off-the-shelf ICs. The developed shield should be modular, to allow testing on an different platforms, not only our PULP-drone but also with a STM32-based drone for easier verification.

2 Tasks

The project will be split into three phases, as described below:

Phase 1 (Weeks 1-5)

1. Investigate and study the state-of-the-art technology of UWB ranging and wireless communication.

2. Introduction to PCB design, Altium: schematics and layout;

3. Getting started with the STM32 environment, IDE, SDK, HAL, and cross compilation/programming;

4. Getting started with the nano-drone platform;

5. Investigate different pressure sensors for the use on nano-drones (absolute and differential);

6. Select sensors to be tested.

1.1 Phase 2 (weeks 5-12)

1. Sensor shield schematic. Specific focus on integrating the PCB-shield with our nano-drone;

2. Shield Layout and PCB production;

3. Component soldering and logic/electrical assessment;

4. Functional test with STEVAL-FCU001V1 and the new custom DW3000 shield.

5. (optional): In-field-test of accuracy improvement with a MoCap system

1.2 Phase 3 (last 2 weeks)

1. Finalizing the tests and optimizations on the final version

2. Write the final document and prepare a presentation.

3 Milestones

By the end of **Phase 1** the following should be completed:

- Good working experience with Altium Design;

- Sensor selection for the custom PCB.

By the end of **Phase 2** the following should be completed:

- Schematic and PCB layout;
- Production, assembly, testing, and assessment.

By the end of **Phase 3** the following should be completed:

- Practical functional verification (electrical and logical);
- Final presentation;
- Final report, including final results;

4 Thesis Organization

The Bachelor's Thesis is the final part of the program and is usually carried out in the sixth semester. During the thesis, students will gain initial experience in the independent solution of a technical-scientific problem by applying the acquired specialist and social skills. The grade is based on the following: (i) Difficulty of the project; (ii) Student effort and learning curve; (iii) Results in terms of quality and quantity; (iv) final presentation; (v) documentation.

A Bachelor's Thesis should take about half of a student's time during one semester, i.e., about 300-400 hours. The thesis includes an oral presentation and a written report, and it is graded. Before starting, the project must be registered in myStudies ("Projects/papers/theses").

4.1 Weekly Report

Weekly meetings will be held between the student and the assistants. The exact time and location of these meetings will be determined within the first week of the project in order to fit the students and the assistants schedule. These meetings will be used to evaluate the status and progress of the project. Beside these regular meetings, additional meetings can be organized to address urgent issues as well. The report, along with all other relevant documents (source code, datasheets, papers, etc), should be uploaded to a clouding service.

4.2 Written report

Documentation is an important and often overlooked aspect of engineering. One final report has to be completed within this project. The common language of engineering is de facto English. Therefore, the final report of the work is preferred to be written in English. Any form of word processing software is allowed for writing the reports, nevertheless the use of LaTeX or any other vector drawing software (for block diagrams) is strongly encouraged by the IIS staff.

4.3 Final Presentations

At the end of the project, the outcome of the thesis will be presented through an oral presentation.

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Appendix B

Declaration of Originality

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

Sensor node shield for PULP based nano-drones

Authored by (in block letters):
For papers written by groups the names of all authors are required.

Name(s):	First name(s):
Martin	Jonas

With my signature I confirm that
- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

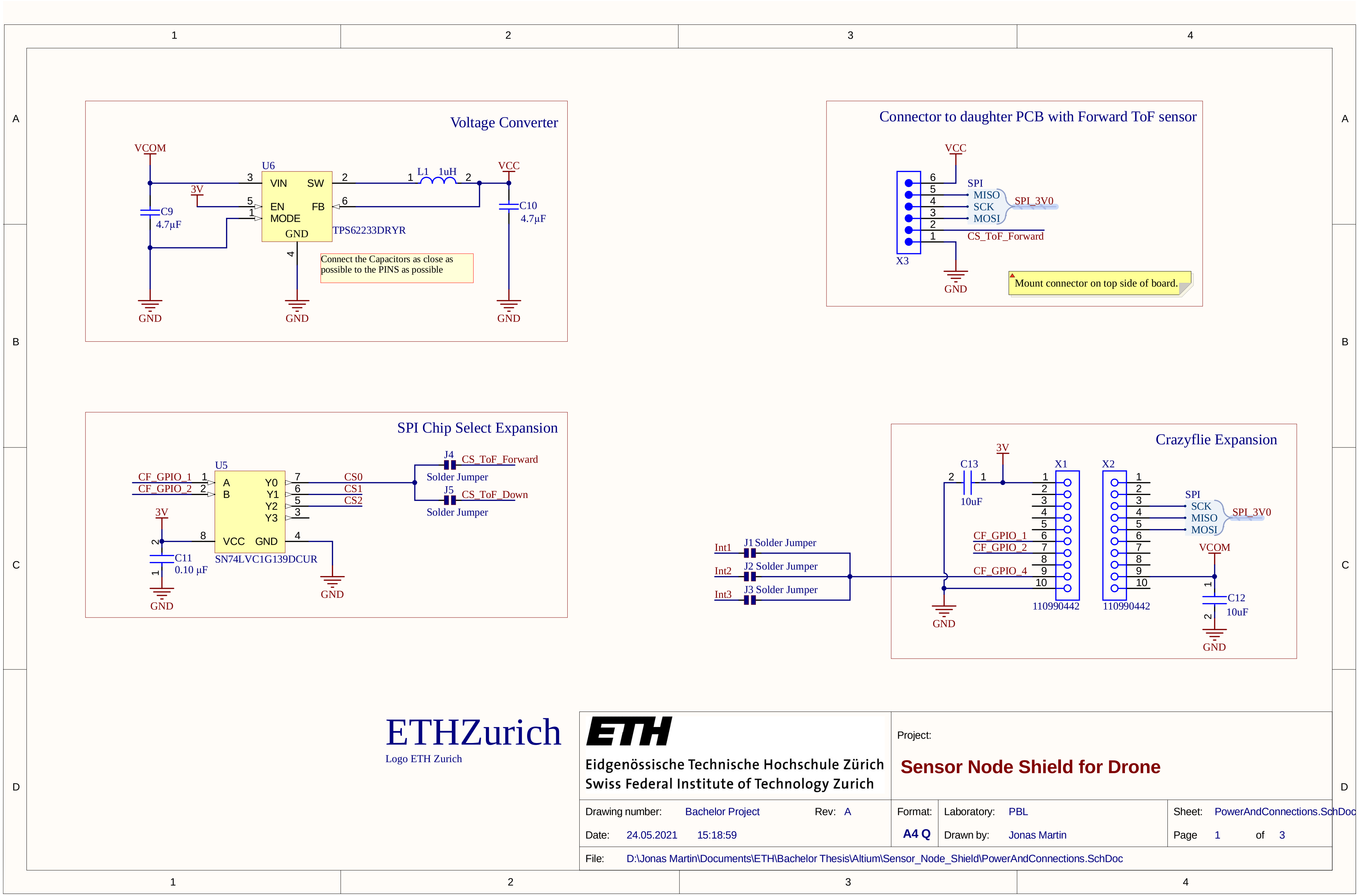
I am aware that the work may be screened electronically for plagiarism.

Place, date	Signature(s)
Herzogenbuchsee, 04.06.2021	Martin

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Appendix C

Schematics



Voltage Converter
VCOM
U6
VIN
SW
EN
FB
MODE
GND
3V
C9
4.7µF
L1 1uH
VCC
C10
4.7µF
TPS62233DRYR
Connect the Capacitors as close as possible to the PINS as possible
GND
Connector to daughter PCB with Forward ToF sensor
X3
SPI
MISO
SCK
MOSI
SPI_3V0
CS_ToF_Forward
Mount connector on top side of board.
SPI Chip Select Expansion
U5
CF_GPIO_1
CF_GPIO_2
A
B
Y0
Y1
Y2
Y3
VCC
GND
CS0
CS1
CS2
J4
CS_ToF_Forward
Solder Jumper
J5
CS_ToF_Down
Solder Jumper
C11
0.10 µF
SN74LVC1G139DCUR
Crazyflie Expansion
C13
10uF
X1
X2
CF_GPIO_4
110990442
C12
10uF
Int1
J1 Solder Jumper
Int2
J2 Solder Jumper
Int3
J3 Solder Jumper
ETHZurich
Logo ETH Zurich
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Project:
Sensor Node Shield for Drone
Drawing number: Bachelor Project
Rev: A
Format: A4 Q
Laboratory: PBL
Drawn by: Jonas Martin
Sheet: PowerAndConnections.SchDoc
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Page 1 of 3
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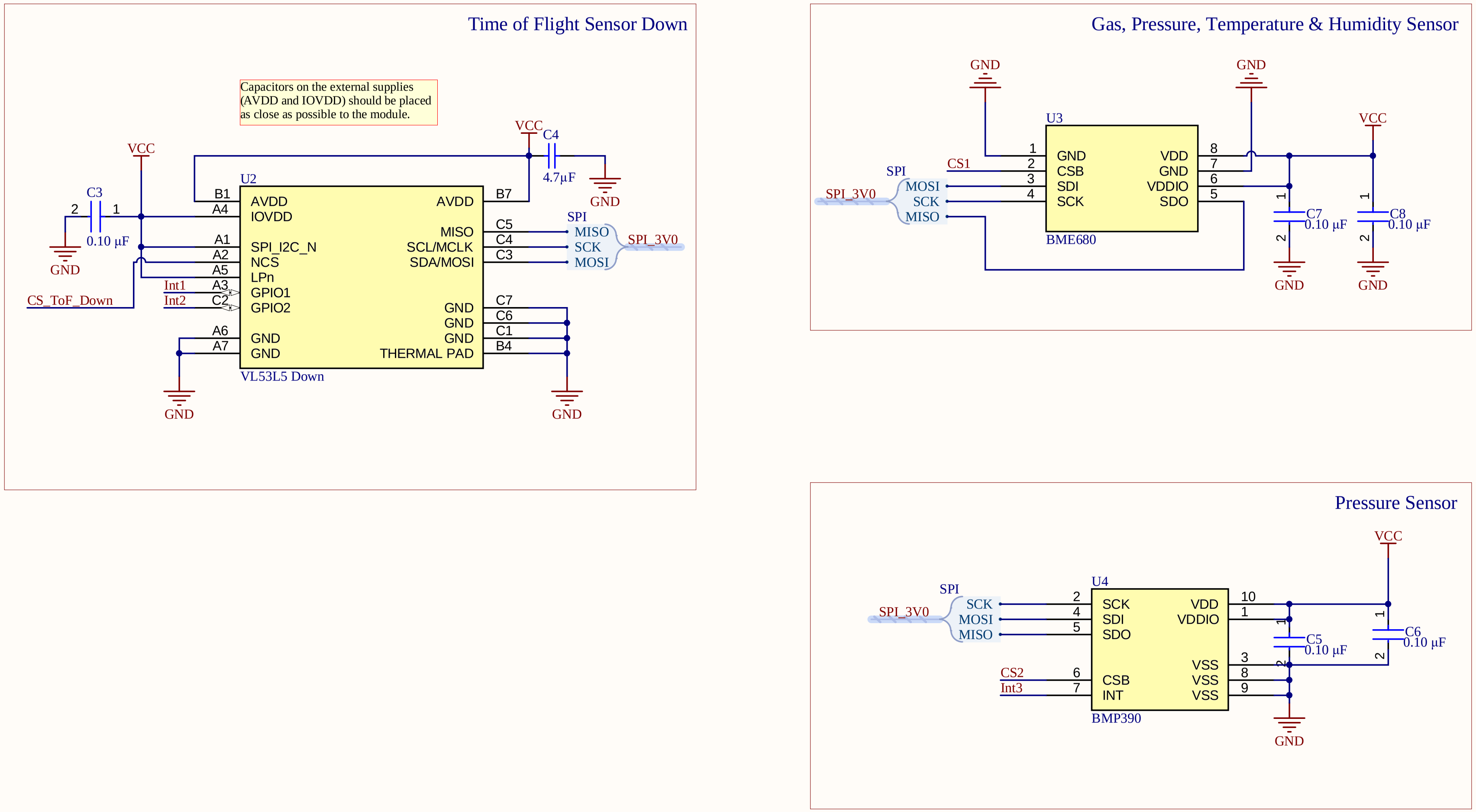

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Project: **Sensor Node Shield for Drone**

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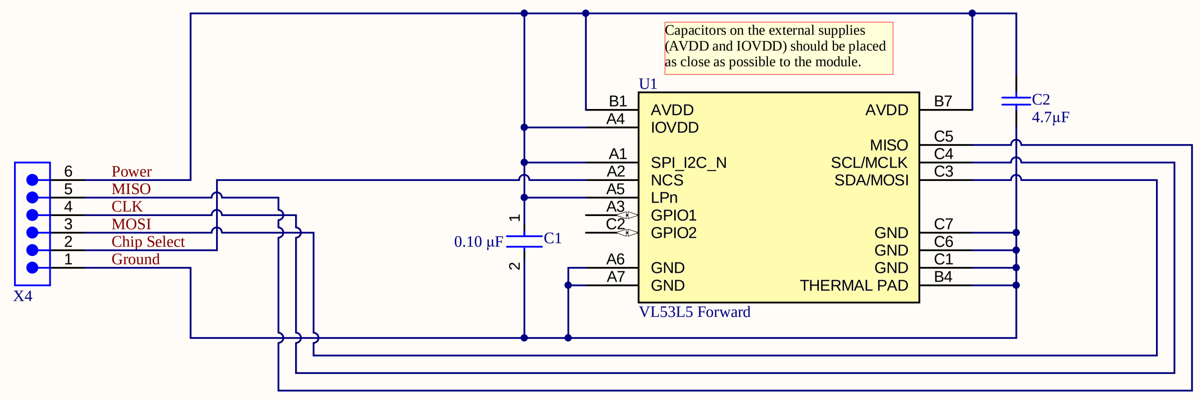

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Date: 24.05.2021 15:18:59	Drawn by: Jonas Martin — Page 3 of 3
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