CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING
DEPARTMENT OF CYBERNETICS
MULTI-ROBOT SYSTEMS

Fully-actuated autonomous multirotor UAV design and construction

Bachelor's Thesis

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Study programme: Open Informatics
Branch of study: Internet of things

Supervisor: Ing.Daniel Heřt

BACHELOR'S THESIS ASSIGNMENT

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II. Bachelor's thesis details

Bachelor's thesis title in English:

Fully-actuated autonomous multirotor UAV design and construction

Bachelor's thesis title in Czech:

Návrh a stavba holonomní autonomní bezpilotní helikoptéry

Guidelines:

The goal of this thesis is to design and build a fully-actuated autonomous multirotor UAV.
The following tasks will be solved:
1. Model the fully-actuated UAV [1] in the Gazebo simulator, using the PX4 [4] SITL.
2. Implement control algorithms and mixers which make use of the fully-actuated platform, and verify them in the Gazebo simulator.
3. Design and implement an interface between the ROS [3] based MRS UAV [2] system, which allows control of the UAV through ROS.
4. Design and construct a real-world fully actuated UAV with an onboard computer running the MRS UAV system and a PX4 autopilot.
5. If external factors and the schedule of the MRS group allows, demonstrate the fully-actuated UAV in a real-world experiment, by executing maneuvers which are impossible for standard underactuated UAVs.

Bibliography / sources:

[1] A. Keipour, M. Mousaei, A. Ashley, and S. Scherer, "Integration of Fully-Actuated Multirotors into Real-World Applications,", Under review.
[2] Baca, T., Petrlik, M., Vrba, M., Spurny, V., Penicka, R., Hert, D., and Saska, M., "The MRS UAV System: Pushing the Frontiers of Reproducible Research, Real-world Deployment, and Education with Autonomous Unmanned Aerial Vehicles", J Intell Robot Syst 102, 26 (2021).
[3] Quigley, Morgan, et al. "ROS: an open-source Robot Operating System." ICRA workshop on open source software. Vol. 3. No. 3.2. 2009.
[4] L. Meier, D. Honegger and M. Pollefeys, "PX4: A node-based multithreaded open source robotics framework for deeply embedded platforms," 2015 IEEE International Conference on Robotics and Automation (ICRA), 2015

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Supervisor's signature   Dean's signature

Declaration

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

I declare that I have prepared the submitted work separately and that I have listed all information sources used in accordance with the Methodical Instructions on adherence to ethical principles in the preparation of university final theses.

V Praze dne ....

Acknowledgments

Abstract

This thesis aims to develop a fully actuated drone. It is a special type of drone with six motors, and its rotors are tilted at a specific angle. This allows the drone to fly without tilting the body during the movement. While developing the software, simulation programs are used. It makes testing the software more accessible and safer. During the building process, 3D printing is used, which allows the creation of atypical parts such as holders of batteries or computation boards.

Keywords Drone, Fully Actuated, 3D print, PX4,ROS

Abstrakt

Tato práce se zabývá vývojem holonomního dronu. Jedná se o speciální typ dronu s šesti motory, jehož vrtule jsou nakloněny pod specifickým úhlem. To umožňuje dronu létat bez naklápění těla při pohybu. Vývoj dronu obsahuje modifikaci již existujícího řídícího softwaru PX4 a ROS, samotné sestavení dronu, zalétání a využití v praxi. Během vývoje dronu je využíváno simulačních programů, které zjednodušují testování softwaru. Při stavbě dronu je používán 3D tisk, který umožňuje vytvoření atypických dílů jako je například držák baterie nebo řídících desek.

Klíčová slova Dron, Holonomní, 3D tisk, PX4,ROS

Abbreviations

CTU Czech Technical University

DOF degree-of-freedom

GPS global positioning system

IMU inertial measurement unit

MRS Multi-robot Systems Group

ROS Robot Operating System

PID proportional, integral, derivative

XML extensible markup language

URDF the unified robotic description format

STL standard triangle language

ESC electronic speed controller

PCB printed circuit board

NPV Net present value

IRR Internal rate of return

RC remote control

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Chapter 1

Introduction

There has been a lot of interest in drones over the last ten years. Nowadays, we can see drones almost everywhere. It starts with small toys for children or drones with cameras for making videos, delivery drones, or special types of drones developed for research in harsh environments. It is possible to buy a ready-to-fly drone from 1000 CZK, which is very cheap. We can also buy a kit where the drone parts are ready for assembly. Also, it is possible to create your own drone from custom parts where the price can vary from a few thousand to tens of thousands of CZK.

1.1   Aim

A conventional drone is limited in its movement. When this drone wants to move, it needs to tilt its body to start moving.

A fully-actuated drone is a special type that allows flying without tilting the body. Detailed information is in chapter 2. PX4 is a control software of the drone, description of it is in chapter 3. This thesis aims to modify the current version of PX4 and implement support for fully-actuated drones. Then integrate this modified PX4 into Robot Operating System (ROS). This system is described in chapter 5.

Verify that the implementation is feasible in simulation programs. Assemble the drone, and prove that the real drone is capable of fully actuated movement. Demonstrate drone usage in real-world experiments.

In addition to the original assignment, as an extra part, create a business plan for a possible company foundation.

1.2   Related works

There have been many implementations that created fully-actuated drones in the past [1] [2]. In the past few years, the organisation Airlab [3] came up with the idea of using the default version of control software PX4. They modified controllers and implemented fully-actuated drone software into PX4, capable of controlling fully-actuated drones and standard under-actuated drones.

Unfortunately, this project ended two years ago. Since then, it has not been updated. PX4 control software and system libraries in the Ubuntu system were updated during that time. It caused incompatibility between Airlab implementation and current versions of PX4 and Ubuntu.

ROS is a widely used system that a MRS at Czech Technical University (CTU) has been using for a long time. They are improving the original version of ROS and developing the control, estimation and simulation platform [4]. Also, MRS managed to integrate communication between ROS with custom packages and default PX4.

1.3 Contributions

This thesis is based on the work of Airlab [3]. I used the ideas and implementation of Airlab control software for PX4 and reprogrammed the incompatible parts of PX4 software. In the last part of my research, I found a way how to implement fully actuated drones into ROS. It is an operating system that allows us to use prepared algorithms and fly the drone autonomously or precisely command it over a computer. Then I assembled the drone and demonstrated usage in a real environment. Also, I created a business plan for a small company that will produce this type of drone.

1.4 Mathematical notation

In the Table 1.1 it is possible to find notation used in this document.

$\overrightarrow{\mathrm{F}}_g$	Gravitational force
$\overrightarrow{\mathrm{F}}_l$	Vertical force
$\overrightarrow{\mathrm{F}}_t$	Thrust force
$\overrightarrow{\mathrm{F}}_{lat}$	Lateral force
$\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2, \hat{\mathbf{e}}_3$	elements of the *standard basis*

Table 1.1: Mathematical notation and notable symbols.

Chapter 2

Drone types

2.1 How does a drone work

The closest vehicle to a drone is a helicopter. It has got one rotor mounted to the roof of the vehicle. This rotor spins, by this, the air is pushed, and thrust is generated.

To move the helicopter, individual rotor blades change their angle of attack during the rotation. A helicopter can have one additional tail rotor. It is used to control yaw.

On the other hand, a drone has multiple rotors, usually four, six or eight. These rotors cannot tilt. They are fixedly mounted to the motors. It means that if the drone wants to move, it needs to vary the throttle of its motors. It causes the tilt of the drone, and then the air is not pushed directly to the ground but slantwise.

For example, if a drone with four rotors wants to move to the left, it is needed to increase the thrust of two right motors and also decrease the thrust of the left motors, which causes the right part of the drone to tilt up. The following picture Fig. 2.1 shows how the throttle of the motor changes during the movement. Red arrows show the throttle of the motors. The black arrow shows where the air is pushed. The picture of the drone is from [5]. I added the arrows to it.

(a) Not moving drone   (b) Drone increasing the throttle on the right side
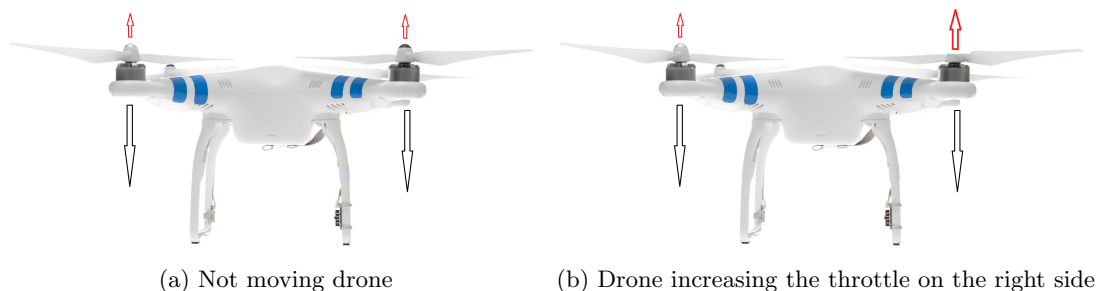
Figure 2.1: Visualization of the drone movement.

Then it is essential to equalise the thrusts of motors. This total thrust is not aiming straight up, but it is tilted. To keep the drone at the same height, creating a vertical force that matches the gravitational force is essential. It is done by increasing the thrust of all motors.

The following picture Fig. 2.2 shows the acting forces on the drone. The black arrow is a gravitational force. The red arrows is the vertical force. The yellow arrow shows the force produced by the motors. The green arrows visualise the resulting force as a sum of yellow and red arrows. As the final force aims to the left, the whole drone will move to the left.
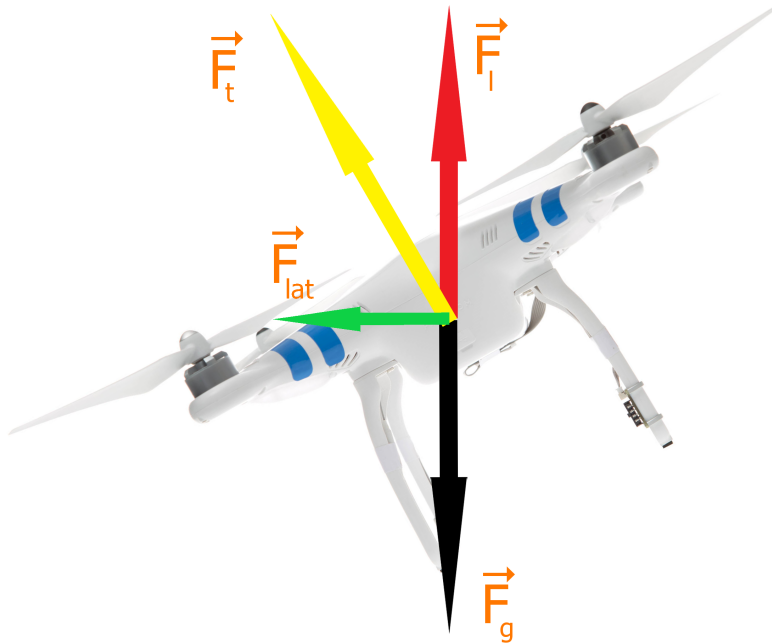
Figure 2.2: Forces acting on the drone

2.2 Under-actuated drone

2.2.1 Construction

Usually, a drone has motors with rotors assembled coplanar with the ground plane. This means that the thrust is generated directly in the vertical direction. Figure Fig. 2.3 shows under-actuated drone model in Gazebo simulator.

(a) Top view of under-actuated drone   (b) Side view of under-actuated drone
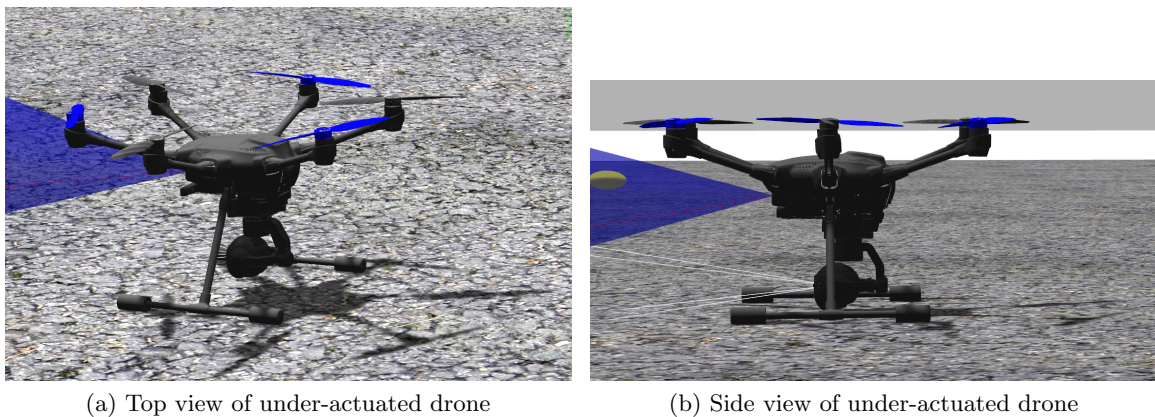
Figure 2.3: Model of under-actuated drone in Gazebo simulator from top view Fig. 2.3a and from side view Fig. 2.3b

The movement of the drone consists of translational and rotational movements. Together they form 6 axes of motion known as the degree-of-freedom (DOF). An under-actuated drone can control less than six degrees of freedom, typically four. Visualisation of degrees of freedom can be seen in Fig. 2.4
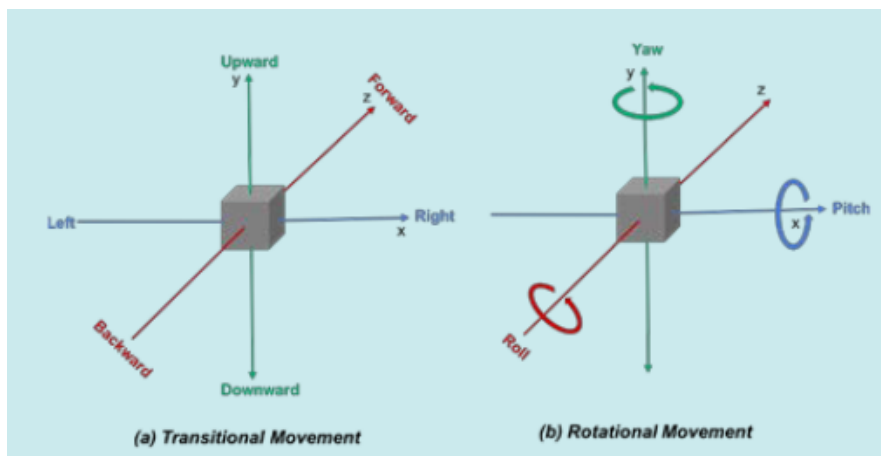
Figure 2.4: Six degrees of freedom: (a) A quad-copter can move longitudinally (forward and backward) only while being tilted, vertically (upward and downward) without tilting, and laterally (right and left) only while being tilted. (b) It can also move rotationally among each axis to produce roll, pitch, and yaw movements. [6]

2.2.2   Advantages and disadvantages

As the air is pushed directly under the drone, the efficiency of energy transformation is very good. The main advantage is the high flight speed, which allows the drone to be used in time-bound disciplines. Among the main disadvantages, we can include tilting during the movement. To move the drone, the drone has to be tilted. A video of a flight can be seen in the attachment. It means that we must use additional stabilisers that try to eliminate tilting and shaking. This can be solved with gimbals.

2.3　Fully-actuated drone

2.3.1　Influence of the design on a thrust generation

The following picture Fig. 2.5 shows the acting forces on the tilted motor mounted on the fully-actuated drone. The black arrow is a gravitational force. The red arrow is the vertical force that has to match the gravitational force to keep the drone at the same vertical speed. The yellow arrow shows the force produced by the motor. The green arrow visualises the resulting force as a sum of yellow and red arrows. As the final force is aiming to the right, the whole drone will move to the right without the need to tilt the entire drone.
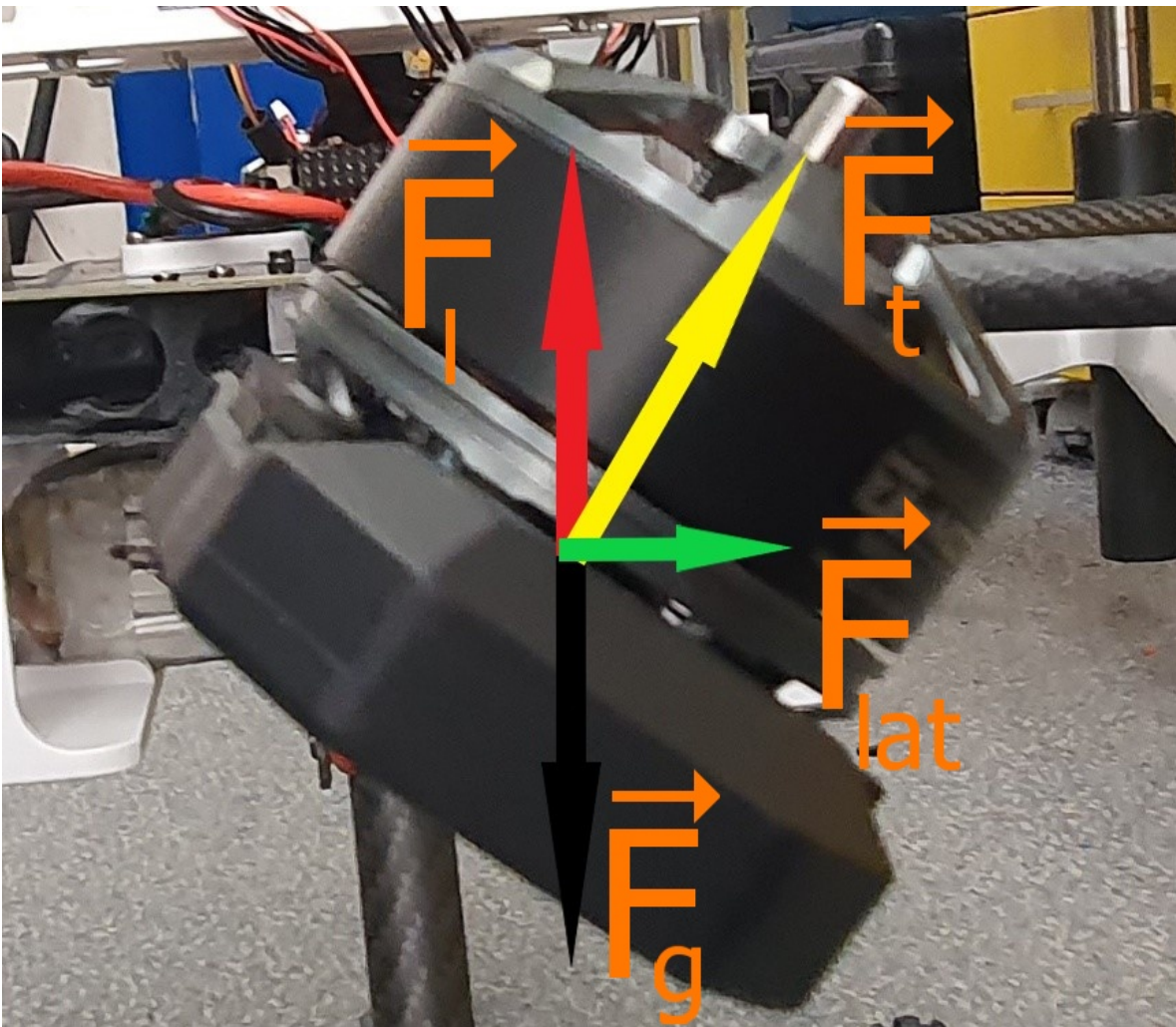
Figure 2.5: Acting forces on a tilted motor

A fully-actuated drone can move thanks to this tilt of the motor without changing roll and pitch. In the picture Fig. 2.7, it is visible that pairs of the motors are tilted under the same angle. The green arrow shows the axis in which each motor generates thrust. In the picture Fig. 2.9 it is the visible a fixed tilt direction of all motors shown by the arrows. To move a fully-actuated drone forward, thrust is increased by middle motors (2 and 1). As the motors are tilted, they generate thrust in the forward direction without tilting the drone's

body. In the picture Fig. 2.6 green arrow visualizes the direction of the thrust generated by motors.

(a) Thrust of non tilted motor used on the under-actuated drone

(b) Thrust of tilted motor used on the fully-actuated drone
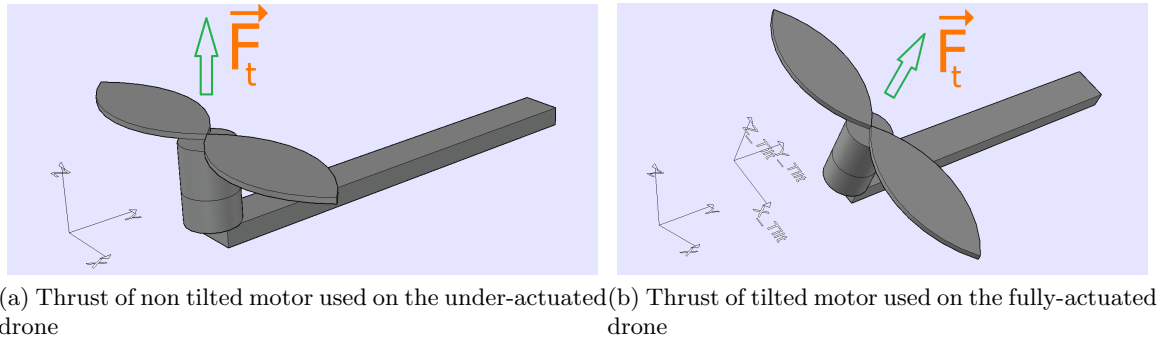
Figure 2.6: Comparison of thrusts with different construction

Also, other motors have to decrease thrust to avoid gaining height.
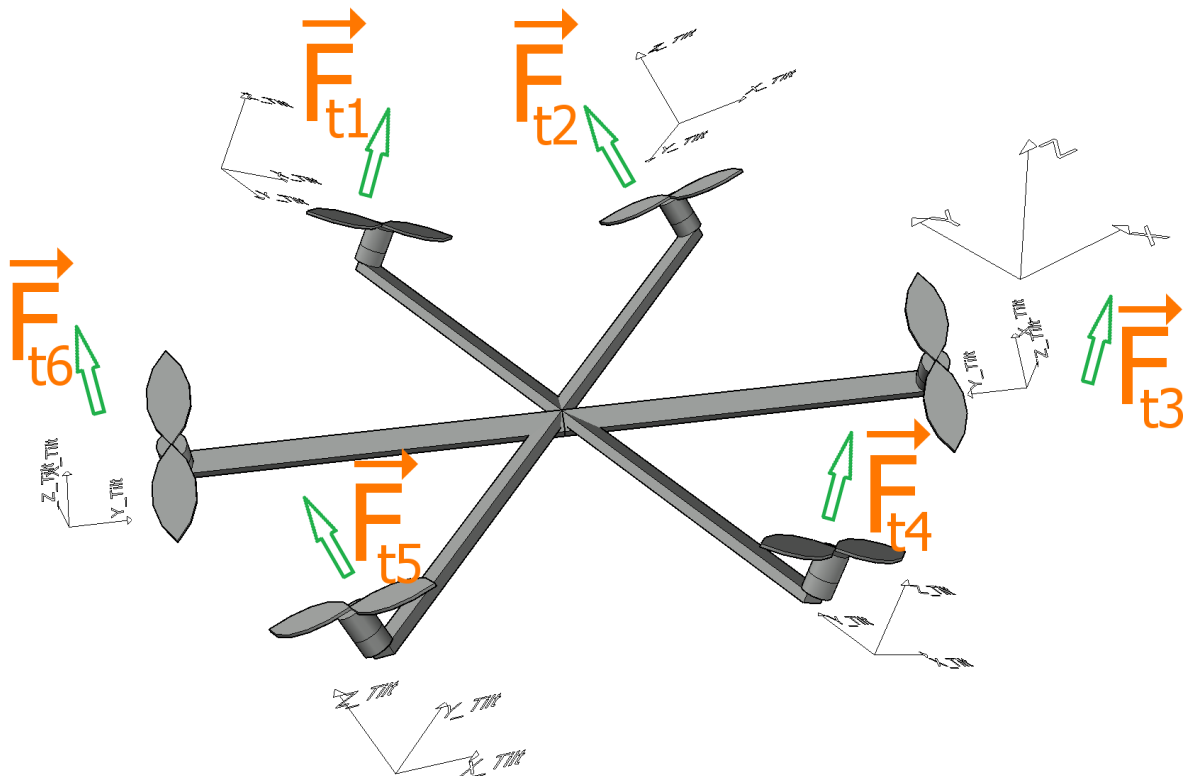
Figure 2.7: Visualization of tilted motors on the fully-actuated drone, green arrows show direction of thrust

The following Fig. 2.8 shows difference in the range of thrust generation of a under-actuated drone and fully-actuated drone.
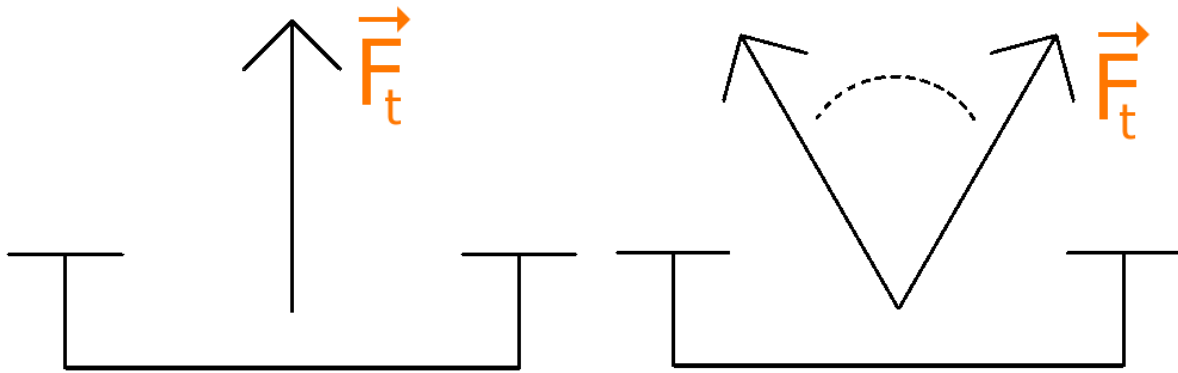
(a) Range of thrust force that under-actuated drone can generate

(b) Range of thrust force that fully-actuated drone can generate

Figure 2.8: Range of thrust of a drone
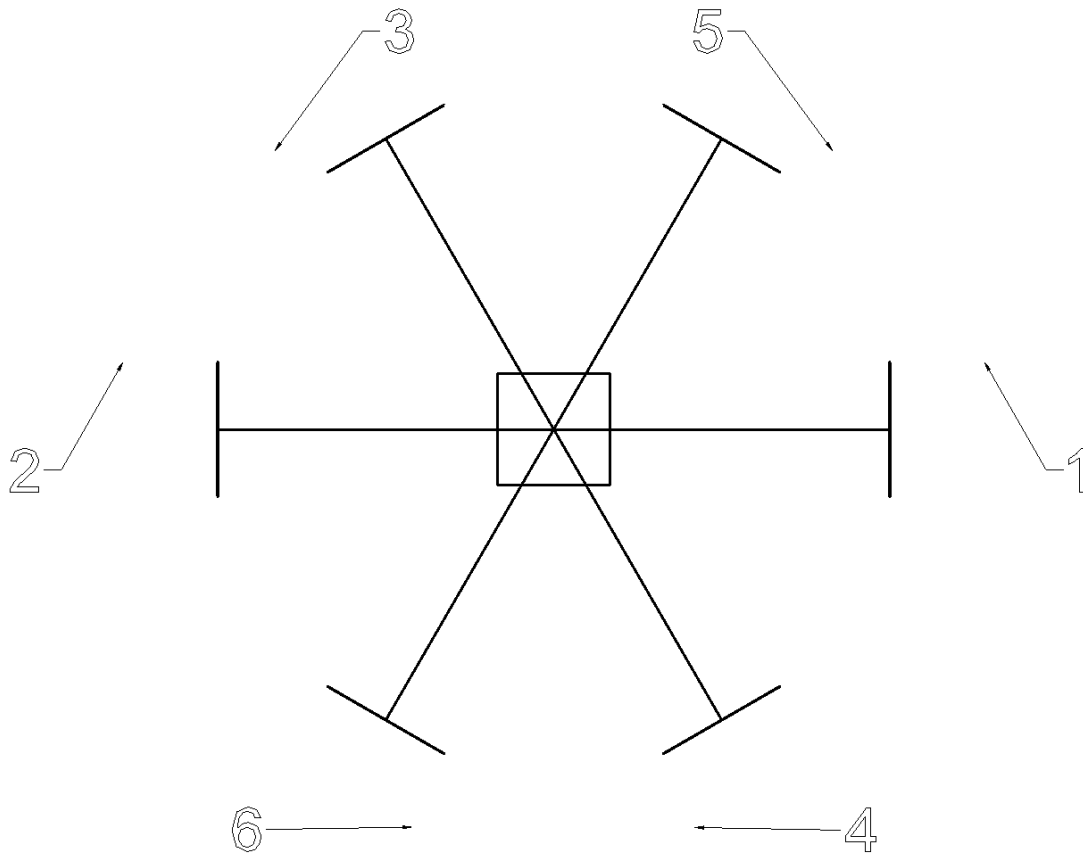
Figure 2.9: Up view shows how the motors are tilted

2.3.2   Construction

The only difference in construction is that the motors with rotors are tilted under a specific angle, usually 30 degrees. This drone is holonomic, it means that it can control all six

degrees of freedom. Figure Fig. 2.10 shows fully-actuated drone model in Gazebo simulator.

(a) Up view of fully-actuated drone

(b) Side view of fully-actuated drone
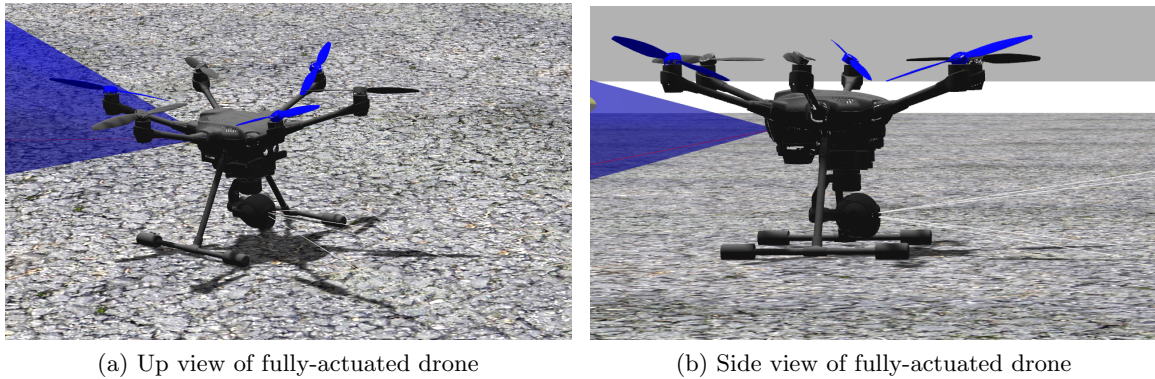
Figure 2.10: Model of fully-actuated drone in Gazebo simulator from up view Fig. 2.10a and from side view Fig. 2.10b

A conventional under-actuated quadcopter also has all six DOF, but only four motors. It leads to four controllable DOF. It can control angular velocity in each axis and total thrust, not tilt. As a fully-actuated hexacopter has six motors, it can control all six DOF. For that reason, it is not possible to create a fully-actuated quadcopter.

2.3.3   Flight modes

A fully actuated drone supports multiple flight modes. The mode under study is called zero tilt mode. During the movement, the drone does not tilt. A video of a flight can be seen in the attachment. Z-axis always aims straight down. Axis $\hat{X}_s$ is the desired yaw direction. Axis $\hat{Y}_s$ is perpendicular to $\hat{X}_s$. Visualized in Fig. 2.11
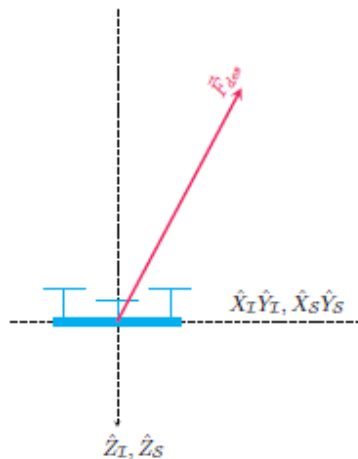
Figure 2.11: Model used for Zero tilt strategy [3]

Other mode that can be used is a fixed tilt mode. This means that the drone tilts under a specific angle without moving laterally. It allows the drone to tilt and move, tilted purposely. It is beneficial for mounting the cameras and sensors without any additional gimbals.

2.3.4   Advantages and disadvantages

The main advantage is that the drone can manoeuvre without tilting or tilt without moving. It is essential when the drone must pick up things from the ground or interact with the environment. This drone has higher energy consumption caused by a tilted motor with rotors. Cosine losses cause this. It is a angle between normal direction and a tilted direction.

$$1 - \cos(30°) = 0.1339 \tag{2.1}$$

$$1 - 0.1339 = 0.866 \tag{2.2}$$

It means that 1 kg of thrust is generated with 86.6 percent efficiency. If the efficiency would be 100 percent, it would generate 1.154 kg of thrust. For that reason, 15,4 percent of a thrust is lost by tilted motors.

By this construction, it has got a slower speed of movement.

Chapter 3

PX4

PX4 is an open-source control software for drones. It allows us to control the drone manually by radio control transmitter or prepare a flight path upfront [7]. The main advantage of PX4 is that it is open-source. This means that source code is publicly available for everyone. It allows modification of software by users. It is possible to interconnect it with sensors, global positioning system (GPS) or telemetry. PX4 provides an offboard mode that allows to control of the drone with an external computer mounted on the drone, where ROS is running. Offboard is the most used mode by MRS.

PX4 is a complex system that consists of smaller modules. These modules communicate with each other by sending messages. A module can read battery status, read data from sensors or control the drone movement. The most important modules are attitude, position and rate controllers. These controllers process position, velocity, yaw rate, pitch rate and roll rate. According to actual values and commands, they adjust the desired position, roll, pitch, yaw, and thrust.

Also PX4 team developed hardware flight controller Pixhawk. It is an advanced autopilot designed and made in collaboration with PX4 [8]. It contains magnetometer, barometer, accelerometer and gyroscope. It is a hardware control unit that processes data from GPS, telemetry and remote control (RC) receiver and sends commands to electronic speed controller (ESC). ESC is a hardware module allowing the Pixhawk to control speed of individual motors. Pixhawk sends signal to ESC and according to it, ESC regulates a speed of a motors.

3.1   Usage

PX4 system can be used not only for hexacopter drones. It can control quad-copters, planes, rovers, helicopters, boats, or balloons.

3.2   Simulation

Nowadays, simulations are used during development. This allows to test the drones without the risk of damaging drone parts in case of errors. For example, the simulation programs that can be used are Gazebo [9] or AirSim [10]. I was using the Gazebo simulator. It is a widely used program that allows interconnection with PX4. Gazebo simulator provides a graphical interface. It is user friendly and offers ROS integration. Detailed description of ROS is in chapter 5. It is possible to run it in real-time and pause it in the simulation. Also, it is very realistic. It has got precise physics. Gazebo contains a lot of plugins that can be used. It allows users to simulate wind. It is possible to manually control a drone with the QGroundControl program and test if everything works fine.

3.3   3D Model

Default PX4 come with predefined drones. Also, it offers a 3D model of a hexacopter drone with conventional construction without tilted motors. As this type of drone is not usual, I had to modify it by tilting the motors. The tilt angle of motors is 30 degrees. This 3D model is then used in Gazebo Simulator. It is a special SDF file that defines how parts are connected to each other, their position, collision areas or direction of rotation of the rotors. Individual modelled parts of the drone are saved in the form of standard triangle language (STL) file. These parts can be customised, for example, in Fusion 360.

When using default PX4 software, lateral forces are zeroed because rotors are turned in pairs against each other. Then the drone behaves like a normal under actuated drone.

3.4   Parameter definitions

Another vital part are files with parameter definitions. It contains parameters for proportional, integral, derivative (PID) controller and values defining maximum speed. Mixer processes commands from a computer and sends modified commands for the motors, detailed description of it is in chapter 4. Airframe definition also defines what mixers are currently used or if it is a drone, plane, or any other vehicle.

3.5   Re-implementation of Airlab´s work

As Airlab group work was very successful, I decided to use their part of the work in PX4 controllers and used them in this project. Some parts of the code were not used because they have been already implemented in the newest version of default PX4. The most used part is the Position controller that implements the flight modes of the drone. Also, parts of the code were not compatible with used libraries, so I had to reprogram them. I decided to use only zero tilt mode in agreement with my supervisor. This flight is the most useful for real world applications. This part of the work was done in the so-called low-level controller.

Chapter 4

Airlab work

As I mentioned in the related works section, the newest and the most successful implementation of fully actuated drones into PX4 software was done by Airlab group [3]. They managed to customise PX4 firmware so it can support fully actuated drones. It is also possible to use this firmware for normal under actuated drones. It has been tested in a simulated environment and also in real-world experiments. Unfortunately, this project ended three years ago. Since then, PX4 firmware has been updated many times, and things from the Airlab version have become incompatible. Now I will describe key features that the Airlab group added.

4.1 Mixer

4.2 Under-Actuated Mixer

During the flight, a computer generates commands for drone control. These commands are used as input into the mixer. Mixer processes these commands and sends modified commands for motors. The standard mixer for an under-actuated drone looks like this:

```
R: <geometry> <roll scale> <pitch scale> <yaw scale> <idlespeed>
R: 6x 10000 10000 10000 0
```

R Stands for multirotor mixer, which combines four control inputs (roll, pitch, yaw, thrust) into a set of actuator outputs intended to drive motor speed controllers [7]. Geometry defines if it is a quadrotor (4), hexacopter (6) or octocopter (8). Roll, pitch and yaw scale define the scaling of controls. Idle speeds determine the speed of motors in case all inputs are zero.

Each of these scaling factors is loaded every time PX4 is powered on. Then they are processed by a mixer. The mixer also processes a geometry file that contains information about each motor. It defines its name, position, axis and if the motors turn clockwise or counterclockwise. Each matrix has six columns because it is used by a hexacopter with six motors. A torque matrix, thrust matrix, and mixer matrix are created from this geometry file. In a torque and thrust matrix with dimension 3x, each column is the torque and thrust generated by one rotor in each axis [11]. The mix matrix is 6x6. Each column is the command to apply to the servos to get a roll, pitch, yaw torque x thrust, y thrust and z thrust [11]. This is performed by a python script that parses the geometry file.

Torque matrix of the under-actuated drone:

$$\begin{bmatrix} -1 & 1 & 0.5 & -0.5 & -0.5 & 0.5 \\ 0 & 0 & 0.87 & -0.87 & 0.87 & -0.87 \\ -0.05 & 0.05 & -0.05 & 0.05 & 0.05 & -0.05 \end{bmatrix}$$

Thrust matrix of the under-actuated drone:

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix}$$

Together they form matrix of the under-actuated drone:

$$\begin{bmatrix} -1 & 1 & 0.5 & -0.5 & -0.5 & 0.5 \\ 0 & 0 & 0.87 & -0.87 & 0.87 & -0.87 \\ -0.05 & 0.05 & -0.05 & 0.05 & 0.05 & -0.05 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix}$$

Mix matrix is computed as pseudoinverse of previous matrix of the under-actuated drone:

$$\begin{bmatrix} -0.33 & 0 & -3.33 & 0 & 0 & -0.17 \\ 0.33 & 0 & 3.33 & 0 & 0 & -0.17 \\ 0.17 & 0.29 & -3.33 & 0 & 0 & -0.17 \\ -0.17 & -0.29 & 3.33 & 0 & 0 & -0.17 \\ -0.17 & 0.29 & 3.33 & 0 & 0 & -0.17 \\ 0.17 & -0.29 & -3.33 & 0 & 0 & -0.17 \end{bmatrix}$$

Once the mixer is loaded, in an infinite loop, computation is running. Roll, pitch, and yaw are used as input for scaling. Each of these input values is clamped in the range from [-1.0,1.0] [11]. Then the mixing is performed.

Variable i stands for the index of the motor in the output vector out. Variable r is the roll angle, r_s is the roll scale, p is the pitch angle, p_s is the pitch scale, yaw is the yaw angle, yaw_s is the yaw scale, x_t is thrust in the x axis, x_s is the thrust scale in x axis , y_t is the thrust in the y axis, y_s is the thrust scale in the y axis, z_t is the thrust in the z axis, z_s is the thrust scale in the z axis , rot is a motor, t_f is the thrust factor, t is the thrust, and i_s is the idle speed.

$$out[i] = r * rot[i].r_s + p * rot[i].p_s + t * rot[i].t_s \tag{4.1}$$

Scale variables come from the mixer file described above. Then yaw is added to outputs according to the type of the drone.

$$out[i] + = yaw * rot[i].yaw_s \tag{4.2}$$

After this mixing is completed. The computed values are scaled by thrust factor, then they are constrained by idle speed defined in mixer file.

If $out[i] < 0$ then it is used:

$$out[i] = -(1 - t_f)/(2 * t_f) + \sqrt{(1 - t_f) * (1 - t_f)/(4 * t_f * t_f)} \tag{4.3}$$

Else:

$$out[i] = -(1 - t_f)/(2 * t_f) + \sqrt{(1 - t_f) * (1 - t_f)/(4 * t_f * t_f) + (out[i]/t_f)} \qquad (4.4)$$

$$out[i] = \begin{cases} i_s, & \text{if } i_s + (out[i] * (1 - i_s)) < i_s \\ 1, & \text{if } i_s + (out[i] * (1 - i_s)) > 1 \\ i_s + (out[i] * (1 - i_s)), & \text{otherwise} \end{cases}$$

Each motor output should be now in the range [idle,1] Visualization can bee seen in Fig. 4.1.
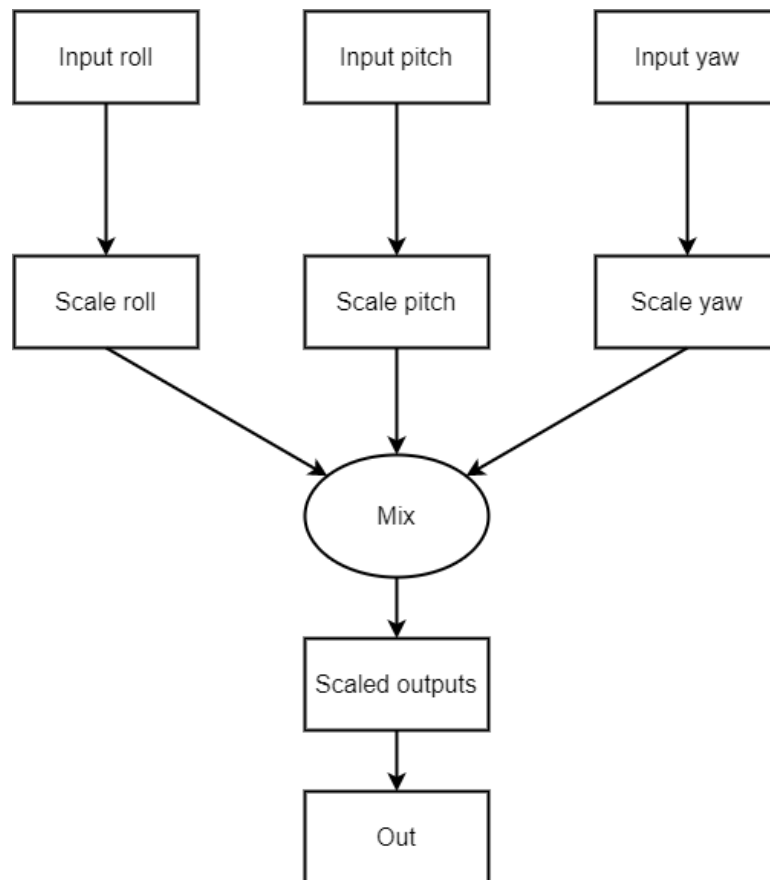
Figure 4.1: Diagram showing processing of additional parameters

4.3   Fully-Actuated Mixer

The fully actuated mixer looks like this:

```
S: <geometry> <roll scale> <pitch scale> <yaw scale> <idlespeed> <x_scale> <y_scale> <z_scale>
S: 6xt 10000 10000 10000 10000 10000 10000 0
```

S means that a fully actuated drone uses this mixer. Here are added scaling parameters for the computation of thrust in each axis. The reason is because of unwanted tilting during the

flight. Other parameters are same as for the under-actuated drone, mixer processing method is also same.

Torque matrix of the fully-actuated drone:

$$\begin{bmatrix} -0.84 & 0.84 & 0.42 & -0.42 & -0.42 & 0.42 \\ 0 & 0 & 0.73 & -0.73 & 0.73 & -0.73 \\ -0.54 & 0.54 & -0.54 & 0.54 & 0.54 & -0.54 \end{bmatrix}$$

Thrust matrix of the fully-actuated drone:

$$\begin{bmatrix} 0.5 & 0.5 & -0.25 & -0.25 & -0.25 & -0.25 \\ 0 & 0 & -0.43 & -0.43 & 0.43 & 0.43 \\ -0.87 & -0.87 & -0.87 & -0.87 & -0.87 & -0.87 \end{bmatrix}$$

Together they form matrix of the fully-actuated drone:

$$\begin{bmatrix} -0.84 & 0.84 & 0.42 & -0.42 & -0.42 & 0.42 \\ 0 & 0 & 0.73 & -0.73 & 0.73 & -0.73 \\ -0.54 & 0.54 & -0.54 & 0.54 & 0.54 & -0.54 \\ 0.5 & 0.5 & -0.25 & -0.25 & -0.25 & -0.25 \\ 0 & 0 & -0.43 & -0.43 & 0.43 & 0.43 \\ -0.87 & -0.87 & -0.87 & -0.87 & -0.87 & -0.87 \end{bmatrix}$$

Mix matrix is computed as pseudoinverse of previous matrix of the fully-actuated drone:

$$\begin{bmatrix} -0.4 & 0 & -0.31 & 0.67 & 0 & -0.19 \\ 0.4 & 0 & 0.31 & 0.67 & 0 & -0.19 \\ 0.2 & 0.34 & -0.31 & -0.33 & -0.58 & -0.19 \\ -0.2 & -0.34 & 0.31 & -0.33 & -0.58 & -0.19 \\ -0.2 & 0.34 & 0.31 & -0.33 & 0.58 & -0.19 \\ 0.2 & -0.34 & -0.31 & -0.33 & 0.58 & -0.19 \end{bmatrix}$$

$$out[i] = r * rot[i].r_s + p * rot[i].p_s + x_t * rot[i].x_s + y_t * rot[i].y_s + z_t * rot[i].z_s \qquad (4.5)$$

The rest of the mixer module works the same as the under-actuated one.

4.4 Controller

Usually, the default input for an under-actuated drone is desired yaw and desired position and/or desired position derivatives. These inputs are then processed in the position controller, and it outputs the full desired attitude setpoint for the attitude controller and thrust setpoints for the mixer module [3].

For a fully-actuated drone, it is a little bit different. As mentioned above, the mixer is modified to support a fully-actuated hexacopter. Then attitude setpoint generator is modified

to support zero tilt mode [3]. In the diagram Fig. 4.2 it is possible to see additional parameters added to the original PX4.
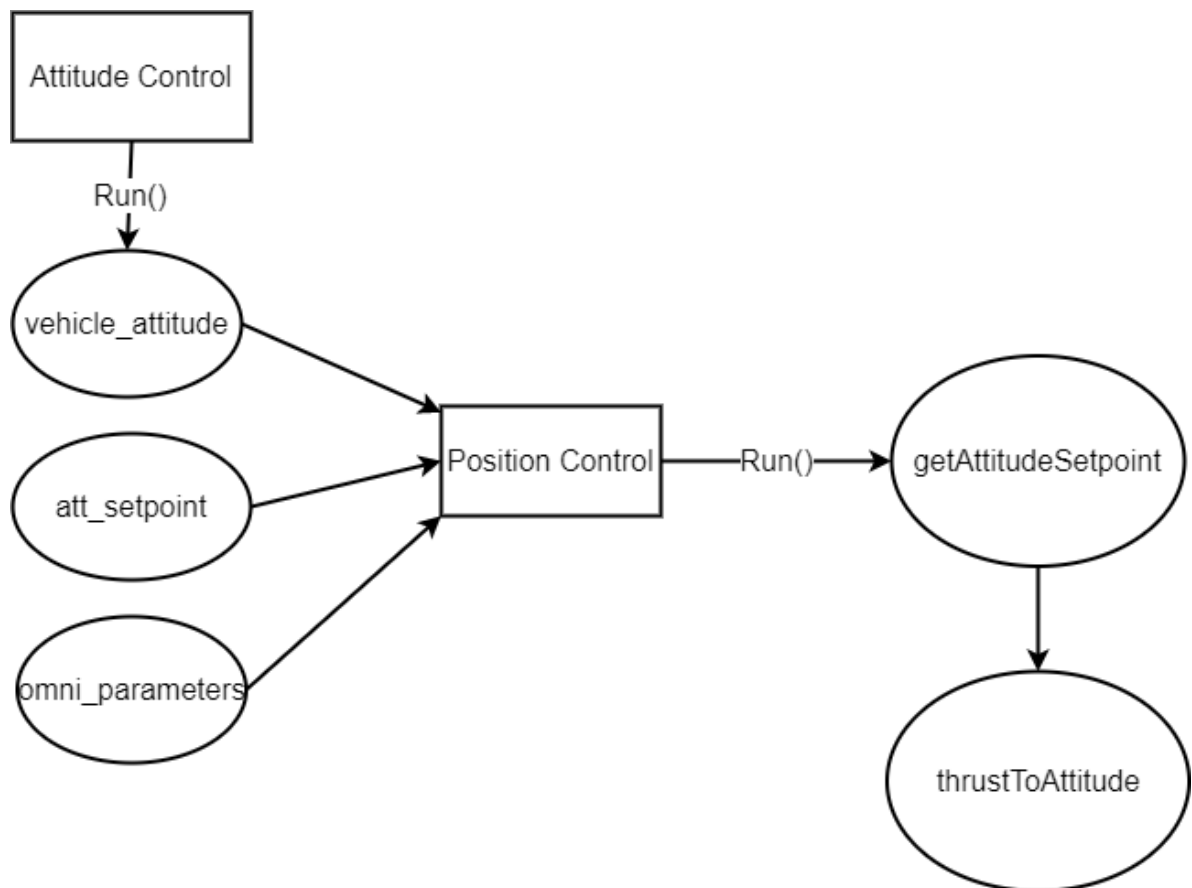
Figure 4.2: Diagram showing processing of additional parameters for position controller

Also, thrust setpoint generation had to be modified. This change is done in the rate controller. Whereas default PX4 is computing thrust only in the z-axis, the fully-actuated version computes thrust in each axis. Fig. 4.3 shows controller with modifications for a fully-actuated drone.
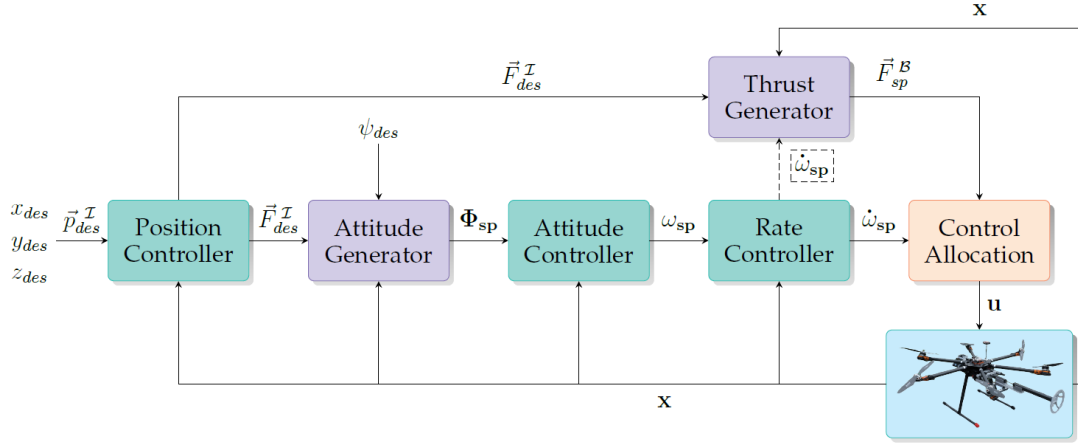
Figure 4.3: PX4 flight controller extended for fully-actuated multirotors. The input is the desired position (and/or its derivatives) and the desired yaw, requiring an Attitude Generation module to calculate the pitch and roll. [3]

4.4.1   Reference attitude setpoint generation for zero tilt mode

A position controller performs this. We select zero tilt mode by setting OMNI_ATT_MODE in airframe definition to 2. OMNI_DFC_MAX_THR is set to 0.1. Setting the value to lower means that the drone is more accurate and flies at lower speeds. Then in position controller, if the statement chooses according to the OMNI_ATT_MODE flight mode. Once zero tilt mode is set, three vectors are created. Individual vectors represent individual axes (x,y,z). Each vector contains coordinates of a rotated vector basis.

For x axis: $\begin{bmatrix} cos\ yaw_{des} \\ sin\ yaw_{des} \\ 0 \end{bmatrix}$

For y axis: $\begin{bmatrix} -sin\ yaw_{des} \\ cos\ yaw_{des} \\ 0 \end{bmatrix}$

For z axis: $\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$

Together they form a rotation matrix: $\begin{bmatrix} cos\ yaw_{des} & -sin\ yaw_{des} & 0 \\ sin\ yaw_{des} & cos\ yaw_{des} & 0 \\ 0 & 0 & 1 \end{bmatrix}$

First two columns present rotation by angle:

$$\mathbf{yaw}_{des} \in [0, 2\pi], \tag{4.6}$$

turns around the origin counter-clockwise [12]. The last column contains 1 because it is in the axis of rotation, which means that it is not changed during the flight. Then this matrix is copied to the attitude setpoint generator, and the valid flag is set to true.

4.5 Message

Important is adding a new type of message:

```
omni_attitue_status
```

Content of this message:

```
Time stamp
Attitude mode
Estimated tilt angle
Measured tilt angle
Estimated tilt direction
Measured tilt direction
Estimated roll tilt
Estimated pitch tilt
```

Then by adding defining parameters, it is possible to change drone behaviour. By this, it is possible to choose a flight mode. It determines the attitude setpoint generator that will produce setpoints for the attitude controller. The second parameter is an upper bound of maximum horizontal scaled thrust. Simply said, it determines how fast the drone will move.

Other parameters that are not needed for zero tilt mode

```
OMNI_ATT_MODE
OMNI_DFC_MAX_THR
OMNI_ATT_TLT_ANG
OMNI_ATT_TLT_DIR
OMNI_ATT_ROLL
OMNI_ATT_PITCH
OMNI_PROJ_AXES
```

As these parameters are not hard-coded in software, it is possible to easily change them by QGroundControl software without re-flashing and calibrating Pixhawk.

Chapter 5

Robot Operating System

ROS is an operating system that helps us with hardware abstraction, libraries, communication etc. It allows asynchronous communication between programs [13]. Thanks to it, we can use data captured by sensors with programs that process raw data, and according to data, the robot adjusts its behaviour.

5.1 Communication in ROS

The system consists of many processes; in ROS they are called rosnodes. These rosnodes communicate with each other by exchanging messages. If some rosnode wants to send messages, it starts publishing these messages to rostopic. Rostopic is a bus that allows message exchange between rosnodes. Once some process wants to receive a published message, it becomes a subscriber of a rostopic. For example, a rosnode reading the GPS data starts publishing data containing the position to a certain restopic. When another rosnode process wants to use this data, it subscribes to this rostopic.

5.2 MAVLink

Communication between PX4 and ROS is ensured by MAVLink [14]. It is a communication protocol based on sending messages. Messages are divided into many types. Currently MRS is using message SET_ATTITUDE_TARGET that contains [15]:

```
time_boot_ms –Timestamp
target_sytem –System ID
target_component –Component ID
type_mask –Bitmap to indicate which dimensions should be ignored by the vehicle.
q –Attitude quaternion (w, x, y, z order, zero-rotation is 1, 0, 0, 0)
body_roll_rate –Body roll rate
body_pitch_rate –Body pitch rate
body_yaw_rate –Body yaw rate
thrust –Collective thrust, normalized to 0 .. 1 (-1 .. 1 for vehicles capable of reverse trust)
thrust_body – 3D thrust setpoint in the body NED frame, normalized to -1 .. 1
```

5.3 3D Model

When using ROS in the Gazebo simulator, a different file format to represent a 3D model of a drone is used. Model is described by the unified robotic description format (URDF) file, it is an extensible markup language (XML) file. It defines the model's parts, orientation, colour, links, and joints. Again I customised the existing model of a hexa-rotor drone, where I adjusted the tilt of the motors.

5.4 Simulation

A simulation mentioned in chapter 3 uses only PX4 control software that is run alone. It controls the drone itself according to human input. Simulation running with ROS is more complex. Integration with ROS provides the ability to use additional sensors like thermal camera, lidar or ultrasound sensor. Individual rosnodes process data from these sensors. PX4 is also running, but it is receiving a specific type of message produced by rosnode from ROS that generates the content of the message according to a human or pre-prepared algorithm that allows movement according to the human or autonomously. It means that the whole setpoint generation is performed by ROS, not in PX4.

In order to run simulation smoothly, it is recommended to have a more powerful computer. Otherwise, it is possible to experience lagging. I have been using my notebook with: Intel Core i7-8750H 6-core processor, NVIDIA GTX 1070-8 GB and 16 GB operating memory. Everything was running smoothly. As this operating system is robust and uses a lot of processes that have to be executed in a specific order, I modified the existing script that prepares everything.

Once Gazebo simulator with ROS is running, it is possible to start controlling the drone. I created a python script that creates a publisher rosnode that sends messages to the drone. The drone then moves according to them. Thanks to it is possible to control the fully-actuated drone with zero tilt mode by ROS.

Message is called [16] :

```
mavros_msgs/PositionTarget Message
```

This message contains [15]:

```
time_boot_ms -time since system boot
target_system -system ID
target_component -component ID
coordinate_frame
type_mask -Bitmap to indicate which dimensions should be ignored by the vehicle.
3D vector of position
3D vector of velocity
3D vector of acceleration
yaw -yaw setpoint
yaw_rate -yaw rate setpoint
```

It contains the required position, acceleration or force and yaw rate. The message is published 30 times per second.

After publishing the message, the drone has to be armed. It means that the drone gets permission to spin motors. Then the drone switches to off-board mode, which means that the drone is not controlled by PX4 over manual control but by an onboard computer where ROS is running. Then the drone moves according to the content of the message. When the simulation is used, only one computer is used, and everything runs on it.

Following Fig. 5.1 shows picture of a drone during the simulation

(a) Landed drone in simulation
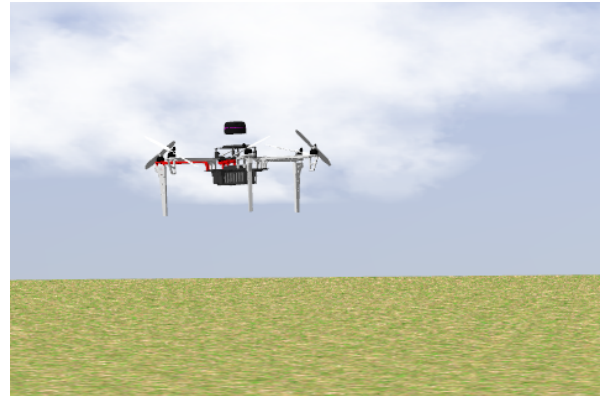
(b) Flying drone in simulation

Figure 5.1: Photo of a drones during the simulation

Fig. 5.2 shows info position, flight mode, usage of a computer and active rosnodes.

Figure 5.2: Custom visualizer created by MRS

Chapter 6

Assembly

I also designed and assembled the drone as a part of the thesis. I was assembling the drone at MRS Lab at CTU at Karlovo Namesti. The lab is very well equipped.

6.1   Tools needed

- iFixit driver kit
- Dremel variable speed rotary tool
- Pencil soldering iron
- Transformer soldering Iron
- Soldering accessories
- Hot air station
- Pliers
- Hand saw
- Meter
- Marker

During the process, I needed some tools. The most used tool was the iFixit driver kit, which contains a lot of bits and is very handy. Soldering irons are for soldering cables connecting motors, ESC and power-boards. The larger transformer soldering iron was used because it has more power needed when soldering thick cables to the power module. Hot air station is used on shrinking tubes that cover soldered cables.

6.2   Parts needed

- Frame: Tarot 680 PRO
- Motors: T-motor MN3510 700KV -6x
- Rotors: T-motor 13x4.4 -6x
- Battery: Tattu 6750mAh 4S
- ESC: BLHeli 32, 51A -6x
- Pixhawk 4 + GPS
- Pixhawk Power Module
- RC transmitter: Hitec Flash 8
- RC receiver: Hitec Optima SL
- Garmin Lidar Lite V3
- Intel NUC PC
- Cables
- Screws
- 3D Printed parts

6.2.1   Frame Tarot 680 PRO

I used Tarot 680 PRO shown in the picture Fig. 6.1. This frame is made from carbon-fibre composites. This makes the structure very durable and light. As it is foldable, it is possible to transport it quite easily, and it is less prone to damage. The main reason why I chose this frame is that the motor mounts are rotatable, which can be seen in Fig. 6.2. It allows rotating the whole mount with the motor at the 30° degree tilt needed by a fully actuated drone without additional adapters. Also, it is possible to quickly rotate motors back and use a drone as an under-actuated one. I used the inertial measurement unit (IMU) in my phone to measure the tilt angle with an application that showed me the actual angle. At first, I calibrated it on the table and then used it to tilt the motors.
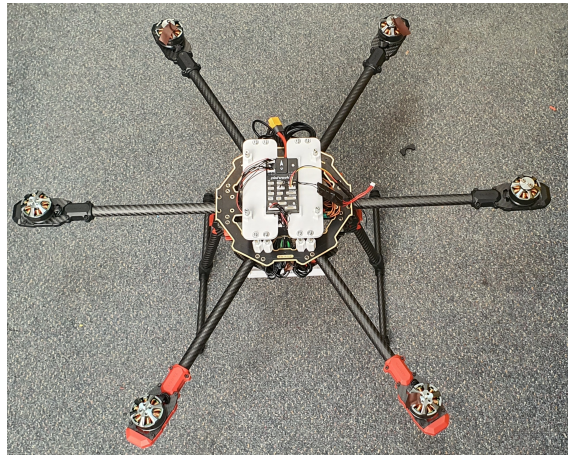
Figure 6.1: Tarot T680
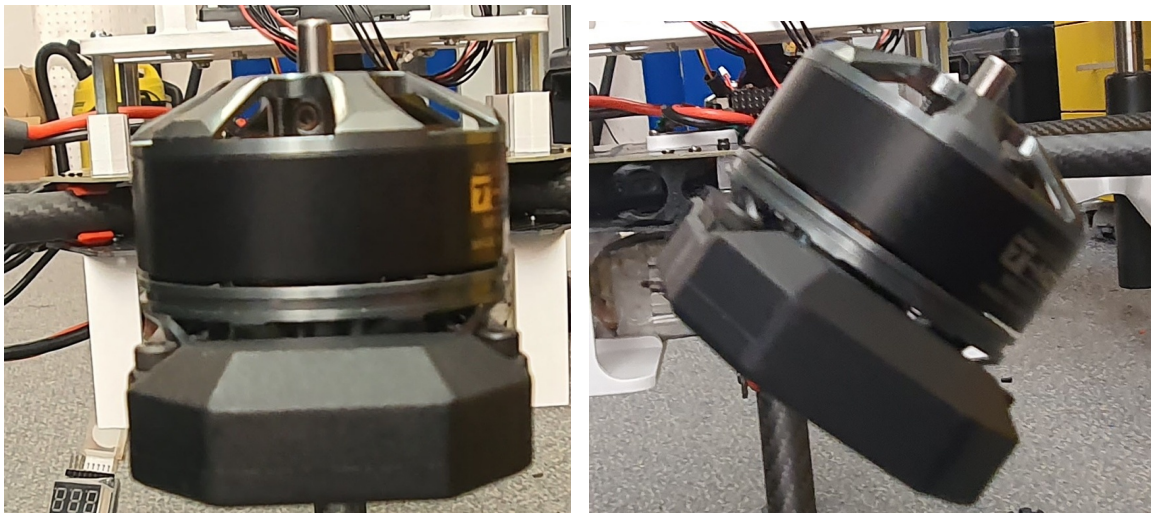
| (a) Motor without tilt | (b) Motor with tilt |

Figure 6.2: Comparison of normal variant in Fig. 6.2a and tilted one in Fig. 6.2b.

6.3   Designing parts

Some parts of the drone needed very specific holders. The easiest way was to 3D print them. While designing, I used the program Fusion 360 because I have already used it for several years and had a practice with it. Fusion 360 has got very intuitive user interface, and for me, as a student is free. These modelled parts can be found in the attachment.

I scanned the drone carbon board on a multi-functional printer and used it as a canvas to make modelling easier. It allowed me to see all internal holes for mounting. Once I designed all mounts and holders, I could see how the drone's base would look. Figure Fig. 6.3a shows drone model in Fusion 360. The yellow part is the drone base; the red part is Intel NUC, Pixhawk, Pixhwak power module and battery. The grey parts are custom-designed in Fusion 360. Figure Fig. 6.3b shows real look of a drone base.
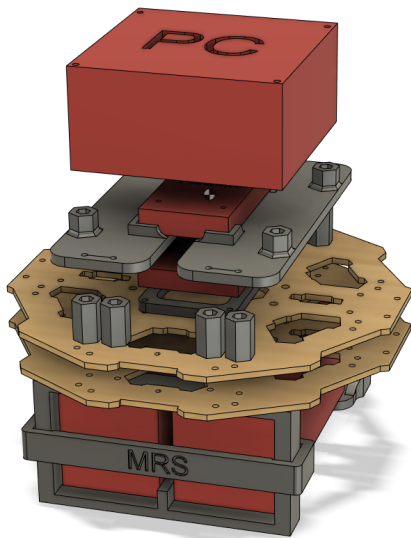
(a) Designed parts in Fusion 360.   (b) Real view
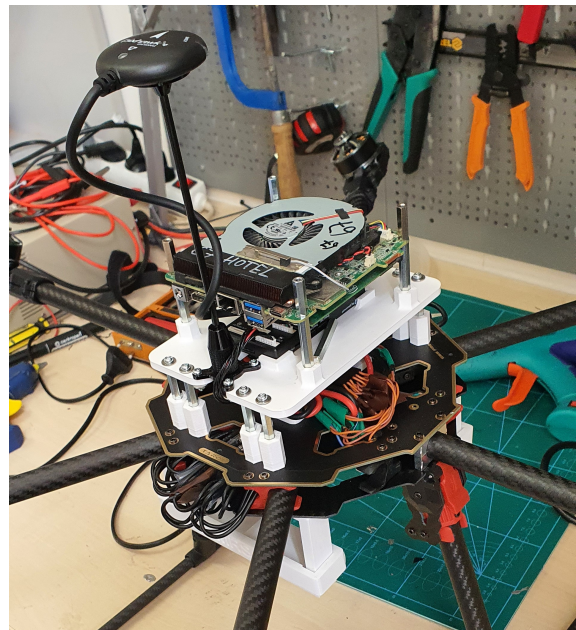
Figure 6.3: Comparison of modeled Fig. 6.3a and real Fig. 6.3b.

6.3.1   Battery holder

The Tarot frame has one battery mount and is not very stable. I designed a custom mount that can hold two batteries. I created additional clips that helped to hold the battery. Both parts can be seen in Fig. 6.4
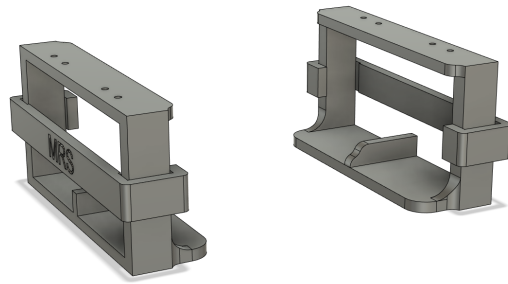
Figure 6.4: Custom designed battery holder in Fusion 360

6.3.2   Power module and computer holder

Due to extra parts that usually are not mounted on the drone, I had to design a holder for a power module seen in Fig. 6.5a. The computer holder is for the Pixhawk computer, and the Intel NUC PC is mounted on the drone's top, seen in Fig. 6.5b.
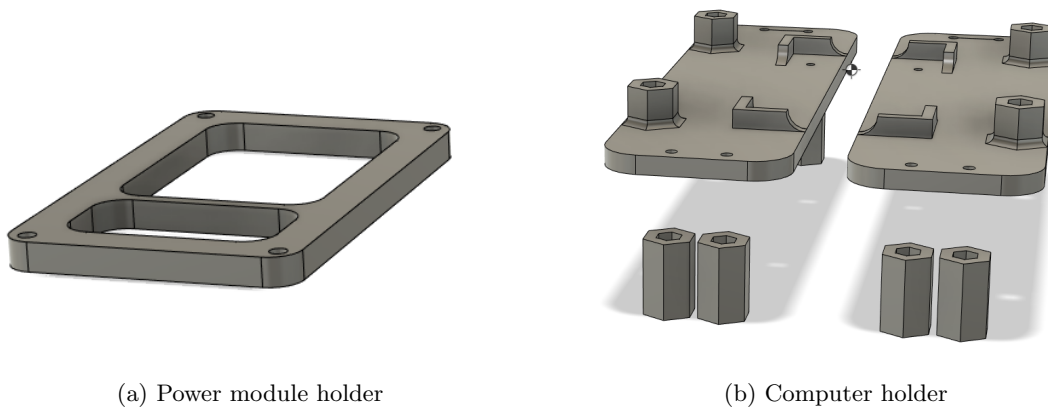
(a) Power module holder

(b) Computer holder

Figure 6.5: Render in Fusion 360 of power holder Fig. 6.5a and the computer holder Fig. 6.5b.

6.4   Printing parts

All parts were printed on 3D Printer Prusa MK2.5 with Octoprint. Octoprint is software that allows me to monitor printer over the internet. I used white and green Devil Design brand PETG material. I have chosen PETG because it is very durable and temperature resistant. Parts were printed with 0.20 mm layer height with Linear Advance, 20 percent infill and two perimeters. Linear Advance is a software feature that allows printers to print at higher speeds. Each filament has to have separately calibrated printer values. Otherwise, printing is not accurate and risky. The real look of parts can be seen in figure Fig. 6.6.

(a) Printed battery holder   (b) Printed computer holder   (c) Printed power module holder
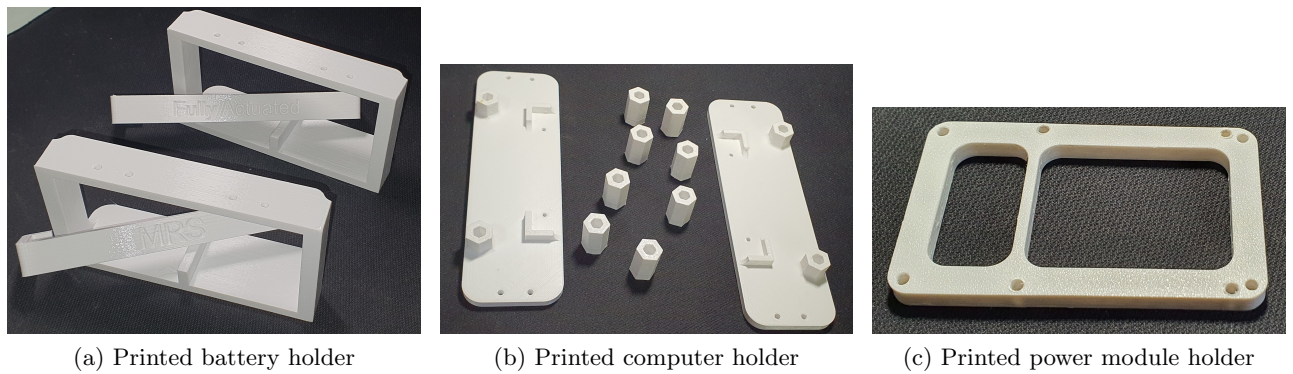
Figure 6.6: Printed parts

6.5   Assembling

The assembly process of the frame was straightforward. I followed the manual for frame assembly. As I used some motors from older, not functional drones, I had to disassemble them first. Motors had too short cables. I had to extend them. Then came for me the most challenging part, the soldering. Cables for motors are pretty thick, and printed circuit board (PCB) of ESC and the power module are multilayered, which means that it takes time until everything is warmed up. It means that high power soldering iron set at high temperature has to be used. Then I had to interconnect ESC, power module and Pixhawk.

After completing the hardware assembly, I moved on to the Pixhawk setup. By program called QGroundControl, I updated firmware to the latest stable version of default PX4. I set a generic hexarotor frame and calibrated sensors according to the instructions. Then I paired the RC receiver mounted on the drone with the RC transmitter. Set proper channel setup, calibrated transmitter and set the flight modes. Then I connected the battery and calibrated ESC and set fail-safe actions. These actions are used when some unexpected event happens. I set a warning for low battery. For RC loss, the drone will land.

With the help of my supervisor, we updated ESC firmware and set the correct direction of rotation of motors. Once everything was prepared, I mounted rotors and tested the drone with an under-actuated PX4 build. After a successful test flight, I tilted the motors and tested the drone with default PX4. PX4 default software was capable of controlling the drone with tilted motors with the behaviour of an under-actuated drone. Then I used a custom PX4 that supports a fully actuated drone for the last part. The last part was tweaking parameters that made controlling the drone easier and more stable.

When using RC transmitter to control the drone, it is possible to choose from two modes. These modes can be changed by a switch located on the transmitter. The drone behaves like a normal under-actuated drone in manual mode, which means that it does tilt when moving. It is possible to switch to position mode. Then it behaves like a fully-actuated drone with zero tilt mode.

Chapter 7

Experiments

7.1 Simulated flight

I simulated drone flight in a Gazebo simulator, controlling the drone by QGroundControl for many hours. During that time, nothing unexpected happened. I was controlling the drone by virtual stick, which is very similar to real controlling by RC transmitter. It was possible to control the drone in manual mode as an under-actuated one and in position mode as a fully-actuated one. I tried taking off, landing and flying. In the air, I tried moving the drone successfully. The slow movement was very smooth, from full movement to sideways and then full move to the opposite side was also good. Also, the drone reacted very well when wiggling with the virtual stick. Then I prepared several scenarios that are available in the QGroundControl program. At first, the drone was orbiting, and then the drone was following the path defined by waypoints. The fly path is visualised on a satellite map with a random place on the Earth. In the attachment, it is possible to find a recorded video of an orbiting, way-point following and manual flight of the drone.

7.1.1 Flight log PX4

Each flight is recorded by PX4 software and saved in a log file. When using simulation, these logs are saved to the hard drive of a computer. Then PX4 offers a web tool that processes these logs and visualises them [17]. It records minimum, maximum speed, flying distance, tilt angle, and flight time. It contains 3D visualisation of a flight. It is possible to see when the drone was controlled in manual and position modes. Graphs show tilt angles, local position, velocity in each axis, acceleration, GPS noise, and generated thrust. These log files can be found in the attachment.

Flight mode, where zero tilt mode is used, has a green background. It is a position mode. In the Fig. 7.1, it is visible that the under-actuated drone has a much bigger roll angle during the flight in comparison with the fully-actuated drone shown in the Fig. 7.2
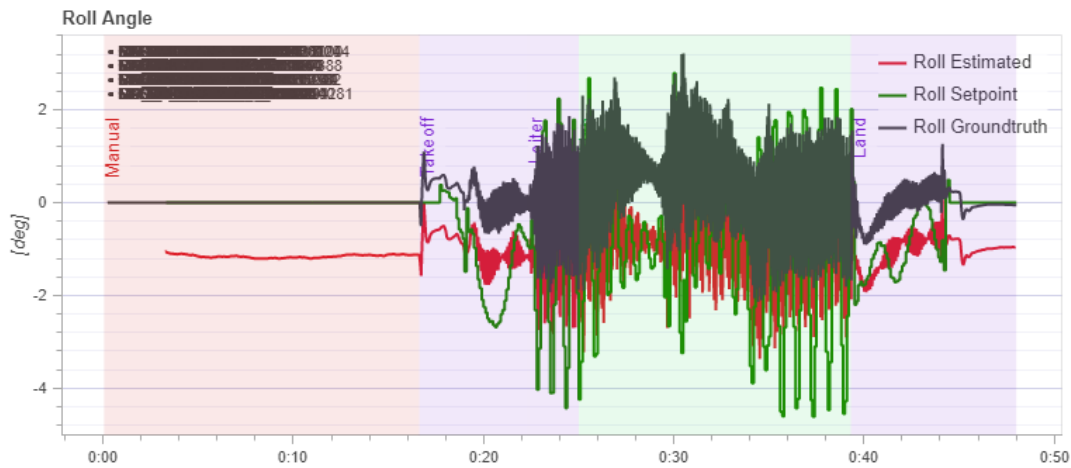
Figure 7.1: Roll angle of under-actuated drone during the simulation flight.
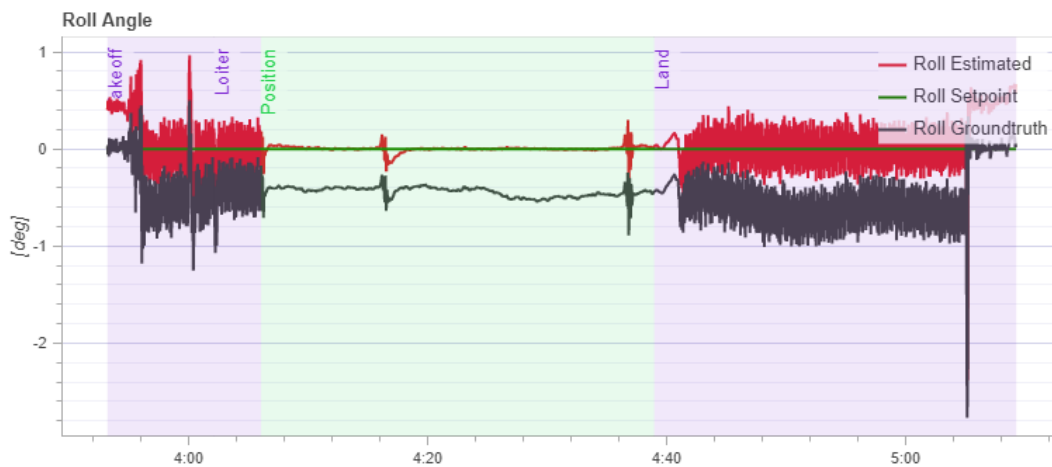
Figure 7.2: Roll angle of fully-actuated drone during the simulation flight.

In the Fig. 7.3, it is visible that the under-actuated drone has a much bigger pitch angle during the flight in comparison with the fully-actuated drone shown in the Fig. 7.4, two deviations in the graph at a time around 4:16 and 4:36 is caused because the drone changed movement from full movement forward to full movement backward. Still, this deviation is less than three degrees. Therefore, it is negligible.
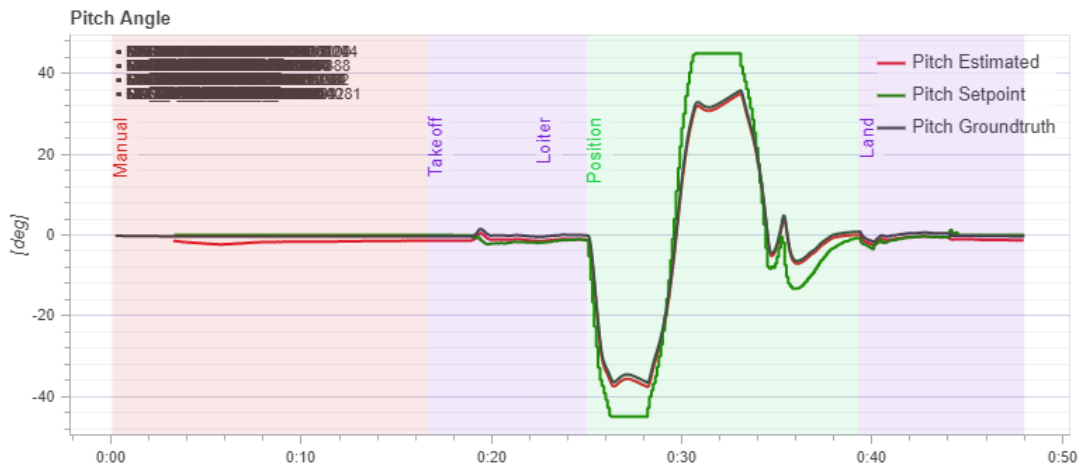
Figure 7.3: Pitch angle of under-actuated drone during the simulation flight.
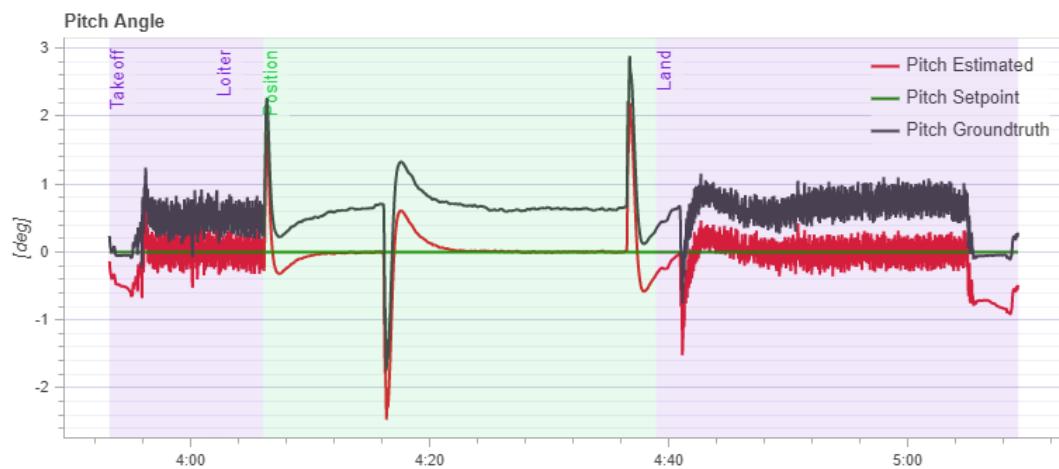
Figure 7.4: Pitch angle of fully-actuated drone during the simulation flight.

In the Fig. 7.5 it is possible to see velocity of a under-actuated drone during the simulation flight.
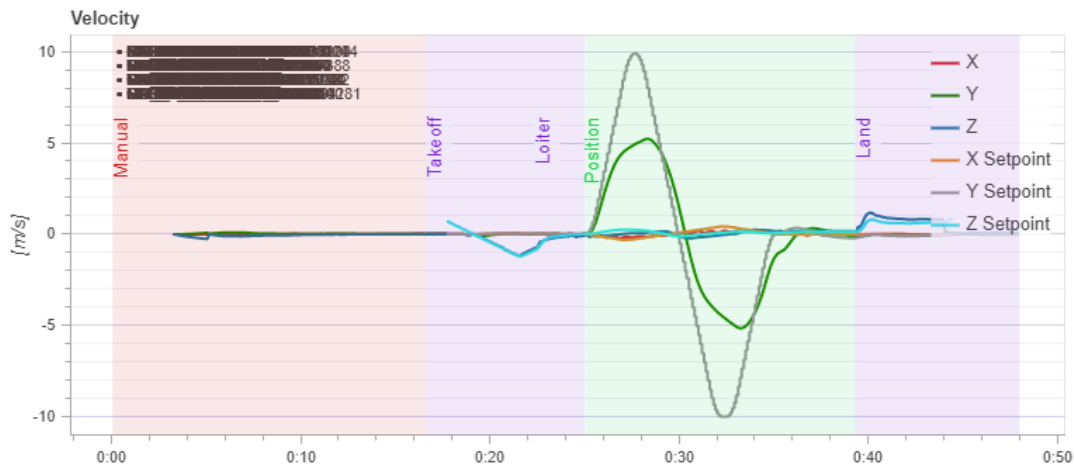
Figure 7.5: Velocity of under-actuated drone during the simulation flight.

In the Fig. 7.6 it is possible to see velocity of a fully-actuated drone during the simulation flight.
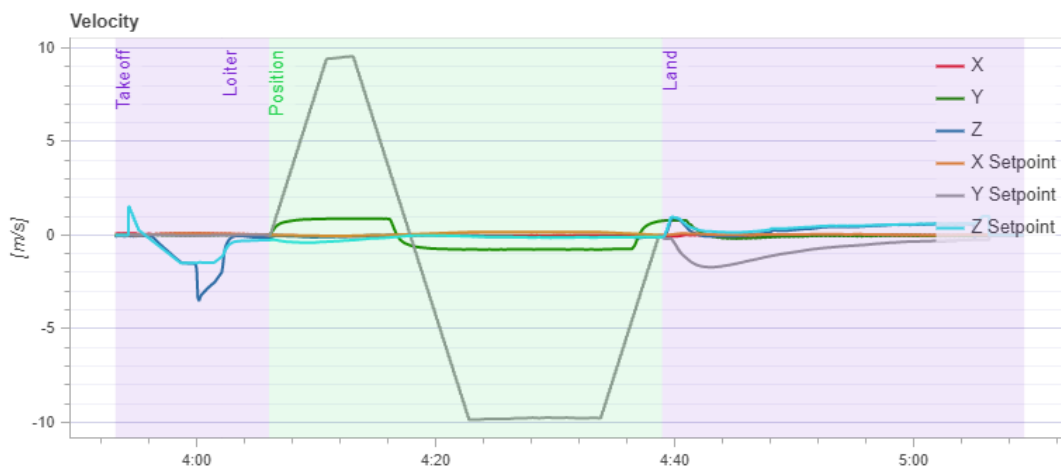
Figure 7.6: Velocity of fully-actuated drone during the simulation flight.

7.1.2   Flight log ROS

The following graphs shows flight log while using PX4 in offboard mode with ROS. Graph Fig. 7.7. shows roll angle of fully-actuated drone.
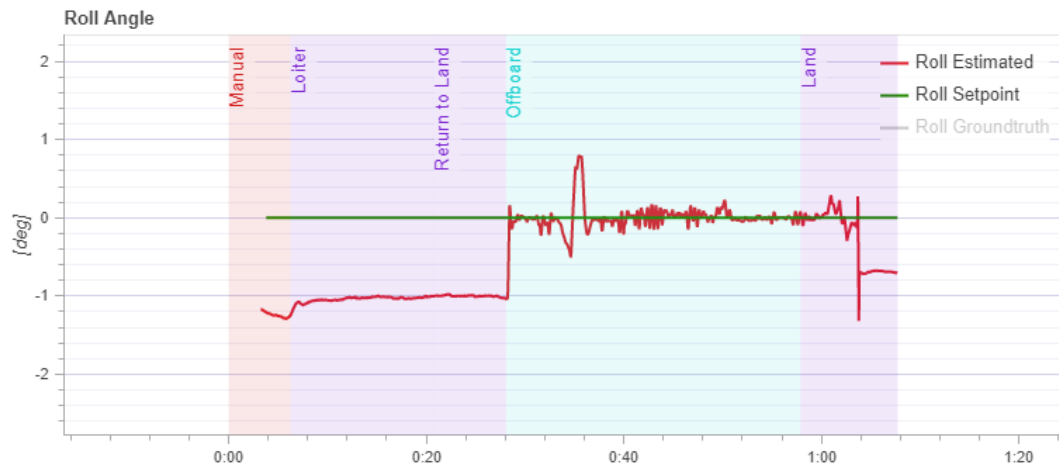
Figure 7.7: Roll angle of fully-actuated drone during the real flight.

Graph Fig. 7.8. shows pitch angle of fully-actuated drone.
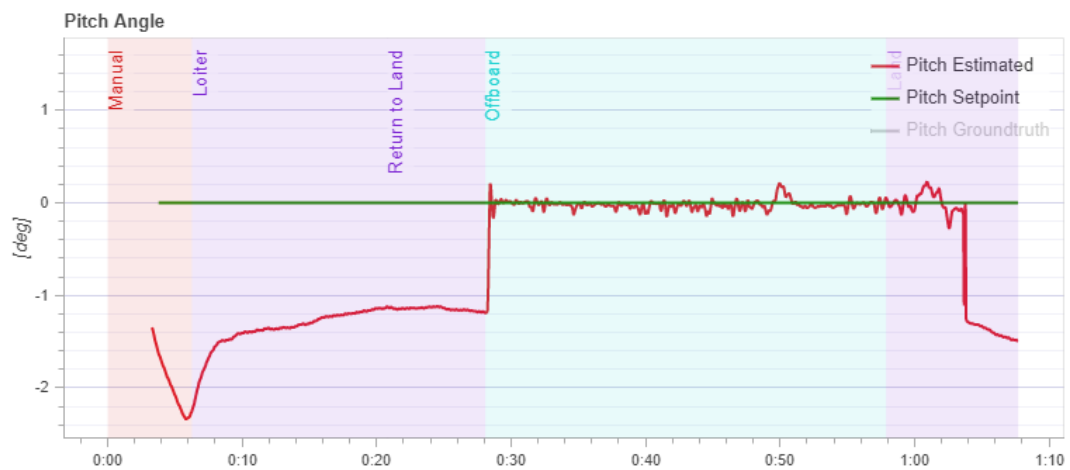
Figure 7.8: Pitch angle of the fully-actuated drone during the real flight.

Following graphs shows, how the drone was moving during the flight in X axis in Fig. 7.9, in Y axis in Fig. 7.10
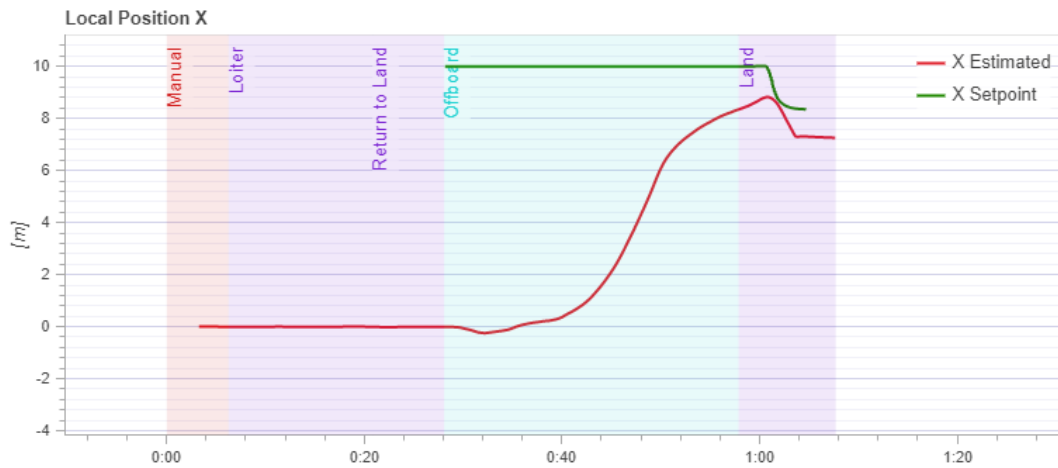
Figure 7.9: Movement in X axis.
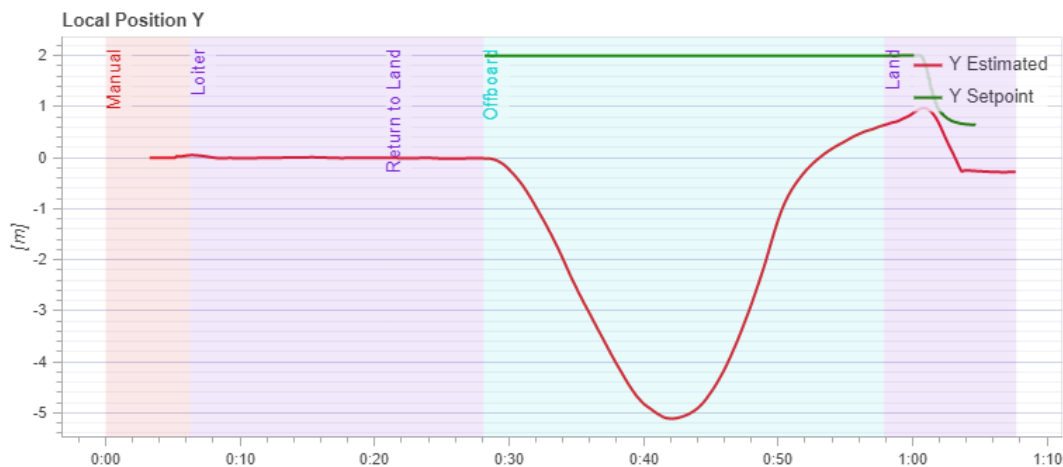
Figure 7.10: Movement in Y axis.

7.2 Real flight

The drone was tested during the MRS camp in Temešvár near Písek. An experienced pilot operated it. The drone was tied with a rope to a heavy barrel for safety reasons. In the event of unexpected behaviour, the drone would not fly away uncontrollably and could not endanger other people. The flight was performed on a meadow with enough space. Drone prepared to fly can bee seen in Fig. 7.11. Drone flying in the air can be seen in the Fig. 7.12.

Figure 7.11: Ready to fly drone

Figure 7.12: Flying drone

Graph Fig. 7.13. shows the roll angle of the fully-actuated drone during the real flight. Again, part of the graph with green background shows the usage of zero tilt mode; the red part is a manual mode where the drone tilts.

Figure 7.13: Roll angle of fully-actuated drone during the real flight.

Graph Fig. 7.14. shows pitch angle of fully-actuated drone during the real flight. Again, part of the graph with green background is showing the usage of zero tilt mode, the red part is manual mode where the drone tilts.

Figure 7.14: Pitch angle of the fully-actuated drone during the real flight.

Following graphs shows, how the drone was moving during the flight in X axis in Fig. 7.15, in Y axis in Fig. 7.16 and in Z axis in Fig. 7.17

Figure 7.15: Movement in X axis.

Figure 7.16: Movement in Y axis.

Figure 7.17: Movement in Z axis.

Last graph shows, how the velocity changed during the flight in Fig. 7.18
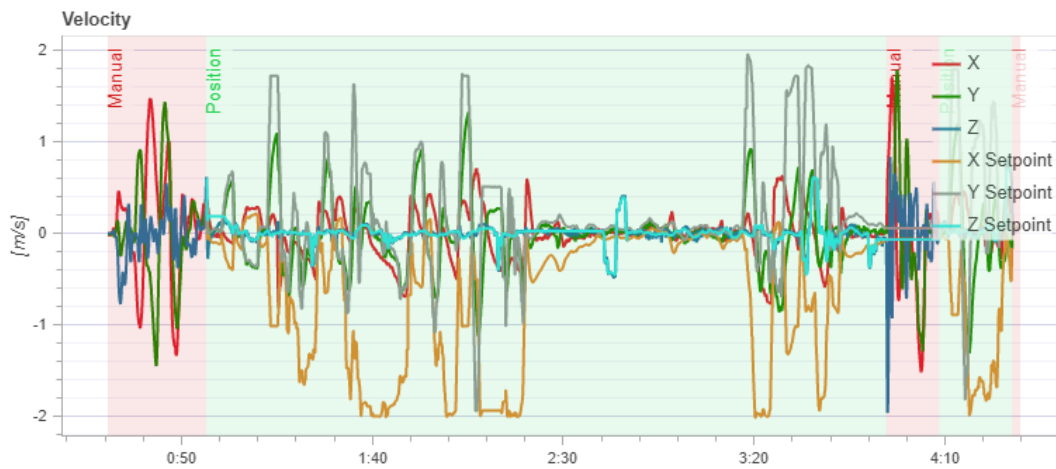
Figure 7.18: Velocity during the flight.

From the graphs above, it is clear that this zero tilt mode is working. The drone's tilt angle is minimal during this mode compared to a normal under-actuated drone. The minimal tilt angle occurs only where the drone moves to the side under full throttle, and then it gets a command to move to the opposite side. However, this minimal angle could be eliminated. It would make the drone very slow and unresponsive. Changing the direction of movement would take too long. This setting is a compromise.

Chapter 8

Business plan

As a part of the thesis, I created a business plan for a company that will deal with the development, assembly and service of drones. It is a company that produces fully actuated drones. The aim is modularity and possibility to exchange components easily.

8.1 Company informations

Field of business: Development, assembly and drone sale.

The legal form of business: Self-employment.

Owner: Majitel: Jan Zejda 30.01.1999, Oboře 381, Trhový Štěpánov, 257 63

Company headquarters: Říčany, Praha-východ

Initially, this company will be run as a secondary activity to the primary employment.

8.1.1 Structure of the company

The company owner will be Jan Zejda, who will also be the only employee from the beginning. As the company grows, it most likely will employ other people, mainly programmers and technicians. The company may become a limited liability company in the future.

8.1.2 Location of the firm

The company will rent an office in Říčany. There is a need for a computer room where the development will be done, customer meetings and another room for servicing and construction of the drones. For better accessibility, I choose Říčany because it is near Prague and the highway.

8.2 Product description

The usual drone consists of several motors, rotors, a frame and a computer. The developed drone is constructed from six motors tilted under a specific angle. Detailed description of the product is in chapter 2.

8.2.1 Dis-advantages of normal drone

As the standard drone has to tilt to move forward, we need to use additional stabilisers for cameras and other sensors. Integration with the environment is, because of it, a way harder.

8.2.2   Advantages of fully actuated drone

The main benefit is that this drone does not have to tilt while moving. It allows the drone to collect objects from the surface at a specific angle. It means that no special stabilisers are needed when using cameras. The open-source system is an advantage. It allows users to tweak and improve control software. Some drone parts are printed on a 3D printer, making the drone cheaper. Also, users can print on their own 3D printed parts.

8.3   Market analysis

The leading competitor is the mass manufacturer DJI, which offers drones from 7 500 CZK. DJI The Mavic Mini includes a camera along with GPS. That drone is listed as the best-selling drone of this brand on the Alza.cz [18] website. Its weight is only 250 g. The advantage is its low price. The disadvantage is the impossibility of installing external equipment on the drone. Other products of this company include model Mavic 3 starting from 53 000 CZK up to 125 000 CZK on Alza.cz. Models vary by camera type, flight time, transmission range for control and maximum speed. Not one, however, non-genuine equipment can not simply be fitted on any of the DJI drones.

Another seller of the drones is the manufacturer Syma. It sells drones from 3200 CZK on Alza.cz, but these drones are considered as toys. They usually have a lower quality camera and poorer control.

8.3.1   Competitors evaluation

Manufacturers produce very affordable drones. Unfortunately, they use designs that are very hard to modify in most cases. Whether it is exchanging the camera for another, replacing components, or installing additional sensors. None of the manufacturers has a drone capable of flight without tilting or targeted tilting during the flight.

8.3.2   Customers evaluation

The primary target is the companies that use drones to inspect high-rise, dangerous or brittle buildings. However, this type of drone is also suitable for rescuers who use drones to discover people and map the situation. It can also be used in agriculture, where a drone can serve as a data collection machine on the field.

8.3.3   Supplier evaluation

There is a smaller supply of components needed for drone construction in the Czech Republic. Luckily, there are shops globally that provide international shipping and import to the Czech Republic. The advantage is the ability to assemble the drone with other but similar components. Thanks to it, the company is not dependent on one particular product type and can react to the unavailability of goods or sudden price changes.

8.4   Marketing

Due to its higher price and specific use, the product is not aimed at mass production but rather for companies dealing with the help of drones to capture data. The goal is to address clients at technology fairs or personal visits to the universities which have the potential that they will use the drone. It is expected that companies will rather order one piece, which they will then test for some time and make another order in the case of satisfaction.

8.5   Management and sources

8.5.1   Aim of this project

The main goal is to create a company that thrives and can develop from the profit from sales. In case of significant success in the Czech Republic, expansion into a foreign market is possible.

8.5.2   Project funding sources

The primary source of money will be the shareholders' equity and the loan from the bank, which will cover initial costs. The loan will be repaid within five years with an interest rate of 12 percent.

8.5.3   Aditional info

The office will be used five days a month. The machine's depreciation rate is linear, 20 percent of the purchase price. As long as the demand can be met, the only employee will be the business owner. In case of significant demand, employing other people for software development, assembly, and servicing the drones is possible. The advantage is that the work on the software can be done externally so that the company can attract students.

8.6   Strategies

The primary goal is to create a drone that can fly without tilting when moving. If this drone will be successful the development of the drone which would intentionally tilt during the flight will begin.

8.6.1 SWOT analysis

	Strengths	Weaknesses
Opportunities	Qualified staff Reaching large clients Establishing long-term cooperation	Reliability of machines Sales stability
Threats	New technology	Insufficient profit for the operation Outrunning by the competition Lack of interest in the product

Table 8.1: SWOT analysis.

8.7 Technology

The listed prices are valid as of 16.12.2021, including VAT. All tables and computations are available in the attachment. To minimise costs, one computer will be used from the beginning for everything- software development and modelling parts, communication with customers and advertising. The soldering station will be used for soldering cables or ESC. 3D Printing will be used, thanks to which it is possible to print the designed parts cheaply. A printer kit will be purchased to reduce costs and assembled. Detailed list of tools is listed in table 8.2.

Equipment				
Component type	Component name	Price per unit [CZK]	Number of units	Total price [CZK]
PC	Dell G5 15 Gaming (5500) Black	37 500,00 CZK	1	37 500,00 CZK
Phone	Samsung Galaxy S21	22 000,00 CZK	1	22 000,00 CZK
3D Printer	Prusa i3-MK3S	20 000,00 CZK	1	20 000,00 CZK
Hot air station	48W SL-20CMC	2 200,00 CZK	1	2 200,00 CZK
Tools		2 500,00 CZK	1	2 500,00 CZK
Total		84 200,00 CZK		84 200,00 CZK

Table 8.2: List of needed tools for assembly and usual work at company

8.7.1 Estimated cost of the drone parts

Costs are calculated for the material as of 8.12.2021. They are calculated just for the material. The total cost of the drone is 60 700 CZK. If I count in development, salary and other things, it will be sold for 100 000 CZK in the first year. Detailed list of drone parts is listed in table 8.3.

Drone parts				
Component type	Component name	Price per unit [CZK]	Number of units	Total price [CZK]
Frame	Tarot 680	3 000,00 CZK	1	3 000,00 CZK
Motor	T-motor MN3510 700KV	1 700,00 CZK	6	10 200,00 CZK
Rotor	T-motor 13x4.4 pár	900,00 CZK	3	2 700,00 CZK
ESC	ESC - BLHeli 32, 51A	450,00 CZK	6	2 700,00 CZK
Cables		1 500,00 CZK	1	1 500,00 CZK
Battery	Tattu 6750mAh 4S	2 400,00 CZK	2	4 800,00 CZK
Computer	Pixhawk 4 + GPS	6 000,00 CZK	1	6 000,00 CZK
RC transmitter	Hitec Flash 8	5 500,00 CZK	1	5 500,00 CZK
GPS	Garmin Lidar Lite V3	2 700,00 CZK	1	2 700,00 CZK
RC receiver	Hitec Optima SL	1 600,00 CZK	1	1 600,00 CZK
PC NUC	Intel NUC PC	20 000,00 CZK	1	20 000,00 CZK
Total		45 750,00 CZK		60 700,00 CZK

Table 8.3: List of needed tools for drone

8.7.2 Estimated additional costs

The car is needed to transport materials and products to trade fairs and the customers. For simplicity, a lease is chosen because it includes summer and winter tires, insurance and service checks. The sum of these costs for the year is then reported in the income statement and cash flow as rent. A detailed list of additional estimated costs can be seen in table 8.4.

Other				
Component type	Component name	Price per month [CZK]	Number of units	Total price [CZK]
Car lease	Skoda Octavia	11 000,00 CZK	12	143 012,00 CZK
Phone tariff	Vodafone Tarif	500,00 CZK	12	6 512,00 CZK
Office rent	Říčany, okres Praha-východ	7 500,00 CZK	12	97 512,00 CZK
Internet	Vodafone Internet	500,00 CZK	12	6 512,00 CZK
Modelling software	Fusion 360	900,00 CZK	12	11 712,00 CZK
Material	Filament	1 000,00 CZK	12	13 012,00 CZK
Other software	Windows10, Microsoft Office...	4 000,00 CZK	1	4 001,00 CZK
Total		25 400,00 CZK		282 273,00 CZK

Table 8.4: List of costs during the year.

8.8 Financing

8.8.1 Necessary finances

It can be seen from the above costs that at least 220 000 CZK will be needed to get started. The sum consists of costs for needed tools, assembly of the one drone used for advertising purposes and costs needed to pay rent and other services for the first three months of its existence before the company begins to generate profit. After considering unexpected expenses, it is ideal to have 300 000 CZK initially.

8.8.2   Funding source

The primary source of money will be the shareholders' equity which amounts to 100 000 CZK. The bank will provide the remaining 200 000 CZK in the form of a loan with an interest rate of 12 percent. How the amount of interest and amortisation changes in the years can be seen in table 8.5.

Loan					
Year	1	2	3	4	5
Interest	24 000 CZK	20 222 CZK	15 991 CZK	11 252 CZK	5 944 CZK
Amortization	31 482 CZK	35 260 CZK	39 491 CZK	44 230 CZK	49 537 CZK
Left	168 518 CZK	133 258 CZK	93 767 CZK	49 537 CZK	0 CZK

Table 8.5: Detailed list of loan

8.9   Finance

8.9.1   Realistic scenario

The company´s annual growth in the number of units sold is expected to be 5 percent. I estimated that the company would sell 15 drones per year, with a 5 percent increase each year. As there is inflation, the material has become more expensive over the years, so the product is also more expensive. Inflation is calculated at 4 percent per year. At the same time, salary for employees is increased by 4 percent per year.

At the end of the 5th year, two additional computers worth 40 000 CZK each, a mobile phone worth 20 000 CZK, two additional drones intended for advertising for 125 000 CZK, another 3D printer for 25 000 CZK and other tools, all in total for 300 000 CZK are bought. These devices will be used from the beginning of the following year, that is why they depreciated from the next year. Another person is also employed. His salary is 30 000 CZK per month, including insurance.

The following table is shortened version of a complete table. They show the first year, the third year, the fifth year and the tenth year. Complete tables can be found in the attachment. Table 8.6 shows cash flow, table 8.7 shows Profit and loss statement, the table 8.8 shows Balance sheet. Net present value (NPV) is 788 680 CZK for 5 percent discount. Internal rate of return (IRR) is 47 percent.

Cash flow statement					
Date	01.01.2022	31.12.2022	31.12.2024	31.12.2026	31.12.2031
Initial cash balance	**300 000,00 CZK**	**90 100,00 CZK**	**279 279,00 CZK**	**591 148,75 CZK**	**1 192 453,36 CZK**
EAT	0,00 CZK	82 797,60 CZK	150 038,50 CZK	228 003,93 CZK	275 143,90 CZK
Depreciation	0,00 CZK	28 980,00 CZK	28 980,00 CZK	28 980,00 CZK	60 000,00 CZK
Material in stock	-65 000,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK
Obligations to the State	0,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK
Net cash flow from operating activities	**-65 000,00 CZK**	**111 777,60 CZK**	**179 018,50 CZK**	**256 983,93 CZK**	**335 143,90 CZK**
Investments	-144 900,00 CZK	0,00 CZK	0,00 CZK	-300 000,00 CZK	0,00 CZK
Net cash flow from investing activities	**-144 900,00 CZK**	**0,00 CZK**	**0,00 CZK**	**-300 000,00 CZK**	**0,00 CZK**
Amortization	0,00 CZK	-31 481,95 CZK	-39 490,95 CZK	-49 537,45 CZK	0,00 CZK
Net cash flow from financing activities	**0,00 CZK**	**-31 481,95 CZK**	**-39 490,95 CZK**	**-49 537,45 CZK**	**0,00 CZK**
Inrease	**-209 900,00 CZK**	**80 295,65 CZK**	**139 527,55 CZK**	**-92 553,52 CZK**	**335 143,90 CZK**
Final state	**90 100,00 CZK**	**170 395,65 CZK**	**418 806,56 CZK**	**498 595,23 CZK**	**1 527 597,27 CZK**

Table 8.6: Realistic scenario cash flow

Profit and loss statement					
Date	01.01.2022	31.12.2022	02.01.2023	04.01.2023	09.01.2023
Revenue	0,00 CZK	1 500 000,00 CZK	1 838 720,00 CZK	2 222 731,26 CZK	3 985 273,07 CZK
Cost of materials	0,00 CZK	-910 500,00 CZK	-1 116 103,04 CZK	-1 349 197,88 CZK	-2 419 060,76 CZK
Wages and salaries	0,00 CZK	-150 750,00 CZK	-184 791,36 CZK	-223 384,49 CZK	-760 519,94 CZK
Rent	0,00 CZK	-282 273,00 CZK	-305 306,48 CZK	-330 219,49 CZK	-401 762,50 CZK
Depreciation	0,00 CZK	-28 980,00 CZK	-28 980,00 CZK	-28 980,00 CZK	-60 000,00 CZK
Operating profit	**0,00 CZK**	**127 497,00 CZK**	**203 539,12 CZK**	**290 949,41 CZK**	**343 929,88 CZK**
Interest	0,00 CZK	-24 000,00 CZK	-15 990,99 CZK	-5 944,49 CZK	0,00 CZK
Economic result of financial operations	**0,00 CZK**	**-24 000,00 CZK**	**-15 990,99 CZK**	**-5 944,49 CZK**	**0,00 CZK**
Extraordinary economic result	**0,00 CZK**	**0,00 CZK**	**0,00 CZK**	**0,00 CZK**	**0,00 CZK**
EBT	**0,00 CZK**	**103 497,00 CZK**	**187 548,13 CZK**	**285 004,92 CZK**	**343 929,88 CZK**
Income tax	0,00 CZK	20 699,40 CZK	37 509,63 CZK	57 000,98 CZK	68 785,98 CZK
EAT	**0,00 CZK**	**82 797,60 CZK**	**150 038,50 CZK**	**228 003,93 CZK**	**275 143,90 CZK**

Table 8.7: Realistic scenario Profit and loss statement

Balance sheet					
Date	01.01.2022	31.12.2022	31.12.2024	31.12.2026	31.12.2031
Assets					
Machines	144 900,00 CZK	144 900,00 CZK	144 900,00 CZK	444 900,00 CZK	444 900,00 CZK
Bank account	90 100,00 CZK	170 395,65 CZK	418 806,56 CZK	498 595,23 CZK	1 527 597,27 CZK
Material	65 000,00 CZK	65 000,00 CZK	65 000,00 CZK	65 000,00 CZK	65 000,00 CZK
Accumulated depreciation	0,00 CZK	-28 980,00 CZK	-86 940,00 CZK	-144 900,00 CZK	-444 900,00 CZK
Sum	**300 000,00 CZK**	**351 315,65 CZK**	**541 766,56 CZK**	**863 595,23 CZK**	**1 592 597,27 CZK**
Liabilities					
Registered capital	100 000,00 CZK	100 000,00 CZK	100 000,00 CZK	100 000,00 CZK	100 000,00 CZK
Loan	200 000,00 CZK	168 518,05 CZK	93 767,32 CZK	0,00 CZK	0,00 CZK
Profit	0,00 CZK	82 797,60 CZK	347 999,24 CZK	763 595,23 CZK	1 492 597,27 CZK
Sum	**300 000,00 CZK**	**351 315,65 CZK**	**541 766,56 CZK**	**863 595,23 CZK**	**1 592 597,27 CZK**

Table 8.8: Realistic scenario balance sheet

8.9.2   Pessimistic scenario

As there is inflation, the material has become more expensive over the years, so the product is also more expensive. Inflation is calculated at 4 percent per year. At the same

time, salary for employees is increased by 4 percent per year. I estimated that the company would sell ten drones per year, with a 5 percent increase each year. The company´s annual growth in the number of units sold is expected to be 5 percent.

The calculation is based on a 30 percent decrease in planned sales, which means it will not be possible to hire another employee after five years. Only one additional computer after five years. The company will continue to prosper and will be able to repay the loan from the bank. After three years, it will start to generate a profit.

The following table is shortened version of a complete table. They show the first year, the third year, fifth year and tenth year. Complete tables can be found in the attachment.

Table 8.9 shows cash flow, table 8.10 shows Profit and loss statement, the table 8.11 shows Balance sheet. NPV is 538 587 CZK for a 5 percent discount, IRR is 22 percent.

Cash flow statement					
Date	01.01.2022	31.12.2022	31.12.2024	31.12.2026	31.12.2031
Initial cash balance	**300 000,00 CZK**	**90 100,00 CZK**	**30 419,19 CZK**	**84 132,65 CZK**	**946 720,62 CZK**
EAT	0,00 CZK	-42 753,00 CZK	23 491,30 CZK	91 130,48 CZK	303 394,44 CZK
Depreciation	0,00 CZK	28 980,00 CZK	28 980,00 CZK	28 980,00 CZK	10 000,00 CZK
Material in stock	-65 000,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK
Obligations to the State	0,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK	0,00 CZK
Net cash flow from operating activities	**-65 000,00 CZK**	**-13 773,00 CZK**	**52 471,30 CZK**	**120 110,48 CZK**	**313 394,44 CZK**
Investments	-144 900,00 CZK	0,00 CZK	0,00 CZK	-50 000,00 CZK	0,00 CZK
Net cash flow from investing activities	**-144 900,00 CZK**	**0,00 CZK**	**0,00 CZK**	**-50 000,00 CZK**	**0,00 CZK**
Amortization	0,00 CZK	-31 481,95 CZK	-39 490,95 CZK	-49 537,45 CZK	0,00 CZK
Net cash flow from financing activities	**0,00 CZK**	**-31 481,95 CZK**	**-39 490,95 CZK**	**-49 537,45 CZK**	**0,00 CZK**
Inrease	**-209 900,00 CZK**	**-45 254,95 CZK**	**12 980,35 CZK**	**20 573,03 CZK**	**313 394,44 CZK**
Final state	**90 100,00 CZK**	**44 845,05 CZK**	**43 399,54 CZK**	**104 705,68 CZK**	**1 260 115,06 CZK**

Table 8.9: Pessimistic scenario cash flow

Profit and loss statement					
Date	01.01.2022	31.12.2022	02.01.2023	04.01.2023	09.01.2023
Revenue	0,00 CZK	1 000 000,00 CZK	1 297 920,00 CZK	1 637 801,98 CZK	2 704 292,44 CZK
Cost of materials	0,00 CZK	-607 000,00 CZK	-787 837,44 CZK	-994 145,80 CZK	-1 641 505,51 CZK
Wages and salaries	0,00 CZK	-100 500,00 CZK	-130 440,96 CZK	-164 599,10 CZK	-271 781,39 CZK
Rent	0,00 CZK	-282 273,00 CZK	-305 306,48 CZK	-330 219,49 CZK	-401 762,50 CZK
Depreciation	0,00 CZK	-28 980,00 CZK	-28 980,00 CZK	-28 980,00 CZK	-10 000,00 CZK
Operating profit	**0,00 CZK**	**-18 753,00 CZK**	**45 355,12 CZK**	**119 857,60 CZK**	**379 243,04 CZK**
Interest	0,00 CZK	-24 000,00 CZK	-15 990,99 CZK	-5 944,49 CZK	0,00 CZK
Economic result of financial operations	**0,00 CZK**	**-24 000,00 CZK**	**-15 990,99 CZK**	**-5 944,49 CZK**	**0,00 CZK**
Extraordinary economic result	**0,00 CZK**	**0,00 CZK**	**0,00 CZK**	**0,00 CZK**	**0,00 CZK**
EBT	**0,00 CZK**	**-42 753,00 CZK**	**29 364,13 CZK**	**113 913,10 CZK**	**379 243,04 CZK**
Income tax	0,00 CZK	0,00 CZK	5 872,83 CZK	22 782,62 CZK	75 848,61 CZK
EAT	**0,00 CZK**	**-42 753,00 CZK**	**23 491,30 CZK**	**91 130,48 CZK**	**303 394,44 CZK**

Table 8.10: Pessimistic scenario Profit and loss statement

Balance sheet					
Date	01.01.2022	31.12.2022	31.12.2024	31.12.2026	31.12.2031
Assets					
Machines	144 900,00 CZK	144 900,00 CZK	144 900,00 CZK	194 900,00 CZK	194 900,00 CZK
Bank account	90 100,00 CZK	44 845,05 CZK	43 399,54 CZK	104 705,68 CZK	1 260 115,06 CZK
Material	65 000,00 CZK	65 000,00 CZK	65 000,00 CZK	65 000,00 CZK	65 000,00 CZK
Accumulated depreciation	0,00 CZK	-28 980,00 CZK	-86 940,00 CZK	-144 900,00 CZK	-194 900,00 CZK
Sum	**300 000,00 CZK**	**225 765,05 CZK**	**166 359,54 CZK**	**219 705,68 CZK**	**1 325 115,06 CZK**
Liabilities					
Registered capital	100 000,00 CZK	100 000,00 CZK	100 000,00 CZK	100 000,00 CZK	100 000,00 CZK
Loan	200 000,00 CZK	168 518,05 CZK	93 767,32 CZK	0,00 CZK	0,00 CZK
Profit	0,00 CZK	-42 753,00 CZK	-27 407,78 CZK	119 705,68 CZK	1 225 115,06 CZK
Sum	**300 000,00 CZK**	**225 765,05 CZK**	**166 359,54 CZK**	**219 705,68 CZK**	**1 325 115,06 CZK**

Table 8.11: Pessimistic scenario balance sheet

8.10 Conclusion of the business plan

The project looks positive. The company earns enough money to cover costs and repay the loan in the first years. In the event of expected growth, the firm can invest in purchasing additional machines and increasing its production capacity. If a pessimistic scenario occurs, the company will still be able to repay the loan. Although the firm will have a negative cash flow for the first three years, later, it starts to be profitable anyway.

Chapter 9

How to run

9.1 PX4

PX4 software is maintained by the git version system. It is needed to clone git repository by command:

```
git clone --recursive https://github.com/zejdajan/px4_firmware.git
```

Simulation can be started by typing this command in the terminal:

```
make px4_sitl gazebo_fully_actuated
```

However, it is possible to command the drone over the existing terminal. It is not user friendly. Command for takeoff is:

```
commander takeoff
```

A better way is to use the QGroundControl program. It allows controlling the drone by virtual joystick, which reminds real levers on RC transmitters. Also, it offers buttons for automatic takeoff and landing.

9.1.1 Building PX4 for Pixhawk

While building the PX4, I encountered a problem with memory. Pixhawk 4 has got only a limited size of memory. As I added another type of mixer and modified controllers, I increased the size of the PX4. It caused memory overflow, and I was getting building errors. For that reason, I removed unused mixers for a helicopter. As a result, the size of the PX4 image decreased, and the building was possible. Firmware is build by command:

```
make px4_fmu-v5_default
```

9.2 ROS

ROS software is maintained by the git version system and Gitman. It is needed to clone the git repository by command:

```
git clone https://github.com/zejdajan/simulation.git
```

Then the installation script can be executed by running a command in an installation folder:

```
./install.sh
```

Then simulation can be started by command:

```
cd simulation
cd example_tmux_scripts
cd fully_actuated
./start
```

On the first run it is needed to run these commands:

```
cd ~/catkin_ws
source ./devel/setup.bash
```

Then it is needed to start publishing a message. It is performed by the command in another terminal:

```
rosrun beginner_tutorials talker.py
```

Then it is possible to verify that message is being sent by typing the command:

```
rostopic echo /uav1/mavros/setpoint_raw/local
```

Then two commands have to be executed in another terminal.

```
rosservice call /uav1/mavros/cmd/arming 1
rosservice call /uav1/mavros/set_mode 0 offboard
```

The first one arms the drone. It means that the drone gets permission to spin motors. The second command changes PX4 flight mode to off-board mode, which means that PX4 does not control the drone over manual control but over ROS. By this time, the drone should be moving to its desired position. If we want to change the drone's desired location, we must stop publishing the messages, modify desired values in a script file, and rerun this rosnode. If we want to exit the whole simulation, it is needed to stop publishing messages by rosnode. Then in the main terminal that shows flight information, all we need to do is to press:

```
Ctrl + a
k
```

Chapter 10

Conclusion

This thesis aimed to use the newest control system PX4. Its description is in chapter 3. Then re-implement older control software developed by [3] into it.

All of the tasks were successfully completed as assigned:

I modeled a fully-actuated drone in the Gazebo simulator using PX4 in chapter 3.

I re-implemented an older incompatible solution of control algorithms and mixers of software for PX4 controlling a fully actuated drone and verified them in the Gazebo simulator in chapter 4.

I implemented an interface between PX4 and ROS which allows control of the unmanned aerial vehicle through ROS, described in chapter 5. It was verified that everything works in the simulation program Gazebo simulator.

I designed and successfully assembled the real fully-actuated drone in chapter 6. In Fusion 360, I designed custom holders of the drone parts. I 3D printed them on a Prusa 3D printer. I was able to mount additional equipment on the drone. After the successful assembly of the drone, I calibrated the drone and prepared the drone for the flight.

I demonstrated the flight of a fully actuated drone during the MRS camp using zero tilt mode in a real experiment in chapter 7. Manoeuvres that are impossible for standard under-actuated drone were shown. Flight logs also showed that the zero tilt mode of a fully-actuated drone is working. I prepared a how-to section that shows how to setup everything for possible future modifications.

I also created a business plan for a possible company foundation in chapter 8. Results showed that this is a good idea for investors.

Chapter 11

References

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