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Master Thesis Report

Presented by

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Making Flips With Quadrotors In Constrained Environments

Jury

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Abstract

Within the rapidly growing aerial robotics market, one of the most substantial challenges in the quadrotor community is performing aggressive maneuvers, especially multi-flip maneuvers. A proper physical definition of the issue is not addressed by the current approaches in the field and several key aspects of this maneuver are still overlooked. It can be shown, in particular, that making a flip with a quadrotor means crossing the parallel singularity of the dynamic model. The aim of the master thesis is to explore the possibility of defining aggressive trajectories for quadrotors on the basis of their dynamic model degeneracy analysis and to adapt various strategies to control the robot in a closed loop. In addition, the possibility of performing the aggressive maneuvers in constrained environments will also be investigated. Therefore, the analysis will be extended from the previous studies to create general feasible trajectories that will allow quadrotors to perform aggressive multi-flip maneuvers while passing through a constrained environment and while guaranteeing a satisfactory degree of robustness to the uncertainties of the dynamic model.

Keywords: quadrotors, parallel robots, aggressive maneuvers, multi-flips, constrained environmen.

Acknowledgements

I would like to express my special thanks and gratitude to my supervisors Dr. Sébastien Briot and Dr. Isabelle Fantoni who gave me the opportunity to work on this wonderful project which encapsulates control theory, dynamics and quadrotors, which are all subjects that are very interesting for me. This project has allowed me to perform research on all of these topics and I am now more knowledgeable thanks to my supervisors. Moreover, I would like to thank them for believing in my capabilities and giving me the confidence and the support when I needed it.

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I would not be here if it wasn't for them.

Notations

I_{xx}, I_{yy}, I_{zz}	Diagonal terms of the inertia matrix
$\omega_x, \omega_y, \omega_z$	angular rates with respect to the x,y and z axes respectively
ϕ, θ, ψ	roll, pitch and yaw angles respectively
l	Arm length of a quadrotor
T	Total thrust input of the quadrotor
τ	Total torque of the quadrotor

Abbreviations

UAV	unmanned aerial vehicle
CoG	center of gravity
MPC	model predictive control
HLC	high level commander
SMC	sliding mode control

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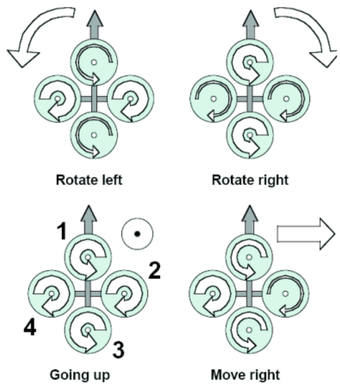
Introduction

The aim of this section is to provide a general summary of the robotic platform that is used for this master thesis and to illustrate the main objective of the research work. In specific, in the sections below, quadrotors and parallel robots are briefly presented.

The quadrotor platform

A quadrotor is a type of unmanned aerial vehicle (UAV) with four rotors and six degrees of freedom. Typically, drones have a small size and low inertia which allows them to be controlled by simple flight control systems. It is typically designed in a cross-configuration such that the electronics are held in the center of the platform and the rotors are placed at the borders. An example of a real quadrotor, namely the DJI Phantom, is shown in figure 1a. The quadrotor is typically built in a way such that a pair of opposite rotors rotates in a clockwise direction, whereas the other pair rotates in a counter-clockwise direction. The attitude and the position of the drone are controlled by changing the spinning speed of the rotors, as showin in figure 1b.

(a) A DJI Phantom quadcopter (UAV)[1]



(b) Representation of the concept of a quadrotor. The width of the arrows is proportional to the angular speed of the propellers.[3]

Figure 1: A commercial quadrtotor platform with a representation of the quadrotor concept.

The distinctive mechanical design of the quadrotor permits the actuation system to control all of the six degrees of freedom even though it is under-actuated. This is due to the fact that the rotational and translational dynamics are tightly coupled. Thus, all the translational and rotational motions can be carried off by properly controlling the magnitude and direction of the spinning speed of the rotors.

[1]https://en.wikipedia.org/wiki/Quadcopter#/media/File:Quadcopter_camera_drone_in_flight.

Over the last few years, quadrotors have gained a large popularity in academia and in the industry. This is due to several reasons, such as:

1. Quadrotors are very simple to design and they can be easily assembled using relatively cheap components.

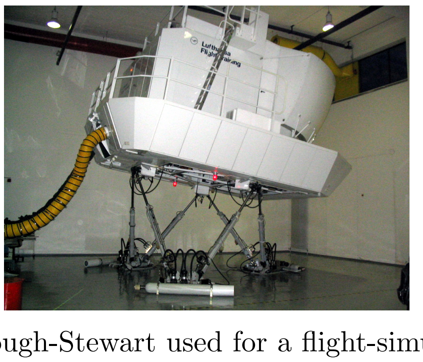
2. As quadrotors became more and more affordable and dependable, the number of real-world applications for quadrotors has grown significantly. They are being used for aerial photography, agriculture, surveillance, inspection tasks, in addition to many other uses as well.

3. Quadrotors are quite agile and maneuverable during flight, especially when compared to other types of UAVs.

However, one of the main challenges in the quadrotors community is the capability to design control and planning methods that will allow the quadrotors to carry out aggressive maneuvers. The fast dynamics associated with typically small dimensions of such agile quadrotors, along with several aerodynamic effects that will become crucial during aggressive flight maneuvers, are just a few of the main problems that are faced during the system control design. Moreover, accurate tracking of the provided trajectory is a big issue in the case of aggressive maneuvers when the rotors are commanded high speeds and accelerations, which will cause rotors to become saturated and may also cause delays.

Parallel manipulators

A parallel manipulator is a mechanical system that consists of two connected platforms, the fixed platform and the moving platform. The latter is linked to the fixed platform thanks to at least two serial chains that are working in parallel. When compared to serial manipulators, parallel manipulators are more accurate and rigid. In addition, the ability to install the motors next to the fixed platform is a very important feature for them. Moreover, parallel manipulators can be used in a wide variety of applications that demand precision and high payload combined with high speed.[4]



(a) Gough-Stewart used for a flight-simulator application.[2]

(b) The "PAR4" 4 degrees of freedom, high-speed, parallel robot prototype.[3]

Figure 2: Two examples of parallel robots.

jpg, accessed on 01/08/2021.

[1] https://en.wikipedia.org/wiki/Stewart_platform#/media/File:Simulator-flight-compartment.jpeg, accessed on 01/08/2021.

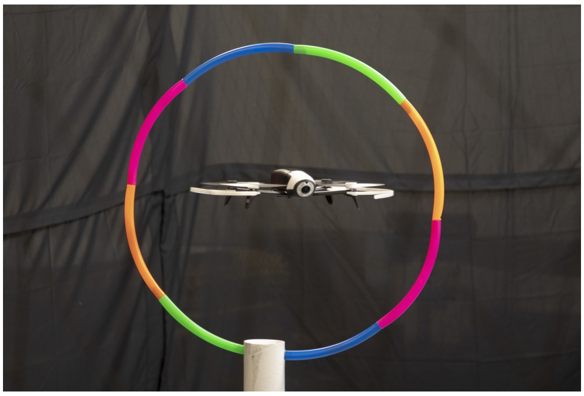
[2] https://en.wikipedia.org/wiki/Parallel_manipulator#/media/File:Prototype_robot_parall%C3%A8le_PAR4.jpg, accessed on 01/08/2021.

However, parallel manipulators are subject to singularities which can lead to big problems in the robot workspace in case they were not handled correctly. Thus, the study of the singular configuartions of parallel manipulators is very important. Because, even just before reaching a singularity, the performance of the parallel manipulator will decrease dramatically. Moreover, the robot may loose the ability of moving in a certain direction, gain uncontrollable motions and the mechanism could even break. The main difference between serial and parallel manipulators is that singularity configurations may also appear inside the workspace of the robot (depending on the dimensions of the robot) and not just at the boundaries of the robot workspace, which can significantly decrease the area of the robot workspace. As a result, many works have been developed by robotics researchers in order to allow parallel manipulators to safely cross these singularities by using trajectory planning and specific control methods.

The goal of this thesis

This master thesis lies at the intersection of parallel robotics and aerial robotics. The two fields may seem very different from each other. However, quadrotors can be seen as a particular case of a parallel manipulator. In fact, a parallel manipulator is made up of a wrench system, applied by the robot limbs on the moving platform. And, this wrench system will define the motion of the moving platform. In the same manner, each propeller in a quadrotor can be considered as a limb of a parallel robot and the moving platform to be controlled can be considered as the body of the drone. Specifically, the goal of this master thesis is to study a distinct class of aggressive maneuvers for quadrotors, namely flip maneuvers. By doing flip maneuvers, full rotations around one or more axes of the body of the quadrotor can be done. In addition, the quadrotor should also be able to perform the flip maneuvers in constrained environments.

(a) Quadrotor performing a triple flip.[5]



(b) Quadrotor going though a loop.[1]

Figure 3: Representation of the issues to be tackled in the master thesis.

[1]https://newatlas.com/drones/muscle-signals-drone-control/#gallery:2, accessed on 01/08/2021.

Outline of the work

The rest of the report is structured as follows:

Chapter 1 provides an overview of the state of the art in the control of quadrotors and will later on focus on the main control method that will be used, namely Model Predictive Control (MPC). Moreover, a literature review of MPC applications on quadrotors will be presented. Furthermore, an overview on the software used to design a MPC controller will be presented. Finally, the state of the art in flipping maneuvers will be presented.

Chapter 2 provides a detailed explanation of the quadrotor dynamics for the planar (2D) and 3D quadrotors. Morever, an Extended Kalman Filter (EKF) is then designed for the planar quadrotor case to be used in the presence of noisy measurements (states) and noisy control inputs. Finally, simulation results using MPC to reach a single waypoint and to follow circular trajectories with and without noise are presented.

Chapter 3 focuses on the trajectory generation of a flip trajectory where different optimization problems with different objective functions and initial conditions will be used in order to find the optimal flipping trajectory that satisfies the dynamic constraints of the quadrotor which will be used in the experimentation phase. Moreover, simulations with a MPC are then performed using the optimal flip trajectory.

Chapter 4 focuses on the simulations that were performed using ROS2 and Gazebo, in addition to the experimentation results.

Chapter 1

State of the art

In the following sections of this chapter, differential flatness, the general control architecture of a quadrotor, different potential control approaches (linear and nonlinear), and the main control method that will be used to control a quadrotor, namely Model Predictive Control (MPC) will be explained.

1.1 Differential Flatness

In the quadrotor community, a well-established finding is that the dynamic model of a quadrotor is differentially flat. Moreover, the control design problem in nonlinear systems will be considerably simplified. Precisely, a system with state $\mathbf{x} \in \mathbb{R}^n$ and input $\mathbf{u} \in \mathbb{R}^m$ is considered to be *differentially flat* if there exists a set of *flat outputs* $\mathbf{y} \in \mathbb{R}^m$ which have the following form:

$$\mathbf{y} = \mathbf{y}(\mathbf{x}, \mathbf{u}, \dot{\mathbf{u}}, ..., \mathbf{u}^{(p)}) \tag{1.1}$$

With,

$$\begin{cases} \mathbf{x} = \mathbf{x}(\mathbf{y}, \dot{\mathbf{y}}, ..., \mathbf{y}^{(q)}) \\ \\ \mathbf{u} = \mathbf{u}(\mathbf{y}, \dot{\mathbf{y}}, ..., \mathbf{y}^{(r)}) \end{cases} \tag{1.2}$$

As a result, the new set of variables is required to be a function of the state, the input and the derivatives of the input. Moreover, this set should also have the same dimensions as the control input. In this manner, it is possible to rewrite both the state and the input in function of the flat outputs and the derivatives of the flat outputs. This is a very useful property in underactuated systems where $m < n$, such as quadrotors, because, it will allow to generate trajectories in the lower dimensional space m, then this trajectory will be mapped into the full dimensional space n. An example of this is shown in figure 1.1 below:

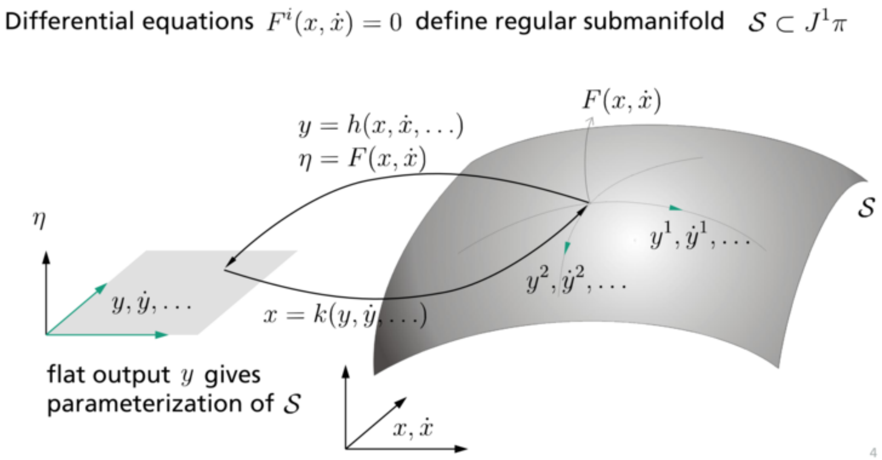


Figure 1.1: Mapping between different dimensional spaces as a result of differential flatness. [1]

Another well known example of systems is a car, in which the underactuation is the result of the nonholonomic constraints that are imposed by the wheels. So, for a car, a generated trajectory for (x, y) position of the rear-wheels is enough to specify all the viable trajectories of the system. Formal proofs that the quadrotor system is differentially flat can be found in [6], and [7] for the full model with first-order aerodynamics. The standard choice of flat outputs for the quadrotor is the coodinates of the center of mass and the yaw angle:

$$\mathbf{y} = \begin{bmatrix} x & y & z & \psi \end{bmatrix}^\intercal \tag{1.3}$$

Consequently, the problem of generating a feasible trajectory for a quadrotor then tracking it can be dimensionally decreased from a 6-dimensional space to a 4-dimensional space. By reason of the tight coupling between the rotational and translational dynamics, then defining a trajectory in function of the flat outputs $\mathbf{y}$ is sufficient to properly define the full dynamics $\mathbf{x}$.

1.2 General Control Architecture

Recently, many researchers have developed interest in the control of quadrotors. As a result, various control approaches have been proposed. The most known control architecture [7] consists of three nested control loops, as shown in figure 1.2, in order to generate the suitable motor commands to follow the desired signal. This controller is known as the cascaded controller. This strategy assumes that the attitude dynamics of a quadrotor are much faster than the translational dynamics.

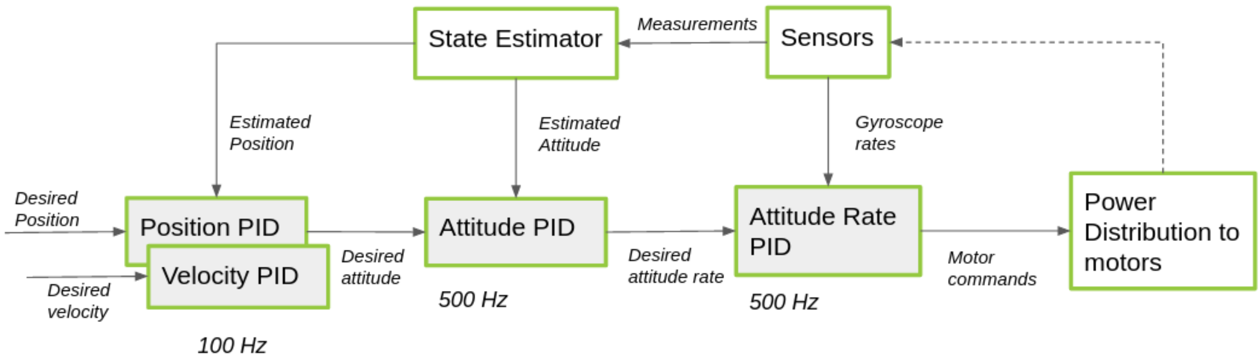


Figure 1.2: Cascaded PID controller that is present on the crazyflie 2.1 quadrotor [2].

In this case, the position and velocity controller, attitude controller and attitude rate controller are all PID controllers. And, it is evident that the attitude dynamics (who's attitude and attitude rate controllers operate at a frequency of 500Hz) are considered to be much faster than the translational dynamics (who's position and velocity controllers operate at a frequency of 100Hz). Moreover,

Attitude Rate PID controller directly controls the attitude rate. It receives the gyroscope rates after they have been filtered and uses the error between the desired attitude rate and current attitude rate, and outputs the motor commands which are then directly sent to the power distribution.

Attitude PID controller directly controls the attitude of the drone. It takes the estimated attitude from the state estimator and uses the error between the desired attitude and the current attitude to output the desired attitude rate.

Position and Velocity PID controller is the most outerloop of the cascaded PID controller. It receives the position or the velocity input from the high level commander which are then handled to output the desired attitude.

1.3 General Control Approaches

1.3.1 Method of Linearization

By using extreme assumptions, it is feasible to apply linear control techniques in order to control a quadrotor ([8], [9]). Particularly, this can be made by doing a linearization of the full dynamic model around an equilibrium point $\overline{\mathbf{x}}$ and by using the assumption that the vehicle is only capable of oscillating lightly around the hover point. It is very easy to observe that a feasible equilibrium is provided by a configuration where the center of mass is at a random position $\overline{\mathbf{r}}$ and all the other elements of the state are set to zero. So, the nominal input $\mathbf{u} = \overline{\mathbf{u}}$ to sustain such equilibrium can be assessed as the thrust that is required to compensate the gravity force:

$$\overline{\mathbf{u}} = \begin{bmatrix} f \\ \boldsymbol{\tau} \end{bmatrix} = \begin{bmatrix} mg \\ \mathbf{0_{3\times1}} \end{bmatrix} \tag{1.4}$$

At this stage, the complete non-linear dynamics that have the form :

$$\dot{\mathbf{x}} = \overline{\mathbf{f}}(\overline{\mathbf{x}}, \overline{\mathbf{u}}) \tag{1.5}$$

can now be linearized around the hover point $(\overline{\mathbf{x}}, \overline{\mathbf{u}})$ as shown below.

$$\dot{\mathbf{x}} = \left[\frac{\partial \mathbf{f}(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}}\right]_{(\bar{\mathbf{x}},\bar{\mathbf{u}})} \mathbf{x} + \left[\frac{\partial \mathbf{f}(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}}\right]_{(\bar{\mathbf{x}},\bar{\mathbf{u}})} \mathbf{u} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{1.6}$$

It can be demonstrated that both matrices $\mathbf{A}$ and $\mathbf{B}$ can be used to determine a linear system that is both controllable and observable [8]. Thus, any control technique that is linear can now be used on the quadrotor in order to keep it around a desired equilibrium point, such as optimal LQR/LQG [10, 11] control or simple PD or PID controller [12, 13].

1.3.2 Nonlinear Control Methods

In order to perform more complex tasks and follow aggressive trajectories, nonlinear control methods are required. A comprehensive literature review on this topic is beyond the scope of this work and several works can be found, such as [14], which provides a general overview on nonlinear control of quadrotors. However, some nonlinear control methods deserve to be mentioned due to their extensive use and applications:

Sliding Mode control It is a control technique that is nonlinear presenting exceptional attributes of robustness,accuracy, easy tuning and execution. The aim of SMC systems is to drive the system states to a specific surface in the state space, called *"sliding surface"*. Upon reaching the sliding surface, sliding mode control allows the states to remain on the close neighborhood of the sliding surface. Therefore, the sliding mode control consists of a controller design with two parts. The first part contains the design of a sliding surface in order for the sliding motion to fulfill design requirements. The second deals with selecting a control law that makes the switching surface interesting with respect to the system state [15]. There exist two main benefits of sliding mode control. Firstly, the behavior of the dynamics of the system can be changed according to a specific selection of the sliding function. Secondly, the response of the closed loop system becomes completely insensitive to some special uncertainties. This principle goes beyond bounded model parameter uncertainties, interference and non-linearity. In a practical sense, SMC allows the control of nonlinear processes that are affected by external noise and heavy model uncertainties. The most important principles of SMC are shown in the following significant references [15, 16, 17]. Researchers have also studied the problems appearing in the practical execution of this class of techniques. [18] Interested readers can refer to the book [19] which presents a very modern overview of the most promising current line of theoretical and practical research in the domain.

Backstepping control The main idea is to divide the system into successive subsystems and to apply a recursive algorithm which will stabilize each subsystem after the other [20]. However, this method is not robust, but it is computationally fast. In order to handle disturbances, Fang et al. [21] implemented an integral backstepping control law, in which the integral term was shown to reduce steady state errors and the response time of the system greatly.

Adaptive control This method is required when the parameters that are characterizing the system contain errors or are unknown. This type of control algorithms contains a parameter adaptation law, which is enclosed in the control to track the desired trajectory of the system, even if the model of the system is not completely known. For instance, Diao et al. [22] obtained good performance even though the inertial parameters of the quadrotor and the aerodynamic coefficients were not perfectly known. This method is convenient in some cases, such as the existence of unpredictable wind [23] or pick-and-place applications with small loads.

In the next section, the main control method that will be used in the master thesis will be explained.

1.4 Model Predictive Control

1.5 Second topic

Chapter 2

Actual work

When dealing with rectangled triangles (see Figure 2.1) I sometimes used this theorem from [24]:

$$a^2 + b^2 = c^2 \tag{2.1}$$

The demonstration is in Appendix A.

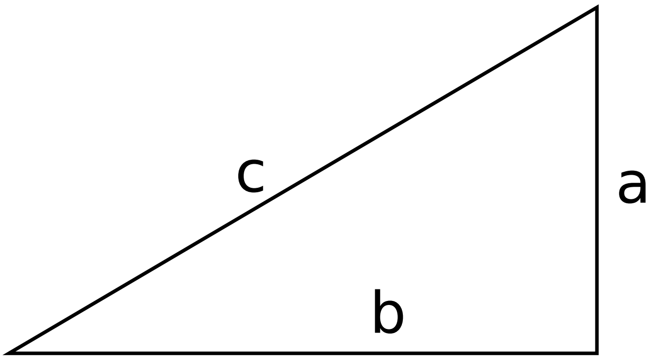


Figure 2.1: A triangle with letters

Chapter 3

Experiments

When trying to draw a rectangled triangle, my program comes up with Figure 3.1 that is neither rectangled nor a triangle.

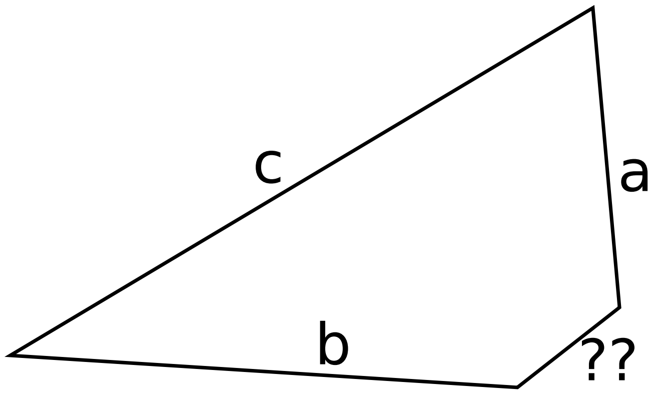


Figure 3.1: Triangle drawn by my program. Note the 4th side.

Unless there is a bug in my program, which is unlikely, this research indicates that the whole theory on triangles having 3 sides has been wrong for years, maybe decades.

Conclusion

Appendix A

Proof of theorem 2.1

Proof. (2.1) was already demonstrated in [25]. □

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