Master Thesis Proposal

Trajectory Planning and Control of a Quadcopter for an Indoor Application

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1 Motivation & Problem Statement

Nowadays, unmanned aerial vehicles (UAVs) are used in many fields of applications and support professional workers especially in areas with safety or budget concerns. Common operation purposes, for instance, range from the quick delivery of goods, the broad scanning and exploration of the environment to different service tasks. The latter gained in importance in areas which can hardly be reached by the human operator and for tasks which require tools that are in physical contact with the environment. This has led to a rapidly growing research field called "aerial manipulation" where UAVs are equipped with tools to accomplish specific tasks. For example, the task of cleaning windows of skyscrapers is costly, unsafe and requires the training of skilled workers. Another similar situation is the geological inspection of impassable terrain, e.g., taking soil samples in the mountains. The control of the flying UAV during physical contact with the environment is a challenging task because it requires the simultaneous control of both translation and rotation of the UAV whilst maintaining a certain orientation of the UAV's manipulator and an optimal contact force on a surface. Most cost-efficient UAVs are underactuated by design which adds additional complexity to the research task.

The main purpose of the work is to develop a hybrid force-motion control algorithm that turns the quadcopter into a versatile and mobile robotic platform. In particular, this thesis focuses on the problem to clean a whiteboard. A force measurement unit with a sponge is the tool of choice, which will be attached to a cantilever mounted on the UAV. An important aspect is the implementation of the inclination of the UAV in order to apply the desired contact forces. For this, an optimal trade-off between the contact force and the stability margin in terms of aerial deviation needs to be found, as the inclination naturally compromises the overall flight stability. In addition, the UAV is supposed to follow a trajectory along the whiteboard. The friction between the sponge and the white board plays a major role regarding the engine control. The quadcopter, tilted in two directions, will have all of its four engines spin at different angular velocities, in order to compensate for the friction, slide along the whiteboard, maintain or adapt the flight height and keep the contact force constant.

2 Aim of the Work

The aim of this work is to develop a trajectory of the UAV that approaches the to-be-cleaned whiteboard, then slide along the vertical surface and apply a predefined contact force and finally go back to the point of origin. The proof of concept shall be shown by means of a simulation and a laboratory experiment.

The underactuated UAV is restricted by design in terms of its maximum contact force. Practical laboratory experiments will show whether a previously drawn line can be cleaned with the chosen UAV. Furthermore, it remains an open question on how to adapt the flight controller such that it can handle the transition between free flight and sliding along a vertical surface. In addition, experiments will show whether the static friction is low enough to allow a stick-slip-free motion. It is contemplated to use an existing open-source flight controller that takes care of the engine control and extend it by additional functionalities.

3 Methods

In a first step, existing approaches in the literature will be reviewed. Afterwards, appropriate algorithms based on model predictive control or flatness-based control, which also account for the contact force at the end effector, will be developed. Furthermore, the algorithm will be tested in simulation and experiments.

A simple trajectory planning module is available from a previous master thesis and a low-level flight controller open-source software can be adapted from [1].

3.1 Literature Review

An extensive literature review sets a good starting point for the scientific evaluation of the state of the art and the examination which principles can be adopted for this thesis.

3.2 Mathematical Modeling

The mathematical derivation of a proper kinematic model including the force measurement unit and the dynamic equations is essential for a model-based control approach. As the simulation is supposed to provide results close to reality, the simulation must rely on an adequate model.

3.3 Simulation

The simulation is necessary to avoid physical damage and to test parts of the concept prior to the implementation on the experimental platform. The state of the art already provides good tools with the necessary interfaces. The behavior of disturbances can be tested and the stability of the controller during sliding motion can be investigated also for varying system parameters.

3.4 Laboratory Experiments

When the simulation shows convincing results, the solution will also be implemented on a laboratory experiment. The position measurement will be accomplished by an Optitrack system [2]. The deviation between the simulation results and the laboratory experiments will also indicate the performance of the model used in the simulation. The laboratory experiments are required to examine if the contact forces exerted on the whiteboard are sufficient for cleaning purposes.

4 State of the Art

Thanks to successful research during the past years, the usage of UAVs has found its way into a constantly growing market. Recent research made a huge step in the autonomous identification of surfaces and the determination of their hardness, see [3] and [4]. These works present an approach on how to slide along uneven surfaces with a fully actuated UAV. They also describe the behavior under the influence of aerial disturbances and lateral force disturbances caused by surface friction during sliding. The conducted experiments with regard to the push-and-slide process with a contact force of up to $5N$ showed results well sufficient for the precision needed for window cleaning. In [3], a contact-based inspection and the control of aerial disturbances with a fully actuated UAV is presented. The general kinematic model, the navigation module and the basic trajectory planning of a similar UAV can be found in previous Master's thesis works, see, e.g., [5] and [6].

The concept of hybrid force-motion control is frequently used in industry, originally referred to as force-position control, see [7]. The concept comes from the robotics research where the positioning of a manipulator is considered and its end effector has to exert a desired generalized force, as, e.g., [8]. The papers [7] and [9] pursue a similar approach to solve a distinct problem in the area of force-position control. In [7], robust force-position control based on the H^{∞}-concept is applied for a combination of manipulator and end effector without a force sensor. In [9], the hybrid force-position control is implemented in a rehabilitation robot for physiotherapy purposes. Therein, a concept to additionally consider the active force contribution of the patient is introduced.

A robot's end effector that interacts actively with the environment is always compromised by a set of holonomic constraints depending on the object or surface that it is interacting with. Therefore, the force-motion control is mostly developed by taking these contraints into account, see, e.g., [10]. This concept is more precisely defined and applied to a quadcopter attached with a tool in [11]. Therein, the structural under actuation is considered and the quadcopter's dynamics are applied to the end effector. For a decoupling of the desired contact force and the motion, knowledge about the dynamics of the UAV are needed, as stated in [12]. With regard to a dynamic switch-over between free flight and the push-and-slide task, the decoupling is an important concept to consider, see [11].

The technical progress of this thesis in comparison to the state of the art is the development of a force-motion control algorithm, similar to [3], however, for an under actuated UAV.

5 Relevance to the Curriculum of Computer Engineering

The main aim of this thesis is to develop a model of a UAV, and extend its flight controller such that it is able to follow a trajectory along a surface whilst applying a desired contact force to it. The approach should be confirmed both by simulation and in a laboratory experiment. Therefore, the research on this topic requires knowledge of the following courses in the curriculum of Computer Engineering:

- 376.000 Automation
- 376.044 Mathematical Modelling
- 376.042 Selected Topics - Automation and Control
- 376.059 Control systems 1
- 376.060 Control systems 2

- 376.061 Laboratory Control systems 1
- 376.062 Laboratory Control systems 2
- 376.058 Optimization
- 376.065 Advanced Methods in Nonlinear Control
- 376.064 Advanced Methods in Mathematical Modeling

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