Automated Execution of Multi-Flip Maneuvers Using a 19-Gram Flyer

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***Abstract*— We present a new experimental method for the generation and real-time implementation of high-speed aerobatic maneuvers, including multiple flips, on a 19-g autonomous quadrotor. The proposed approach is based on a gain-scheduling control strategy, where two *linear time-invariant* (LTI) controllers are employed to switch between a normal flight mode and a high-speed aerobatic flight mode. All the real-time algorithms involved in flight control are implemented and run using on-board power, sensors and computing capabilities in order to maintain complete autonomy during flight. Fully autonomous high-speed aerobatic behavior is accomplished with the use of a new method for speed planning, the generalization of the notion of multi-flip maneuver and the empirical identification of the flyer's dynamics, required for trajectory generation and controller synthesis. Compelling experimental results demonstrate the suitability of the proposed approach.**

I. Introduction

The generation and real-time implementation of high-speed maneuvers using quadrotors has been an important research topic in the field of robotics during the last few years. For example, [1] and [2] report the use of well-equipped normal-sized[1] quadrotors in the implementation of aerobatic experiments performed in highly structured arenas, instrumented with motion-capture systems and ground computing capabilities. The main result of the research presented in this extended abstract is the development of the capabilities required to enable a small-sized[2] quadrotor to fly autonomously while performing aerobatic maneuvers, including consecutive single, double, and triple flips about the flyer's roll principal axis and a non-principal axis. To the best of our knowledge, to this date, the flyer used in this research is the smallest controlled quadrotor to have autonomously accomplished three consecutive flips while remaining stable.

Multi-flip maneuvers require fast acceleration and deceleration of the flyer's angular velocity, and rapid robust stabilization to avoid vehicle stall, while operating in the presence of aerodynamic disturbances and actuator latency. Here, we introduce a specialized angular-speed planning method that, combined with a gain-scheduling control strategy, makes possible the robustly stable control of the experimental quadrotor. The proposed angular-speed planning and controller synthesis methods are based on the generalization of the notion of multi-flip maneuver to any body-fixed axis passing through the flyer's center of mass and the introduction of the concept of generalized flipping angle. As an example, we present maneuvers that include a single flip, double flips and triple flips about the body-axis that deviates 45° from the roll principal axis, $\boldsymbol{x}$, in the body-fixed roll-axis-pitch-axis plane ($\boldsymbol{x}$-$\boldsymbol{y}$ plane).

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[1]Normal size refers to quadrotors with *propeller-tip-to-propeller-tip* (PTPT) distances in the range $[35, 70]$ cm and weights in the range $[0.25, 2]$ Kg.

[2]The quadrotor weighs 19 g, including its battery, and has a PTPT distance of 13 cm.

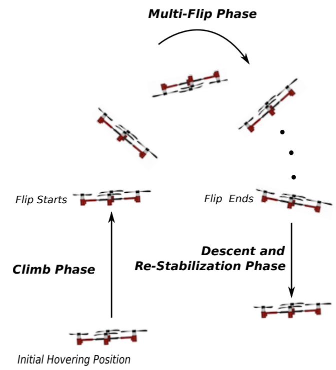


Fig. 1: The whole process of a multi-flip maneuver is composed of three phases: climb, multi-flip, and descent and re-stabilization. At the beginning, the quadrotor is hovering at a certain altitude and then is triggered to start the multi-flip maneuver. All three phases are autonomously controlled through only on-board sensors and control algorithms.

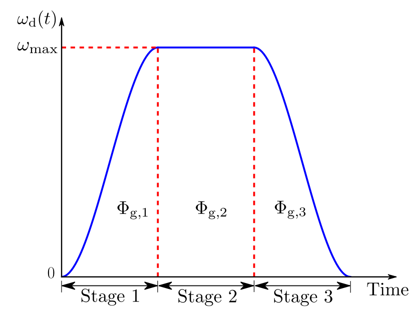
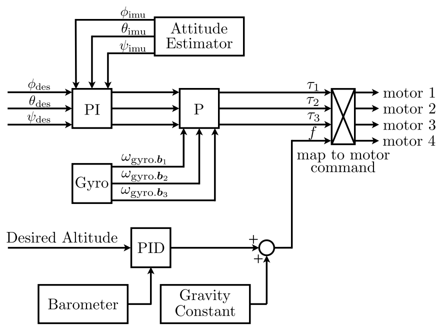


Fig. 2: Generalized flipping speed reference, $\omega_{\rm d}(t)$.

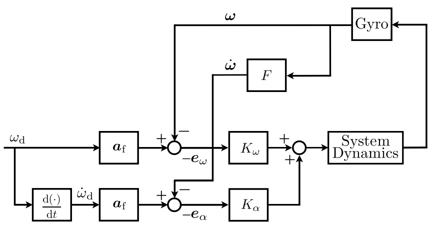
We believe that the results presented in this abstract are significant because during the execution of the experiments discussed here, the quadrotor flies carrying its own on-board power, sensing and computing capabilities, remaining fully autonomous during the performance of multi-flip maneuvers, which is the main difference with the experiments implemented with the use of motion-capture systems in highly-structured arenas, as done in [1] and [2], for example. Additionally, limited by the flyer's overall small size and low thrust-to-weight ratio, essential components of the quadrotor, such as motors, sensors and sources of power are stringently constrained in size, weight and performance. All these constraints, combined, make the synthesis and implementation of robust real-time controllers experimentally challenging.

II. The Process of a Multi-Flip Maneuver

As shown in Fig. 1, a multi-flip maneuver is a process that can be divided into three phases: climb, multi-flip, and descent and re-stabilization. The climb phase is necessary because it provides extra distance to avoid collisions with the ground and an upward translational speed necessary to reduce the falling distance while flipping in the air. The multi-flip phase starts when the control references for the robot's angular velocity and acceleration are varied so that it is forced to rotate about a chosen body axis. The multi-flip phase ends when the measured flipping angle reaches an *a priori* defined target angle, typically $2n\pi$, where n is referred

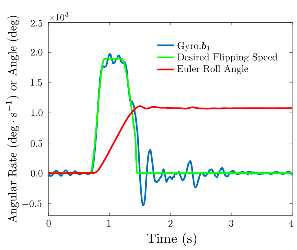


(a) Controller for Regular Flight.

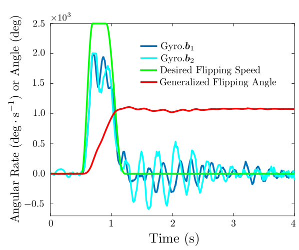


(b) Controller for Multi-Flip Aerobatic Flight.

Fig. 3: Gain-scheduling-based control structure implemented on-board. **(a)** Block diagram of the PID controller used during regular flight and the climb phase. **(b)** Block diagram of the controller used during the multi-flip and re-stabilization phases, defined in Fig. 1. Here, K_{ω} and K_{α} are positive diagonal gain matrices, $\boldsymbol{a}_{\text{f}}$ is a vector defining the flipping axis and F is an estimator filter. Notice that ω_{d} and $\dot{\omega}_{\text{d}}$ are scalar signals, and $\boldsymbol{\omega}$ and $\dot{\boldsymbol{\omega}}$ are vector signals.

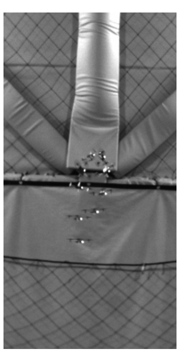


(a) Triple Flip (Roll Axis).



(b) Triple Flip (45°).

Fig. 4: **(a)** Triple flip about the body-fixed roll principal axis. The red line is the measured generalized flipping angle, equal to the Euler roll-angle in this case. The green line is the flipping speed reference and the blue line is the measured angular velocity about the body roll principal axis. **(b)** Triple flip about the generalized axis that lies in the body-frame $\boldsymbol{x}$-$\boldsymbol{y}$-plane and deviates 45° from the $\boldsymbol{x}$ axis. In this case, since the flipping axis is $[1/\sqrt{2}\ 1/\sqrt{2}\ 0]$, the speed reference for the angular velocities about $\boldsymbol{x}$ and $\boldsymbol{y}$ is $1/\sqrt{2}$ as large as the generalized flipping speed reference. Gyro.$\boldsymbol{b}_1$ and Gyro.$\boldsymbol{b}_2$ are the measured angular speeds about $\boldsymbol{x}$ and $\boldsymbol{y}$, respectively.


(a) Single Flip (45°).


(b) Double Flip (45°).


(c) Triple Flip (45°).

Fig. 5: Single-flip, double-flip and triple-flip maneuvers about a 45° generalized flipping axis. In these three figures, the multi-flip maneuver stars from the left bottom hand-side and ends at the right bottom hand-side.

to as the number of flips. Then, the last phase, descent and re-stabilization, starts. Two flight modes are employed during the execution of a multi-flip maneuver. In the climb phase, the quadrotor operates in the regular flight mode, which means that the attitude angles and angular velocities of the flyer vary slowly and stay small. During the multi-flip and descent phases, the quadrotor operates in the aerobatic flight mode, associated with large variations of the attitude angles and angular velocities of the robot's body. Two independent LTI controllers are turned on and off, according to a gain-scheduling strategy, to switch between flight modes.

III. The Notion of Generalized Multi-Flip

Normally, the notion of multi-flip maneuver refers to a $2n\pi$ angle rotation about the roll or pitch principal axis of the flyer (where n is the number of flips). Here, we generalize the concept of multi-flip maneuver to rotations about any body-fixed axis passing through the flyer's center of mass. A *generalized flipping angle* is defined as the angle with its vertex in the flipping axis, measured in the plane perpendicular to the flipping axis, generated between the horizontal plane of the inertial frame and the line created by the intersection of the $\boldsymbol{x}$-$\boldsymbol{y}$-plane of the body frame with the plane perpendicular to the flipping axis. This definition is very similar to that of the roll-angle in the Euler Z-Y-X convention. This similarity can be used to generate the generalized angular trajectories and speeds.

IV. Flipping Speed Planning

Fig. 2 shows a generic generalized flipping speed reference, $\omega_{\text{d}}(t)$. This signal, combined with the direction of the flipping axis, define a reference velocity. Here, the symbols $\Phi_{\text{g},1}$, $\Phi_{\text{g},2}$ and $\Phi_{\text{g},3}$ denote the amount of rotation accumulated during each of the three stages of the signal, corresponding to the area under the curve of $\omega_{\text{d}}(t)$ aggregated during each stage. The total area under the curve of $\omega_{\text{d}}(t)$ is $\sum_{i=1}^{3} \Phi_{\text{g},i} = 2n\pi$, where n is the number of flips. The maximum allowed flipping speed is denoted by ω_{max}. The first and third sections of the flipping-speed reference are generated using cubic functions to guarantee that the angular acceleration remains continuous.

V. Controller Design and Implementation

The proposed control scheme is shown in Fig. 3, which is composed of two controllers: one for regular flight, in Fig. 3-(a), and other for multi-flip aerobatic flight, in Fig. 3-(b). The controller employed during regular flight, in Fig. 3-(a), is designed using linearized dynamics of the quadrotor and employs *single-input–single-output* (SISO) *proportional integral derivative* (PID) loops to independently control the robot's Euler angles and altitude. The controller in Fig. 3-(b) is employed during the multi-flip phase, and the descent and re-stabilization phase of the aerobatic maneuver. This controller uses the robot's angular velocity and angular acceleration errors as feedback in order to generate the vector control signal.

VI. Experimental Results

Fig. 4 shows two triple-flip maneuvers about the body-fixed roll principal axis and the 45° non-principal axis, respectively. Fig. 5 presents the time-lapse plots of single-, double- and triple-flip maneuvers about a 45° generalized flipping axis. These time-lapse images were selected from videos taken using a high-speed camera at 240 *frames per second* (fps). The whole set of experiments can be found at http://www.uscamsl.com/resources/ICRA2016/MultiFlip.mp4.

References

[1] D. Mellinger, N. Michael, and V. Kumar, "Trajectory generation and control for precise aggressive maneuvers with quadrotors," *The International Journal of Robotics Research*, vol. 31, no. 5, pp. 664–674, 2012.

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