An Educational Quadrotor Testbed for $\mathcal{L}_1$ Adaptive Control

Charles Ray, Sheng Cheng, and Naira Hovakimyan

I. Introduction

Quadrotors are becoming increasingly prevalent in today's world. Their mechanical simplicity and aerodynamic maneuverability make them suitable for a wide range of applications - which places them in an equally wide range of environments. Each new application and environment brings with it a host of challenges that cannot be easily described or parameterized, e.g., aerodynamic drag, wind, and payloads with unknown or unexpected properties, which can all introduce uncertainties that deteriorate flight performance. Adapting control inputs in response to these uncertainties is therefore a desirable feature of a quadrotor's controller.

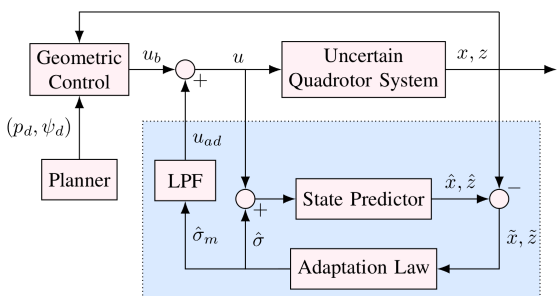

Fig. 1. Block diagram of $\mathcal{L}_1$ adaptive control for quadrotors.

One attractive solution to this problem is the $\mathcal{L}_1$ adaptive control. $\mathcal{L}_1$ adaptive control lumps all forces and moments not present in the nominal quadrotor dynamics together as uncertainties and estimates them using a state estimator and piecewise-constant adaptation law - both of which are easily computed. It comes with robustness and stability guarantees [1] as well. In short, $\mathcal{L}_1$ adaptive control offers cheap, accurate uncertainty estimation with guarantees on its performance and has been proven to work effectively.

However, the above work with $\mathcal{L}_1$ adaptive control is not easily transitioned to the realm of education. While the $\mathcal{L}_1$Quad project shows promise, it was implemented on custom-built hardware with a commercial flight controller. These features may be desirable in a research setting, but they present significant hurdles to classroom use. In the next section, we present an educational quadrotor testbed to bring $\mathcal{L}_1$ adaptive control into the classroom.

*This work is supported by National Aeronautics and Space Administration (NASA ULI) grant 80NSSC22M0070 and National Science Foundation (NSF) under the RI grant #2133656.

C. Ray is with the Department of Aerospace Engineering. S. Cheng and N. Hovakimyan are with the Department of Mechanical Science and Engineering. All authors are with the University of Illinois Urbana-Champaign, USA. (email: {cfray2,chengs,nhovakim}@illinois.edu)

II. Experiment

Our solution is to implement $\mathcal{L}_1$ adaptive control on a Crazyflie 2.1 quadrotor [2]. The Crazyflie is a nano-scale quadrotor drone designed for research, development, and education. It boasts open-source firmware, extensive documentation, and a low price point - all of which make it extremely attractive for this application. It is already in use as an educational tool in a large number of universities and institutions around the world. Implementing $\mathcal{L}_1$ adaptive control on a Crazyflie will improve the accessibility of both the algorithm itself and adaptive control as a whole.

Fig. 2. Crazyflie 2.1 with a cup fixed on top. Adding weights to the cup during flight is one possible way to demonstrate the $\mathcal{L}_1$ adaptive controller's ability to compensate for uncertainties induced by unknown weights.

We will introduce uncertainty to the system by placing a 6g weight into a cup fixed to the top of the Crazyflie, increasing the mass of the drone by roughly 20%. Without $\mathcal{L}_1$ adaptive control the drone will deviate noticeably from its setpoint and may even crash. With $\mathcal{L}_1$ adaptive control activated, however, the drone will compensate for the added uncertainty, leading to improved tracking performance. We use only onboard sensors, including an IMU, accelerometer, and an optical flow deck. No external measurement systems, such as GPS or motion capture technology, are used. The result is an implementation of adaptive control that is cheap, fast, and effective, and thus ideal for an education.

Though this work is presented without external measurement systems, such systems could be incorporated. Motion capture systems such as Vicon can be used to improve localization precision, leading to better tracking performance.

References

[1] Z. Wu*, S. Cheng*, P. Zhao, A. Gahlawat, K. A. Ackerman, A. Lakshmanan, C. Yang, J. Yu, and N. Hovakimyan, "$\mathcal{L}_1$ adaptive augmentation of geometric control for agile quadrotors with performance guarantees," *arXiv preprint arXiv:2302.07208*, 2023.

[2] "Crazyflie 2.1." [Online]. Available: https://www.bitcraze.io/products/crazyflie-2-1/