Robust adaptive control of a quadrotor helicopter

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This work presents a direct approximate-adaptive control, using CMAC nonlinear approximators, for an experimental prototype quadrotor helicopter. The method updates adaptive parameters, the CMAC weights, as to achieve both adaptation to unknown payloads and robustness to disturbances. Previously proposed weight-update methods, such as e-modification, provide robustness by simply limiting weight growth. In order to let the weights grow large enough to compensate unknown payloads, the proposed method relies on a set of alternate weights to guide the training. The alternate weights produce nearly the same output, but with values clustered closer to the average weight so that the output remains relatively smooth. This paper describes the design of a prototype helicopter suitable for testing the control method. In the experiment the new method stops weight drift during a shake test and adapts on-line to a significant added payload, whereas e-modification cannot do both.

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1. Introduction

Exhibiting open-loop unstable dynamics, the quadrotor poses challenges to present-day control engineers and several significant results appear in the literature (Table 1). Linear controls successfully stabilized the prototype X-4 Flyer in the presence of step-disturbances, while attached to a test platform [1]. Later the same research group tested a newer Mark II prototype without disturbances [2]. The STARMAC-II prototype achieved free-flight hovering using PID controls [3], where it was noted that wind disturbances cause the control to fail. Later, the same group accomplished path following outdoors [4]. Another prototype achieved autonomous flight in [5], where a linear control maintained stable hover providing robustness to small disturbances. Nonlinear controls can substantially expand the region of controllable flight angles compared to linear controls. A tethered Spectrolutions HMX-4 quadrotor used state inputs from a camera fed into a feedback-linearization control, without disturbances [6]. Nonlinear controls also achieved robustness to impulse disturbances, both in simulation [7,8] and using a test-stand experiment [9,10]. In [11,12], a nested-saturations controller stabilized a Draganfly III in the presence of impulse disturbances, and results were compared to linear feedback controls. A pre-trained neural-network stabilized a Draganfly II quadrotor in hover without disturbances [13]. Adaptive neural network controls successfully stabilized quadrotors in simulation [14,15]. Our proposed control strategy differs from those before as it aims to be both adaptive to model uncertainty (payloads) as well as robust to disturbances.

The nonlinear function approximator known as the Cerebellar Model Arithmetic Computer (CMAC) [17] provides fast learning or adaptation, similar to Radial-Basis-Function networks. The CMAC contains local basis functions with hypercube domains, or cells, and dealing with only the activated cells provides on-line computational efficiency. The CMAC is an associative memory equivalent to a neural network, although with normalized basis functions it also becomes a fuzzy approximator. Fast-adaptation and computational efficiency appear to make the CMAC ideal for use in direct adaptive control for the quadrotor. However, when sinusoidal disturbances cause inputs to oscillate between adjacent cells near the origin, the corresponding adjacent weights tend to drift to large positive and negative values causing control oscillations or chatter. An oscillating control signal may lead to sudden increases in state error, called bursting. Chattering can excite unmodeled dynamics causing instability [18]. Techniques traditionally used in direct adaptive control for robust weight updates restrict performance to stop the weight drift. These traditional techniques include parameter projection [19], deadzone [19], and e-modification [20]. The e-modification method appears attractive because it requires neither a-priori training on the model (like projection) nor knowledge of the bounds on disturbances (like deadzone) in order to guarantee uniformly ultimately bounded (UUB) signals. Because restricting weight magnitudes negatively affects performance in payload adaptive schemes, we seek an alternative method.

The proposed method for robust weight updates prevents adjacent weights from drifting far in opposite directions. In the new