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Adaptive Fault-Tolerant Control System Design for Rotary-Wing UAV

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Abstract

The design of an adaptive control system was obtained by modifying an existing version of a quadcopter control system that allowed for stable flight in ideal conditions. The existing roll, pitch and yaw rates were corrected with proportional-integral (PI) controllers. The constant P and I gains were modified to be time-varying functions, which were derived using the system's Lyapunov function candidate. After testing on a Simulink model, this system will be uploaded to a Pixhawk-controlled quadcopter to be tested in a hardware-in-the-loop experiment.

Introduction

As drones are developed for an increasing number of missions such as aerial mapping, building inspection, and delivery, the question of safety for both the drones and people nearby becomes more urgent. Drones have been capable of decent balance and course correction when disturbed, but their ability to recover from significant mechanism faults remains partial at best. As such, research into safe designs and advanced, robust control systems continues to make headway. There are two ways of achieving the latter: an active fault detection system, and an adaptive control system. Both methods aim to dynamically modify the onboard control system of a drone mid-flight to correct its control actions to account for a mechanism fault, such as a damaged motor or propeller. However, while both aim to allow the aircraft to continue flying, they differ in their implementation. The former requires onboard sensors that detect the fault. For example, a set of sensors connected to the motors of a quadcopter can immediately give an onboard computer information of which motor is damaged, which would then choose an appropriate control system to counteract the effect of the fault. While this method has the benefit of more informational telemetry and involves more planning (and therefore better preparation for) a number of faults, it is not without faults of its own; it requires a set of extra measurement devices, which in turn add weight to the drone, and require higher battery capacity as well as the ability to process such sensor data. In addition, a fault in a propeller, a very common issue in remote control (RC) flight caused by small collisions, is difficult to detect. Sometimes, the latter option, adaptive control system design, is a better solution. This method is purely analytical and requires no additional onboard hardware. Furthermore, it does not require preparation of several fixed control systems designed for a set of predictable faults. By creating time-varying proportional, integral and derivative (PID) gains that depend only on the dynamics and inertia of the system, as well as the default (correctly functioning) PID gains, a control system that immediately adapts to an abstract fault can be created.

Results

Discussion of the definition of the D and P terms is out of the scope of a poster. However, it must be mentioned that P is the matrix defined by a stability criterion equation that is necessary to solve the Lyapunov equation and ensure a stable system. This criterion involves the use of a constant mu, which is chosen by trial and error. Ideally, there is a mu value that allows the adaptive control system to stabilize without the PI gains exceeding realistic values. After going through this process, a mu of 1000 was chosen. The graph on the right shows the trial and error process. The mu value was chosen when the roll output matched the input in a quick enough time. Mu values that were higher created PI gains that were unrealistically high, up to 10 times the default PI gains, which will overcompensate

Adaptive Gain Derivation Process

The design of a control system begins with the definition of system dynamics. A quadcopter is modelled as in the following image: To design the control system, it is enough to examine the three main maneuvers of a quadcopter, roll, pitch and yaw, separately; the following will be a derivation of the time-varying adaptive gains and their control diagram. The default roll control system used by a Pixhawk-equipped quadcopter is given by the diagram on the right.

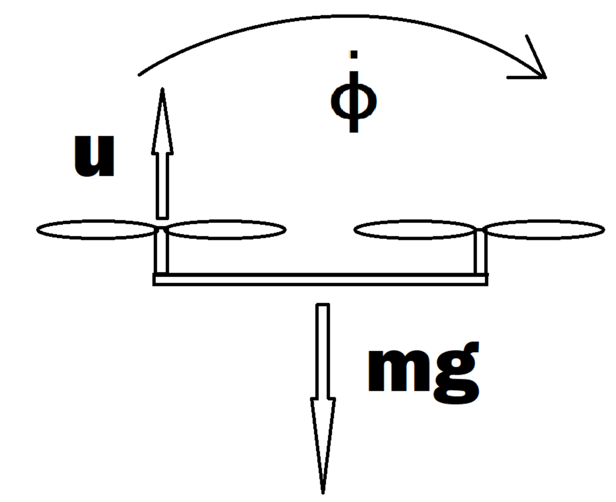


Fig. 1: Force diagram of the quadcopter roll maneuver.

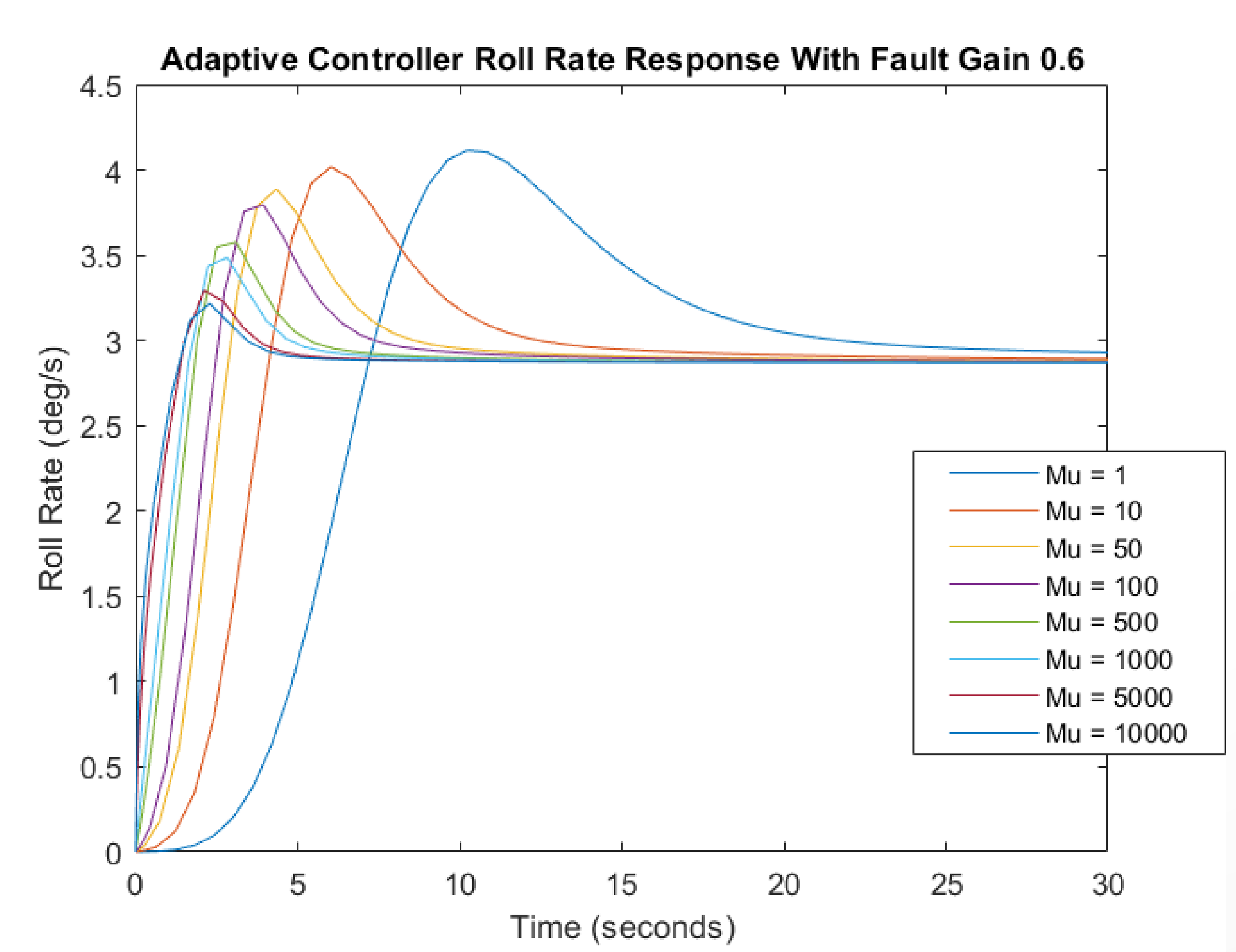
The adaptive control system in this investigation will replace the second PI controller in the figure above, which uses the difference in roll rates. It will also use a PI control scheme. The dynamics for a rolling quadcopter are defined:

$$I\ddot{\phi} = \Lambda u$$

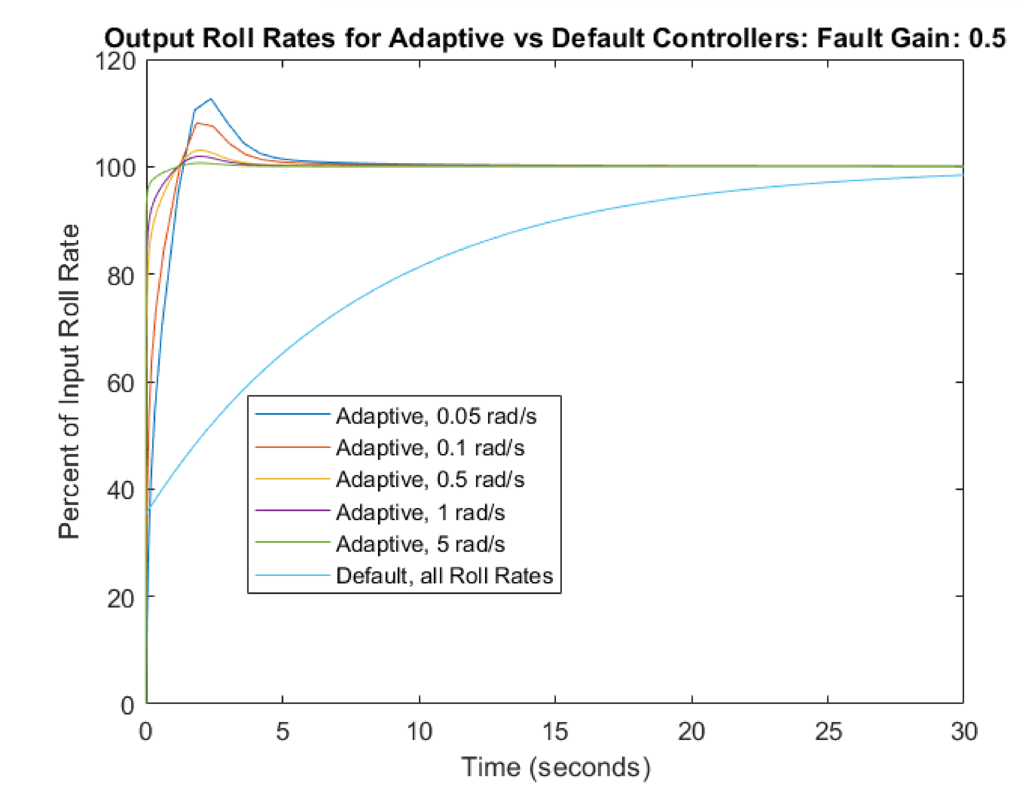
Where I is the moment of inertia along the roll axis, phi is the angular roll position, capital lambda is the fault gain, and u is the control action. The error e used to define the time-varying control gains was the difference between intended and actual roll rate. These equations were used to set up a Lyapunov function candidate. Using that with a required stability criterion equation, the system was solved such that it would create time-varying proportional and integral gains that would adapt to faults in the quadcopter's thrust ability. The resulting gains are defined in terms of solved quantities and quadcopter parameters (such as roll inertia) as follows:

$$\dot{\hat{k}}_I = (DPE + E^T P D^T)\int e$$

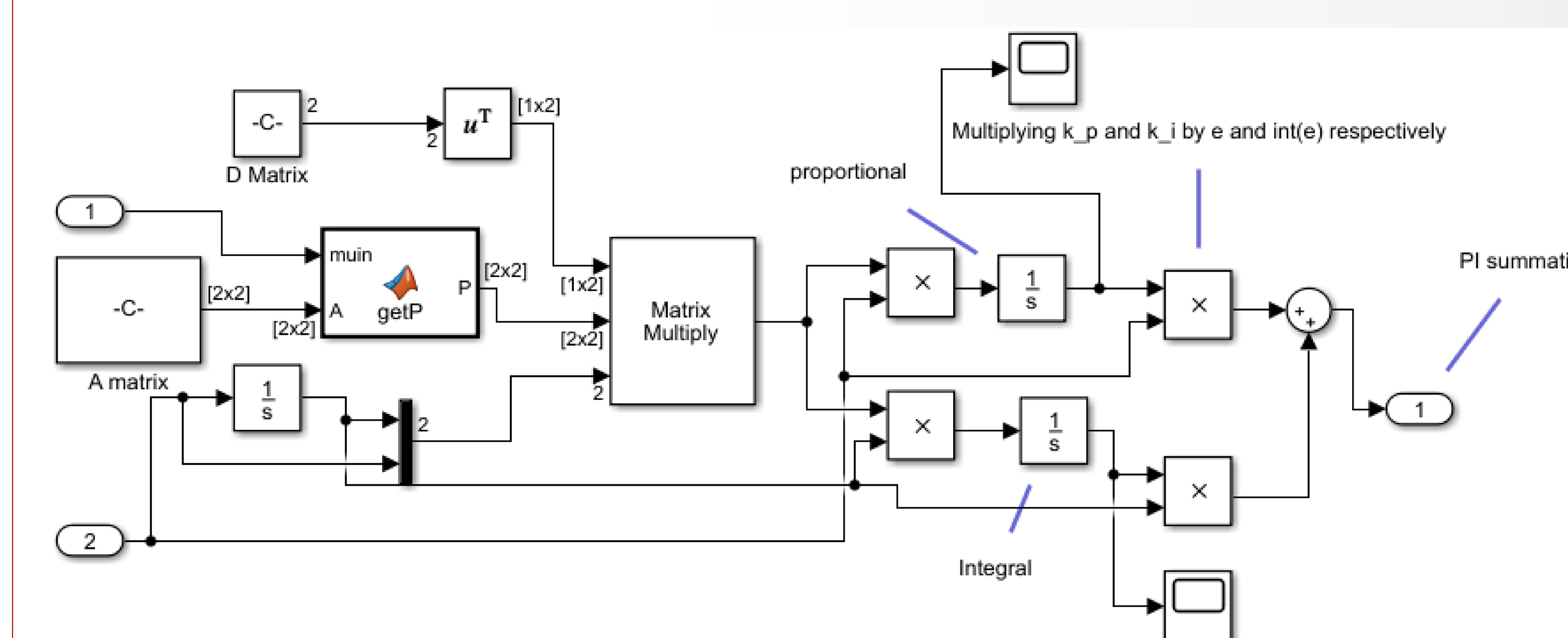
$$\dot{\hat{k}}_P = (DPE + E^T P D^T)\, e$$



Results (continued)



the error and cause the quadcopter to lose control. On the left is a diagram showing the roll rate outputs of the default and adaptive controllers. The blue line at the bottom shows that the default controller took 25 seconds to reach the input roll rate with a 50% thrust reduction, or A 0.5 fault gain. The default controller performed the exact same way for each roll rate. The adaptive controller's response varied for each roll rate; however, in each case, the adaptive controller achieved the desired roll rate much more quickly (within 5 seconds) than a normal PI controller. The adaptive controller block diagram is derived from the formulas given in the derivation process and is pictured below:



Conclusion

By making use of the dynamics of the quadcopter roll error, the adaptive controller is able to constantly update its proportional and integral gain values to optimally correct the maneuver much more effectively than the default controller with constant gains. During the design of such a controller, it is crucial to chose the right coefficient for a given quadcopter roll inertia; a poorly chosen value can cause the time varying gains to rise too high and overcompensate for roll errors. An alternative method that uses a reference model to calculate error can be used to design the functions for time varying gains. In the future, this project will be extended to more realistic experiments. In the near future, the control system will be implemented for yaw and pitch maneuvers, and tested on a FlightGear simulation, and later a flight test.

References

[1] Quan, Quan. Introduction to Multicopter Design and Control. Springer Singapore, 2018.

[2] Lavretsky, Eugene, and Kevin A. Wise. Robust and Adaptive Control: with Aerospace Applications. Springer, 2013.