Development of a Control Algorithm with Kalman Filter enhancement to control the altitude of a Quadcopter.

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Abstract

This paper presents the development and assessment of an advanced altitude control system for the "Bzzz" quadcopter. Employing a robust integration of a Kalman Filter and control algorithms, the study aims to achieve precise altitude stabilization under varying environmental and operational conditions. The control system is based on real-time data from multiple sensors, including a time-of-flight (ToF) sensor, a barometer, and a GNSS sensor, which collectively offer comprehensive altitude data with varying degrees of accuracy. The system dynamics are encapsulated within a linear state-space model, which facilitates the implementation of a Proportional-Integral-Derivative (PID) controller and, subsequently, a Model Predictive Control (MPC) system for improved responsiveness and accuracy. Despite meticulous system modelling and control design, initial simulations indicated suboptimal performance, which prompted further investigation into system dynamics and control strategy refinement. This paper details the iterative process of system modelling, parameter estimation via Kalman Filtering, and control optimization, highlighting the challenges encountered and the solutions employed to enhance system reliability and performance. The results demonstrate the efficacy of the Kalman Filter in state estimation and underscore the critical dependencies between system modelling accuracy and control strategy effectiveness. All code used in this report can be found at (https://github.com/ben120-web/Quadcopter).

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Introduction

In this lab, we embark on the task of designing an estimation and control system for the "Bzzz" quadcopter, as depicted in **Figure 1**. The objective is to develop a robust system that enables the quadcopter to maintain a constant altitude, regardless of external factors and disturbances. To achieve this, we leverage a combination of sensors, including a time-of-flight (ToF) sensor, a barometer, and a global navigation satellite system (GNSS) sensor.
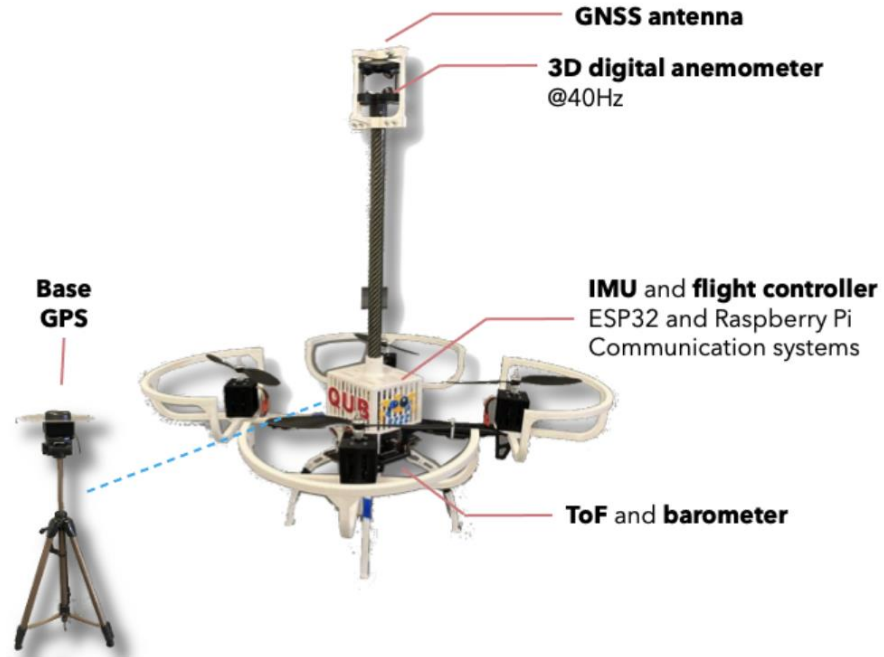

Figure 1 Picture illustrating the Bzzz quadcopter.

The ToF sensor provides measurements of the distance from the ground with a standard error of ±6 cm, while the barometer estimates altitude with an error of ±25 cm. Additionally, the GNSS sensor, coupled with a base GNSS station, offers precise altitude estimates with a standard error of ±5 cm. These sensors serve as crucial components in our estimation framework, allowing us to accurately infer the state of the quadcopter.

To model the dynamics of the quadcopter, we consider the forces acting upon it, namely the weight mg and the force exerted by the propellers F_{prop}. Through experimentation, we establish a model for the lifting force $F_{\text{prop}} = \alpha\tau + \beta$, where $\alpha > 0$ and $\beta < 0$ are constants dependent on the battery's charge level. Utilizing this model, we derive the quadcopter's dynamical equations, enabling us to predict its vertical acceleration and velocity.

With our system model in place, we turn our attention to estimation. Employing the Kalman filter, we aim to estimate the unknown parameters α and β while simultaneously inferring the quadcopter's state variables, including altitude and velocity. Leveraging sensor measurements from the GNSS, ToF, and barometer sensors, we construct an estimation system capable of accurately tracking the quadcopter's state despite uncertainties and disturbances.

Furthermore, we design a control system that utilizes the altitude estimates obtained from our Kalman filter to enable the quadcopter to maintain a constant altitude. Our controller adjusts

the throttle reference signal sent to the quadcopter's motors, ensuring precise altitude control in various scenarios, including sudden changes in altitude, GNSS signal interruptions, battery drainage, and sensor biases.

In this report, we present our proposed estimation and control system, along with experimental results demonstrating its effectiveness in diverse real-world scenarios. Additionally, we discuss the rationale behind our parameter choices and provide justifications for our design decisions. Through rigorous testing and analysis, we aim to validate the performance and reliability of our estimation and control system for altitude hold in quadcopters.

Methodology

In this section, we delve into the simulation and control of an altitude system, primarily focusing on the integration of a Kalman Filter for state estimation and a Proportional-Integral-Derivative (PID) controller for altitude regulation. This approach leverages the robustness of Kalman filtering for noisy data and the effectiveness of PID control in maintaining a desired setpoint under varying conditions.

System Model

The system's dynamics are modelled using discrete-time state-space equations. The state vector z. z consists of the altitude z and velocity z′ such that $z = [z, z']^T$. The system's state evolution is governed by the following linear equations:

$$z_{k+1} = Az_k + Bu_k + Gw_k$$
$$y_k = Cz_k + v_k$$

Where A is the state transition matrix, B is the control input matrix associated with the throttle input u. G is the matrix mapping the process noise wk to the state vector, assumed to be identical to B, and C is the output matrix. Wk and vk represent the process and measurement noise, modelled as zero-mean Gaussian noises with covariances Q and R respectively:

$$A = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.5\,\Delta t^2 &] \\ \Delta t &] \end{bmatrix}$$

$$C = \begin{matrix} 1 & 0 \end{matrix}$$

Kalman Filter

The Kalman filter is employed to estimate the systems state by minimising the mead of the squared error. The filter iterates through two main phases: prediction and update.

1. Prediction:
$$z_{k|k-1} = Az_{k-1|k-1} + Bu_{k-1}$$
$$P_{k|k-1} = AP_{k-1|k-1}A^T + GQG^T$$

2. Update:

$$K_k = P_{k|k-1}C^T(CP_{k|k-1}C^T + R)^{-1}$$
$$z_{k|k} = z_{k|k-1} + K_k(y_k - Cz_{k|k-1})$$
$$P_{k|k} = (I - K_kC)P_{k|k-1}$$

PID Controller

A PID controller is used to compute the control input uk based on the altitude error. The PID control law is given by:

$$u_k = K_p e_k + K_i \int e_k dt + K_d \frac{de_k}{dt}$$

Where ek is the error between the desired altitude and the measured altitude. Kp, Ki and Kd are the proportional, integral, and derivative gains respectively.

The system was simulated, and results are shown in the next section.

Results

Figure 2 below shows the response of the system. It is evident that the controller/estimation system is not operating correctly.
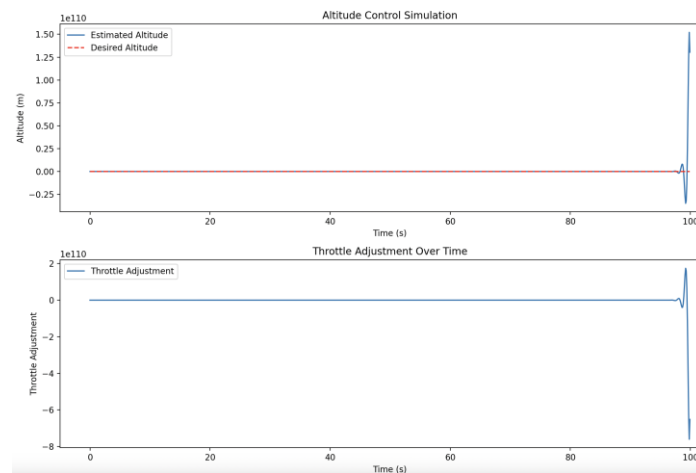

Figure 2 Quadcopter altitude over time.

It was not obvious what was incorrect within the setup of the PID controller, so in an attempt to resolve this I tried to implement an MPC controller. This should provide a more robust method of minimising the error.

Figure 3 below shows the behaviour when an MPC in implemented over a PID controller. The desired performance is still not met, the throttle adjustment seems to be correct however the estimated altitude of the quadcopter is incorrect. This potentially points to an error in the system dynamics.
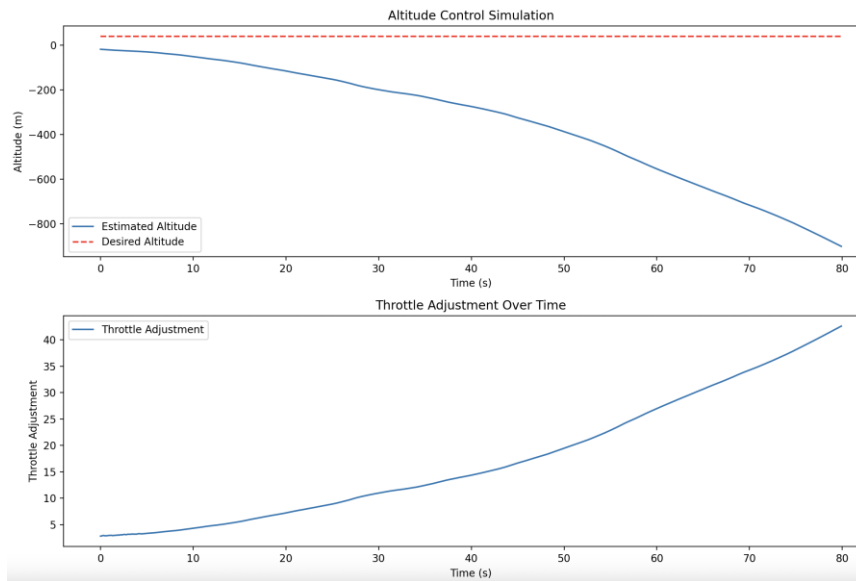
Figure 3 MPC controlled system.

To confirm the error was in the controller, the estimated position of the Kalman filter was plotted alongside the actual position. **Figure 4** validates the performance of the Kalman filter as it can accurately predict the position.
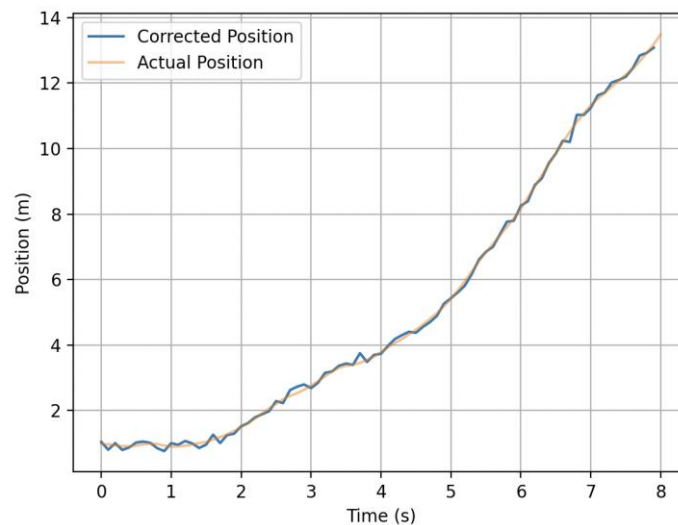

Figure 4 Kalman predicted vs actual positions.

Conclusion

This report investigates the design of a control and estimation system to control the altitude of a quadcopter device. In summary, an effective control system was unable to be implemented. However, results show that the Kalman filter was correctly designed, and simulations provide evidence that it can accurately predict the position of the quadcopter. Both Proportional, Integral, Derivative (PID) and Model Predictive Control (MPC) controllers were implemented on Python and estimations from the Kalman filter were input into each.