QUADROTOR ROLL AND PITCH STABILIZATION USING SYSTEM IDENTIFICATION BASED REDESIGN OF EMPIRICAL CONTROLLERS

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) are currently one of the hot topics of study which have numerous applications such as remote sensing, aerial surveillance, exploration, search and rescue, transport, scientific research and armed attacks. In this work we consider a test-bed for the design of a low cost flight controller for a quadrotor and we demonstrate the design of the roll and pitch controllers on an experimental setup through the stages of data collection, modeling, control design and verification. The procedure consists of four stages: 1) Experimental determination of controller coefficients, 2) Data collection, 3) System identification, 4) Controller redesign by tuning coefficients with a numerical search. It is observed that the system designed as such is capable of achieving satisfactory pitch and roll stabilization, and coefficient tuning on the identified model noticeably improves the settling time and steady state oscillation amplitude.

KEY WORDS

Discrete time, linear estimation, aerial vehicles, quadrotor, UAV, four rotor helicopter, vehicle control.

1. Introduction

Unmanned Aerial Vehicles (UAVs) have by now gained great importance in both military and civil sector [1-4]. With each passing day, new controller designs emerge in this field [5-7]. An important subset of UAVs is quadrotors, which have become popular recently due to their small size and maneuverability. Studies on quadrotors include attitude stabilization, estimation and multi-vehicle configurations [8-10].

In the present work we attempt to demonstrate roll and pitch-axes stabilizing controller design approach on an experimental test-bed in an attempt to form a foundation for our ultimate research goals of building a unique quadrotor system from bottom up. For this purpose we built custom quadrotor hardware and implemented software procedures to drive the servomotors, carry out measurements, communicate data, and control the attitude of the UAV, using reasonable cost and commonly available electronic components. An important contribution of this paper is to illustrate a simple process to improve empirically determined controllers so as to improve the overall closed-loop response of the system. This involves identifying a transfer function around the desired equilibrium (which is the horizontal axis for roll or pitch stabilization) and performing a numerical search using this model to tune the coefficients. The rest of the paper will explain the methodology, present experimental results and discuss the findings.

2. Methodology

The basic quadrotor model used in the study is shown in. Figure 1. F_1, F_2, F_3 and F_4 are the forces applied by the motors. By effects of these forces, pitch angle (θ), roll angle (ϕ) and yaw angle (ψ) are produced.

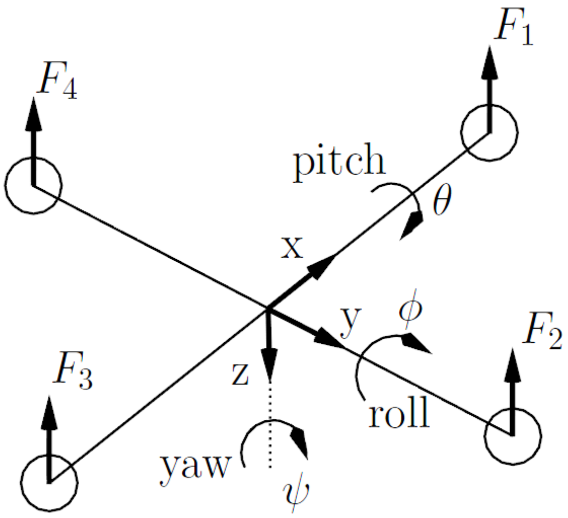

Figure 1: Simple Quadrotor Model

2.1 Hardware Design

The general overview of the hardware design can be seen in Figure 2.

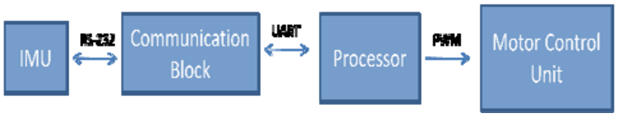

Figure 2. General Overview of the Hardware Design

For the IMU we utilize Microstrain-3DM-GX2, which contains a triaxial accelerometer, triaxial gyro, triaxial magnetometer, and an on-board processor running a sensor fusion algorithm. For the communication block we implement a voltage level converter in order to map the output of the IMU into UART voltage levels. As for the microprocessor, a PIC32MX795F512L has been used which can operate up to 80 MHz. The test platform hardware is shown in Figure 3. As mentioned previously, for the sake of example we shall individually consider the stabilization of the roll angle ϕ or pitch angle θ; hence, the quadrotor has been fixed in the setup to allow for rolling or pitching behavior only.

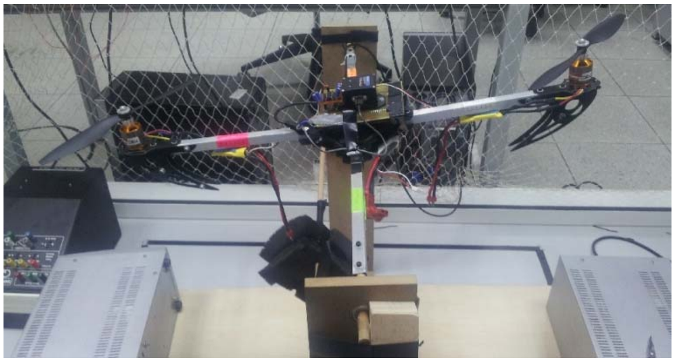

Figure 3. Experimental Quadrotor Test Platform

After the roll and pitch controllers are designed and tested, we shall disassemble the test bed and connect only a few ropes to the floor; this allows for the UAV to hover freely in two dimensions while limiting its maximum altitude since we are yet to design an altitude controller.

2.2 Software Design

The pitch angle θ and roll angle ϕ is calculated from the outputs of the IMU using the following equations

$$\theta = \tan^{-1}\left(\frac{a_x}{a_z}\right) \tag{1}$$

$$\phi = \frac{a_y}{a_x \sin\theta - a_z \cos\theta} \tag{2}$$

where a_x, a_y and a_z are the accelerations read from the inertial sensors in the x, y, z axis respectively. This calculated angle is then processed by a Kalman filter so as to obtain a cleaner and more precise measurement. The process and measurement noise covariances of the filter were obtained empirically as $Q = 1$ and $R = 3$. Following filtering, the measurements enter a PID controller, whose block diagram is illustrated in Figure 4.

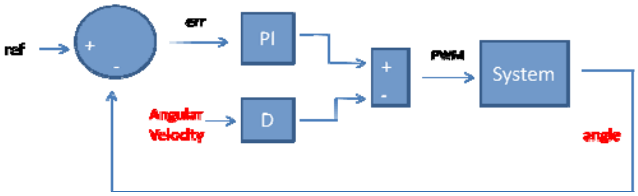

Figure 4. Block Diagram of the PID Controller

Note from the figure that for better numerical accuracy, the derivative term is used directly from the angular velocity measurements obtained from the IMU instead of numerically differentiating the error signal. Note also the minus sign in front of the D term since for a constant roll angle reference we have $\frac{derr}{dt} = \frac{d}{dt}(\mathrm{ref} - \mathrm{err}) = -\frac{d}{dt}\mathrm{err}$. The method we employ in determining the PID coefficients consists of four stages: 1) Experimental determination of the PID coefficients, 2) Data collection, 3) System identification, 4) Controller redesign by tuning coefficients with a numerical search. For the first stage we run the experimental setup and use heuristic rules of thumb, such as slowly increasing P until the system somewhat oscillates around the horizontal, then adding a D term to reduce oscillations and finally adding an I term to eliminate the steady state error. The values resulting from this procedure are $K_p = 0.35$, $K_i = 0.01$ and $K_d = 0.05$, which produced in a closed loop system capable of stabilizing the roll and pitch angle, but the response was slower than desired and quite jittery. For this reason we proceed with the extra tasks described below.

2.3 System Identification

We perform system identification using experimental data obtained from the PID coefficients mentioned above with the goal of producing a linear model around the operating point $\phi \approx 0$ and $\theta \approx 0$. The system input is selected as the mean-shifted pulse width modulation value (PWM) that is fed to the servomotors rotating the propellers. The outputs are the roll angle ϕ and the pitch angle θ. Numerous system identification techniques were applied to the data through the use of MATLAB System Identification Toolbox, but the best results were achieved with subspace identification (N4SID) [11], and the transfer functions for these models are shown in (3) and (4). The sampling period is $T_s = 0.029\,s$, which is the rate that we process data for our particular hardware/software configuration.

$$H_{roll}(z) = \frac{2.881\, z^5 - 2.501\, z^4 - 0.1687\, z^3 + 0.3733\, z^2 + 1.51\, z - 0.9951}{z^6 - 0.8117\, z^5 - 0.006187\, z^4 - 0.02259\, z^3 + 0.3682\, z^2 + 0.201\, z - 0.298} \quad (3)$$

$$H_{pitch}(z) = \frac{-2.402\, \mathrm{z}^6 + 1.522\, \mathrm{z}^5}{\mathrm{z}^6 - 0.6012\, \mathrm{z}^5 - 0.07561\, \mathrm{z}^4 - 0.01995\, \mathrm{z}^3 + 0.03405\, \mathrm{z}^2 + 0.04376\, \mathrm{z} - 0.04997} \quad (4)$$

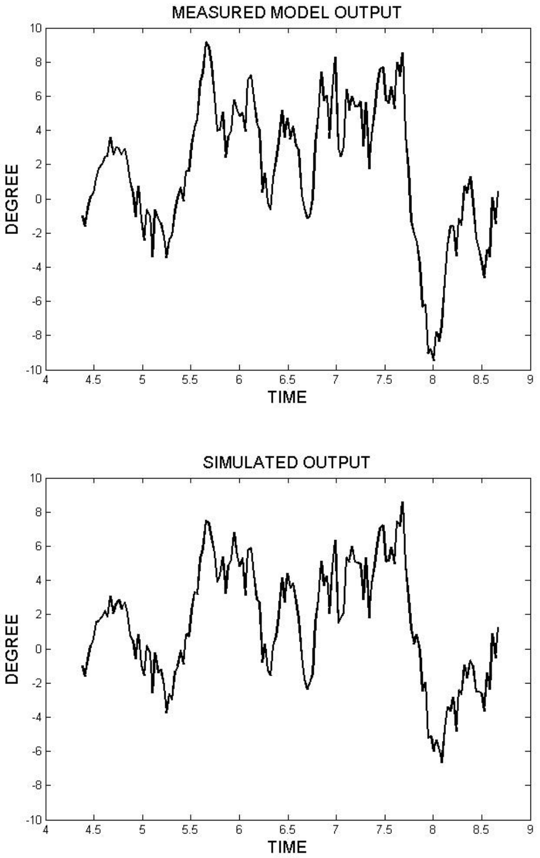

Figure 5. Measured output (top) and simulated model output (bottom) for pitch angle

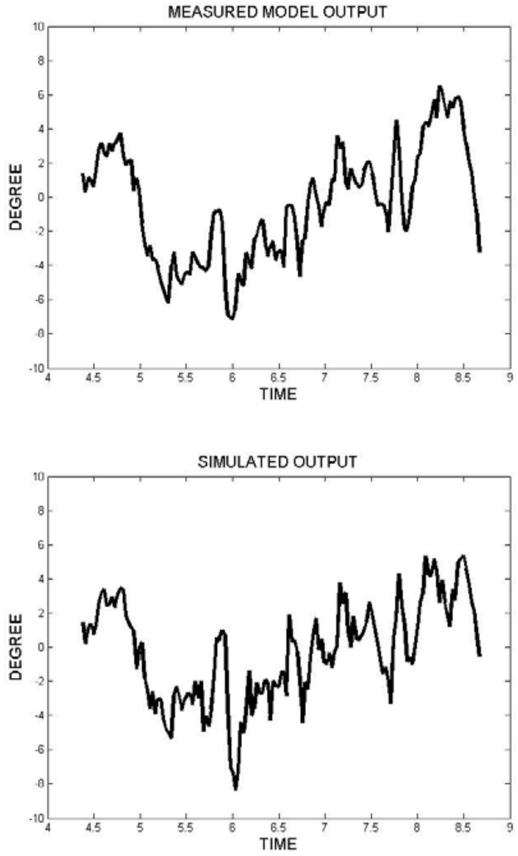

Figure 6. Measured output (top) and simulated model output (bottom) for roll angle

One can observe a good agreement between the output measured from experiments and the output simulated from the model, which are compared in Figure 5 and Figure 6.

2.4 Controller Redesign

With the model of the system at hand, we now proceed to redesign the controller so as to improve the performance of the closed loop system, in particular, the time it takes for the system to settle. For this purpose we set up a numerical search problem in MATLAB within a five percent neighborhood of the empirical coefficient values, and look for a solution that minimizes the settling time. This process yields the coefficient values $K_p = 0.4$, $K_i = 0.03$ and $K_d = 0.05$, using which we form the discrete time PID controller

$$\mathrm{C(z)} = \mathrm{K_p} + \mathrm{K_i}\frac{1 + \mathrm{z}^{-1}}{1 - \mathrm{z}^{-1}}\frac{\mathrm{T_s}}{2} + \mathrm{K_d}\frac{1 - \mathrm{z}^{-1}}{\mathrm{T_s}} \quad (5)$$

where the derivation in discrete time is approximated as $\mathrm{y(k)} = \frac{\mathrm{u(k)} - \mathrm{u(k-1)}}{\mathrm{T_s}}$ and the integration in discrete time is approximated as $\mathrm{y(k)} = \mathrm{y(k-1)} + \frac{\mathrm{u(k)} + \mathrm{u(k-1)}}{2}\mathrm{T_s}$.

3. Experimental Results

After the design of pitch and roll controllers, the quadrotor was detached from the test setup (Figure 3) and was started directly from the floor as shown in Figure 7. Ropes were tied to the sides for security purposes in case something unexpected happens; they are normally loose and do interfere with the quadrotor's motion.

Figure 7. Experimental Quadrotor Test Platform

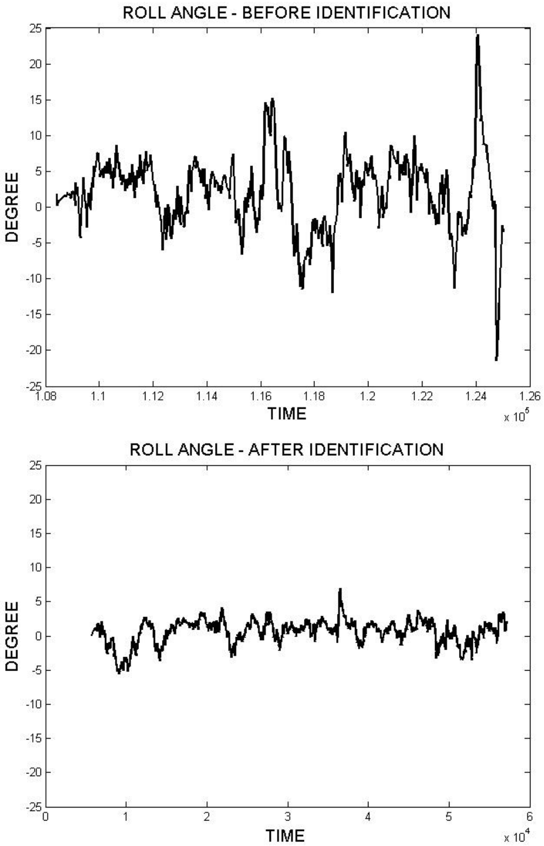

Figure 8. Experimental results showing the roll angle ϕ with empirical PID coefficients (top) and PID coefficients tuned on the identified model (bottom)

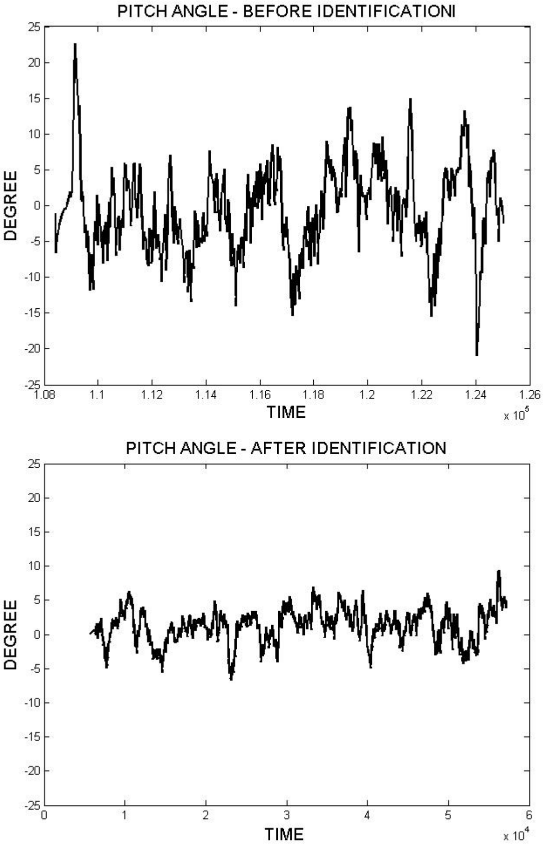

Figure 9. Experimental results showing the pitch angle θ with empirical PID coefficients (top) and PID coefficients tuned on the identified model (bottom)

Figure 8 and Figure 9 show a comparison between two sets of the experimental results: the response of the closed-loop system with the empirical PID coefficients and the response of the closed-loop system with the PID coefficients tuned on the model obtained from system identification. It can clearly be seen that the tuned coefficients have improved the closed-loop response significantly; the roll and the pitch angle settle much faster, and once amplitude of the steady state oscillations are lower.

4. Conclusions and Future Works

This paper presented a quadrotor roll and pitch axes control system based on a PID controller. The controller was first tuned experimentally so that the response stays around the horizontal, after which mean-shifted servomotor PWM values, and the roll and pitch angle readings from IMU were stored to form the input-output data set. This set was subjected to system identification so as to produce transfer functions of the quadrotor system around the origin, and it was observed that the model can reproduce the system response quite acceptably. Using a numerical search procedure, the PID coefficients were then tuned around a local neighborhood of the empirical PID for a faster settling time. The coefficients obtained from this procedure were tested on the experimental setup and it was observed that the settling time as well as the steady state oscillations of the closed-loop system was improved.

Future research directions include extending the results to the control the yaw axis, as well as the testing of the approach presented on different air vehicles.

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