

EMBEDDED ONBOARD CONTROL OF A QUADROTOR AERIAL VEHICLE

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Abstract

The quadrotor aerial vehicle is a structure that has recently been investigated by several teams due to its inherent ability to hover in place while carrying small payloads. This structure has required significant processing power to adequately control due to the requirement of a minimum of four control loops for stable flight. A pilot-in-the-loop system has been implemented by multiple research teams where control is handled by onboard processing systems such that the onboard system provides the stability control while the pilot gives flight commands via a standard hobby RC system [1]. While several teams around the world have successfully created autonomous flight using the quadrotor platform, they have all relied on significant base-station computing for control of the flight [1] and traditional control methods not meant for changing systems. This is due, in part, to the fact that many control methods are computationally intense and, for a small, mass sensitive vehicle, large and powerful processors are out of the question. For a system requiring at least four control loops (roll, pitch and altitude), it is a stretch to consider onboard computing for this platform. However, if the autonomous quadrotor is to be of any use in completing a real mission, its computing power will need to be onboard. Fortunately, multi-core microcontrollers have recently come into use for complex systems such as the quadrotor. This paper outlines an attempt on the part of the authors to implement a lightweight, onboard controller for the quadrotor platform, and describes an attempt at adaptively controlling the structure. This controller consists of four multi-core microcontrollers for a total of thirty-two single cores. The system and its control method are described here along with the physical implementation and results.

Introduction

Because the traditional fixed-wing airplane suffers from low maneuverability in tight spaces and does not have the ability to hover in place, micro-UAVs of non-traditional structure have been given greater attention in recent years. One of these designs is the quadrotor. The quadrotor is a helicopter design with four dual-axis, symmetrically located points of thrust. This thrust is provided by fixed-pitch rotors, which are commonly driven by four electric motors.

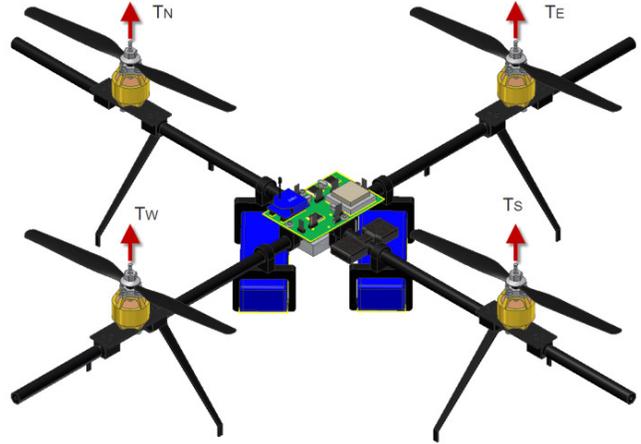


Figure 1. The Quadrotor Aerial Structure

Normally, the flight control electronics are mounted such that the center of gravity falls into the center of the structure at a level slightly below the line of thrust for added stability [1], [2]. A traditional helicopter possesses a tail with a rotor that is used to counteract the yaw thrust created by the spinning rotor. However, unlike a traditional helicopter, the quadrotor has two rotors spinning clockwise and two rotors spinning counterclockwise to eliminate the yaw thrust, thereby eliminating the need for a tail.

With the use of four fixed-pitch rotors, control is seemingly easier than that of a traditional helicopter with one point of thrust. To pitch or roll the quadrotor, the control system must only unbalance the thrust of two rotors on the same axis. Given that the controlled axes (roll, pitch and yaw) are not singularly related to the controlled motor speeds, a set of transformation equations must be developed. From observation, the following equations (1-4) that describe the action of the structure can be written [3].

$$T_T = T_N + T_S + T_E + T_W \quad (1)$$

$$T_R = l(T_W - T_E) \quad (2)$$

$$T_P = l(T_N - T_S) \quad (3)$$

$$T_Y = \frac{\kappa}{\alpha}(T_N + T_S - T_W - T_E) \quad (4)$$

In Equations (1) through (4), T_T , T_R , T_P , T_Y , T_N , T_E , T_S and T_W represent total thrust, roll thrust, pitch thrust, yaw thrust and motor/rotor thrust from the north, east, south and west motor/rotor combinations, respectively. The constants l , k and α represent the length from the center of the structure to the thrust point, the drag coefficient and the thrust coefficient, respectively. Together, these four equations can be represented as a transformation matrix, M , shown in Equation (5) that relates attitude thrust to motor thrust.

$$T_A = MT_M \rightarrow \begin{matrix} \begin{bmatrix} T_T \\ T_R \\ T_P \\ T_Y \end{bmatrix} \\ T_A \end{matrix} = \begin{matrix} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 0 & -1 & 1 \\ 1 & -1 & 0 & 0 \\ \kappa/\alpha & \kappa/\alpha & -\kappa/\alpha & -\kappa/\alpha \end{bmatrix} \\ M \end{matrix} \begin{matrix} \begin{bmatrix} T_N \\ T_S \\ T_E \\ T_W \end{bmatrix} \\ T_M \end{matrix} \quad (5)$$

However, because the attitude is being sensed and the rotor thrust controlled, the inverse of the transformation matrix, as given in Equation (6), is more useful.

$$T_M = M^{-1}T_A \rightarrow \begin{matrix} \begin{bmatrix} T_N \\ T_S \\ T_E \\ T_W \end{bmatrix} \\ T_M \end{matrix} = \begin{matrix} \begin{bmatrix} 0.25 & 0 & \frac{1}{2l} & \frac{\alpha}{4\kappa} \\ 0.25 & 0 & \frac{-1}{2l} & \frac{\alpha}{4\kappa} \\ 0.25 & \frac{-1}{2l} & 0 & \frac{-\alpha}{4\kappa} \\ 0.25 & \frac{1}{2l} & 0 & \frac{-\alpha}{4\kappa} \end{bmatrix} \\ \end{matrix} \begin{matrix} T_T \\ T_R \\ T_P \\ T_Y \end{matrix} \quad (6)$$

A substantial amount of research by others has yielded a plethora of information on the subject [4]. However, there is one very big difference between these studies and the quadrotor design discussed here. Most quadrotors have the computations and control systems running on a base station, such as a workstation computer, and only contain onboard electronics to sense and perform the calculated control signal received via some wireless link [5], [6]. Realistically, due to many factors including cost and security, the reduction of dependence on a wireless control signal is necessary if these devices are to function long term and in the real world. The quadrotor described in this paper is completely independent of a base station. All sensing, control and actuation needed for flight is done onboard via four multi-core microcontrollers containing a total of thirty-two computing units. While the system is not dependent on a base station, it does send signals back to a monitoring station so that criti-

cal information can be monitored during the development phase of this research.

When controlling a flying object, adequately descriptive models are not exactly linear nor are their parameters predictable. The literature provides examples of adequately descriptive models but the models are linearized around an operating point and the design continues from there [3], [7]. These same sources indicate success in flight with near constant external parameters such as temperature and pressure, but no analysis has been found regarding flight performance over a wide operating range that is indicative of the real world. Since the field of adaptive control was created for flight [8], it seems the quadrotor aerial vehicle would benefit from an application of adaptive control given that the model for flight changes with temperature, humidity, pressure and altitude. In this paper, the hardware design of the system that gives the structure onboard control, the methods used for control of the system and preliminary results of the research are discussed.

The Design

To perform adequate control and monitoring of performance, sensing on the quadrotor currently includes GPS, an Attitude Heading Reference System (AHRS), a sonar sensor, temperature sensors and an analog-to-digital converter (ADC) for reading the battery voltage. The AHRS is the "9 DOF Razor IMU" from SparkFun Electronics. Sonar, the Parallax Ping Sensor, is used to measure altitude in low-level operations such as takeoff, landing and low-level flight, where GPS is not accurate enough. Critical to monitoring and the safety of the equipment and researchers are the temperature sensors. Due to the use of lithium-polymer batteries (4 cell, 6Ah), there is a risk of serious damage if the batteries do not stay within an operational voltage range. Therefore, the battery pack temperature and voltage are carefully monitored and displayed on the base station at all times. If any of the variables reach predefined boundaries, they will trigger fail-safe protocols to safely land the quadrotor to prevent damage to itself and others.

Another aspect of monitoring for safety purposes is the ADC used to monitor the battery voltage. This is vital because if the lithium-polymer battery drops below ~13 volts, it could internally damage the battery and cause it to explode in flight or shortly after landing, thereby causing serious damage to the quadrotor or the research team. The quadrotor is equipped with a GPS module (Parallax PMB-248) affixed to the top of the circuit board. GPS is used in real time to give the current latitude, longitude, and an approximate altitude at an update rate of 1Hz. For the purposes of equipment recovery and flight data logging, the GPS

coordinates will also be transmitted back to the monitoring station. For communication between the quadrotor and the base station monitoring station, Zigbee communication modules are used. These modules offer a very reliable, short-range 2.4GHz communication channel ideal for this application. At the other end of the Zigbee transmission is the monitoring center. This system exists to display critical flight information for development purposes; however, near the end of the development phase of this research, the monitoring station will become unnecessary. On the quadrotor, there are four motors with four corresponding motor controllers. The motor controllers are Turnigy TR_B25A for outrunner brushless motors. The motors are Rimfire 35-36-1200kv brushless motors. While the motor controllers connect directly to the battery pack, the onboard electronics require both 3.3V and 5V. For purposes of efficiency, switching mode power supply (SMPS) modules are used to regulate the battery voltage down to the necessary operating voltage.

Since there is a tremendous amount of computing required to maintain stable flight and to stay on course, there are four separate Parallax Propeller multi-core microcontrollers onboard the quadrotor. The microcontrollers can communicate and pass data between themselves so that the computing loads can be separated and balanced. Each of the four microcontrollers has a specific task. The first of the microcontrollers computes the data from the AHRS and passes that data on to another microcontroller. This microcontroller has been left largely unloaded such that a Kahlman filtering approach can be implemented to filter the data as the large motor currents induce significant noise into the sensed AHRS data. The second microcontroller connects to the four motor controllers and is responsible for sending the commanded speed for each motor via a traditional repeating 10-20ms servo pulse. The third microcontroller receives and interprets the GPS information, calculates heading and waypoints, and monitors the temperature sensors because both the GPS and temperature sensors have low bandwidth requirements. The fourth controller is the “central hub” for communication as it routes the information coming from the other three microcontrollers to the appropriate locations, as well as reading the data from the Sonar sensor and broadcasting the monitored information out through the Zigbee module.

When it came time to choose rotors for the quadrotor, few choices were available due to the need for matched tractor and pushers rotors. A tractor rotor creates thrust with a clockwise rotation, whereas a pusher rotor creates its thrust from a counterclockwise rotation. Because of the nature of research and development, the initial choice has been to use inexpensive models, given the initial abuse they have re-

ceived in the testing phase. The rotors are ten inches in diameter with a pitch of 4.5. This is a very aggressive pitch and provides an excellent amount of thrust. The downside to these rotors is that they are quite flexible and fragile, which results in chips in the leading edge of the rotor and flexing at high speeds, reducing efficiency.

Mechanically, most of the structure is carbon fiber and those points that experience significant force are aluminum, which include the center cross connection piece, the motor mounts, and the motor mount to carbon fiber connectors. On the outside of the motor mounts, a connection is available for a safety ring and a tether for test flights. This connector is made from ABS plastic as a sacrificial break point to prevent a catastrophic event requiring an entire airframe rebuild. Altogether, the system weight is approximately two kilograms. Figure 2 is a picture of the current prototype.



Figure 2. Quadrotor with Onboard Control

Embedded Control

Stable flight control of a quadrotor includes four control loops: pitch, roll, yaw and altitude. The pitch and roll controllers can be identical or near identical, as the model is the same, while the altitude and yaw controllers are fairly simple. The focus of this study was on the roll and pitch controllers. Many other researchers [3], [7] begin with a system model, a linearization attempt around some operating point, a standard control system design, and then use some method to create a digital implementation of the controller. For example, Pounds et al. [3] developed the linearized model around a thrust, T_0 , as shown in Equation (7).

$$\dot{T}_i = -AT_i + Bu_i \quad (7)$$

where $i = N, S, E, \text{ and } W,$

$$A = \frac{2}{\tau} + \frac{3\kappa}{2\sqrt{\alpha}}\sqrt{T_0}, \text{ and } B = \frac{2\sqrt{\alpha}\kappa}{\tau}\sqrt{T_0}$$

Their model was used to design a double lead compensator for control in the roll and pitch channels. They went on to say that “suitable control performance was obtained.” Of course, since the model was linearized around T_0 , the flight control performance was only optimized at this level of thrust. An adaptive control system does not always require a system model; it can develop a model itself through a system identification routine. The particular adaptive controller selected for the pitch and roll channels was an adaptive PID controller based on the success of others using the non-adaptive version of the PID controller on this structure [8].

The chosen adaptive PID algorithm uses the weighted recursive least squares method of identification [9], [10]. It is designed to control systems that can be adequately represented with a second-order equation [10]. While the pre-linearized model given by Pounds et al. [3] was not second order or linear, the approximation of the system as second order was made in order to satisfy the requirements of the algorithm. The generic system model is given in Equation (8).

$$\frac{y(k)}{u(k)} = \frac{b_1q^{-1} + b_2q^{-2}}{1 + a_1q^{-1} + a_2q^{-2}} = \frac{B(q^{-1})}{A(q^{-1})} \quad (8)$$

The control works by first adding a stable pole to the closed-loop characteristic equation and using pole shifting as shown in Equation (9).

$$(1 + a_1q^{-1} + a_2q^{-2}) \rightarrow (1 + \alpha q^{-1})(1 + a_1\alpha q^{-1} + a_2\alpha^2 q^{-2}) \quad (9)$$

In Equation (9), $0 \leq \alpha \leq 1$. The control equation for the adaptive PID is given in Equation (10) and the PID structure in Equation (11).

$$u(k) = \frac{P(q^{-1})}{R(q^{-1})} y_r(k) - \frac{G(q^{-1})}{R(q^{-1})} y(k) \quad (10)$$

$$u(k) = \frac{-S_T K_i}{(1 - q^{-1})(1 + r_1 q^{-1})} (y_r(k) - y(k)) \quad (11)$$

$$+ K_p y(k) + \frac{K_d(1 - q^{-1})}{S_T(1 + r_1 q^{-1})} y(k)$$

In Equations (10) and (11), K_i , K_p and K_d are the PID gains and S_T is the sampling time. From these two equations, P , G and R can be defined as follows:

$$R(q^{-1}) = (1 - q^{-1})(1 + r_1 q^{-1}), G(q^{-1}) = g_0 + g_1 q^{-1} + g_2 q^{-2}, P(q^{-1}) = -S_T K_i \quad (12)$$

By combining Equations (8) and (10), the closed-loop system can be written as shown in Equation (13).

$$\frac{y(k)}{y_r(k)} = \frac{B(q^{-1})P(q^{-1})}{A(q^{-1})R(q^{-1}) + B(q^{-1})G(q^{-1})} \quad (13)$$

If the resulting characteristic equation is solved by setting it equal to Equation (9), the coefficients can be matched, resulting in a system of simultaneous equations, as shown in Equation (14).

$$\underbrace{\begin{bmatrix} 1 & b_1 & 0 & 0 \\ a_1 - 1 & b_2 & b_1 & 0 \\ a_2 - a_1 & 0 & b_2 & b_1 \\ -a_2 & 0 & 0 & b_2 \end{bmatrix}}_J \underbrace{\begin{bmatrix} r_1 \\ g_0 \\ g_1 \\ g_2 \end{bmatrix}}_Z = \underbrace{\begin{bmatrix} 1 - a_1 + \alpha + a_1\alpha \\ a_1 - a_2 + a_1\alpha^2 + a_1\alpha^2 \\ a_2 + a_2\alpha^3 \\ 0 \end{bmatrix}}_H \quad (14)$$

In order to solve the system of equations, J is inverted and simplified before being implemented into the program as the inverse of a 4x4 matrix which, while tedious, can be completed in closed form especially since many of the cells are zero. Once Z is determined, the PID gains (see Equation 15) can be solved for using Equation (11).

$$K_i = \frac{-(g_0 + g_1 + g_2)}{S_T}, \quad K_p = \frac{g_1 + 2g_2}{1 + r_1}, \quad (15)$$

$$K_d = S_T \left[\frac{r_1 g_1 - (1 - r_1) g_2}{1 + r_1} \right]$$

These gain values are then used to update the control signal, $u(k)$. In combination with the weighted recursive least squares method, the adaptive PID algorithm described above was implemented into the Parallax Propeller multi-core microcontroller. With the combination of the proprietary Parallax Propeller high-level language (called SPIN) and assembly language for the floating-point mathematics, the controller was able to sustain an algorithm iteration time of less than 50ms, an acceptable time given that the sam-

pling time of the feedback (S_T) was on the order of 100ms. While this control algorithm was successfully implemented in an embedded environment, the results were not in accordance with expectations. The adaptive algorithm and linearized model were verified using Matlab and a suitable performance was achieved. The adaptive PID controller, derived above, is sufficient for systems that can be modeled by a second-order system—see Equation (8). Based on tests, it was determined that the quadrotor structure cannot be sufficiently modeled for the purposes of adaptive control with a second-order system. Had the linearized model more closely approximated the system, the adaptive controller may have been better able to provide suitable control.

Upon completion of the adaptive PID control testing, work began to implement a standard PID controller for the pitch, roll and altitude channels with the intent to implement a gain scheduling adaptive PID controller. As others have found, the traditional digital implementation of the PID controller is suitable for controlling the quadrotor in flight. However, while the channel controllers have been tuned using standard methods for a single thrust point at hover, the team will be continuing to develop adaptivity into the control strategy. Since suitable PID gains have been determined for each of the channels, the strategy currently under development is to fall back to the adaptive PID control explained here and set initial conditions on the calculated PID gains equal to the traditionally determined PID gains found by tuning. Furthermore, the team plans to limit the calculated PID gains to a range above and below the traditionally gathered PID values such that the adaptive control algorithm has freedom to auto-tune the loop but not enough freedom to cause a catastrophic flight pattern.

Conclusion

The hardware design was successfully implemented on a custom designed, two-layer, printed circuit board (PCB). Using surface mount technology whenever possible allowed the creation of a very small PCB measuring 2.5" x 3.75". With the exception of the batteries, motors, motor controllers, sonar sensor and temperature sensors, all components occupied real estate on the PCB. Care was taken to locate off-board connections nearest to the place to which they would connect to minimize weight in cabling and unnecessary complications. The placement of the motor controllers was also carefully considered as they must dissipate significant heat during heavy current flow. They were located directly below the flow of air under the rotor. While this reduces the lift achieved, it does allow the components to run cooler. Problems were

encountered, but eventually the mechanical and electrical components were made fully functional and capable of executing the control developed on board the quadrotor.

For purposes of testing the control system, single-axis tests were used. These tests required a test rig that would balance the quadrotor on one axis so that the control system could be tuned along each axis. This rig consisted of two tripods that were used to hold two mounted plastic bearings to which the quadrotor was mounted. While this cannot assist in the testing of multiple-axis control, it provided a starting point. Once suitable single-axis control was achieved, tethering was used to test the combination of the control in multiple axes along with on-line tuning of the altitude control.

Battery life is a major concern with any UAV. From a physics standpoint alone, it takes more energy to hover than to glide through the air [11]. The use of more motors makes the craft more maneuverable but also requires more power. With the initial motors, a flight time of fifteen to eighteen minutes was calculated depending on flight conditions such as temperature and wind. However, once the motors were upgraded, the flight time was reduced to ten to thirteen minutes.

From a control standpoint, it was determined that the adaptive PID controller based on a second-order model is not sufficient for the control of a quadrotor on the pitch or roll channels due to the insufficiency of the second-order model to adequately model the quadrotor. However, the adequacy of the standard PID control was validated on the pitch, roll and altitude channels. Further work is being considered using the known tuning parameters from the non-adaptive PID in the adaptive PID to both inform the algorithm of a good starting point and to limit the gains to some range around the known tuning parameters.

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