The Design and Implementation of a Quadrotor Flight Controller Using the QUEST Algorithm

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Abstract

Formally posed in 1965, the problem of optimal attitude estimation from vector measurements has been a hot topic of research in the aerospace community. This paper provides a survey of open source quadrotor helicopter autopilots that demonstrates that the Unmanned Aerial Vehicle community has largely ignored the optimal attitude estimation work to date. Furthermore, the effectiveness of a quadrotor helicopter autopilot utilizing attitude estimates from optimal attitude estimation techniques is evaluated.

1 Introduction

Optimal attitude estimation techniques used in the Aerospace industry have been known for several decades. However, the results of the work have been largely ignored by the Unmanned Aerial Vehicle (UAV) industry. The goal of this paper is to demonstrate the successful implementation of a quadrotor autopilot based upon optimal attitude estimation techniques.

This paper has three parts. First, a brief introduction to optimal attitude estimation is covered. Next, to justify the claim that UAVs largely ignore the known optimal attitude estimation methods a survey of existing quadrotor helicopter autopilots to examine their methods of attitude estimation. Finally, a quadrotor helicopter autopilot is implemented and tested to demonstrate the effectiveness of optimal attitude estimation techniques such as QUEST in the control systems of quadrotor helicopter autopilots.

2 Optimal Attitude Estimation

In 1965 Dr. Grace Wahba, then a graduate student, formally posed the problem of estimating the optimal rotation between a set of observed vectors and a corresponding set of reference vectors [5][6]. Restated, the problem is to minimize the loss function

$$L\left(A\right) \equiv \frac{1}{2}\sum_{i} a_i |\mathbf{b}_i - A\mathbf{r}_i|^2 \tag{1}$$

where A is the rotation matrix, a_i are non-negative weights, $\mathbf{b}_i$ are the body measurement vectors and $\mathbf{r}_i$ are the reference vectors. Solutions to this problem yield the optimal rotation.

Many responses have resulted with the early ones being primarily iterative in nature. Later methods were developed that were non-iterative. Of these, the Quaternion Estimator (QUEST) algorithm has been the most widely used algorithm [3][4]. A survey of attitude estimation techniques can be seen in [2].

3 Survey of Open Source Quadrotor Autopilots

Several open source autopilots exist for quadrotor helicopters. An analysis of four such autopilots and their attitude estimators has shown a variety of approaches used.

3.1 AeroQuad (http://aeroquad.info/)

The AeroQuad is a quadrotor autopilot based on the Arduino microcontroller platform.

Figure 1: The AeroQuad Quadrotor Helicopter

Hardware:

CPU: Atmel ATMega 328 8-bit microcontroller operating at 16 MHz.

Sensors: SparkFun 5DOF IMU with an additional IXZ500 dual axis rates gyro to supply the third rates gyro measurement.

User Input: Radio Control (RC) receiver receiving input from an RC handheld transmitter and ZigBee protocol using an XBee can be used.

Motor Control: Standard RC brushless motors controlled by RC brushless electronic speed controllers (BESCs). Output to the BESCs occurs at 400Hz (normally RC BESCs are controlled at 50 Hz).

Software:

The software is programmed in a variant of the C language used by the Arduino platform.

Attitude Estimation:

Euler angles roll and pitch are computed by $\phi = tan^{-1}\left(\frac{a_x}{\sqrt{a_y^2+a_z^2}}\right)$ and $\theta = tan^{-1}\left(\frac{a_y}{\sqrt{a_x^2+a_z^2}}\right)$. The resulting values are then fed into a complementary filter yielding filtered estimates of roll and pitch.

Control:

Control of the roll and pitch angle rates is performed by PID controllers. The target values of the controllers are set by the input from the RC receiver modified by attitude estimates from the accelerometers. As there is no yaw estimation as such the target values of the yaw PID controller come exclusively from the RC receiver.

3.2 MikroKopter (http://www.mikrokopter.com/)

The MikroKopter project is a long running quadrotor autopilot system from Germany. The current MikroKopter quadrotor helicopter platform is known as the MikroKopter ME. All major components of the MikroKopter system are custom designed.

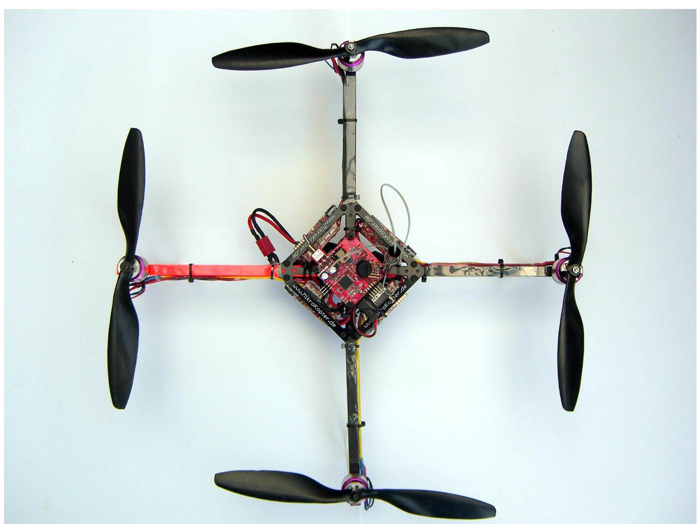

Figure 2: The MikroKopter ME Quadrotor Helicopter

Hardware:

CPU: Atmel ATMega 644P operating at 20 MHz.

Sensors: Sensors for the MikroKopter include a LIS344ALH 3-axis accelerometer, Analog Devices ADXRS610 single axis rates gyros on all three axes and a barometric pressure sensor to estimate altitude.

User Input: User input comes from an RC receiver. Alternatively, input can come from a serial input permitting the use of wireless communications systems such as Bluetooth.

Motor Control: Custom BESCs are used to control RC brushless motors. Communication with the BESCs is over the I2C protocol.

Software:

The flight control software of the MikroKopter platform is programmed in C. Functionality of the MikroKopter has been split out amongst different processors on separate circuit boards. The lowest level functionality, receiving user input and maintaining attitude control, is on one board while GPS input and position control is on a second board.

Attitude Estimation:

Attitude estimation of roll and pitch rates is accomplished by computing the difference between the predicted and measured accelerometer values and by integrating the gyros. The resulting estimates are filtered.

Control:

Control is performed by PD controllers on each axis. The target rates are set by user input and output from the PD controllers is sent to the custom BESCs.

3.3 Paparazzi (http://paparazzi.enac.fr/)

The Paparazzi project is a long running autopilot project supporting many types of aircraft. Initially the project focused on fixed wing aircraft before moving into Vertical Take-Off and Landing (VTOL) fixed wing aircraft. The quadrotor platform and autopilot, the Paparazzi Booz, is an extension of the VTOL autopilot. The Paparazzi autopilots have been successfully used to win a number of UAV competitions.

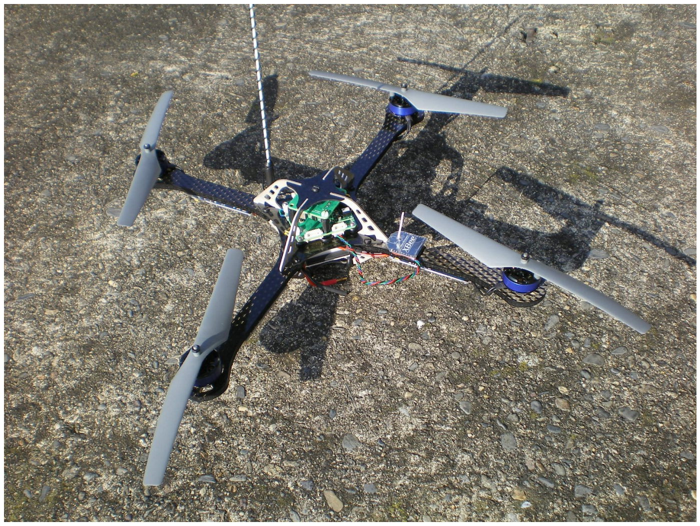

Figure 3: The Paparazzi Booz Quadrotor Helicopter

Hardware:

CPU: NXP LPC2148 microcontroller operating at 60 MHz.

Sensors: The Paparazzi project has developed a custom three axis IMU for the Booz utilizing Analog Devices ADXL320 accelerometers and ADXRS610 gyros for rates measurement. Alternatively, a Cloud Cap Technologies Crista IMU may be used with the Paparazzi Booz.

User Input: User input comes from an RC receiver.

Motor Control: BESCs designed for the MikroKopter and Ascending Technologies aircraft as well as OpenBLDC and modified Turnigy RC BESCs may all be used to control RC brushless motors.

Software:

The Paparazzi project develops their flight control software in C with several possible target architectures.

Attitude Estimation:

Attitude estimation is achieved through the use of an Extended Kalman Filter (EKF). The attitude is propagated forward by integrating the rates gyros and updated with measurements from the accelerometers and magnetometers.

Control:

Control of the Paparazzi Booz comes in a variety of modes: angular rates, attitude, hover and navigation. All control systems are implemented as PID controllers. When in angular rates and attitude modes the controllers only control the rates or attitude, respectively, whereas hover and navigation modes employ layered controllers to control position and velocity as well.

3.4 Vicacopter (http://vicacopter.com/)

The Vicacopter autopilot project touts itself as the only open source English language source code helicopter autopilot. The autopilot support two configurations: a minimal autopilot with rates gyros and sonar transducer and a full autopilot with 6 Degree of Freedom (DOF) IMU, magnetometer, barometer and GPS. The Vicacopter autopilot is available on two platforms: the Microchip PIC microcontroller and the Gumstix Computer on Module (COM) system.

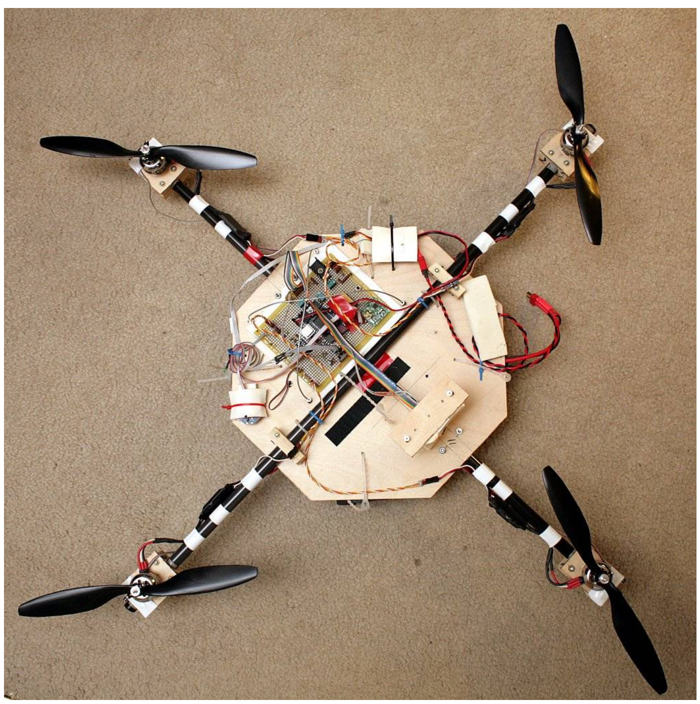

Figure 4: The Vicacopter Quadrotor Helicopter

Hardware:

CPU: Marvell PXA255 on the Gumstix COM at 600 MHz.

Sensors: The sensor complement of the Vicacopter includes a SparkFun MicroMag 3 three axis magnetometer, an Analog Devices ADXRS613 on each axis, an Analog Devices ADXL330 three axis accelerometer, an u-blox 5 GPS receiver and a VTI SCP1000 barometric pressure sensor.

User Input: User input is from RC receiver.

Motor Control: Output is through RC brushless motors controlled via RC BESCs.

Software:

The software is programmed in C and takes advantage of the POSIX compliant Linux operating system of the Gumstix.

Attitude Estimation:

Attitude estimation is accomplished via a seven state EKF. The first four states are the attitude quaternion components and the last three states are the gyro biases. The predict state portion of the EKF uses information from the gyros and state update comes in two phases, first using input from the accelerometers and then using input from the magnetometers.

Control:

The Vicacopter has two control methods available: PID and Artificial Neural Network. Both methods apply layered controllers to control attitude, velocity and position.

4 Autonomous Control of a Quadrotor

Of the open source autopilots only two (Paparazzi Booz and Vicacopter) used attitude estimates in their control systems, the other two used rotational rates. Neither of the autopilots utilized known techniques for optimal attitude estimation. All of the autopilots examined make the assumption that the vehicle is operating in or at near hover and the measured acceleration is that of the gravity vector.

Gebre-Egziabher and Elkaim have postulated that given the dynamics of micro air vehicles (MAVs), optimal attitude estimation techniques may not yield the necessary performance needed for controllability [1]. To test the hypothesis of a quadrotor helicopter controllability using estimates from an optimal attitude estimation technique, a quadrotor helicopter autopilot was developed and tested. The algorithm utilized is a variant of the QUEST algorithm. In the implementation the Newton-Raphson method is limited to a single iteration. Literature states that convergence is frequently attained within the first iteration and my tests have concluded the same.

4.1 Design

The developed quadrotor autopilot is quite small and performs only a few key functions. First measurements from the IMU are acquired and the observations are fed into the QUEST algorithm. Next a target attitude is computed using the input from the RC receiver. A difference quaternion is computed between the two attitudes. The difference quaternion is then converted to Euler angles and used in three PD controllers. The derivative component of the PD controllers is derived from the gyro measurements of the IMU.

4.2 Implementation

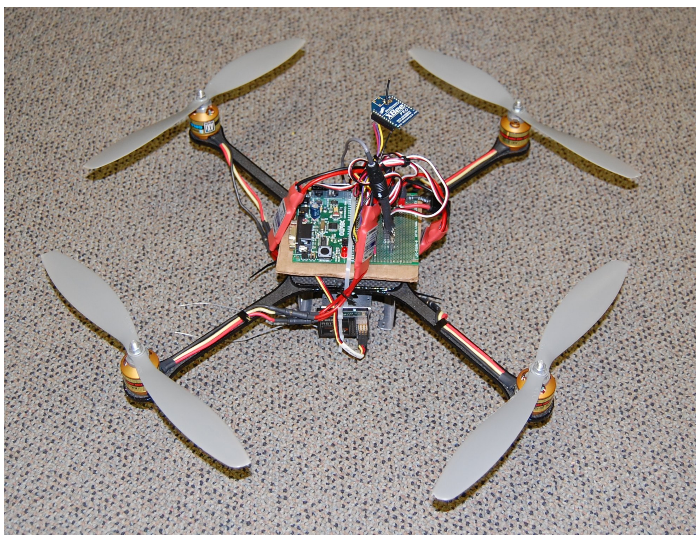

Figure 5: The Developed Quadrotor Helicopter

Hardware:

CPU: NXP LPC2106 at 60 MHz.

Sensors: MEMSense nIMU providing accelerometers, rates gyros and magnetometer measurements on all three axes.

User Input: User input is from a Futaba FASST R617FS RC receiver. Although not used for input, a serial interface is also available over ZigBee wireless using an XBee transceiver.

Motor Control: Output is through Turnigy Plush 25A RC brushless motors controlled via RC BESCs.

Software:

The software is programmed in less than 1600 lines of C.

Attitude Estimation:

QUEST algorithm using the Earth's geomagnetic field declination vector and the gravitational acceleration vector as two reference vectors. The observation vectors are measured by the nIMU's magnetometers and accelerometers.

Control:

Control is accomplished via three PD controllers. The proportional components are measured by the error between the estimated attitude quaternion and the desired attitude quaternion. The derivative components are measured from the rates gyros on each axis.

4.3 Results

Tethered flights demonstrated stable hover and the ability to control the UAV. Unfortunately, there were intermittent "jumps" observed in the vehicle. These are believed to be arising from noise coming from the IMU. Given the low sampling rate of the nIMU (max 156 Hz) in comparison to the sampling rates of the other vehicles ($>$ 1000 Hz), attempts to filter the noise have been met with limited success. Since the vehicle suffered intermittent failures of attitude stabilization, no untethered flights had been attempted.

5 Conclusion

The intermittent failures notwithstanding, the vehicle test showed considerable response to control. As such, future work should include replacing the IMU with one that permits a higher sampling rate to attempt to eliminate the noise issue. A comparison of the QUEST based controller and the EKF based approach presented by Gebre-Egziabher and Elkaim is also worth investigation.

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