BASIC CONTROL FOR FOUR ROTOR AUTONOMOUS AERIAL AGENT

**JONATHAN MCLEAN, CONNECTICUT COLLEGE, USA,
JMMCL2@CONNCOLL.EDU
GARY PARKER, CONNECTICUT COLLEGE, USA, PARKER@CONNCOLL.EDU
NEWELL SEAL, CONNECTICUT COLLEGE, USA, NSEAL@CONNCOLL.EDU**

ABSTRACT

Aerial robotics provides many practical applications in fields such as search and rescue and surveying. In order to advance the research in aerial robotics, an inexpensive test platform is required. Our four-rotor platform provides researchers with a inexpensive, fully scalable test platform for future studies. Its completely on-board processing removes the need for a virtual tether in the form of a radio transmitter, allowing for completely autonomous operation.

KEYWORDS

robotics, aerial agents, four-rotor design, autonomous robot, autonomous agent control

1. INTRODUCTION

The field of aerial robotics is useful in many practical applications from surveying work to search and rescue to data collection tasks. However, there is often much effort in keeping autonomous agents airborne. Airplanes, though capable of easily generating lift, are not necessarily as agile as required for situations such as interior navigation. Also, autonomous control of yaw, pitch and roll in an airplane-style agent requires much on board processing, reducing the processing available to the task at hand. Helicopter-style agents, though much more adept at interior navigation, and fine movement in general, are arguably even more difficult to control, requiring minute adjustments to individual rotor blades, as well as tail control to prevent spin out.

There is an alternative to these two styles: a four rotor aerial autonomous agent. The general shape of the robot is that of a cross, with a motor/rotor assembly at each tip and a central platform for power and control boards. The benefits of such a design are that it retains the Vertical Take-Off/Landing (VTOL) style of flight of a helicopter, as well as a similar level of agility, but with a much more simplified control structure. Yaw, pitch and roll are all controlled by varying the speed of pairs of motors. The robot is also inherently stable in flight, which a natural gyroscopic effect generated by the rotors themselves, whereas a helicopter requires the additional tail rotor for stability. The four rotor design therefore allows the designer more opportunities for task handling with less time devoted to controlling the actual robot.   Online retailer RCToys has acknowledged the viability of the four rotor design and has made available through its retail outlets the Draganflyer Four Rotor Radio Controlled Aircraft. Though not an autonomous agent, the Draganflyer is a lightweight aerial platform, made of modular parts. RCToys also sells the components of the Draganflyer online, allowing hobbyists to mimic its construction with proven parts.

Tayebi and McGilvray in their own research prove that it is physically possible to achieve stable flight using a four-roto design. And though not implemented, they produce a number of equations modeling the flight dynamics [1]. McKerrow developed a simulation based on models of a four-rotor design [2]. By modeling many factors

involved in the flight physics of the design, including inertia, Coriolis acceleration, force balance, thrust, etc, McKerow has developed a simulator that accurately models an RCToys Draganflyer Four Rotor aircraft. An accurate simulation of Draganflyer physics allows researchers to test various computer control schemes without damaging expensive physical agents.

Pounds et al. have developed their own model four-rotor flyer (X4 Flyer) [3]. Unlike that modeled by McKerrow, the X4 Flyer is designed to be rugged and practical, with a possible lift capability of 1 kg. The flyer is comprised of high performance rotors and speed controllers. It features Bluetooth communication for transferring information and state to a base computer, and it's frame is built with aluminum and carbon-fiber sandwiched with foam. This provides durability, and is also designed to allow the center of gravity to be easily shifted.

Groups at MIT and Vanderbilt have explicitly used the Draganflyer aircraft in their own research [4, 5]. Each group utilizes off-board computing in calculating flight trajectories. The commercial Draganflyer controllers are hooked up to the radio transmitters, with a desktop computer acting as a stand-in for a human controller. The computers are relayed sensor information from the aircraft, and utilize this information in their decision making processes before transmitting motor controls back to the flyer through the transmitter.

In this paper we present a fully autonomous aerial platform, which we call Griffen, that does not require the use of either an external computer or external transmitter, allowing for complete untethered flight. Though others have used the RCToys radio transmitter as a known control structure, it severely limits the flight capabilities of agent, virtually tethering it to within a few hundred feet of the transmitter. By utilizing all on-board processing, the agent is free to act in the completion of its goal without distance restrictions. In addition, reducing the need for communication with a base computer eliminates another potential point of failure in the overall architecture.

RCToys states that the simplified flight physics present in their product allows for easier handling than that of a normal helicopter for the human user via a radio controller. This simplification for humans translates to simplified autonomous control of the craft without the need for intensive computing power, thus making an affordable, autonomous platform for further research. Because this research is based upon the assumption that the Draganflyer, a commercially successful product, has achieved its goal of making flight simple for users, the design of our flyer is similar, in fact utilizing kit parts available from RCToys website.

2. CONSTRUCTION

The RCToys Draganflyer is a four rotor aerial vehicle capable of Vertical Take-Off and Landing (VTOL) flight [Figure 1]. The frame of the Draganflyer is built primarily of carbon fiber tubing and nylon mountings. In the center of the frame is a nylon cross connector into which each of the carbon fiber flight arms [see Figure 1 A] is inserted and fixed via screws producing tension at the points of connection. Nylon support brackets are next placed on each of the carbon fiber arms. These brackets provide a mounting for the carbon fiber battery tray located beneath the central cross section [see Figure 1 B]. This battery tray comes with pre-applied Velcro to attach the battery.
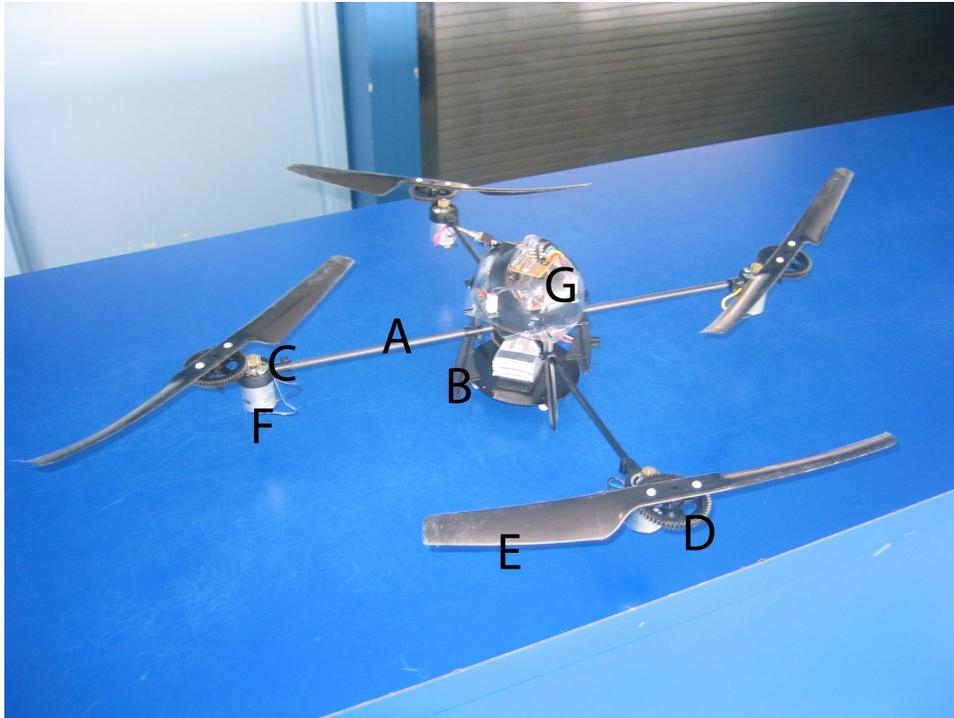
Figure 1: Griffen at rest.

The carbon fiber flight arms are all hollow, allowing motor control cables to run through them out to the motors. These cables terminate on one end at the motors and the other end at the cross section in one large female connector providing individual power and ground lines to each of the motors. At the end of each of the flight arms is a nylon motor mount [see Figure 1 C]. Motors are connected to the mounts via a single screw. The mounts also contain a mounting point for the rotor gear [see Figure 1 D], allowing the pinions on the top of each motor to properly contact the rotor gears.

Each of the main gears of the Draganflyer kit contains two bearings to allow for easy rotor rotation. The bearings measure 1/8" high, 1/4" diameter and 7/64" inside diameter. A nylon spacer is then placed inside the bearings so that the screw will fit tightly. The screw is then screwed into the motor mount, fixing the main gear to the motor mount. The rotors are then attached to the main gear via two nylon screws. Each of the rotors measures 12 3/8" long [see Figure 1 E], with two angled for clock-wise rotation and another two angled for counter-clockwise rotation. The rotors are nylon injected, which according to RC Toys, makes them "virtually indestructible."

The motors driving the rotors are Mabuchi 380 brushed DC motors [see Figure 1 F]. Each motor works with an optimal voltage of 7.2V. The motors spin at a load-less 26,000 rpm, but with a loaded max efficiency of 19,000 rpm, drawing 6 amps, and producing 375.0 g/cm of torque. These motors are more than capable of producing the thrust necessary to lift the nylon/carbon fiber frame of the Draganflyer, as well as its electronics package [see Figure 1 G]. Motor heat-sinks are available to provide heat dispersion for the motor casings, but they are only truly required for long duration flights and above average temperatures and therefore are not utilized.

3. ELECTRONICS

The body and construction of Griffen does not differ from the Draganflyer; its frame and motors are all Draganflyer kit parts. Differences between Griffen and the Draganflyer arise in the area of electronics. The Draganflyer is designed to be controlled by a human with a Futaba radio controller. The human controller is able to adjust the speed of the motors, and thus is able to adjust the roll, pitch and yaw of the Draganflyer.

Without a human, control of these factors is left to the electronics. It is up to the micro controllers to properly adjust roll, pitch and yaw, and this is achieved through varying voltage inputs to the motors. This is due to the inherent properties of the motor architecture. Each motor on an axis is spinning the same way as the other motor on the axis. However, each opposing axis motors spin in opposite directions. For example, on Griffen, the North-South axis motors are spinning clockwise, while the East-West motors are spinning counter clockwise [Figure 2]. This produces forces that stabilize the yaw of the flyer assuming all rotors are producing equal thrust vectors. However weight distribution in the central platform can affect the effect of the motors.
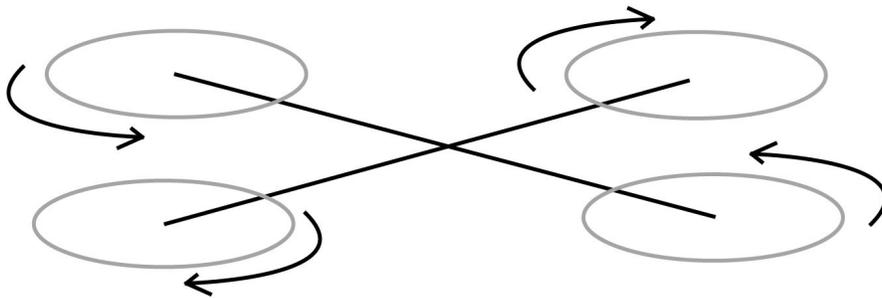
Figure 2: Rotor Rotation on Griffen

Flight control of a four-rotor is achieved through the relation between opposing motor speeds. To adjust the position on the roll and pitch axis you adjust the appropriate motor speeds. To adjust roll, you would affect the speeds of the east-west axis, and to adjust pitch you would affect the speeds of the north-south axis. All adjustments must be done in a proportional way. For example, to roll to the east while maintaining altitude you must decrease the speed of the east motor, while increasing the speed of the west motor by the same amount. This holds true for pitch movement as well. Finally, to yaw in a certain direction you decrease the speed of both motors spinning in the opposing direction. This reduces the inherent gyroscopic effect, allowing the craft to yaw. For example, to yaw clockwise, you would need to decrease the speed of the motors spinning counter-clockwise [see Figure 2].

With these relatively simple physics in place, controlling the Griffen becomes a means of controlling the speed of the motors. However, unlike the Draganflyer which has a human controller, Griffen must do all calculation and motor control via on-board microprocessors and sensors. No parts of the original Draganflyer electronics were used in this research. They have been replaced by a scalable microprocessor architecture based upon the Parallax BASIC Stamp 2 (BS2). Griffen currently contains two microprocessors to complete the rudimentary goal of sustained, balanced flight: a motor controller and a balance controller.

The motor controller is designed to control the speed of the motors directly. It regulates the speed of the motors based on pulsed commands out to an electronic speed control (ESC) per motor [Figure 3]. These ESC's are Electrifly C-7 Nano speed controllers. They receive two inputs: a power/ground input from the power source that will be driving the motors, as well as an input from the motor controller. Based on the input received from the motor controller, the voltage from the power source is regulated. The motors spin slower when they receive less voltage, and faster when they receive more. In this way, a digital microprocessor is able to control the speed of the motors.
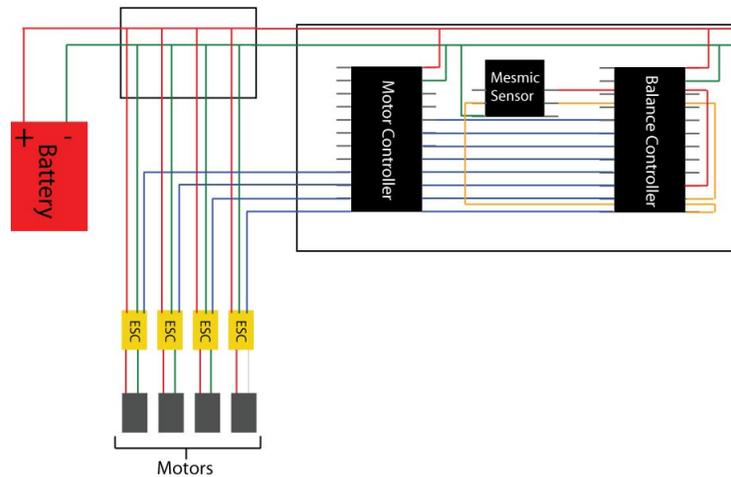

Figure 3: Griffen Micro Controller Schematic

There is also a 2-axis accelerometer produced by Mesmic which interfaces well with the BS2 architecture. This tilt sensor provides a x-axis reading and a y-axis reading in digital format to the balance controller. Each axis receives its own direct connection to the balance controller. The sensor also draws power from another connection to the balance controller. The mesmic calculates a zero-balance as well as Griffen's current pitch and roll. Griffen is unable to calculate its yaw. There are 8 direct connections between the balance controller and the motor controller, allowing the balance controller to provide data to adjust the speed of the motors.

Griffen contains one power source, a powerful 11.1 V 3-Cell Lithium Polymer battery, to provide power for its four motors and all of its electronics. The LiPol contains 1320 maH, able to drive the motors for about 20 minutes of continuous flight. The BASIC Stamps draw directly from the battery as they are able to regulate the high voltage down to an appropriate voltage. The ESCs are also directly connected to the battery as they too can regulate the voltage. It is fully rechargeable, while also being lightweight. Though LiPols are more physically fragile than NiCads or NiMH, the power-weight ratio is ideal for aerial autonomous agents. As long as it does not somehow get punctured, the payoff is worth the risk.

4. CONTROL PROGRAMS

In order to accomplish the task   of untethered autonomous flight, the

microcontrollers would need to have full control over all aspects of the hardware, as well as competent instructions in how to fly the vehicle. The basic control program is one designed to allow Griffen to hover after takeoff. The first part of the program is the initialization sequence. The ESCs and the tilt sensor must be initialized before they are used. The ESC's are typically used in conjunction with a radio transmitter sending out radio signals to adjust the voltage. Griffen not being controlled by a radio needs to emulate these signals via the microprocessors.

This feat is achieved through the use of pulse width modulation (pwm). The PBASIC micro controller language provides a full suite of pulse width modulation commands including that used by Griffen: PULSOUT. By timing the pulse outs in a loop a proper pwm is utilized to control the ESCs. The ESCs require a sequence of BREAK, FULL THROTTLE, BREAK commands before they will accept incoming signals. This is because these ESCs are designed with fail safes built in to prevent unexpected motor startups which could damage expensive hobby aircraft. The motor controller sends out these proper pulses to each of the four ESC's before it begins its flight mode.

Once in flight mode, the controller waits for input from balance sensor. However, adjusting based upon the balance sensor every computational cycle produces overcompensation in the balance algorithm, thus only once every four cycles is the balance sensor polled. Once polled, the motor controller adjusts the proper motors with different power ratios. If the motor does not receive an adjust command from the balance controller it simply maintains the current power ratios. The combination of the polling and computation fits within the appropriate timing to emulate the necessary pulse outs, thus allowing the ESCs to operate smoothly.

The balance controller also needs to be initialized. The mesmic sensor does not immediately produce calibrated data and needs to be zeroed before each flight session. This is done by finding the average of a fixed number of readings while the robot is on a level surface. Once it has calibrated itself it will not re-zero. Thus any re-zeroing will need to take place at the beginning of the next flight session.

Once the sensor has been zeroed and the agent is airborne the microcontroller constantly produces balance information. For every computation cycle the controller polls the mesmic sensor, calculates the absolute distance the current tilt is from the zero balance, and then produces a tilt severity rating. This tilt severity rating is based on a polynomial regression, giving a lesser degree of severity to less unbalanced sensor readings, and a higher degree of severity to more unbalanced readings.

5. TESTS

The first goal of Griffen was to be able to hover. In order to achieve this goal, Griffen's operational capability was severely restricted in order to control as many variables as possible. The first major restriction is in the allowed range for operational speed. Though typically capable of a wide range of motor speeds determined by pulse width modulation, the available speed was limited to a range of only 3% of its full capability. The launch speed is located in the middle of this 3% window, allowing for +/- 1.5% speed differential in either direction. The launch speed also restricts the flight ceiling to about 2.5 feet.

The reduced flight ceiling and the goal of hovering flight resulted in the a lower level of fine control necessary to maintain balance. In a more full-featured version, motor speed will be adjusted on a polynomial scale to compensate for adverse conditions such as gusts of air or rapid object-avoidance. However, to achieve hovering from a

balanced take-off requires only minimal adjustments to motor speed, most to accommodate for natural motor tendency and imperfect rotor balance. Thus, motor speed was only incremented or decremented by a fixed amount whenever an imbalance was detected by the tilt sensor.

To attain this level of control required much trial and error testing in the real world while monitoring the effect of changing the pulse out values. Tweaking the pulse out value combined with collecting observations revealed certain traits of the pulse outs, such as appropriate intervals to compensate for natural motor tendencies, as well as flight ceilings at different pulse out values. All of these observations allowed to model the ideal hover situation.

Other factors were constantly tested in real world application, such as the balance threshold value. With the current configuration, when the balance controller is zeroed, a threshold is applied to its zero values. This is because observation of the mesmic sensor indicated that even when working under optimal conditions, inputs on a perfectly balances surface could still fluctuate. Testing for an appropriate threshold provided a value that would compensate for the naturally variable output from the mesmic and therefore appropriately offset the balance severity measure.

Through continued adjustment a proper control program was produced. Observations of Griffen in flight using this controller showed that it contained the computational prowess to maintain a balanced, hovering flight. Though initial conditions on each flight, such as unbalanced motor initiation produced ungainly movement in the beginning, after 20-30 seconds of flight the balance equations would minimize the pendulum-like movement enough to produce a hover. There is slight drift even when hovering, but this can be accounted for by imperfectly aligned rotors or natural motor tendencies and will be corrected when additional sensors are installed [Figure 4].

Figure 4: Griffen in flight finding its balance.

6. CONCLUSIONS

Griffen and the Draganflyer model in general provide a stable research platform in aerial autonomous agents. The inherently stable four-rotor design allows for the power, control and indoor-nature of a helicopter without the need for complex rotor control. The scalable and modularized BASIC Stamp microcontroller architecture also allows for a variety of different research opportunities.

Continuing work will include creating a more advanced basic platform including Sonar ranging sensors for obstacle avoidance and altitude determination. These would

allow for truly autonomous maneuvering, particularly in a cluttered environment. These are the environments in which four rotor vehicles are supposed to excel, so it would only be fitting to provide Griffen with such capability.

There will also be focus in coalition formation amongst 3 of these agents. The Coalition Based Aerial Robotics (CBAR) initiative at Connecticut College hopes to utilize the Griffen platform as a method of studying coalition formation in aerial agents. Again, the ease of controlling the agents affords researchers more time to focus on formation algorithms without the worry of physically unstable agents. Such research could produce results in predator prey style scenarios as well as other problem solving tasks.

Finally, there is hope to apply Genetic Algorithms into Griffen's flight programming. At the moment such factors as natural motor tendencies and rotor position can adversely affect performance, minimizing similarities between flight sessions conducted even on the first day. With GA's, Griffen would be able to utilize both on-machine learning and simulation learning to produce the most reliable flight control parameters for any given situation. The possibilities of the Griffen platform are many, aided by the inherent stability and simplicity of the platform.

REFERENCES
[1] A. Tayebi and S. McGilvray. "Attitude stabilization of a four-rotor aerial robot." In 43rd IEEE Conference on Decision and Control, December 12-17, 2004.
[2] P. McKerrow. "Modeling the Draganflyer four-rotor helicopter." In IEEE International Conference on Robotics and Automation, 26 April - 1 May, 2004.
[3] P. Pounds, R. Mahoney, P. Corke. "Modeling and Control of a Quad-Rotor Robot." Proc. Australasian Conference on Robotics and Automation 2006.
[4] M. Valenti, B. Bethke, G. Fiore and J. How. "Indoor Multi-Vehicle Flight Testbed for Fault Detection, Isolation and Recovery." In AIAA Guidance, Navigation and Control Conference and Exhibit, 21-24 August, 2006.
[5] Vanderbilt University. Vanderbilt Embedded Computing Platform for Autonomous Vehicles. <http://www.vuse.vanderbilt.edu/%7Ekootj/Projects/VECPAV/>.