

# Stable Flight and Object Tracking with a Quadricopter using an Android Device

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## Abstract

We discuss a novel system architecture for quadricopter control, the Robocopter platform, in which the quadricopter can behave near-autonomously and processing is handled by an Android device on the quadricopter. The Android device communicates with a laptop, receiving commands from the host and sending imagery and sensor data back. We also discuss the results of a series of tests of our platform on our first hardware iteration, named Jabberwock.

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# 1 Motivation

## 1.1 Objectives

We approached this project with three goals in mind: stable flight, telepresence with an Android device, and simple blob tracking for the helicopter. For stable flight control, we wanted a system that could maintain a hovering state within a narrow radius of a given point (our target radius was ten feet), and could respond to commands sent from a host computer. For telepresence, we wanted to be able to visualize the Android device's location, orientation, acceleration, and velocity in real-time, as well as receive a video stream that compensated for network latency and low bandwidth. Finally, we wanted a system that would be able to grossly track objects on the ground to follow them using a naive color-matching algorithm implemented on the Android device.

## 1.2 Potential Applications

The applications for this platform are numerous; for example, the Robocopter platform could be invaluable as a remote surveillance tool. One application for which autonomous quadricopters are already being used is disaster relief: the EU is currently funding the AWARE project [Erman et al., 2007], whose goal is to create cooperative quadricopters to survey disaster sites and bring in light loads, such as dried food or medicine. The Robocopter platform is capable of doing much of what the AWARE quadricopters can do, but at much lower cost; since the platform requires only an Android device and about four hundred dollars of hardware, they can be manufactured extremely cheaply.

## 1.3 Progress

At the time of writing, we have attempted stable flight but have ultimately failed. We performed multiple outdoor tests, but have yet to see any sort of stability. We discuss why we think this is the case in Section 7.2.2. In one of the tests, the Jabberwock completely lost control and, instead of flying, attempted to dig a hole. In this test, the chassis was severely damaged. The electronics, thankfully, escaped unscathed. This fall, we plan on rebuilding the chassis and returning to our tests. We will implement the platform changes discussed in Section 7.2.2 to prevent the catastrophic failure we experienced with the platform, as outlined in this paper.

## 1.4 Future Goals

We have discussed various uses of the Robocopter platform. Currently, we would like to implement a more robust blob tracking to allow the helicopter to track objects as they move. Currently, since the blob tracking is performed via

color matching, changes in lighting or orientation of the tracked object can result in a lost lock. Tracking based on something more robust, such as SIFT features, would make our blob tracking perform much better. We would also like to implement dynamic panorama creation, in which the helicopter performs a series of predefined acrobatics to take photos which cover a solid angle of 180 degrees. From this, we can create a panorama from the helicopter's current location; such birds-eye panoramas would be unusual, if not unique, and would be both creatively and technically interesting to generate.

## **2 Pilot Android Application**

The Pilot program has two core functionalities. The first is the actual robotic control of the quadrocopter itself; the second is communication with the control server. The parallel processing required in these distinct tasks is complicated by the performance requirements of the program. Flight control processing must take place in real time – or an extremely close approximation. Communication with the control server, on the other hand, yields priority to flight control. Consequently, a great deal of effort went into prioritizing inter-thread communications and access of shared data. For flight control algorithms, blocking on locked data is unacceptable, since timely performance is essential; instead of blocking, they will use the most recent, locally stored version of the data requested. For communication algorithms, accessing flawed data is unacceptable; the control server must not receive out-of-date information portrayed as current.

### **2.1 Flight Control**

Flight control itself is divided into two main components: navigation and guidance.

#### **2.1.1 Navigation**

Navigation determines a desired velocity vector for the quadrocopter. In “manual” mode, it simply accepts this vector from the control server. In “autopilot” mode, or when the connection is lost, autopilot subroutines determine the desired velocity vector. It's determination is based on two factors. The first is its current location. The second is either previously transmitted autopilot instructions, or pre-programmed safeties (for low power, bad network, etc.).

#### **2.1.2 Guidance**

Guidance takes the desired velocity from Navigation, and uses PID loops to adjust individual motor speeds to achieve and maintain that vector. To improve

the performance of the PID loop, the system is transformed into an approximately linear one. The transformation accounts both for the quadratic relationship between motor speed and thrust, and for changing effects of motor thrust as its orientation changes.

### 3 Server Software

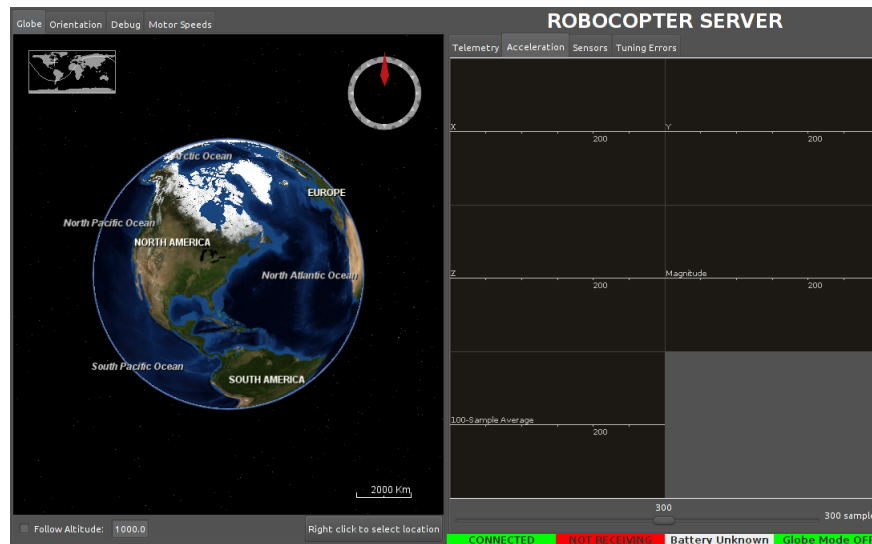


Figure 1: A screen capture of the chopper control software.

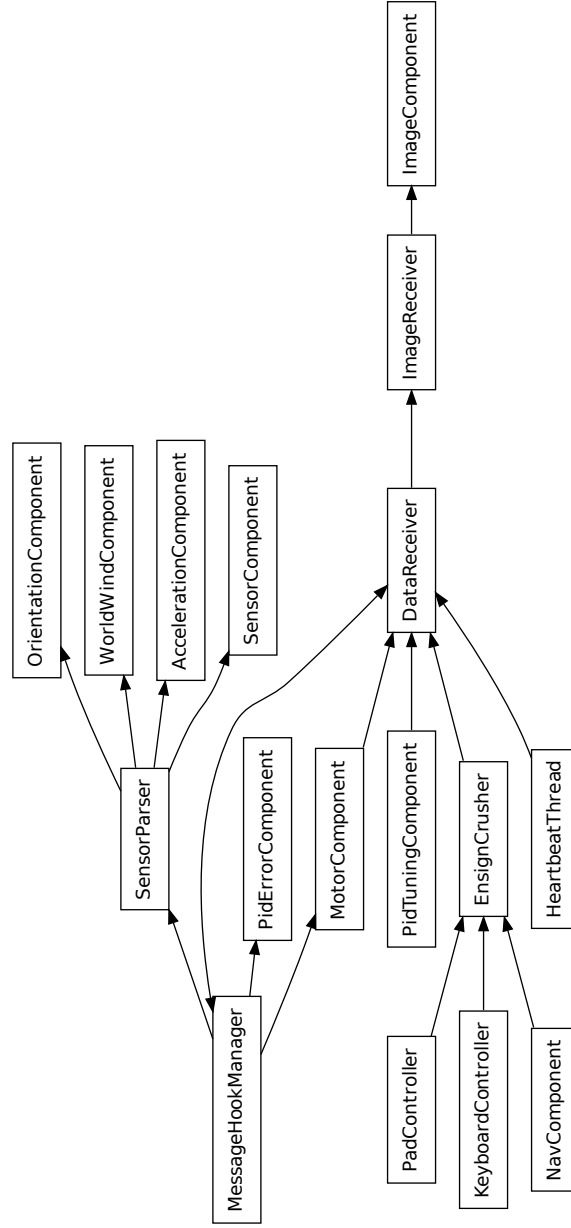


Figure 2: The architecture of the host system

The software is designed for two purposes: control and telepresence. We have implemented a system which allows us to monitor acceleration, orientation, temperature, location, and even magnetic flux. We also are streaming video from the helicopter to the server software, which is displayed in the UI. We have a control subsystem that allows us to control the helicopter from a mouse-based system, a keyboard-based system, or a Microsoft XBOX controller.

The architecture of the system is shown in Figure 2.

### 3.1 Message Handling

Sensor readings from the phone are transmitted to the server using very simple strings, as is described in Section 4.3. These are received and placed into a message queue which handles all subsequent processing. The various components of the UI and backend are all programmed as plugins to this message queue handler. Each plugin registers a list of prefixes with the message queue – these define the messages that that plugin is capable of processing. For example, the orientation component handles only messages with the prefix “ORIENT”, while the PID tuning component handles anything that starts with “GUID” or “NAV” (for guidance and navigation, respectively). The appropriate messages then get passed onto these components who handle the messages themselves.

The message handler receives a huge firehose of information, and only about 10% of the plugins need to respond to any given message. In early implementations, every plugin received every message, which meant that about 90% of the work on each message was useless. In instrumenting early builds using VisualVM, we found that about 60% of the processing done by the server was trying to handle each of the messages, and often the queue would fill faster than it was emptying. Two fixes improved this: the prefix-based handling (which cut down on processor usage) and multithreaded plugins. Some of the plugins were blocking the processing of later messages because the plugins were given new messages synchronously – switching to an asynchronous update mechanism for some of the heavier plugins allowed us to decrease latency in sensor readings and other easier-to-process messages.

### 3.2 Telepresence

The main thing we tried to accomplish in designing the UI was to make it as easy to understand what the helicopter was doing as possible, and be able to access all of the data the Android platform was capable of giving us. We also wanted it to be easy to detect error conditions at a glance for faster operator response to emergencies.

We eventually decided that, for many sensors, graphing them was the most intuitive way to do this. To graph them, we rolled our own graphing package (which was later released as SimpleGraph, a standalone Java line graph

library). For three, however, there were more intuitive ways of displaying our data.

For orientation, we used a 3D representation of the helicopter that accurately mirrors the orientation of the actual phone, which is easier to read than trying to apply three rotations in your head. We used the Java3D<sup>1</sup> game library for this, because it was the most resource-efficient in our testing.

For location, we chose to mimic the Google Earth interface and used NASA's World Wind<sup>2</sup> mapping software. This is an extraordinarily powerful library, and the only one we could find of its kind. Though poorly documented, it is open source and very easy to use. Consequently, we dropped it into our UI quickly and seamlessly.

The last visualization we used was a very simple top-down view of the helicopter for the motor speeds, in which each "motor" is given a color from red to green, denoting the current speed of the motor.

## 4 Communication

Communication is composed of two main components: telemetry and commands/data. Each is relayed on separate ports, since commands must be relayed as synchronously as possible and telemetry will be asynchronous.

### 4.1 Telemetry

The telemetry modules continuously run the Android's preview functionality, at 5fps. Each frame is saved to a buffer as it is available, overwriting the previous frame. When the Android has finished sending one frame to the control server, it immediately copies the buffer and starts sending the frame. The result is real time telepresence, at approximately two to four fps and a lag of less than one second.

### 4.2 Commands and Data

Commands and data are relayed in the form of strings over standard Java sockets. When the connection is lost, the Android device immediately tries to reconnect, continuing to do so indefinitely. While the connection is lost, autopilot is enabled and the "communication lost" pre-programmed instruction set is engaged.

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<sup>1</sup><https://java3d.dev.java.net/>

<sup>2</sup><http://worldwind.arc.nasa.gov/java/>



### 4.3 Message Formats

Messages between the Android and the control server are sent as strings, delimited by colons. The strings from the control server – commands – contain the instruction itself, prefixed by a sequence of meta-data describing the instruction. Similarly, data from the Android device contain not just the data, but also a prefix tag describing the data. This enables somewhat efficient analysis on each end: messages can be routed only to those components that are registered to process a given prefix tag. Messages are not transmitted directly between the Android device and the control server. Instead, they are routed through a separate, dedicated broker server. This enables the control server itself to operate easily from different IP addresses, and hence from various locations. It also allows for easy logging and playback of sessions – the broker server logs all data and commands, and can replay a session later for analysis.

## 5 Jabberwock

A list of parts used is supplied in Appendix A.

### 5.1 Design of the Chassis

The chassis design has fluctuated the most over the process. While the software stack was fairly well thought out early on, we wrote it to be hardware-independent. At first, the plan was to use a kit chassis and buy our own components, as this would mean that all of the components would be guaranteed to work together. However, as time went on, we realized that the added cost of a robust chassis was higher than the value we would get out of it, and we decided to build our own.

Using a 3D printer, we were able to print whatever plastic parts we desired out of ABS plastic. ABS is a rigid and strong plastic – it is best known for being the raw form of a Lego brick – and is very cheap to buy in large quantities. Jabberwock was printed on a Makerbot that is capable of printing objects up to 10cm by 10cm by 13cm: it wasn't large enough to build the entire helicopter in one go. Our design, therefore, had to account for the fact that no individual custom-made part could exceed these dimensions.

We opted for a design that is slightly different from most commercially-available quadricopter designs, for both pragmatism and strength. Our design features a large block in the middle made of sandwiched layers, each of which holds a narrow-gauge brass pipe in place. A rendering of this component can be seen in Figure 3. These brass pipes extend 25 cm out either side of this center block. On the end of each pipe is a motor unit, consisting of two sandwiched ABS pieces that attach the motor to the pipe. This can be seen in Figure 4.

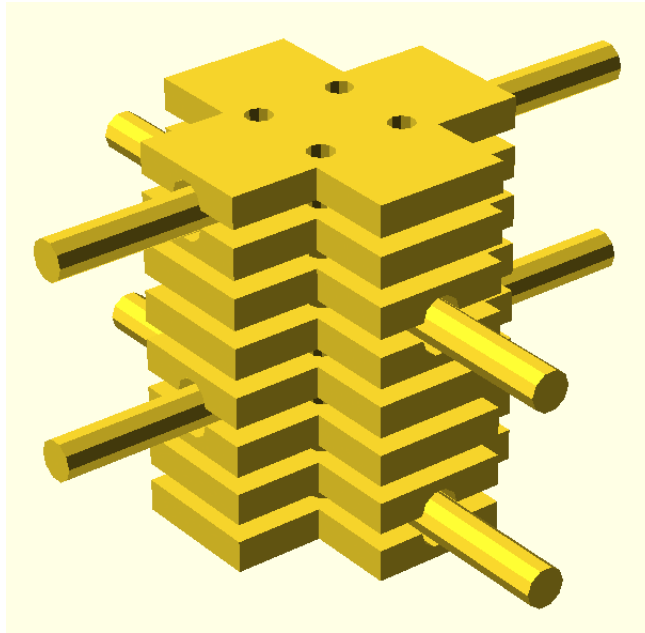


Figure 3: The center assembly upon which the electronics and Android device are mounted.

The first and last layer of the center block each have eight mounting holes with a captive nut locked in between the outer layer and next layer. This allows us complete modularity in terms of hardware attachments without ever having to reprint – all we must do is make sure new components are compatible with the mounting screws already built in, and we can hotswap our hardware easily.

## 5.2 Electronics Design

In designing the electronics, we went for as much redundancy as possible, and only used parts that had ratings at least 50% over our estimated needs. We estimated that the helicopter would have a weight of approximately 1 kg (actual weight was slightly higher) so each motor-propeller pair needed to be rated to carry at minimum 500 grams. In addition, we wanted to be able to put different payloads on the helicopter in the future (if we wanted to mount a video camera, for example) so we ended up using motor-propeller pairs that are capable of a very large range of possible thrusts, from around 50 grams to about 1.5 kg per motor. In later testing, we learned that the helicopter was neutrally buoyant when all motors were set to about 30%.

For our control hardware, we chose to use an Arduino because we had experience coding for the Arduino platform, and because it provides many li-

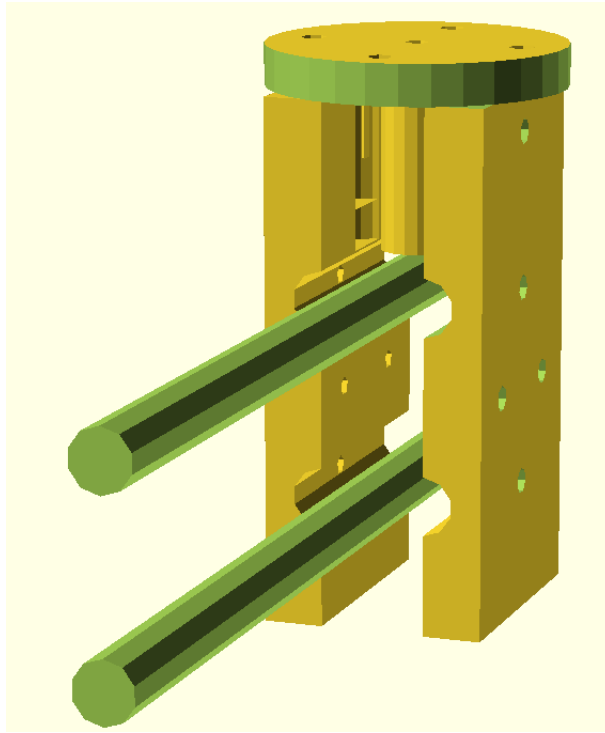


Figure 4: A motor mount on the end of a pipe.

libraries that are helpful for motor control and sensor readings. While the sensor reading libraries were not used for Jabberwock, in later iterations we plan may use rangefinding sensors for landing and three-dimensional map creation, so we wanted to ensure we had the capability to hook that in to the existing system.

We chose our other parts based on online reviews and price. One of our goals was to keep this project as cheap as possible for two reasons. Firstly, we wanted to be able to pay for the thing, and secondly, we were interested in seeing just how cheaply this could be done. In the end, we managed to keep the cost low – \$440 after tax and shipping.

We did make one fairly nonconventional decision in terms of electronics design. While many designs use only one battery to power the entire system, we chose instead to have four batteries – one for each motor. This has the disadvantage that we have to monitor four battery charges instead of one, the wiring is slightly more complex, and the batteries can discharge at different rates. However, having the four batteries has one distinct advantage: increased longevity. Having all four batteries means we can stay flying for longer, which is a clear advantage.

## 6 Blob Tracking

We would like the Robocopter platform to be able to track gross objects based on color. To that end, this semester, we implemented a blob tracking algorithm that can run on both Android and a standard JVM. The algorithm is capable of image segmentation, labelling and object motion tracking. The architecture of this algorithm is outlined in Figure 5.

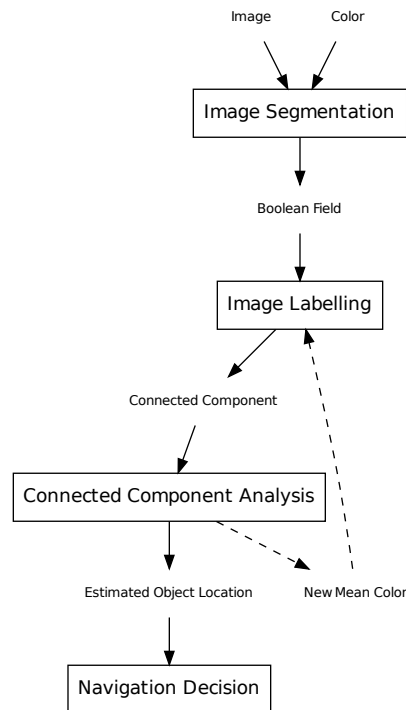


Figure 5: Architecture of the blob tracking system

### 6.1 Algorithm

#### 6.1.1 Image Segmentation

For image segmentation, we used an adaptive algorithm that segments an image based on a color and a threshold. There is a matching phase, and then a learning phase. In the matching phase, the segmenter takes an RGB image and outputs a binary image, representing color matches. Treating color as a

3-vector, the output image is defined by 1, where  $O$  is the output image,  $I$  is the input image,  $C$  is the target color and  $t$  is the threshold. After the output is computed, it iteratively expands this field. Each iteration passes through the image, activating any pixel that has a neighbor who is active. The number of expansion passes is configurable, but we found the best results with a single expansion pass.

$$O_{(x,y)} = \begin{cases} 1 & : ||I_{(x,y)} - C|| < t \\ 0 & : \text{otherwise} \end{cases} \quad (1)$$

The learning phase happens after labelling and connected component analysis. After connected component analysis, the system has a best-guess for which blob in the segmented image represents the object which we are tracking. We find the mean color within that blob, and take the mean of that color and our current color. The resulting midpoint is set to be the new target color. This adaptation ensures that moderately slow changes in lighting will not effect the performance of object tracking.

### 6.1.2 Image Labelling

We used a standard two-pass algorithm to find the connected components in the result of segmentation that uses 4-connectivity to define pixel adjacency. The first pass of this algorithm labels each pixel based on whether its neighbors above and to the left are set. It also records when there is a equivalence collision (i.e., when both the pixel above and to the left are labelled, but they have different labels). In this case, it adopts the label of the lowest value (the parent label) and records the two labels in an equivalence table. The second pass then iterates over the image, replacing child labels with parent labels. The result is a list of Area objects, each of which contains a centroid and size.

### 6.1.3 Connected Component Analysis

The result of segmentation and labelling usually returns multiple labelled areas. The analysis step attempts to determine which of the areas is the one which we are tracking. Since we were unsure of the rate at which the Android device would be capable of processing images, we wanted to make this step independent of location. If the phone could only process a few frames per second, it is possible that the tracked object could have moved significantly between frames. We could not, therefore, make the assumption that the closest area to the area we detected last was our target. Instead, we made the assumption that the size of the object in the frame would be relatively invariant. Based on this assumption, we chose to take the blob whose area was most similar to the previously detected area as our target.

#### 6.1.4 Reaction and Tracking

Once we have the in-frame location, we translate this to coordinates centered on the origin. For example, if the centroid of an area was detected to be in the center of the image, the resulting coordinates would be (0, 0). We then translate this into a navigation 3-vector, in which the Z-component is zero, and the X- and Y-component are the corresponding values in these coordinates, multiplied by a scaling factor. This is then passed to *Navigation*.

### 6.2 Performance and Results

Since we were unable to maintain stable flight, we were unable to test the reaction and tracking step. However, we found that the tracking worked well. In lighting-invariant conditions, it was able to track an object as either the object or the camera was moved. To test it, we set up the blob tracking to run on a laptop while receiving imagery from the Droid. The laptop was able to segment these images faster than it received them from the Droid, which places a lower bound of 5 Hertz on the frequency of which this algorithm is capable. Further testing is needed before we can know how fast the algorithm is capable of running on an Android device, especially while said device is running the rest of the Robocopter system.

## 7 Testing

### 7.1 Pilot Application Testing

For budget reasons, we did much of the initial Pilot development on the android emulator. As one might imagine, this proved to be a poor platform for developing robotic control software.

The emulator does not, in fact, actually emulate many hardware functions very well. The camera functionality does not properly implement several guaranteed methods: for example, a `Camera.parameters` object on which `getSupportedPreviewSizes()` is called returns null, though the API specifies that a list is guaranteed. Less culpably, calling most bluetooth-related methods will crash the program on the emulator.

A persistent developer can code around these drawbacks, testing other aspects of the program on the emulator. More damaging is the speed at which the emulator runs: it is very, very slow. This is hardly unexpected, but running moderately complex control algorithms at even 10 Hertz quickly becomes untenable.

Another hazard we noticed was more subtle. On the emulator, many sensors are not implemented, and those that are return constant values. The orientation sensor is an instance of the former; the acceleration sensor one of the

latter. On a real phone, this is obviously not the case, and many bugs in the software only became apparent after migrating from the emulator to the Droid. For instance, the emulator always read the azimuth value as zero: consequently, it never actually executed a coordinate transformation of the velocity vector from the absolute frame to the relative frame. On the emulator, the two were the same; on the Droid, they literally never are. This is a crucial piece of code that was not properly tested for quite some time.

## 7.2 System Testing

### 7.2.1 Systematic Delays

Initially, we encountered a substantial delay in sending motor speeds from the Pilot program to the Arduino. After some testing, we determined that the source of the delay was not, in fact, in our code, but rather in the android inter-application messaging system. The published Amarino library runs a service – `AmarinoService` – to interface applications on the phone to the Arduino over bluetooth. Applications send messages by broadcasting a system-wide Intent object, which is sent to `AmarinoService`, processed, and transmitted over bluetooth. Since our control loop runs at 10 Hertz and submits 4 motor values per loop, we were broadcasting system-wide Intents at the rate of 40 Hertz. This proved to be too much for Android, which could not process the Intents nearly fast enough.

A graph of desired versus actual motor speeds is shown in Figure 6. The red line indicates desired motor speeds, as determined by the Guidance object, calculated in real time. The green line indicates the time at which those commands were actually sent over bluetooth by the `AmarinoService`. The above graph indicates not just a delay between the two, but an increasing delay, suggesting an Android system queue to which elements were being added faster than they were being removed.

We resolved this problem by bypassing the Intent-broadcast system entirely. In fact, we spliced the entire Amarino application into our own. When all components were run in the same JVM, we could easily access the `AmarinoService` explicitly from Pilot and process messages directly, instead of waiting for Android to resolve the broadcasts. A similar graph to the one in Figure 6 is shown in Figure 7; Figure 7, though, shows the results of this modification.

While perhaps inelegant, this solution worked quite well. The convergence between Guidance and `AmarinoService` is approximately perfect.

### 7.2.2 Control loop stability

After actual testing, it appears that the hardware limitations of the Droid may preclude stable control of such a complex system. The orientation sensor on the Droid, even at its fastest setting, only registers new values at ever 100ms or so

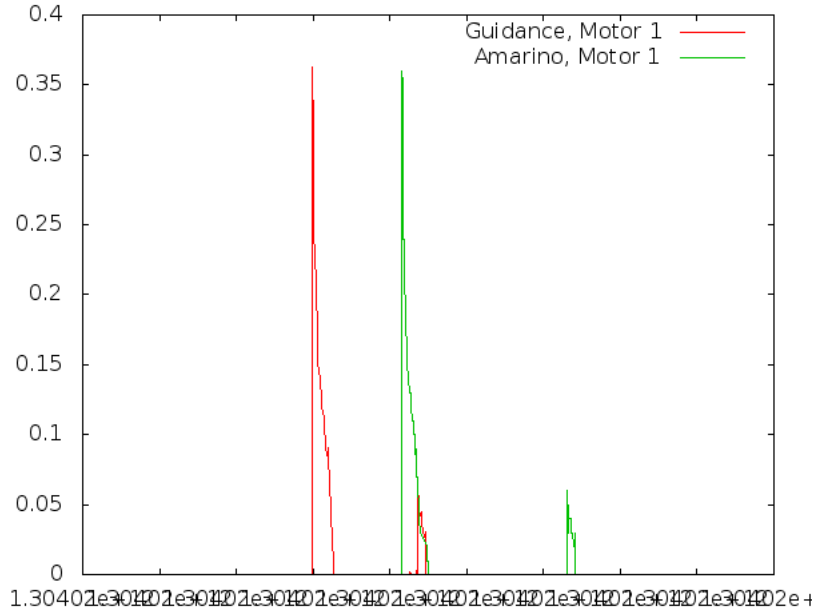


Figure 6: Actual motor speeds vs. broadcasted motor speeds

(this delay is not consistent). Consequently, there is no purpose in running the PID control loop at faster than 10hz. However, the quadricopter loses stability in well under a second. The shift from “stable” to “irrecoverably unstable” can occur in as few as 3 or 4 tenths of a second—and therefore only 3 or 4 iterations of the PID loop. While precise tuning might make control possible, even perfect tuning is likely to yield poor control at best. And obtaining even “acceptable” tuning at this point seems to be a futile endeavor.

## 8 Future Improvements

Moving forward, we have a number of enhancements planned that we think will drastically improve stability. Most importantly, we will be using a newer Android device to pilot the quadricopter. This device—an HTC Evo 3D—possesses 4 times the processing power of the Droid, and includes a gyroscope. Between the two, we expect both more accurate orientation readings and a faster sample rate. We hope to run the control loop at 33hz, instead of the current 10hz.

We will also implement changes to the control algorithms themselves. First, we will not attempt to directly control the speed of the quadricopter. Instead, we will endeavor to control its orientation directly, and control speed indirectly by altering target orientation. Second, as discussed earlier, PID control works



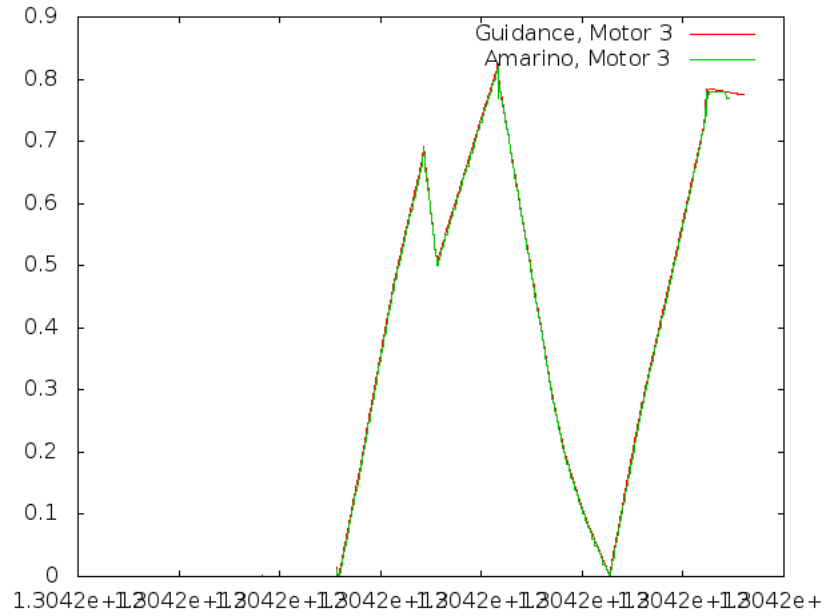


Figure 7: Actual motor speeds vs. broadcasted motor speeds, post-modification

best on a linear system. Quadricopter mechanics, however, are far from linear. Consequently, the transformation from linear control variables—on which the PID loop operates directly—to the non-linear motor speeds is of the utmost importance. Deeper analysis of the transformation we used on the Jabberwock platform showed it to be quite flawed. We have developed a newer algorithm that we believe is far more accurate.

The chassis design will also undergo significant alteration, to improve stability. Each arm will be comprised of three brass rods, instead of two. Additionally, we will move the batteries from their current positions on the arms to a new position under quadricopter’s center of gravity. Between these two changes—and the software changes mentioned above—we anticipate a hugely improved quadricopter system.

## A Parts and Prices

Item	Supplier	Quantity	Price
Chassis Hardware	McMaster-Carr	N/A	\$32.60
Turnigy 2217 Brushless Motors	HobbyKing	4	\$14.04
Counterforce Propeller Pair	NG Hobbies	5	\$6.95
Arduino Microcontroller	SparkFun	1	\$29.95
Turnigy 15 Amp ESC Controller	HobbyKing	4	\$10.58
BlueSmirf Gold Bluetooth Modem	SparkFun	1	\$64.95
Turnigy 2200mAh 3S LiPoly Battery	HobbyKing	5	\$11.96
Arduino ProtoShield Layout PCB	SparkFun	1	\$16.95
HobbyKing Fast Battery Charger	HobbyKing	1	\$39.99

## B Code Repository

A single github repository is used for version control of the server, client and broker, as well as this essay.

<http://github.com/haldean/droidcopter>

## References

Aysegul Tuysuz Erman, Lodewijk van Hoesel, and Paul Havinga. AWARE: Platform for Autonomous Self-Deploying and Operation of Wireless SensorActuator Networks Cooperating with AeRial ObjEcts. *CTIT Symposium*, 2007.