Autopilot Integration on Micro Aerial Vehicles

By

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Department of Aerospace and Mechanical Engineering

Abstract

Micro Air Vehicles (MAVs) are small, unmanned aerial systems that typically have a smaller than 12” wingspan. There are many practical applications for these MAVs, ranging from military use to real estate. In this project, we integrated autopilot control systems onto a pair of Vertical Take-off and Landing (VTOL) MAVs. These control systems are responsible for stabilizing the inherently unstable tail-sitter airframes, allowing for stabilized flight by human operator or automated flight plans. Two autopilot control systems were developed, which were shown to be capable of stabilizing their airframes and executing maneuvers.

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1 Introduction

1.1 Scope of the Document

To describe the final component design for two autopilots as well as the software design and analysis required to make them functional.

1.2 Changes since CDR

A couple of component changes have been made after lab testing all of our chosen parts. The RC reciever has changed from the Futaba Mini to the Berg 4L and the GPS was changed to a UBlox Max-6q after testing showed significant improvement in satellite acquistion speed and overall tracking. The scope of the project also changed for the indoor system. After testing and reviewing what had been done with GINA, it was determined that GINA was merlely a wireless IMU. This meant that the autopilot functionality, and control system needed to be designed from the ground up as minimal software was available to do much of anything with GINA.

1.3 Problem Statement

Every year the University of Arizona enters the International Micro Air Vehicle Competition (IMAV). The Micro Air Vehicle Club has placed in the top 3 for the past 8 years at IMAV competitions and they are entering this competition again. There is a separate indoor and outdoor competition with scoring weighted towards smaller vehicles with more autonomy. There is an aerospace senior design team designing and building the airframes and skins for the airplanes. The smaller airframe has only minimal space and mass availability which necessitates the use of a smaller and less powerful autopilot. Upon completion of the project, the senior design team will teach members of the Micro Air Vehicle Club how to control the airplanes and the club will take the planes to competition.

1.4 Project Scope

This project seeked to implement two autopilots for two micro air vehicles for entry in the 2012 IMAV Competition. The outdoor plane has a 11” wingspan, while the indoor plane has a 8” wingspan. This necessitated the use of two different autopilots with separate user interfaces and control algorithms. The outdoor autopilot was to be autonomous in all but target recognition and can follow flight plans if given a set of GPS waypoints. Target acquisition and recognition were not to be implemented as computer vision is very complex and time consuming to program. The indoor MAV has a smaller autopilot and is not be able to receive GPS signals. As a result it will be more directly controlled and depend on a combination of Inertial Measurement Unit (IMU) readings and camera-aided user inputs. However, it was discovered after the CDR that the GINA Autopilot used on the indoor airframe was a far less developed project than was initially advertised. With consultation from our sponsors, the indoor project scope shifted from developing an autopilot control system to developing and polishing a GINA firmware/groundstation pair which could effectively stabilize the indoor airframe, while allowing for sophisticated autopilot functionality to be implemented in the future.

1.4.1 Indoor MAV

The first MAV will be semi-autonomous via stabilized flight (AUTO1) and will complete specified tasks during the indoor competition at IMAV2012 while utilizing the GINA autopilot board.

1.4.2 Outdoor MAV

The second MAV will be fully autonomous (AUTO2) and will complete specified tasks during the outdoor competition at IMAV2012 while utilizing the Paparazzi Lisa/M autopilot board.

1.5 Product Expectations

Both MAVs are expected to complete all competition tasks. The outdoor MAV will perform them autonomously with human observers. The indoor MAV will perform its tasks in a stabilized fly-by-camera mode

1.6 Customer Description

1.6.1 Dr. Jonathan Sprinkle

Dr. Sprinkle maintains the Compositional Systems Laboratory and is involved in Autonomous Vehicle Research. He is a more recent addition to the project and joined to give ECE students an opportunity to gain practical experience in controls and robotics.

1.6.2 Dr. Sergey Shkarayev

Dr. Shkarayev maintains the Micro Air Vehicle Laboratory and advises the Micro Air Vehicle Club. He has been the traditional supporter of this team as well as the Aerospace team.

2 System Requirements

Unless otherwise specified as "DESIRED", the following requirements must be met:

2.1 Functional Requirements

1. Indoor MAV will be able to execute all indoor competition tasks via stabilized flight
2. Indoor MAV will be able to execute all indoor competition tasks fully autonomously (DESIRED)
3. Outdoor MAV will be able to execute all outdoor competition tasks via stabilized flight
4. Outdoor MAV will be able to execute all outdoor competition tasks fully autonomously (DESIRED)
5. Outdoor MAV will be capable of executing flight plans fully autonomously
6. Both MAVs will establish a wireless communication link to the ground control station and update it continuously
7. Outdoor MAV will be able to modify and accept new flight plans wirelessly

2.2 Technology Requirements

1. Indoor MAV will use GINA autopilot
2. Outdoor MAV will use Lisa/M autopilot
3. Both MAVS will perform attitude estimation via an inertial measurement unit
4. Outdoor MAV will utilize GPS for additional attitude, altitude, and velocity estimation
5. Outdoor MAV will utilize barometer for additional altitude estimation (DESIRED)
6. Both MAVs will be capable of streaming live video feed to ground control station

2.3 Performance Requirements

1. Flight of both MAVs will be able to be terminated via a kill switch as a safety measure
2. Both MAVs will be able to land in a target area with diameter of 5 meters (DESIRED)
3. Both MAVs will be able to fly within a closed area of 1 meter by 1 meter (DESIRED)
4. Both MAVs will be able to take off via an operator
5. Outdoor MAV will be able to take off fully autonomously (DESIRED)
6. Both MAVs will be able to traverse an obstacle filled area and recognize targets via an operator
7. Outdoor MAV will be able to traverse an obstacle filled area and recognize targets fully autonomously (DESIRED)
8. Both MAVs will be able to drop an item via an operator
9. Outdoor MAV will be able to drop an item fully autonomously (DESIRED)
10. Both MAVs will be able to perform an endurance test via an operator
11. Outdoor MAV will be able to perform an endurance test fully autonomously (DESIRED)
12. Indoor MAV will be able to perform a performance test within a specific time period via an operator

2.4 Utilization Requirements

1. Total cost of both MAVs must not exceed $3,000
2. Both MAVs will be able to compete in IMAV2012 competition

2.5 Trade-Off Requirements

1. Having both MAVs working with less features is more important than having only one with more features

2.6 System Test Requirements

1. Acceptance test plan will be completed before IMAV2012 competition

3 Summary of CDR Results

Our Critical Design Review described our analyses behind selecting each of our systems as well as subsystem components. The results of the trade studies are discussed here.

3.1 Components

GPS There were three main contenders for the GPS module during the PDR: the LS20031, FV-M8, and Venus GPS. All three have approximately the same size, mass, power consumption, and accuracy. After testing the LS20031 against some older GPS units in the lab, it was evident it did not provide the advantage that we thought it did. As a result we chose to use a new UBlox receiver called the UBlox Max-6q.

Modem There was a pretty clear winner during the modem trade studies: the XBee Pro XSC. While slightly shorter-ranged than the competing modules, the XBee was significantly smaller, lighter, cheaper, and consumed less power than its alternatives.

Camera A similar situation arose when comparing camera modules. While the DX201 had the highest resolution, the KX-1 was by far the cheapest, smallest, and lightest module. The small loss of resolution will not significantly impact the image quality.

RC Receiver The choice of RC Receiver was more complicated, but we eventually selected the Berg 4L on the basis that it uses the 72MHz band, a less-common alternative to the 2.4GHz band, which will be heavily trafficked during competitions. This, combined with the low price and longer range, led us to select it over the smaller, lighter, 2.4GHz Futaba R6004FF.

3.2 Autopilots

Indoor Autopilot System: GINA We selected the GINA system for the indoor platform, largely on the basis of its minimal power consumption. GINA offloads all computation to the ground station, and thus can use a low power microcontroller to perform all of its tasks. The downside of this arrangement is that the craft will cease to operate if it loses contact with the ground station, but this risk is minimal in an indoor competition.

Outdoor Autopilot System: Lisa/M We selected the Lisa/M autopilot for the outdoor platform on account of its modularity. It will allow us to add/remove sensor and transmitter modules very easily, should we have any issues with a particular component. It also has a higher degree of autonomy than the GINA system, in that it can safely operate at range without reliable contact with the ground station.

4 Top-level Design of Final Design Concept

The autopilot system consists of several components which will estimate the airframe's state, determine the necessary rates for stability, and control the servos to stabilize the airframe via a PID control scheme.

4.1 Airframe

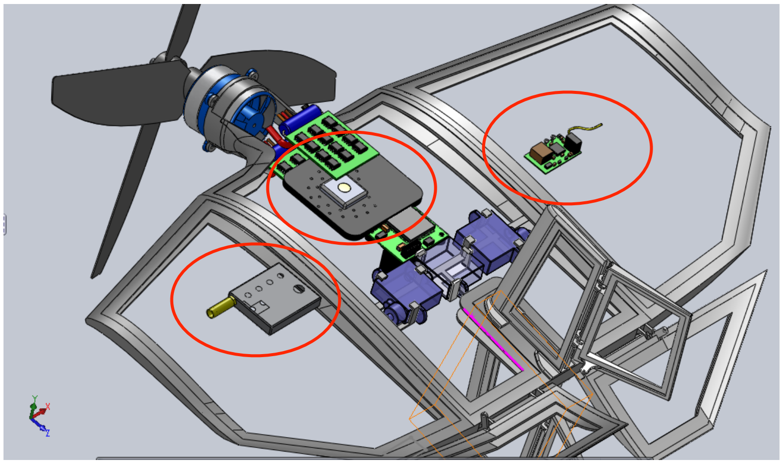


Figure 1: Mini-Vertigo MAV (Top)

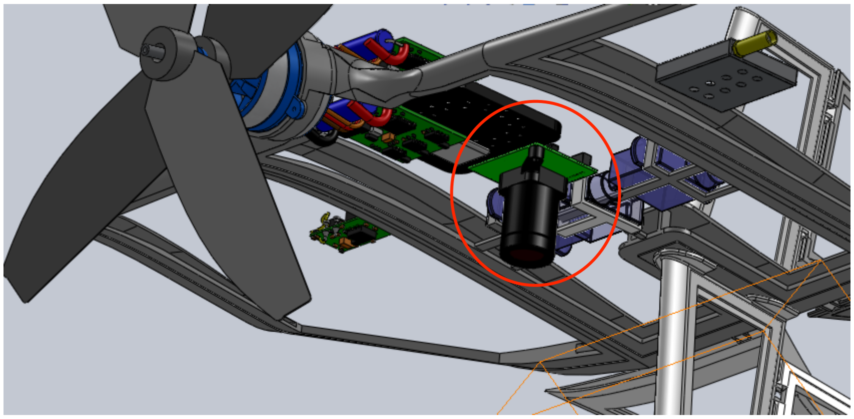


Figure 2: Mini-Vertigo MAV (Bottom)

The airframes which will be used for the indoor and outdoor competitions will be a 8" fixed-wing MAV and a 11" fixed-wing MAV, respectively. Both of these MAVs will resemble the same design with the 8" fixed-wing being a scaled down version of the 11" airframe. The images above are from last year's projects iteration so the components circled in red will not be utilized in the final design.

4.2 Autopilot

The autopilot stabilizes the airframe via a PID controller and transmit/receive data to the ground control station via the modem.

4.2.1 Paparazzi Lisa/M Autopilot

The Lisa/M board contains the microcontroller and logic of the control system. All of the sensors are attached to this as well as servos to be able to control the plane fully autonomously.

4.2.2 GINA Autopilot

The GINA board contains the microcontroller and all associated sensors and servo connectors. The control system logic is performed on the ground control station and not the board itself.

4.2.3 PID Controller

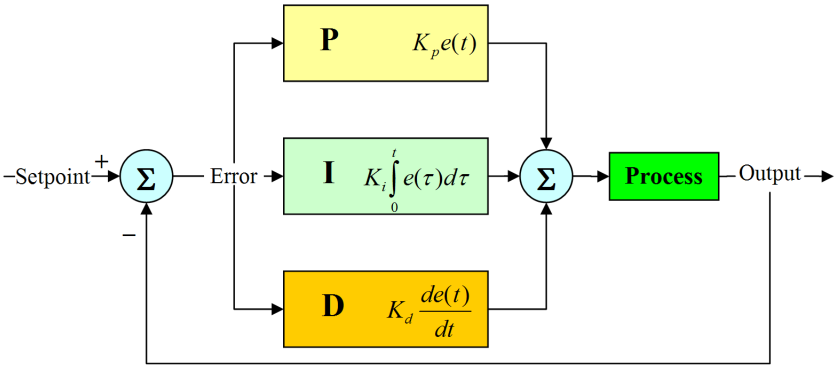


Figure 3: Block Diagram of a PID Control Scheme

Although the system we are controlling is inherently nonlinear, the PID controller will attempt to maintain the airframe around a linear operating point [2]. Ideally, this control scheme will be able to transition between vertical and horizontal flight [1].

4.3 Inertial Measurement Unit

The IMU will fuse the sensor data from the gyroscopes, accelerometers, magnetometers, and GPS to give an accurate estimation of the aircraft's orientation via an extended (non-linear) Kalman filter.

4.3.1 Gyroscopes

The gyroscope will measure the angular rates in three axes.

4.3.2 Accelerometers

The accelerometer will measure the acceleration in three axes.

4.3.3 Magnetometers

The magnetometers will measure the magnetic fields in three axes.

4.4 Pressure Sensor

The pressure sensor (combined with the GPS) will be able to measure the altitude of the airframe (Lisa/M only).

4.5 GPS

The GPS will be used to determine the latitude, longitude, and altitude of the airframe (Lisa/M only).

4.6 Telemetry Radio and Modem

The radio and modem will transmit and receive all of the desired data between the ground control station and the autopilot board on the airframe.

4.7 RC Receiver

The RC receiver will be used to receive transmissions from the pilot's remote control and send it to the autopilot.

4.8 Servos

The servos will be used to change the control surfaces to the desired values which will be controlled by the autopilot board and RC receiver.

4.9 Brushless DC Motor (and Electronic Speed Controller)

The brushless DC motor and speed controller will be used to control the rate of spin of the contra-rotating propellers attached to the motor.

4.10 Camera

The camera will be mounted on the airframe and used to capture video.

4.11 Camera Transmitter

The FM transmitter will be used to send the video feed from the camera back to the GCS.

4.12 Ground Control Station

The ground control station will display and send information to and from the autopilot board on the airframe.

4.12.1 Paparazzi Lisa/M Ground Control Station

The Paparazzi GCS will display telemetry data from the autopilot board and be able to send flight plans to the autopilot board.

4.12.2 GINA Ground Control Station

The GINA GCS will receive data from the autopilot board, determine the necessary changes to make to stabilize the airframe via the control system, and transmit the necessary changes to the autopilot.

5 Subsystem/Sub-assembly and Interface Design (Hardware)

The systems each consist of a core autopilot system as well as peripherals that will be integrated onto a MAV. Different peripherals has been selected for GINA and Lisa due to the fact that each system has a different use case. GINA is an indoor platform whereas Lisa is an outdoor platform. This distinction requires the selection of different hardware to meet the specific requirements of the indoor and outdoor platforms. GINA will operate in 2 control modes: manual control and stability augmented control. Lisa will operate in 3 control modes: manual control, stability augmented control, and autonomous. In implementing these 2 systems, the hardware peripherals that were chosen . This section outlines the details of these selections and the functionality each peripheral brings.

5.1 Paparazzi Lisa/M

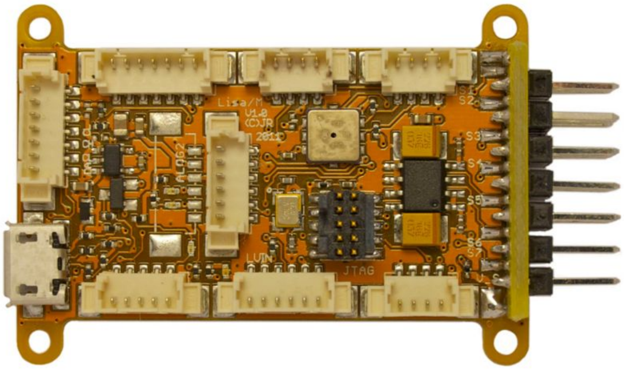


Figure 4: Paparazzi Lisa/M Autopilot Board (Top)

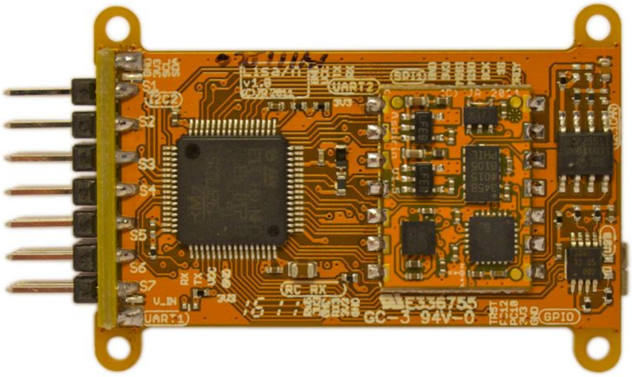


Figure 5: Paparazzi Lisa/M Autopilot Board (Bottom)

Component	**Description**
Autopilot	Paparazzi Lisa/M Autopilot
Modem	Digi Xbee Pro
GPS	UBlox Max-6q
Camera	KX-1
RC Receiver	Berg 4L

The Lisa/M Autopilot system is the platform used for the outdoor MAV. The Autopilot is a controller board with a STM microcontroller, 3-axis gyro, 3-axis accelerometers, and 3-axis magnetometer. The Autopilot is the main assembly and therefore is the central interface for all the other hardware. The ST microcontroller can be programmed to support custom hardware by implementing the device driver and then compiling and uploading the source. Since this is the central source this board contains the ability to connect all of the other electronics to it. The IMU is contained onboard, but all other hardware components are plugged into the Lisa/M board. This provides a very modular approach allowing for a wide range of different sensors and technologies to be implemented.

5.1.1 Peripherals

The peripherals for the autopilot system are each classified as a subsystem. Each is essential to the system working as specified by the requirements. The peripherals of this system consist of anything connected to the Lisa/M board. In keeping with the system requirements this will include a Wireless Modem, GPS, DC motor, 3 servos, and 2 cameras.

Peripherals such as the GPS, Modem, and cameras provide data back to the system and others such as the DC motor and the servos are controlled by the information that the onboard sensors retrieve.

5.1.2 Communication

The Modem and corresponding GCS base station receiver are responsible for the wireless data communication between the autopilot and the GCS. These components are essential and the MAV must remain in the modem/receiver range so that telemetry and camera data can be fed back to the GCS and video monitor. The selected modem operates on the 900MHz frequency spectrum. There are not too many devices that utilize the 900MHz spectrum, but we will include more details in the risk analysis section.

5.1.3 IMU

The IMU has already been integrated into the Lisa hardware and firmware. This IMU uses a 3-axis gyro, two 3-axis accelerometers and a 3-axis magnetometer. The extended Kalman filter has already been designed and implemented in the firmware.

5.1.4 Microprocessor

The STM32 Microprocessor is a very powerful 32-bit microprocessor and can handle all of the mathematical computations required by the control algorithm. The microprocessor is designed using the ARM Cortex-M3 architecture so its processing capabilities are above and beyond the needs of our system. This will allow for new additional sensors to be added if necessary. The core sensors that will be used such as GPS, IMU, Modem will have no issue connecting to the microprocessor.

5.1.5 GPS

Figure 6: Ublox Max-6q GPS Receiver

The Ublox Max-6q GPS is a critical component for an autopilot system. This sensor locates satellites and acquires a lock on the satellite. At least 3 of the satellites are needed to be able to triangulate the signal and determine the position on earth to some accuracy. This allows the MAV to know its position on the earth's surface as well as the altitude that it is at. Using the altitude value the MAV can hover using control code to maintain altitude. This sensor makes full autonomous flight possible outdoors since the MAV is able to know where it is at all the time.

5.1.6 Modem

Figure 7: Digi Xbee Pro 900MHz Modem

The Digi Xbee Pro 900MHz Modem allows for communication between the Lisa/M board and the GCS. This modem can communicate with the basestation from 24km away assuming it has line of sight. For all practical purposes this project does not need any more than 4km range. Due to the fact that this modem is capable of that far of range the data rate is not as fast. Max data rate is about 115 kb/s. This is more than enough to transmit telemetry data back to the ground station so the low data rate is not an issue.

5.1.7 RC Receiver

Figure 8: Berg 4L RC Receiver

The Berg 4L RC receiver is responsible for allowing communication between the Lisa/M autopilot and the pilot's RC Controller. This allows the pilot to control the plane completely when in manual control mode and control where the plane moves when using the stability augmentation mode.

5.2 GINA

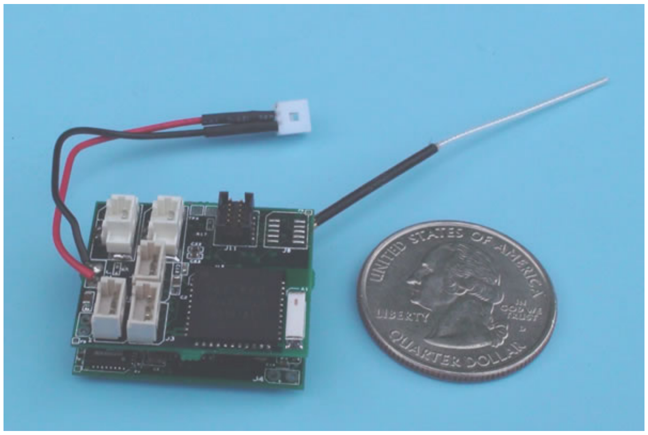


Figure 9: GINA Autopilot Board

Component	Description
Autopilot	GINA Wireless Inertial Stabilization System - Texas Instruments MSP430F2618 - Kionix KXSD9-1026 3-axis Accelerometer - Analog Devices ADXL345 3-axis Accelerometer - Invensense ITG3200 3-axis Gyroscope - 3-axis HMC5843 Magnetometer - Atmel AT86RF231 802.15.4 Radio
Camera	KX-1
RC Receiver	Berg 4L

The GINA Autopilot system is the platform used for the indoor MAV. The Autopilot is a controller board with a Texas Instruments MSP430 microcontroller, 3-axis gyro, two 3-axis accelerometers, 3-axis magnetometer, and a 802.15.4 radio for communication with the Ground Control Station. The Autopilot is the main assembly and therefore is the central interface for all the other hardware. The MSP430 can be programmed to support custom hardware by implementing the device driver and then compiling and uploading the source. Since this is the central source this board contains the ability to connect all of the other electronics to it. Other electronics are connected to the board using a daughter-board. Components such as DC motors, servos, and cameras are attached to the system in this manner.

5.2.1 Peripherals

The peripherals for the autopilot system are each classified as a subsystem. Each is essential to the system working as specified by the requirements. The peripherals of this system consist of anything connected to the daughter-board discussed earlier. In keeping with the system requirements this will include a DC motor, 3 servos, and 2 cameras.

Peripherals such as the camera provide data back to the system and others such as the DC motor and the servos are controlled by the information that the onboard sensors retrieve.

5.2.2 Communication

The onboard 802.15.4 radio and the corresponding base station radio are responsible for the communication between the autopilot hardware and the Ground Control Station software. These are critical components since the control computations are all done by the Ground Control Station and sent back to the autopilot which then signals the moving components based on the data it receives from the GCS. The radio operates on the 2.4GHz spectrum, which is a common frequency for other types of data communication. So interference is a concern that will be assessed in the risk analysis.

5.2.3 IMU

The IMU has already been integrated into the GINA hardware and firmware. This IMU uses a 3-axis gyro, two 3-axis accelerometers and a 3-axis magnetometer. The extended Kalman filter has already been designed and implemented in the firmware.

5.2.4 Radio

The Atmel AT86RF231 radio allows the GINA board to communicate with the GCS. It sends the data at a maximum rate of 2Mbps so it can handle quick transmission of the critical data, as well as the camera feed.

5.2.5 Microprocessor

The Texas Instruments MSP430 is a low power processor that is capable of performing the tasks outlined in the system requirements. The processor is powerful but very power cautious. In addition the tasks required of it are mainly device communication, so no heavy computations are done on this chip. All of the heavy processing is done by the Ground Control Station, this chip mainly serves as a communication interface between sensors and hardware.

5.2.6 Mote

Figure 10: avrBasestation Mote

The avrBasestation mote is a usb dongle that contains an Atmel avr microprocessor and a Atmel AT86RF230 82.15.4 radio. This connects to a Linux based computer that has Python installed. This device is controlled by a python module that interfaces with Ground Control Station, allowing communication with the GINA board that is located on the MAV.

5.3 Camera

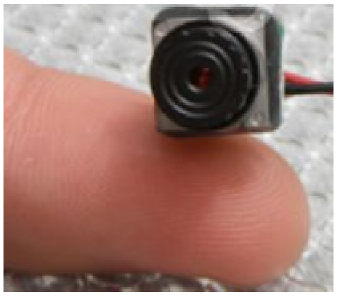


Figure 11: KX-1 Camera

The camera subsystem is essential to the MAV as it will be used to fly via a video feed on the GCS. This allows the pilot to fly in stability augmentation mode and not have a line of sight to the plane. A second camera may be used to provide reconnaissance to an operator. The KX-1 camera provides a very small package size and is light in weight. The only drawback is the resolution is not as good as some of the larger cameras. 2 of these cameras can be added to the system using a dedicated video modem, so that the main modem is not overloaded by the data that has to be transmitted from the camera sensors.

5.4 Hardware Interfaces

The interfaces for the two Autopilot systems include the human-system interface, the modular interfaces, and the internal interfaces.

The human-system interfaces is defined as how the user will interact with the autopilot. This occurs at the beginning of a flight to the end of a flight. The user can also interact with the GCS when the plane is stationary to adjust necessary parameters. The most common human-system interaction occurs during flight when the pilot is flying the vehicle or an operator is using the GCS to set waypoints for the vehicle to fly to. The telemetry and video link also provide another source of human-system interaction as it allows the operator to get live information from the MAV. The modular interface is how the external components connect to the autopilot system. This can be seen as board or component level interface. The last interface is the internal interface of the hardware components. This occurs at the chip level. The internal interface is how each chip communicates with one another.

5.5 Paparazzi Lisa/M

5.5.1 Human-System Interface

The Human-System interface is the Ground Control Station. This is located on the Ground Station Computer and uses a Basestation to communicate with the Lisa/M board.

The Ground Control Station is described in more detail in the Software Interfaces section. This is the main method of interaction between Humans and the System. The other form of interaction will occur between the pilot and the MAV for the cases of augmented stability and manual mode. The pilot will use a RC Controller to communicate with the RC Receiver located on the MAV and will be able to directly control it.

5.5.2 Modular Interface

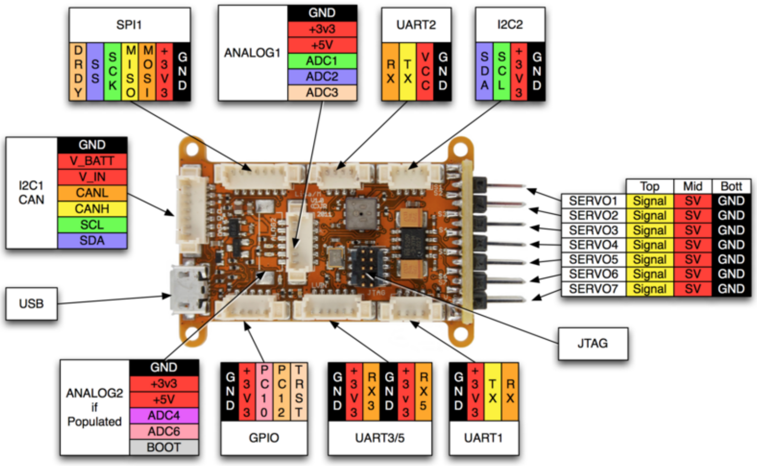


Figure 12: Lisa/M Pinout

5.6 GINA

5.6.1 Human-System Interface

The Human-System interface for GINA is a Ground Control Station. The GCS was developed to be able to send Commands to GINA through a simple intuitive interface for the user. In addition the GCS shows the user pertinent information regarding the status of the autopilot system such as latency, voltage levels, state, and stability of the plane as well as visual graphs that show raw sensor data and computed values from the control loops. The user can also make quick adjustments to control loop gains and change the neutral positions of the servos for doing quick tests then the configuration file can be saved so that on the next startup all of the current values can be quickly loaded. The pilot interfaces with GINA using an RC Controller that is plugged in via USB to communicate with the GINA board to be able to control the MAV.

5.6.2 Modular Interface

The GINA Daughter-board allows for the connectivity of all of the other hardware components to the main GINA system board. All of the components attached to the main GINA board are not modular so there are no ports located on that board with the exception of the port to plug in the daughter-board. The daughter-board however allows for the addition of other sensors as well as all of the power electronics like the DC motors and servos.

6 Algorithm Description and Interface Document (Software)

6.1 Device Drivers

Since we are dealing with the development of additional firmware for the autopilot platforms it is essential to discuss device drivers. A device driver is a piece of software that enables a system to interact with a component. For example an autopilot system that wants to interact with a sensor. A device driver must be written that allows the autopilot system to communicate with the sensor. This involves first determining the way in which the devices will communicate. In the cases presented in this design the device will be interacting directly with the microprocessor for both architectures. The device code must be written and added to the firmware source that is then uploaded to the board. Both the GINA and Lisa/M platforms are written in C however GINA uses the TI MSP430 and the Lisa/M uses a STM32 ARM Cortex M3. These differences are important as the way the low level code is written may vary.

6.2 Lisa/M

The following diagram shows the flow of the Paparazzi software for Lisa/M. The external sensors are colored in purple. Each of these sensors are handled by the respective device drivers. The data is then transferred to the state estimator matrix which is then converted to more meaningful data. The controllers(yellow) then analyze the data and have the autopilot perform some action.

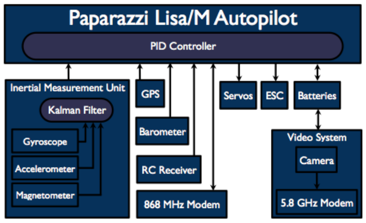
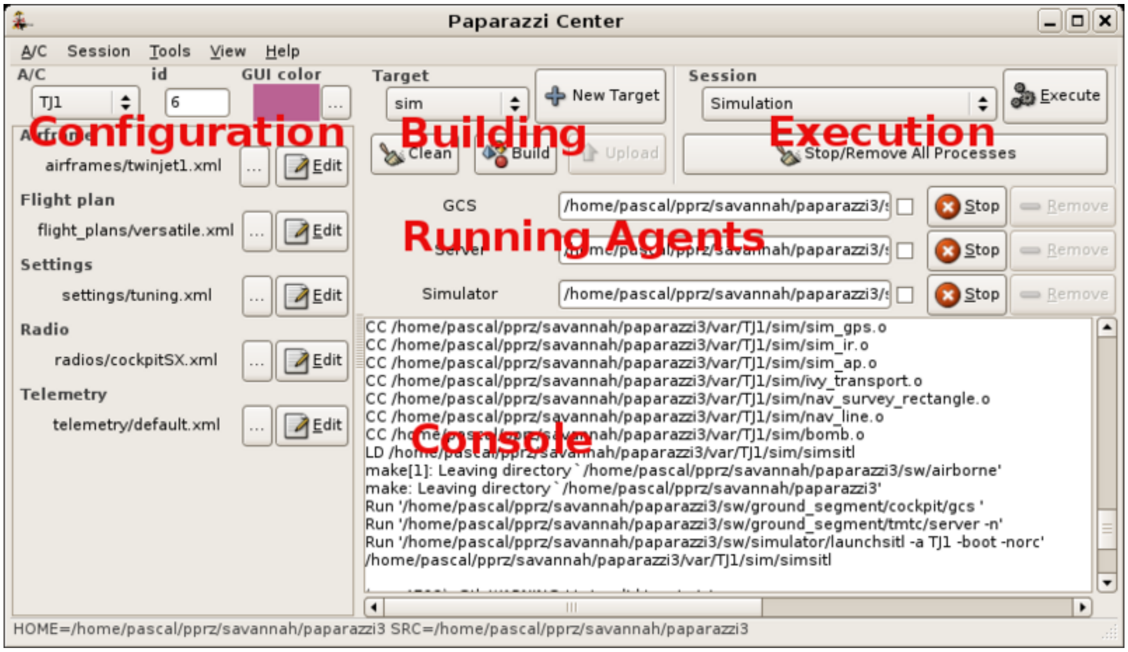


Figure 13: Lisa/M Software Diagram

Paparazzi Center is a graphical interface that allows the operator to easily configure, compile, upload the firmware to the Lisa/M board. The Paparazzi Center is designed to run on Debian Linux Systems including Ubuntu. The Autopilot system designer is responsible for ensuring that the configuration files have been properly set up and that all of the specifications have been meet by the firmware being uploaded. After the firmware has been loaded, Paparazzi Center can also be used to launch the Ground Control Station.



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GUI color
Target: sim
Session: Simulation
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Flight plan: flight_plans/versatile.xml
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Radio: radios/cockpitSX.xml
Telemetry: telemetry/default.xml
GCS: /home/pascal/pprz/savannah/paparazzi3/s
Server: /home/pascal/pprz/savannah/paparazzi3/s
Simulator: /home/pascal/pprz/savannah/paparazzi3/s

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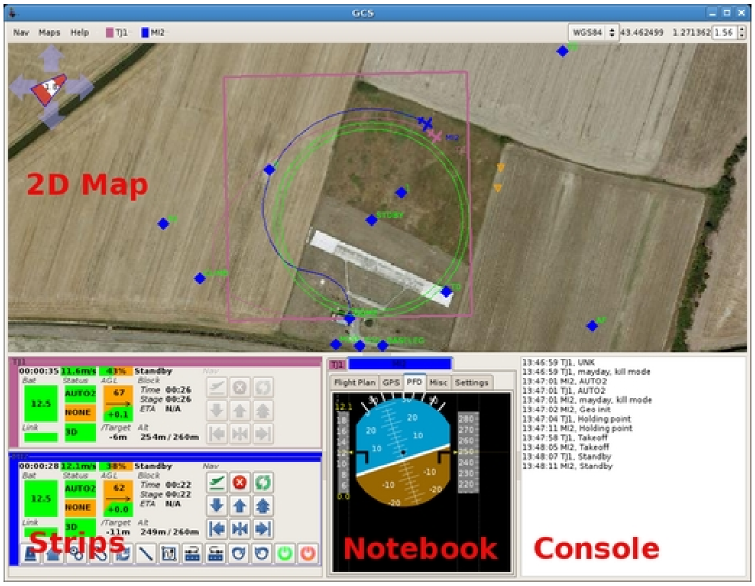
LD /home/pascal/pprz/savannah/paparazzi3/var/TJ1/sim/simsitl
make[1]: Leaving directory `/home/pascal/pprz/savannah/paparazzi3/sw/airborne'
make: Leaving directory `/home/pascal/pprz/savannah/paparazzi3'
Run '/home/pascal/pprz/savannah/paparazzi3/sw/ground_segment/cockpit/gcs '
Run '/home/pascal/pprz/savannah/paparazzi3/sw/ground_segment/tmtc/server -n'
Run '/home/pascal/pprz/savannah/paparazzi3/sw/simulator/launchsitl -a TJ1 -boot -norc'
/home/pascal/pprz/savannah/paparazzi3/var/TJ1/sim/simsitl
```

HOME=/home/pascal/pprz/savannah/paparazzi3 SRC=/home/pascal/pprz/savannah/paparazzi3

Figure 14: Paparazzi Center

The Ground Control Station is used to monitor the status of the MAV as well as make adjustments to control gains. The GCS can be used to issue commands to the aircraft as well. It is the official communication method between the Ground Station Hardware and the Lisa/M board. The main screen can be used to show a video feed from a camera onboard the MAV or a Google Maps view of the flight plan and vehicle location. The GCS has buttons for issuing commands as well as tuning the MAV in-flight.



```
13:46:59 TJ1, UNK
13:46:59 TJ1, mayday, kill mode
13:47:01 MI2, AUTO2
13:47:01 TJ1, AUTO2
13:47:01 MI2, mayday, kill mode
13:47:02 MI2, Geo init
13:47:04 TJ1, Holding point
13:47:11 MI2, Holding point
13:47:58 TJ1, Takeoff
13:48:05 MI2, Takeoff
13:48:07 TJ1, Standby
13:48:11 MI2, Standby
```

Figure 15: Lisa/M User Interface

6.3 GINA

The following diagram outlines the basic interaction between the software subsystems.

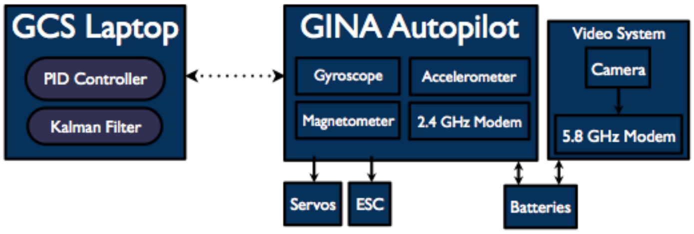


Figure 16: GINA Software Subsystem

6.3.1 Firmware

The Firmware consists of implementations for all of the device drivers, low level communication protocols, pwm generation, and communication from the MSP430 to the Atmel RF chip. Many of the drivers already existed for communication over I2C with the gyro, accelerometer, and magnetometer. However, code was developed to enable pwm output to both the servos and the speed controllers. In addition the code for sending packets over the Atmel RF chip needed to be modified to support our ground control station.

6.3.2 Groundstation

The groundstation was developed from the ground up and is designed specifically for use with the GINA autopilot system.

The ground station consists of a main window composed of three panels: pid control, servo control, and graphs. The Pid controls tab allows the user to modify the proportional, integral, and derivative gains as well as adjust the gyro gains directly. The left side of the groundstation is where the user can interact with the gina thread that runs in the backround. This thread is responsible for directly communicating with the gina hardware and passes all the information back to the gui through a thread safe queue. Another thread safe queue is used to send the commands from the groundstation gui to the gina hardware.

6.3.3 Threading

Threading is a critical component in the design of the groundstation. The main thread is the gui thread. This is launched when the user runs the groundstation.py file. The gina.py thread is a worker thread that is in constant communication with the gina hardware. The final thread that is executed is the rc thread. This is used to keep communication with the rc controller connected over USB.

7 Analysis

Here we discuss the considerations we've had to make about certain system-level concerns. Details have sometimes been addressed in other sections of this report, but we will summarize them here.

7.1 Control Loop Delay and Stabilization

While the Lisa/M's on-board microcontroller can compute control information almost as quickly as the sensors can be read, the distributed computing architecture of the GINA platform required us to consider the effect of communications delay on its control loop in order to ensure that it will not cause instabilities. After consulting with our mentor, Dr. Sprinkle, we developed a target loop rate of 50Hz, providing a control loop delay (delay from sensor reading to servo response) of 20-25ms. In order to meet this requirement, we had to separate GINA's attitude control loops into two parts: the original, Kalman filtered, state-based PID controllers for overall maneuvers, and a set of much faster gyro-stabilization control loops which counteract high-frequency transients before they can destabilize the airframe. The gyro-stabilization loops act directly on the raw gyro sensor readings transmitted from GINA, allowing them to bypass the propagation delay through the Kalman filter. Our stabilized hover tests showed that these gyro control loops were the key to stabilizing the airframe.

7.2 Battery

The batteries are outside of the scope of our work—they fell in the Aerospace team's domain. As such, we can't provide calculations of the battery life of either aircraft, but we have been given an estimate of 10-15 minutes depending on maneuvers.

7.3 IMU Accuracy and Drift

Both platforms are equipped with extended Kalman filters for state estimation, in order to improve precision and accuracy. The outdoor platform gets the full benefit, in that its accelerometers and gyroscopes will provide precise transient state information, while the GPS and magnetometer will serve to correct drift and maintain long-term accuracy of the state estimate. The indoor platform, without GPS or reliable magnetometer data, is more vulnerable to drift in state estimates, impacting its ability to operate fully autonomously. For this reason, the indoor aircraft is meant to operate under RC control. Future iterations may be able to implement sonic rangefinder or computer vision-based algorithms for determining location in order to counteract IMU drift.

8 Development Plan and Implementation

This section details our development plan from the CDR, and how the implementation of each portion occurred in practice.

8.1 Familiarize with GINA and Paparazzi

This was a simple but crucial step in the build. We were to connect the GINA and Lisa/M autopilot boards to the programmers, laptops, and other electronics and ensure that they respond as anticipated to external commands and programs. This step was to be complete when the programmers and boards interface correctly with the ground stations.

Implementation This step was implemented as planned and on-schedule—but it was during this implementation that we realized the incompatibility between the latest GINA hardware and the existing software/firmware.

8.2 Control System Development

We had originally hoped to have a numerical model for the aircraft for use in MATLAB, which would allow us to develop simulations for design and verification of control systems.

Implementation The technical difficulties on the outdoor airframe, combined with the change of scope on the indoor airframe, reduced the priority of this stage of development. Our control systems design work focused on stabilizing the indoor airframe. To this end, we found developed a two-layered control system for the GINA autopilot. The first layer of control is a negative feedback loop based on the raw gyro data from the GINA IMU, which actuates the servos to counteract high-frequency perturbations in the aircraft attitude. This control system proved capable of stabilizing the airframe in hover, allowing for a second layer of control based on PID error minimization with the Kalman state and RC control.

8.3 Paparazzi GPS Implementation

The outdoor frame is controlled by the Paparazzi and must be capable of waypoint navigation via GPS. In order to implement this the GPS was implemented before integration into an airframe, and simulations were run to ensure that the controller responds as expected and converges to the given path. This step would be complete when the GPS can be accessed through the autopilot and the autopilot can determine its coordinates.

Implementation The technical issues surrounding the outdoor airframe prohibited a full-system test with GPS, but the GPS subsystem was thoroughly tested independently, and found to meet our specifications. This more-or-less assures that it will integrate with Paparazzi without incident, due to the modular design of Paparazzi's peripheral usage.

8.4 Paparazzi Implementation

The Lisa/M board was to be the first implemented as it is the more powerful of the two systems. The board would be connected to the airframe, servos, and speed controllers and rigorously tested to insure that commands deflect the desired control surfaces by the correct amount. At this point specialized programming for this year's competition tasks would be possible as IMAV will publish this year's requirements. This step would be complete when the Paparazzi board is successfully incorporated into the 11" airframe.

Implementation The above-described test was carried out successfully, but vibration noise issues arose when the motor was throttled up. We were unable to overcome the vibration issues, and so further design of competition task maneuvers was impossible.

8.5 GINA Implementation

The GINA board was to be implemented second as a simpler case of the Lisa/M board, and then tested in the same manner. This board was the more sensitive of the two to sample rates and latency as it has minimal on board processing. Instead it streams data to a ground station which processes the data and sends the appropriate control responses. Thus this latency depends on the ground station as well and would have to be tested with both systems in conjunction. We anticipated that if the response time is significantly less than the time the aircraft takes to change attitude by 30o at maximum maneuvering the latency will not be an issue. If it was close to, or greater than this value further testing and adjustments to the ground station would be required to reduce this time. However, if the aircraft is statically stable and dynamically neutral or stable this would not be a problem. This step would be complete when the GINA is successfully implemented into the 8“ airframe and it is confirmed that the ground station can respond quickly enough to maintain dynamic stability.

Implementation After discussion with one of our sponsors, we set a 50Hz control loop rate as our target. After a significant amount of optimization and multithreading, we were able to hit this target update rate, providing a 20-25ms delay between sensor reading and servo response. Hover testing showed that this architecture was sufficient to stabilize the aircraft.

8.6 Camera Development

The camera support was to be developed simultaneously for both systems. The camera needed to be connected to the transmitter and settings optimized to insure sufficient resolution and frame rates to identify obstacles and targets in real time. This step would be complete when the ground stations can see the video feed live from the airframes.

Implementation The camera subsystem was developed and tested in parallel with initial implementations of the autopilots. It was tested and found to meet our performance requirements.

8.7 Modem Integration - Paparazzi

The modem would be integrated with the Paparazzi as a final step before flight testing to allow remote access from range. This would require in lab confirmation that it relays signals reliably before flight testing. This step would be complete when the Paparazzi can be accessed remotely via the modem attached to the airframe.

Implementation This subsystem was implemented and tested, although the outdoor aircraft was never able to flight test.

8.8 Flight Testing

The final stage would be confirmation of all systems flight capability by performing competition tasks. These tests would be conducted with a skilled RC pilot to intervene in case of catastrophic failure in order to avoid damage to the airframe and electrical components. This would be an iterative process where the pilot would give feedback to the design team and adjustments will be implemented as needed. This step wouldbe complete when the pilot can control the aircraft easily and the aircraft can complete competition tasks with the required amount of human interaction.

Implementation The outdoor (Paparazzi-based) platform was grounded by noise issues due to efficient vibration coupling of the IMU to the motor through the airframe skin. As a result, the outdoor airframe was not able to fly. The indoor (GINA-based) platform was tested in a hover configuration and found to be stable, but the motor could not produce enough thrust to maintain altitude with a two-cell battery. A three-cell battery would burn out the motor, so the indoor airframe was not extensively tested in flight.

9 Requirements Review

9.1 Functional Requirements

Reqt	Description	Priority	Status
1	Indoor MAV will be able to execute all indoor competition tasks via stabilized flight	Must	Met by GINA with more powerful motor
2	Indoor MAV will be able to execute all indoor competition tasks fully autonomously	Desired	Not met
3	Outdoor MAV will be able to execute all outdoor competition tasks via stabilized flight	Must	Prohibited by vibration issues
4	Outdoor MAV will be able to execute all outdoor competition tasks via fully autonomously	Desired	Not met
5	Outdoor MAV will be capable of executing flight plans fully autonomously	Must	Prohibited by vibration issues
6	Both MAVs will establish a wireless communication line to the ground control station and update	Must	Met by XBee Modem and GINA
7	Outdoor MAV will be able to modify and accept new flight plans wirelessly	Must	Met by Lisa/M

Table 1: Functional Requirement Review

9.2 Technology Requirements

Reqt	Description	Priority	Status
100	Indoor MAV will use GINA autopilot	Must	Met
101	Outdoor MAV will use Lisa/M autopilot	Must	Met
102	Both MAVs will perform attitude estimation via an inertial measurement unit	Must	Met by Lisa/M and GINA
103	Outdoor MAV will utilize GPS for additional attitude, altitude, and velocity estimation	Must	Met by UBlox GPS
104	Outdoor MAV will utilize barometer for additional altitude estimation	Desired	Not met
105	Both MAVs will be capable of streaming a live video feed to the ground control station	Must	Met by KX-1 camera and modem

Table 2: Technology Requirement Review

9.3 Performance Requirements

Reqt	Description	Priority	Status
200	Flight of both MAVs will be able to be terminated via a kill switch as a safety measure	Must	Met
201	Both MAVs will be able to land in a target with diameter of 5 meters	Desired	Untested, likely met by GINA
202	Both MAVs will be able to fly within a closed area of 1 meter by 1 meter	Desired	Untested, likely met by GINA
203	Both MAVs will be able to take off via an operator	Must	Untested, likely met by GINA
204	Outdoor MAV will be able to take off fully autonomously	Desired	Unmet
205	Both MAVs will be able to traverse an obstacle filled area and recognize targets via an operator	Must	Untested, likely met by GINA
206	Outdoor MAV will be able to traverse an obstacle filled area and recognize targets fully autonomously	Desired	Unmet
207	Both MAVs will be able to drop an item via an operator	Must	Unavailable in mechanical design
208	Outdoor MAV will be able to drop an item fully autonomously	Desired	Unmet
209	Both MAVs will be able to perform an endurance test via an operator	Must	Untested, likely met by GINA
210	Outdoor MAV will be able to perform an endurance test fully autonomously	Desired	Unmet
211	Indoor MAV will be able to perform a performance test within a specific time period via an operator	Must	Untested

Table 3: Performance Requirement Review

10 Acceptance Test Plan

There will be two levels of testing essential to the success of the aircraft: component-level and system-level. Individual components will be tested for correct operation, and then the control systems as a whole will have to be able to complete all competition tasks.

10.1 Component Level Tests

All of the component tests are largely procedural—a failed test is likely indicative of either a damaged or misused component, and the consequences of either are minimal compared to the consequences of failing the system tests (new part must be ordered or wiring must be checked).

GPS Module The GPS module will be mounted in the outdoor platform, powered by the aircraft's power source. We will check that the module is able to get a cold fix in less than a minute in clear skies, and update precise location and velocity data (within the expected error margins).
Result: The GPS module met the cold-fix and error margin performance requirements.

Modem The modem will be tested to ensure that it can transmit to the ground station with sufficient bandwidth to carry all of the run-time data (video stream + telemetry) with some headroom. This test will reflect expected operating conditions (at distance and mostly-clear line of sight).
Result: The modem was not tested under full load, but was tested found to be able to transmit video stream.

Camera The camera should provide a video output to the modem when connected to the aircraft's power supply.
Result: The camera was tested in the laboratory with the video stream viewed on a monitor, and found to meet our requirements.

RC Receiver The RC module should correctly transmit operator commands (throttle up, steer) to the appropriate servos and motors.
Result: The RC module was tested by operating the Lisa/M airframe on a testbench, and control surfaces were observed reacting correctly to RC commands.

Servos The servos should respond appropriately to low level commands, such as bank and pitch.
Result: Some servos were unresponsive, but were replaced with working servos. In other cases, the polarity of control outputs needed to be reversed. After these changes, all servos met the requirements.

10.2 System Level Tests

System level tests were to center on the control systems and the autopilot's ability to guide the plane through various maneuvers necessary for the IMAV 2012 competition. Due to the technical difficulties that arose, only simple system level tests were conducted on each airframe:

Paparazzi The Paparazzi airframe was grounded due to vibration coupling with the motor. However, we were able to verify the IMU attitude tracking and correct control surface response with zero throttle. Also, extensive simulations were conducted to test the effectiveness of the control systems in tracking commands.

GINA GINA was tested in a hovering configuration and found to be dynamically stable. Due to the underpowered motor, we were unable to test maneuvers or PID control.

11 Closure

All of the components are now integrated, functional, and respond correctly. There have been no significant component changes since the Midsemester Update as the GINA platform now provides stabilized flight sending commands at about 50 Hz. Originally there was some concern about the feasibility of employing GINA but the system was rebuilt from the ground up. There are now two layers of controls. The first layer is a simple derivative controller that helps the pilot maintain control. The second layer is a 6 degree of freedom proportional integral derivative controller.

LISA functions correctly in both 5 and 6 degree of freedom models. Upon implementation into the larger airframe flight testing began and significant issues arose. The motor created large enough vibrations that the AHRS reported rotation in each dimension of up to 45 degrees. This meant that the plane was virtually unusable as the autopilot thought the stationary plane was oscillating wildly. The group sought to overcome this by a combination of mechanical damping and electronic filtering. However the combination never fixed the gyro drift. The autopilot was then tested on a larger airframe and functioned correctly. The greater mass and absorption of this glider dampened the vibrations to the point that they were no longer a concern. This implies that prior to competition some changes will have to be made to the structure of the airframe and the electronic filtering to determine whether it is possible to use the existing set-up. If it is not possible the Micro Air Vehicle will need to prepare a different platform for the outdoor competition. The club already has some Zagi flying wings and could easily and quickly alter one for participation in the competition if required. The team has already created significant documentation to aid in replicating and understanding the work performed during the last year. This will also be valuable should there be a follow on group to attempt to add additional features such as computer vision or sonar to either of the flight systems. As of this date the autopilots and accompanying electronics are prepared for participation in the International Micro Air Vehicle Competition 2012.

References

[1] Adrian Frank. Hover, transition, and level flight control design for a single-propeller indoor airplane, 2007.

[2] R.F. Stengel, J.R. Broussard, and P.W. Berry. Digital controllers for vtol aircraft. *Aerospace and Electronic Systems, IEEE Transactions on*, AES-14(1):54 –63, jan. 1978.

A Budget and Suppliers

A.1 Budget

The budget for this project is \$3,000 (USD).

A.2 Bill of Materials

A.2.1 Indoor Platform

	Component	**Cost**
Autopilot	Warpwing GINA	\$300.00
IMU	Integrated	N/A
Modem (2)	Integrated/Included	N/A
Camera	RangeVideo KX-1	\$50.00
Video Modem	5.8 GHz Transmitter	\$20.00
Video Receiver	5.8 GHz Receiver	\$35.00
	Total	\$405.00

A.2.2 Outdoor Platform

	Component	**Cost**
Autopilot	Paparazzi Lisa/M v2.0	\$150.00
IMU	Aspirin v2.1	\$100.00
GPS	uBlox MAX-6Q	\$69.99
Modem (2)	XBee PRO-900	\$78.00
Camera	RangeVideo KX-1	\$50.00
Video Modem	5.8 GHz Transmitter	\$20.00
Video Receiver	5.8 GHz Receiver	\$35.00
Miscellaneous	CP2102 USB-to-Serial Converter	\$21.95
	Total	\$524.94

B Project Management

The team has was able to stay on track throughout most of the project. The Lisa/M system was on track for all deliverables; however, the development for GINA took some unexpected turns throughout the project. The scope of the project initially turned out to be far to aggressive and had to be scaled back as essentially no code had been written fro the GINA system prior to us starting the project. At the start of GINA development, it was non-functional with no way to even communicate with the basestation computer. The project scope as approved by our sponsors as well as the project deadlines and milestones were changed to allow the necessary time to build an autopilot system from the ground up.

B.1 Schedule Status (Gantt Chart)

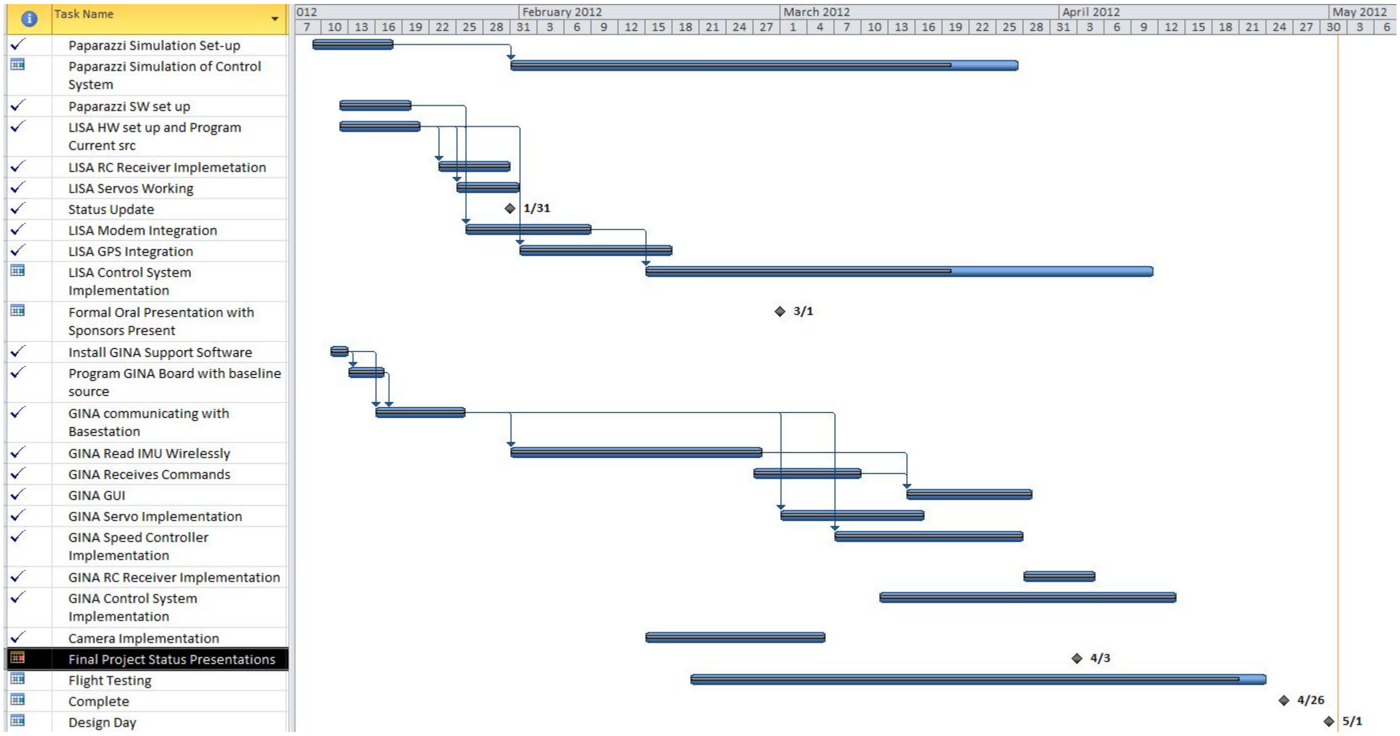


Figure 17: Project Management - Gantt Chart

The major deliverables are listed as tasks in the chart above.

B.2 Resource Allocation

Chris worked mainly on Lisa/M platform. Jared ran simulations of the control algorithms used for the airframes. Daniel and Kyle worked on the GINA Platform.

C List of Acronyms

AUTO1: Stabilized, semi-autonomous flight/fly by wire
AUTO2: Fully-autonomous flight
DC: Direct current
GCS: Ground Control Station
GINA: Guidance and Inertial Navigation Assistant (Autopilot)
GPS: Global Positioning System
IMAV: International Micro Air Vehicle Competition
IMU: Inertial Measurement Unit
IR: Infrared sensor
Lisa: Lost Illusions Serendipitous Autopilot
Lisa/M: A Lisa design focusing on cost and simplicity.

MAV: Micro Air/Aerial Vehicle
RC: Radio/Remote Control

D Roles and Responsibilities

D.1 Chris Wozny

Chris was the team leader and also worked on integrating components with the Lisa/M Autopilot system.

D.2 Daniel Schucker

I was resposible for the software design and devlopment for GINA. I Designed the Ground Control Station that was resposible for interacting with the GINA hardware. In the ground control station, I developed capabilities for the user to start communication with a GINA Board, end the communication when the mission is over and the aircraft has landed. I also developed a telemetry systems to be able display pertinent information to the user in the form of both data and graphical output. In addition to developing the groundstation software, I also developed additions to the firmware code. The firmware code had to be able to communicate with all of the sensors internally on the board, communicate with the ground control station via an RF chip and antenna, and also output Pulse Width Modulation signals to the servos and the speed controllers. While there was already a good amount of firmware code in place, a few of the files needed to be adapted for our use and the pwm file needed to be rewritten altogether. So one of my tasks was to get pwm working for the servos and speed controllers. Finally, I assisted with any device driver related problems relating to the ground control station basestation mote.

D.3 Jared Hainsworth

This project was somewhat out of my normal realm of experience and so was a great opportunity to learn more about the basics of control loops and filtering. In the first semester we focused on report writing and component selection. During this time we were each assigned sections for each report and presentation. I generally addressed the introductions, history, scope of the project, and some of the expectred challenges in these reports. For component selection we were each assigned certain components and expected to do the trade study to be used in reports and presentations. I did this for the radio controllers, researching advantages of different frequencies and controllers. We went with these controllers until the second semester when we discoverd several complications. Firstly, the controllers I had picked were not legal in Germany as they used the 900 MHz band. They also appeared to interfere with the servos and made them jittery. Third we actually found smaller, better controllers in the lab than the cheap ones we had found the first semester. In later reports and presentations I also addressed something of the nature of autopilots in general and proportional derivative controllers (PIDs) in gneneral. This was a very good assignment for me as I had not yet taken a class in topic and had to learn fairly quickly the basics of control theory. During the second semester there was a much greater focus on programming and testing. GINA was covered by Kyle and Daniel so I was not involved beyond answering occasional questions about aircraft, what values probably were, and what outputs meant. Essentially I was the reference for aircraft stability and controls. I primarily focused on the paparazzi system with Chris though as it was written in C and relatively similar to the languages I had used previously like Java. I altered the configuration files to model a plane as close to ours as I could and then Chris helped me set up and run the Paparrazi simulations. We could then view the graphs we showed in presentations of the commands and subsequent responses of the aircraft that helped us tune the gains. I assisted Chris with the vibrations testing. He throttled and recorded data while I cut up and applied various density foams in different ways in an attempt to minimize the vibrations shown. We even went so far as checking the balance of the motor and rebalancing the prop. I also researched the JSBsim interface and worked on building a configuration file from the Solid Works models of the aircraft. This was a more complex and accurate simulation as it provided six degrees of freedom instead of the five offered by the Paparazzi simulator. JSBsim can also be ported into various simulators to allow you to fly the plane in a full radio controlled simulation mode similar to the capabilities of programs like X-Plane. Second semester, for the reports and presentations my responsibilities were essentially the same as the first semester. As we neared the end of the semester I was in charge of designing the poster. Chris also asked me to take over maintaining the Engineering Notebook. So I have been uploading records of our e-mails and exchanges to d2l. For the final presentation I was assigned to summaraize the overview, motivation, and simulation as that was my main focus during the second semester. This was a very good opportunity for me and I feel that I understand the requirements for a control system whether on an aircraft or elsewhere much better.

D.4 Kyle Merry

Kyle was responsible for control loop implementation on the GINA platform. He determined the sensor values being returned by GINA, and rescaled them into physical units (g's, deg/sec) corresponding to motions on the airframe. He set up a 6DOF Kalman Filter to produce reliable attitude state estimates from these values. Using these state estimates, he designed and implemented a PID control system which would allow the pilot to control the aircraft via RC. After finding that the Kalman filter added unacceptable propagation delay and couldn't stabilize the aircraft, he augmented with a secondary feedback control system based on the raw gyro sensor data, and verified that this was capable of stabilizing the aircraft. He also wrote the driver to use RC input from a Futaba T7CAP RC controller through USB, circumventing the need to put an RC reciever on the aircraft itself.