Implementation of Mechanical, Electrical, and Feedback Control Systems In Unmanned Aerial Vehicles

by

Derrick Tan

Submitted to the Department of Mechanical Engineering in Partial
Fulfillment of the Requirement for the Degree of

Bachelor of Science in Mechanical Engineering
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Abstract

The thesis objective was to design an unmanned aerial vehicle that was capable of stable, autonomous flight. A fixed wing aircraft was chosen to simplify some of the flight characteristics and avoid some of the challenges found in rotary wing machines. Two aircraft were tested: a large and heavy gasoline powered aircraft and a smaller and much lighter electric powered sailplane. An autopilot was implemented into both platforms that would fly the aircraft and allow the measurement of flight vehicle characteristics. A link with the vehicle was created by installing a radio modem that allowed communication between the autopilot and a ground computer. This allowed updates to the controllers PID feedback loops to change flight characteristics and made the recording of flight parameters possible. This would be useful later in the analysis of data. To control the vehicle remotely, a ground computer was used that ran systems monitoring software. It also allowed the programming of flight plans to the autopilot. Combining these systems together proved successful and stable flight was achieved in both aircraft. By using the same autopilot in both vehicles, it was proven that the electronic system could be modular and transplanted between various vehicles.

Thesis Supervisor: David Trumper
Title: Professor, Department of Mechanical Engineering

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In addition, I would like to recognize the MIT Unmanned Aerial Vehicle Team for giving me a basis in UAV design and helping me bring my excitement for flight, mechanics and electronics together.

Of all the thanks I have to give, the greatest acknowledgement I have is to God who has given me the many opportunities to learn and grow. He has given me the wonderful opportunity of studying at the Massachusetts Institute of Technology and has blessed me in all ways imaginable.

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Contents

List of Figures

Chapter 1

Introduction

Fully autonomous flight without human input has been a challenge engineers have been working on for many years. Aircraft including airplanes and helicopters capable of autonomy fly completely under computer control where only high level commands such as "takeoff", "land", and "fly to point X" are input. We shall refer to these autonomous aircraft as UAVs or unmanned aerial vehicles in the next few chapters. To fly these aircraft, the operator is only required to give the aircraft a flight altitude and destination while the aircraft takes care of the rest. As can be imagined, there is a lot that flight computers do in order to accomplish these seemingly simple tasks since environmental conditions such as wind and obstacle avoidance must be taken into account.

Flight in itself is tricky as the orientation and speed of the aircraft relative to the oncoming air stream determines if the aircraft ascends, descends, or turns. Thus the computer must know exactly how the aircraft is moving through the air in order to control the desired direction of movement. Another aspect to take into account is the fact that physical limitations such as the structural integrity of the airframe determine just how fast or how much stress the aircraft can take before structural failure occurs. Thus there are optimal airspeeds to maintain altitude, ascend at a particular rate, or descend at another rate. With so much to do in constantly changing environments, the computer must take in data that helps it to decide just what it has to do to accomplish its task.

Exactly how the plane banks to make a turn, or how much control input the computer gives to accomplish its task determines just how well the aircraft flies. The quality of flight can be measured by how efficiently the aircraft accomplishes its task time wise or how well it achieves its goals without stressing the airframe. The best of both cases is desired.

1.1 Background

The goal of accomplishing unmanned, computer controlled flight has made itself a desirable problem to solve. Technology has allowed aircraft to fly higher, faster, and more efficiently than ever thought possible and now a new limitation has made itself known. The human body is incapable of withstanding high gravitational forces or the extreme conditions aircraft oftentimes fly in. Up in the atmosphere, the air is thin and contains little oxygen. It is also extremely cold with temperatures falling as low as -70 degrees Celsius at operating height. These two factors combined make it impossible for a human to survive without some type of life-support system. This adds to the complexity and cost that must be built into any human controlled aircraft.

With the advent of computer technology, planes have proven capable of flying remotely with manual controls at a ground station. This has partially solved the problem by taking the operator out of the aircraft but does not solve the problem that human error is the greatest cause of all flying related accidents. 80% of all accidents are caused because of human error in some form and more than 50% of this error is caused by pilots flying the aircraft. If the right computer controls were implemented, more than 40% of all accidents could be avoided by taking human error out of the picture.

Another advantage of autonomous aircraft is the fact that once they are commanded what to do, the operator no longer has to worry about the details of flight since the computer now handles the situation. This could be very useful to the scientific community in projects that require long flight times or involves flying great distances. Since these flights could be completely controlled by computer, an operator could assign the aircraft to whatever job is required and let the aircraft do the rest of the work. In this way, the operator would be freed to work on more important problems that deserved his attention.

Not only a valuable resource to the scientific community, autonomous aircraft could also be used to save lives on the battlefield. Instead of risking the lives of men in manned reconnaissance aircraft, autonomous vehicles could instead be used to scout out dangerous areas. If the aircraft is shot down, no life would be lost. In another situation, search and rescue oftentimes requires large areas of land to be scanned for people and an autonomous vehicle could do this job around the clock. This could save precious hours that could mean life and death to someone. With all these advantages to computer controlled aircraft, there is no wonder why people have great interest in working on this problem.

1.2 Thesis Objective

This design project outlines the implementation of systems needed to create a fixed wing aircraft capable of flying programmed flight plans to Global Positioning System (GPS) coordinates on its own. The end aircraft should be capable of transitioning between manual pilot and autopilot control so it can be tested safely if the onboard computer crashes or the control settings are not correctly matched to the aircraft parameters. Having a computer fly an aircraft infers that no matter what situation or attitude the plane is in, the computer must know what to do. If the airplane is in a dive, it must know to pull up in order to avoid over speed and sheering of the wings. If it is at a high pitch, it must know to push the nose down and increase the power output of the engine or a stall could occur. In a turn, the airplane must know what bank angle to roll to and what rudder angle to use so sideslip is reduced as much as possible.

In order for the aircraft to accomplish all these things, many sensors and inputs are needed that give the computer enough information about its environment to make decisions. Air pressure indicators for measuring airspeed, gyros for orientation relative to ground, GPS for position, voltage indicators for onboard power, and sonar to sense close proximity with the ground are all needed to make the airplane fly. And even with these inputs, the airplane must know what to do with each piece of information. The airplane must consider each input and decide its importance in order to choose what it has to do to accomplish its objective. Once the airplane is capable of decision, it can then be called a completely autonomous aircraft. It is the challenge of successfully designing and implementing together all electrical, mechanical, and feedback systems required for flight that this design project aims to achieve.

1.3 Thesis Organization

In the following chapters I will discuss the steps I took towards fulfillment of my thesis objective. In Chapter 2, I will explain the reason for selection of a fixed wing aircraft as the airframe for basing this research. In Chapter 3, I will discuss two aircraft I built and modified. In Chapter 4, I will describe the electronics, software, and computers used for this project including the autopilot and ground control station. Chapter 5 will discuss methods used for flight testing. Finally, in Chapter 6, I will summarize my accomplishments and discuss the future for work on this project and other autonomous aircraft.

Chapter 2

Selection of Aircraft Type

After comparing various types of flying machines, the fixed wing aircraft was selected as the base from which stable flight would be achieved from. Although there are many other types of aircraft, fixed wing was the most appropriate choice for this thesis project.

2.1 Description

A fixed wing aircraft is what most people are familiar with as they include all the most common commercial air transportation aircraft in use today. In the most basic case, fixed wing airplanes use ailerons located on their wings to roll the airplane, a rudder on the vertical stabilizer to yaw the plane, and elevators on the horizontal stabilizer to pitch the plane. The wing provides a lifting force to the vehicle which results in drag so an engine provides thrust and power to counteract this force. In this fashion, an airplane is able to manipulate its attitude and vary its speed to accomplish flight.

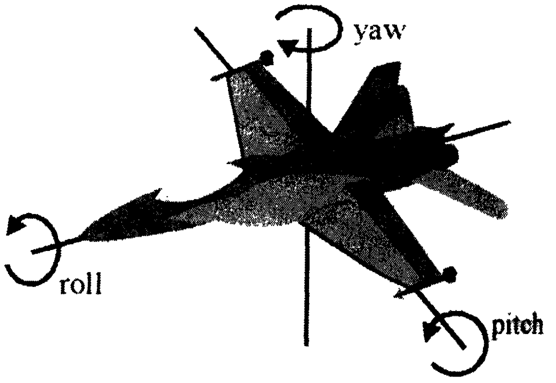


Figure 2.1: Pitch, Yaw, and Roll Axis

Because the effects of different control surface movement are almost entirely constrained to their relative axis, creating a control system is simplified greatly. Fixed wing aircraft will be compared to rotary wing aircraft in the next section.

2.2 Advantages

Fixed wing aircraft have many advantages in this particular research study. The end goal is to create an aircraft that demonstrates autonomous flight. This could be done with any type of flying machine however the possibility of using this device and research in future scientific and military applications is another goal. Although rotary wing aircraft are capable of achieving autonomous flight, they sacrifice the flight duration, simplicity, and low cost that a fixed wing aircraft has to offer. Because of their simplicity mechanically, fixed wing aircraft are able to be manufactured smaller and for a lower price which make this means of flight quite attractive. Most real world applications in industry value these characteristics more than adding the hovering benefit of helicopters. Aerodynamically, airplanes can also be made inherently stable meaning neutral control inputs would result in a stable glide which means less risk of a bad crash. Helicopters and any other hovering type of aircraft face the dilemma of always being in an unstable state in need of correction to remain dynamically stable. For these reasons a fixed wing aircraft was chosen.

Chapter 3

Aircraft Design

Two aircraft were used for testing with the autopilot that represented very different kinds of machines. It was desired to prove that no matter what airplane the autopilot was placed in, parameters for the feedback loops could be changed to adapt to the airframe. The first aircraft tested was a large gasoline powered aircraft that was unfortunately lost in shipping in May however a good amount of testing had been done with the machine before the loss. The second aircraft was a smaller and much lighter electric sailplane. In the end, it was shown that no matter what aircraft was chosen, autonomy could be achieved.

3.1 Kangke Monocoupe 90A

3.1.1 Design Parameters

In choosing the airframe for the first unmanned aerial vehicle, many requirements had to be met. The goal was set forth that the aircraft had to be capable of taking real time video during flight to allow a reliable way of monitoring the attitude of the aircraft separate from any other electronics. To further complicate the problem, it was desired that flight be made very stable and vibration free so that images taken by the camera would be accurate enough to identify targets and thus their GPS positions to make this UAV a very functional reconnaissance aircraft. These requirements meant that the aircraft would need to fly smoothly and slow enough to take accurate image data yet fast enough to cover distance at a decent rate. To be a useful tool to customers such as the scientific community and military, the aircraft would also need to have good flight duration, range, and lifting capabilities that would allow a useful payload to be accommodated. The ability for short takeoffs and landings for small fields was also a priority.

With these requirements, the Kangke Monocoupe was selected as the best aircraft for the intended application. It is a ¼ scale model of a 1930s aircraft called the Monocoupe 90A.

Figure 3.1: The Monocoupe 90A UAV

The model aircraft has a 98 inch wingspan with a wide chord giving it the capability for lifting large loads. With so much wing area, the wing loading is low enough to allow for very low speed landings and takeoffs which satisfy one of the requirements. This particular model also offers an interior with enough volume for a sizeable payload. With such a large aircraft, there would be no problems in carrying all the present and future avionics and camera equipment. A high winged aircraft, the Monocoupe is also inherently stable.

3.1.2 Calculated Stress Modeling and Bench Level Analysis

Because the Monocoupe would be carrying much more weight than the original design was intended for, analysis was done on the actual airframe's structure to ensure it was strong enough to handle any kind of loads it would be subjected to. Modifications would later be made to account for any possible problems found in analysis.

The most important structure considered was the actual wing design as this would bear the load of the entire airplane. The wing is made mostly from high density balsa and basswood in a structure that seemed quite strong. The two wing halves and body are joined by a thick aluminum tube. Even though it seemed strong, calculations had to be done to ensure the integrity of the structure. Because of the wood structure, there would be a lot of deflection and bending under load relative to metals such as aluminum but as long as nothing fractured, the wing would fulfill all requirements. A safety factor of three times the normal load was used to account for possible stresses encountered during a flight. These stresses could be induced by bumpy wind conditions, poor autopilot control, or future desire of making the plane more responsive in turns.

The simplified case of this problem was the case of beam bending where a solid beam is supported at its ends, i.e. wing tips, with a weight being supported at its midpoint, i.e. fuselage and load of the plane. Knowing this, I measured the dimensions of the structure of the wing and found the centroid of the cross section where there is no stress. After this, I was able to calculate the moment of inertia of the wing which allowed the findings of stresses and strains in the wing structure. Because the exact modulus of elasticity of the wood was not known, only approximations could be made however calculations showed that the structure would be strong enough. I also calculated the radius of curvature as a function of bending moment and the expected deflections of the wings. As seen from figure 3.1, the wing is also supported by wing struts so the load bearing capacity of the full structure would be even stronger than what I calculated. This reassured me that the wing would be able to handle almost any kind of stress placed upon it.

To test my calculations, bench level experiments were done on the aircraft while on the ground. This would ensure that if failure did occur, I would not lose the expensive electronics in a crash. The airplane was supported purely by its wingtips and weight was added at the center until it was shown that the wing structure could bear the load. This verified my calculated findings and made me confident that the airplane would perform as expected. A second bench level experiment was done on the fuselage and landing gear of the aircraft to make sure they could take the stresses of ground handling well. All tests were passed.

3.1.3 Modifications to the Airframe

Modifications were made to increase the usable space within the airplane. The original design called for servos, engine ignition, and battery to be located within the main cabin but this severely reduced useful space. Instead, the servos that controlled the elevator and rudder were relocated to the farthest point back in the airplane as possible. This not only opened up space but also had the added plus of reducing the amount of play in the control surfaces. The original design also called for the ignition battery, ignition, and engine servo to be located behind the firewall in the main cabin but this also took up useful space. Again, modifications were made and all these components were relocated out of the main cabin and into spaces surrounding the engine. Relocation opened up significant amounts of space.

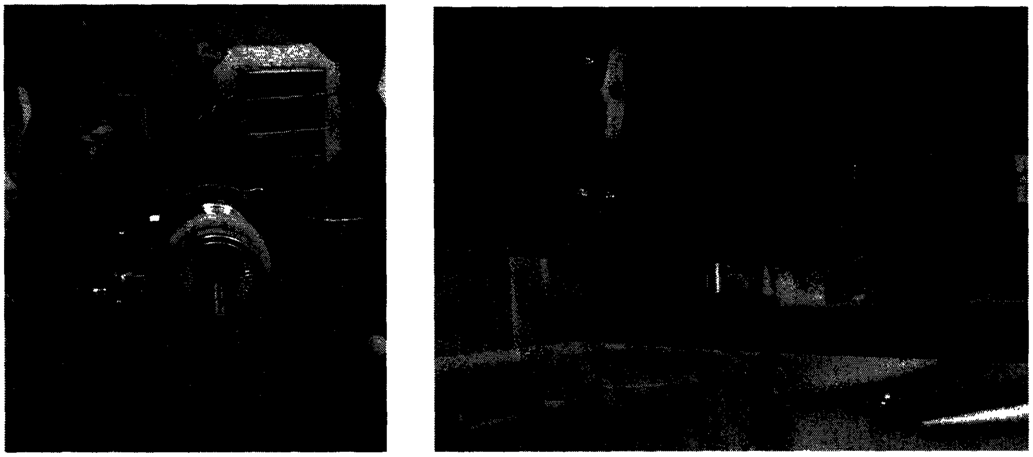


Figure 3.2: Engine and Servo Installation

The first power plant used on the Monocoupe was a 25.4cc Zenoah gasoline engine. It had sufficient power but needed to work harder than desired to pull the plane up to altitude. The plane, loaded with all the avionics, required more power.

Figure 3.3: Old Engine Replaced

Thus a second, larger engine replaced the Zenoah to deliver this power. A 39.4cc Brison engine was installed that not only weighed approximately the same as the smaller engine but output significantly more power. This engine allowed the plane to climb vertically and hover on engine thrust alone. With this setup, the plane flew with authority.

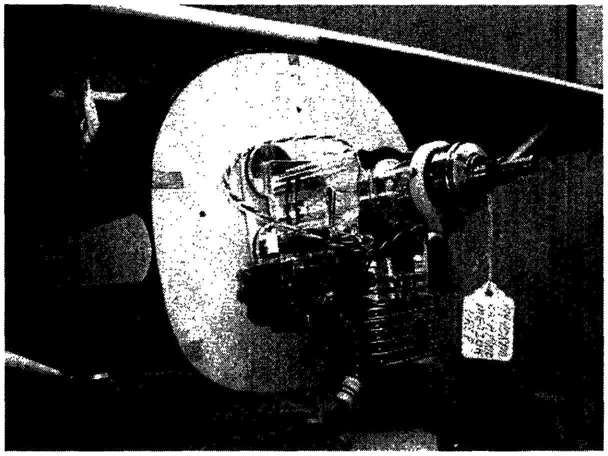


Figure 3.4: New Engine Installed

During flight tests for structural integrity, the Monocoupe's airframe was put through various aerobatic maneuvers and a problem not related to the airframe's strength was brought to attention. A minute after inverted flight, the engine would sputter and die. The immediate culprit was thought to be the fuel system as a new mounting technique had been used to save space. The system was composed of three gas tanks in series. Two 32 ounce tanks served as the main tanks and were mounted vertically while a small horizontal header tank was placed between these tanks and the engine.

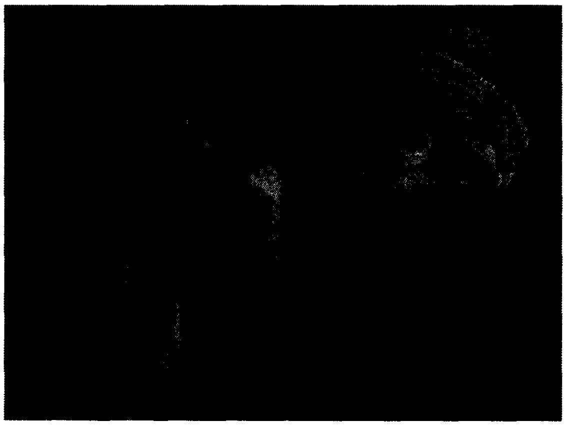


Figure 3.5: Gas Tank Installation

The header tank was used because it was thought that it would prevent the possibility of air bubbles entering the fuel line. It turned out that the tank only delayed the bubbles from reaching the engine and didn't eliminate the problem. Thus the header tank was removed and the two main tanks were remounted horizontally. This took up useful space but solved the problem and completely eliminated any engine failures.

Oftentimes, aircraft are designed for responsiveness to control input, but this comes at a cost of less stability. The Monocoupe was designed in this way so that initial flights unveiled a tendency for pitching oscillations. For the purpose of reconnaissance however, flight that is predictable and as stable as possible is desired. Thus it was determined that modifications to the original airframe design had to be made. The fuselage of the aircraft was lengthened by four inches and the stabilizer and rudder were enlarged by 50 percent to dampen any oscillations that existed. This moved the aerodynamic center rearward and farther behind the center of gravity of the aircraft making it more stable. Once flight tests commenced, all prior stability issues disappeared.

Figure 3.6: Fuselage Lengthening

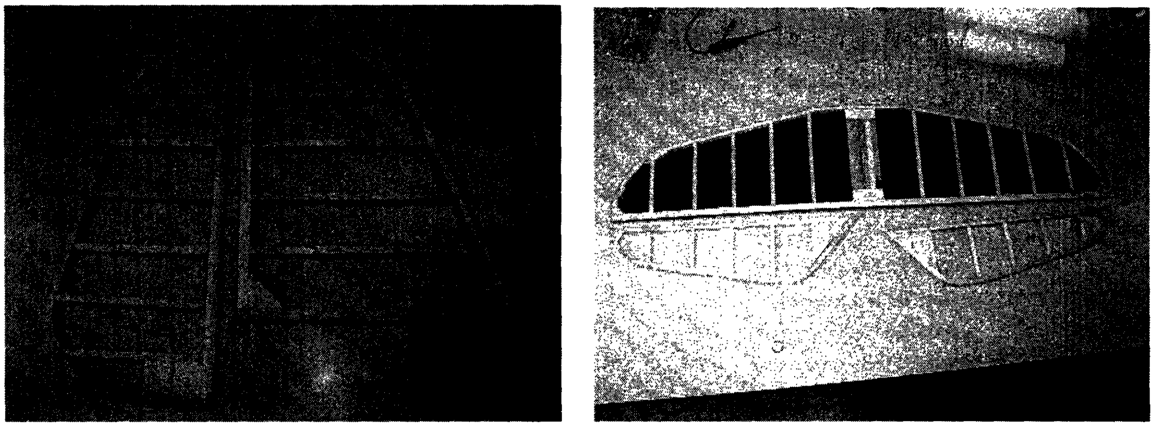


Figure 3.7: Larger Tail Surfaces

Testing revealed another weakness of the aircraft design. The airframe had been designed to fly at a lower weight but the current configuration held three times the fuel as well as electronic and video equipment. With all of this added weight, the landing gear bent on hard landings. Thus the gear was modified to accommodate the extra load. Struts with spring suspension were added to soften landing stresses and hold the weight of the plane.

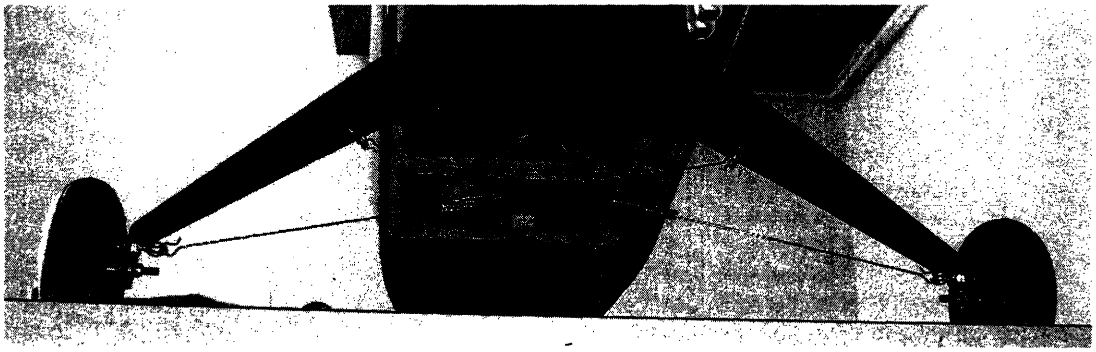


Figure 3.8: Landing Gear Suspension

Redundant controls were built into the aircraft just in case anything failed during flight. With two ailerons and two flaps, control would be maintained even if one failed. The elevator was split into two parts, each powered by a separate servo to ensure the elevator would still be functional if one servo died. Using redundant controls, the airplane was ensured to land safely in the event of a single mechanical failure.

3.1.4 End Performance

Overall, the aircraft design was completely successful as it achieved all goals set forth for it. The final airplane was very stable as inputting no control to the airplane results in straight and level flight. The gasoline engine gave the Monocoupe a cruising speed of 75 mph allowing crisp video while also allowing the UAV to cover significant distances in a timely manner. The powerful engine allowed the plane to takeoff within 10 feet while flaps allowed a slow landing speed and landing distance of 40 feet. The large fuel capacity gave the airplane a flying duration of 2 hours and range of 150 miles.

3.1.5 Conclusions

Many lessons were learned from the Monocoupe. With its eight and a half foot wingspan and powerful engine, the aircraft was able to lift a heavy payload without affecting the flight dynamics of the airplane much. This gave flexibility in the instrumentation and controls as weight was not a large concern. It also allowed the lifting of test equipment before the final autonomous aircraft was put together. In the commercial perspective, this plane was quite successful as it combined autonomy, a flexible payload with good flight duration and long range. For flight testing with the autopilot, this proved invaluable as testing could be done continuously without bringing the airplane back in for more fuel.

The strength of this aircraft was also its weakness however. The size of the plane meant that there were limited sites testing could be done at. A large plane needs a large field to fly from and the only field available was located one and a half hours south of Boston. This meant that testing could only be done on weekends as my class schedule would not allow the time needed for testing during weekdays. Weather did not cooperate during the winter and early spring months either so many testing days were scrapped due to rain and snow. Finally, the Monocoupe 90A needed significant modifications to fly stably and with the gasoline engine, the aircraft was high maintenance above all else.

3.2 Spirit Elite Sailplane

3.2.1 Design Parameters

With many lessons learned and after the Monocoupe had been lost in shipping, a second aircraft was selected to continue work. Because it had been difficult to find times to test the first airplane, it was decided that a smaller electric aircraft would be the next airframe used. This would allow testing at the fields of MIT since electric power is extremely quiet. The plane would also fly slower, thus requiring less space to fly in. Yet another benefit was the fact that some customers to the UAV market look specifically for aircraft that use clean electric power and are small enough to be hand launched. One concern with selection of the new aircraft however was the fact that electric aircraft have not been known to carry a significant payload or have long flight times. Batteries are heavy energy storage devices and gasoline by comparison contains significantly more energy per unit weight. With this in mind, it was decided that the new aircraft would have to fly extremely efficiently and thus a sailplane was the obvious choice. Sailplanes have been known as aircraft requiring the least amount of power to fly and are even capable of gaining altitude on rising currents of air known as thermals alone.

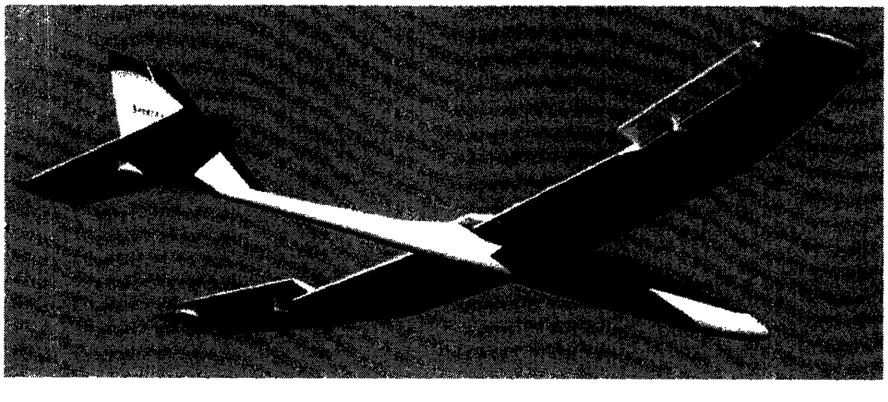


Figure 3.9: Spirit UAV

The Spirit Elite sailplane was chosen for its large wing area that would enable it to carry the required payload. It was also chosen because it had the required control surfaces for the autopilot to utilize. Many sailplanes rely on rudder/elevator/spoiler control surfaces in this size of aircraft but the Spirit had the needed ailerons and flaps that would allow the autopilot to fly most efficiently. With electric power, this plane would also be able to fly at local fields. The new found flexibility for testing made testing during weekdays possible. A smaller electric plane also meant it was much easier to transport with little to no maintenance required to keep the plane flight worthy.

3.2.2 Calculated Stress Modeling and Bench Level Analysis

With the Spirit sailplane, I took the same steps of verifying the structural integrity of the wing as were taken with the Monocoupe. The difference in wing design was significant but overall the calculations were similar. Again the wing was made from high density balsawood and basswood. The wing joiner was made from a solid steel rod. What makes a sailplane wing different from the average airplane's wing is that it has a high aspect ratio and a slim profile. This makes flight more efficient since it reduces drag however it also makes the strength of the wing a concern. With such a wide wing, a large moment is created at the center which wants to break the wing in half and the fact that the wing is thin only adds to the concern for possible structural failure. One comforting factor was the fact that the sailplane would not be carrying as much weight as the Monocoupe. Batteries would power the aircraft and thus there wouldn't be the half gallon of gasoline stressing the wing like the Monocoupe. I had also decided to remove some of the components of the electronics package the Monocoupe had been carrying from the Spirit's package. While the Monocoupe had used sonar and matching electronics to sense the ground, the Spirit would not have to do the same since it would never take off or land autonomously. Without landing gear, the Spirit was meant for hand launch and recovery. Also, the Spirit would not be carrying video equipment since only the minimum required electronics were wanted on this plane to reduce the weight. This meant that fewer and smaller batteries were needed to power the onboard electronics.

With all this in consideration, I was relieved to find that the load the wing was required to support was much less. During the calculation of strains and stresses, I used a load safety factor of two instead of the factor of three I had used on the Monocoupe. I did this because I knew the sailplane would be less responsive and thus there would be fewer chances of stressing the wings highly because of faulty control input. Like the Monocoupe calculations, I was able to simplify calculations by assuming this was a problem of beam bending. I took the cross section of the load bearing members and calculated their moments of inertia. With this I was able to then calculate the stresses and strains in the wing. From here, I could then calculate the radius of curvature due to bending and the final deflection of the entire wing. End calculations showed a surprisingly high amount of deflection but that could be explained by the high aspect ratio of the wing. Stresses and strains showed that the wing would be able to handle the load placed upon it.

A bench level experiment was done after calculation to verify findings. The wing was supported at its ends and a load placed at its midpoint. Though there was flex, it seemed that the wing would be able to hold. Of concern however was the fuselage boom that extended to the tail. The fiberglass material it was made of seemed brittle and the possibility of failure seemed quite possible with the stresses of landing with an added payload the sailplane was not designed for. Thus I resorted to strengthening it with a layer of carbon fiber and fiberglass cloth. This seemed to work well and I no longer worried about boom breakage.

3.2.3 Modifications to the Airframe

Modifications to the Spirit sailplane were not as extensive as they were on the Monocoupe as less was required. Overall the changes reflected increasing the strength of the aircraft while reducing the final weight.

Originally, the design called for heavy wood push-pull control rods for moving the tail control surfaces but this was unneeded material weight and actually posed other problems. With the extra weight in the tail, ballast weight had to be added to the nose of the aircraft to put the center of gravity of the plane in the correct location. To remedy this problem, I opted for a light carbon fiber push pull control method on the horizontal stabilizer which not only reduced the weight of the mechanics but also strengthened it.

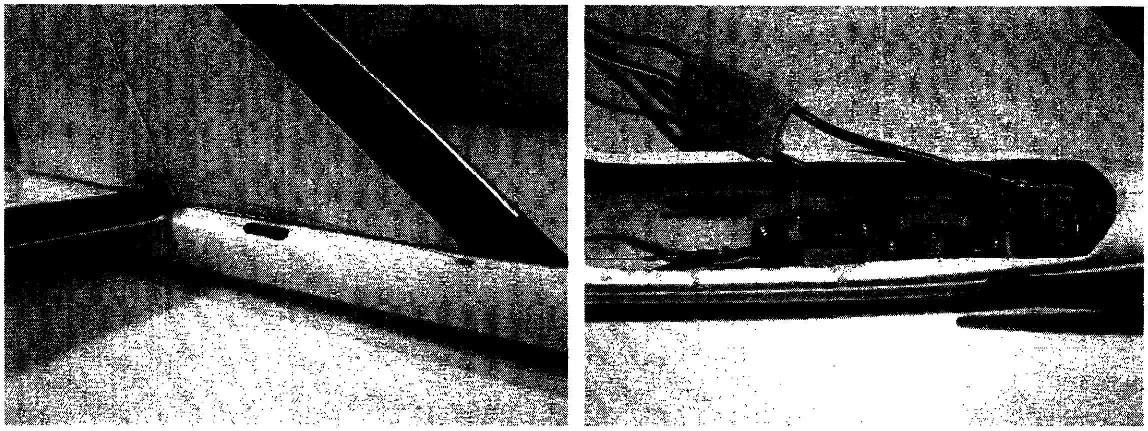
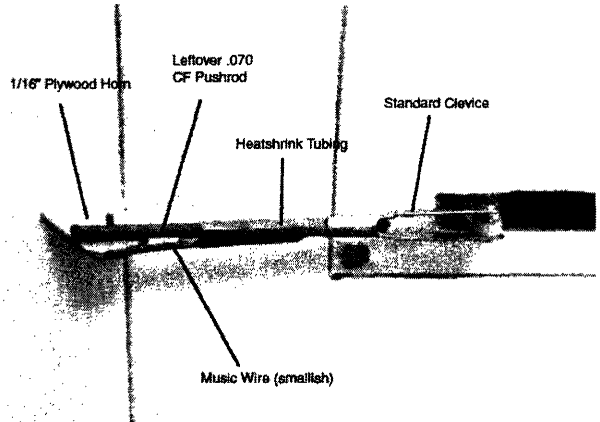


Figure 3.10: Pull-Pull Actuation Control Design

For the vertical stabilizer, I completed a pull-pull design that almost reduced the weight of parts to zero. How this works is strong and thin fishing line is used to pull the rudder in one direction and a matching line is used to pull the rudder in the other direction. A servo on the other end creates movement. Added weight is only that of the two lines and control horn. But taking away the original control horn and push-pull setup meant a significant reduction in weight. With this method I was able to balance the airplane without any ballast weight at the nose.



Note: Horn is hardened with thin CA as well as heatshrink, music wire and CF pushrod. Clevice is also attached with CA to CF rod.

Figure 3.11: Wing Push-Pull Control Rod Design

Similar modifications for lightening were added to the control rods of the wings. This had the added benefit of increasing the throw angles obtainable and was done by using carbon fiber rods and plywood control horns.

The most significant modification to the Spirit Elite was the addition of an electric power system. The original design was for a pure glider with no support for power. Thus I cut off the nose and created a firewall mount from plywood. This was fastened into place and created a sturdy support for the motor and gearbox which would later be installed. Research was done on optimal power systems for this size sailplane and the weight that had to be carried. A brushed motor system was selected that would provide 300 watts of power while being quite affordable in cost. Once the motor was received, it had to be modified since the gearbox would reverse the direction of rotation at the propeller. I took the motor apart and retimed it for the proper rotation direction and optimal efficiency. It had been previously calculated that the motor, gearbox, propeller setup would take 26.3 amps of current to run at full power. In an actual bench level test, it was found that 27.1 amps was the peak current and this verified the predictions I had for the system.

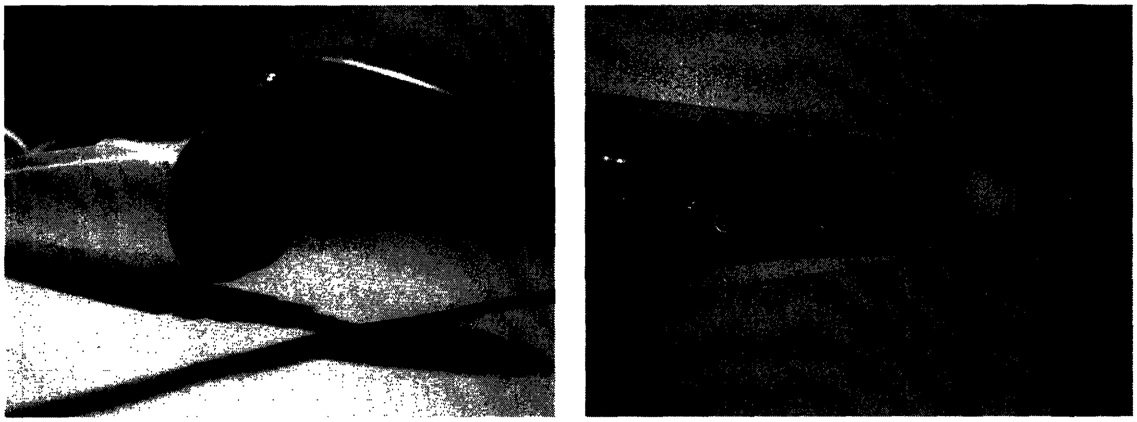


Figure 3.12: Power System Installation

To power the motor, a lithium polymer battery was selected as the best energy storage device. This chemistry battery is the highest energy and power density battery on the market which was very important for this application. At 11.1 volts and 4.2 Ah capacity, it weighed only nine ounces. It was also capable of supplying more than 63 amps of continuous current if needed. With this specification, I expected the voltage sag when under load to be low and thus efficiency would be high.

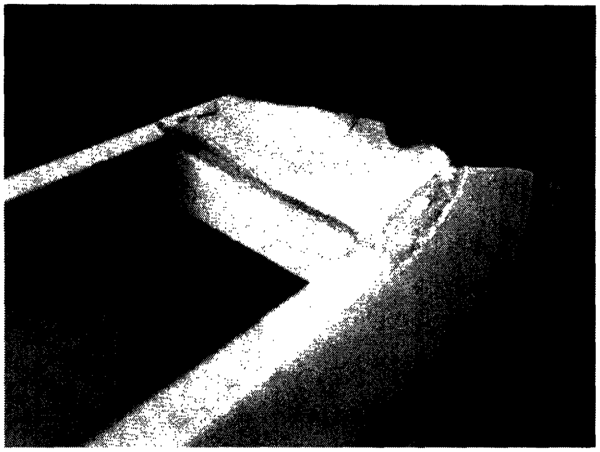


Figure 3.13: Wing Saddle Strengthening Modification

The last modification to the airframe came after much test flying. Unforeseen landing stresses had cracked the fiberglass of the wing saddle and thus strengthening was needed. Carbon fiber was added to the entire perimeter of the saddle and a basswood box was used to strengthen the area. Flight tests after this modification showed that the area was now strong enough and further breakage did not occur.

3.2.4 End Performance

The Spirit sailplane achieved the performance goals desired. With electric power and a slower airspeed I was able to test the aircraft at MIT's field without worries of disturbing people. The sailplane was extremely stable, more so than the Monocoupe and any type of disturbance to the aircraft's flight resulted in an immediate tendency to correct any error. Control response from the plane was slower as expected but adequate for autopilot control. Cruising speed fully loaded was approximately 35 mph and the glide slope was shallow. Takeoffs were more sedate compared to the Monocoupe as the Spirit was not over powered like the previous machine. Flaps allowed a slow controlled landing speed. The Spirit Elite did not have the flying duration the Monocoupe had however it was decent at a time of 20 minutes. Thermals could increase the flight times however. With these specifications, the range of the sailplane was approximately 10 miles.

3.2.5 Conclusions

The aspect of a smaller electric powered aircraft achieved a whole new set of goals. Little maintenance was needed to keep the sailplane in flying condition and portability allowed testing to be done even in small spaces. With an aircraft of this nature, testing could be done whenever time and weather allowed. A product like this would target customers that desire to have a UAV that can be hand launched and recovered quickly while requiring no knowledge of the complications that a gas engine aircraft bring into the picture.

Being a small aircraft however, the Spirit had a limited payload capacity and flight duration was relatively short. Battery packs could be changed quickly to resume flight but having to "refuel" the plane meant that the range of the aircraft was also limited. In the end, this vehicle proved to be a better airframe for testing as flights could be done on any given day weather allowing. This meant that studies on flight dynamics could be done more frequently and thoroughly.

Chapter 4

Electronics Design

Because systems design was a priority and the engineering of a complete autopilot from scratch was unfeasible, a commercial autopilot was chosen as the main electronic brain for the system. This would not be the only device needed to support an autonomous aircraft however as communications and ground stations would be needed to maintain safe control of the aircraft. Although a commercial autopilot was used, understanding of its components and other electronics design was used in this project to help me in work I am currently doing on creating a full autopilot from the ground up, a future implementation into the UAVs.

4.1 Autopilot

The requirement for the autopilot was quite simple in idea but complicated in actual capabilities. It had to be able to fly an aircraft with relative stability and accuracy so tests could be done and data taken. Flying stably however requires that the flight computer is able to sense its attitude relative to Earth in all three axis. This would determine the outputs of the control surfaces on the aircraft. Flying stably also meant that the aircraft would have to know its movement relative to the oncoming wind to prevent stall situations. Furthermore, to follow a programmed path, it would have to be able to track its movement from point to point. After contacting many commercial autopilot companies, the MP2028g board developed by Micropilot was decided upon because of size, weight, and cost. At ten centimeters by four centimeters and only 28 grams weight board alone, this autopilot was capable of achieving the autonomy I was looking for at this point. The small size also allowed flexibility in installation possibilities with the device. We shall refer to it as the autopilot or MP2028g interchangeably in the next few sections.

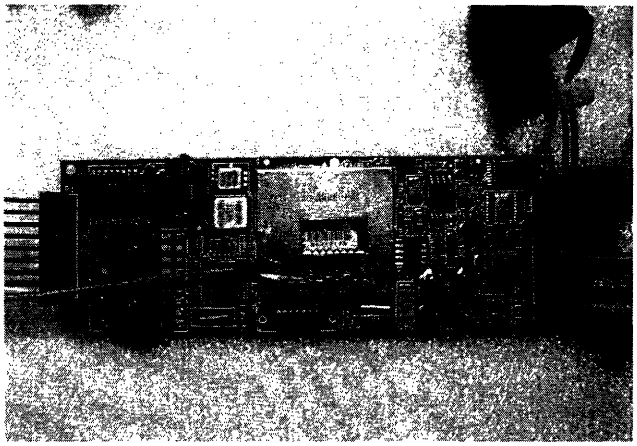


Figure 4.1: Micropilot MP2028g Autopilot

4.1.1 Sensors, Output, and Other Equipment

To sense the movement of the aircraft, the autopilot incorporated a set of gyros and accelerometers in all three axes. This would allow the computer to know if the airplane was banking, descending, or flying in all orientations possible. With this information, the computer would be able to know what outputs to the control surfaces would be needed in order to maintain the desired flight path. To sense airspeed, a static air pressure sensor and a second pressure sensor exposed to the forward wind speed combined were capable of giving accurate speed. This doubled as an altitude sensor as the difference in pressure from ground level to flight level allowed the computer to determine altitude to within a foot. A sonar sensor and electronic board were interfaced with the autopilot when installed in the Monocoupe to give finer measurements of altitude to within a centimeter. This served useful when flying close to the ground. Finally, to track position over the ground over time, a Global Positioning System (GPS) unit was implemented into the autopilot. With all the required sensors implemented into the system, the autopilot was able to fly the aircraft.

The MP2028g outputs its desired response via eight channels each devoted to separate controls such as ailerons, horizontal stabilizer, throttle, and rudder. Each channel supplies an analog pulse width modulation signal command which a mechanical servo motor interprets into mechanical movement. Because of the size of the Monocoupe UAV, seven of the channels were utilized for control as two servos each were needed for the ailerons, flaps, and elevator. The Spirit UAV only required five but the same functionality was accomplished.

Other additions to the airframes to allow functionality of the autopilot were the addition of pitot tubes for airspeed, sonar for ground elevation, and GPS antenna for ground location lock. Furthermore, supporting structures were built to secure the autopilot so the gyros and accelerometers would give accurate data.

4.1.2 PID Feedback Loops

The MP2028g controls the UAV using a series of PID feedback loops. The term feedback loop refers to any mechanism that controls a system by adjusting the input of the system based on the measured output of the system. An example of a feedback loop from the MP2028g is the elevator from pitch feedback loop. The elevator from pitch feedback loop controls the elevator's deflection to minimize the difference between desired pitch and the plane's actual pitch, as measured by the onboard gyros. There are 12 feedback loops used by the MP2028g to fly the UAV. These feedback loops are listed in Table 4.1 Feedback Loops.

Table 4.1 Feedback Loops

Name	Controls	Description
0 aileron from roll	aileron	Controls the ailerons to minimize the difference between desired roll and actual roll.
1 elevator from pitch	elevator	Controls the elevator to minimize the difference between desired pitch and actual pitch.
2 rudder from Y accelerometer	rudder	Controls the rudder to minimize the difference between the desired value for Y accelerometer and the actual value. This is the feedback loop that coordinates turns.
3 rudder from heading	rudder	Controls the rudder to minimize the difference between desired heading and actual heading. This feedback loop is used during takeoff to keep the aircraft on the correct heading.
4 throttle from speed	throttle	Controls the throttle to minimize the difference between desired speed and actual speed. This feedback loop is used during final approach and when

		the option to control speed via throttle and altitude via elevator is selected.
5 throttle from altitude	throttle	Controls the throttle to minimize the difference between desired altitude and actual altitude. This feedback loop is used when the option to control altitude via throttle and speed via elevator is selected.
6 pitch from altitude	desired pitch	Controls desired pitch to minimize the difference between desired altitude and actual altitude.
7 pitch from AGL	desired pitch	Controls desired pitch to minimize the difference between desired altitude and actual altitude as measured by the AGL board. This feedback loop is enabled during landing and controls the flare.
8 pitch from airspeed	desired pitch	Controls the desired pitch to minimize the difference between desired airspeed and actual airspeed. This feedback loop is enabled during climb and during level flight when the option to control altitude via throttle is selected.
9 roll from heading	desired roll	Controls the desired angle of bank to minimize the difference between the desired heading and the actual heading. This feedback loop is enabled any time the MP2028g is navigating.
10 heading from crosstrack error	desired heading	Controls the desired heading to minimize the distance between the MP2028g and the line defined by the previous waypoint and the next waypoint. This feedback loop is enabled when the fromTo command is being run in Horizon.
11 pitch from descent	desired pitch	Controls desired pitch to minimize the difference between desired descent rate and actual descent rate.

The term PID refers to a particular method of control. A PID loop has three gains and each of the letters P, I, and D refer to one of these three gains. The P stands for proportional and refers to the gain that acts directly on the difference between the desired value and the actual value of the system being controlled. For example in the elevator from pitch feedback loop, the P term is applied to the difference between the desired pitch and the actual pitch. This gain is referred to as Kp. The mathematical expression for the P term contribution to the elevator from pitch feedback loop is shown below.

$$\text{Elevator deflection} = \text{Kp} \times (\text{desired pitch} - \text{actual pitch})$$

The I stands for integral and refers to the gain that acts on the sum of all the errors since the feedback loop was started. This gain is referred to as Ki. For example, in the elevator from pitch feedback loop, the I term is applied to the sum of all pitch errors. Over time, all of the pitch errors are added together and this total, when multiplied by the I gain, will trim the aircraft. The mathematical expression for the I term contribution to the elevator from pitch feedback loop is shown below.

$$\text{Elevator deflection} = \text{Ki} \times \int(\text{desired pitch} - \text{actual pitch})\, dt$$

The D term stands for differential and acts on the rate of change of error. This gain is referred to as Kd. In our example using the elevator from pitch feedback loop the D term acts on the rate of change of pitch. The mathematical expression for the D term contribution to the elevator from pitch feedback loop is shown below.

$$\text{Elevator deflection} = \text{Kd} \times d/\,dt\,(\text{desired pitch} - \text{actual pitch})$$

If we continue with the example of the elevator from pitch feedback loop, the MP2028g calculates the desired pitch as follows:

$$\begin{aligned}\text{Elevator deflection} = {} & \text{Kp} \times (\text{desired pitch} - \text{actual pitch}) \\ & + \text{Ki} \times \int(\text{desired pitch} - \text{actual pitch})dt \\ & + \text{Kd} \times d/dt\,(\text{desired pitch} - \text{actual pitch})\end{aligned}$$

This calculation is performed repeatedly by the autopilot to achieve flight. The phrase feed forward refers to an additional term that is sometimes added to a traditional PID feedback loop in order to improve the performance of that loop. This term is usually used to anticipate a required control input and so the name feed forward. An example of when a feed forward may be included is to control the adverse yaw that results as the UAV rolls into a turn. In the example of rudder from Y accelerometer, the value for rudder is calculated as follows:

$$\begin{aligned} \text{Rudder} = {} & \text{Kp} \times (\text{desired Y accelerometer} - \text{actual Y accelerometer}) \\ & + \text{Ki} \times \int (\text{desired Y accelerometer} - \text{actual Y accelerometer})dt \\ & + \text{Kd} \times d/dt\,(\text{desired Y accelerometer} - \text{actual Y accelerometer}) \\ & + \text{Kf} \times \text{ailerons} \end{aligned}$$

The fourth gain, Kf, is the feed forward gain. It acts to coordinate turns much faster than if the feedback loop simply waited for the adverse yaw caused by the ailerons to generate uncoordinated flight, which is detected by the Y accelerometer.

By doing this calculation for the required PID loops many times per second, the autopilot is able to control the aircraft and produce stable flight. This assumes that the proper gains have been set.

4.1.3 Manual Override and Control

Because it was known that the autopilot would not have the correct gains set from the first flight, it was obvious that manual control for the aircraft would have to be implemented so the aircraft would not crash. This was done by adding a remote control to the system that worked off of the common 72Mhz R/C band dedicated to model aircraft. The Micropilot would plug directly into a normal R/C receiver and a separate channel on this band would be used to signal the autopilot into automatic or manual control. By flipping a switch on a 72Mhz transmitter, control could be restored to the user or the flight computer. Thus while in manual control, I would be able to fly the aircraft directly from the R/C transmitter and save the aircraft if anything should go wrong. This system proved invaluable for safety and practical reasons.

4.2 Ground Station

The ground station consisted of two laptop computers running two different processes. One laptop computer ran software to communicate with the MP2028g over a radio modem and monitor flight system status. The other laptop connected to the TV tuner and recorded video from the plane. When flying the Monocoupe, both ground computers were used simultaneously. With the Spirit sailplane however, only the laptop used for communications software was needed since the aircraft did not offer the video function.

4.2.1 Software

To first configure the autopilot and make sure the sensors were reading back acceptable values, Hyperterminal, found on most Windows computers, was used to communicate with the MP2028g. With Hyperterminal, I was able to command the MP2028g to acquire its GPS location and read back values from the gyros, accelerometers, and pressure sensors. I could also give commands to the autopilot regarding flight and path planning however I resorted to another more user friendly method of doing this.

A second program used was a specially developed software package for communicating, controlling, and programming the autopilot. It is called Horizon and it interfaced with the autopilot through an RS-232 serial connection. Horizon was basically a visual interface that made programming and working with the autopilot much easier.

Figure 4.2: Horizon Ground Control Software Window

Parts of the window included a map area that showed progress of the UAV while in flight and the waypoints planned for the mission. Another area included the instrument panel which displayed airspeed, altitude, and attitude relative to earth. A status bar at the bottom of the screen allowed monitoring of link quality and exact GPS coordinates. Finally, another displayed panel allowed easy links to programming and control options. With Horizon software, I was able to watch many elements of the UAV at once in a small concise window.

A separate element of Horizon was the programming package for the UAV. I learned to write flight plans for the autopilot in the same way programmers would write C computer language code. Specific commands were used to tell the UAV to fly at certain altitudes, bank for a turn, or fly towards GPS coordinates and waypoints. With these plans I was able to compile general flight plans that would allow me to test the flying characteristics of the aircraft. Added benefits were preprogrammed holding patterns that could be forced on the UAV even when the aircraft was in the middle of a flight plan.

4.2.2 Video System

Real time, onboard wireless video was used to monitor the flight of the UAV as it flew its course and tests were done. It allowed verification that the aircraft was operating normally and that flight was stable even when the aircraft would be out of visual range. The video feed also allowed recording of test flights which could be used later to analyze a flight.

The wireless video camera was mounted to the airplane's wing via a soft foam mount to help reduce vibrations and provide the best picture quality possible. A servo tilted the camera up and down to allow a forward as well as straight down view. During normal flight the camera would be pointed forward so that the horizon could be used as a reference for the stability of flight. Pointing forward also allowed me to watch the engine and make sure it was running smoothly. When the camera was pointed straight down, it was possible to look for ground reference points to make sure the aircraft was where I was expecting it to be.

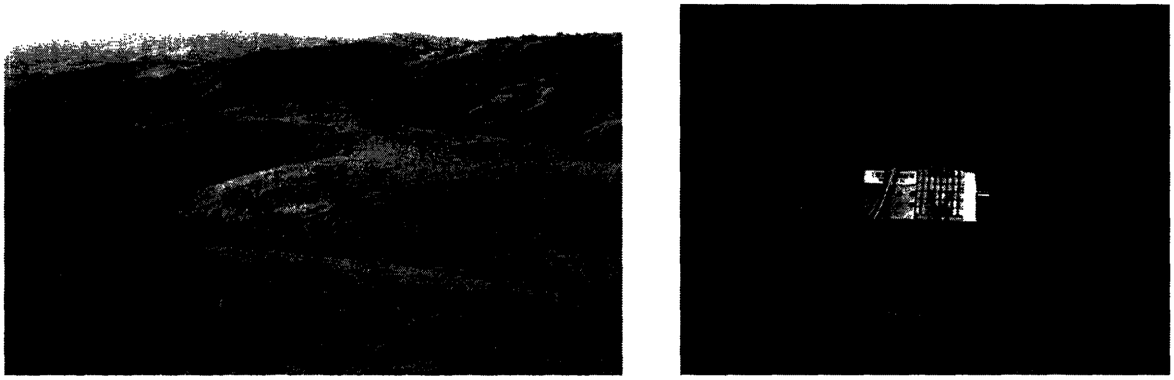


Figure 4.3: Wireless Video

A 470 line color CCD camera was chosen to give a high resolution video feed for recording and a 71 degree field of view lens was installed. This gave a good situational awareness with the images taken. All images and video were relayed to the ground via a 2.4 GHz, 600mW transmitter located within the airplane's main cabin.

At the ground station a receiver was used to collect the video data to be analyzed. Tests with common video receivers had produced video that showed static and snow due to multipath issues and interference. To clean up the video, a new receiver called a Diversity Receiver was used which consisted of two receivers receiving the transmitted video signal while a separate circuit compared the two signals and selected the best one to output. This created crisp, almost unbroken video. The analog output of the receiver was input into a television tuner which then output a digital signal via USB 2.0. This was then recorded directly to a hard drive within a laptop to allow the video to be rewound and analyzed. To enhance the range of the video receiver, the common dipole antennas were replaced with 14 decibel patch antennas. This roughly quadrupled the range when the antennas were pointed at the aircraft.

4.3 Ground to UAV Communications

The MP2028g autopilot is completely capable of autonomously functioning without any support from the ground. If it is programmed with a flight plan before a mission starts, it is capable of switching to a flight plan once the R/C transmitter tells it to go into autopilot mode. This is useful when the aircraft is already flying smoothly however at my stage, the UAV had never even taken flight with all the electronics on board. Thus no preliminary gain setting in the PID loops was reliable and had to be updated for the plane to fly well. Thus a real time communications system was needed to monitor aircraft functions and update the gain settings of the UAV mid-flight. Research was done to find the best means of creating a wireless link to the aircraft and a pair of radio data modems were decided upon. The radio modems consisted of two long-range 900 MHz frequency-hopping spread-spectrum data modems made by Freewave Technologies. With these powerful modems, a link could be established with the aircraft up to 60 miles away line-of-sight and data rates were possible at up to 115.2 kbps. With embedded electronics, they were able to establish secure communications, reject noise, and retransmit lost data.

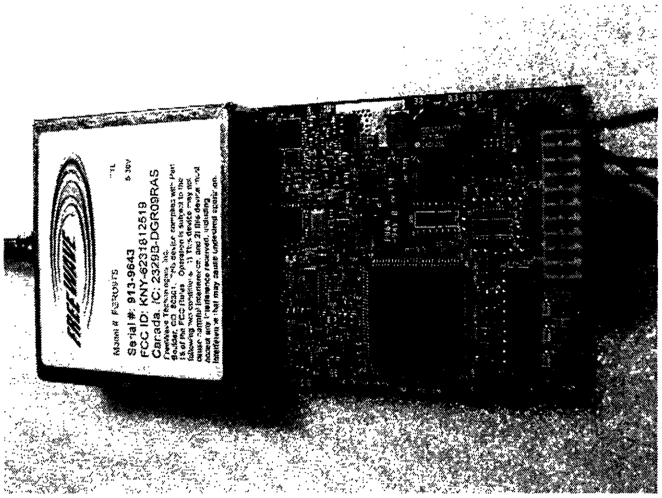


Figure 4.4: Freewave Radio Modem Board

Finding radio modems was not the end solution to wireless communication however. The autopilot communicates through RS-232 signals while the Freewave modem communicates through TTL signals. Connecting the two together would result in useless data being transmitted. Thus a converter was needed to translate the signals into information both electronic boards could understand. A MAX232ACPE chip was found that could do just this with the added benefit of requiring extremely little power to operate. With the addition of capacitors to the chip, a board was soldered that would function as the converter needed to facilitate good communication.

At the ground station, much less work had to be done to create a link between the modem and laptop computer. Only programming of radio modem settings and a simple serial connection were needed to create a successful link.

4.4 Power

With energy hungry electronics on board the aircraft mostly due to the powerful transmitters and servos, a source for power was needed that was lightweight and high capacity. Lithium ion technology was chosen just for these requirements. Although they cannot supply as many amps and as much power as lithium polymer batteries, they have a higher energy density and thus they were better suited for the purpose of powering the electronics. Two custom battery packs were created with the lithium batteries to power all of the aircraft's electrical systems. The first battery was a 7.4 volt lithium-ion pack that directly powered both the MP2028g and the radio modem. The second battery was a much larger 11.1 volt pack capable of supplying nearly five amp-hours of current. This battery powered a DC/DC converter that supplied five volts to all of the servos, camera, and video transmitter. With the capacity of these batteries, power was good for at least two hours.

On the ground, power was supplied to the radio modem and video receiver equipment via a twelve amp-hour sealed lead acid battery. This provided almost unlimited working time and thus power on the ground was only limited by the length of time the laptop batteries could last which was around two hours.

4.5 Final Electronics Layout

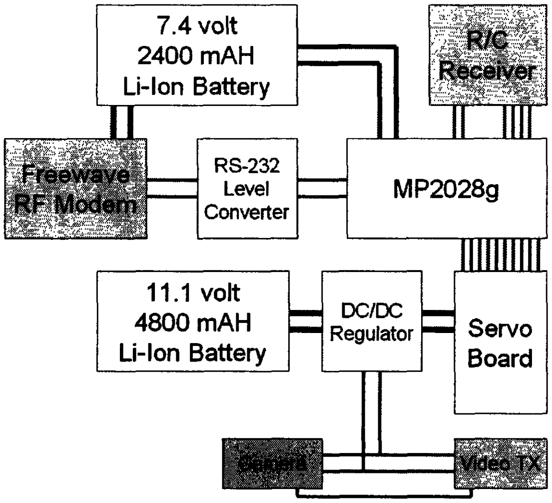


Figure 4.5: Final Electronics Layout

This was the final layout of all the electronics used onboard the Monocoupe UAV. The Spirit UAV used the same layout minus the camera and video transmitter.

Chapter 5

Flight Testing

5.1 Process to Achieve Stable Autonomous Flight

Setting Gains

The performance of a feedback loop is strongly influenced by the values assigned to its gains. If the gains are too small, the feedback loop will take a long time to reduce its input error to zero. If the gains are too large, the feedback loop will oscillate and become unstable. It is possible to calculate the optimum gains for a particular system, but this requires an accurate mathematical model of the aircraft and is very complex. Because this thesis project was concerned with the effects of gains on the flight of the aircraft, the obvious method was to just fly the aircraft and see what the response was. This would also produce test results that would be useful for later analysis.

The configuration of the feedback loops used by the MP2028g is shown in Figure 5.1 Level Flight. These are the same feedback loops listed in Table 4.1 Feedback Loops. Figure 5.1 Level Flight shows how the output of some of the feedback loops feed the input of other feedback loops. Not all of the feedback loops are enabled at any one time. During flight, the autopilot enables and disables feedback loops in order to accomplish its user defined mission. For example, if the MP2028g is at its target altitude while flying towards a waypoint, the feedback loops shown in bold in Figure 5.1 Level Flight are enabled. If, rather than flying level, the MP2028g is climbing then the feedback loops shown in bold in Figure 5.2 Climb are enabled. If the MP2028g is descending then the feedback loops shown in Figure 5.3 Descent are enabled.

Example: Level Flight

The feedback loops that are enabled while the MP2028g is holding altitude are shown in bold in Figure 5.1 Level Flight. This example assumes that the MP2028g is configured to use the elevator to control altitude and the throttle to control airspeed.

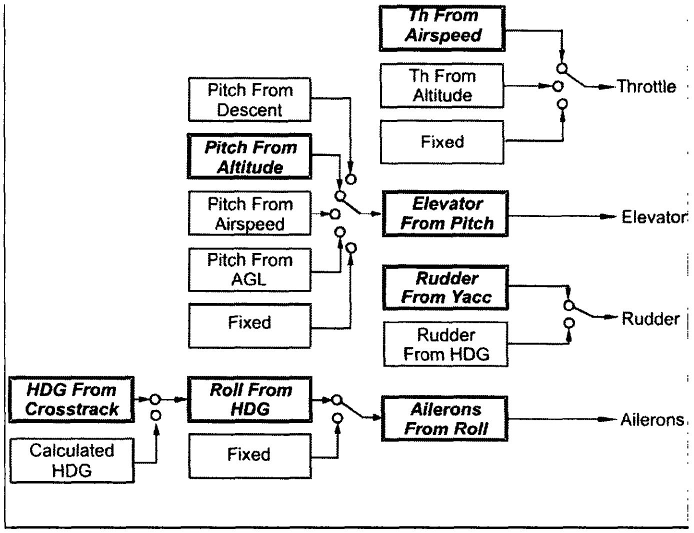


Figure 5.1: Feedback Loops Implementation for Level Flight

Example: Climb

The feedback loops that are enabled when the MP2028g is climbing while flying to a waypoint are shown in bold in Figure 5.2 Climb.

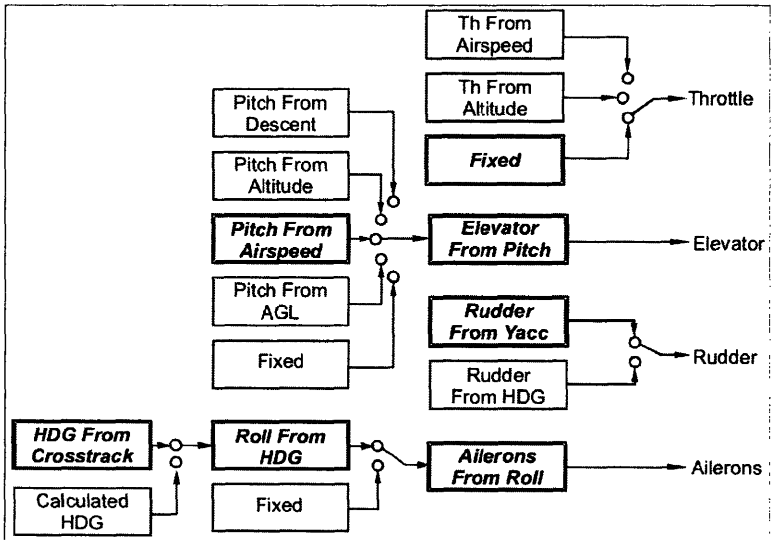


Figure 5.2: Feedback Loops Implementation for Climb

Example: Descent

The feedback loops that are enabled when the MP2028g is descending while flying to a waypoint are shown in bold in Figure 5.3 Descent.

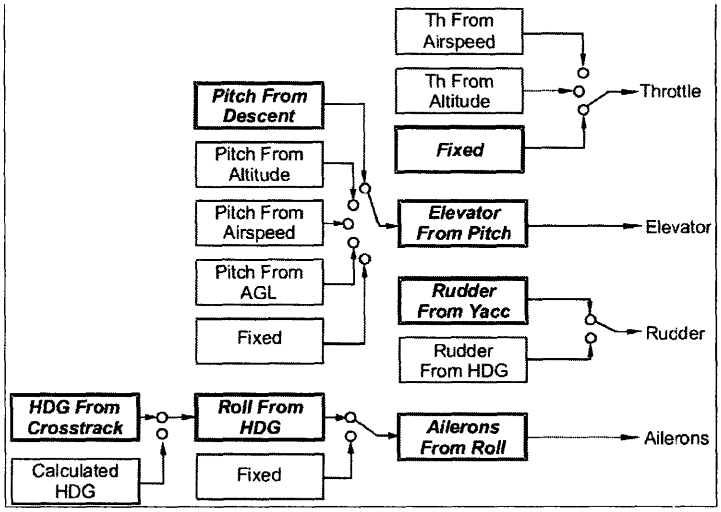


Figure 5.3: Feedback Loops Implementation for Descent

5.2 Testing Individual Feedback Loops

Once the MP2028g was installed and operating correctly, the next step was to adjust the feedback gains. While setting gains, the R/C receiver was installed in the aircraft so that I could take control of the plane should gain settings prove unstable. During tests, I would fly the plane to altitude, switch to autopilot control, and then observe the plane's behavior. In the beginning stages of testing, I would then land and change gains since the preliminary settings made the airplane too unstable for me to change gains and fly the aircraft manually at once. In later testing when flight became more stable, I was able to use the radio modem to adjust the gains in flight using the Horizon software.

The gains for the UAV were set in the following order:

1. Elevator from pitch, rudder from Y accelerometer and ailerons from roll
2. Pitch from airspeed and roll from heading
3. Pitch from altitude
4. Throttle from altitude
5. Throttle from airspeed
6. Rudder from heading

I started from the first step and worked on finding the correct gains for the elevator from pitch, aileron from roll, and rudder from y accelerometer feedback loops. The autopilot was programmed to takeoff, climb to 750 feet, and end in a circuit command. The autopilot was not flying the aircraft during the takeoff and climb commands but these commands allowed the autopilot to follow what I was doing manually. Autonomous control was not switched on until the circuit command was reached.

Once a safe altitude had been obtained, I switched to computer control to watch for the plane's behavior. If the plane's nose seemed to pitch up and down, I reduced the gains in the elevator from pitch feedback loop. If the plane's wings rocked side to side, I reduced the gains in the ailerons from roll feedback loop. If the plane's nose yawed from side to side, I reduced the gains on the rudder from yaw feedback loop. When reducing gains, I took a methodical approach to get the best settings. In increments, I reduced a gain by 25% until oscillations seemed to disappear. To determine which individual terms required reducing, I considered how fast the plane was oscillating. If the plane was oscillating several or many times each second, then the P, D or both the P and D terms were slowly reduced. If the oscillation was slow at a rate of about one time each second or less, then I reduced the I term of the feedback loop. This was done for most of the gains and feedback loops for the MP2028g that were active for straight and level flight.

The rudder from y accelerometer feedback loop was adjusted slightly different from the other loops. This particular loop contained four terms with the fourth term being the feed forward term from the aileron position to the rudder position. This term is used to make coordinated turns and reduce the amount of side-slip created if banking turns are done with ailerons only. This gain was adjusted independently of the other gains by first setting this gain to zero. This decoupled the yaw and roll axis and allowed me to adjust them independently. Once they had been adjusted appropriately, I reintroduced this gain and then adjusted it until the plane flew in a stable fashion.

Once all the gains were stable, I tried increasing the gain of those feedback loops that had not yet been adjusted. Again I took a methodical approach and increased the gains in 25% increments. This was done until instability occurred. I noticed that before the plane became unstable, it tended to become twitchy. This served as a warning sign and as soon as I saw this behavior, I reduced the appropriate gains.

Another test was done on the flight of the aircraft. As the throttle could be adjusted from the ground manually, gains were tested at a variety of airspeeds. I noticed that as the airspeed increased, there was a tendency for the gains to require reduction. This made sense since a higher airspeed also meant that less control input was needed to produce the same effect on the plane at lower airspeeds. Thus it was determined that in order to have the best performance overall, the gains should be set to be stable at the highest airspeed that the airplane was meant to fly at. This would prevent cases of overcorrection and resulting unstable oscillations.

Chapter 6

Conclusion

Through the course of this project, I learned a great deal about the systems required to build a successfully flying unmanned aerial vehicle. I will close my thesis report by summarizing my accomplishments and discussing the appropriate next steps and possible future of this project.

6.1 Accomplishments

In this section I will discuss the various systems of an unmanned aerial vehicles I built and how the final aircraft satisfied my thesis objective.

6.1.1 UAV Systems Built

Monocoupe UAV

The Monocoupe UAV is a gasoline powered aircraft extremely capable of facilitating any type of research work presented to it and is an ideal platform for testing. With an eight and a half foot wingspan, the Monocoupe was capable of lifting a large payload. The cabin contained room to hold large quantities of test equipment and the autopilot. Modifications were done to increase the inherent stability of the aircraft, increase the internal volume, add strength to weak points, and provide for longer flight duration. This aircraft finished with a flight range of 150 miles and 75 mph cruise speed. The only downside of this aircraft was the large open space needed to fly it. The large gasoline engine was loud and required constant maintenance however the benefits of the aircraft were overwhelming. If a large flying field had been easily accessible, this aircraft would have been the optimal platform.

Spirit UAV

The Spirit UAV picked up on what the Monocoupe left out. It was desired to create a second aerial platform that could be tested in smaller, more restricted space fields. The Spirit was able to do just this. As a smaller aircraft powered by electric power, noise was not an issue and the aircraft could be flown in almost any space. This allowed for testing to be done on almost any day weather permitting. Modifications to the aircraft included the lightening of heavy components and the strengthening of parts that would be stressed with the added payload. A firewall was added to allow the addition of a motor for power. The downside of the aircraft however was the limited range and duration the aircraft could fly. This was explained by the limited electric power the batteries could store as the technology of today has not advanced far enough. The Spirit UAV however filled the niche of a small hand-launchable aircraft that could be used almost anywhere with little to no maintenance required.

Autopilot and Electronics Design

The Micropilot MP2028g autopilot was used as the basis for the electronics in the UAV as designing a complete autopilot from the ground up is a complete project in itself. The autopilot implemented three-axis gyros, accelerometers, GPS, sonar, and airspeed to allow for proper sampling of the environment in order to control the aircraft. A radio modem was utilized to allow real-time communications between the autopilot and ground computers during flight. In order for proper communication between autopilot and modem, a board was designed that translated RS-232 and TTL protocols. Power to aircraft electronics was provided via two lithium-ion batteries. For safety purposes, a manual control system was implemented into the electronics package which allowed me to control the aircraft from a normal R/C transmitter. Finally, software on a laptop provided the basis for the ground control system. It allowed visual display of data received real time from the UAV and provided a means for updating the aircraft's waypoints in the middle of a test. Hyperterminal and Horizon software were used to write and program flight plans into the autopilot.

Additions to the system implemented on the Monocoupe UAV included a real time video system for further monitoring of flight. Directional antennas and Diversity receiver were used to reduce interference and improve video quality.

Systems Implementation

The electronics system was installed into both the Monocoupe and Spirit UAVs for flight testing. Further modifications for systems integration included the installation of pitot tubes, supporting mechanical structures for the electronics, and GPS antenna.

6.1.2 Successful Flight Testing

Throughout all testing done with the aircraft, all ended successfully and no crashes were recorded. Manual control override allowed control when the autopilot's gain settings resulted in unstable, oscillating flight. Throughout the UAV design process, safety was a priority and this was definitely achieved.

6.1.3 Fulfillment of Thesis Objective

My thesis objective was to design and build an unmanned aerial vehicle capable of fully autonomous stable flight. Having designed and built both the Monocoupe and Spirit UAVs, I believe that I have satisfied this goal.

6.2 Extensions of Work

This project leaves a lot of possible future work to be done. At this point the aircraft flies autonomously in level flight however not all gains have been optimized to allow for quick descents and ascents. Because of this, autonomous takeoffs have yet to be achieved and would involve the refining of feedback loops. Sonar is also not currently present on the Spirit UAV and thus autonomous landings are not possible. In order to land, altitude error accuracy must be within an inch or else the landing flare of the aircraft could result in impact with the ground at high speeds or a stall situation which would also result in a crash. If sonar is implemented into the system, then further feedback loops would be utilized to account for the landing situation. Once installation is complete, autonomous landings would also be possible and involved feedback loops would have to be tested.

Something left to be desired is the accuracy of the flight path of the aircraft. Currently the GPS installed on the aircraft results in a position accuracy of plus or minus ten feet. This is a significant error that could magnify other errors found in the analysis of data in image or video used for identifying targets. Differential GPS could be implemented into this system to improve position accuracy. By installing GPS at the ground station and implementing software that compares data from this GPS and the one installed on the aircraft, atmospheric errors could be eliminated. This would allow accuracy of the position coordinate of the aircraft to be within a few centimeters.

6.3 The Future of Autonomous Aircraft

The success of unmanned aerial vehicles in the present age shows a small glimpse of the potential these vehicles have in the future. Although their presence in modern day aircraft is increasing, there are many applications of UAVs that have yet to be explored. Currently they are almost exclusively found in military reconnaissance aircraft but as the technology continues to advance and prove itself, we may begin to see applications of fully computer controlled aircraft in the commercial passenger market as well. Their addition to flight would improve reliability and safety all in one package. In the science arena, the potential these vehicles have for research and advancement is tremendous and it is only time before UAVs become a common tool of the scientific community. Everywhere in the world, people have seen the benefits of autonomous aircraft and the future of the technology looks bright. It is very probable that one day computer controlled aircraft will become a part of our everyday lives.

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