AN ELECTRIC POWER SYSTEM FOR AN AUTONOMOUS BLIMP

NSF Summer Undergraduate Fellowship in Sensor Technologies
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ABSTRACT

This paper describes the design and implementation of an experimental electric power system to replace a gasoline system of a 30-feet unmanned autonomous blimp. The project was motivated by limitations and inefficiencies of the gasoline system. Autonomous flight requires extended duration flight and maneuvering capabilities that can be realized with an electric power system. In order to fully exploit the advantages of electric flight, the gondola housing the power and control systems was redesigned for minimum weight as a carbon fiber frame structure. With the optimal motor-propeller combination for the chosen motors, electric flight was possible at less than half of the power compared to the gasoline system indoors for 30 minutes. Increased maneuverability gained from the ability to stop, restart and reverse the motors in flight was an important step towards controlling the blimp with an onboard computer. The weight reduction of the gondola effectively increased the payload capacity, allowing for neutrally buoyant flight and additional sensor and control equipment. The electric power system significantly increased the blimp's flight capabilities and provided the foundation for future work towards a fully autonomous blimp capable of operating alone or together with other robots in a multi-robot environment.

1. INTRODUCTION

A blimp effectively combines the capabilities of airplanes with those of hot air balloons in one aircraft. This unique combination of maneuverability and the ability to float with relatively low power requirements makes a blimp an ideal research platform for sensor and control technology. A group of undergraduates at the University of Pennsylvania work on a continuous project to build and improve a 30-foot unmanned blimp for autonomous flight.

This paper describes a project to convert the power system of that blimp from gasoline to electric power. Limitations of the gasoline power system motivated the search for an alternative system, which led to the design and implementation of an experimental electric system. Throughout this paper, "current" refers to the gasoline power system, while "new" refers to the electric one.

With maneuverability and endurance being main issues for autonomous flight, we see electric flight as the ideal solution for our blimp and as a basis to build on with future improvements.

2. BACKGROUND

2.1 History of the STWing/SEAS Blimp Project

The STWing/SEAS Blimp is an ongoing undergraduate research project at the University of Pennsylvania. It was started in 2000 by members of the Science and Technology Wing (STWing) residential living group and currently has approximately 20 members. The project is affiliated with the School of Engineering and Applied Science (SEAS) and the General Robotics, Automation, Sensing, and Perception (GRASP) Laboratory at Penn, as well as with the robotics group at Carnegie Mellon University in Pittsburgh, PA.

The blimp was purchased ready to fly when the project was started. Since then the team has implemented many redesigns and improvements such as larger, more effective control surfaces, a stronger mounting system for the engines, and onboard cameras and computing. Members of the team come from disciplines ranging from engineering to science and business.

2.2 Configuration of the Blimp

Our current blimp (see Figure 1) is a 30-feet long, 7-feet in diameter, helium-filled airship powered by two 2.2 horsepower gasoline engines. A gondola made of injection-molded plastic is attached with large surface area Velcro strips to the bottom of the envelope. The engines are mounted to both sides of a hollow aluminum shaft passing through the gondola that can be rotated 180 degrees to orient the engines. The engines' power is sufficient to overcome wind speeds of up to 10 miles per hour. The flight ceiling is at 400 feet, above which decreased ambient pressure can cause the blimp's envelope to burst; usually we operate below 150 feet.

At the tail, the blimp is equipped with elevators and rudders for directional control attached with Velcro strips and drawstrings. Our current control surfaces have close to full range of motion with deflections of almost ± 90 degrees from the neutral position. This large range is achieved by a direct drive system using digital servos with high torque and holding power. The servos also allow for easy reversibility and speed control.

With a volume of 900 cubic feet, the blimp's envelope has a maximum lift capacity of approximately 18 pounds. In addition to that, we are required by the FAA to fly 5 pounds heavier than air. Given the weight of the current gondola (7.5 pounds), the gasoline engines (4.5 pounds each), and 2 liters of gasoline (approximately 3 pounds), we have a net payload capacity of about 3.5 pounds for sensors and control equipment. However, flying heavier than air significantly reduces the blimp's endurance.

Currently the blimp can be equipped with a camcorder mounted inside the gondola for data collection. As space inside the gondola is limited, additional equipment is carried in a basket underneath the gondola. At an experimental stage, an onboard computer is able to read data from a camera as well as from a global positioning system (GPS) sensor on top of the envelope and stream the data through wireless Ethernet (802.11b) to a computer on the ground.

Eventually the onboard computer together with cameras, gyroscope sensors, and GPS will be controlling the flight of the blimp. Until then, however, flight is controlled manually through use of a remote control for rudder and elevator control as well as engine pitch and throttle.

Figure 1: The current blimp after a test flight.

2.3 The Blimp as Part of the MARS Project

MARS ("multiple autonomous robots") is an ongoing project at the GRASP lab at Penn. A group of wheeled autonomous robots can interact and collaborate without outside influence. It is planned to integrate the blimp into the project as an aerial component supporting the ground-based robots. With the ability to hover above the robots on the ground, the blimp will be able to track and guide the group. The blimp's cameras will significantly extend the robots' sensor range and therefore their range of operation. To be effective as part of MARS, the blimp needs to be as maneuverable as possible and be able to fly for extended periods of time without having to refuel.

2.4 Project Goals

The main objective of the blimp project is to develop and constantly improve the airship as a platform for sensor and control technology. We are working toward a fully autonomous blimp, controlled by the onboard computer, which operates by itself or in a multi-robot environment. With its advantages over gasoline power, we believe that an electric power system will be an important step toward automated and extended duration flight.

3. MOTIVATION

3.1 Limitations of Gasoline Power System

3.1.1 Inefficient Motor-Propeller Combination

The current Zenoah G-23 gasoline engines are rated at 2.2 horsepower at 10,000 RPM. Each drives a three-bladed 13 x 10 Zinger propeller at 7,000 to 10,000 RPM in flight. The motor-propeller combination is capable of delivering a maximum static thrust of 11 pounds. Considering the weight of the gasoline system of approximately 12 pounds (2 engines and gasoline), the power system has a thrust-to-weight ratio of less than one (approximately 0.9 pounds of thrust per pound weight). As the motors are more than sufficiently powerful to fly our blimp, these numbers suggest that in combination with the small 13-inch propellers a significant amount of the power is lost due to inefficiency. The 6000 W (4.4 horsepower) available produce only 0.0018 pounds of thrust per Watt. This low efficiency can be explained by looking at the principle behind propellers. As a rotating wing, a propeller produces thrust efficiently only as long as the airflow over it remains attached. At very high speeds as in our case, the turbulences caused by the propeller itself cause flow separation to occur, which leads to a significant drop in lift.

3.1.2 Limited Maneuverability

The more control one has over a vehicle, the easier is it to have a computer take over. In case of our blimp, the main means of controlling its flight are the engines and control surfaces. Because of the high weight and power requirements of a starter system, the engines must be started on the ground prior to takeoff. After that they can be throttled up and down, but only together on both sides simultaneously, resulting in a large turning radius. Without the ability to start engines in flight, reversing them is not possible. In the event of an engine failure, the blimp has to land in order to have its engine restarted.

3.1.3 Pollution

Noise and exhaust gases are two limiting factors for the blimp’s use as surveillance aircraft and for environmental research. At full throttle, the engines noise comparable to a loud lawn mower without muffler at close range. On average, per hour of operation, approximately 2 liters of gasoline are burned and exhausted by the engines. This introduces significant error into experiments, such as CO_2 measurements or air quality measurements throughout a volume of air.

3.2 Extended Capabilities with Electric Power System

3.2.1 Extended Duration Flight

With a gasoline power system, there is always a finite amount of flight time before the blimp needs to be refueled. In our current setup, the maximum flight time on a full tank of gasoline is approximately 45 minutes. For small blimps like ours, gasoline-powered flight time is typically longer than electric as a result of the high weight of the required batteries. However, while the power requirements for a blimp scale with the square of its length, the available payload capacity scales with the length cubed. Therefore it is possible to accommodate almost any power system's weight by making the blimp large enough. A sufficiently large blimp (approximately twice as long as our current model), equipped with solar panels in addition to its rechargeable batteries, could theoretically fly continuously without refueling. Going beyond solar power, for higher power requirements, a larger blimp could be powered by a fuel cell and operate for extended periods without refueling.

3.2.2 Differential Thrust

One of the main limitations of the current system is its limited maneuverability. With an electric system, these limitations virtually disappear. Engine speed can be controlled electronically using reversible speed controls, which solves the problem of not being able to stop, restart, and reverse the engines. At the same time, with separate speed controls, each motor can be controlled individually. While the current design always needs some forward velocity and its control surfaces to change the direction of flight, differential thrust allows turning on the spot, with the two propellers turning in opposite directions. Unlike a gasoline-powered blimp, an electric one can reverse the thrust of its engines to come to a stop in calm air to float without engine power and then restart its engines to continue its flight.

3.2.3 Stable Flight Conditions

A computer controlling the flight of an airship needs a basic set of parameters describing how the blimp will react to weather (e.g., gusts of wind) and what reactions should follow. For a gasoline power system, there is no fixed set of parameters, as the weight is changing during flight with gasoline being burned. The rate of weight loss is highly dependent on flight and weather conditions and cannot be predicted reliably. With an electric power system, on the other hand, there is no weight loss during flight, making it the ideal system for fully computer-controlled, autonomous flight.

4. PROJECT DESCRIPTION

4.1 Objective

The main component of the project was the conversion of the current gasoline power system to an electric one. The goal was to design an experimental electric system to test the new technology and do performance tests and calculations. In order to avoid significant limitations, part of the project was to design and build a new gondola to house the system, allowing for unconstrained design of the electric system. Also, during the transition period from gasoline to electric, both systems are available and ready for flight. Because of weight constraints, a target flight time with electric power was set at 20 minutes in good flying conditions (i.e., no wind or indoors).

4.2 Design

4.2.1 Motor-Propeller Combination

The motor-propeller combination was chosen as the starting point for the design of the electric system. In order to limit the number of batteries and the amount of current needed, geared Astroflight 1000W Cobalt airplane motors were chosen. Geared down 3.3:1, the motors were capable of spinning propellers up to 18 x 10 at 4,000 to 6,000 RPM while requiring 20–25A of current. For maximum thrust, Master Airscrew Scimitar 18 x 10 two-bladed propellers were used. A thrust test of both motors together suggested a maximum static thrust of the combination of approximately 7 pounds at 4500 RPM. The significantly reduced power of the system (2000 instead of 6000 W) was the main reason for the drop in static thrust. However, this combination was capable of producing 0.0035 pounds of thrust per Watt, which is nearly twice the amount of the current system at a thrust ratio of 0.78.

4.2.2 Batteries

Deciding on the motors to use mostly specified the required batteries. Based on advice from Bob Boucher of Astroflight Inc., we used two 8-cell Sanyo 2400 NiCad battery packs per motor. At full throttle the batteries were discharged within 5 to 7 minutes; however, with only partial thrust, flights of up to 30 minutes were possible.

4.2.3 Gondola

Design constraints were imposed on the gondola by the shape of the attachment interface with the envelope, the size of the propellers, and the dimensions of the onboard computer. The traditional shape of the current gondola of injection-molded plastic was abandoned and replaced with a more functional design. To minimize weight while keeping structural stability, stock carbon fiber tubing was chosen to build a two-level frame structure. The top level provided the same shape as the current gondola with the same Velcro attachment. The second level was larger than the top level in order to accommodate either of two possible control computers. Also, the overall height of the two-level structure was much smaller compared to the current model. In order to get sufficient clearance for the propellers, the motors were mounted on both sides of a carbon fiber tube supported below the actual gondola. With the space inside the gondola limited to batteries, a computer, and some sensors essential for basic navigation, additional sensors had to be attached to the bottom of the second level of the structure. The frame design provided a convenient interface for attaching sensors.

4.3 Assembly

4.3.1 Carbon Fiber Frame

Stock carbon fiber tubing of two sizes (ODs 0.5 and 1.12 inches) was used for a central two-level frame structure, with the thinner tubes running along the length of the gondola and the thicker tubes running across for stability and shape (see Figure 2).

Figure 2: The carbon fiber frame structure of the new gondola.

The 0.5-inch tubes were slid through holes drilled through the centers of the 1.12-inch tubes horizontally and vertically and then fixated using LORD High Performance Fast Setting Epoxy. At the top level, the shape was dictated by the shape of the attachment interface with the envelope. With the cross supports cut to size, wooden inserts were epoxied into the ends to increase the surface area for attaching carbon fiber strips to give the gondola its shape. The left and right sides of the top level were made from 3-inch-wide and 1/16-inch-thick carbon fiber strips screwed and epoxied to the cross supports. For the nose and tail curvatures, more flexible 1/32-inch-thick strips were used and snapped into the stronger side strips. For additional strength and to attach the Velcro strip holding the entire gondola to the blimp, rivets were used to reinforce overlap areas between two carbon fiber strips. For the second level a similar procedure was used but with 2”-wide strips. Finally, the lower tube holding the motors was supported using 0.25-inch diameter tube from the tail end cross support on the second level (see Figure 3).

Figure 3: The completed bare carbon fiber gondola.

4.3.2 Motor Mounts

Instead of having both engines rigidly attached to the same aluminum shaft, the new gondola was built with two independent mounts. An aluminum faceplate on a tube was inserted into the carbon fiber tube and secured. The outer assembly with the motor attached to a short shaft rotating through two tapered roller bearings was then bolted to the faceplate. Tapered bearings were necessary because the spinning propellers created thrust forces along the axis of rotation, which conventional ball bearings might not be able to handle. For servicing purposes, the outer assembly can easily be removed (see Figure 4).

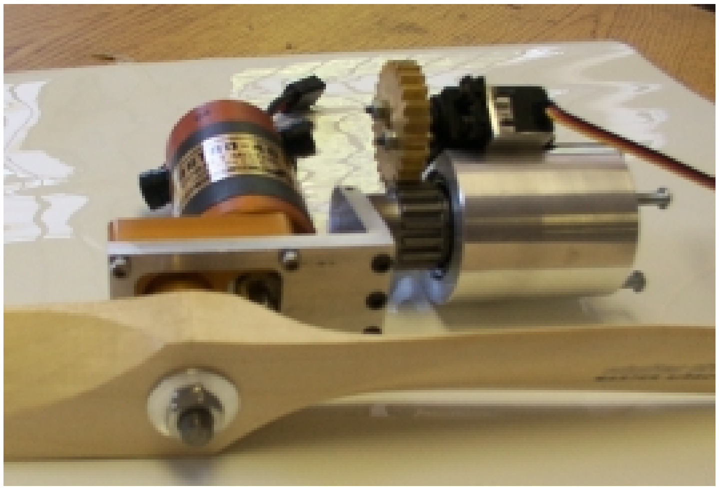

Figure 4: The removable part of the new motor mounts.

In the new setup, each motor is oriented individually by a digital high-torque servo. The servo’s 180 degrees of motion were geared up 2:3 to an effective 270 degrees for the motors. This allows the motors to be pointed up and back as well as down and back, and therefore to slow down the motion of the blimp more effectively. The axis of rotation of the motor assembly was set as close to the center of mass of the motor-propeller combination as the gear system allowed, unbalanced in such a way as to orienting the motors down when spinning freely, such as if the servo failed. In case of such an accident, the blimp would therefore descend. As an additional safety feature, the digital servo’s fail-safe position was programmed such that the motors point down. This setting specifies the position the servo goes to when it loses radio contact to the transmitter. In most situations both motors were still oriented identically. However, the system was also capable of orienting them individually.

4.3.3 Battery Attachment

To keep wires as short as possible between batteries and motors, the batteries had to be placed as close to the motors as possible. They also had to be placed so that heat could easily escape. The back support of the shaft was chosen as an ideal place for the batteries, allowing the wires to run along the diagonal support for the most direct path. As major contributors to the system’s weight, the batteries also had to be secured so that they would not shift during flight while still be easy to change. The batteries were attached with Velcro strips to the battery packs and carbon fiber tubes, and a safety catch system kept them from falling.

4.3.4 Wiring and Electromagnetic Shielding

With the batteries placed near the diagonal supports of the motor shaft, the total wire length to the motors was approximately 18 inches. Using 16 gage or larger wire and special low-resistance connectors, resistance in the power wires was negible, minimizing energy loss from heating the wires. The speed control also functioned as safety power switch, cutting power to the motors when the radio signal was lost

Electromagnetic interference was an issue because of the onboard computer as well as wireless Ethernet to the ground and remote control. While running, both motors produce a significant electromagnetic field, especially when accelerating, decelerating, or changing direction. The gondola was designed so that the computer would be located as far from the motors as possible, and oriented in the weakest part of the magnetic fields; no additional shielding was necessary.

4.3.5 Camera and Antenna Mounts

The blimp communicates with ground-based computers through 2.4-GHz wireless Ethernet. An external antenna was used to extend the communication range of the PCMCIA slot wireless cards on the laptop. To minimize interference from the electromagnetic field produced by the motors, the antenna was mounted horizontally pointing forward from the nose of the gondola. Standard mounting hardware for the antenna was used to fasten it to the carbon fiber tubes. In addition to the antenna, the nose of the gondola also houses a PC web cam on a two-axis pan-tilt mount for basic orientation and navigation.

5. DISCUSSION AND CONCLUSIONS

The project was very successful and met or exceeded all of the requirements stated above. Ready to fly with all necessary batteries, the new gondola weighed 13.5 pounds, which is a 33% weight reduction relative to the current system. The available payload was increased significantly: approximately 4.5 pounds could be added before neutral buoyancy was reached. During the first test flight of the new system, the blimp flew for approximately 30 minutes at various speeds on the same battery packs before the available thrust was reduced significantly.

For the remote controlled test flight, with only 4 available transmitter channels with proportional range, differential thrust and individual motor pitch capabilities were disabled. With the introduction of computer control, this limitation will be eliminated. Without the onboard computer, the heavy batteries in the back of the gondola shifted the blimp’s center of mass back and made the envelope point up. However, by adding the computer to at the front of the gondola, this imbalance will be corrected.

The electric power system designed and built during this project is a working and reasonably comparable alternative to the current gasoline system. It was shown that electric flight of our blimp is possible under good flying conditions for about half an hour without recharging. Maneuverability was increased significantly, and will increase even more with computer control in the near future. With the changes described in this paper, our blimp is now ready to become an autonomous airship that can fly fully computer controlled (see Figure 5).

Figure 5: The new blimp during its first test flight.

6. RECOMMENDATIONS

A number of improvements could increase the endurance of the electrical blimp and make it more fit for future applications as an autonomous airship. First, some of the weight reserves should be used for additional batteries or higher-capacity batteries to increase flight time to approximately 1 hour, comparable to the current gasoline-powered flight time as well as give us more thrust. Second, the blimp's computer control system should be updated to take advantage of the added capabilities, and computerized test flights should be conducted. Third, in order to increase maneuverability, the current control surfaces should be replaced by active surfaces that would allow the blimp to turn on the spot without requiring forward motion with the main motors.

7. ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Jim Ostrowski, for his support and encouragement during my project this summer. I also thank Vito Sabella, the technical director of the blimp team, for his input throughout the summer, as well as the blimp team for helping with the test flight. For technical support I would like to thank Bob Boucher from Astroflight Inc., who helped choose the battery-motor-propeller combination, as well as Jeff Allot from General Composites Inc. for his advice about working with carbon fiber. Thanks to Bob Miller and Wally Szczesniak for suggesting improvements to my designs and making the motor mounts, as well as for letting me use the machine shop. I would also like to thank Dr. Jan Van der Spiegel and the entire SUNFEST faculty and staff for the organization of the program. Finally, thanks to the National Science Foundation and to Microsoft Corporation for their financial support of SUNFEST, as well as to the mechanical engineering department at the University of Pennsylvania for supporting my project through the Herbert J. and Selma W. Bernstein Class of 1945 Summer Internship.