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WING AND GLIDING DYNAMICS OF A FLAPPING WINGED ORNITHOPTER

GARY PARKER AND JOHNNY BORBONE
Computer Science Department
Connecticut College
New London, CT, USA
{parker, jborbone}@conncoll.edu

ABSTRACT — The Great Albatross, having the largest wingspan of any extant bird, is a highly efficient flier, using unique flapping and gliding techniques to cover great distances with little exertion. The main issue in the development of an Albatross robot is overcoming the problem of needing to use a significant amount of material in order to simulate its flapping motion. This can be solved by using other factors, such as air resistance as a force to position the wings. All biological components of a bird's wings are essential in capturing the proper flight dynamics. This includes their shape, which is why providing camber to the wings is important in providing the proper amount of lift for a bird simulating robot. In this paper, we discuss the problems faced when trying to replicate the biological flight of an Albatross and discuss a wing design that uses camber and air resistance to assist in flight.

Key Words: flapping, ornithopter, Albatross, robot, wing design, gliding

1. INTRODUCTION

The Albatross is among the largest birds in the world and is the largest seabird. The Wandering Albatross has an average wingspan of ten feet in length, the most of any living bird. The Albatross is the master of energy efficiency, done so through the effective use of gliding. During a glide, an Albatross only drops one meter for every twenty-three meters that it has travelled, which is the highest glide ratio of any bird [1]. The secret to this energy efficient gliding is their wing dynamics. The wings are stiff and cambered, with thickened streamlined leading edges. They are aided in soaring by a shoulder-lock, which is a tendon that locks the wing when fully extended, allowing the wing to keep outstretched without any muscle expenditure. The combination of the stiff, cambered wings and the ability to keep the wings extended without exerting extra energy allows the Albatross to fly and glide incredibly long distances, using very little energy or flapping.

There are several kinds of flying robots, but the one that most closely replicates the flying and gliding dynamics of a bird is the ornithopter, because it uses flapping as its primary source of lift and thrust.

Few scientists have attempted to replicate the dynamics of a bird in flight. Although it does not quite fit the description of a robotic bird, the RoboSwift is currently the most well known robotic bird. The RoboSwift is inspired by the common Swift. The Swift is one of nature's most efficient flyers, which is why it has inspired both airplane engineers and robotics engineers alike to emulate its flying techniques. Aside from its striking visual similarities to a real bird, the RoboSwift is actually not a robotic bird at all. It has few aeronautical similarities to that of the Swift, other than its ability to bend its wings along a horizontal axis during flight to change its wing area and allow it to increase speed [2]. Its wings do not even flap, so it cannot be considered an ornithopter. It is pulled through the air using a propeller on the front of its body.

One of the scientists who has made an effort to replicate avian flight is Sunil K. Agrawal, a professor of mechanical engineering at the University of Delaware [3]. He has been working on robotic flying "birds" that are considered ornithopters. Agrawal's bird is able to maintain flight in the air for several minutes, and withstand impact upon landing. The wings of the robot do not contain a joint, nor do they have any camber, which makes their flapping pattern more closely related to that of a large insect (such as a dragonfly) opposed to that of a bird. Also, unlike the Albatross, Agrawl's bird robots do not have the ability to glide. They simply flap their flat mylar wings repeatedly to maintain lift and achieve enough thrust to propel themselves forward.

Other researchers, such as J.D DeLaurie at the Institute of Aerospace Studies, have done extensive work on ornithopters to determine the best way to effectively understand the relationship between wing design and wing function [4]. DeLaurier has produced a wing design that optimizes lift and thrust. He proposes the idea that a wing should still have the ability to have pitch and bend although it is stationary at the place where it is connected to the gear mechanism. The idea behind this is that the wing's construction should be elastic enough to bend and pitch due to the amount of air resistance and pressure being applied to it as it flaps through the air. DeLaurier's final analysis was that the wing needed to be stiff and rigid on the front side (mounting spot), with a bend throughout (elastic axis). A certain amount of curvature was needed in the entire wing and this measured amount of curvature is camber. He discovered that the wing should be angled with the mounting spot (leading edge) higher than the back, and this angle is determined by the length of the wing. This angle will optimize gliding distance when the wing is stationary. This can be applied to the flight of an Albatross because the stiff, cambered front of an Albatross wing has both pitch and bend, while the feathers along the rear edge of the wing provide elasticity.

Similar to research done by DeLaurier, a group of researchers also referred to the modified strip theory, which will state that the leading edge of the wing is the root, and all other motion in the wing can be associated to the root as a reference point [5]. The researchers used this theory to implement a flexible flapping wing. The flexibility of the wing allows for the flapping motion to be perpendicular to the flapping axis, which assumed a figure eight motion when in a flapping cycle. This is caused by aerodynamic forces.

Gregg Abate at the Air Force Research Laboratory, assisted by Roman Y. Krashanitsa, Dmitro Silin and Sergey V. Shkarayev, have also done research on flight dynamics. Abate and his team conducted a series of tests to find the best flight dynamic of an ornithopter to achieve optimum stability. The test machine that they use is a CyBirdP2, and they tested it by mounting it in a wind tunnel. They blew a constant wind at it to simulate flight velocity, and then flapped the wings at different frequencies [6]. They tested how stable the bird was at each flapping frequency with an onboard flight control system. Similarly, researchers from the Animat Lab, came to the conclusion that for small wings, such as the ones tested, high frequency flapping is required to stabilize slow flight, whereas lower frequency flapping is required to stabilize fast flight [7]. This can be applied to an Albatross also when looking how often an Albatross flaps its wings during the duration of its flight. The highest frequency wing flapping is during the launch when it is moving the most slowly, and the lowest frequency wing flapping is when the Albatross has reached its comfortable flying height, and is going the fastest.

Che-Shu Lin, Chyanbin Hwu, and Wen-Bin Young also did some essential research that discloses why it is important that Albatross wings are stiff in relation to their size. Their research approaches the problem of flapping flight with a very biological viewpoint on how a wing should be constructed based on a bird's wing, but does not actually test any of the discussed topics. They construct a body to mount the wings on out of a gear mechanism, motor, and battery. The wings are then constructed out of very thin plastic and carbon fiber tubes [8]. They test only two different wing constructions to see whether or not there is much difference. Neither of the wings have camber, but both are elastic so they have pitch and can bend. They tested two very different sized wings, both of which flapped at the same frequency. They discovered that no matter how big the wing is when the elasticity of the wing is proportional to the size, the wings will always have the same amount of thrust and lift when flapping at a constant frequency. This is because as the wing size increase, so does the elasticity, and as the elasticity increases, so does the thrust, as well as the air resistance. Therefore, since an Albatross's wings are so large, they have to be stiff, otherwise when they flapped the elasticity would counteract the thrust and lift provided by the flap. A team at MIT did similar research, and concluded that a slow flapping robot with large wings was the most efficient flier [9].

In this paper, we discuss ongoing research on wing and gliding dynamics of an ornithopter. We use knowledge about Albatross gliding abilities, as well as the knowledge that camber and elasticity are both equally important aspects of flight. In this research, we recreate avian flight similar to that of an Albatross by using large wings made of Styro-Foam, that have both camber and elasticity.

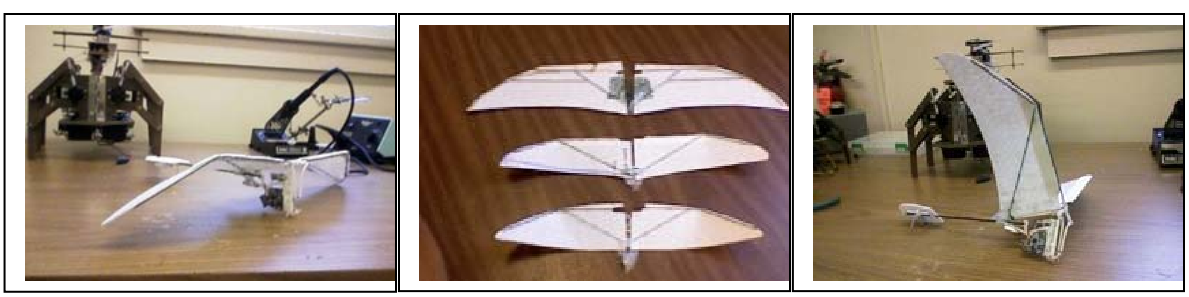

Figure 1. Ornithopter with Firm Felt

2. IS REPLICATION OF AVIAN FLIGHT ON A MACHINE EVEN POSSIBLE?

The question of whether or not replicating avian flight is even possible has proved to be a difficult one to answer. The issue of complexity vs. matter is incredibly hard to conquer. A bird's wing is very complex in the way that it flies. It bends and rotates in six degrees of freedom with each flap. Simulating this requires a great deal of material (motors, gear mechanisms, rods, strings, etc), and the more material that is used in an effort to make the machine more biologically correct, the heavier the machine gets.

A bird is remarkably lightweight. All if the bones in a bird are hollow, allowing for optimal weight efficiency. Simulating this on a machine has proven to be difficult because finding such lightweight materials is virtually impossible. The lighter the material, the weaker it is, and the weaker the material, the less likely that it will have the ability to hold the bird in the air.

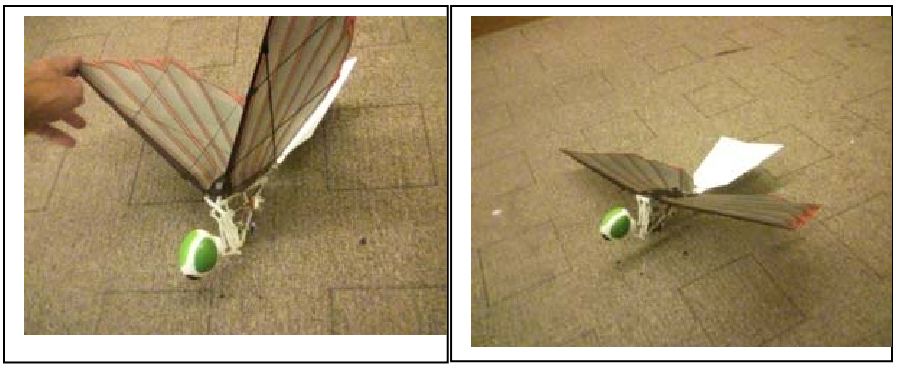

Figure 2. Ornithopter with membrane plastic wings

Our approach to solving this problem was to utilize the force of air. We use air resistance as the driving force that allows the wings of the robot to simulate the figure eight motion of a bird while the wings are flapping. This allows us to preserve the complexity of the wings while providing the extra lift and thrust required to keep the bird in the air. This was done by cutting the wings, vertically, along the leading edge, and then reattaching them by taping their bottoms using lightweight packing tape (as shown and described later). The purpose for having the wing fold up and down while flapping, aside from trying to make it more biologically correct, is to maximize surface area on the downwards flap (while the wing will be folded up in resting position) and minimize air resistance on the upwards flap (while the wing is folded down).

3. DEVELOPMENT PROCESS AND RESULTS

Thus far, we have tried three different materials for the wing design: Firm Felt, membrane plastic, and Styrofoam. The first wing design, as seen in Figure 1, was made of a material called Firm Felt, which was unsuccessful because it did not have the ability to fold, so it only had one degree of freedom. Also, these wings were not cambered, so they did not provide enough lift for the robot. Although wings without camber can still generate lift force if the amount of thrust that is produced by the wings exceeds the amount of drag force, this was not the case with our wings because the mechanism was not producing enough thrust. This was also an issue when membrane plastic wings (Figure 2) were tested. The third set of wings, and best to date, were the Styrofoam wings (Figure 3), which had the ability to fold up and down when flapping in order to maximize surface area on the way down to provide optimal thrust, and minimize surface area on the way up in order to decrease overall friction. The obvious reason why these wings can immediately be asserted as the most successful is because no other wings were able to support the ornithopter while gliding. Additionally, these wings were cambered, so their shape provided natural lift for the robot when soaring thought the air.

Although this wing design proved to be successful, the Figure 3 bird still did not have the ability to glide in between flaps, which is an important aspect in capturing the biological likeness of the flight dynamics of an actual bird. In order to achieve this goal, the wing size to weight ratio had to be greater, which is demonstrated by an Albatross. Using Albatross design information, a larger model was built, as seen in Figures 4 & 5, with a wingspan measuring 134.62 cm. The wings were still constructed with the ability to fold, using the hinge design from the previous, smaller model (Figure 6). Attached to the back of these wings are plastic membrane sections, cut out from earlier membrane wing models (Figure 5). This membrane plastic captures air on the downward flap, and is elastic enough to provide some thrust when releasing the air. Once the wing design was finalized, an onboard 3.7volt battery was attached to run a small DC motor, and the voltage was resisted to only 2.1 volts, to allow for slower flapping.

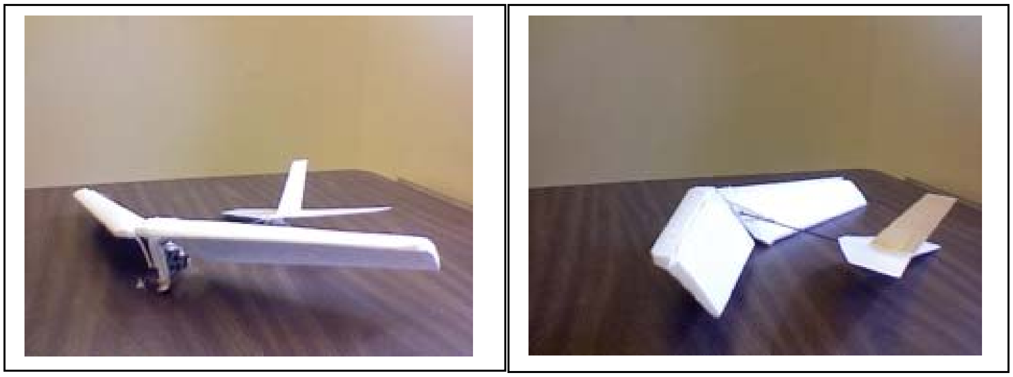

Figure 3. Ornithopter with Styrofoam wings

Test flights involved launching the robotic bird from a steady height. As a result of 20 flight tests with the same variables, we found that after a launch at 71 cm, the average altitude of the machine is 10.17 cm higher while flapping twice (about 2 seconds) than after travelling the same distance while gliding (Table I). This illustrates that the figure eight flapping motion of our machine, modelled after the Albatross, has successfully replicated avian flight dynamics.

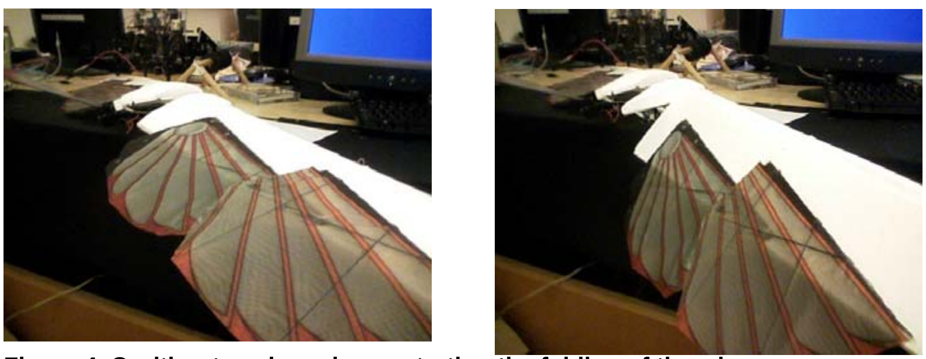

Figure 4. Ornithopter wings demonstrating the folding of the wings

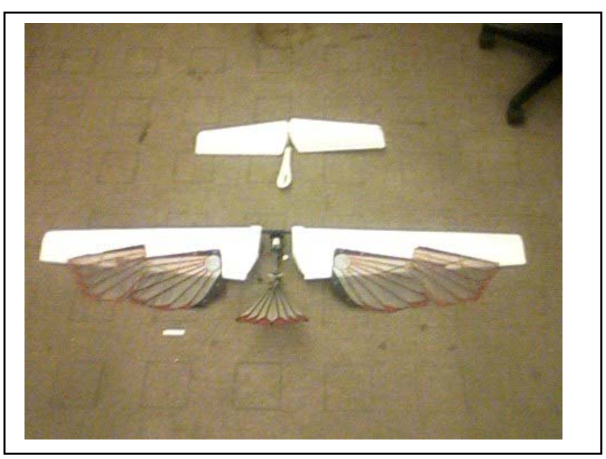

Figure 5. Full-scale newest ornithopter against previous generation ornithopter

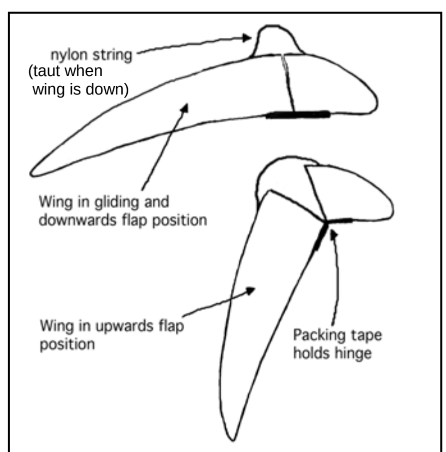

Figure 6. Cross-Section of ornithopter wing

Table I. Test Flight Result Comparison. Results after 20 flight tests while taking the recorded height of the machine after the same period of airtime.

	Mean (cm)	Standard Deviation
Gliding	43.6	2.25
Flapping	53.77	2.28

4. CONCLUSION

Due to the inability to obtain materials that can simulate the bone structure of a bird, we have determined that the best way to simulate the flight dynamics of a bird in a machine is to build the wings in such a way that the air can manipulate the wings into flapping in the same figure eight motion as a bird's wings. The way to replicate the best flapping dynamics is to find the largest wing to body ratio, similar to that of an Albatross, and model the machine according to that. We found that using some form of membrane on the cambered wings will allow for enough lift and thrust to show that the machines' flight does improve while flapping, in comparison to strictly gliding. At this point, the robot has no balancing mechanism, so its flight is limited to a minimal number of flaps, because as soon as the machine becomes off balance in the air, it plummets to one side or another.

5. FUTURE WORK

While we had some success with the wing dynamics of the robotic bird, there are still a number of advancements that we would like to make in the future. The next step is to add a control chip to the frame, so that a servo can be attached to the tail for directional and balance control. Sonar sensors will be attached to the front for obstacle avoidance. These sensors will allow for the robotic bird "see" how far away an object is located in front of it, so that it can adjust the direction of the tail. With these future additions, along with further work on the flight dynamics of the wings, the robotic bird will be autonomous and a reasonable simulation of an Albatross.

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