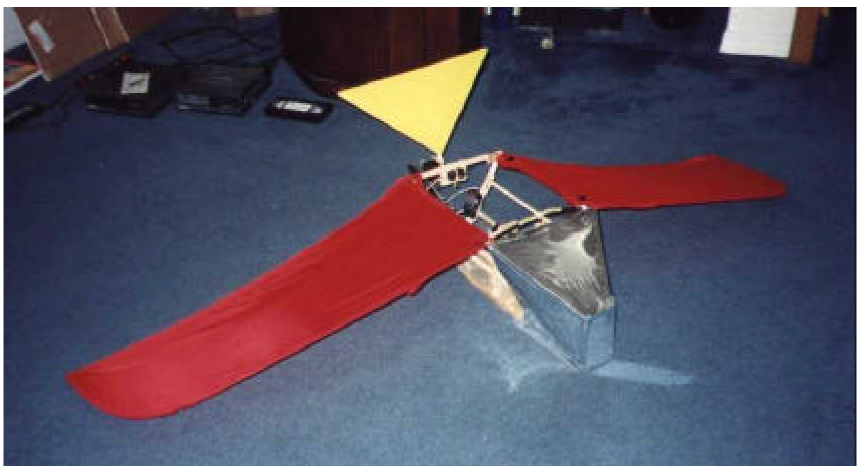
Big Bird: An Autonomous Ornithopter



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Abstract

The purpose of this project was to design, build, and test an autonomous ornithopter. An ornithopter is essentially a mechanical bird. The mobile platform consists of several components: the base, flapping assembly, wings, tail, and nose. We elected to build our ornithopter using an electric motor and membrane wings rather than a gas engine and aeroelastic wings. We designed and built an electrolytic tilt sensor circuit, a voltage monitor, and an emergency takeover circuit. We implemented balancing, takeover, and landing behaviors using these sensors and assembly language programs running on a 68HC11 microcontroller. All software was coded in assembly language to minimize code size and avoid unnecessary complications. Experiments were conducted to optimize the tilt sensor sensitivity, the thrust produced by the wings, and to determine the main battery discharge curve. We determined the drag of our design was too large for the bird to fly; however, modifications and upgraded components could allow for a successful design in the future.

Executive Summary

The goal of this project was to design an autonomous ornithopter. To accomplish this we first needed to build a radio controlled ornithopter, which we then could make autonomous. The body was constructed of balsa wood, cyanoacrylate glue, epoxy, Monokote covering material, and aircraft plywood. The flapping assembly was homemade and consisted of the above materials in addition to PVC piping, steel rods, ball bearings, and rubber bands. An electric model airplane motor was the source of actuation, powered by a NiMH battery. The wings were made of carbon rod and rip-stop nylon. The tail was constructed of balsa and covered with rip-stop nylon. Two servos provided elevator and roll motions for the tail.

We implemented balancing, emergency takeover, and landing behaviors. To provide sensory input to the behaviors, we made a pitch and roll sensing circuit, a battery voltage monitor, and routed a takeover signal from the receiver to the microcontroller. All behaviors were written in assembly language and run on a MC68HC11 microcontroller. We used the output compare, input capture, and A/D converter subsystems of the controller to implement these behaviors. We tested the bird's flying capabilities using different flapping amplitudes and wing designs. This included a set of tests with a secondary fixed wing to provide additional lift. We were unable to achieve flight with our design, other than a powered descent. The drag proved to overpower the thrust produced. Future work should focus on aeroelastic wings and a more streamlined design.

Introduction - Flapping Flight Theory

Aerodynamics involving flapping wings differs in many ways from conventional aerodynamics, however some conventional rules apply. First, the lift produced by the vehicle must exceed the vehicle's weight if it is to climb in altitude. Second the thrust produced by the vehicle must exceed the drag if is to accelerate in the forward direction. The lift produced by the wings of an ornithopter differs from that of a conventional airplane. There are two major types of wings used for ornithopters, membrane wings and aeroelastic wings. Membrane wings consist of flat material that is stretched between the leading edge spar and the root chord. They are generally capable of producing decent downstroke lift, but do not usually generate positive upstroke lift, because the camber of the wings reverses on the upstroke. Aeroelastic wings on the other hand have a fixed camber and therefore can generate positive lift throughout the flapping cycle. These wings pitch and twist as a function of the force applied. This allows them to operate much more efficiently then the membrane wings. Unfortunately, with this efficiency of operation, comes along an increase in complexity of design. It is for this reason that we chose to design and build membrane wings instead of aeroelastic wings, despite their reduced efficiency. Because of our design choice, the remainder of this theory section will focus on membrane wing aerodynamics. This theory is extracted from, The Ornithopter Design Manual[1], by Nathan Chronister, where a more detailed explanation can be found.

Forces Throughout the Flapping Cycle

A conventional airplane uses a propeller for thrust and fixed wings for lift. An ornithopter's membrane wings must provide both of these forces using the same surface. The forces on the membrane wings vary throughout the flapping cycle, in addition to variations in force along the span of the wings. First we will focus on the temporal variations. On the downstroke air is displaced in a downward and backward direction, pushing the wings upward and forward as shown in the figure below.

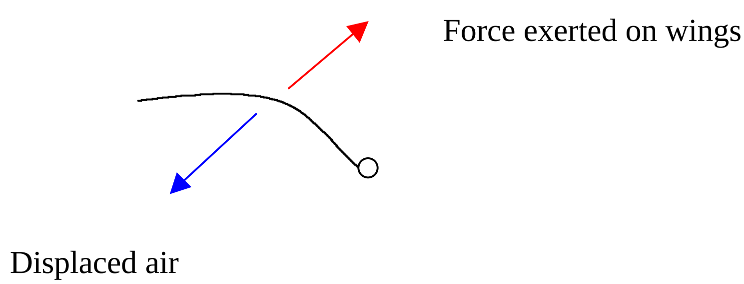

Fig. 1 - Downstroke Forces

Because the front edge of the membrane is fixed to the leading edge spar, and the trailing edge of the membrane is free to swivel within the limits of the material, the trailing edge always lags behind the leading edge. This causes a change in pitch depeding on the direction of motion of the wings. On the downstroke the trailing edge is higher than the leading edge, and so the resultant force on the wings as a forward component. If this were not so, the wings would not be able to generate any thrust.

On the upstroke, this situation is reversed. The trailing edge is lower than the leading edge and so the resultant force on the wings is angled down and forward as is displayed in the figure below. Additionally the camber of the wings reverses to negative.

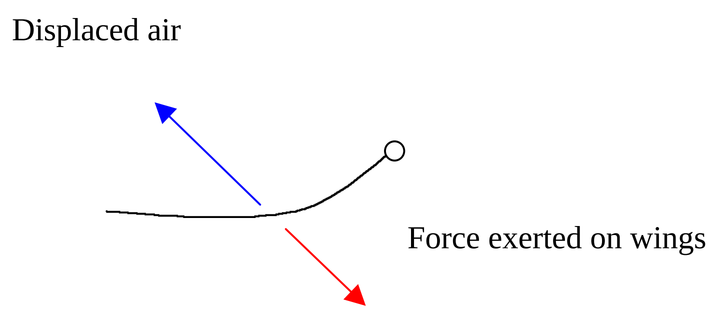

Fig.2 - Upstroke Forces

Averaging out the upstroke and downstroke forces results in the net force shown below. As can be seen this force contributes solely to thrust. No net lift if generated from this configuration.

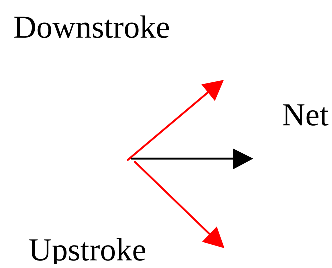

Fig. 3 - Net Forces

Redirecting Thrust

In order to obtain net lift, the line about which the wing hinges must be angled up relative to the direction of motion. This rotates each of the above vectors counter-clockwise by the number of degrees between this hinge line and the angle of motion as is show below.

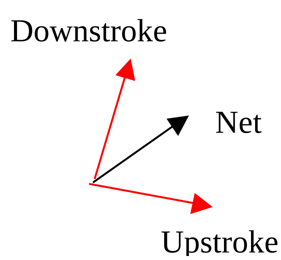

Fig. 4 - Redirected Thrust

Now as can be clearly seen in the diagram above, the net force is no longer solely in the thrust direction. There is also a lift component to it. Most ornithopters, ours included, cannot maintain a hinge angle steep enough relative to the direction of motion to generate enough lift to stay in the air. In fact, since a greater force is needed to lift the ornithopter than to push it, the hinge angle would have to be greater than 45 degrees in order to support the bird. This is obviously not the case. Instead, the additional lift necessary is created in way similar to conventional aerodynamics, by moving air over a cambered surface. It differs, however, in that the camber of a membrane wing changes significantly with respect to distance from the root chord as well as changing from upstroke to downstroke.

During the downstroke, the wing maintains a positive camber as air fills the membrane from the bottom. This results in lift being generated over the entire length of the wing. On the upstroke, the camber of most of the wing reverses since the air is filling the membrane from the top. In the figure below, the main spars of the wing are shown. They form the skeleton of the wing to which the membrane is attached.

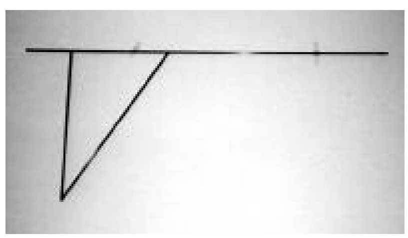

Fig. 5 - Wing Frame

On the upstroke, the air presses against the large portion of the membrane to the right of the triangular piece. Due to the large surface area of this section, the force is sufficient enough to reverse the camber of this portion of the wing. It also pulls the material in the triangular section taught enough that so that the camber is not reversed in this inner section. This is why lift varies so much over the span of the wing. The inner portion of the wing is still capable of generating positive lift on the upstroke, due to it maintaining positive camber. Meanwhile the tip of the wing generates negative lift on the upstroke. At some point between the root chord and the wingtip, an area exists where no lift is generated. It is the inner portion of the wing that generates the extra lift that is needed to support the weight of the ornithopter.

To optimize the amount of lift generated in this manner, the inner portion of the wing, inside the triangle, would need to be expanded. Unfortunately, this cannot continue indefinitely, as an area of negative lift is needed that can keep the material taught over the triangular section. Additionally, the vertical speed of the material increases with distance from the body. Therefore the force needed to keep this inner section taught increases as well.

Stability in Gliding and Soaring Flight

Most birds alive today have wings that are set high on their bodies. Since the weight of the bird is below the wings, and the wings are holding the bird in the air, the bird acts like a pendulum. The stable point for a pendulum is at its bottommost extension. When a bird rolls to one side or another, the weight of the body acts to return the bird to its upright position, and hence provide stability. Additionally, when viewed from the front or back, many birds' wings form a v-shape. This v-shape, or positive dihedral angle, increases the stability of the bird. This occurs for two reasons. According to Georg Ruppell, in his book Bird Flight[2], when a bird has a positive dihedral angle, and rolls to one side, the lift on the lower wing has a larger vertical component, than does the upper wing. Although both wings produce the same amount of lift, this lift is perpendicular to the wings. As one wing is tilted more than the other is, this wings lift is mostly in the horizontal direction, while the other wing's lift is mostly vertical. This additional force acts to return the bird to its stable position. By increasing the dihedral angle, the lift on the upper wing is reduced in the vertical direction, thereby increasing the stabilizing force.

The second reason for the increase in stability of a dihedral angle, is the raising of the average wing height. When a bird has a positive dihedral angle, the average wing chord is located higher up than before. This increases the length of the pendulum, and therefore increases the stabilizing force. The above reasons are why most birds maintain a high wing with a positive dihedral angle.

Integrated System

Big Bird's mechanical systems are composed of two separate assemblies: the flapping assembly and the tail assembly. The flapping assembly consists of an electric motor, gearbox, "T" mechanism (described in Actuation section), and the wings themselves. There are also support structures for these components that are discussed in the Mobile Platform section of this paper. The purpose of the flapping assembly is to provide the lift and thrust that the bird needs in order to fly. The tail assembly consists of two Futaba S148 servos, and the tail itself. The tail is used to steer the bird.

Big Bird is controlled using a Motorola 68HC11 chip on an MSCC11 board from Mekatronix. An electrolytic tilt sensor from the Fredericks Company was used to allow our bird to determine its pitch and roll with respect to the “level” position. Some external circuitry was custom made around this sensor. Circuits were also built to allow for remote control overriding of the onboard computer, and for a sensor that monitors the voltage of the batteries that are used to power the wings. When released, Big Bird tries to balance itself using readings from its tilt sensor, allows a remote user to override all microprocessor commands using a radio transmitter, and signals when its batteries are drained to the point that it will soon no longer be able to flap.

Mobile Platform

The mobile platform was the main focus of our attention in this project. It consists of several important subsections: the base, the gear assembly, the wing support cage, the tail, the nose, and the wings. We will discuss each of these sections in detail.

The Base

The base of the robot consists of a 3” wide by 16” long by 3/8” thick piece of balsa wood glued lengthwise with a 2” wide by 14” long by 3/8” thick piece of balsa (see Fig. 6). We also provided extra support at the joint by gluing two triangular sections of balsa (one on each side) at the joint. The base of each triangle is ½” wide and they are about 3” tall. They were the same thickness (3/8”) as the rest of the base. These provided a more tapered transition from the 3” wide balsa to the 2” wide balsa. All of these joints were glued with model airplane CA glue. This is a special type of superglue that can be purchased at a model hobby shop (we purchased all of our wood and glue at "The Hobby Shop" on the corner of University Ave. and 34th Street).

In order to strengthen the joint, we cut a piece of 1/32" thick model airplane plywood to fit over it. We allowed the piece of plywood to extend 3" along the length of each of the two pieces of balsa. We then glued down the plywood with CA glue. This provided *a lot* of extra strength, and should be done at any joint where balsa needs high strength.

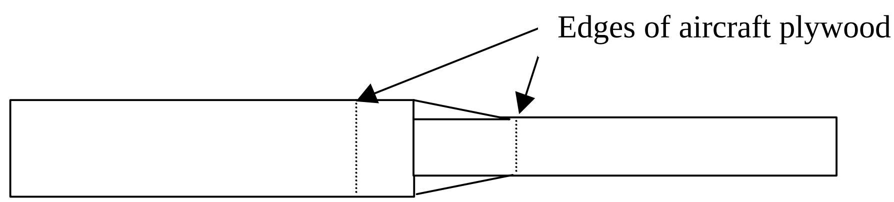

Fig. 6 - The Base

The Gear Assembly

This section of the ornithopter was the one we spent the bulk of our time building. Originally, we wanted to purchase a professional gearbox from a machining company. However, the only ones that we could find cost over $200 dollars, and we could not convince any of the companies to donate one to us. The main lesson we learned in building this assembly was to **purchase a professional gearbox if possible**! This assembly took a long time to design and build, and we continuously had to improve it as the semester progressed. However, our final design is very sturdy. We will discuss each of its components separately.

__The Large Pulleys__

After many different attempts at creating pulley wheels, we decided to try to make some from PVC tubing (we bought this at Lowe's). We used 2 3/8" outside diameter PVC to make our pulleys because we wanted to have a relatively large gear reduction (1:5) for each stage in our gearbox. For each pulley, we cut a 9/16" wide ring off of the PVC pipe and squared off the ends of the ring with sandpaper. Next, we cut two 3" diameter circles out of plywood using the T-tech machine. Finally we cut a 9/16" long piece of ½" diameter wooden dowel to use as a strengthener along the central axis of the pulley. The pulleys were made by first gluing a PVC ring onto one of the plywood circles using CA glue. This step requires some care because the ring must be glued on as centered as possible. Next, we glued a piece of dowel to the plywood circle. The axis of the dowel extends along the axis of the PVC ring, and needs to line up as close as possible to create a well-balanced pulley. Finally, glue the other plywood circle to the other side of the ring, and to the dowel. After this has dried, drill the appropriate size axle hole through the center using a drill press. See figure 7 below for a graphical view of the parts.

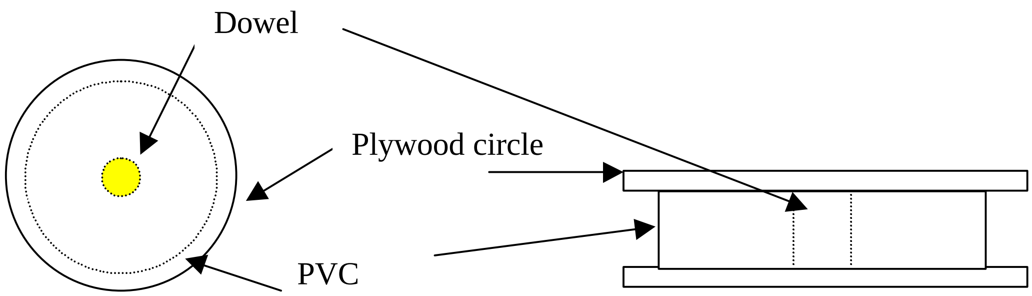

Fig. 7 – Large Pulleys

The Small Pulleys

We could not use the same idea for our small pulleys as we did for the large ones because we needed them to be too small. We needed their diameter to be no larger than about ½" an inch in order to create our 1:5 gear reduction ratio. At first, we tried to use pieces of dowel and drill holes through the center of them to make the pulley, but this proved to be much harder than it sounds. It was impossible for us to drill through the center of the dowel and so the dowel wobbled at least ¼" up and down.

Our next idea was to look at a craft store (Joanne's Fabrics) and see if we could find any thread spools that we could use as pulleys. We found none, but did find a bag of ½" diameter wooden cylinders with holes pre-drilled through their central axes. They were the perfect size, but eventually we abandoned them because they tended to break under the high stresses in our assembly. They would work wonderfully for a lower torque assembly that may be needed in many other projects.

Our final design came by a bit of luck. We found a small aluminum rod, 3/8" in diameter with a hole already drilled through the central axis. We needed to only widen the hole slightly, slip surgical tubing onto the rod to widen the diameter of the rod and provide better grip, and cap the two ends of the rod with two 1 ½" diameter washers to make our pulleys. The length of rod used was 9/16". See figure 8 for a graphical view of the parts.

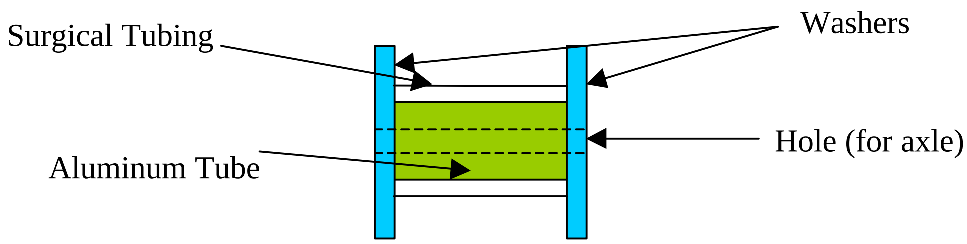

Fig. 8 - Small Pulleys

The Belts

When we decided to use pulleys for our project, we needed to obtain pulley belts from somewhere. Steve remembered seeing replacement vacuum cleaner belts at Wal-Mart. We went there and found that they had several different sized belts for different types of vacuum cleaners. We bought two belts made for a Hoover vacuum cleaner because they seemed to be the closest to the length we needed. They are ½" thick (which is why we made the pulleys 9/16" wide) and about 12" in circumference. They worked well for a long time, and were strong enough to handle the loads of our bird. However, as our project progressed, we ran into a few problems with them. First, as our load reached its final point (with the wing material on), the belts began to slip on the small pulleys. In order to stop this, we would have to install the belts tighter, but this meant increasing the diameter of the pulleys (our axle placement is fixed). A second problem we were having is that the belts would sometimes catch on the edges of the larger pulley wheels and begin to "ride" onto the edges of the pulleys. This problem was enough to usually freeze-up the motor, and had to be solved.

We tried to solve these problems by gluing strips of sandpaper around the inside lip of the larger pulleys to increase their diameter, and thus tighten the belts. After spending a lot of time on this, we realized it would not work. No matter how tight we got the belts, they still slipped, and still caught the edges of the larger pulleys. After many weeks of trying other solutions, we decided to try replacing the belts with No. 64 rubber bands. They worked great! They still caught the edges as the larger belts did, but we found that if we used several, even if one hit the edge, the others would keep the gears going at the same speed until the rubber band worked itself away from the edge of the pulley. You can see the vacuum cleaner belts are used early on in figure 9.

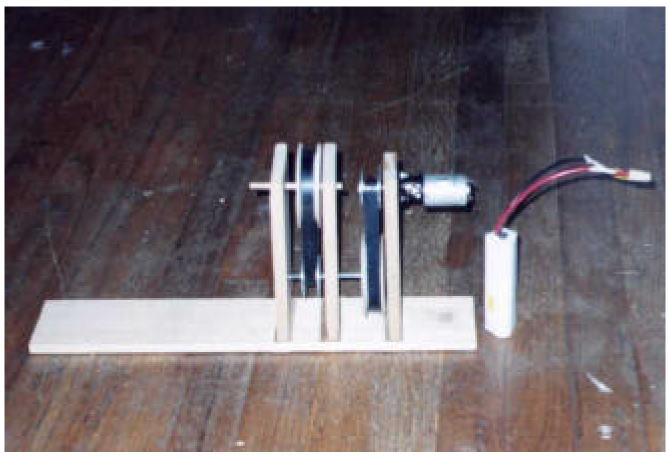

Fig. 9 – Early gearbox

The Axles

Originally, all of our axles were 3/16” diameter wooden dowels. The first time we loaded the gear assembly with covered wings, these axles snapped apart. We ended up using two different axle materials after this. On the first set of gears, we used a piece of 3/16” diameter by 6” long carbon rod that was leftover from building the wings (from Gone With the Wind Kites). However, in order to provide extra strength to the final output shaft, we used a 3/16” diameter by 3 ½” long solid steel rod for this axle.

The Support Structure

In order to hold all of the gears and axles in the correct spots, we needed to build a support structure. This structure consists of three identical balsa/aircraft plywood assemblies. Each piece of balsa measures 3” wide by 6½” tall by 3/8” thick. Then we covered both faces of each balsa piece with a piece of 1/32” thick aircraft plywood using CA glue. These faces need strength because they will hold the ball bearings that will hold the axles. Each of these support pieces was attached to the base (discussed earlier) 2 ¾” apart from each other using two wood screws. The center support is about 10” from the front edge of the base, but this placement is not critical. To strengthen this attachment, we glued ½” wide strips of aircraft plywood across the 3” wide section of the base on the top and bottom at each point where a support was going to be placed. Then, we drilled holes through the base, and screwed into the support structures. Next, we backed the screws out and filled the screw holes with thin CA glue and let the glue dry. This strengthens the wood around the holes after it is dry so that the screws will give a stronger hold. After the glue dried, we screwed the supports back on, and then CA glued around the base of the middle and motor supports. We did not glue around the base of the third support (nearest the nose) so that we could remove it to replace belts, and make other changes. See figure 10 for a picture of the supports on the base.

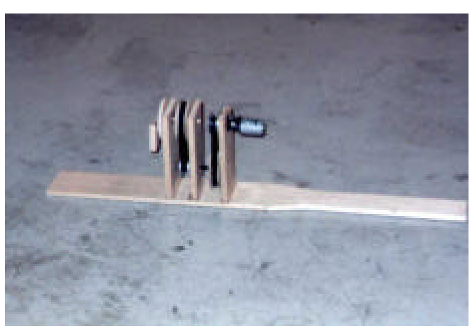

Fig. 10 – Gearbox supports on base

The Motor

Originally, we planned on using a .049 cubic inch model airplane gas motor (bought from Norvel via the Internet). After breaking in our motor, we thought that it would be best to use an electric motor instead. The gas motor was very loud and would have to be run outside. This would have made it time consuming to test parts of the gear system as we put it together. Also, the gas motor was hard to start, and therefore was not as dependable as an electric motor would be.

Our first electric motor was a Speed 400 model from the Great Planes Company. We also bought a 1:2.7 gearbox as an initial gear reduction for the motor. The motor turned out to not be strong enough to run the wings at more than 1 flap per second when they were covered.

Our second motor was a Speed 500 electric motor from the same company. It is capable of outputting over 300W if we need it to. We bought a 1:2.6 gearbox for this motor. This motor is much more powerful, and can flap our wings at over two flaps per second.

Putting it all together

The most important step in making the gearbox is to carefully put the parts together. The first step we had to accomplish was to mount the motor on the back support structure. The first electric (Speed 400) was easy to mount because it had a mounting flange on the front face of the gearbox. We had to only drill a hole large enough for the gearbox axle to fit through, and then drill holes for mounting the motor. The second electric (Speed 500) was more difficult to mount because there was no mounting flange on the gearbox. In short, we had to widen the hole in the support to accommodate the axle of the new gearbox, and we had to glue pieces of dowel to the back of the support as standoffs. Then, we drilled through these standoffs and screwed from the front of the support, through the standoffs, through the gearbox, and into the front face of the motor to attach the motor (the motor can be seen attached in figure 9).

Next, we placed one of the small pulleys on the axle of the gearbox and bolted it on with the supplied nut. We used Loctite (a gritty liquid which we bought from Lowe's) to keep the nut from vibrating loose.

The next step was to determine where to drill the holes in the supports for the ball bearings. We determined this by placing one of the vacuum cleaner belts on the motor pulley, and stretching it around one of the big pulleys. Then, while stretching the belt taut, we eyeballed the location for the ball bearings on the wooden supports, and drilled the ½" diameter holes to accommodate them.

Then we glued the ball bearings into their holes, and placed the remaining pulleys onto the axles. The placement of large and small pulleys can be seen in figure 9. After all of the pulleys were in place and the belts were lined up, we used epoxy to attach the pulleys permanently to the axles.

The final step in building the gear assembly was to glue two leftover plywood circles from the pulleys to each other, and attach these to the output shaft of the gear assembly. This particular connection needs extra strength in order to handle the strong loads at the output shaft. We tried for over a month to glue the wheel on. It would work, but eventually fail after a few minutes of flapping. Finally, we decided to make a stronger attachment by drilling a perpendicular hole into the output shaft and then screwing a screw into the side of the output shaft.

The method we used to drill the hole into the shaft is worth mentioning. It is very hard to drill into cylindrical shafts. We devised a very effective method for doing this. First, drill a hole the same diameter as the shaft into the side of a piece of scrap hardwood. Then, drill a smaller hole perpendicular to the first from the top face of the scrap wood. This hole should intersect the first hole drilled from the side. Then insert the cylindrical rod into the first hole to the depth you wish the perpendicular hole to be drilled through the rod at. Finally, use the small perpendicular hole as a guide to drill into the shaft. This method produced very nice, centered holes without much trouble.

After the hole was drilled, we gouged a recess into the face of the pulley for the screw to sink into. Then we slipped the pulley onto the shaft, screwed the screw into the shaft, and slid the pulley back so the screw fit into the recess in the face of the pulley. Then we CA glued the pulley to the axle and the screw into the slot. See figure 11 for a picture of this.

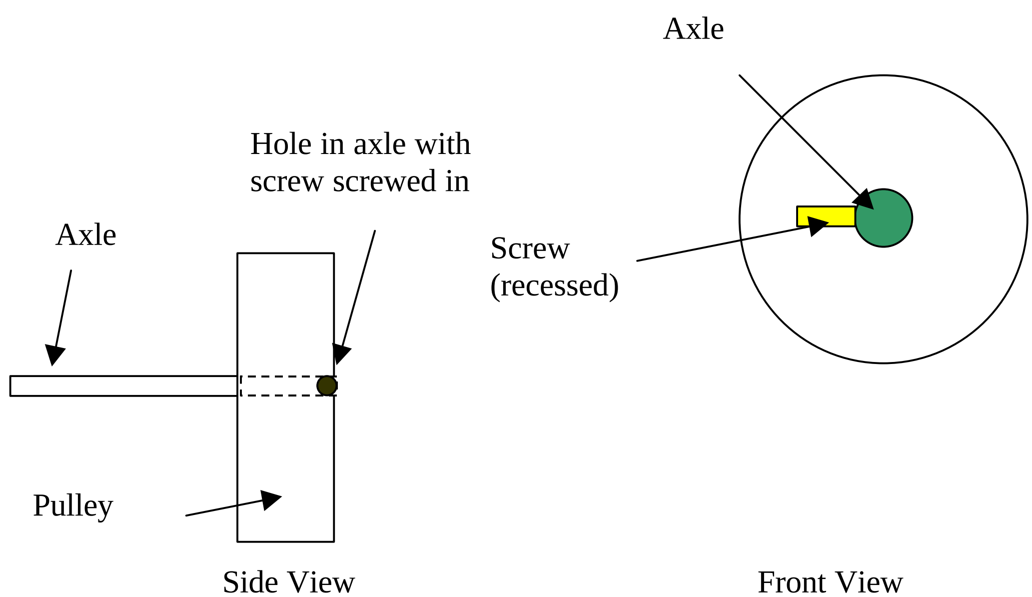

Fig. 11 - Output shaft.

This method was also eventually used on the final large pulley in the gear reduction stage because of the large stress put on this pulley.

The Wing Support Cage

This structure holds the wings at the proper height in relation to the output shaft of the gear assembly. No specific instructions can be given on where to place the flapping axis of the wings. The placement must consider a balance of how much force the engine must produce to flap the wings, where the mid-level of the wings' flap should be located, and how wide the ornithopter will be. A detailed discussion can be found in the references[1].

After balancing our options, we designed the cage so that the wings' flapping axes were about 5" above the central axis of the output shaft, and about 6" to the side. The cage is made of ½" by ¼" strips of balsa. Ball bearings are all placed at each of the four places where the wings' flapping axes will be supported. These spots are also reinforced with aircraft plywood strips. All gluing was done with epoxy to give extra strength to this cage. A picture of the cage mounted on the base around the gear assembly can be seen in figure 12. The top edges each measure 11 ¼" across, the bottom edges measure 2" across each , and the angled supports are 9 ¼" long each. The front-to-back supports are 13 ½" long to accommodate the front-to-back length of the wings.

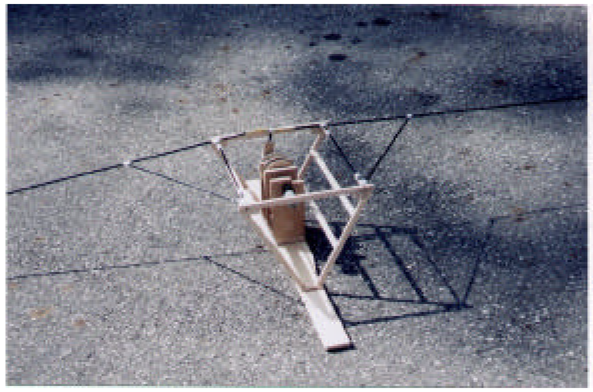

Fig. 12 – Body and wing skeleton

The Tail Assembly

The balsa tail went through two different designs. The first idea was to make the tail an isosceles right triangle with a 1' wide back edge. Hinges attached the two back corners to the rest of the tail (see fig. 13). These back flaps could be alternately pulled up perpendicular to the tail by a Cirrus sub-micro servo using fishing line. There were also rubber bands on the underside of the tail to return the flaps to their original positions after the servo ceased to pull them up. The final component of this tail was a second Cirrus sub-micro servo that was used to lift the tail as a unit up and down. This allowed the tail to steer the bird up and down. The tail was covered with rip-stop nylon (from JoAnn's fabrics).

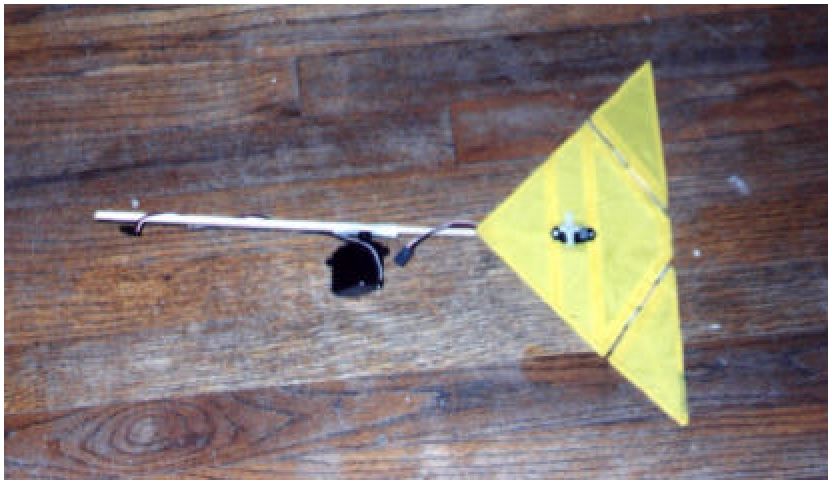

Fig. 13 – Old tail

This tail turned out to be too small. The flaps had no chance of steering the bird because of their small surface area. We eventually moved on to a second, simpler design. This design consists of a single right isosceles triangle made of balsa and covered with rip-stop nylon. The tail provides up and down movement of the bird in the same manner as with the first tail. The steering action is provided by rotating the tail about its central axis (from the right angle vertex to the middle of its hypotenuse) using a second servo. This allows the tail to steer the air as a whole and provide much better turns. In our design, the turning servo is mounted to the bird, and the elevator servo is mounted to this servo. Then the tail is mounted to the elevator servo (see fig. 14).

Fig. 14 – New tail

The Nose

The nose was the easiest part of the bird to build. We made it using CA glue and Monokote sheeting (we purchase Monokote from the hobby store). The nose was made in a freeform manner, with no special attention given to its shape and angles. After the balsa frame was completed, we covered it with Monokote using a model aircraft iron. The nose can be seen in pictures in the appendix.

The Wings

The wings went through several different phases through the course of this project. The basic underlying structure remained the same throughout, though. The wing frames were constructed using .198” diameter hollow carbon rods. The front spars of the wings are 30” long, the inside spars are 13” long, and the triangular spars are 15” long. The inside spar was glued perpendicular to the front spar 6” from one end of the front spar. The 15” long triangular piece was glued from the tip of this inside spar to the front spar (see fig. 15).

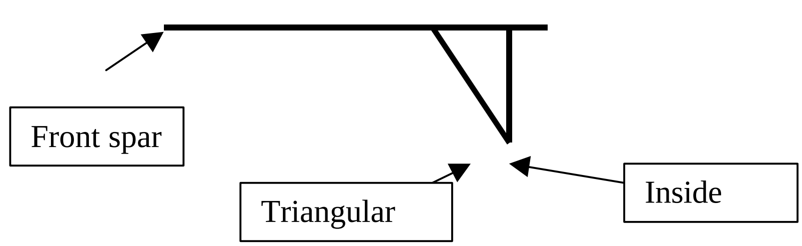

Fig. 15 – Wing frame

The technique by which these pieces were glued together is important. It is not sufficient to just sand the tips of the carbon rods so that they fit together at the proper angles and then glue. This connection is too weak and cannot handle the high stresses of flapping. We decided to lash (surround with windings of string) the joints with 100% cotton string, and then soak the string in superglue. This structure dried rock solid and created strong joints.

All of the wing coverings were sewn out of rip-stop nylon. The first set of wings was in the shape of a right triangle (see fig. 16). Eyelets were sewn at each vertex of the triangle so that bungee cord could be attached at each corner. The bungee was used to stretch the wing covering over the wing frames. The edges of the wings were attached to the frames using Velcro. After testing them, we realized these wings were too small.

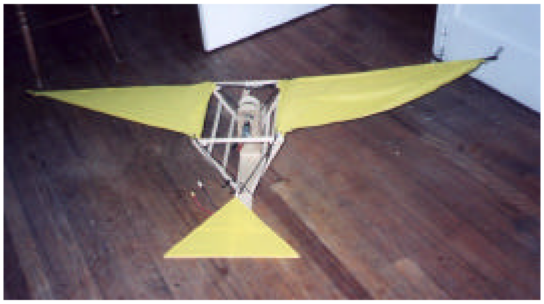

Fig. 16 – First wings

In order to increase the surface area of our wings, we needed a way to make them wider at the wingtips. We accomplished this by CA gluing 1/16” thick pieces of solid carbon rod inside the tips of the first wing frame. They extended 15” from the tip of the first frame. These rods are very flexible, and we were able to bend them down and perpendicular to the front spar (see fig. 17).

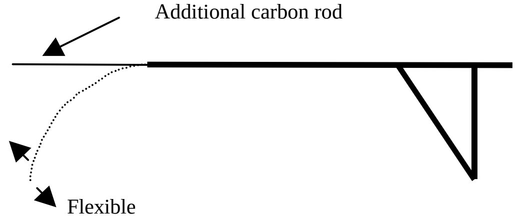

Fig. 17 – New wing frame

The addition of this rod allowed us to create a rip-stop nylon covering that has over twice the area of the first set of wings. As with the first set of wings, we sewed eyelets at the corners of the wings, and stretched the wings over the frame with bungee. We also sewed a small pocket along the front edge of the wing stretching from tip to the point where the triangular spar attaches to the front spar. We slipped this pocket over the carbon rods to attach the wings to the frame. Finally, we sewed a few buttons to the material in other spots to wrap around the spars of the wing frame and attach the material there.

Actuation

Electric Motor

In order to provide enough force to flap the wings at a speed over 2 flaps per second, we bought and installed a Graupner Speed 500 Race electric motor. It has an operating voltage range from 3.6 V to 8.4 V without a gearbox, and 6 V to 12 V with a gearbox. The no-load speed is 21,200 RPM. The idle current drain is 2 A, while the stall current drain is 96 A. The current at which the motor is operating at max efficiency is 14

A. The max efficiency without a gearbox is 76 %. The total weight of the motor is 164 g.

Servos

The tail assembly needs to be able to lift up and down and roll left and right. In order to accommodate these two directions of motion, we used two Futaba Standard Servos. These servos provide approximately 42 oz-in of torque, which we found was strong enough for our application. Initially, we bought 3 Cirrus sub-micro servos. These servos are very small and light, and provide 21 oz-in of torque. When we started out this project, we initially had in mind a smaller bird, and thought these servos would be strong enough for our needs. Unfortunately, as the dimensions of the bird grew, these little servos were no longer strong enough to lift the tail effectively.

We mounted one of the large servos on the trailing edge of the flapping cage. This servo provided roll movements for the tail. To this servos was attached the tail spar. On the tail spar, closer to the tail, the second servo was mounted. This servo provides elevator motion. By using a combination of elevator and roll motions on the tail, we can achieve the same effect as ailerons.

Batteries

To provide the high current needed for the electric motor, we used a 6 cell, 7.2V, 1200 mAh, NiMH battery. We obtained the 6-oz. battery pack from Hobby Lobby International, Inc. We chose NiMH over NiCd because it provides almost twice the running time for the same weight. It also capable of putting the high currents needed.

The servo battery we used was Futaba 4.8 V NiCd standard servo pack. They were capable of outlasting the motor batteries because the current drain on them was much lower.

The microcontroller battery is a rechargeable NiMH 9V battery from Radio Shack. It conforms to the standard 9V-battery size.

Flapping Linkages – T-Bar

To the surface of the output wheel we mounted a small wooden axle. The other end of this axle goes into a ball bearing on a rectangular piece of wood. This rectangular piece forms the base of the T-Bar. The top of the T-Bar and a vertical extension piece is made of carbon graphite rod, the same material as the wing spars. We lashed the horizontal top to the extension piece, which was then glued firmly into the rectangular base. As the output wheel goes around, the T-Bar is forced up and down. Once the top of the bar is attached to the wings, it is limited to an almost vertical motion, imparting this motion to the leading edge wing spars.

Fig. 18 – T - bar and surgical tubing

Surgical Tubing

Connecting the T-bar to the leading edge wing spars are two pieces of surgical tubing. The surgical tubing was obtained from a slingshot replacement kit (Model 3330) made by Marksman. The surgical tubing serves as a universal joint, allowing for rotating in several directions. This joint proves more useful than an elbow joint because it allows for slight misalignments between the T-bar and the leading edge spars. Additionally, the elastic properties of the surgical tubing prove useful. On ornithopter files better when the downstroke is faster and more powerful than the upstroke. When the T-bar is going down and the wings are going up, the surgical tubing is stretched because the leading edge spars cannot go down as far as the T-bar. The stretching of the tubing slows down the upstroke and stores some energy in the elasticity of the surgical tubing. When the T-bar comes back up, the wings are going down, and the tubing releases the energy it has stored. This speeds up the downstroke, contributing to a more powerful downstroke than upstroke.

Sensors

There are three main types of sensors on Big Bird, an electrolytic tilt sensor, a battery monitor, and a takeover sensor. The tilt sensor monitors the pitch and roll of the ornithopter so that we can implement a behavior to stay balanced. The takeover sensor monitors the pulse width of channel four of the radio control receiver unit. It watches to see when we push the channel four transmitter stick all the way to the right. This is our signal to the bird that we wish to take over control from the microprocessor. When the stick is moved all the way to the left, control is given back to the microprocessor. The takeover sensor is responsible for distributing this control. The final sensor on Big Bird is the battery monitor. The battery monitor watches the voltage of the battery. When the battery voltage drops to 6 V, the battery monitor sets a flag in the software that we use to implement a landing behavior.

Electrolytic Tilt Sensor

In order for Big Bird to be able to balance while in flight, he needs to have a sensor to measure his pitch and roll relative to the plane of the earth. The Fredericks Company (2400 Philmont Ave, Huntington Valley, PA. 19006-0067) donated a dual-axis electrolytic tilt sensor to us (Model # 0717-4405-99 Rev. C). The factory publishes a test circuit that can be used in conjunction with the dual-axis sensor, but we elected to design our own circuit in order to keep the parts needed to a minimum. The suggested test circuit can be found in the Fredericks' catalog entitled "Electrolytic Tilt Sensors", but we will not discuss it further here since we did not use it.

The electrolytic bulb measures tilt by acting as a series of variable capacitors. The sensor consists of a glass bulb that is partially filled with a capacitive fluid, and has five internal vertical metal rods mounted in a '+' configuration (see fig. 19). As the sensor tilts along one axis, the amount of fluid between one outside pole and the center pole becomes greater, and the amount of fluid between the other outside pole and the center pole becomes less. Thus the capacitance increases between the first set of poles, and decreases between the second set of poles. If we apply an AC signal on the two outside poles of and axis, then the AC voltage measured at the center pole varies depending on the tilt of the sensor. This technique can be used to determine the tilt on both axes.

Tilt Sensor Circuitry

We designed a custom circuit to power and interpret the results of the tilt sensor. The circuit diagram can be seen in figure 20. There are five major blocks that make up

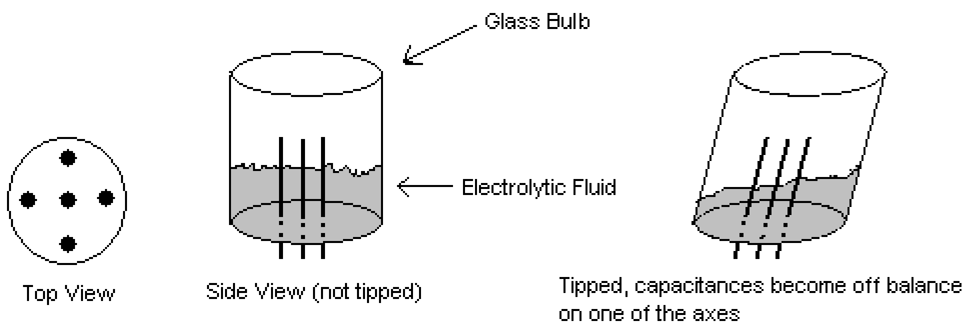

Fig. 19 – The electrolytic tilt sensor

the circuit. The first is a square-wave oscillator. It creates the 1250Hz AC signal used to power the electrolytic bulb. The frequency of 1250Hz was chosen because it gives an impedance of around 130Ω (this will affect our sensitivity), and allows for easy filtering of the output signal into a DC voltage (requires a small filtering capacitor).

The second block is the axis selection block. It is a multiplexer that allows the microprocessor to select from which axis it is going to take its measurements. One of the major simplifications that we made in our circuit is that both axes of the tilt sensor share the amplifier and AC/DC conversion circuits. This allows us to have less hardware on the bird, but requires us to switch between axes as we take measurements.

The third block is the electrolytic sensor. It has "leg" resistances on both sides of both axes to limit the current that flows through the bulb. According to the part specifications, this current should not exceed 15mA. These "leg" resistances were one of the variables we tested in our experiments to see how they affected the operation of the circuit.

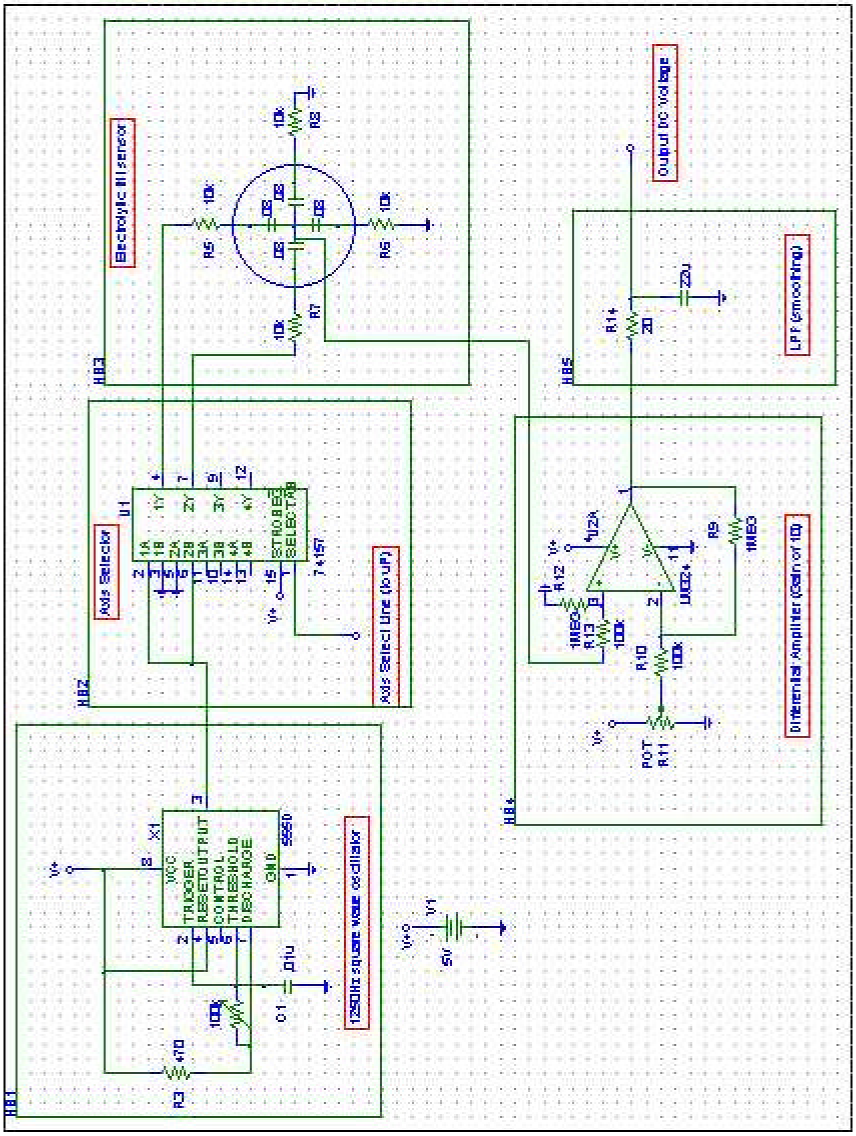

Fig. 20 – Sensor Circuit

The fourth block is a differential op-amp amplifier with a gain of 10. It takes the AC output wave from the center pin of the electrolytic bulb and amplifies the difference between this wave and a reference DC voltage by a factor of 10. The reference voltage can be altered using the 10kΩ potentiometer in this functional block. Using this potentiometer, we can adjust the center of our amplified range.

The final block is an integrating filter. The filter takes the AC square wave output of the differential amplifier and integrates it into a DC signal. This DC signal is what is read by the microprocessor to determine what its pitch and roll are.

Tilt Sensor Software driver

The driver for this sensor was fairly easy to implement. Using one output compare module (OC5), we created periodic 21ms readings of the A/D port. We used 21ms updates because the processor is also running servo pulse width modulation (PWM) routines on three other output compares. By giving the sensor update routine the same period as the servo routines, we can begin the sensor routine during a common dead portion of all three of the servo routines (during the long "low" time of the PWM pulse), and guarantee that this will always be where it runs.

One A/D pin is connected to the DC output from the sensor board and reads the tilt level of the currently selected axis. Two queues, one for each axis, are stored in memory. They keep track of the past sensor readings for each axis. The depth of each queue is specified at the top of the program listing in the macro QUEUE_LENGTH. After a queue is filled, it is averaged, and then overwritten with new data as it arrives. The most recently computed average value is kept in a global variable (ROLL_AVG or PITCH_AVG). These values can be used by a behavior that needs the current pitch and roll.

The only other function of the driver is to multiplex the axis. This is done by toggling PORTB, pin 1 between one and zero. The algorithm is simple:

1) Toggle PORTB, pin 1 (done at the end of the interrupt service routine (ISR)).
2) Exit the ISR.

3) At the start of the next interrupt, perform an A/D on the sensor pin.

4) Do the bookkeeping routines to update queues.

5) Go to step 1).

All of the code that has been written so far for this project can be found in the appendix.

Tilt Sensor Experimental Layout and Results

To characterize our tilt sensor, we mounted the sensor board, on a small sheet of plywood, aligning the axes with the sides of the wood. Placing the wood near the edge of a level desk, we used a protractor to measure the angles at which each voltage measurement was recorded. This setup is far from perfect, but our accuracy in measuring with the protractor is believed to be within a degree. The voltage measurements were taken using a Radio Shack Pocket Digital Multimeter (Model #22-179A), set to DC measurement. We recorded all values within a series, either pitch or roll, at one sitting.

Pitch and Roll Series 1 Data

This experiment was the first using the actual circuitry that will be used on Big Bird. As such, we did not have a clear idea what resistance values would be optimal for our particular sensor. The Fredericks Company provided us with expected values of resistors to obtain the desired characteristics; however, we were not using the exact sensor that they specified. In addition, we designed our sensor circuitry quite different from their design. We therefore had to make an educated guess as what values would be best for our circuit. This experiment is conducted using the resistance values determined by our educated guessing. We estimated that our sensor had an impedance around 100 ohms and we wanted to use as small a resistance as possible while still keeping the current under the specified maximum of 15 mA. We therefore chose 470 ohms as a good starting value for the sensor leg resistors.

The data taken in Series 1 of our experiments is shown below. As can be seen from the Voltage/Degree chart, the slope has nonzero value only between –20 and 20 Degrees. This defines the useful range for the sensor. Outside this range, the curves are approximately horizontal, and we therefore would not be able to detect any significant difference in voltage between angles.

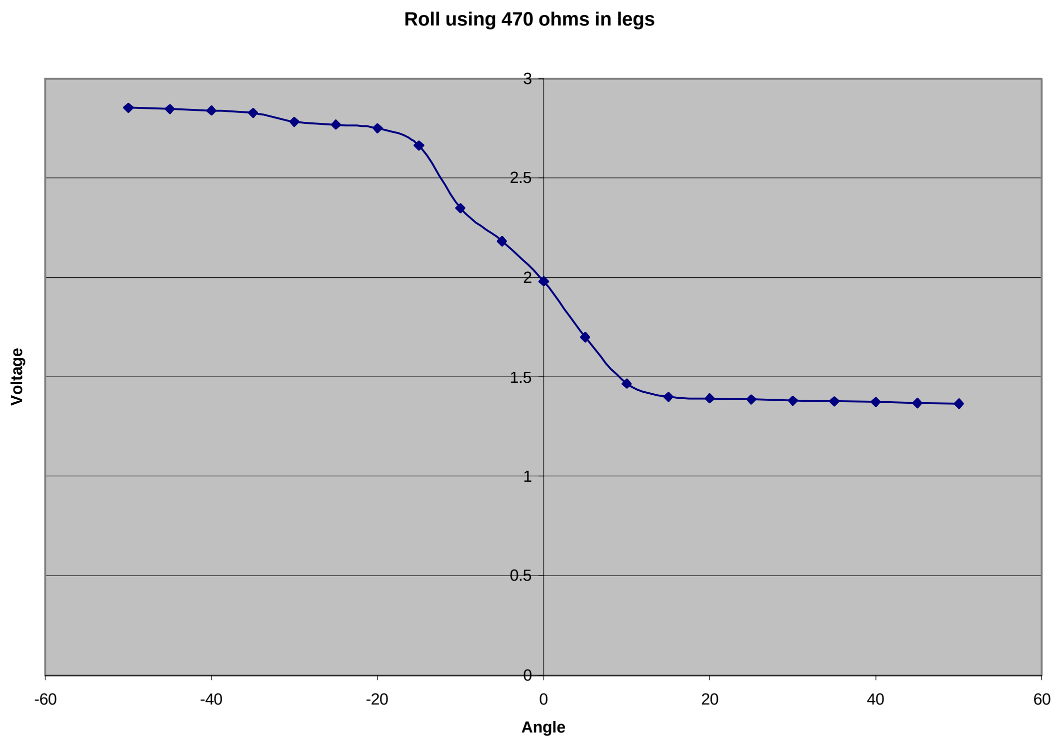

Fig. 21 - Roll Series1 Chart

	Roll (x) using 470 ohms			Voltage(V) Statistics	
Angle(deg)	Voltage(V)	dV per 5 Deg	dV per Deg		
-50	2.853	0.006	0.0012	Mean	2.049952381
-45	2.847	0.009	0.0018	Standard Error	0.142946685
-40	2.838	0.01	0.002	Median	1.98
-35	2.828	0.047	0.0094	Mode	#N/A
-30	2.781	0.013	0.0026	Standard Deviation	0.655064003
-25	2.768	0.018	0.0036	Sample Variance	0.429108848
-20	2.75	0.087	0.0174	Kurtosis	-1.948899871
-15	2.663	0.315	0.063	Skewness	0.138490007
-10	2.348	0.166	0.0332	Range	1.487
-5	2.182	0.202	0.0404	Minimum	1.366
0	1.98	0.28	0.056	Maximum	2.853
5	1.7	0.233	0.0466	Sum	43.049
10	1.467	0.067	0.0134	Count	21
15	1.4	0.009	0.0018		
20	1.391	0.005	0.001		
25	1.386	0.005	0.001		
30	1.381	0.004	0.0008		
35	1.377	0.003	0.0006		
40	1.374	0.005	0.001		
45	1.369	0.003	0.0006		
50	1.366				

Table 1 – Roll Series 1 Data

This can also be expressed in terms of sensitivity. The following chart displays the sensitivity of the sensor throughout the tested range. This was computed by taking the instantaneous slope between each of our data points. The chart is in terms of the delta voltage per degree. From this chart, it is easy to see that the useful range of the circuit is only between –20 and 20 degrees, where the sensitivity is greater than resolution of the A/D on the 68HC11.

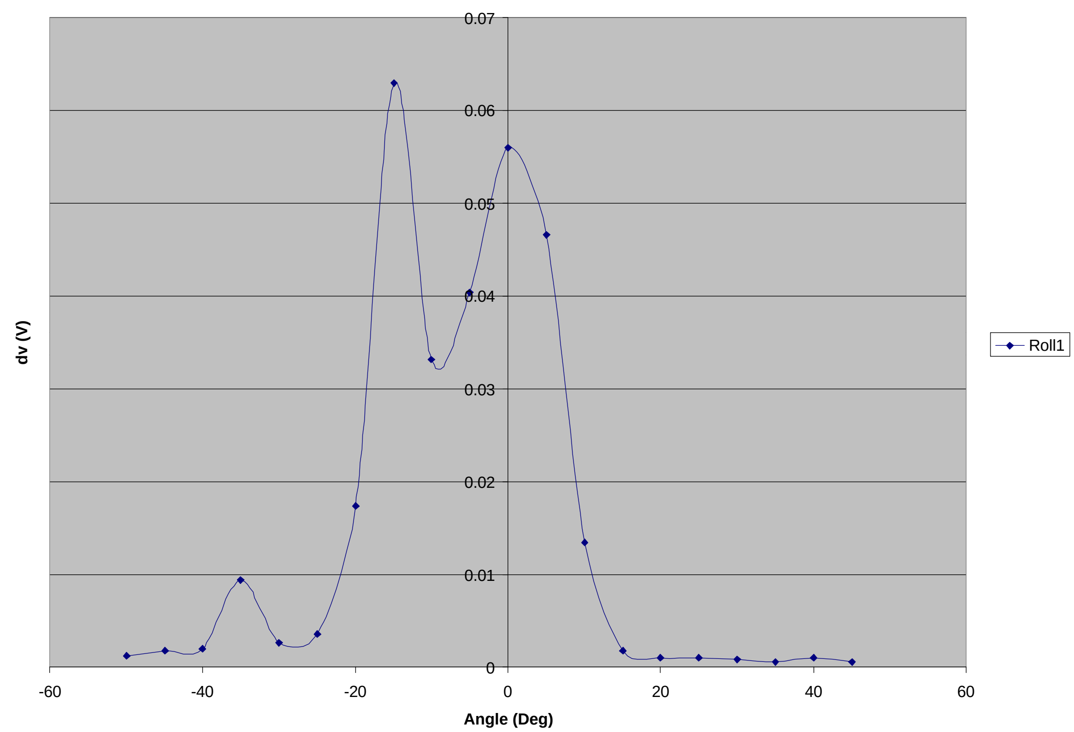

Fig. 22 - Roll 1 Sensitivity

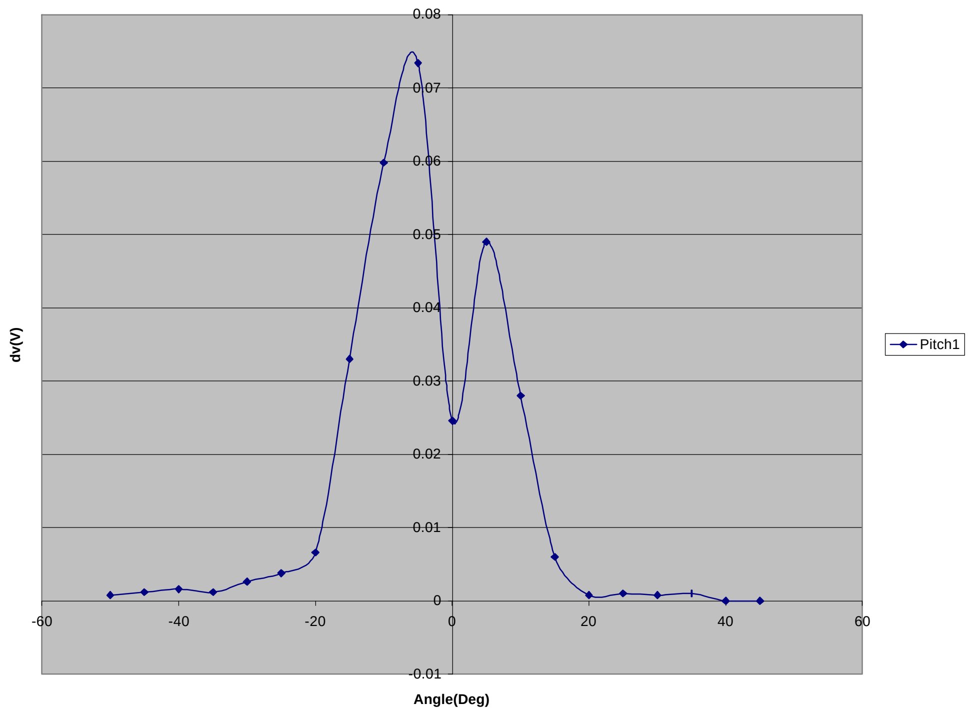

Fig. 23 - Pitch Sensitivity

Pitch and Roll Series 2 Data

This series of data was taken using 220 ohms resistors in the sensor legs in place of the 470hms resistors. This was done in hopes of increasing the sensitivity of the sensor. As can be seen from the charts below there is no noticeable increase in sensitivity or in useful range.

		Roll(x) using 220 ohms in legs			
Angle(deg)	Voltage(V)	dV per 5 Deg	dV per Deg	Voltage(V)	
-50	2.879	0.004	0.0008		
-45	2.875	0.007	0.0014	Mean	2.153666667
-40	2.868	0.008	0.0016	Standard Error	0.1467824
-35	2.86	0.008	0.0016	Median	2.19
-30	2.852	0.012	0.0024	Mode	#N/A
-25	2.84	0.015	0.003	Standard Deviation	0.67264146
-20	2.825	0.017	0.0034	Sample Variance	0.452446533
-15	2.808	0.085	0.017	Kurtosis	-1.959616425
-10	2.723	0.265	0.053	Skewness	-0.111257585
-5	2.458	0.268	0.0536	Range	1.506
0	2.19	0.099	0.0198	Minimum	1.373
5	2.091	0.296	0.0592	Maximum	2.879
10	1.795	0.339	0.0678	Sum	45.227
15	1.456	0.049	0.0098	Count	21
20	1.407	0.011	0.0022		
25	1.396	0.006	0.0012		
30	1.39	0.005	0.001		
35	1.385	0.005	0.001		
40	1.38	0.004	0.0008		
45	1.376	0.003	0.0006		
50	1.373				

Table 2 – Roll Series 2 Data

Roll Series 3 Data

After having unsuccessful results with the 220-ohm resistors, we decided to head in the other direction and increase the resistance. We therefore chose a value of 1K for this series of measurements. We did not repeat the pitch measurements with this new configuration because we felt the roll sensitivity had not increased enough and this would also be indicative of the pitch. From the charts below, it can be seen that the sensitivity may have increased slightly. More noticeable is the shift in peak sensitivities that has been occurring among many of our charts. This is caused by our adjustment of the offset voltage of the op-amp. We have been adjusting the op-amp offset between series, to compensate for differences in the two leg resistors. The leg resistors are intended to be matched, however, there were minor differences in resistance and this caused the center (0 degree) voltage to drift away from our desired center. We adjusted the offset to try and re-center this, however as can be seen from all of our charts, we did not always get the center voltage to remain consistent.

		Roll(x) using 1K in legs			
Angle(deg)	**Roll3 V**	**dV per 5 Deg**	**dV per Deg**	**Voltage**	
-50	2.863	0.006	0.0012		
-45	2.857	0.012	0.0024	Mean	2.078666667
-40	2.845	0.007	0.0014	Standard Error	0.144550557
-35	2.838	0.013	0.0026	Median	2.015
-30	2.825	0.013	0.0026	Mode	#N/A
-25	2.812	0.032	0.0064	Standard Deviation	0.662413869
-20	2.78	0.156	0.0312	Sample Variance	0.438792133
-15	2.624	0.112	0.0224	Kurtosis	-1.93715899
-10	2.512	0.27	0.054	Skewness	0.051057125
-5	2.242	0.227	0.0454	Range	1.516
0	2.015	0.153	0.0306	Minimum	1.347
5	1.862	0.233	0.0466	Maximum	2.863
10	1.629	0.202	0.0404	Sum	43.652
15	1.427	0.049	0.0098	Count	21
20	1.378	0.009	0.0018		
25	1.369	0.006	0.0012		
30	1.363	0.004	0.0008		
35	1.359	0.005	0.001		
40	1.354	0.003	0.0006		
45	1.351	0.004	0.0008		
50	1.347				

Table 3 – Roll Series 3 Data

Roll Series 4 Data

This series of data was taken using 10K resistors in the legs. We increased the resistance from the former 1K values because we saw in increasing trend in sensitivity as we increased the resistance.

	Roll Using 10K in legs				
Angle(deg)	Roll4 V	dV per 5 Deg	dV per Deg	Voltage	
-50	2.786	0.009	0.0018		
-45	2.777	0.014	0.0028	Mean	2.279142857
-40	2.763	0.026	0.0052	Standard Error	0.097839915
-35	2.737	0.04	0.008	Median	2.372
-30	2.697	0.036	0.0072	Mode	#N/A
-25	2.661	0.03	0.006	Standard Deviation	0.448358817
-20	2.631	0.067	0.0134	Sample Variance	0.201025629
-15	2.564	0.055	0.011	Kurtosis	-0.625460723
-10	2.509	0.079	0.0158	Skewness	-0.694311746
-5	2.43	0.058	0.0116	Range	1.407
0	2.372	0.068	0.0136	Minimum	1.379
5	2.304	0.059	0.0118	Maximum	2.786
10	2.245	0.074	0.0148	Sum	47.862
15	2.171	0.075	0.015	Count	21
20	2.096	0.095	0.019		
25	2.001	0.105	0.021		
30	1.896	0.123	0.0246		
35	1.773	0.145	0.029		
40	1.628	0.186	0.0372		
45	1.442	0.063	0.0126		
50	1.379				

Table 4 – Roll Series 4 Data

Roll Series 5 Data

After deciding that we had reached an appropriate resistance value for the circuit. We decided to try increasing the gain of the op-amp to 20 instead of 10. This was done in hopes of better mapping our range from 0V to 5V. With the gain set at ten our range varied from about 1.3V to 2.85 V. If we could increase the range from 0V to 5V, then the sensitivity would increase throughout all measurable angles. The charts below show the measurements we obtained using an op-amp gain of 20. As can be seen from the charts, an increase in sensitivity was not obtained. In fact, a decrease in sensitivity is evident.

	Roll using 10K, gain=20				
Angle(deg)	Roll5 V	dV per 5 Deg	dV per Deg	Voltage	
-50	2.839	0.01	0.002		
-45	2.829	0.009	0.0018	Mean	2.143047619
-40	2.82	0.011	0.0022	Standard Error	0.135000767
-35	2.809	0.012	0.0024	Median	2.16
-30	2.797	0.014	0.0028	Mode	#N/A
-25	2.783	0.024	0.0048	Standard Deviation	0.618651233
-20	2.759	0.06	0.012	Sample Variance	0.382729348
-15	2.699	0.122	0.0244	Kurtosis	-1.846404679
-10	2.577	0.149	0.0298	Skewness	-0.128019864
-5	2.428	0.268	0.0536	Range	1.482
0	2.16	0.184	0.0368	Minimum	1.357
5	1.976	0.105	0.021	Maximum	2.839
10	1.871	0.133	0.0266	Sum	45.004
15	1.738	0.139	0.0278	Count	21
20	1.599	0.135	0.027		
25	1.464	0.074	0.0148		
30	1.39	0.013	0.0026		
35	1.377	0.008	0.0016		
40	1.369	0.006	0.0012		
45	1.363	0.006	0.0012		
50	1.357				

Table 5 – Roll Series 5 Data

Pitch and Roll Series 6 Data

Having decided to return to a gain of 10 with leg resistors of 10K. We matched the leg resistor values as close to each other as possible, on both the pitch and roll axes. This was done in hopes of centering the sensitivity and range around 0 Degrees, which corresponded to approximately 2 V. The four matched leg resistors had actual values of 9.79 K each. We also balanced the resistors used in setting our op-amp gain, as it simplifies the equations that describe the op-amp. The op-amp uses two 100K and two 1M resistors. The actual values for the resistors were 97.9 K matched and 1.010M matched, respectively. As can be seen from the charts below, the sensitivity was spread more uniformly throughout the usable range. Notice how the voltage changes almost linearly throughout the entire tested range.

	Roll using 9.79K, gain=10				
Angle(deg)	Voltage	dV per 5 Deg	dV per Deg	Voltage	
-50	2.742	0.059	0.0118		
-45	2.683	0.088	0.0176	Mean	2.008809524
-40	2.595	0.095	0.019	Standard Error	0.097444358
-35	2.5	0.077	0.0154	Median	2.018
-30	2.423	0.077	0.0154	Mode	#N/A
-25	2.346	0.07	0.014	Standard Deviation	0.446546148
-20	2.276	0.065	0.013	Sample Variance	0.199403462
-15	2.211	0.052	0.0104	Kurtosis	-1.202562478
-10	2.159	0.065	0.013	Skewness	0.039093377
-5	2.094	0.076	0.0152	Range	1.369
0	2.018	0.076	0.0152	Minimum	1.373
5	1.942	0.067	0.0134	Maximum	2.742

10	1.875	0.065	0.013	Sum	42.185
15	1.81	0.079	0.0158	Count	21
20	1.731	0.09	0.018		
25	1.641	0.091	0.0182		
30	1.55	0.109	0.0218		
35	1.441	0.047	0.0094		
40	1.394	0.013	0.0026		
45	1.381	0.008	0.0016		
50	1.373				

Table 6 – Roll Series 6 Data

	Pitch Using 9.79K, gain=10				
Angle(deg)	Pitch6 V	dV per 5 Deg	dV per Deg	Column1	
-50	2.782	0.059	0.0118		
-45	2.723	0.093	0.0186	Mean	2.042809524
-40	2.63	0.106	0.0212	Standard Error	0.097075048
-35	2.524	0.077	0.0154	Median	2.05
-30	2.447	0.083	0.0166	Mode	#N/A
-25	2.364	0.063	0.0126	Standard Deviation	0.444853753
-20	2.301	0.064	0.0128	Sample Variance	0.197894862
-15	2.237	0.059	0.0118	Kurtosis	-1.083724754
-10	2.178	0.06	0.012	Skewness	0.019831172
-5	2.118	0.068	0.0136	Range	1.405
0	2.05	0.075	0.015	Minimum	1.377
5	1.975	0.052	0.0104	Maximum	2.782
10	1.923	0.059	0.0118	Sum	42.899
15	1.864	0.075	0.015	Count	21
20	1.789	0.098	0.0196		
25	1.691	0.069	0.0138		
30	1.622	0.113	0.0226		
35	1.509	0.099	0.0198		
40	1.41	0.025	0.005		
45	1.385	0.008	0.0016		
50	1.377				

Table 7 – Pitch Series 6 Data

Comparison of Series 1-6

The chart below, in Figure 24, shows all six roll series plotted on the same chart for easy comparison. Notice how the linear region of the early sets of data is much steeper and covers smaller range than the final series. Also notice that all six sets start and end at about the same point. That is because the op-amp is saturating at these points, which does not change regardless of our sensor leg resistances. As can be seen from the chart, the final set of measurements, with the balanced 10K resistors gives a fairly linearly curve over almost the entire range.

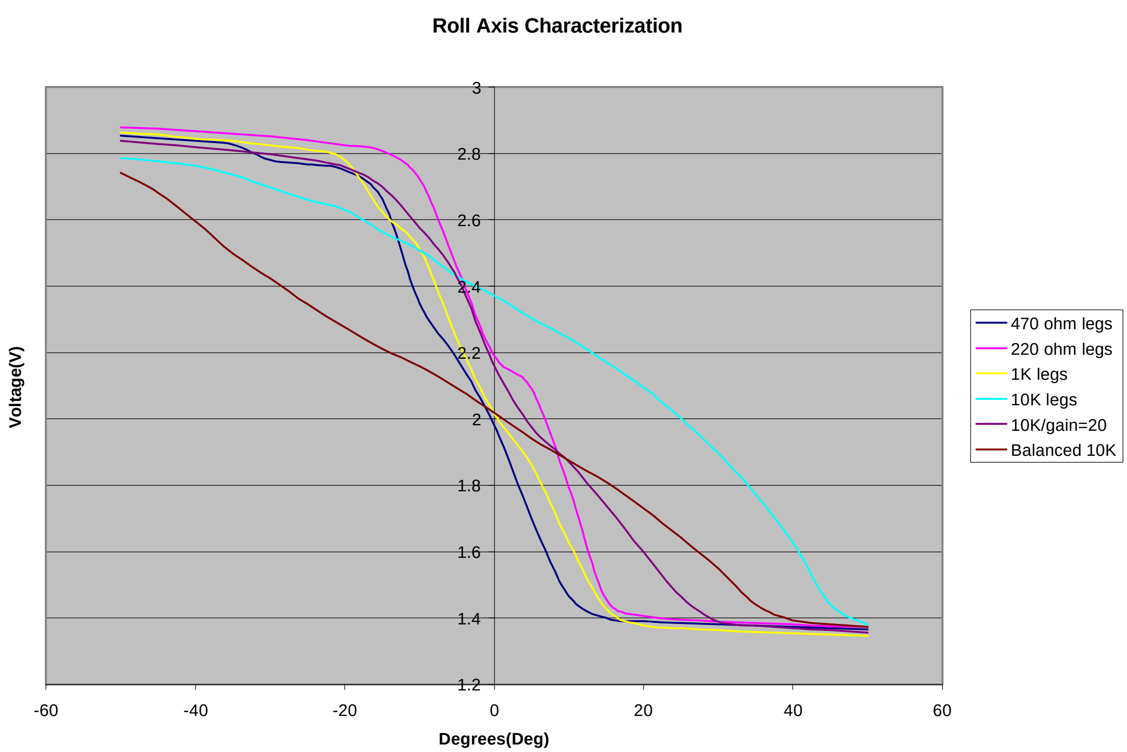

Figure 24 - Roll Axis Characterization

Another view of this data below, in Figure 25, shows how the voltage changes rapidly over the interior of the range on the early sets of measurements. This chart which is an elevation map of voltages vs. degrees, clearly shows the uniformity in the final set of measurements.

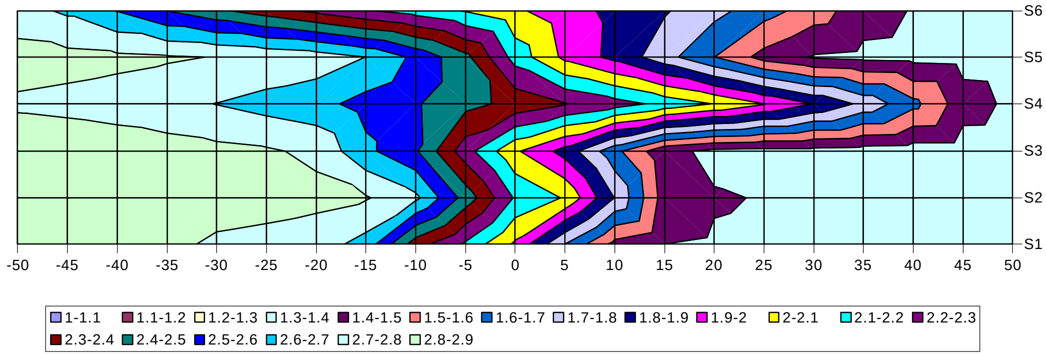

Figure 25 – Roll Axis Contour

A comparison of sensitivity values for the roll axis also reveals the changes that occurred with different values of leg resistances. Sensitivity was calculated by taking the voltage difference between 5-degree measurements. This approximated a first order derivative of the data. The sensitivity of the roll axis from series 1-6 is shown below in 3D graph and contour graph below in Figures 26 and 27 respectively.

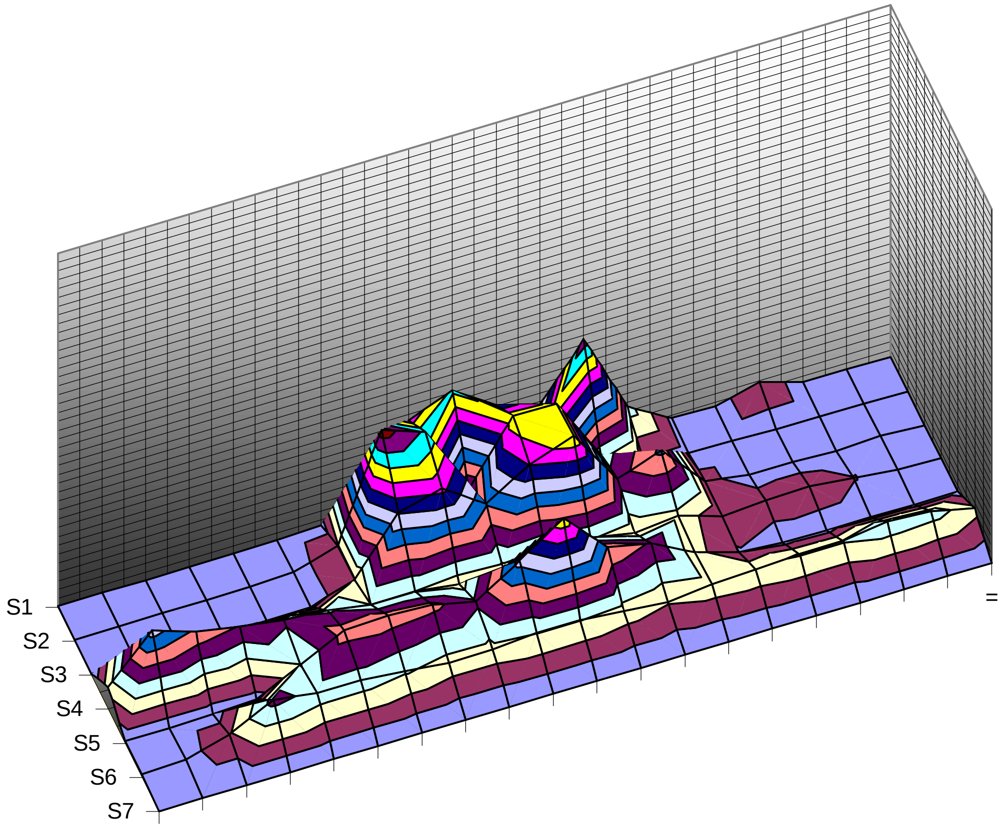

Fig. 26 – Roll Axis Sensitivity

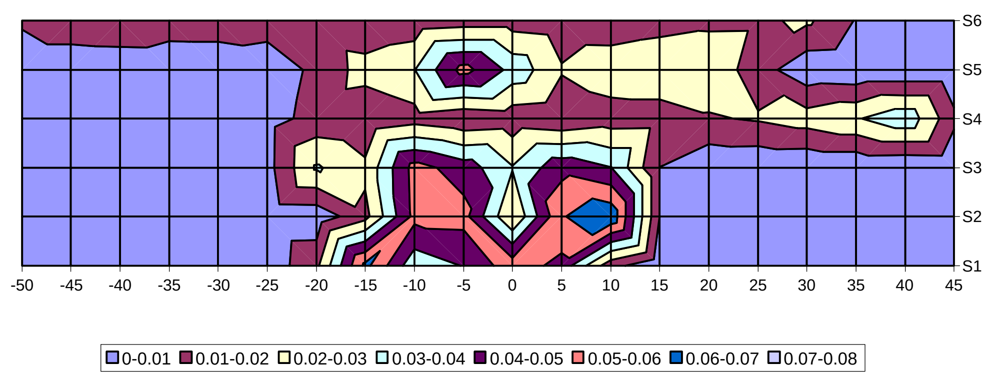

Fig. 27 – Roll Axis Sensitivity Contour

In the chart above, S7 is added for padding so that Series 6 is made visible. S7 is not a series of measurements. As you can see, Series 6 has a wide range of values that are readable by the A/D port. The contour graph above is provided just for clarity, as the 3D graph can get a little confusing. Again you can see the extended range of the last data series.

Tilt Sensor Conclusions

By adjusting the resistance values in the sensor legs, and changing the op-amp gain, we were able to optimize our sensor circuitry for our needs. The next logical step for us will be to characterize the effects of vibration on the sensor, as it will be in almost constant vibration when mounted on the ornithopter. Luckily for us, we don't need highly accurate measurements (down to the degree). In order to control the ornithopter, we only need to generalize our orientation into five distinct categories for each axis: far left, left, center, right, and far right.

The only problem we encountered during our characterization was a time constant problem with the sensor. This is due to the capacitance of the sensor and resistance of the legs, as it takes time to charge and discharge. In our circuit, we switch between both axes every 21 ms. We were worried that this time constant would pose a problem, however we have found that the sensor does still work with the rapid switching, but it centers itself about a different voltage. We may need to re-characterize the sensor after we finish debugging the software that activates the axes.

Battery Monitor

The battery monitor's primary responsibility is to monitor the voltage of the battery. As the battery voltage drops, its ability to flap the wings is reduced. At some critical point, it can no longer provide the force necessary to move the wings and the motor stalls. As mentioned earlier in the section describing the motor, the stall current is 96 A. At this high of a current it does not take long for the batteries to overheat. In order to protect the battery from this dangerous situation, we decided to initiate a landing sequence before we reach this point. Below is the voltage characterization for the NiMH batteries along with the cutoff point we chose. The raw data is displayed first followed by the characterization curve in Fig. 28.

Time(s)	Voltage(V)
0	8.27
5	6.83
10	6.72
15	6.72
20	6.66
25	6.6
30	6.55
35	6.48
40	6.37
45	6.45
50	6.43
55	6.32
60	6.56
65	6.49
70	6.44
75	6.37
80	6.35
85	6.25
90	6.35
95	6.3
100	6.29
105	6.27
110	6.22
115	6.28
120	6.21
125	6.37
130	6.14
135	6.15
140	6.13
145	6.12
150	5.98
155	5.96
160	6.04
165	5.93
170	5.85
175	5.86
180	5.66
185	5.62
190	5.38
195	4.55
200	5.09
205	5.32

Table 8 - Battery Voltage Data

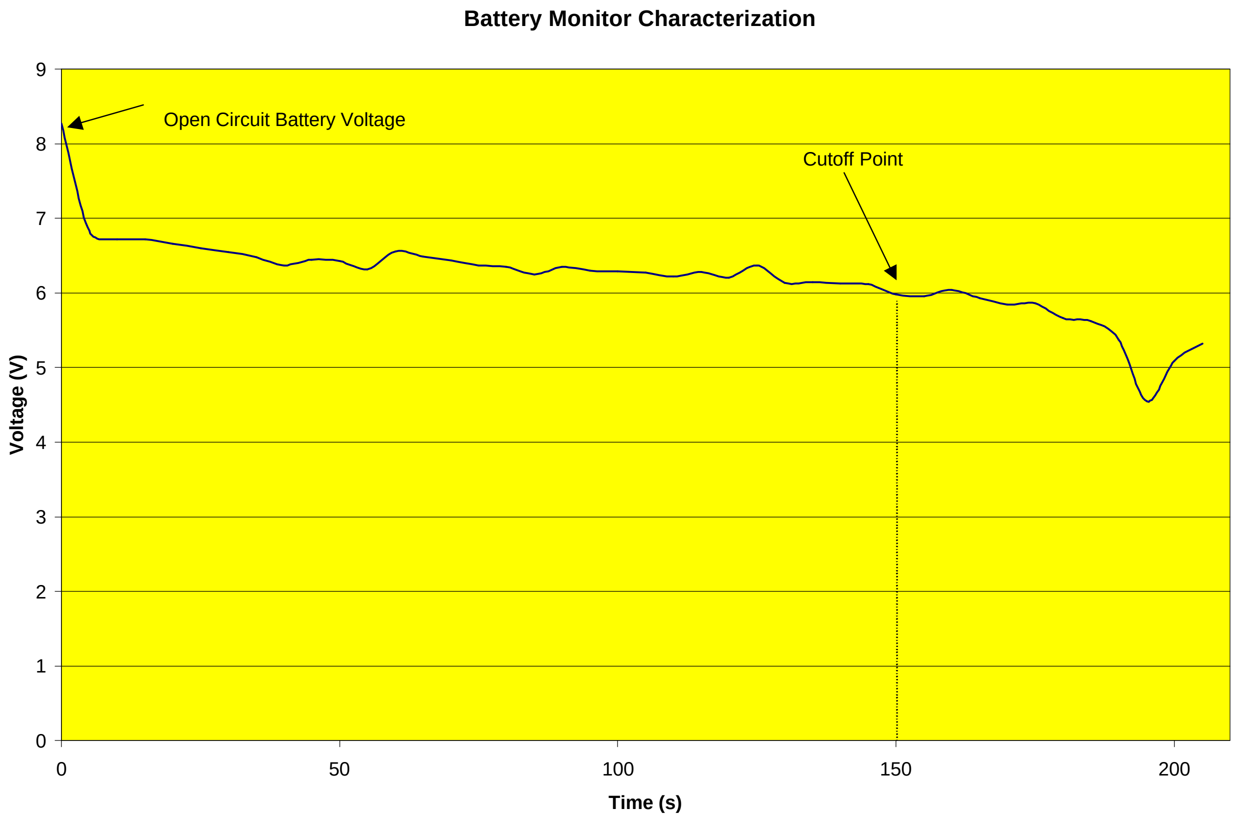

Fig. 28 - Battery Characterization Curve

As can be seen in the chart above, the open circuit voltage of a freshly charged NiMH battery is 8.4 V. This is slightly higher than the listed voltage of 7.2 V. When the battery is connected to the circuit, the voltage drops almost immediately to a voltage much closer to the listed voltage of the battery. Notice that around 180 seconds, the voltage drops significantly, this is the point where the battery can no longer power the wings. We wish to avoid this undesirable situation and set the cutoff point for 6 V, which occurs at 150 seconds (as can be seen above).

The battery monitor, which consists of a simple voltage divider network, cuts the battery voltage in half so that it can be read by the A/D subsystem of the 68HC11. When the A/D reads a voltage below 3 V, it sets a flag in the software. The flag is used to initiate a landing signal behavior.

Takeover Sensor

Our first takeover circuit was implemented in hardware. It worked well, but we abandoned it in order to save weight. The circuit diagram is in the appendix, for any people who may want to use this circuit in the future. It monitors a channel of the receiver and integrates the pulse of the pulse width modulation. It then compares this value with a preset value using two comparators. If the stick is pulled left, the flip-flops will flip the logic circuitry and cause the relays to switch to microprocessor control. If the stick is pulled right, the comparators will cause the flip-flops to flip and the logic circuitry causes the relays to switch to transmitter control.

Eventually, we moved to a software-based implementation to save weight. It is briefly discussed in the Behavior section of this report.

Behaviors

Balancing

Big Bird's balancing behavior is probably his most important behavior. Without it, he would have no way to tell whether or not he is flying level. The software for this behavior monitors the average current voltage reading from the tilt sensor for both the pitch and roll axes. It then compares each of these values to the voltage values corresponding to “no tilt” (one for each axis), and then linearly maps the difference between each pair onto the range of controlling values for the servos. Servo position changes are made by overwriting a single memory location (of the form SERVx_UP, where x is the servo number). This location is what is read by a particular servo to determine where it should be turned to.

Output compare 5 is used to periodically read all external sensors. The tilt sensor is multiplexed between axes by this routine, and each axis’ voltage values are stored in a separate queue of values. The length of both queues is defined by a macro at the beginning of the program. The subroutine AVGLEVEL is used to average the current values in each queue and store the average values to variables used by the routine BALANCE.

Takeover

A second important behavior is the takeover behavior. In order to be able to correct for errors while Big Bird is “learning” to balance itself, we need a way to override the microcontroller’s control of him while he is flying. The takeover behavior is controlled using a leftover channel on our transmitter, and is implemented in software in the input capture number one interrupt service routine. It monitors channel four from the receiver, and looks for a change in the channel’s output. If the transmitter stick is pulled fully in one direction, the routine switches control to the microcontroller by flipping a bit that controls the external takeover circuit. If the stick is pulled fully in the other direction, the routine switches control to the transmitter by flipping the bit in the other direction. The switching is done using a quad two-input-one-output multiplexer.

Landing

The landing behavior monitors the voltage level of the battery pack that is powering the wings. When it falls below a predefined level, the tail is wagged up and down to signal that the bird must land soon. This behavior is the first one that has the capability of overriding other behaviors. It also has several software “locks” associated with it.

The first lock is locked upon reset. The landing behavior waits until the battery has been applied, and then looks for the voltage to drop below the threshold value. Otherwise, the bird would signal that it needs to land upon every reset, unless the wings were flapping beforehand.

Once this lock has been opened, the behavior looks for the voltage to drop below the threshold value. At this point, the bird subsumes both the balancing behavior and the takeover behavior. Then it wags the tail up and down. Finally, it ceases to subsume the balance and takeover behaviors, and subsumes itself. In this manner, the tail can wag without being overridden by the balancing behavior or the remote control through the takeover behavior. And, once the behavior has completed, it may never run again until after reset.

Experimental Layout and Results

We conducted experiments to optimize the tilt sensor used in Big Bird’s balancing behavior. These experiments have been previously described in the Sensors section of this report. We also conducted experiments in an attempt to optimize the flapping and wings of Big Bird. These will be described here.

Wing Size

Big Bird's wings went through several design stages. These have been previously described in the Mobile Platform section. It was clear that the first set of triangular wings were too small after we tried flapping them for the first time. They produced almost no thrust. As a result we redesigned the wing frame and were able to double the wing area. This set of wings produced much more thrust, and thus we decided to perform other experiments using this set of wings.

Amplitude

By altering how far away from the center of the gearbox's output wheel we placed the flapping tee, we could alter the amplitude of the flaps. We experimented with many different values of amplitude to determine the advantages of each. We discovered what we expected to discover – the small amplitude provided fast flaps, but not as much thrust, and the large amplitude provided slower, higher thrust flaps. Also associated with the larger amplitude was a more jerky flapping motion. We compromised by settling on an amplitude approximately in the middle of the range we experimented with. It provided thrust, but was not so jerky that it caused the bird to gyrate wildly.

Additional Wings

After we had given up on trying to optimize our membrane wings and flapping amplitude, we decided to add a set of fixed, cambered wings. These wings provided the lift that we felt was missing and not allowing our bird to fly. In theory, these wings should have allowed Big Bird to fly. They were used on a glider of comparable weight and provided enough lift for it to fly. However, Big Bird would still not stay airborne.

When we ran with him he would lift out of our hands, but as soon as we released him, he would slow down and drop. This experiment provided us with enough evidence to conclude that Big Bird doesn't have enough thrust to fly.

Conclusion

We made several attempts at a radio controlled/autonomous ornithopter. Although we weren't successful at achieving powered flight, we did achieve a powered descent. We did not exhaust the available as we ran out of time, giving us hope for the future. We developed several important construction techniques that will be valuable on other projects. These include the universal joints from surgical tubing, the casting of the wing joints using cotton string lashing and CA glue, a technique for drilling through metal rods, an inexpensive lightweight pulley system, and a technique allowing us to sturdily screw into balsa wood. We also used a technique, introduced to us by the owner of The Hobby Shop, that allowed us to strengthen balsa joints by gluing aircraft plywood to them.

In the future, we would like to develop a more streamlined body. In order to achieve this, it will be necessary to obtain a manufactured gearbox. Our pulley system, although lightweight, is large in size and difficult to work with. It would be ideal for a less demanding application, however under the heavy loads we submitted it to, it continually needed repairs. We would also like to experiment with aeroelastic wings[3] to achieve a more efficient flap. Additionally, we would like to try using a gas motor instead of the electric motor, as the energy density of the gas is much higher than any batteries existing to date.

Documentation

[1] Chronister, Nathan, The Ornithopter Design Manual, The Ornithopter Modeler's Society, 1996

[2] Rupell, Georg, Bird Flight, Van Nostrand Reinhold Company, New York, NY, 1997

[3] DeLaurier, James D., "Ornithopter Wing Design", Canadian Aeronautics and Space Journal, V40 No 1, Mar 1994, p 10-18

Vendors/ Suppliers

The Fredericks Company
P.O. Box 67
2400 Philmont Ave
Huntingdon Valley, PA 19006-0067
(215) 947-2500
http://www.frederickscom.com/

Gone with the Wind Kites
200 Industrial Road - #100
San Carlos, CA 94070
(650) 594-1055
http://www.gwtw-kites.com/

Hobby Lobby
5614 Franklin Pike Circle
Brentwood, TN 37027
(615) 373-1444
http://www.hobby-lobby.com/

The Hobby Shop
Corner of University Ave and W 34th St.
Gainesville, Fl

Radio Shack
3315 SW Archer Rd
Gainesville, Fl 32608
(352) 375-2426

Wal-Mart

Mekatronix
316 NW 17th Street, Suite A
Gainesville, FL 32603
(407) 672-6780
http://www.mekatronix.com

Jo-Ann's
Corner of NW 43rd St and NW 16th Ave
Gainesville, Fl

Appendix

A1 – Pictures

A2 – Complete Pitch And Roll Data

	470 ohms	470 ohms	220 ohms	220 ohms	1K	10K	10K, gain=20	9.79K, gain=10	
Angle(deg)	Roll1 V	Pitch1 V	Roll2 V	Pitch 2 V	Roll3 V	Roll4 V	Roll5 V	Roll6 V	Pitch6 V
-50	2.853	2.85	2.879	2.88	2.863	2.786	2.839	2.742	2.782
-45	2.847	2.846	2.875	2.876	2.857	2.777	2.829	2.683	2.723
-40	2.838	2.84	2.868	2.872	2.845	2.763	2.82	2.595	2.63
-35	2.828	2.832	2.86	2.867	2.838	2.737	2.809	2.5	2.524
-30	2.781	2.826	2.852	2.858	2.825	2.697	2.797	2.423	2.447
-25	2.768	2.813	2.84	2.849	2.812	2.661	2.783	2.346	2.364
-20	2.75	2.794	2.825	2.841	2.78	2.631	2.759	2.276	2.301
-15	2.663	2.761	2.808	2.826	2.624	2.564	2.699	2.211	2.237
-10	2.348	2.596	2.723	2.797	2.512	2.509	2.577	2.159	2.178
-5	2.182	2.297	2.458	2.61	2.242	2.43	2.428	2.094	2.118
0	1.98	1.93	2.19	2.42	2.015	2.372	2.16	2.018	2.05
5	1.7	1.807	2.091	2.161	1.862	2.304	1.976	1.942	1.975
10	1.467	1.562	1.795	1.921	1.629	2.245	1.871	1.875	1.923
15	1.4	1.422	1.456	1.632	1.427	2.171	1.738	1.81	1.864
20	1.391	1.392	1.407	1.413	1.378	2.096	1.599	1.731	1.789
25	1.386	1.388	1.396	1.399	1.369	2.001	1.464	1.641	1.691
30	1.381	1.383	1.39	1.389	1.363	1.896	1.39	1.55	1.622
35	1.377	1.379	1.385	1.384	1.359	1.773	1.377	1.441	1.509
40	1.374	1.374	1.38	1.38	1.354	1.628	1.369	1.394	1.41
45	1.369	1.374	1.376	1.377	1.351	1.442	1.363	1.381	1.385
50	1.366	1.374	1.373	1.373	1.347	1.379	1.357	1.373	1.377

A3 – Source Code

```
***************************************************************************
* PROGRAM:      FINAL.ASM
* PROGRAMMER:   MICAH O'HALLORAN AND STEVE HOROWITZ
* DATE:         DEC. 2, 1998
* VERSION:      1.5
* DESCRIPTION:  THIS PROGRAM OUTPUTS A PWM SIGNAL APPROPRIATE FOR DRIVING
*               STANDARD SERVOS.  THE PERIOD FOR THE TOTAL WAVE IS
*               ABOUT 21ms, AND THE PWM VARIES BETWEEN ABOUT 1.05ms (LOW)
*               TO ABOUT 1.9ms (HIGH).  NOTE THAT THE TIMING OF THIS PROGRAM
*               DEPENDS ON THE SETTINGS OF PR0 AND PR1 IN THE TMSK2 REGISTER.
*               IT ALSO CONTAINS THE ROUTINE FOR THE TAKEOVER INPUT CAPTURE.
*               IT IMPLEMENTS THE LANDING BEHAVIOR, TAKEOVER BEHAVIOR, AND
*               BALANCING BEHAVIOR.
* USES:         OC2, OC3, OC4, 0C5, IC1
***************************************************************************
*
* DATA SECTION
*
***************************************************************************
* INTERRUPT VECTORS

                ORG $FFFE
                FDB    MAIN

                ORG $FFE0
                FDB    OC5_ISR
                FDB    OC4_ISR
                FDB    OC3_ISR
                FDB    OC2_ISR


                ORG     $FFEE
                FDB    IC1_ISR
****************************************************************************
* CONSTANTS
****************************************************************************
*

TCTL1   EQU    $1020
TCNT    EQU    $100E
TFLG1   EQU    $1023
TMSK1   EQU    $1022
TMSK2   EQU    $1024
CFORC   EQU    $100B
TOC1    EQU    $1016
TOC2    EQU    $1018
TOC3    EQU    $101A
TOC4    EQU    $101C
TOC5    EQU    $101E
TCTL2   EQU    $1021
TIC1    EQU    $1010
TIC2    EQU    $1012
TIC3    EQU    $1014
PORTB   EQU    $1004
OPTION  EQU    $1039
ADCTL   EQU    $1030
ADR1    EQU    $1031
ADR2    EQU    $1032
ADR3    EQU    $1033
ADR4    EQU    $1034
DDRC    EQU    $1007
PORTC   EQU    $1003
PORTE   EQU    $100A
PACTL   EQU    $1026
```

```
****FOR SERVOS*****
PULS_LEN EQU    42000           ;THE LENGTH OF ONE PERIOD OF SIGNAL
MID_POSITION EQU 3000           ;MIDDLE POSITION (IN E-CLOCKS) OF SERVOS
OC2_START_DELAY EQU 1000        ;THE E-CLOCK DELAY BEFORE OC2 SHOULD START

****FOR TAKEOVER SYSTEM****
MICRO_ON EQU    %11111110  ;BITMAPS FOR SETTING PORT B
RCVR_ON  EQU    %00000001  ;
PULLED_LEFT EQU   2500     ;THE THRESHOLD VALUE FOR STICK TO COUNT AS "LEFT"
PULLED_RIGHT EQU  3400     ;"    "        "      "    "   "   "    " "RIGHT"

****FOR SAMPLING ROUTINE****
ROLL_ON EQU     %11111101       ;THE MASK FOR TURNING ROLL MEASUREMENT ON
PITCH_ON EQU    %00000010       ;THE MASK FOR TURNING PITCH MEASUREMENT ON
OC5_DELAY EQU   4000            ;DELAY FROM START OF OC4 BEFORE OC5 RUNS
QUEUE_LENGTH EQU 4              ;LENGTH OF PITCH AND ROLL QUEUES

****FOR BALANCING BEHAVIOR****
MID_LEV_ROLL   EQU %01100111    ;MID LEVELS FOR TILT AND PITCH
MID_LEV_PITCH  EQU %01101111    ;


****FOR LANDING BEHAVIOR****
*BAT_THRESH    EQU  %10011001    ;LANDING TAKEOVER THRESHOLD VALUE (3V)
BAT_THRESH  EQU %00011001

*****************************************************************************
* END OF CONSTANTS
*****************************************************************************



*****************************************************************************
* VARIABLES
*****************************************************************************
*
                        ORG     $0042           ;STORE ALL VARIABLES IN THIS SECTION

****GLOBAL VARIABLES****
TEMP_VAR    RMB   2            ;MAKE A TEMPORARY VARIABLE FOR ALL'S USE

****FOR SERVOS******
SERV1_UP    RMB   2            ;THE 'UPTIMES' OF THE PWM FOR SERVOS
OC2_TIM_LO  RMB   2            ;THE LENGTH OF LOW TIME TO COMPLETE A CYCLE
SERV2_UP    RMB   2            ;
OC3_TIM_LO  RMB   2            ;
SERV3_UP    RMB   2            ;
OC4_TIM_LO  RMB   2            ;

****FOR TAKEOVER SYSTEM*****
IC1_START   RMB   2            ;KEEPS THE FIRST EDGE OF IC1
SUBSUM_TAK  RMB   1            ;KEEPS TRACK OF SUBSUMPTION OF TAKEOVER SYSTEM

****FOR SAMPLING ROUTINE****
CUR_ROLL   RMB   2
CUR_PITCH  RMB   2
PITCHQ     RMB   QUEUE_LENGTH
PITCH_AVG   RMB   1
ROLLQ      RMB   QUEUE_LENGTH
ROLL_AVG    RMB   1

****FOR LANDING ROUTINE****
ARM_LAND    RMB   1            ;0 =NOT YET ARMED, 1 = ARMED
SUBSUM_LAND RMB   1            ;ALLOWS LANDING TO SUBSUME ITSELF (WHEN DONE)
BAT_MEAS    RMB   1            ;HOLDS LATEST BATTERY MEASUREMENT

****FOR BALANCING ROUTINE********
SUBSUM_BAL  RMB   1            ;ALLOWS PROCESSES TO SUBSUME BALANCING

*****************************************************************************
```

```
* END OF VARIABLES
*****************************************************************************


                    ORG $F800

****************************************************************************
* MAIN PROGRAM
****************************************************************************
*
MAIN    LDS     #$0041

                    LDD     #MID_POSITION   ;INITIALIZE ALL 3 SERVOS TO MID_POSITION
                    STD     SERV1_UP
                    STD     SERV2_UP
                    STD     SERV3_UP

                    LDAA    TMSK2          ;SET TIMER PRESCALAR TO FASTEST SETTING
                    ANDA    #%11111100     ;
                    STAA    TMSK2          ;

                    LDAA    #%00000000     ;INITIALIZE PORT C'S VALUE
                    STAA    PORTC          ;
                    LDAA    #%11111111     ;SET PORTC TO ALL OUTPUTS
                    STAA    DDRC           ;


                    LDAA    PORTB          ;SET THE CONTROL TO INITIALLY BELONG TO THE
                    ANDA    #MICRO_ON      ;MICROPROCESSOR
                    STAA    PORTB          ;(DON'T ALTER OTHER BITS)

                    LDAA    PORTB          ;SET TO READ THE ROLL AXIS FIRST
                    ANDA    #ROLL_ON       ;ON DATA MEASUREMENTS
                    STAA    PORTB          ;

                    LDAA    OPTION         ;TURN ON A/D CONVERTER
                    ORAA    #%10000000     ;
                    STAA    OPTION         ;

          LDAA    $FF           ;DELAY FOR THE START OF
MAIN_AD_DELAY    DECA                 ;THE A/D ROUTINES
          BNE     MAIN_AD_DELAY

                    LDD     #PITCHQ        ;GET THE FIRST SLOT IN QUEUE1
                    STD     CUR_PITCH      ;AND MAKE A POINTER TO IT

                    LDD     #ROLLQ         ;GET THE FIRST SLOT IN QUEUE2
                    STD     CUR_ROLL       ;AND MAKE A POINTER TO IT

                    LDAA    #0
                    STAA    SUBSUM_BAL     ;TURN BALANCING ON
                    STAA    SUBSUM_TAK     ;"    TAKEOVER  "
                    STAA    SUBSUM_LAND    ;"    LANDING   "
          STAA    ARM_LAND      ;DISARM
          STAA    BAT_MEAS      ;SET BATTERY MEASUREMENT TO 0

                    JSR     INIT_IC1       ;INITIALIZE THE IC1 PROCESS
                    JSR     INIT_OCS       ;INITIALIZE ALL OUTPUT COMPARES

                    CLI                    ;TURN ON INTERRUPTS

HERE            LDAA    PORTE         ;LOAD PORTE DATA
          ANDA    #%10000000    ;MASK BIT 7
          BNE     DIS_ROL       ;IF !=0, DISPLAY ROLL DATA
DIS_PIT LDAA    PITCH_AVG     ;SHOW BINARY RUNNING TOTAL
          STAA    PORTC         ;ON LEDS
          BRA     MAIN_1        ;WAIT ON INTERRUPTS
DIS_ROL LDAA    ROLL_AVG
          STAA    PORTC
```

```
MAIN_1  LDAA    SUBSUM_BAL      ;CHECK FOR SUBSUMPTION OF BALANCE
                BNE     SKIP_1          ;SUBSUME BALANCE IF '1'

                JSR     CHK_BAL         ;BALANCE THE BIRD

SKIP_1  LDAA    SUBSUM_LAND     ;CHECK FOR SUBSUMPTION OF LANDING
                BNE     SKIP_2          ;SUBSUME IF '1'

MAIN_2  JSR     LAND_CHK        ;CHECK FOR LANDING NEED

SKIP_2  BRA     HERE


************************************************************************
* END OF MAIN
************************************************************************

************************************************************************
*               SUBROUTINE-LAND_CHK
*
* INPUTS:       NONE
* OUTPUTS:      CHANGES SERV1_UP,SERV2_UP
* DESTROYS:     REGISTERS A AND B AND X
* DESCRIPTION:  THIS SUBROUTINE TRIGGERS LANDING SIGNAL
************************************************************************

* THIS FIRST SEGMENT LOOKS FOR INITIAL BATTERY APPLICATION, THEN ARMS
* THE LANDING MECHANISM

LAND_CHK LDAA   ARM_LAND        ;CHECK IF ARMED
                BNE     SKIP_ARM        ;IF NOT 0, WE ARE ALREADY ARMED

                LDAA    BAT_MEAS        ;LOAD THE LATEST BATTERY MEASUREMENT
        STAA    PORTC
                CMPA    #BAT_THRESH     ;LOOK FOR THE FIRST TIME BATTERY IS APPLIED
                BHI     ARM_NOW         ;IF LARGER THAN THRESHOLD, ARM LANDING MECHANISM
                BRA     RET_LAND_CHK    ;ELSE RETURN

ARM_NOW  LDAA   #1              ;ARM THE LANDING MECHANISM
                STAA    ARM_LAND        ;
                BRA     RET_LAND_CHK    ;RETURN

* THIS SEGMENT CHECKS TO SEE IF WE HAVE FALLEN BELOW OUR THRESHOLD

SKIP_ARM LDAA   BAT_MEAS        ;GET LATEST MEASUREMENT
                CMPA    #BAT_THRESH     ;COMPARE TO THRESHOLD
                BLS     LAND_EDG        ;WE FOUND THE DIP TO INITIATE LANDING
                BRA     RET_LAND_CHK    ;ELSE, RETURN

* INITIATE LANDING PATTERN

LAND_EDG LDAA   #1
                STAA    SUBSUM_TAK      ;SUBSUME TAKEOVER AND BALANCING
                STAA    SUBSUM_BAL      ;ROUTINES

                LDAA    PORTB           ;TAKE CONTROL OF TAIL (OVERRIDING
                ANDA    #MICRO_ON       ;REMOTE CONTROL, IF NECESSARY)
                STAA    PORTB           ;

                LDD     #MID_POSITION
                STD     SERV1_UP

                LDD     #4000           ;PULL TAIL TO ONE EXTREME
                STD     SERV2_UP        ;

                LDAA    #$FF
LP_1_OUT LDX    #$621           ;WAIT FOR ABOUT .2 sec
LP_1_IN  DEX
                BNE     LP_1_IN
                DECA
```

```
                BNE    LP_1_OUT

                LDD    #2000       ;PULL TO OTHER EXTREME
                STD    SERV2_UP    ;

                LDAA   #$FF
LP_2_OUT LDX    #$621       ;WAIT FOR ABOUT .2 sec
LP_2_IN  DEX
                BNE    LP_2_IN
                DECA
                BNE    LP_2_OUT

                LDD    #4000
                STD    SERV2_UP

                LDAA   #$FF
LP_3_OUT LDX    #$621       ;WAIT FOR ABOUT .2 sec
LP_3_IN  DEX
                BNE    LP_3_IN
                DECA
                BNE    LP_3_OUT

                LDD    #2000
                STD    SERV2_UP

                LDAA   #$FF
LP_4_OUT LDX    #$621       ;WAIT FOR ABOUT .2 sec
LP_4_IN  DEX
                BNE    LP_4_IN
                DECA
                BNE    LP_4_OUT

                LDAA   #0
                STAA   SUBSUM_TAK    ;END SUBSUMPTION
                STAA   SUBSUM_BAL    ;

                LDAA   #1
                STAA   SUBSUM_LAND   ;SUBSUME SELF PERMANANTLY

RET_LAND_CHK     RTS         ;DONE, SO RETURN


***************************************************************************
*                  SUBROUTINE-CHK_BAL
*
* INPUTS:      NONE
* OUTPUTS:     CHANGES SERV1_UP,SERV2_UP
* DESTROYS:    REGISTERS A AND B
* DESCRIPTION:  THIS SUBROUTINE SETS UP CALLS TO BALANCE SUBROUTINE
***************************************************************************
*
CHK_BAL LDAA    ROLL_AVG       ;SET UP REGS FOR SUB CALL
          LDAB   #MID_LEV_ROLL   ;
          JSR    BALANCE         ;CALL BALANCE

          SUBD   #MID_POSITION   ;SUBTRACT OFF MID POSITION
          STD    TEMP_VAR        ;MAKE A TEMP STORE
          LDD    #0              ;NEGATE THE RESULT
          SUBD   TEMP_VAR        ;
          ADDD   #MID_POSITION   ;

          STD    SERV1_UP        ;SET SERVO

          LDAA   PITCH_AVG       ;SET UP REGS FOR SUB CALL
          LDAB   #MID_LEV_PITCH  ;
          JSR    BALANCE         ;CALL BALANCE
          STD    SERV2_UP        ;SET SERVO

          RTS
```

```
***************************************************************************
*                 SUBROUTINE-BALANCE
*
* INPUTS:      TILT READING IN REGISTER A
*            MID-TILT VALUE IN REGISTER B
* OUTPUTS:     THE VALUE TO SET THE SERVO AT IN REGISTER D
* DESTROYS:    REGISTERS A AND B
* DESCRIPTION:  THIS SUBROUTINE TAKES IN A READING, COMPARES IT TO
*            THE CENTER READING, AND LINEARLY MAPS THIS ERROR ONTO
*            THE SERVO RANGE (2000 TO 4000). IT RETURNS THIS VALUE
*            IN THE D REGISTER.
***************************************************************************
*
BALANCE SBA               ;SUBTRACT THE CENTER VALUE FROM MEASURED
                BLO    BAL_LOW       ;IF TILT VALUE < MID LEVEL VALUE
                TAB
                CLRA              ;
                BRA    BAL_1        ;
BAL_LOW TAB
                LDAA    #$FF        ;IF RESULT IS NEG, DO OPPOSITE
BAL_1   LSLD              ;MULTIPLY BY 32
                LSLD              ;
                LSLD              ;
                LSLD              ;
                LSLD              ;
        LSLD
                ADDD    #MID_POSITION   ;ADD TO SERVO MID_POSITION

                RTS              ;RETURN

***************************************************************************
*                 SUBROUTINE-INIT_OCS
* INPUTS:      NONE
* OUTPUTS:     NONE
* DESTROYS:    NONE
* DESCRIPTION:  THIS SUROUTINE SETS UP ALL SERVO OC PINS TO BEGIN AT 0V, RISE
*            ON THE FIRST COMPARE, AND ENABLES ALL OC INTERRUPTS.  IT SETS
*            OC5, WHICH IS USED TO TIME SAMPLING, TO BE DISCONNECTED FROM
*            THE OUTPUT PIN.
***************************************************************************
*

INIT_OCS       PSHA              ;PRESERVE CONTENTS OF REG. A

                LDAA    PACTL         ;SET I4/O5 FUNCTION TO O5
                ANDA    #%11111011     ;
                STAA    PACTL         ;

                LDAA    #%10101000     ;CLEAR OC2-4 PINS TO 0V ON FORCE
                STAA    TCTL1         ;DISCONNECT OC5 FROM ITS PIN

                LDAA    #%01110000     ;FORCE COMPARES ON OC2-4 PINS
                STAA    CFORC         ;

                LDD     TCNT          ;GET CURRENT TIMER VALUE
                ADDD    #OC2_START_DELAY ;ADD A CERTAIN DELAY BEFORE
OC2
                STD     TOC2          ;STARTS

                ADDD    #150          ;ADD DELAY TO START OF OC3
                STD     TOC3

                ADDD    #150          ;ADD ANOTHER DELAY TO START OF OC4
                STD     TOC4

                ADDD    #OC5_DELAY     ;ADD DELAY FOR SAMPLING ROUTINE
                STD     TOC5          ;TO BE IN DEAD PART OF 21ms PERIOD

                LDAA    #%01111000     ;CLEAR ANY PENDING FLAGS
                STAA    TFLG1         ;
```

```
                        LDAA   #%11111100    ;SET OC2-4 PINS TO 5V ON FIRST
                        STAA   TCTL1         ;SUCCESSFUL COMPARE.

                        LDAA   TMSK1         ;TURN ON OC2-5 INTERRUPTS, BUT DON'T
                        ORAA   #%01111000    ;ALTER OTHER BITS IN TMSK1
                        STAA   TMSK1         ;

                        PULA                 ;RESTORE CONTENTS OF REG. A

                        RTS                  ;RETURN


*************************************************************************
*          ISR - OC2_ISR
* DESCRIPTION:  HANDLES THE OC2 INTERRUPT REQUESTS
*************************************************************************
*
OC2_ISR    LDAA   TFLG1      ;CHECK FOR VALID INTERRUPT
                        ANDA   #%01000000    ;
                        BEQ    RET_OC2       ;IF NOT VALID, RETURN

                        STAA   TFLG1         ;IF VALID, CLEAR OC2F

                        LDAA   TCTL1         ;CHECK TO SEE IF OC2 PIN WAS SET
                        ANDA   #%01000000    ;OR CLEARED ON THE COMPARE
                        BEQ    OC2_CLRD      ;IF 0, IT WAS JUST CLEARED TO 0V

                        LDD    TOC2          ;ELSE, IT WAS JUST SET
                        STD    OC2_TIM_LO    ;TEMP SAVE OF TIME
                        ADDD   SERV1_UP      ;ADD THE UP TIME OF THE PULSE
                        STD    TOC2          ;STORE TIME FOR NEXT COMPARE

                        LDAA   TCTL1         ;CLEAR ON NEXT COMPARE
                        ANDA   #%10111111    ;
                        STAA   TCTL1         ;

                        LDD    OC2_TIM_LO    ;FIND THE END OF THE PERIOD
                        ADDD   #PULS_LEN     ;AND STORE INTO TIM_LO
                        STD    OC2_TIM_LO    ;

                        BRA    RET_OC2       ;RETURN

OC2_CLRD    LDD    OC2_TIM_LO    ;GET PREV. CALC. END OF PERIOD
                        STD    TOC2          ;AND PUT INTO COMPARE REGISTER

                        LDAA   TCTL1         ;SET ON NEXT COMPARE
                        ORAA   #%11000000    ;
                        STAA   TCTL1         ;

RET_OC2    RTI


*************************************************************************
*          ISR - OC3_ISR
* DESCRIPTION:  HANDLES THE OC3 INTERRUPT REQUESTS
*************************************************************************
*
OC3_ISR    LDAA   TFLG1      ;CHECK FOR VALID INTERRUPT
                        ANDA   #%00100000    ;
                        BEQ    RET_OC3       ;IF NOT VALID, RETURN

                        STAA   TFLG1         ;IF VALID, CLEAR OC3F

                        LDAA   TCTL1         ;CHECK TO SEE IF OC3 PIN WAS SET
                        ANDA   #%00010000    ;OR CLEARED ON THE COMPARE
                        BEQ    OC3_CLRD      ;IF 0, IT WAS JUST CLEARED TO 0V
```

```
                LDD    TOC3         ;ELSE, IT WAS JUST SET
                STD    OC3_TIM_LO   ;TEMP SAVE OF TIME
                ADDD   SERV2_UP     ;ADD THE UP TIME OF THE PULSE
                STD    TOC3         ;STORE TIME FOR NEXT COMPARE

                LDAA   TCTL1        ;CLEAR ON NEXT COMPARE
                ANDA   #%11101111   ;
                STAA   TCTL1        ;

                LDD    OC3_TIM_LO   ;FIND THE END OF THE PERIOD
                ADDD   #PULS_LEN    ;AND STORE INTO TIM_LO
                STD    OC3_TIM_LO   ;

                BRA    RET_OC3      ;RETURN

OC3_CLRD        LDD    OC3_TIM_LO   ;GET PREV. CALC. END OF PERIOD
                STD    TOC3         ;AND PUT INTO COMPARE REGISTER

                LDAA   TCTL1        ;SET ON NEXT COMPARE
                ORAA   #%00110000   ;
                STAA   TCTL1        ;

RET_OC3         RTI


****************************************************************************
*               ISR - OC4_ISR
* DESCRIPTION:  HANDLES THE OC4 INTERRUPT REQUESTS
****************************************************************************
*
OC4_ISR         LDAA   TFLG1        ;CHECK FOR VALID INTERRUPT
                ANDA   #%00010000   ;
                BEQ    RET_OC4      ;IF NOT VALID, RETURN

                STAA   TFLG1        ;IF VALID, CLEAR OC4F

                LDAA   TCTL1        ;CHECK TO SEE IF OC4 PIN WAS SET
                ANDA   #%00000100   ;OR CLEARED ON THE COMPARE
                BEQ    OC4_CLRD     ;IF 0, IT WAS JUST CLEARED TO 0V

                LDD    TOC4         ;ELSE, IT WAS JUST SET
                STD    OC4_TIM_LO   ;TEMP SAVE OF TIME
                ADDD   SERV3_UP     ;ADD THE UP TIME OF THE PULSE
                STD    TOC4         ;STORE TIME FOR NEXT COMPARE

                LDAA   TCTL1        ;CLEAR ON NEXT COMPARE
                ANDA   #%11111011   ;
                STAA   TCTL1        ;

                LDD    OC4_TIM_LO   ;FIND THE END OF THE PERIOD
                ADDD   #PULS_LEN    ;AND STORE INTO TIM_LO
                STD    OC4_TIM_LO   ;

                BRA    RET_OC4      ;RETURN

OC4_CLRD        LDD    OC4_TIM_LO   ;GET PREV. CALC. END OF PERIOD
                STD    TOC4         ;AND PUT INTO COMPARE REGISTER

                LDAA   TCTL1        ;SET ON NEXT COMPARE
                ORAA   #%00001100   ;
                STAA   TCTL1        ;

RET_OC4         RTI


****************************************************************************
*               ISR - OC5_ISR
* DESCRIPTION:  HANDLES THE OC5 INTERRUPT REQUESTS
****************************************************************************
```

```
*
OC5_ISR       LDAA    TFLG1         ;CHECK FOR VALID INTERRUPT
              ANDA    #%00001000    ;
              BNE     OC5_BEG       ;IF NOT VALID, RETURN FROM ISR
              JMP     RET_OC5

OC5_BEG       STAA    TFLG1         ;IF VALID, CLEAR OC5F

              LDD     TOC5          ;SET TOC5 TO NEXT INTERRUPT
              ADDD    #PULS_LEN     ;TIME
              STD     TOC5          ;

              LDAA    #$10          ;BEGIN THE A/D CONVERSION
              STAA    ADCTL         ;PROCESS

              LDAA    #15           ;DELAY FOR OVER 32ms
AD_DELAY      DECA                  ;
              BNE     AD_DELAY      ;

              LDAB    ADR2
              STAB    BAT_MEAS ;READ BATTERY, STORE TO VAR

              LDAB    ADR1          ;GET DATA JUST MEASURED

              LDAA    PORTB         ;CHECK TO SEE IF WE JUST
              ANDA    #%00000010    ;MEASURED PITCH OR ROLL
              BEQ     IS_ROLL       ;

IS_PITCH      LDX     CUR_PITCH     ;GET POINTER TO PITCH QUEUE
              STAB    0,X           ;SAVE LATEST PITCH
              LDAB  PORTB
              ANDB    #ROLL_ON      ;SET TO MEASURE ROLL NEXT
              STAB  PORTB

UPDATE_DATA   LDD     CUR_PITCH     ;GET CURRENT Q POINTER
              SUBD    #PITCHQ       ;SUBTRACT Q STARTING POINT
              CPD     #QUEUE_LENGTH-1 ;SEE IF WE ARE AT THE END OF THE Q
              BEQ     RESET_PITCH   ;SET CUR_PITCH BACK TO PITCHQ AND
UPDATE LEVEL2
              LDY     CUR_PITCH     ;INCREMENT CUR_PITCH POINTER
              INY
              STY     CUR_PITCH     ;
              BRA     RET_OC5       ;DONE WITH PITCH UPDATE

RESET_PITCH   LDX     #PITCHQ       ;GET POINTER TO START OF Q
              STX     CUR_PITCH     ;RESET CURRENT PITCH POINTER
              LDY     #PITCH_AVG
              LDAB    #QUEUE_LENGTH
              JSR     AVGLEVEL
              BRA     RET_OC5       ;DONE WITH PITCH UPDATE


IS_ROLL       LDX     CUR_ROLL      ;GET POINTER TO Q
              STAB    0,X           ;SAVE LATEST ROLL
              LDAB    PORTB
              ORAB    #PITCH_ON     ;SET TO MEASURE PITCH NEXT
              STAB  PORTB


UPDATE_ROLL   LDD     CUR_ROLL      ;GET CURRENT Q POINTER
              SUBD    #ROLLQ        ;SUBTRACT Q STARTING POINT
              CPD     #QUEUE_LENGTH-1 ;SEE IF WE ARE AT END OF Q
              BEQ     RESET_ROLL    ;SET CUR_ROLL BACK TO PITCHQ AND
UPDATE LEVEL2
              LDY     CUR_ROLL      ;INCREMENT CUR_ROLL POINTER
              INY                   ;
              STY     CUR_ROLL      ;
              BRA   RET_OC5   ;EXIT ISR

RESET_ROLL    LDX     #ROLLQ        ;RESET Q POINTER TO START OF Q
```

```
                                  STX    CUR_ROLL      ;
                                  LDY    #ROLL_AVG     ;GET AVERAGE VALUE
                                  LDAB   #QUEUE_LENGTH
                                  JSR    AVGLEVEL

RET_OC5      RTI           ;RETURN FROM OC5_ISR

******************************************************
*  Subroutine:  AVGLEVEL   ***************************
*
*  INPUT:   X => BASE ADDRESS OF VALUES TO AVG (LEVEL ADDRESS)
*       Y => ADDRESS TO STORE AVG (LEVEL+1 ADDRESS)
*         B => NUMBER OF VALUES ON LEVEL ( MUST BE POWER OF 2)
*  OUTPUT:  LEVEL+1 ADDRESS
*  DESTROYS:   X,Y,A,B
******************************************************

AVGLEVEL PSHY

                 CLRA

                 PSHB      ;SAVE TEMP FOR LATER
                 PSHA      ;CLEAR MSBYTE FOR Y
                 PSHB      ;TEMP FOR Y
                 PSHA      ;CLEAR MSBYTE FOR Y
                 PULY      ;HAS NUMBER OF VALUES ON LEVEL

                 DECB
                 ABX       ;POINT TO LAST VALUE
                 LDAB  0,X     ;GET VALUE

LEVEL_LOOP  DEX       ;POINT TO PREV VALUE
                 DEY
                 BEQ   ADD_DONE ;EXIT WHEN ALL VALUES ADDED
                 ADDB  0,X     ;ADD PREV VALUE
                                  BCC    LEVEL_LOOP

                 INCA      ;COUNT OVERFLOWS
                 BRA   LEVEL_LOOP

ADD_DONE PULX      ;GET # OF VALUES
                                  XGDX            ;SWAP TEMPORARILY
                                  LSRD            ;INITIAL DIVIDE BY 2
                                  XGDX            ;SWAP BACK
                 BEQ   COMP_AVG_DONE

COMPUTE_AVG    LSRD          ;DIVIDE THE TOTAL BY 2
                                  XGDX            ;TRADE VALUES
                                  LSRD            ;DIVIDE THE COUNTER BY TWO
                                  XGDX            ;TRADE VALUES AGAIN

                 BNE   COMPUTE_AVG

COMP_AVG_DONE   PULY
                                  STAB    0,Y
                 RTS

**************************************************************************
*          SUBROUTINE-INIT_IC1
* INPUTS:     NONE
* OUTPUTS:     NONE
* DESTROYS:    NONE
```

```
* DESCRIPTION:  THIS SUROUTINE SETS UP THE IC1 FUNCTION TO BEGIN CAPTURING
*            ON A RISING EDGE, AND ENABLES INTERRUPTS
************************************************************************
*
INIT_IC1 PSHA          ;SAVE CONTENTS OF REGISTER A

                LDAA  #%00010000    ;SET IC1 TO CAPTURE ON RISING EDGES
                STAA  TCTL2      ;

                LDAA  #%00000100    ;TURN OFF IC1'S FLAG
                STAA  TFLG1      ;

                LDAA  TMSK1      ;TURN ON IC1 INTERRUPTS, BUT DON'T INTERFERE
                ORAA  #%00000100    ;WITH OTHER INTERRUPT BITS
                STAA  TMSK1      ;

                PULA         ;RESTORE THE CONTENTS OF REGISTER A

                RTS          ;RETURN FROM THE SUBROUTINE

************************************************************************
*                ISR - IC1_ISR
* DESCRIPTION:  HANDLES THE IC1 INTERRUPT REQUESTS
************************************************************************
*
IC1_ISR  LDAA  TFLG1      ;CHECK FOR VALID INTERRUPT
                ANDA  #%00000100    ;IF INVALID
                BEQ   RET_IC1    ;RETURN FROM ISR

                STAA  TFLG1      ;ELSE, CLEAR THE FLAG

                LDAA     SUBSUM_TAK          ;IF 1, THEN CONTROL IS SUBSUMED
                BNE      RET_IC1            ;TO ANOTHER HIGH PRIORITY PROCESS

                LDAA  TCTL2      ;CHECK TO SEE IF RISING OR FALLING EDGE WAS
                ANDA  #%00100000    ;CAPTURED
                BEQ   IC1_ROSE    ;IF ZERO, RISING EDGE WAS CAPTURED

IC1_FELL LDAA  TCTL2      ;SET IC1 TO CAPTURE ON RISING EDGE NEXT
                ANDA  #%11011111    ;
                ORAA  #%00010000    ;
                STAA  TCTL2      ;

                LDD   TIC1       ;GET THE CAPTURED TIME
                SUBD  IC1_START     ;SUBTRACT THE PREVIOUSLY CAPTURED TIME

                CPD   #PULLED_LEFT   ;CHECK TO SEE IF STICK IS PULLED LEFT
                BLO   IC1_MICR_ON      ;IF SO, GIVE CONTROL TO MICROPROCESSOR

                CPD   #PULLED_RIGHT  ;CHECK TO SEE IF STICK IS PULLED RIGHT
                BHI   IC1_RCVR_ON    ;IF SO, GIVE CONTROL TO RECEIVER

                BRA   RET_IC1    ;ELSE RETURN FROM ISR

IC1_MICR_ON LDAA  PORTB      ;SET PORTB[0] TO ZERO WITHOUT DESTROYING
                ANDA  #MICRO_ON      ;OTHER PORTB VALUES
                STAA  PORTB      ;

                BRA   RET_IC1    ;RETURN FROM ISR

IC1_RCVR_ON LDAA  PORTB      ;SET PORTB[0] TO ONE WITHOUT DESTROYING
                ORAA  #RCVR_ON   ;OTHER PORTB VALUES
                STAA  PORTB      ;

                BRA   RET_IC1    ;RETURN FROM ISR

IC1_ROSE LDAA  TCTL2      ;SET TO CAPTURE ON FALLING EDGE NEXT
                ANDA  #%11101111    ;
                ORAA  #%00100000    ;
                STAA  TCTL2      ;
```

```
            LDD   TIC1        ;GET THE TIME OF CAPTURE
            STD   IC1_START       ;AND STORE IT TO A TEMP VARIABLE

RET_IC1  RTI          ;RETURN FROM INTERRUPT
```