Project Number: MQP GSF M112

AFFORDABLE COMPACT HUMANOID ROBOT

FOR AUTISM SPECTRUM DISORDER IN CHILDREN

A Major Qualifying Project Report:

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By

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1. Human Robot Interaction
2. Robotics

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ACKNOWLEDGEMENTS

ABSTRACT

Autism is a disorder that primarily affects the development of social and communication skills. Interacting with humanoid robots that provide simple emotional response and interaction has been shown to improve the communication skills of autistic children. In particular, early intervention and continuous care provide significantly better outcomes. Currently, there are no robots capable of meeting these requirements that are both low-cost and available to families of autistic children for in-home use. This project created a humanoid robot that is affordable, non-threatening, durable, and capable of interacting with an autistic child. This robot has the ability to track the child with the webcams in its 3-DoF eyes and 3-DoF head, open and close its 1-DoF beak and 1-DoF each eyelids, and raise its 1-DoF each wings. These attributes will give it the ability to be used for the diagnosis and treatment of autism. As part of this project, the robot and the electronic and control software have been developed, and integrating semi-autonomous interaction, teleoperation from a remote healthcare provider, and initiating trials with children in a local clinic are in progress.

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1. INTRODUCTION

1.1 Executive Summary

Autism is a disorder that affects development of social and communication skills. Robots are being used as one of the newest tools for diagnosing and treating autism. As autistic children have been shown to respond well to robots, robots are proving to be a promising advancement in autism therapy. The repeatability of robotic movement combined with visual tracking may allow for more precise and repeatable tests to be used in the diagnosis of autism.

Currently, few robots exist for the purpose of the diagnosis and treatment of autism; those that do tend to be used primarily for research purposes. Due to the scarcity of these robots and their high cost, most autistic children will never have a chance to interact with them, and those children who are fortunate enough to get face time with a robot will not get much.

The goal of this project was to create a robot capable of interacting with a small child for the purpose of diagnosing and treating autism through early intervention (EI). An additional goal was for the robot to be used in the child's home such that the child would be able to have a significant face time with the robot. As such, the robot would need to be affordable by families of autistic children and portable, meaning small and weighing little. As a household robot may not be protected the way that one in a clinic might, the robot would need to be durable and able to withstand the type of harm a small child might be expected to do to a stuffed animal, like squishing it, poking it, tearing at its appendages, and dropping it on the floor.

This interactive robot would need moving appendages and sensors so the robot would have something to react to. So as not to discourage interaction, the robot would need to be nonthreatening. The robot would need two modes of operation: a completely autonomous one both for diagnosis and treatment, and a teleoperated mode so that a clinician could operate the robot primarily for the purpose of diagnosis.

A prototype robot was designed and built. It is in the form of a cartoonlike penguin for a nonthreatening appearance. It has two wings able to move up and down independently of each other, a head with the same three degrees of freedom (DOF) as a human head, a beak that can open and close, eyes with the same three DOF as human eyes and eyelids that can open and close independently of each other. The head and eyes were designed to be able to move with human speed. Each eye contains a webcam. The total cost of the purchased components of the robot was less than $1000. The robot was able to fit in a box 8in. x 12in. x 15in. excluding the wings which have a span of 20in. from the tip of one to the tip of the other. The final weight of the robot was light enough to be easily lifted by most adults. The robot has many compliant features such that pulling on any of its appendages will cause the appendages to move but not to break. Some appendages are able to be compressed or twisted without damaging the robot. Internal components are either suspended or rigidly attached in order to offer

some protection or control if the robot were to be dropped. The robot is controllable through a graphical user interface (GUI.)

Additional work would be required to allow the robot to interact autonomously with a child. The primary limitations of the design are that that the robot moves somewhat jerkily and is not designed to have the lowest cost if it were to be manufactured in large quantities. Redesign of the servo moving functions in the code could allow for less-jerky movements. Use of motors and motor controllers instead of servos could further smooth movement. Cost analysis and redesign could yield a more optimal design for the quantity of robots to be made.

1.2 Literature Review

1.2.1   What Is Autism?

Autism, more formally called autism spectrum disorder (ASD), is a disorder that primarily affects development of social and communication skills. It usually becomes apparent that a child has this disorder sometime between the ages of 18 months and 3 years. Affected children tend to have problems with communication, social interaction, response to sensory information, play, and behaviors. (1)

Those with autism have difficulty communicating. They may have difficulty with words, such as not knowing many or even any words or choosing to use gestures rather than words when communicating. They may not look at what others are looking at, and they may not point to draw attention to what they are interested in. Starting and perpetuating conversations may not be possible for them. They may rhyme nonsensically, repeat memorized phrases, and have difficulty referring to themselves such as using the word "you" instead of "I." (1) These communication issues are related to the social interaction issues those with autism tend to have.

Communication issues found in those with autism may cause difficulties with social interaction. Autistic people often are withdrawn and would rather spend time alone. Whether because of an inability or a lack of desire, they may not make many friends. They may show a disregard for others' emotions, and they may not respond to eye contact or facial expressions. (1)

Social interaction issues may stem from other issues as well, such as how those affected with autism respond to sensory information. In general they have either a more or less severe response than normal to all types of sensory information. The most common senses affected are auditory and touch. They may not respond to loud noises, or they may perceive normal noises as painful. Physical contact may seem to them to be overpowering and they may have a heightened response to pain. Contrarily, they may have a lessened response to pain, and they may show unusual behaviors such as rubbing or licking objects. These unusual behaviors are just a small portion of the atypical behaviors exhibited by Autistics. (1)

Unusual behaviors displayed by Autistic people may include having very few and specific interests and having difficulty changing tasks. Contrarily, they may have short attention spans and may be somewhat

hyperactive. They may instead be the exact opposite of overactive. They may have an intense desire for repetition and may have difficulty breaking away from routine. They may even be aggressive to themselves and others sometimes accompanied by extreme tantrums. (1) These behaviors may be related to the communication and social interaction issues they also exhibit.

Additional atypical behaviors exhibited by Autistic children include idiosyncrasies in how they play. The children may not imitate others' actions. They may prefer playing by themselves and playing the same way every time they play. Their play lacks creativity and involves very little pretending. (1)

1.2.2   What Is Asperger's?

Asperger's Syndrome is often characterized as a less severe form of autism. It is much like autism in that those affected may have difficulty picking up on social cues, body language, and speech pitch and tone, and they may have difficulty overall with social situations. Other similarities include dislike of routine changes, having very few in-depth interests, talking a lot and about only their own interests, and increased sensitivity of one or more of the five senses. (2)

Currently, Asperger's and autism are differentiated between, however. Those affected by Asperger's may have a style of speaking that is both very formal and seemingly too advanced for their age – they may use larger and more formal words than those of the same age who are unaffected by Asperger's. They may display atypical facial expressions and postures. Also, those with Asperger's may appear to improve and grow out of some of their symptoms; for example, they may learn ways of coping with social situations, and they may learn to recognize some social cues. (2)

1.2.3   What Are Some Traditional Therapies Used for the Treatment and Improvement of Autism?

Treatments for ASD fall into two categories, cognitive and behavioral (3); this work focuses primarily on treating the behavioral aspects of autism since there is already extensive work in the area of improving cognitive development in children with ASD. Early treatments tailored to the specific Autistic individual can cause significant improvement. The treatments usually fall into one of the following categories: medication, occupational therapy, physical therapy, speech-language therapy, dietary change, and applied behavior analysis. (1)

As a dietary change, it may help some children with autism to follow a gluten-free or casein-free diet. These changes have not been proven to help, and not all experts agree with it. Medications are used to help relieve emotional and behavioral problems such as trouble sleeping, mood swings, aggression, hyperactivity, compulsions, anxiety, impulsiveness, and irritability. Medicine cannot cure autism or any of its symptoms, but it can help to temporarily relieve many symptoms. (1)"Sensory integration and vision therapy (1)" are used, but almost no research has been done to show how effective they are. (1)

Applied behavior analysis (ABA) relies on one-on-one teaching that "reinforces the practice of various skills. The goal is to get the child close to normal developmental functioning. (1)" This type of program usually is done at the home of the child with behavioral psychologist supervising. Because of these characteristics of the treatment, it can be exceptionally expensive, unaffordable by many families, and

outside funding for such treatment can be very difficult to gain. (1) This is one area where a robot may be of great value.

1.2.4 Have Robots Ever Been Used for the Treatment and Improvement of Autism and How?

Robots are being used as one of the newest forms of autism treatment. "While interacting with robots, children with autism exhibit social behaviors, such as imitation, eye gaze and joint attention…These social behaviors are typically rare in children with autism, but evidence suggests that robots trigger them more often in such children… (3)" (4) The idea is that "robots are able to elicit certain desirable social behaviors in children with autism that are not typically observed in therapies not involving robots (3)." Robots as simple as *Keepon* (Figure 1), a four DoF robot, can provide simple interaction (4).
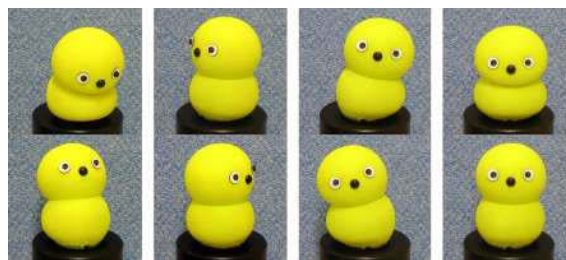
Figure 1 *Keepon*, **and Interactive Robot (4)**

Technology is being used increasingly to help diagnose autism at earlier ages. Yale researchers are examining whether the eye-gaze patterns of infants can show signs of autism (5) (6). Italian researchers are using sensors to detect other sorts of abnormalities in infants targeting abnormalities that would point to autism. These sensors test the children's responsiveness to visual and audio cues, how they move their arms and legs, and how they handle and play with a ball (7). One reason to use technology to aid in diagnosis is to gain a more reliable diagnosis. Traditionally, autism is diagnosed by a clinician who interacts with the child. Due to the fact that the clinician cannot repeat the exact same actions each visit with the child, and it takes several periods of interacting with the child to gain a diagnosis, the clinician could diagnose children differently each time. Using a form of technology for diagnosis makes the tests more repeatable thus making the diagnosis more reliable (3).

Children with autism tend not to initiate social interactions. They do, however, appear to respond well to rewards, and clinicians have succeeded in getting autistic children to ask for toys by showing them that they will receive the toy only if they asked for it. Researchers at USC created a robot that blows bubbles when the button on its back is pressed; this reward of blowing bubbles "…encourages the child to engage the robot proactively… (8)" (3)

Children with autism often need to learn turn-taking skills, such as allowing the person they are conversing with to do some of the talking. Robots have been created at the University of Hertfordshire and the University of Southern California to react to children who play with them (9) (8). One of these robots plays tag with children, alternating between doing the "tagging" and the running away from the one doing the "tagging" thereby getting the children to take turns (3).

When adults imitate autistic children, the children begin to see that they can imitate the adults the way the adults are imitating them. Imitation can help improve hand-eye coordination, which is another weak point of autistic children, and it can help improve communication skills. Robots have been used in place of adults for imitation therapy, and in some cases the autistic children had an easier time imitating the robots than imitating humans. At the University of Pisa, the FACE robot imitates children's facial expressions, and it was found that the autistic children had an easier time imitating the expressions on FACE than on an actual human face (10). Other robots, like KASPAR (Figure 2), are very expressive as well (5).

Figure 2 KASPAR, An Expressive, Interactive Robot (5)

It is believed that part of the reason why autistic people have trouble understanding facial expressions is due to the complexity of how the human face shows emotions. Each time a person smiles, the expression is a little bit different. To those with autism, it could appear to be a different emotion being expressed each time. Looking at a person's face can often cause sensory overload for an autistic person. Robots with faces that can express different emotions, having better repeatability in how they express those emotions, could be used to help autistic children learn about different facial expressions of emotions (3). The University of Hertfordshire's robot, KASPAR (Figure 2), is able to more simply express emotions, thereby not producing sensory overload in autistic children looking at its face (12) (5).

1.2.5   What Areas of Improvement Are There for These Autism Robots?

Autism robots have several areas in which they can improve. Many of the existing robots are very expensive and not available for purchase even by families that could afford them. In addition, these robots may not be portable, and some of them are unable to withstand the physical treatment any child might give a robot. All of these shortcomings prevent the robots from being used to help autistic children improve, instead allowing the robots to be used primarily for research purposes. Improving upon or removing these shortcomings could allow for an autistic child to have his or her own robot for continued care at home.

1.2.6   Considerations for Humanoid Interactive Robots

Humanoid robots meant to communicate and interact with humans have a vastly different set of requirements than industrial robots. The primary concern is in making sure that no user of this type of robot will come to harm. The robot needs "a motion space that corresponds to that of human beings and a lightweight design." The robot must be somewhat humanlike in appearance and dexterity. "…its kinematics should be familiar to the user, its motions predictable, so as to encourage inexperienced persons to interact with the machine." (6)

In order for a robot's humanoid features to be believable, they must very closely mimic the movements of humans. There are two main types of head and eye coordinated movements: saccades and smooth pursuing. Smooth pursuing refers to keeping the point of interest in middle of the field of view by coordinating both the neck and eye movements. Saccades refers to much faster movements of the eyes to focus on something. The eyes can move up to 300 degrees per second. The angular velocity of each axis of the neck is 160 degrees per second (7). "Average ranges of motion for pitch and roll rotations in adults are about +/- 45 degrees. (8)"

There are many difficulties in creating robots that move like humans. These problems include "development of a suitable motor system, able to replicate…the same ranges of motion, speeds, and accelerations…" and being able to process images fast enough to use the visual information to control the motors. (7) Retina-like cameras may assist in cutting down on the image processing speed because there is a smaller amount of data in a retina-like image yet it still gives enough information about a field of view. (7)

One way to replicate human eyes in a robot is for the eyes to have one shared DOF for the up and down movements and two DOF for the side to side movements (7). One realization of a neck joint involved four degrees of freedom (DOF), three in the lower part of the neck and one in the upper part of the neck. In the lower part of the neck, one DOF allowed the neck to bend to the side, another allowed it to bend forward and backward, another gave it a yaw rotation. In the upper part of the neck, one DOF gave the robot the ability to nod its head (6). Another realization of a humanoid robot also had a 4 DOF neck mechanism and two eyes sharing the same tilt DOF (9). Another way to move a robotic neck is with a "tendon-driven parallel manipulator." In this example, three "tendons" were equally spaced around the neck, each tendon having the ability to pull but not to push, each tendon shortened by a motor positioned at the base of the neck. In this scenario, tensions too high or low in the tendons could cause breakage or misalignment of parts of the robot, so force sensors were used for monitoring (8).

1.3 Project Goals

By the end of the project have a robot that

- Is fully documented with notes for each part such that it could be reproduced by individuals knowledgeable in the area of robotics engineering
- Is affordable by families with autistic children, meaning made for under $1000.
- Is small, preferably less than 2.0 ft. x 1.5 ft. x 1.5 ft.
- Is portable, meaning weighing less than 30 pounds and having all electronic and mechanical components fully contained within it
- Has compliance, meaning able to withstand human abuse, wear, and tear
- Has two eyes
    - They rotate together, up and down, equal amounts off center, with a total range of 90 degrees
    - They rotate independently back and forth, have the ability to move equal amounts off center for a total range of 90 degrees
    - They can rotate with a speed of 300°/sec
- Has a head that moves separately from the body
    - Moves up and down
    - Tilts left and right $\pm45^o$
    - Rotates left and right
    - Moves with a speed of 160°/sec
- Has a speaker and the capability to play a .wav file
- Has a microphone and the ability to record sound
- Has at least one low-cost camera used to aid in eye-tracking
- Each degree of freedom is either controllable by a user through an interface or is fully autonomous.
- Can run without external power for at least one hour.

2. MECHANICAL DESIGN

2.1 Overall Robot Layout

The overall goal was to design and build a small robot that would be non-threatening, portable, affordable, and able to interact with autistic children. The robot was chosen to have the outward appearance of a cartoon-like penguin, as penguins are a stereotypically cute and non-threatening and are commonly caricaturized to make them appear more so. Initially, the robot's interactive components were to be eyes and a head that moved like human eyes and a head with three degrees of freedom (DoF) each and two wings with one DoF each. By the end, two actuated eyelids and one beak with one DoF each were also included in the robot design.

In order to accommodate all actuated components, the design involved a robot with four "plates" (Figure 3). Plate 0 is the bottom piece of the robot and is intended to remain in contact with whatever the robot is placed upon. Plates 1 and 2 are at the midsection of the robot and when the head turns, the plates rotate with respect to each other. In this initial setup, the wings were on Plate 2. The majority of the electronics were to be placed between Plates 0 and 1. Plate 3 is main piece of the head of the robot.
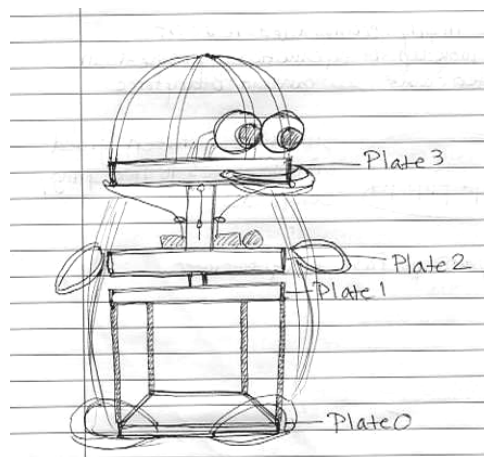
Figure 3 Overall Organization of the Robot in the Initial Design Phase

Later on, the robot design was revised to have another plate between Plates 0 and 1 for some added compliance, but it was removed due to some problems that are discussed later. The final layout is similar to the initial layout, except that the wings are attached to Plate 1 rather than Plate 2.

2.2 Eye Design

The robot design included two eyes that could pan individually and tilt together. The eyes would need to move at similar speed and with similar range of motion as human eyes. Each eye contains a small camera to be used as part of an eye-tracking system or for general observation of what the robot is to be interacting with. The eye design evolved from large spheres with a total of three DoF to smaller spheres with actuatable eyelids used for additional expressiveness.

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2.2.1   Gimbal Concept

The initial eye design (Figure 4) made use of a four-bar linkage to tilt the eyes with the motor placed farther back in the head. A servo located at the outside on the top of each eye allowed the eyes to pan. Special eye socket joints only allowed each eye to pan and tilt.
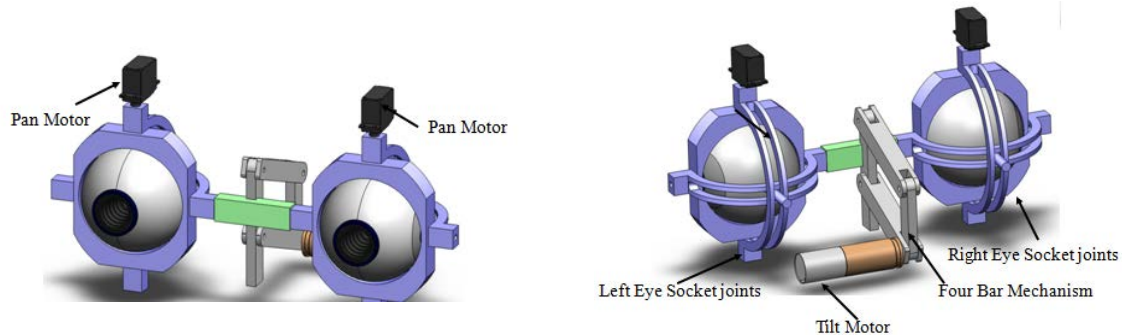
Figure 4 Original Eye Design (10)

The smallest servos that would be able to move the eyes at the right speed were not very small and would cause the eyes and the eye mechanism to be larger than desired for the overall desired size of the robot. Other eye mechanisms (Figure 5) were explored in an attempt to reduce the overall size of the eye mechanism.

A gimbal is a mechanism that allows rotation about only a single axis. Combining gimbals can allow rotation about multiple axes. Several gimbal combinations (Figure 5) were considered as possibilities for the eye mechanism.

To tilt the eyes, the mechanisms pictured in Figure 5B through Figure 5D would use a cable wrapped around the central horizontal piece that would be wound up by a servo from another location in the robot; the mechanism in Figure 5A would use a cable or a servo directly driving the gimbal from the outside; the mechanism in Figure 5E would have a servo directly driving the gimbal from between the eyes; and the mechanism in Figure 5F would use a four-bar attached to the gimbal between the eyes. Panning of each eye could be achieved by mounting a servo on the outside of the eye and gimbal or on the inside of the eye.

Figure 5 Six Gimbal Concepts for Eye Pan and Tilt

It quickly became clear that the size of the servos would drive the gimbal design to be quite large as well, so the gimbals did not improve upon the initial design in this regard, but other factors like manufacturing and cost needed to be considered. The gimbals would be simple to manufacture using a laser cutter and a vertical mill or a rapid prototype (RP) machine. To machine the mechanism shown in Figure 4 would require multip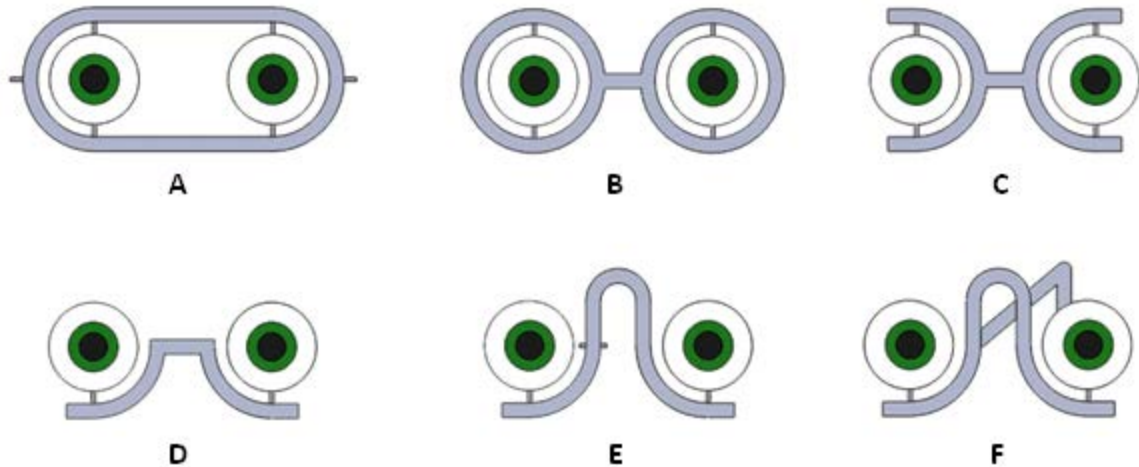le complicated parts to be machined, and a RP of it would use significantly more material than one of the gimbal designs, thus while still a feasible option, it was dismissed in favor of a considerably less expensive gimbal design.

2.2.2 Servo Placement

In the initial design concept, a servo located outside the eye would be stationary. For the gimbal designs, a pan servo located inside the eye would move when the eyes tilted, but if located outside the eye, it would move considerably more and potentially protrude from the head in the finished robot. The tilt servo could not work if placed inside the eye. Thus, it was decided that a pan servo should be located within each eye, and the tilt servo should be located outside the eyes. From then on, it became a matter of which tilt mechanism should be used and how to position the pan servos within the eyes.

Many options for how to incorporate a tilt servo for the eyes existed. As in Figure 5A, a servo attached to the far right or left of the gimbal could drive the eyes up and down, with the other side of the gimbal supported; Figure 5E illustrates a gimbal setup in which a servo placed directly between the eyes could tilt them; and Figure 5F shows a four-bar linkage attached to the gimbal at a point between the eyes, which could be driven by a servo on the other side of the linkage. Alternatively, a cable could be attached to these points instead of a servo, and in Figure 5B-D, the cable could wind around the piece between the eyes.

A cable-driven mechanism can have problems with wear. As such, it was determined that a cable-mechanism modeled after that found on a bicycle would be optimal. This sort of mechanism (Figure 6) has a long, flexible tube that the cable moves through, with each end of the tube held firmly in place.

The cable can move smoothly through the tube, and the tube can be easily routed along circuitous paths, whereas a cable by itself would follow a straight path from one fixed end to the other.
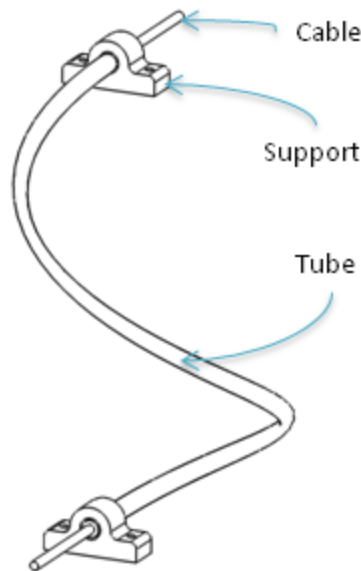
Figure 6 Cable-Guidance Mechanism Similar to That Found on a Bicycle

Analysis of the cable-driven system revealed that it was not viable for the eyes. The cables would be routed along the neck of the robot through a central cutout in the head. As the head moved but the eye cables did not, the effective cable length would change, thus the eyes would appear to move when the head moved unless the servos winding the cables moved simultaneously. As this would require too much coordinated movement, and the desired motion could be achieved by controlling fewer DoF at a time, this concept was dismissed. The variation of this concept with the servos winding the cables located on top of the head instead of lower down on the body was dismissed because the whole purpose of having cables was to allow the eyes to be driven from much lower on the robot for a lower center of gravity and if the servos were to be located on top of the head, the cables provided an unnecessary complication.

Figure 7 First Complete Design and Prototype of the Eye Mechanism

The first eye-mechanism prototype (Figure 7) utilized the gimbal design shown in Figure 5E, but the gimbal structure was too flimsy; the fit of the servo between the eyes was too tight; the only servo small enough to fit between the eyes was of inferior quality for the precision required for the eyes; and with the addition of eyelids, the servo was unable to produce the necessary torque. The second prototype of the eye mechanism (Figure 8) made use of the gimbal design with a four-bar linkage shown in Figure 5F.
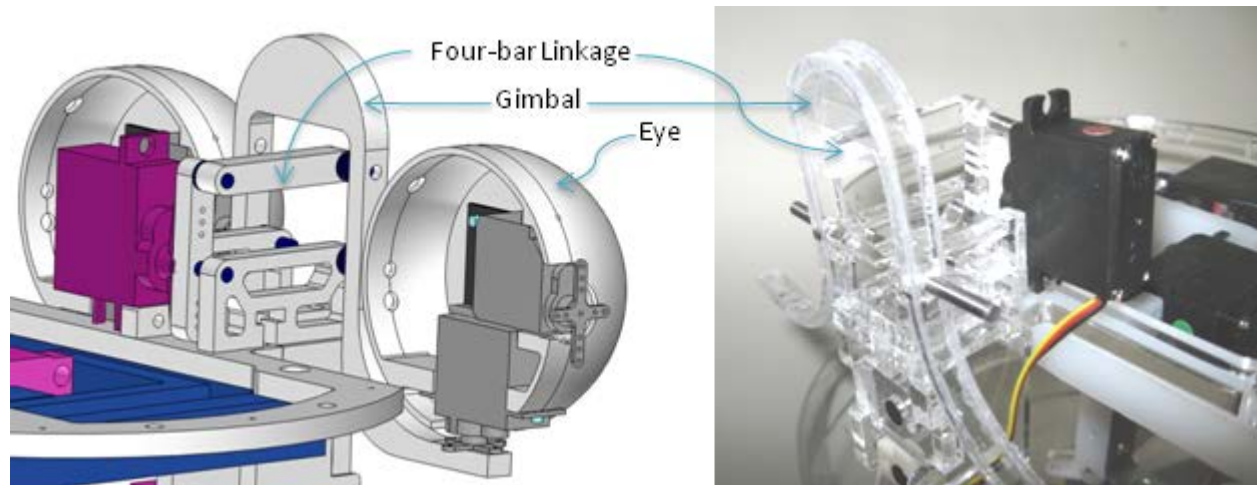

Figure 8 Second Complete Design and Prototype of the Eye Mechanism

2.2.3   Camera Placement

Initially, it was decided that there should be one camera in each eye so that it would be possible for the eyes to "focus" at the proper distance, meaning look directly at the person with which it would be interacting. If only one eye had a camera, it would be a bit of a guessing game as to which point in space the eyes should focus on, and if guessed incorrectly, the person might not feel as though the robot was actually looking at and making eye contact with them. Further, this enables stereo vision which will be useful for tracking the child and the environment. One possibility was to use a camera in one eye and some sort of a rangefinder in the other as another way to tell exactly where the person was in the field of view but cutting the image processing, something that takes a significant amount of processing, in half. Eventually it was decided that two cameras should be used so that the outward appearance of each eye would be the same to avoid frightening the person the robot would be interacting with.

The next hurdle was to find small, inexpensive cameras. It was easy to find small, inexpensive cameras, but they would be missing all the necessary circuitry that comes with the cameras in a typical webcam. Cameras with the proper circuitry tended to be too expensive. One idea was to buy inexpensive webcams, remove all of the aesthetic packaging from around them, and use just the useful parts. It was impossible to determine anything but the most approximate size (comparing the size of the camera to its usb connector in the pictures online), and so eventually, some cameras were purchased in the hopes that they were a useable size. Many weeks later, the cameras arrived and were taken apart (Figure 9). They turned out to be a useable size, so they were measured and modeled in SolidWorks so that the eyes could be modeled appropriately.
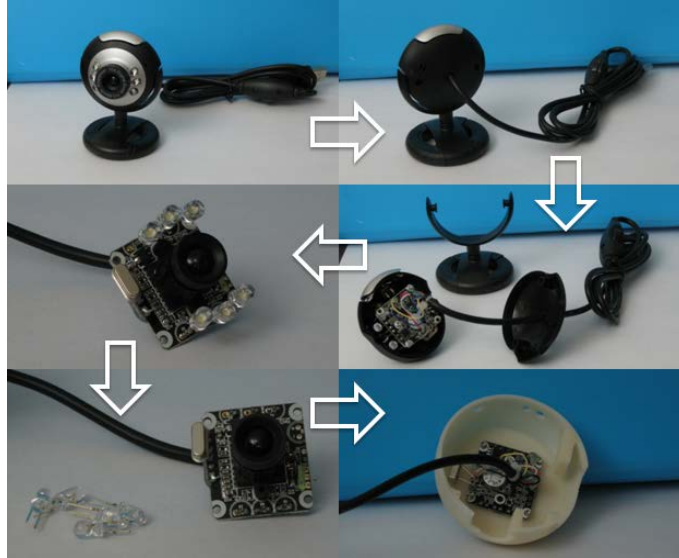
Figure 9 Disassembly of Webcams to Make the Eyes

2.2.4 Initial Eye Design and Prototype

An initial model of the eyes was created (Figure 10). As eyes are spherical, they would be difficult to machine or laser cut, so they were intended to be made on the RP machine. In order to have as few RP parts on the robot as possible, the eye was designed as two pieces: a front piece that would be a partial sphere to look like an eye, and a back piece for the servos and cameras to mount to. The intent was for both pieces to be made on the RP machine in this prototype, but for the back piece to be machinable for future iterations. The hope was that an added benefit would be that the servos and cameras would be easier to attach to the eye in this two-piece design. The prototype of this design is shown in Figure 11.
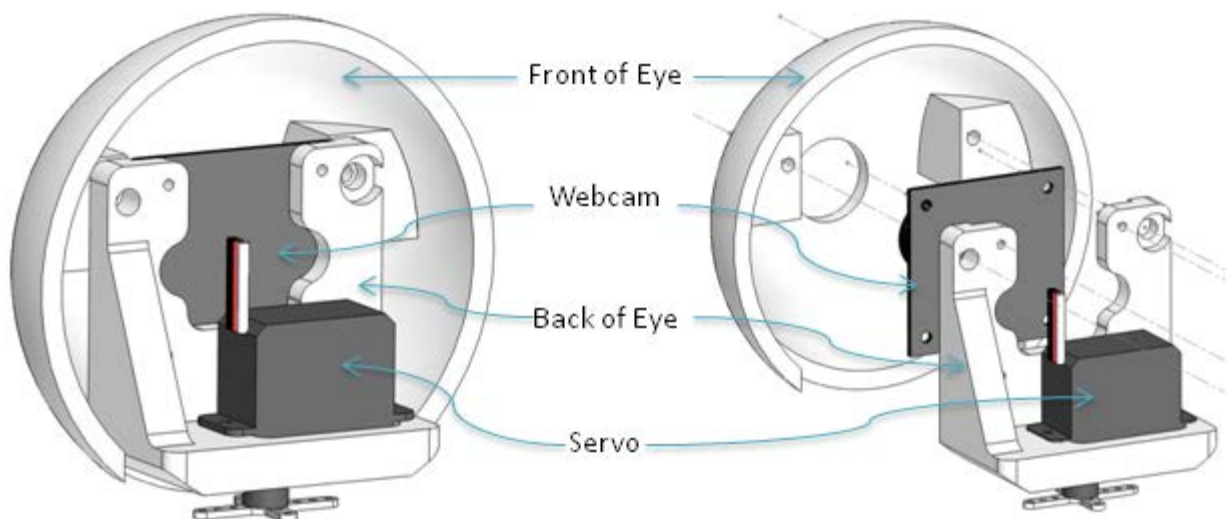
Figure 10 Initial Eye Design Modeled in SolidWorks

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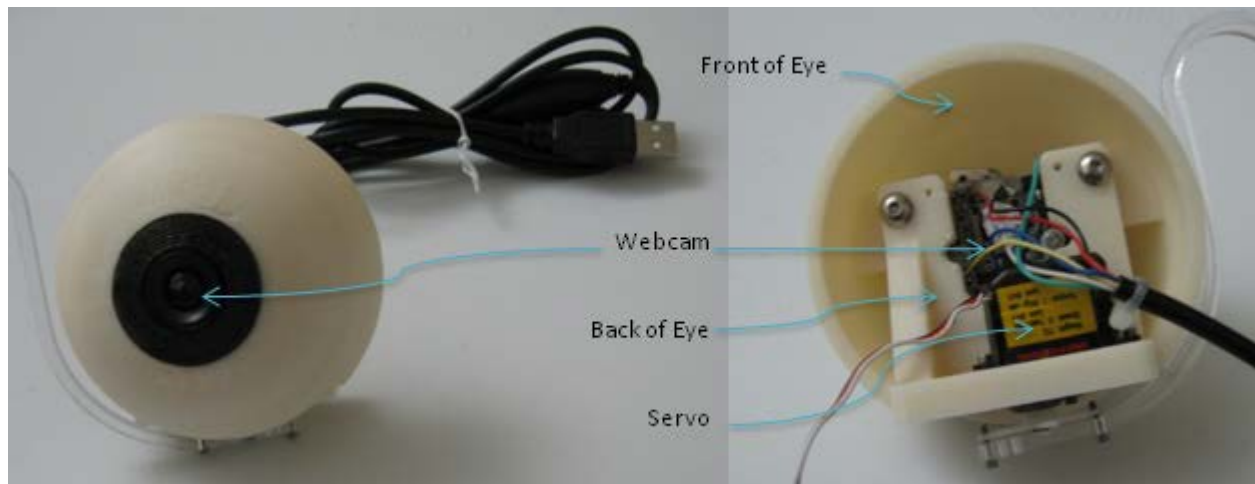
Figure 11 Prototype of the Initial Eye Design with Cameras and Servos

2.2.5 Eyelids

As in many projects, the design requirements can and do change along the way. After the initial eye design was prototyped, the requirements changed to specify that the robot should have eyelids in order to be more expressive. Adding eyelids to the current design was not a simple task, so it made sense to redesign the eyes from scratch.

The first question was as to where to place the servos to drive the eyelids. If located outside of the eyes, when the eyes panned, the servos could protrude from the head, causing the non-threatening and cute robot to lose both those qualities. The only desirable solution was to place the servos within they eyes. Many hours of rework yielded a bulky eye design (Figure 12), when the initial eye prototype was already too large.
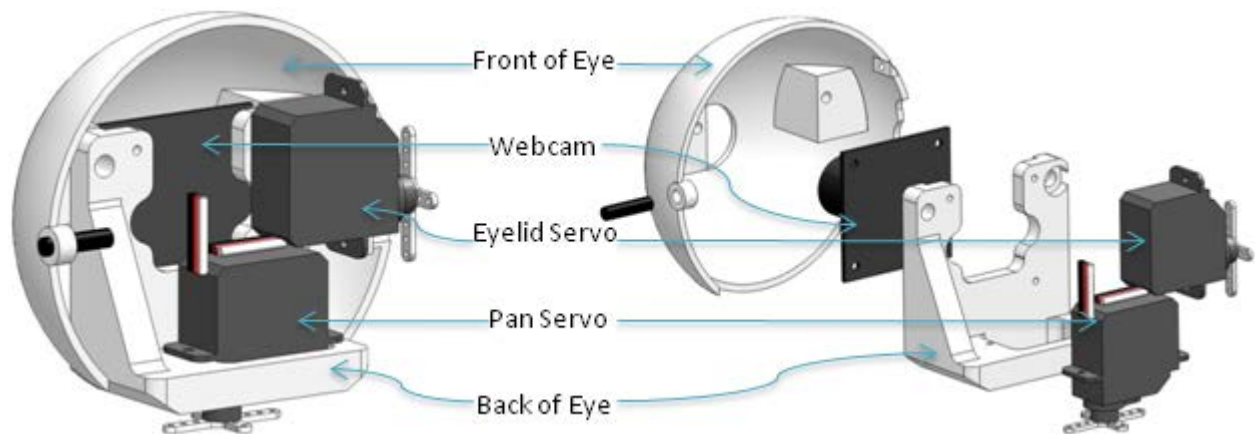
Figure 12 Initial Design that Incorporated Actuators for Eyelids

2.2.6 Final Eye Design and Prototype

The eye design was reduced to a single piece that all servos and cameras mounted to, the camera was moved farther back in the eye, all mounting surfaces were reduced in thickness, and the thickness of the

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outside aesthetic spherical piece was reduced to the minimum thickness that could be created on the RP machine. Small holes were designed into the side of the eye, giving tools access to screws in order to facilitate assembly. These changes allowed the final eye design (Figure 13) to be much smaller, but not so small as to remove the beneficial cartoon-like appearance. Figure 14 shows the prototype of the final eye design.
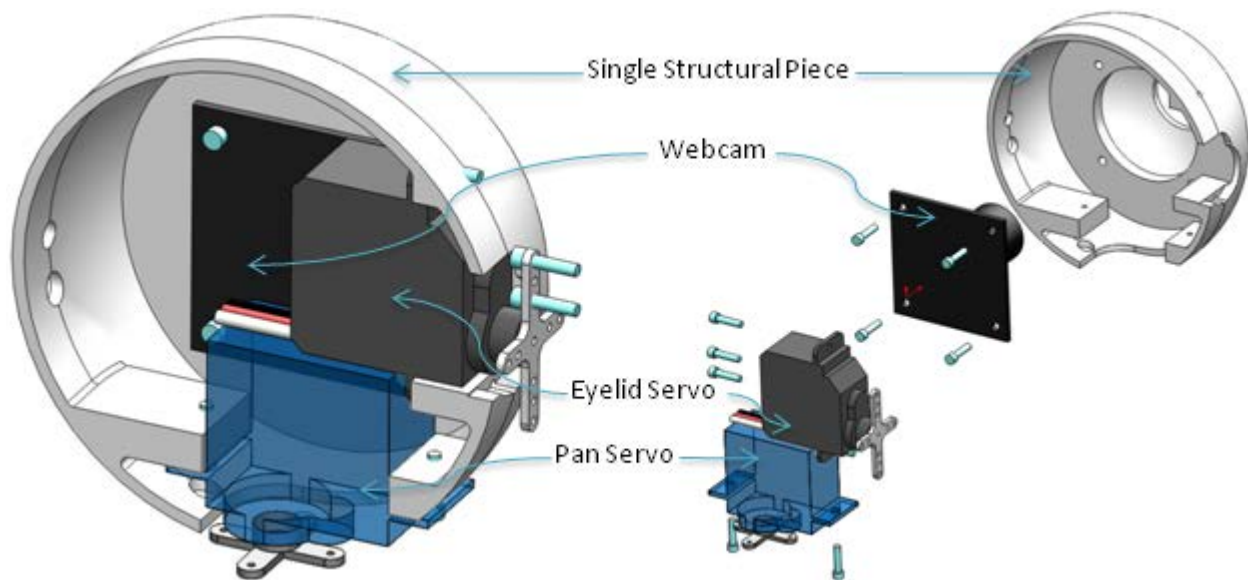
Figure 13 Final Eye Design
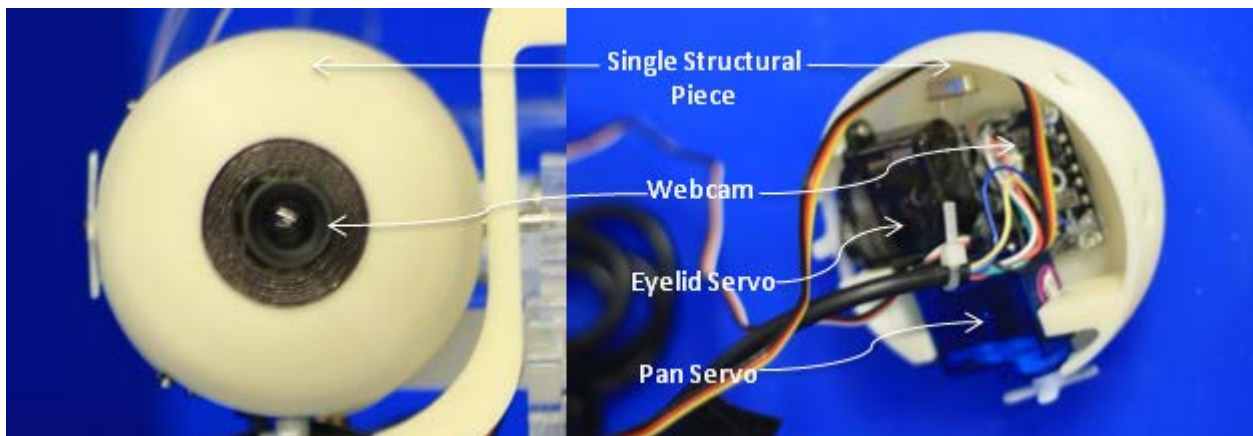
Figure 14 Prototype of Final Eye Design

2.3 Head Design

The head needed three DoF: pan, roll, and tilt. It also required one or more joints to allow for the motion, a way to attach the eyes, actuators, structure, and compliance.

2.3.1 Tilt and Roll Mechanism Design

The initial head design (Figure 15) was a cable-driven parallel manipulator head with each elastic limb having a spherical joint at the bottom and a universal joint at the top. This original design was feasible, but needed to be evaluated for its cost, size, weight, and manufacturability.
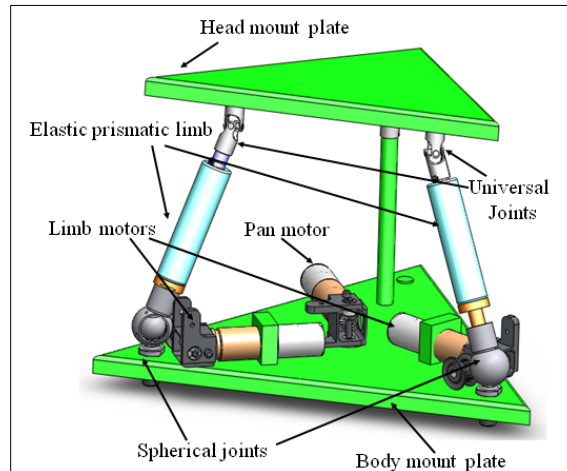
Figure 15 Original Head Design (10)

The first step was to pick out some of the purchasable components from a retailer, in this case McMaster-Carr. The smallest universal joints McMaster had to offer were 0.5 inches in diameter and 2 inches long, so large that the overall robot design would have to be scaled up to be much larger than desirable. Additionally, at over $25 each, the universal joints would be 7.5 percent of the maximum desired cost for the robot, and much of the budget would need to be used for more expensive items like motors or servos. This design would involve other expensive purchasable parts like spherical joints and somewhat custom springs as well as a few complex machined parts, driving its cost up very high. Given the amount of metal that would be used, it would be quite heavy. This design could clearly be improved upon for all criteria.

The first redesign (Figure 16) reduced the number of universal joints from 3 to 1, placed toward the top. The head would be cable-driven, allowing for the motors or servos to be placed at the base, thus lowering the design's center of mass, making the robot less likely to tip over. In addition, the servos would only have to move the weight of the head and eyes, unlike in some designs in which the servos would have to move their own weight as well.
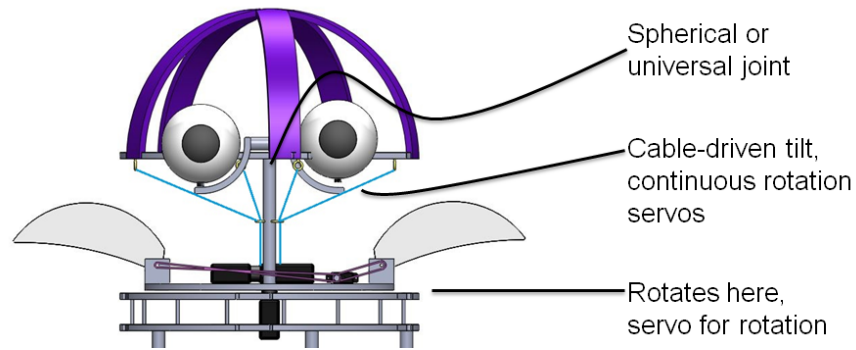
Figure 16 Cable-Driven Head Redesign

The cables would wind onto the servo shaft as shown in Figure 17. There would be a cable for each direction, as in one for moving the head down and one for moving the head up, as the cables would only be able to pull and not push, like muscles. The idea behind the cable winding mechanism is that it would turn and one cable would retract the same amount as the other would extend.
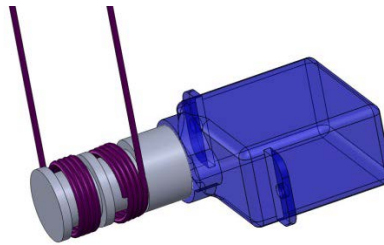
Figure 17 Servo Attachment for Winding Cables

This redesign still had disadvantages however. It had no built in compliance, so if a child were to grab the head and pull or twist, or if the head got hit, components would break. One idea was to put torsion springs between the servo and its attachment, and another was to put extension springs midway along each cable, but both of these solutions were complex, and complexity adds cost. Instead, a compliance layer was designed into the robot (Figure 18) It would prevent the robot from breaking if the head were twisted or pushed on, but not if the head was pulled on.
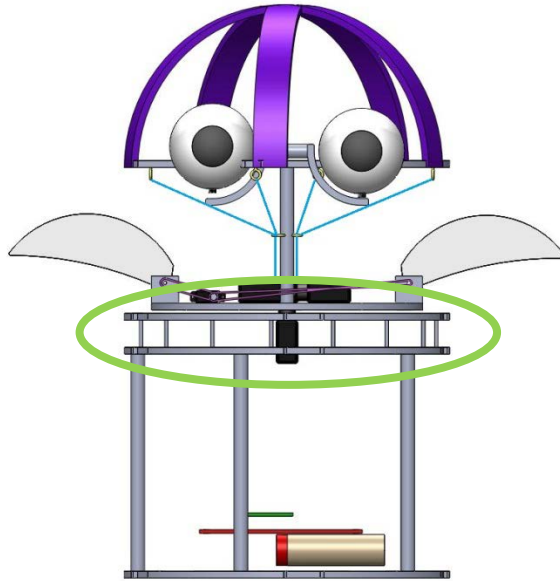
Figure 18 Layer of Wires for Compliance

Additional shortcomings of this design lay in the universal joint. It was determined that the universal joint did not have the range of motion necessary to mimic that of the human neck and head. They were only designed to bend up to 25 degrees in all directions. The joint could bend up to 90 degrees in some directions, but it would make it so that the head could not bend more than 25 degrees in both the roll and tilt directions. Therefore, a universal joint would not allow for the goals of this robot to be realized.

After designing the eyes, it became clear that gimbals have a large range of motion, and so one was able to replace the universal joint with only a small amount of design rework. The initial head gimbal was circular (Figure 19), mimicking a typical gimbal in its shape, but it quickly became clear that a rectangular gimbal (Figure 20) would be significantly easier to manufacture.
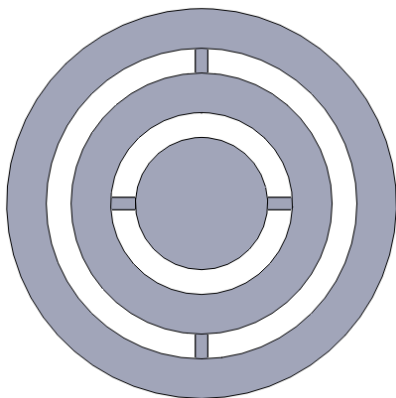
Figure 19 Sketch of Circular Gimbal Design   **Figure 20 Sketch of Rectangular Gimbal Design**
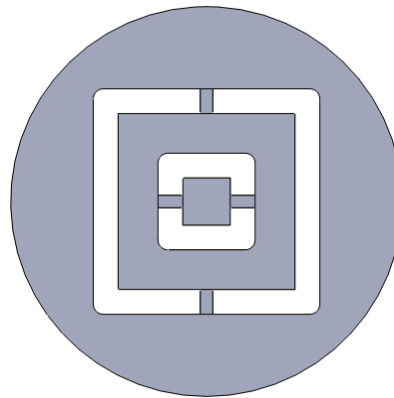
During the preliminary design review (PDR), it was pointed out that the way the cables were setup, to move the head forward, for example, the cable attached to the back of the head would need to extend a

different amount than the cable attached to the front of the head would need to retract. As such, two actuators rather than one would be needed for this motion. It seemed impractical to have two actuators controlling one DOF, so the design was revised to have the servos directly driving each axis of the head. This design became the final design. Its model is pictured in Figure 21 and its prototype is pictured in Figure 22.
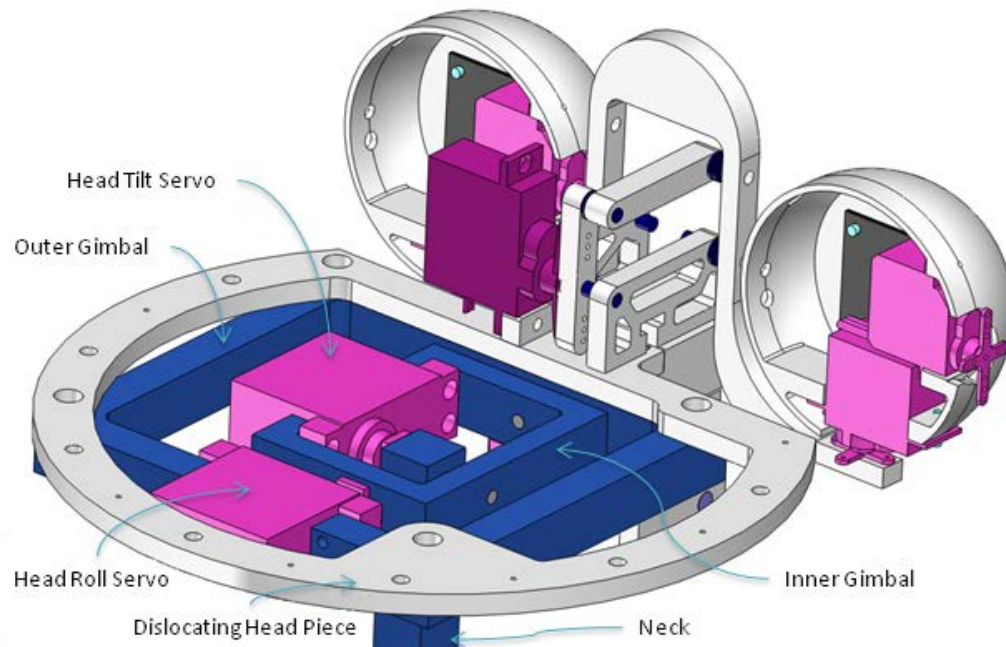
Figure 21 SolidWorks Model of the Final Head Gimbal Mechanism
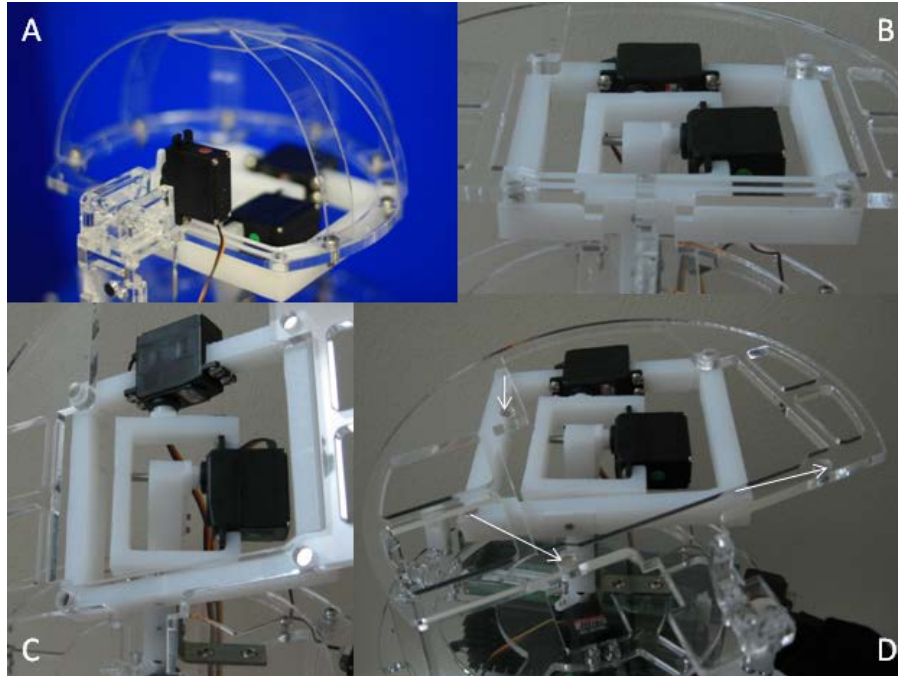
Figure 22 Prototype of the Final Head Gimbal Mechanism

Figure 22 displays the final head design in A, a close-up of the final gimbal in B, the gimbal in a different position in C, and what happens to the head when it gets pushed or pulled on in D. The gimbal works smoothly and is a successful proof of the gimbal concept.

2.3.2   Pan Mechanism and Neck Design

The pan motion of the head is actuated by a servo located fairly low in the robot. The servo horns attach to a plate that rests on several screws, and the neck piece is attached to this plate by two angle brackets. This created a sturdy way to mount the neck and have the head pan. This design (Figure 23) did not change very much over the course of the project. There were other concepts, but none of them seemed feasible, so they were not modeled or prototyped. This design has the benefit of being somewhat simple with purchasable parts and parts that are simple to machine making it relatively low cost.
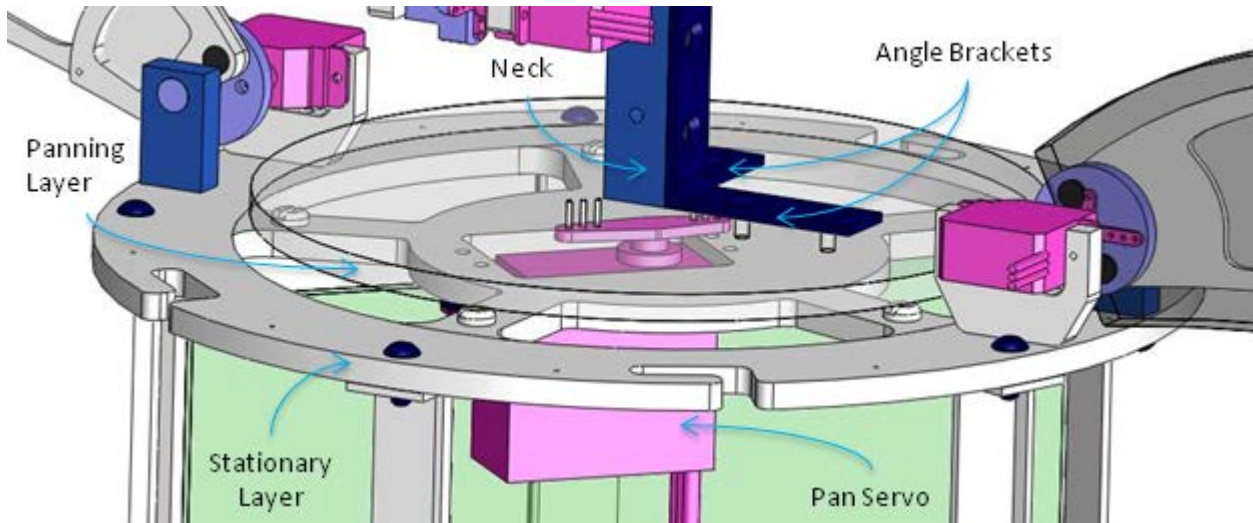
Figure 23 Head Pan Mechanism Design

As the design appeared feasible from the SolidWorks model, a prototype was made. Basic testing showed that the concept worked and that no real improvements would need to be made to it. Figure 24 is a picture of this prototype.
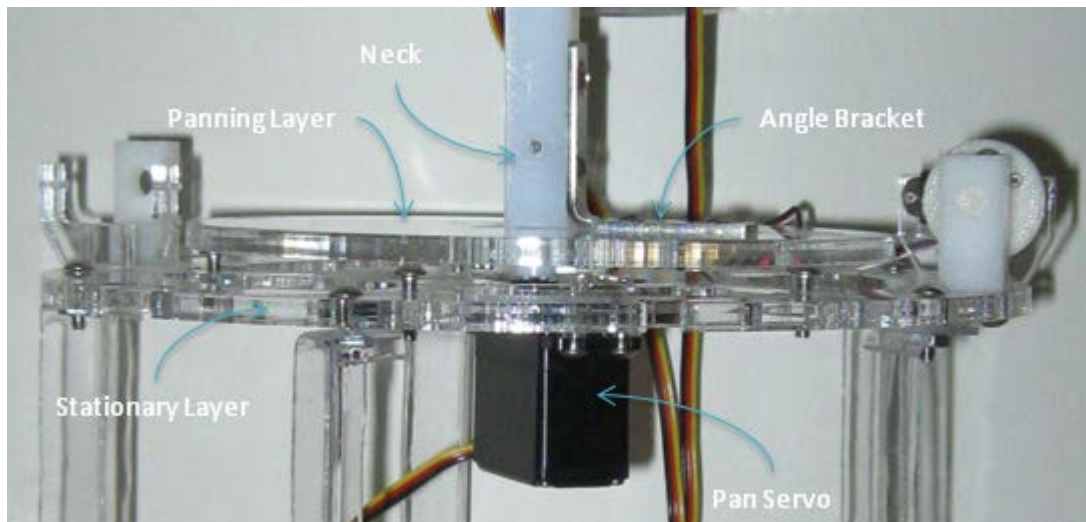
Figure 24 Head Pan Mechanism Prototype

2.3.3   Compliance Elements

The head structure (Figure 25) needed some amount of rigidity to hold its shape, but not so much rigidity that this structure could not double as a compliance element. The first idea was to make the structure out of strips of the thin, flexible foam that can be bought in sheets at craft stores. As the same sort of structure would be needed for the body, and the body of the robot would need more rigidity, strips of thin polycarbonate were determined to be the optimal material as polycarbonate is easily obtainable and flexible.
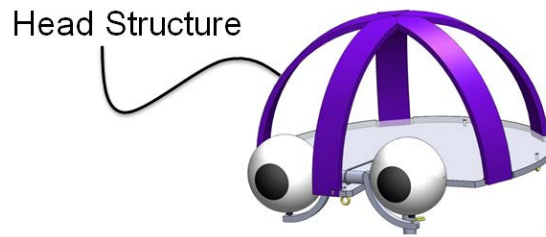
Figure 25 Head Structure

All rotational movements had built-in compliance at this point, but there was nothing accounting for if the head was pulled on. One concept was to hold the head on with strong magnets, such as neodymium magnets. This would protect the servos from damage, however, if the head separated from the body, the only thing holding it one would be wires, which are also susceptible to damage from being pulled on. Additionally, a head separating from a body could have devastating psychological consequences for a small child. A solution was to also attach the head to the body with cord which would be loose under normal operation, but would hold the head on when the magnets separated. This would mean that if the head was pulled on, the magnets would separate, the head would separate just slightly from the body and be held on by the cord, the servos and wires would be protected from harm, and the head could easily be placed, the magnets would reattach and align the head, and the robot could resume normal operation.

2.4 Other Parts of the Robot

2.4.1 Wings

The wings went through many iterations before reaching their final design. Initially, they were firmly attached to a layer of the robot (Figure 26.) This layer rotated when the head rotated, meaning that the wings would rotate with the head. The next iteration of the wings involved designing them into a level below their previous one so that they would not turn when the head turned and instead stay put. These initial designs of the wings had them being cable-driven by a single servo, giving them a combined one DoF.
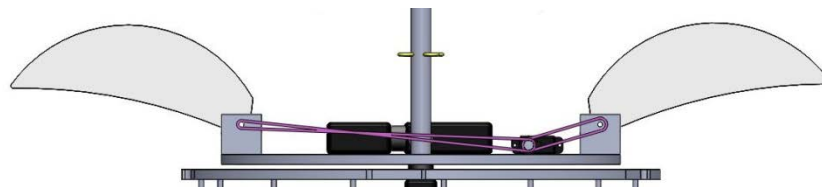
Figure 26 Initial Wing Design

In the preliminary design review, it was noted that if a child were to grab onto a wing and try to lift the robot by it or just pull on it, parts of the robot might break. Some additional compliance needed to be added in. The first concept (Figure 27) involved a wing assembly (comprised of a wing, a servo, and other necessary components) that would rest on a layer of the robot in normal operation but would

detach from the robot if pulled upon. This concept had two disadvantages: If the robot were to be turned upside down, the wing would come off; and the servo would still be attached to the rest of the robot through its cable, so the cable would likely end up broken.
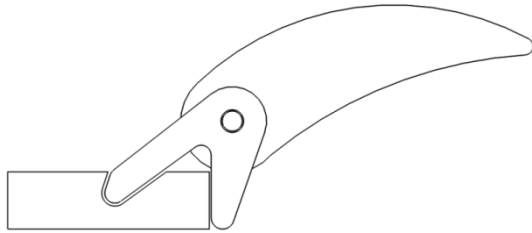
Figure 27 First Wing Compliance Concept
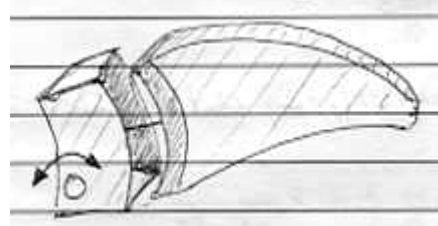
Figure 28 Second Wing Compliance Concept

Other similar solutions involved holding the wing on with a springy mechanism, like a clothespin, but they, too, involved the servo remaining attached by its cable. A variation involved the clothespin-like piece be the wing itself, so that when pulled on, only the wing would come off, leaving the servo behind. Another variation (Figure 28) involved two pieces that fit together connected by a cable, the cable attached to something sturdy so that it would be able to survive the force instead of the servo having to. In an effort to simplify these feasible designs, the spring was removed, and the wing would be attached by a snap fit (Figure 29).
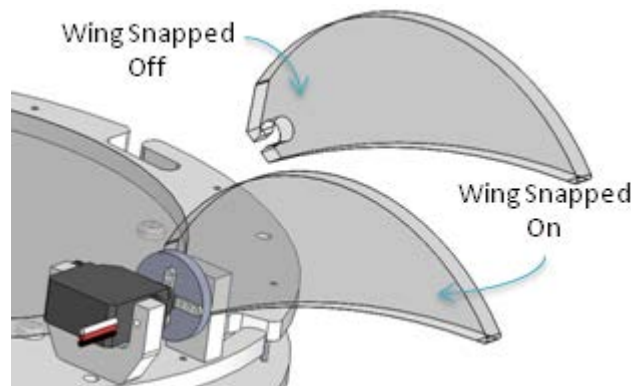
Figure 29 Wing That Can Snap On and Off

Given the tools at hand, the most practical way to make the complex shape of the wing would be with the laser cutter. Given also that the most available material to prototype with on the laser cutter was acrylic, this design would not work well, as acrylic does not flex much before breaking, and the snap fit would require a certain amount of flex in the wing. Additionally, to have a nice snap fit, parts of the wing and what it was snapping around would have to be held to very tight tolerances, tolerances that would add an unnecessary expense to this application.

Finally, it was suggested by multiple people that magnets might be a way to add compliance to a system. A new design was created that involved two magnets in the wing and two in the piece attached to the servo. This setup would allow the servo to drive the wing, but if the wing was pushed up or down, the

magnets would shear apart, and the wing would come off leaving the servo undamaged. The wing could easily be placed back into its starting position. For this design, each wing was driven by one servo rather than having both wings driven by the same servo, as this reduced mechanical complexity. This wing design was prototyped and determined to be too small, so a slightly larger version was prototyped. It, too, was determined to be too small, so a third version was made and determined to be an adequate size.

The wing only had compliance in once direction. To give it compliance in the remaining directions, most of the rest of the wing was to be made out of thin polycarbonate. With polycarbonate, the wing would flex if pushed on, bent, or twisted in the remaining directions. This was the final design, and the SolidWorks model of it can be seen in Figure 30. The prototype of this design can be seen in Figure 31.
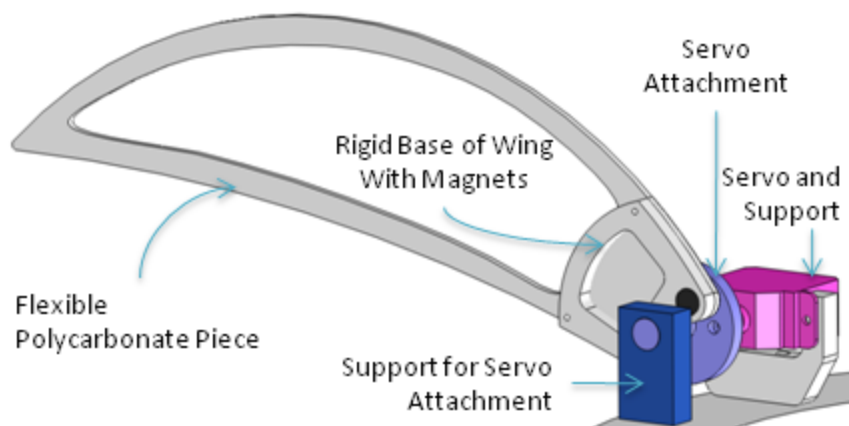
Figure 30 Final Wing Modeled in SolidWorks
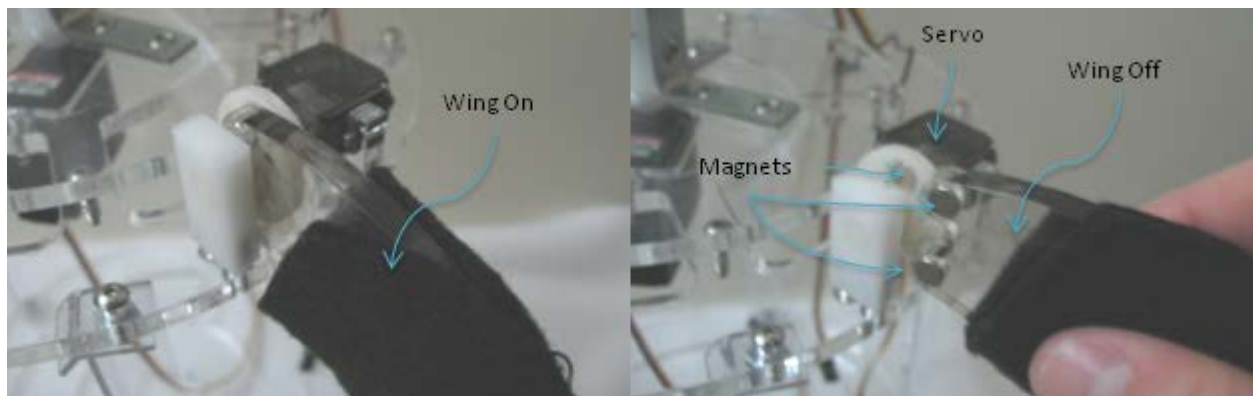
Figure 31 Final Wing Design Prototype

2.4.2   Beak

The beak was designed to have one DoF. The lower half of the beak can move while the upper half remains stationary. Each half of the beak is meant to attach by a magnet and an alignment pin. The

mechanism for the beak was designed and prototyped (Figure 32), but the part that looks like the beak has not yet been constructed. It could be a RP part or made from fabric and stuffed.
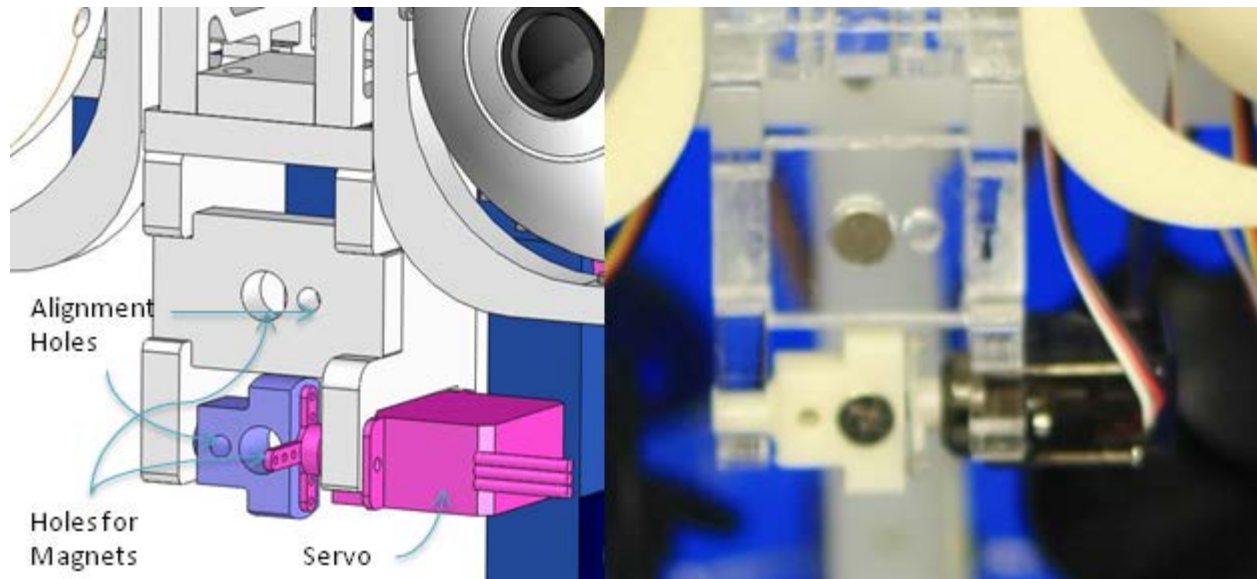
Figure 32 Design and Prototype of 1-DoF Beak Mechanism

2.4.3   Tail

The majority of electronic components were to reside within the robot, so there needed to be a simple way to access them. That way is through the tail. The design involved a tail-shaped cover that would flip up (Figure 33). There were two logical locations for the pivot to be along the tail. The bottom part of the tail was prototyped, but the top cover never was.
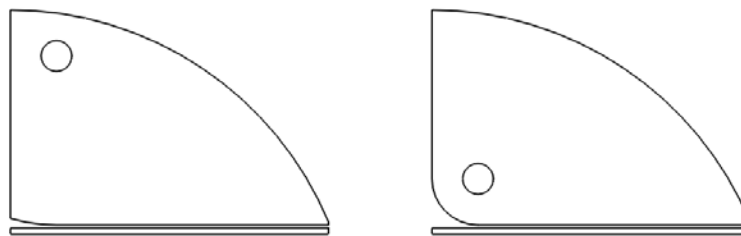
Figure 33 Tail Flip-Up Cover for Electronics Access

2.5 Robot Appearance

It is very difficult to model the soft outer-covering of something like a stuffed animal in SolidWorks. One attempt is shown in Figure 34. A model can be created, but accurately prototyping that model can be anywhere from difficult to impossible.
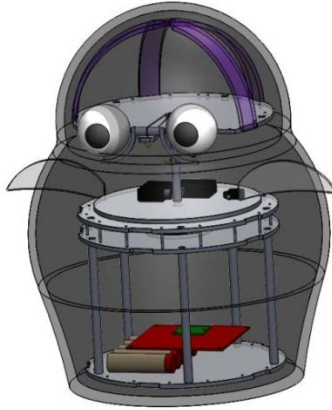
Figure 34 SolidWorks Model of Aesthetic Components of Robot

Taking a device that was designed focusing on mechanical and electrical functionality and not on aesthetics and then making it look like something is very difficult. Generally, mechanical engineers and industrial designers would work closely throughout the design process to get a functional device with the right outward appearance. Here, that was not possible, and despite careful consideration along the way of the robot's outward appearance, it was still difficult to make the robot look like a penguin. Figure 35 shows the robot without and with its penguin-like features.

The feet were sewn and stuffed. The wings and body of the covering were sewn as well. To make the covering fit the body well, the top was gathered and sewn. The beak is just a cone of fabric sewn together; eventually it needs to be two pieces attached to the beak mechanism so that it can be actuated. The covering for the head was tricky, and as it is pictured, it is incomplete and not sewn together; this must be fixed. In addition, the body of the covering will need to be stuffed so that the structure of the penguin is not obviously visible through it.
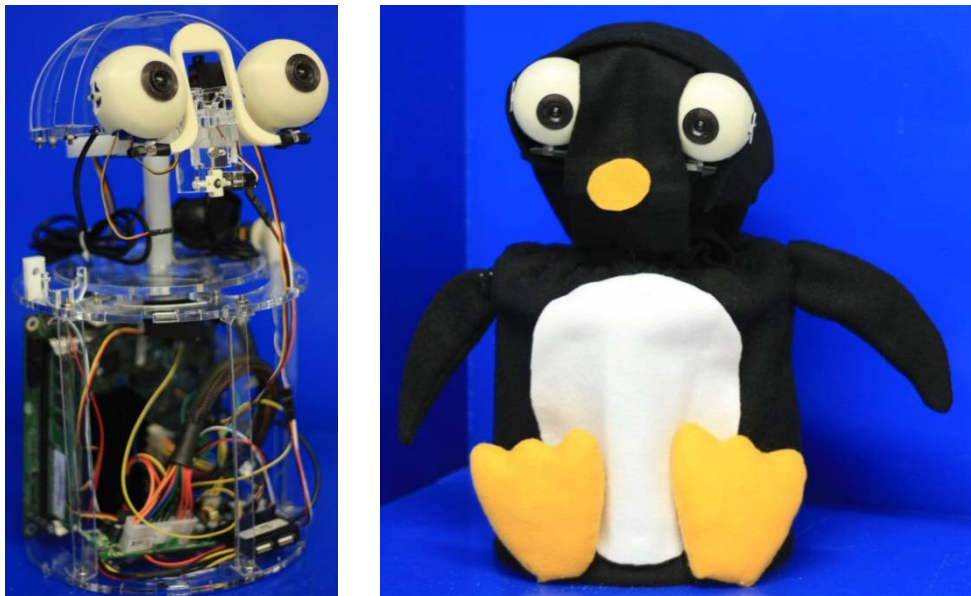
Figure 35 Robot Prototype and Making it Look Like a Penguin

3. ELECTRICAL HARDWARE DESIGN

3.1 System Architecture

Initially, the control system was to be setup as shown in Figure 36. A Beagle Board or gumstix would be at the heart of it all. Webcams would communicate with the board through USB, and the board could control servos over RS 232. A sort of power module would be attached to a battery and a wall wart and would take care of charging the battery when the robot was plugged into the wall and make sure that the robot could run off of battery power and run while it is charging. A keyboard, mouse, and monitor would be hooked up to the Beagle Board to program and detached during normal robot operation.
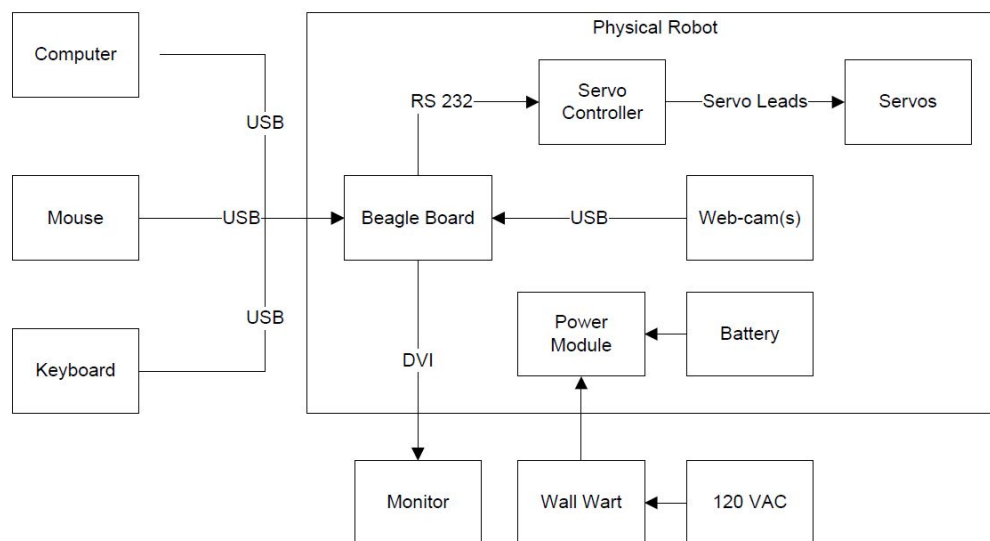
Figure 36 Initial Block Diagram

The final system organization (Figure 37) is very similar except instead of a Beagle Board, there is a single board computer with an atom processor (similar to a netbook); there is no power module, only a power adapter, and it is also possible to program the computer through another computer attached to the robot's computer by an Ethernet cable. In this final system organization, the single board computer can be programmed and controlled in two ways: one by plugging a mouse, keyboard, and monitor into it and using it as one would a desktop computer; the other by connecting it to another computer with an Ethernet cable and opening up software to remotely connect to the single board computer. The single board computer is powered through a power adapter. The two webcams are connected to the single board computer using USB. The two servo controllers would be daisy chained to each other, one of them connected to the single board computer communicating over RS 232, and the eleven servos that control the robot's eleven DoF are connected directly to the servo controllers.
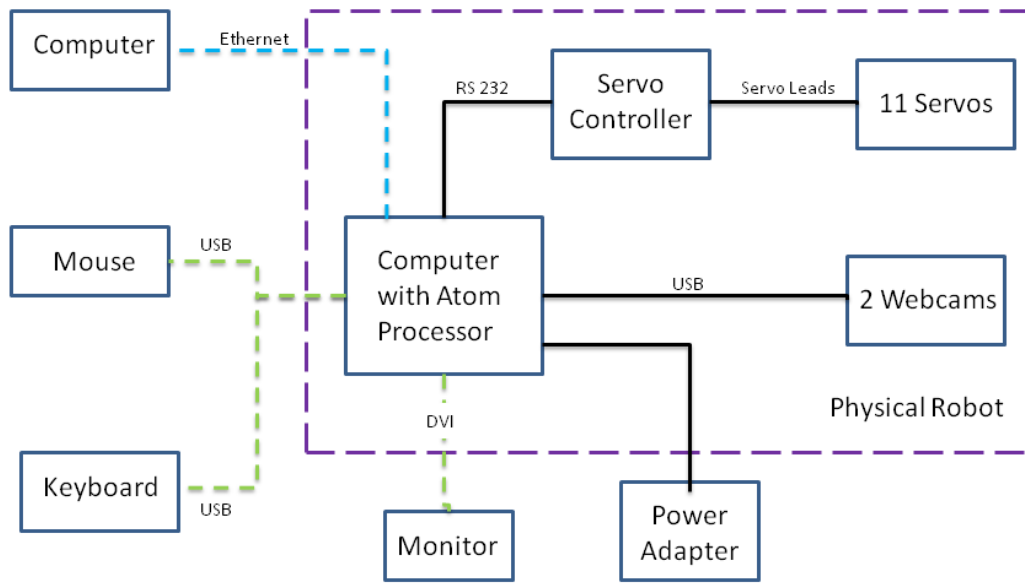
Figure 37 Final Block Diagram

3.2 Actuators: Servos vs. Motors

As with many robotics projects, completely separating the mechanical and electrical components is impossible. Part of the electrical design that was very important to the mechanical design was deciding which actuators to use. Properly selected motors could move at the right speed to the correct position and do it quietly, but it is not that simple. Well-designed motor controllers would need to be used, and they could be expensive or need to be designed and made specifically for this application. Properly selected hobby servos could be made to move at the correct speed to the right position, driven by inexpensive, purchasable servo controllers. It would be easier to select useable hobby servos than motors in an affordable price range.

Eleven hobby servos similar to the one shown in Figure 38A were chosen for the robot. The servos had varying maximum speeds and torques, each carefully selected such that the desired speeds and torques could be achieved. The eyelids, the beak, and the wings made use of four inexpensive, tiny servos that were not of an excellent quality. These inexpensive servos would often switch repeatedly between two close positions, causing the servo to heat up from the vibration. Originally, these servos were to be used for the eyes, but better quality servos were necessary for all DoF that would be required for eye-tracking. The remaining six DoF were controlled by HiTEC brand servos, which while being significantly more expensive, were also of significantly better and sufficient quality, able to move to and stay at a position without vibrating or heating up. The servos each have at least ninety degrees of travel.

In addition to eleven hobby servos, two of the servo controllers shown in Figure 38B were chosen for the robot. The servo controllers can each control up to eight servos, which is why two are needed for this application. Daisy chaining the servo controllers can allow for 128 servos to be controlled from a single serial port, and the single board computer has two serial ports. Since it seems unlikely that any

design of the robot would need to control greater than 256 servos, the servo controllers do not limit the robot in terms of the number of servos that can be used.

A   B
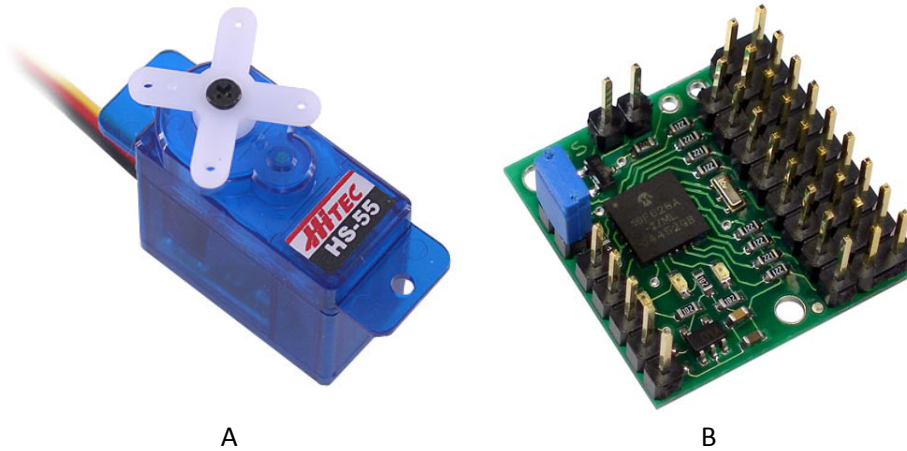
Figure 38 Servo and Servo Controller (10) (11)

Hobby servos have the drawback of making a loud sound while they move. It may be possible to lessen the sound by changing specific parts of the code, in particular, the part of the code that controls the velocity of the servo. The sound a servo produces may be related to how quickly it tries to rotate to a destination position. Causing the servo to move more slowly to its destination position could diminish the noise produced.

3.3 Sensors

The only sensors initially integrated into the robot are the web cameras in the eyes. They are meant to be used in eye-tracking or to give somebody teleoperating the robot a way to see who the robot is interacting with. Other sensors were considered, such as one or more touch or bump sensors, to try to gauge if the child is trying to interact with the robot. These touch sensors would allow the robot to try to prompt the child to play with the robot and give the robot feedback to determine to what extent the child is interacting with it.

A rangefinder was considered as an alternative to one of the webcams in the eyes to cut down on cost and processing. It would be used to determine how far away a face was, while the webcam would be used to locate the face along the other two axes. This idea was dismissed for fear that the eyes would appear asymmetrical, and that could be unsettling.

3.4 Power

Two project goals were to have the robot be able to run on battery power for one hour and to make the robot portable. The length of time for which the robot can run on battery power is one factor in how portable the robot is. Thus, the power requirements for the project were important to consider.

Out of the box, the single board computer can be powered using a power supply or an AC adapter. The goal was to make use of that to charge a battery, and run off of it while the battery charges, and then to have the entire robot be able to run on battery power alone for some period of time. As such, a power module would need to be developed so that the robot would run off of the correct power source in the appropriate circumstances.

As a first step, a type of battery needed to be chosen. Nickel-metal hydride (NiMH) batteries were chosen for this project because they are common and much safer to use than some other types of batteries. NiMH batteries can store enough power in a small enough space to be of use in this application. NiMH batteries fall into a price range typical of most batteries; despite this, they are not inexpensive in the quantities required for the robot to operate for one hour solely on battery power.

The intention was to use the 14.4V NiMH battery of a Roomba that was donated to this project by Andrew Lewis. The battery needed to be tested to determine if it was still good, as the usage history and age of the battery were unknown, and batteries can go bad with poor use or enough time. A device was acquired for the purpose of recording how the battery discharged to determine how good the battery was, but there ended up being no time to use the device. The packaging a Roomba battery comes in was removed and replaced with heat shrink, and wires were soldered onto the battery so it would be easier to charge.

The next step was to come up with a method of charging the battery while the robot was still operating. Research showed that there were several ways to charge NiMH batteries. The very safe way to charge was a simple circuit to setup, but it would take a many hours for the battery to charge this way. The faster way to charge the battery would charge the battery in a practical amount of time, but it was unsafe unless well-monitored with temperature or other sensors so as not to over-charge the battery. It was determined that Texas Instruments sold components that would take care of the difficult circuitry associated with charging NiMH batteries, but these components would not charge batteries with voltages as high as 14.4V. Battery chargers specifically for NiMH batteries could be bought, but they were too large, very expensive, and would require some amount of manual operation where the goal was to avoid manual operation other than plugging and unplugging the robot from the wall.

One solution to this charging problem would be to buy new NiMH batteries with voltages low enough to be used with the components from Texas Instruments. This would allow for a somewhat simple charging solution.

4. SOFTWARE DESIGN

4.1 Code

A project goal was to develop an interface for the robot that could be used for control of the robot from within a higher level software application. The robot is programmed using java. The decision to use java was based primarily on two reasons: Java is object-oriented, and object-oriented made a lot of sense for this application; and Java had a free library, RXTX, to be used for serial communication, already written

for it, and serial communication would prove to be very important to the success of this project, but there was not enough time to write it from scratch. Linux was chosen as the operating system because it was free and has a lot of useful software already written for it. The specific type of Linux chosen was Ubuntu Netbook Edition, and the operating system was installed on a flash drive.

The software was written with the structure pictured in Figure 39 in mind. The idea behind the structure was to mimic the physical entity being controlled. There are six main classes: PABI_Penguin, Wing, Eyes, Head, Beak, and Servo. A PABI_Penguin contains instances of Eyes, Head, Beak, and two instances of Wing called eyes, head, beak, leftWing, and rightWing respectively because the penguin robot has eyes, a head, a beak, and two wings. The Wing class has an instance of a Servo called wingServo, and the Beak class has an instance of a Servo called beak Servo. The Eyes class has five instances of Servo called tiltServo, rightServo, leftServo, leftEyelidServo, and rightEyelidServo. The Head class has three instances of Servo called rollServo, panServo, and tiltServo. A PABI_Penguin breaks down into eleven instances of Servo, just like how on the physical robot, there are eleven servos that control eleven DoF.

The Servo class is one of the most important classes as is provides physical functionality to the other classes. It keeps track of the six bytes sent to the servo controller over RS 232, a number specifying a servo position, and the units associated with that number. In addition, it stores the number corresponding to the part of the servo controller a servo is plugged into, and the minimum and maximum values that can be sent to the servo to alter its position. The Servo class contains methods to initialize the servo, move the servo, and change the units of the position being specified for the servo to move to. Each class has several methods which are summarized in Table 1. The methods that still need to be written are marked with an asterisk.

Currently, only servo position control has been implemented. The servo controller has some functionality that allows for velocity control. To add velocity control into the software, either the servo controller's functionality could be used to move the servo at a certain velocity with periodic checks to see if the servos have moved to the desired position, or some code could be written to at specific time intervals, increment the servo position by a certain amount. This functionality could all be achieved with some additional variables and methods in the Servo class.
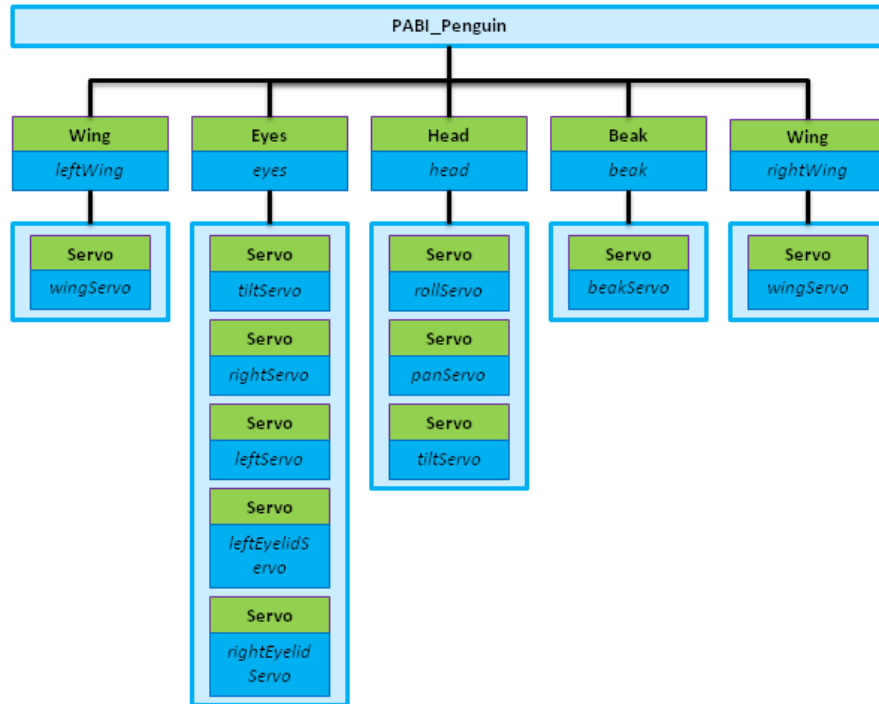
Figure 39 Software Organization

Table 1Methods

Class	List of Methods
Servo	*initialize, convertPosUnits, moveServo*
Wing	*raise, getPosition*
Eyes	*panLeftEye, panRightEye, tilt, openLeftEye, openRightEye, getLeftEyePan, getRightEyePan, getTilt, getLeftEyelidPosition, getRightEyelidPosition, getLeftEyeCoordinateFrame*, getRightEyeCoordinateFrame**
Head	*tilt, roll, pan, getTilt, getRoll, getPan*
Beak	*open, getPosition*
PABI_Penguin	*sleep, wakeUp, homePosition, lookAtPoint*, playSound*, recordSound*, getImageLeft*, getImageRight*,getBatteryVoltage**

4.2 Graphical User Interface

The robot is currently operable by a Graphical User Interface (Figure 40). It has sliders that can be moved to control each DoF. This interface is primarily intended to demonstrate and test the robot functionality. This will be integrated into higher level software that includes vision, tracking, and behaviors.
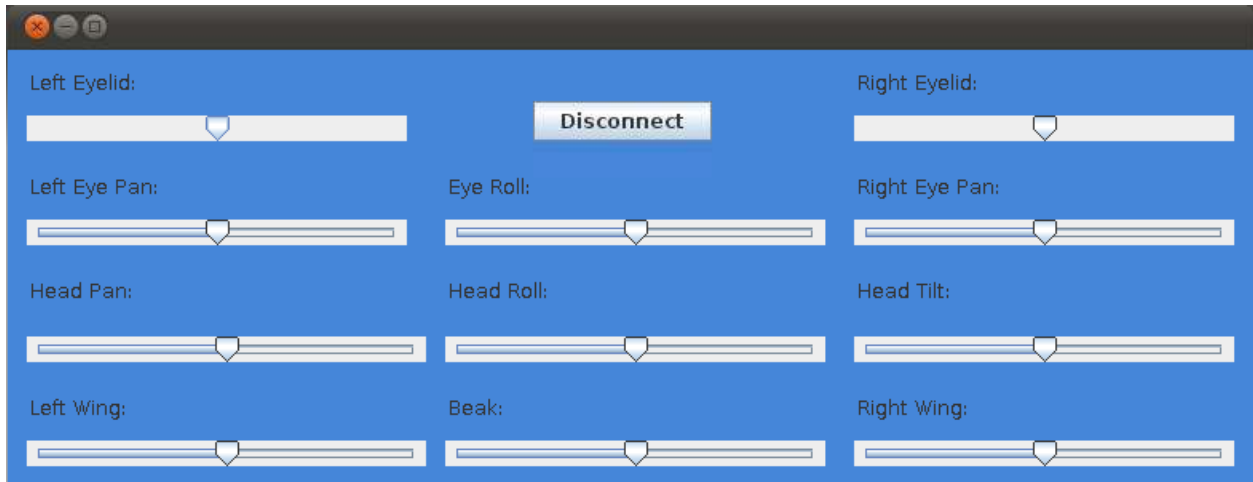
Figure 40 Graphical User Interface for Controlling Each DoF of the Robot

4.3 Process

The initial setup of the computer, all the way through installing Ubuntu Netbook Edition went smoothly. Following that was a series of problems, all seemingly unrelated, that significantly slowed down the progress of the project.

The first problem was in reading from a flash drive. It appeared that the problem stemmed from the operating system being installed on another flash drive and that it was having trouble recognizing other flash drives. In order to install most of the software necessary for writing and testing code for the project, it was necessary to have wireless, but in order to setup wireless, the computer needed to have WPI's current wireless certificates, and the only known way to get them on the computer was to transfer them on a flash drive. Additionally, the serial communication library, RXTX, was necessary for code development, but in order to get it, it was necessary to have an internet connection or to transfer files using a flash drive. There was no way around being able to read from a flash drive.

It appeared that the computer could recognize some flash drives, but not read them. Formatting them on the Linux computer would sometimes make them accessible on that machine, but would render them unreadable on a Windows machine. Formatting them on the Windows machine would sometimes cause them to be readable on the Windows machine, but would render them unrecognizable on the Linux machine. Through a seemingly random sequence of formatting the flash drives and switching which machine they were in, it became possible to transfer the wireless certificates. Wireless was setup, all necessary software was installed, and some code to control the servos was written. A SourceForge account was already setup, and the intent was to commit the code the next day after getting Subclipse or some similar software working. The very next day, the computer would not boot up.

The computer would get stuck partway through booting every time. It was unclear what had happened to cause this. Some websites suggested that something had gotten corrupted, but it could be repaired by reinserting the original flash drive Ubuntu was installed from and choosing a particular repair option.

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The repair appeared to work, but each time it was tried, it got stuck partway through the process. Using a Windows machine and another Linux machine, the files were attempted to be read or at least copied over, but that did not work. After exhausting all known and researched options, it became clear that it was time to wipe the flash drive and reinstall the operating system, losing all progress on the code forever..

Another issue encountered along the way was that the netbook layout for Ubuntu is not intuitive, and has several features hidden. In acquiring help with the project, those who were extremely familiar with Linux found themselves unable to navigate through the netbook edition. Eventually it was suggested that while it was the netbook edition, it could be changed to by laid out just like Ubuntu Desktop Edition. This quick fix worked and prevented the need for an entirely new operating system, Ubuntu Desktop Edition, to be installed.

The final problem discovered was with swap space. Swap space is a part of a drive that gets written and rewritten to frequently. This frequency of writing to the drive would be fine with a normal hard drive, but if on a flash drive, could ruin the flash drive very quickly. Using the terminal, swap space for the flash drive was disabled. Strangely enough, this had been done during the install of the operating system, and it should not have needed to be repeated. While this should be a permanent fix, swap space may have been reallocated on the flash drive, so it may need to be disabled again.

4.4 Anticipated Problems

The heat sink for the computer is located in the middle of the body cavity of the robot in the final design. With the skin on the robot, for extended periods of operation, the entire robot could overheat. This means that the computer might get too hot, and the large amount of heat could pose a fire hazard. Whether this is actually the case still needs to be investigated, as it is a safety issue, and if it is an issue, it needs to be determined how long the robot would need to operate for before this would become an issue.

Potential solutions to this problem include installing quiet fans and leaving gaps in the skin of the robot for improved air flow and cooling; changing the orientation of the computer such that the heat sink could protrude from a hole in the penguin skin in the back where it is not visible; and placing the computer, power supply, and battery inside a nest-like object the penguin robot sits on to better isolate the components from the rest of the robot and to allow for better air flow.

5. DISCUSSION

The product of this MQP is a robot that is interactive, nonthreatening, and portable that is controllable through an interface. A SolidWorks assembly that is a correct model of the robot without its skin was created, parts of the robot were prototyped, and the entire robot was built. Powering the robot with a battery was investigated. A paper detailing this project was submitted to the IEEE Engineering in Medicine and Biology Conference for 2011 (Appendix A.) The project, with its SolidWorks models and documented code, could easily be progressed by a group of students and researchers.

The robot design and prototype met most of the task specifications. Despite this, there is room for improvement. The main areas the robot can be improved in are related to the choice of materials and manufacturing processes used, both to improve up cost and functionality.

Some challenges associated with the mechanical head design included incorporating hobby servos. Hobby servos are not symmetrical, which meant that in order to incorporate them in a design, most surrounding components could not be symmetrical either. Interestingly, as this adds complexity to the mechanical components, it also adds cost to manufacture them, meaning that incorporating hobby servos instead of symmetrical but more expensive components could prove to actually indirectly be the more expensive option.

In an effort to standardize parts of the design, the original design of all layers of the robot was the same, meaning that each layer had the same shape. This is an improvement because it costs less to make multiples of a single part than to make multiple different parts. Although differently sized pins would have been easier to design in, all pins were standardized to be the same size so that a single box of dowel pins could be bought to be used for every pin in the robot

5.1 Recommendations

After proceeding through the prototype development process, it became clear that there are areas for improvement in future iterations of the robot. All acrylic pieces should instead be made from a material that is unlikely to break upon impact but also able to be laser cut, like acetal. The head gimbal should be made from acetal as well to allow the side holes for the servo to be easily machined and the remainder to be laser cut; machining the entire piece is very difficult, making it an expensive piece. Additionally, redesigning the parts so that they could be machined more easily would cut down the costs for small numbers to be made, and redesigning the parts to be molded could cut down the costs for larger quantities. Many of the RP parts should be redesigned to be manufactured other ways, although some of them, like the front of the eyes and the eyelids, will need to be RP parts or molded to create their complex shape.

The targeted number of robots to be made affects the manufacturing processes that should be used to optimize the overall cost of the robot. The cost of the robot was optimized for a quantity of one making use of the tools available at WPI. The most cost-efficient manufacturing methods will change with the number of units being made, and manufacturing processes that have a large fixed cost, like molds, will become the most cost-effective if a large number of units are to be made.

When the head moves, it comes to a sudden stop and jiggles at that position for a second or two. This is problematic for the vision system. It could be improved with some additional control in the code, by using motors and adequate motor controllers, or by a mechanical redesign. These and other possible solutions should be considered, as this is a problem that is important to fix.

All removable pieces, including the head, the wings, and the beak need to be tied on with some sort of cord. This will keep them from coming off entirely, a sight that could prove to be quite disturbing. The cord would be loose during normal operation, and after the magnets separated from each other, the cord would be taut and hold the piece onto the robot until it could be placed back in the correct location. Additionally, the robot needs a beak to be actuated.

The computer is very slow. As it has not yet been used for eye tracking, it is unclear as to whether the image processing would also be too slow. It is also unclear what is causing the computer to be so slow, but it may be due to the operating system being installed on a flash drive. Access to a flash drive is much slower than access to a hard drive.

5.2 Future Work

Much was completed on this project, but there is still much more to be done before this project can be considered complete or taken to the next step. Some of these next steps will be completed before another student would take over the project.

A preliminary step, however, is to get the robot to be autonomous rather than just teleoperable through an interface. The first step to making the robot autonomous is to get it tracking eyes and faces with its own eyes and head. This should not be very difficult as the code to control individual servos has already been written and there is plenty of code out there for detecting faces and eyes.

A major goal of the project was to have the robot be able to operate on battery power alone for an hour and be able to operate while charging the battery. This part of the project was never finished, but would be an improvement to the robot, so it may be worth exploring.

The robot could be significantly improved with redesign. After trials with clinicians and autistic children to determine whether it is feasible to use the robot for its intended purpose, the overall design, materials, and manufacturing techniques should be evaluated and optimized for the quantity of robots that are expected to be made. Some suggestions for these revisions can be found in the Recommendations section.

The outward appearance of the robot needs to be improved upon. The head is too big and somewhat lopsided, and its appearance may keep it from being accepted by a child. The shape of the body could be improved upon by creating some sort of a shell around the electronics and putting stuffing or batting between that and the fabric on the outside to stuff it.

It needs to be determined whether the robot will overheat in its current state. The heat sink for the computer, the part that is giving off most of the heat, is right in the middle of the robot with very little

air flow. If it is determined that the robot would overheat, it should also be determined how much operating and idle time it takes for this to happen, and the robot should be redesigned to prevent overheating as a more permanent solution.

The robot could become more interactive if it had more sensors in it. Touch or bump sensors of some sort would allow it to sense physical interaction. A microphone would allow it to use sound as a sensory input or just to record it as a diagnostic tool. As a counterpart to a microphone, a speaker could be used to produce sound as another way of prompting a reaction from the person with whom the robot was interacting.

One of the next steps for the project is to get additional feedback from practicing clinicians and begin trials with clinicians and autistic children to see how each party feels about the device. As the purpose of the robot is to interact with autistic children, it is very important to get it interacting with them as soon as possible so as to optimize the experience.

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APPENDIX A: PAPER SUBMITTED TO EMBC 2011

An Affordable Compact Humanoid Robot for Autism Spectrum Disorder Interventions in Children

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Abstract— **Autism Spectrum Disorders are impacting ever-increasing number of children. The disorder is marked by social functioning that is characterized by impairment in the use of nonverbal behaviors, failure to develop appropriate peer relationships and lack of social and emotional exchanges. Providing early intervention through the modality play therapy has been effective in improving behavioral outcomes for children with Autism. Interacting with humanoid robots that provide simple emotional response and interaction has been shown to improve the communication skills of autistic children. In particular, early intervention and continuous care provide significantly better outcomes. Currently, there are no robots capable of meeting these requirements that are both low-cost and available to families of autistic children for in-home use. This paper proposes the piloting the use of robotics as an improved diagnostic and early intervention tool for Autistic children that is affordable, non-threatening, durable, and capable of interacting with an autistic child. This robot has the ability to track the child with its 3-DOF eyes and 3-DOF head, open and close its 1-DOF beak and 1-DOF each eyelids, raise its 1-DOF each wings, play sound, and record sound. These attributes will give it the ability to be used for the diagnosis and treatment of autism. As part of this project, the robot and the electronic and control software have been developed, and integrating semi-autonomous interaction, teleoperation from a remote healthcare provider and initiating trials with children in a local clinic are in progress.**

I. INTRODUCTION

Autism is a complex developmental disability that typically appears during the first three years of life and is the result of a neurological disorder that affects the normal functioning of the brain, impacting development in the areas of social interaction and communication skills. Statistics show that Autism Spectrum Disorders (ASD) are impacting ever-increasing numbers of children. The Center for Disease Control and Prevention, estimates that an average of 1 in 110 children in the U.S. have ASD (www.cdc.gov). Autism is a spectrum disorder, which means that symptoms and characteristics can present themselves in wide variety of combinations from mild to severe.

Using the Diagnostic Statistical Manual, 4th Ed. [1], autistic disorder, 299.00, is diagnosed using specific criteria. The child who is to be labeled or classified as autistic must show delays in the development of: 1) social interaction, 2) communication and 3) behaviors. Social interaction includes non-verbal behaviors such as eye contact or gaze, facial expression, body posturing and gestures that regulate social

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interaction. In addition to characterizing ASDs, deficits in social behavior impact children's ability to function spontaneously and independently. Unlike typically developing peers who independently attempt, practice, and master social interactions, children with ASD have difficulty with awareness of the social world and as such do not independently develop capabilities with social interactions. Consequently, targeted social intervention is required in order to help children with ASD develop social capabilities.

In addition to delays in language, social skills, and academics, children with Autism have delays in play. Children with autism often lack knowledge about the physical properties of objects, resulting in play that is limited in frequency, variety, and symbolic quality [2], [3]. Technology can aid in diagnosis by producing visual and audio cues as well as recording the response of the child, and it can potentially perform these functions with more repeatability than a human could, making methods for more reliable diagnosis and treatment efficacy monitoring [4].

There is currently no specific cure, however there are treatments plans, biomedical, therapeutic and educational, to remediate the delayed development and ameliorate behaviors. No one method alone is effective in treating Autism. The early education of autistic children [5], weighs heavily on behavioral and communication approaches seen in applied behavioral analysis (ABA). Many researches and practitioners have developed interventions to teach play activities to children with autism served through Early Intervention (EI). However, research is lacking in integrating robotics as an effective method of Early Intervention. Play has an important role in child development with many potential contributions to therapy, education and enjoyment, and play therapy can help improve communication skills[6]. Current therapy is limited in that it is expensive and difficult to have available frequently - it is typically restricted to a clinic or school
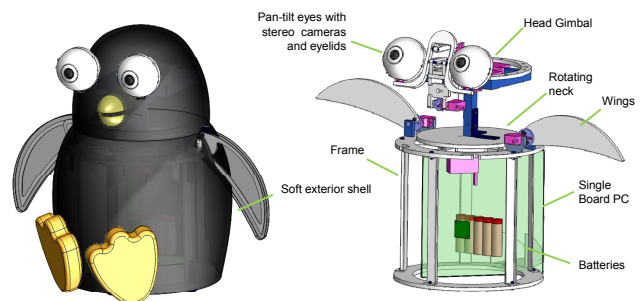

Fig. 1. Conceptual visualization and schematic drawing of the robot. This humanoid robot is affordable, non-threatening, durable, and capable of interacting with an autistic child.

setting. Since the school year is often 180 days, even school-based therapy leaves 180 days unaccounted for. Children with autism need constant instruction, which the proposed system can provide by enabling continuous home care, which could vastly improve the outlook.

Autistic children have been shown to imitate and have eye contact more frequently with robots. These behaviors are exhibited more often in treatment sessions that utilize robots[4]. In [7], the authors investigate how a small minimally expressive humanoid robot can assume the role of a social mediator - encouraging children with autism to interact with the robot, to break their isolation and importantly, to facilitate interaction with other people. Their results demonstrate that the robot effectively helped to mediate and encourage interaction between the children and co-present adults.

Kozima *et al* [8] designed a 4 degree of freedom (DOF) interactive robot Keepon to interact with children with autism where it worked as the pivot of triadic play with adults or other children. Giorgio et. al [9] presented an open systems platform iCub to support collaborative research in cognitive development. Distinctive with other robots, the robot presented here, based in part on our previous research efforts [10], takes on the form of a cartoon-like penguin and is named PABI: Penguin for Autism Behavioral Intervention (©*2011 Dickstein-Fischer*) as shown in Fig. 1. Being inexpensive to manufacture, robust, and easy to operate means that they could be made readily available to families of autistic children, making this autism therapy tool available for frequent and in-home use.

II. METHODS

A. Requirements

The proposed robot is designed to be a low-cost, compact, easy to use system that can be used the in the traditional school and clinic setting, but also brought home for enhanced continuous care. By enabling the robot to be brought home, the effects will be significantly amplified due to the increased interaction time that the child has with the robot. The robot will be able to be used as an autonomously acting "toy" to play with and interact with as described in [6]. But, it will also be able to be used in a teleoperated mode where a clinician can operate the device remotely (from within the same room or a remote site) and control the robot's motions while receiving video and audio streams. PABI may also be used to assist in diagnosis and assessment where the robot can not only interact with the child, but also monitors the child's body and eye motions to assist in quantitative assessment. This assessment can be used to update and modify the robot's autonomous behavior as the child's level of interaction improves.

One primary goal was to make the robot robust enough to handle the rigors of being used as a toy at home. It therefore must withstand the sort of abuse inflicted on a stuffed animal by a child. This means it would have to survive being dropped, picked up by different parts, and have parts of it forced in all different directions. As such, special attention

was devoted to the materials the robot was constructed out of and the ways in which each appendage was attached.

An annotated conceptual drawing of the robot is shown in Fig. 1. The cartoon-like penguin for that PABI takes on enables the use of human-like emotions, while remaining simple and non-threatening. The robot has 11 degrees of freedom (DOF): 3-DOF head/neck with 3-DOF for a pair of eyes and an additional 1-DOF for each eyelids, a 1-DOF beak, and 1-DOF for each of the wings. The head has cameras in each eye to assist in face-tracking, and the robot also has a speaker and a microphone for recording and interacting with the child.

B. Mechanical Design

The robot's main structure is composed of three main tiers: the base where the control and power electronics reside, the fixed upper level where the wings are located, and the rotating top level which holds the pan-tilt gimbal unit for the head. These tiers, as well as several servo mounts and other parts, were made from acrylic in this iteration of the robot due to its low cost and its ability to be cut on the laser cutter. The frame of the robot is shown in Fig. 2.
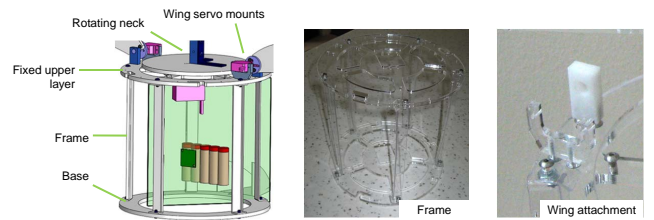

Fig. 2.   The 3-tier acrylic frame of the robot.

1) Head and Eyes: The head achieves its tilt and roll from a gimbal as shown in Fig. 3. Servos move the gimbal, and dowel pins help it to rotate about the preferred axis. To improve the robustness of the design, high strength rare earth magnets hold the head plate to the gimbal; twisting and pulling abuse of the head will cause it to safely dislocate from the gimbal such that the servos do not get damaged as shonw in Fig. 3 (right). Elastic cord keeps the head from separating entirely from the body. A servo pans the head, and it is protected from damage by the magnets in a similar fashion as well.
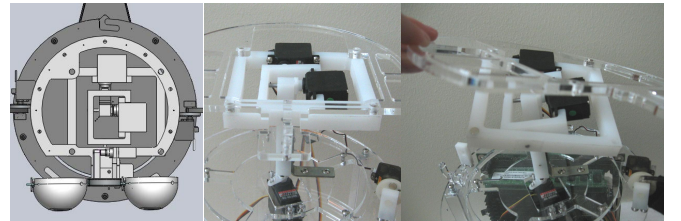

Fig. 3.   Penguin head gimbal provides tilt and roll of the head and is mounted upon a neck rotation.

The eyes each have an independent rotation of $\pm 90°$ about the vertical axis so that they can pan left and right, and they have a coupled rotation of $\pm 45°$ about the horizontal axis so that they tilt up and down together providing 3-DOF
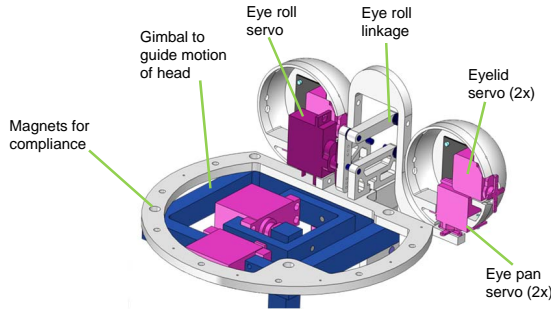
Fig. 4. The structure of the penguin's eyes. The robot has 3-DOF eye motion plus control of the eyelids. Each eye incorporates a camera in the pupil to provide stereo vision capabilities.

with speeds controllable up to $300deg/sec$. A further 2-DOF includes independent control of eyelids. The servo that tilts the eyes is attached to the eyes with a four-bar linkage as shown in Fig. 4. The remaining servos that drive the eyes and eyelids are located within the eyes themselves. Making the eyes large enough to accommodate the servos enhances the intended cartoon-like appearance of the robot - large eyes are a typical feature of non-threatening cartoon-like creatures.

2) Feet, Beak, and Wings: The robot's appendages both give the penguin a more friendly cartoon-like appearance and also enhance the ability to present emotions and evoke responses from the children. Both of the penguin's wings can be independently controlled. The wings, being one of the most probable appendages to be pulled or twisted, were designed to withstand pulling and twisting in any direction. They are attached to the body by magnets, allowing them to be driven by a servo, but if they were pulled on, they would separate from the body with no damage to the servo. Most of the wing is made from thin polycarbonate, giving it compliance in all of the directions that the magnets do not as shown in Fig. 5.
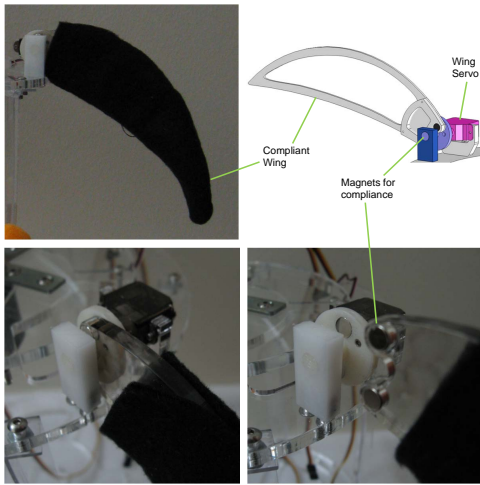

Fig. 5. The robot's independently controllable, compliant wings.

The penguin's feet are soft, made of felt and batting as shown in Fig. 8. They can be played with by the child, and if they are squished, no harm comes to them. They are

attached to the body of the penguin with Velcro, so when they are pulled on, they separate from the body of the penguin, causing no damage, and can be reattached easily. The beak is made of the same materials and with the same compliance as the feet, but the compliance is achieved with magnets and alignment pins rather than Velcro. When interacting with the child, the beak may be moved in a coordinated way with non-verbal sounds and utterances that the robot makes and it may also be controlled to help demonstrate the robots emotional state.

C. Control System

The robot has two modes of operation: autonomous mode and teleoperation mode. In autonomous mode, the robot interacts with the child with no direct control by a clinician. It is able to observe the child's body motion and head movement, and the robot's head and eyes can move correspondingly. The wings and beak can also be used to generate interactive motion, and recorded sounds can be used to communicate emotion and render a playful environment. In teleoperation mode, a therapist (either at a remote site or with the child) could observe the child's behavior through stereo cameras and operate a joystick to control robot movement. Semi-autonomous control, such as face tracking, can still be utilized in this mode. In either mode, the robot can further be used as a diagnosis tool to record children's behavior including body motion, gaze direction and other parameters, and evaluate the treatment progress in terms of qualitative metrics.
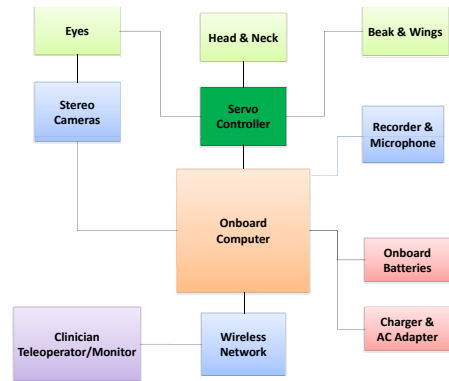

Fig. 6. Block diagram of the robot's system architecture.

1) Controller Hardware: An Intel Atom-based single board computer (SBC) serves as robot's computational core. This computer has identical capabilities of a standard Netbook including the low power consumption. The SBC provides sufficient computational power for image processing and natively includes networking, data storage, and a USB interfaces to peripherals such as the the webcams, while maintaining a low cost. Two servo servo controller modules made by Pololu are used to interface the computer with the actuators, each can drive 8 servos from a single serial port. These servo controllers were chosen for their low cost and ease in adding additional DOF. The electronics are suspended with elastic cord such that they would avoid damage in a

fall. The robot runs on the Ubuntu Linux operating system, and it is installed on a 16GB flash drive. Since the device is intended as a research tool, a well define Java API is provided to control the robot motions.

2) Software Interface: As the robot is intended to interact with children by active movement or to observe children behavior during diagnosis, head pose and gaze direction estimate is a key factor to the humanoid robot operation. For head pose estimate, an appearance template method [11] is used to detect six facial features (four corners of eyes and two corners of mouth) by normalized correlation. 3D stereo matching is then performed to determine the Cartesian position of each feature. Head pose estimate can be cast as optimization problem [11]

$$\underset{R,t}{\arg\min} \sum_{i=0}^{N-1} \omega_i (Rx_i + t - y_i)^T (Rx_i + t - y_i) \quad (1)$$

where N is the number of features, x_i is feature position vector in the 3D feature model and y_i is the position measurement of a feature acquired in the feature tracking and ω_i is the weighting factor obtained during feature tracking.

The algorithm is implemented with the software package FaceAPI® (Seeing Machines Limited, Australia). It allows highly robust and real-time face tracking and provides head position and orientation coordinates per frame of video. Head motion in $\pm 80°$ is allowed for successful detection. It is also robust to partial occlusions, illumination, skin color variation and glasses etc. Fig. 7 shows six head gaze tracking snapshots. The person moves head up, down, left and right, while the head gaze coordinates are overlaid with images during difference head orientation. The software provides the position and alignment of the head coordinate frame which can be used in both face tracking for interaction and gaze tracking for diagnosis and monitoring.
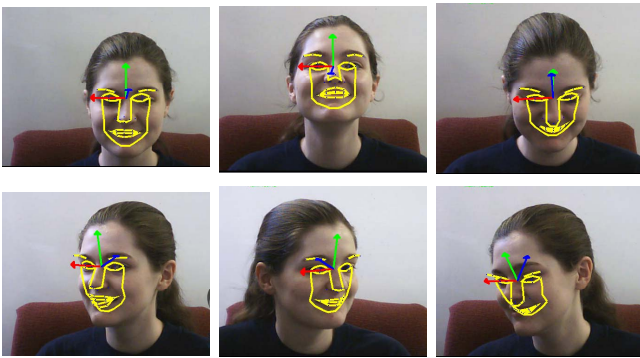

Fig. 7. A series of head gaze tracking snapshots showing the head gaze coordinates during difference head orientation. The software tracks the location and orientation of the child's head with respect to the cameras in the eyes, gaze direction can be inferred from the shown coordinate frame.

III. DISCUSSION

PABI has been designed as a research platform for robot-assisted therapy of children with Autism. The robot has many applications after it has been fully developed; it will be able to be used to autonomously produce repeatable sounds and gestures and to record the response of the child for use in the diagnosis of autism. It will have a teleoperation mode such that a professional trained in the diagnosis of autism can sit and control it, using it as an interface. The robot will soon be capable of interacting autonomously with an autistic child. We intend to refine the control software and begin trials with the system in the very near future. After demonstrating and validating the concept, future iterations of the robot will have further refined designs including tougher materials such as Delrin and be designed for manufacturing in larger volumes.
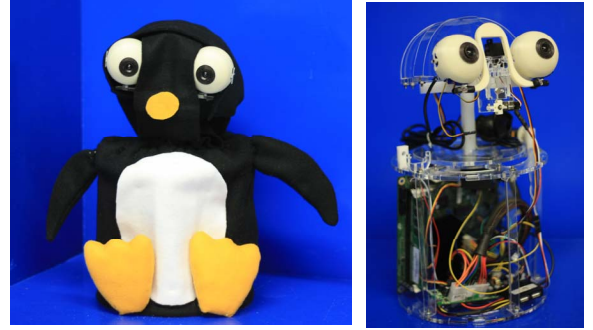

Fig. 8. PABI©: Penguin for Autism Behavioral Interventional

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