Robotic Face to Simulate Humans Undergoing Eye Surgery

Luis Ramos, Steven Valencia, Shawnak Verma, Karina Zornoza, Melissa Morris, Sabri Tosunoglu

Department of Mechanical and Materials Engineering
Florida International University
10555 W Flagler Street
Miami, Florida 33174

lramo070@fiu.edu, svale049@fiu.edu, sverm005@fiu.edu, kzorn001@fiu.edu, mmorr009@fiu.edu, tosun@fiu.edu

ABSTRACT

This paper outlines the design and implementation of a facial robot which can perform realistic eye movement to simulate eye surgery conditions. This model also appends to a slit lamp which an ophthalmologist will test. The focal point of the project is the realistic eye movement which will be controlled remotely by the user. The design has been made in such a manner that anyone in the world who has a 3-D printer can access it and replicate the project. Hence, the project incorporates global design elements in it. Moreover, it is made of biodegradable plastic PLA and is environmentally-friendly.

Keywords

Eye surgery, robotic face, simulation, eye movement, remote control.

1. INTRODUCTION

Robotics is a growing field of engineering that has the capability to automate the most difficult processes making them significantly more complex and accurate at the same time. One of the first pioneers of humanoid robotics was Leonardo Da Vinci, who in 1495 created a mechanical armored knight that was able to perform certain body gestures [1]. This science has entered many industries such as car manufacturing, military applications, aerospace, and others. However, there is still an industry that remains relatively untouched by robotics. This is medicine. This industry encompasses many constrains that impedes robotic development. One the biggest constrains is equipment testing. There are certain procedures that cannot simply be performed on humans due to the risk it carries.

This work will be focused on the development of a robotic face that simulates human gestures undergoing eye surgery. The robot will serve as testing platform for ophthalmologist around the world to experiment and test laser equipment. The main points of interest for the robotic face are the precise and realistic movement of the eyeballs and the eyelids. Such movements will be control by the user remotely and applying a code that was developed using experimental data of human eyes. The prototype was made of biodegradable plastic components along with electrical and mechanical components that puts together a compact design suitable for medical practices.

2. LITERATURE SURVEY

The overall intention of robots is to simplify human assignments making them sensible. In other works, robots are used to do work. Nowadays “androids” have become remarkably sophisticated and their primary objectives has shifted from industry uses to services uses. One of the most important aspects of creating a robotic face that imitates human gestures is to be able to have a better understanding of human behaviors when exposed to unfamiliar situations. Robots have become an essential tool for companies, especially in the manufacturing industry where automation plays an important role for efficiency and cost reduction. However, the development of humanoids is relatively new for the medical field due to the implications for testing new equipment. The health care system is ready to accept increased efficiency and cost improvements seen in manufacturing as a result rising health costs and a growing elderly population. Hence, humanoids that replicate human expressions open the door for a bright future for that has captured the attention of world.

2.1 Application

Since this work was focused on human gestures, some level of automation had to be taken into consideration in order to achieve realistic goals. There are four levels of autonomy: human operated, human delegated, human supervised, and fully autonomous.

The technology industry is widely known for the use of robots. However, these machines in most cases do not perform essential tasks. They have been presented to the public as state-of-the-art prototypes that have great potential for the future. Well-known humanoids such as the Toyota Partner Robot and Honda Asimo are perfect examples of these prototypes. Other important applications are seen in space missions with NASA Robonaut and DRL’s Justin Robot which are both tele-operated [2].

3. DESIGN

Figure 1 illustrates only the eyelid mechanism. This first prototype was chosen to use cables as main driver system for the eyes. It is important to note that for the open-close displacement of the upper and lower lid, a metallic rope would be implemented. This motion can be easily calculated by treating the gesticulation as a four bar mechanism.

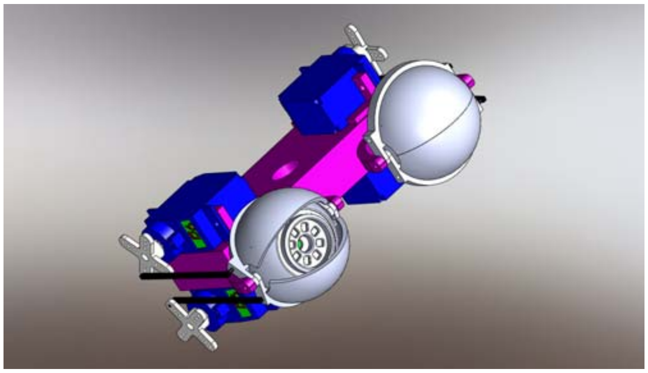

Figure 1. Design of Cable/Tendon System for Eyelid Mechanism

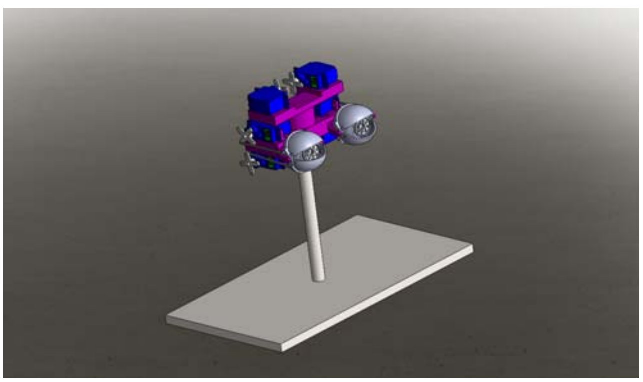

Figure 2. Design of Cable/Tendon-System for Eyelid and Eye Mechanism

Figure 2 displays the entire prototype for the cable/tendon system. This 3D model includes the actuation mechanism for the two eyes. Therefore, the eyelids are moved by implementing four single servos, two on each side. These servos connect to the upper and lower lid with a cable or metallic rope that acts as a four bar mechanism. Furthermore, the eyes are connected to the actuation system by using thin steel wire. These wires are a great and inexpensive solution to drive the two degree of freedom needed for the left-right and up-down motion of the eyes. The servos in control of this transfer of motion are located in a separate piece situated on top of the frame. This piece holds two servos. Each servo has the task to move one degree of freedom for each eye. Hence, it is expected to have four different lines connected to one servo at the time.

3.1 Structural Design

The proposed design is a unique one because it is made using a 3D printer and therefore is extremely affordable. It is also able to adequately mimic the movements of a normal eye. It can move almost in accordance with the degrees of freedom of a biological eye. The model uses a swashplate mechanism which is used to move the eyeball in different directions. A swashplate is a device used in mechanical engineering to translate the motion of a rotating shaft into reciprocating motion, or to translate a reciprocating motion into a rotating one. There are strings which pull the eyeballs in every direction and the strings are controlled by servo motors attached at the back of the model.

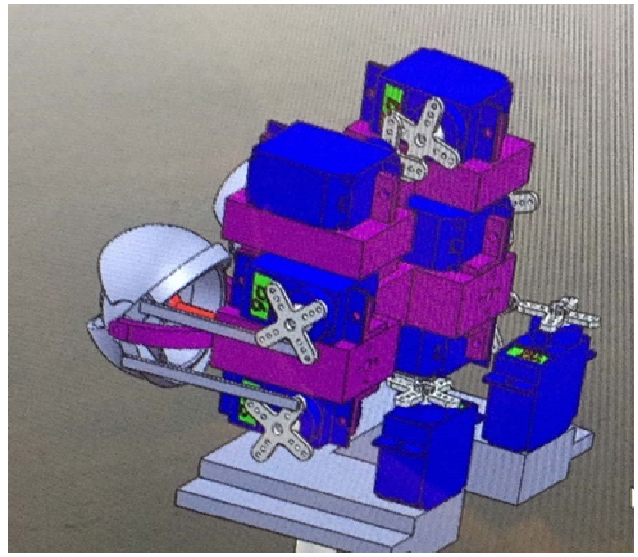

Figure 3. Back View of Design with Servo Motor Arrangement

3.2 Material Selection

For the manufacturing of the robotic face, since it is 3D printed, the use of a PLA plastic was used. PLA (Polylactic Acid) has been selected due to its properties. Being strong, durable and malleable. PLA is considered a thermoplastic. This means that this material can be recycled, since it can be heated to its melting point (150-160 degrees Celsius) multiple times without significantly affecting its properties. One disadvantage of this material is that it has relatively low glass transition temperature between 44 and 63 degrees Celsius [7]. This disadvantage makes it unsuitable for high temperature applications.

This prototype has been mainly 3D printed, so materials needed for the manufacture are mostly those needed for the printing phase.

3.3 Component Design/Selection

All the components used to build the robotic face were chosen based on their properties including strength, cost, performance and attainability. Components like the servo motors, SG90, were chosen based on their easy programmability and their low cost, while still able to meet the task of generate the movements of the face. In order to operate the motors, a T12ZA controller has been used for the remote control of the mechanism. An Arduino UNO R3 has been utilized to program our servo motors so they generate the appropriate movements to simulate how human eyes move. Common hardware such as screws, springs and hinges allow for easy replacements.

4. ANALYSIS

There were two main analysis made for this prototype; motion and acceleration. In order to create a competitive prototype that outperforms other medical robots in the industry, this project focused heavily on the motion and acceleration of all the operational parts. The reason this was important is because accuracy played a vital role of the final outcome. The movement of the eye, eyelid and other mechanisms have to have a very low error to increase the precision of the laser targeting the retina. In addition, the CAD measurements were made according to average geometry of human anatomy. Other analysis such as structural investigations were made to increase the robustness of the overall design. However, there are not significant external loads anticipated that affect the global performance of the simulation.

4.1 Kinematic Analysis and Animation

Among all robotic mechanism there is one frequently used in the robotic industry: a four bar mechanism. This mechanism was applied to most actuators. The concept gave better understanding of the final position of either the eyelid closure at its two points. The same was implemented for the eye travel, yet, the up-down and left-right was driven by only one actuator for both eyes.

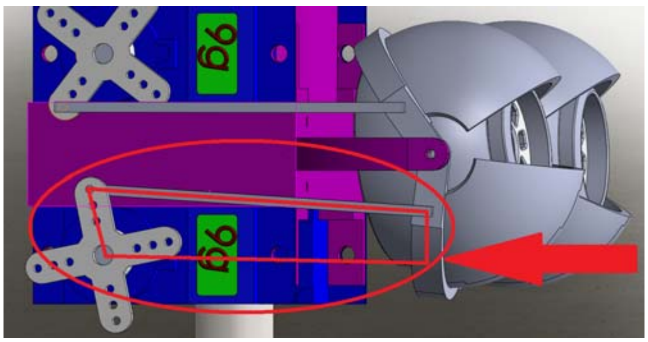

Figure 4. Four Bar Mechanism Implemented for All Actuators.

The parameters used for the eyelid closures were based on standard data from the US National Library of Medicine [3]. For this sequence, the eyelid was positioned as a closed eye (90 degrees). A motor was place on each servo running at 200 Hz which seem to be the most realistic human frequency. Table 1 shows part of the data collected from the CAD simulation run for one second.

Table 1. Eyelid Angular Displacement for 1 Second at 200 Hz

Frame	Time	Frame1-1 Angular Displacement (deg) Ref. Coordinate System
1	0.000	-8.9311E+01
2	0.040	-8.9039E+01
3	0.080	-8.8240E+01
4	0.120	-8.6971E+01
5	0.160	-8.5314E+01
6	0.200	-8.3380E+01
7	0.240	-8.1293E+01
8	0.280	-7.9185E+01
9	0.320	-7.7185E+01
10	0.360	-7.5417E+01
11	0.400	-7.3987E+01
12	0.440	-7.2982E+01
13	0.480	-7.2464E+01
14	0.520	-7.2464E+01
15	0.560	-7.2982E+01
16	0.600	-7.3987E+01
17	0.640	-7.5417E+01
18	0.680	-7.7185E+01
19	0.720	-7.9185E+01
20	0.760	-8.1293E+01
21	0.800	-8.3380E+01
22	0.840	-8.5314E+01
23	0.880	-8.6971E+01
24	0.920	-8.8240E+01
25	0.960	-8.9039E+01
26	1.000	-8.9311E+01

5. CONSTRUCTION

Most of this prototype was designed to be 3D printed. The 3DP 1000 printer shown in Figure 5 below was utilized. This industrial printer was facilitated by UTC Aerospace Systems to manufacture the frame, and other components.

Figure 5. 3DP 1000 Printer

The first parts to be printed were the pole holder and the frame. The frame houses the eyes and the actuation systems. The pole holder was printed in order to a single piece, but this can also be made of metal which is more rigid. The frame is the largest assembly in the robotic face. It took two and a half hours to print using about $3 in materials.

The next step in the printing process were the smaller components that make up the eyes. This included the eye lids, swash plates, and eyeballs as well as smaller pieces that hold the servos to the connectors that hold the lids together.

After collecting all the components, both printed and not printed, the assembly part of the process began. A soldering gun, screw drivers, pliers, and many small screws were utilized for the construction.

Four servo motors were needed to control the eye lids, one for each lid. The next step was to add the servos that would control the eyes themselves. The horizontal motion and vertical motion of the eyes are each controlled by two servos. Figure 6 displays the preliminary construction with these eight servos.

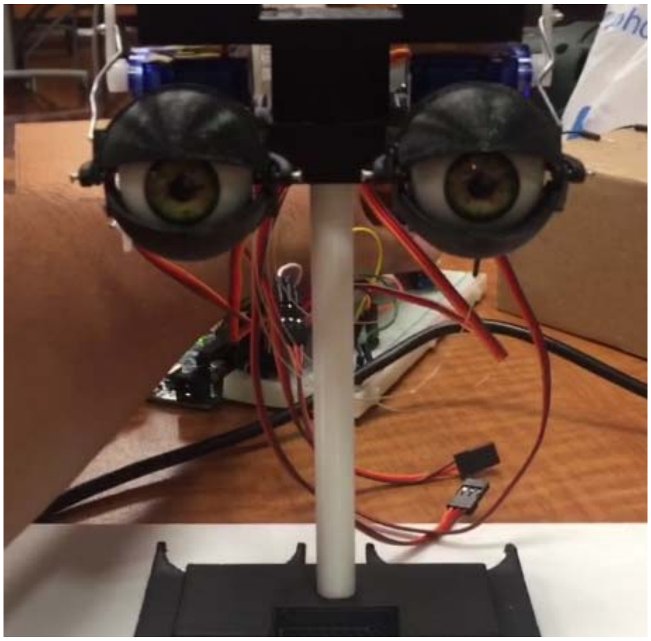

Figure 6. Beginning Assembly Stage

To assure that the tension in steel wire cables does not interfere with the other steel wire cables, plastic tubes enclosed them (see Figure 7).

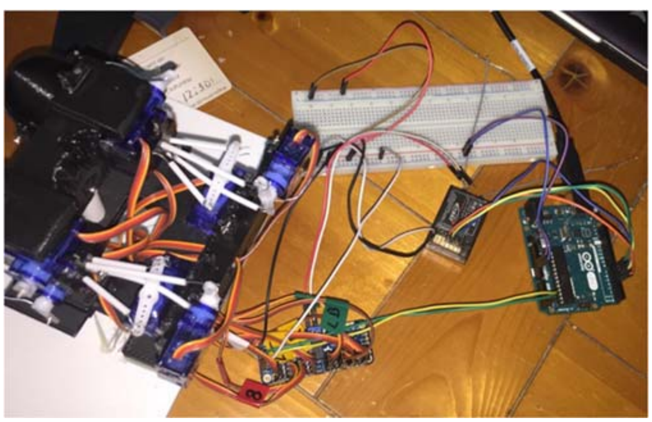

Figure 7. Configuration of Eight Servos with Tubes Enclosing Steel Wires

Finally, to make a further aesthetically realistic prototype, a human face mold was added over the prototype as seen in Figure 8 through 10.

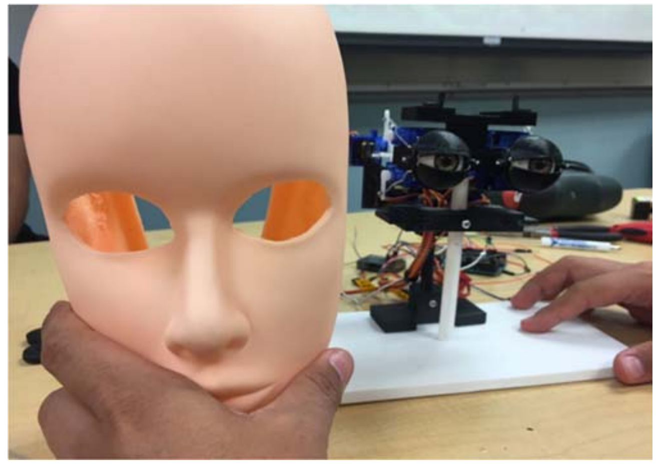

Figure 8. Mannequin Face to Enclose Prototype

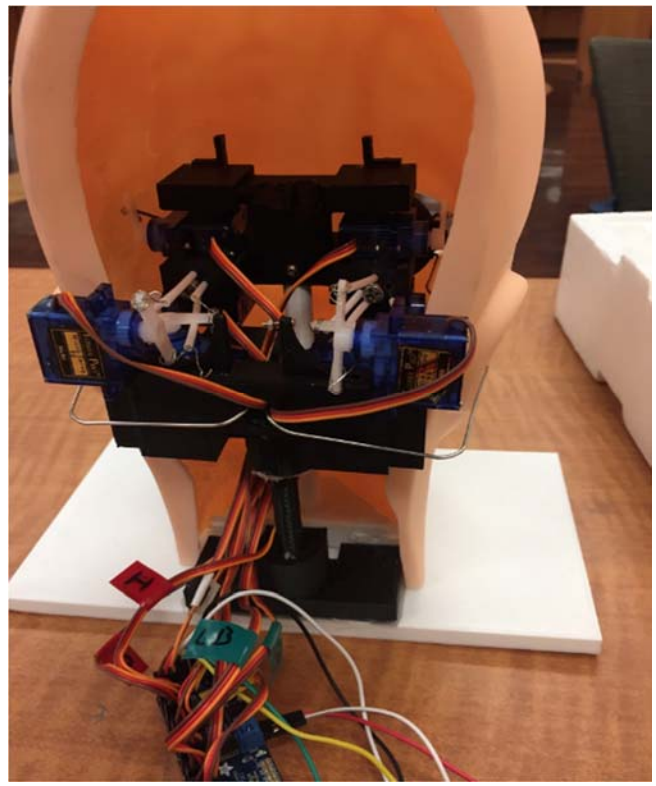

Figure 9. Mannequin Face Enclosing Prototype

6. TESTING AND EVALUATION

This section provides an overview of the testing process of the project.

6.1 Design of Experiments – Description of Experiments

The main purpose of this robot is to simulate eye movement. Therefore, it was necessary to test the full movement of these eyes. Several Arduino programs were created to analyze how the servos would generate the movement of the eyes and the eyelids.

One of the important specifications about the SG90 servos is that they do not possess a continual motion configuration. These means that its range of motion is limited. In the case of the SG90 servo, its range of movement is between 0□ and 180□. For our testing analysis, the first step was to test the sweep motion of the servos which was done by creating a code to operate the servo utilizing a potentiometer as an analog input. Utilizing a potentiometer allowed us to have more control over the motion and to better understand how the rotation of the gear would move the eyes or the eyelids.

Figure 10. Completed Prototype

After testing and analyzing the rotation of the servo motors, another program was created to generate the opened and closed configuration for the eyelids. Since the eyelids play an imperative role in how surgeries are done, if a patient closes an eyelid during the surgery how would the slit lamp react to this or how a trainee doctor would react to this event should be determined.

The next scenario is the case when the eyes move in the horizontal direction. During some eye surgeries or when inspecting the eye before a surgery, a patient may be required to move his eyes left or right so the doctor can look at certain areas of the eyeball better. The vertical motion of the eyes was done to accomplish the same criteria as the horizontal.

The final stage of testing is to integrate all the components together and running a final test on the software. For this final stage a program was created to utilize a RC controller and its receiver to control the full movement of the mechanism. The whole purpose of these tests is to ensure the hardware and software function correctly, ensure that the software developed control the hardware the right way, and that it meets all the criteria specified in this report.

6.2 Test Results and Data

Before even starting to test the software, we needed to ensure our hardware was properly set up and that it could withhold the stresses generated due to the movement of the eyes and eyelids. Figure 11 shows the factor of safety obtained when analyzing the main frame of the hardware utilizing the Von Misses theory. For the SolidWorks simulation, the input is the force transmitted through the shafts (for the eyelids) or the wire (for the eyeballs) due to the torque produced by the servo motors. After running the simulation, the hardware had a factor of safety of 1.3 which means that it is just safe enough to undergo the stress produced by the servos.

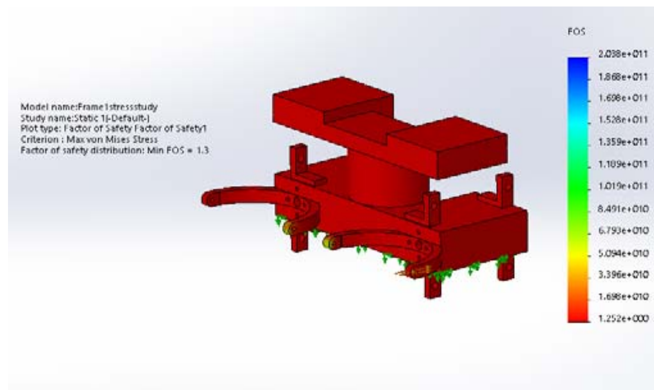

Figure 11. Factor of Safety Analysis on Solidworks

After ensuring our main frame was capable of withholding the stresses, an analysis of the four-bar linkage mechanism, which is implemented in the robot to drive motions, was done. This analysis was to predict the range of angles at which the eye will operate and to predict how much the motors would have to be rotated to achieve the desired positions of the eyes. The same theory was applied to study the mechanism utilized to move the eyelids.

6.3 Evaluation of Experimental Results

An analysis of the four-bar linkage mechanism to move the eyelids. It was done on MATLAB to make sure the servo motors move only a certain amount of degree to simulate exact eyelid opening and closure. Moreover, the same had to be done for the horizontal and vertical motion of the eyeball. The lengths of every part that aided movement was taken from the SolidWorks assembly and a 2D sketch was made using those lengths. Then the change in those lengths and their orientation was calculated because the movement of the eyes changes everything. Therefore, all the lengths were calculated within the confines of the eyeball movement. These changes in length were then converted into the degrees by which the servo motors must turn to provide precise and realistic movement to the eyeballs.

Despite the calculations, there was a lot of trial and error involved to get the exact numbers. Moreover, the left and right motors were not the same distance apart due to a small degree of human error in the manufacturing process. Hence, the program for both the motors had to be tweaked slightly to accommodate that difference.

The above process was repeated for the vertical motion of the eyeballs as well.

6.4 Improvement of the Design

After doing all the previously mentioned tests, the project began to focus on three major obstacles which hindered the proper functioning of the eyeballs.

The first obstacle was regarding the tension in the fishing line we used to connect the motors with the eyeball. The fishing line lacked the tension required for smooth movement of the eyeball. It would slack during testing of the up and movement of the eyeball. It would climb as expected but as soon as the command to move down was implemented, gravity would take over and the eyeball would free fall as if hinged to nothing. Moreover, it was very difficult to tie the fishing line and without a constrained path, it would take any random shape. The group decided to switch to a small diameter aluminum wire. The aluminum wire was small enough go through tiny holes initially designed for the fishing line, but most importantly the tension in the wire ensured smooth functioning of the eyeball.

The second problem overcome in this project was in using the space behind the frame to mount the servo motors. The initial design led to very tight space in which the fishing line would get entangled with the servo motor cables. It would also compromise the functioning of the eyeballs because of all the entanglement. In addition, it made disassembly a long and arduous task. Rather than design something new, existing 3D printed parts were salvaged to create a new adjustable platform which was installed below the frame. Its height can be adjusted and two motors were installed on that platform which ensured horizontal movement of the eyeball. Another rejected frame was installed vertically behind this platform and the servos attached to this platform took care of the vertical movement of the eyeball. In these platforms, there is also a wire sink where the servo motors' wires go and they don't entangle with the other aluminum wire. Moreover, disassembly became very convenient after these design additions.

The third obstacle was regarding the number of servo motors the design used. The initial design included only two servo motors which controlled the horizontal and vertical movement of the eyeballs. This concept looked promising in the design phase but during testing, it suffered severe problems in synchronicity. The wires moving the farther eyeball would be less tense and would regularly fail in moving their respective eyeballs when compared to their counterparts.

Moreover, when it was decided to use the aluminum wire, the crossing of the wires became obsolete since the aluminum wire did not regain its shape when it was bent. It had to be kept straight and the motors had to be placed parallel to the holes the lines came out from. Therefore, it became imperative that two servo motors be used for each eyeball. It also gave the luxury of testing each eyeball separately.

7. CONCLUSION

This project's main goal was to design, analyze, manufacture, and test a robotic face to simulate eye surgery. With the main concern being the robotic eyes, this was the focal point of the project. Much research was done and the information collected was used to create several design alternatives. After deliberation on which alternative was the best concept the best one was chosen. Next, the feasibility and the cost were analyzed.

After these were all formulated and finalized, the manufacturing stage began. Since this is still an early prototype, it is not yet in an optimal state. In the future, the hope is that this will be manufactured with top-of-the-line materials, upgraded electrical components, and improved programming. These will make the look and movement of the robotic face be that much more realistic and precise. If more time is spent on the programming, then more advanced facial expressions will be able to be extracted making the robotic face a more enhanced one.

8. ACKNOWLEDGMENTS

The authors extend their thanks to Rodrigo Arredondo for his assistance in the programming of the prototype.

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