Design of an Expressive Human-Like

Robotic Head for an Assistive Robot

A Thesis Presented

by

Brian Allison

to

The Graduate School

in Partial fulfillment of the

Requirements

for the Degree of

Master of Science

in

Mechanical Engineering

Stony Brook University

May 2009

Stony Brook University

The Graduate School

Brian Allison

We, the thesis Committee for the above candidate for the

Master of Science degree,

hereby recommend the acceptance of this thesis.

Prof. Goldie Nejat, Ph.D., Advisor
Department of Mechanical Engineering, Stony Brook University

Prof. Imin Kao, Ph.D., Chair
Department of Mechanical Engineering, Stony Brook University

Prof. Anurag Purwar, Ph.D., Member
Department of Mechanical Engineering, Stony Brook University

Jeffrey Helgeson, Sr. Engineer, Member
American Defense Systems, Inc.

This thesis is accepted by the Graduate School.

Lawrence Martin

Dean of the Graduate School

Abstract of the Thesis

Design of an Expressive Human-Like

Robotic Head for an Assistive Robot

By

Brian Allison

Master of Science

in

Mechanical Engineering

Stony Brook University

2009

In this thesis, the mechanical design of an anthromorphic robotic head is proposed as a potential social interface for human-robot interaction. The novelty of the robotic head is the mechanism designed for actuation of the facial muscle control nodes. Facial muscles are grouped and actuated together based on their physical location on the face as well as by their similarities in direction of displacement and transitional motion. The

relationships between these muscle groups allow the design of a unique actuating mechanism that creates a mechanical dependency between certain nodes. The actuating mechanism is mounted remotely from the head and connected to the face muscle nodes via several cables. The linkage system of the mechanism is designed based on the maximum displacement of each node. These displacements are indicated by measurements taken from 2D images of a human subject making each expression. Experiments presented herein verify: (i) the facial actuation mechanism translates each muscle node the displacement required to accurately express each emotion, and (ii) the facial expressions displayed for each of the six basic emotions are highly recognizable by humans during one-to-one human-robot interaction. Furthermore, conclusions on the proposed design, highlighting the potential applications and future work are presented.

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to first thank my advisor, Professor Goldie Nejat, for her much appreciated guidance and support throughout my research work and thesis. I would also like to thank Professor Peisen Huang for allowing the use of his 3D scanner to create the necessary face model for this work. I would also like to thank George Lurhs for assisting with the fabrication of the structure brackets. Thank you to Emmeline Kao for aiding in the development of the skin material and face mechanism, as well as Joseph Meloy for his assistance with the simulations. Finally, I would like to thank all of my lab mates throughout the two years of my graduate study.

Chapter 1 Introduction

1.1 Motivation for Assistive Robots

As the U.S. prepares for the first round of baby boomers to turn 65 in 2011, it must prepare for the approximate 8 million that could need long term care from nursing homes and home health providers by 2040 [1]. To meet these challenges, healthcare organizations need to adopt the use of advanced technologies in their patient care process. Innovative socially assistive robots can help meet the current and future demands put forth by an aging population and nursing staff shortages, and provide measurable improvements in an individual's health status [2]. Assistive robotics focuses on aiding, motivating and assessing those in need. The social interaction, guidance, and support that an assistive robot can provide patients, the elderly and the disabled can be very beneficial to patient-centered care. In the future, the use of assistive robots will be one of the most important service applications of robotic systems.

1.2 Research Problem Statement

Currently most assistive robots consist of an embodied robotic head, i.e. Pearl [3] and Kaspar [4], or a monitor that displays a computer generated image of a face, i.e.

Clara [5]. The head of a robot, as with a person, is the interface by which both nonverbal and verbal communication occurs. If the head has an unpleasant or unfamiliar appearance a feeling of discomfort may occur in the individual interacting with the robot. In turn, this will limit communication and not allow the assistive robot to perform as intended.

The objective of this thesis is to develop an expressive head for an assistive robot that will encourage social interaction between a human and itself. In order to make the communication and interaction with the robot more natural and comfortable, the head will be modeled after that of a human. In addition to a physical resemblance of a human, it will also be able to mimic specific emotions via the nonverbal display of a number of facial expressions as well as verbal content. By possessing human embodiment and producing facial expressions during social interactions, the robot head will enhance interaction to a level that the assistive robot can perform optimally. In this thesis, I will present the mechanical design of an assistive robot head emphasizing its potential as a social interface. The robot head will be effectively integrated into the human-like socially assistive robotic platform developed in our research laboratory.

Prior to a more detailed description of the research problem at hand, a brief review of the pertinent literature in the area of assistive robots is provided.

1.3 Literature Review of Assistive Robots

The pertinent literature is reviewed herein within two main categories: (i) Animal/Pet-Like Assistive Robots, and (ii) Human-Like Assistive Robots.

1.3.1 Animal/Pet-Like Assistive Robots

Recently, a class of animal/pet-like robots has been emerging for interactive stimulation. The psychological value of this class of robots is based upon the unique combination of such features as interactivity, life-like appearances, and imitating behaviors [6]. For example, Paro is a toy-like interactive robot modeled after a baby seal, having fur, whiskers, moving eyes and flippers, seen in Figure 1-1. A seal was chosen since most people do not have any preconceived notions of how a seal should act. This allows the individual interacting with the robot to develop their own unbiased opinion based on their experience with the robot. Paro responds to touch, sound, sight, and temperature [7]. Studies directly involving Paro have shown that introducing the seal-like robot to the elderly has the potential of improving their moods, reducing their dependency on the nursing staff and decreasing burnout scores for the nursing staff [8].

Figure 1-1: Paro [7].

Sega has created several animal/pet-like assistive robots. Their most popular is a robotic cat by the name of Yume Neko [9]. The body of the robotic cat is extremely soft, providing it with a lifelike appearance, as seen in Figure 1-2. Tactical sensors are placed at several locations on the body to allow it to react to the person interacting with it. This robot is commonly used in elderly homes to sooth the patients, although it cannot monitor the emotional response of the person it is interacting with [9].

Figure 1-2: Yume Neko by Sega [9].

Another example is iCat developed by Phillips, which is a cat-like immobile plastic robot that displays facial expressions via moving eyes, eyelid and lips, as seen in Figure 1-3 [10]. iCat is designed to have interfaces to aid in agenda-keeping, monitoring, companionship, information providing, and memorizing medication data. Studies that have utilized iCat were based primarily on the acceptance of the robot by elder subjects [10]. Some studies found that the subjects became confused and could not interpret the robot’s functionality due to its cat-like appearance and limited number of interfaces.

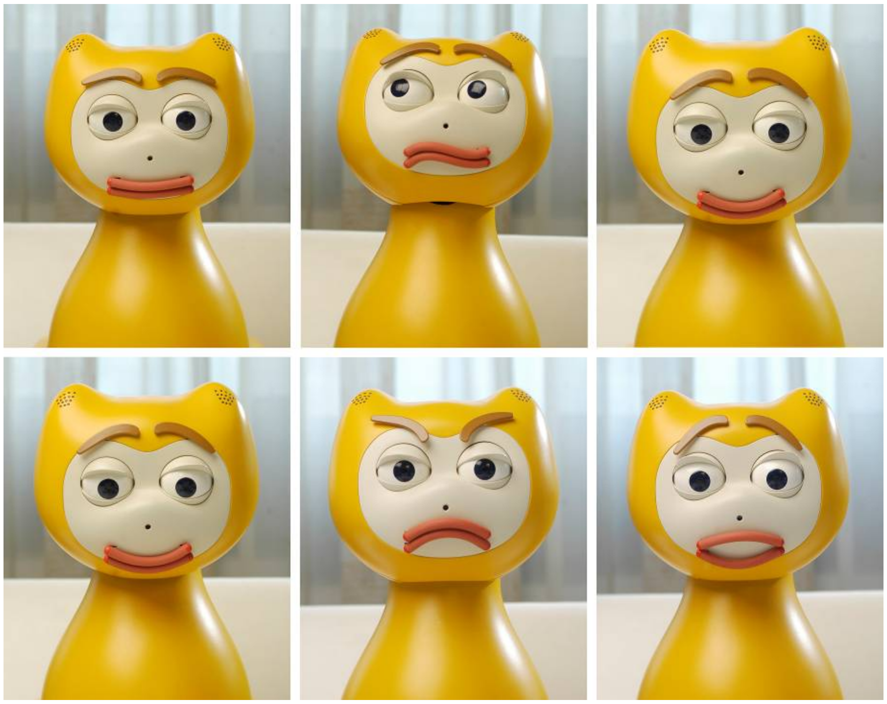

Figure 1-3: iCat by Philips [10].

1.3.2 Human-Like Assistive Robots

To date, most of the interactive assistive robots that have been developed to aid with patient care do so with minimum or no natural biomimetic or emotional social interaction, mostly consisting of a wheeled vehicle carrying a computer monitor projecting an image of a software agent or human. One of these robots is the Patrol Robot, which is an autonomous mobile robot that is capable of traveling around a hospital to check the condition of patients [11]. Although this robot can analyze its patients' state based primarily on facial expression recognition, it has no way of reciprocating a reaction to the patient. This is because it is not equipped with any means of expressing itself. It does not possess a head like structure capable of reacting to the sensory feedback it receives from the patient. Even though this robot is designed to be in constant contact with patients while it monitors them, its design is primarily based on a mobile platform equipped with sensors for navigation and face recognition purposes. Another assistive robot designed for home and hospital monitoring of patients is SIRA [12]. SIRA's primary task is also to monitor the state of elderly or disabled patients in a hospital, nursing home or house. The design is targeted at fast navigation of a home/hospital, yet lacks the communication interface to accurately determine the state of the patient. Its only means of human-robot interface is via speech and is used primarily to learn its environment. This robot has a similar design to the Patrol Robot and also has no means of physically/emotionally expressing itself in reaction to the speech interface it provides for interaction between a human and itself.

Clara is another assistive robot that has a somewhat more human appearance, Figure 1-4, [5]. Its purpose is targeted at assisting cardiac patients with repetitive lung exercises that must be performed ten times per hour for several days following cardiac surgery. It has a monitor that displays a human head for communication with the patient it is monitoring. The video and voice of the human is pre-recorded and played back during interaction.

Figure 1-4: Clara [5].

Pearl is a socially assistive robot that was designed to be used to remind elderly people about their daily activities [3]. The robot has a cartoon-like face with moving eyes and eyebrows, as seen in Figure 1-5, that allow her to express simple emotions and a touch screen monitor for communication. Studies with Pearl based on appearance and social behavior of the robot versus the task to be completed by the patient suggest that the robot's appearance or demeanor systematically influences people's perceptions of a robot (i.e., if the robot is obnoxious), and their willingness to comply with the robot's instructions [13]. Participants did not find a playful robot more compelling and expected the robot to look and to act appropriately given the task context.

Figure 1-5: Pearl [3].

Another assistive robot aimed at aiding the elderly is Domo, Figure 1-6, [14]. This robot's methods of assistance are slightly different than those previously mentioned. Utilizing its arms, Domo can physically grab objects and hand them to a wheelchair bound or elderly person in their house or nursing home. The robot's head consists of two alien-like eyes that it uses to gaze at the person whom it is interacting with. It lacks any other means of displaying emotions in the form of facial expressions. This drastically limits the amount of emotional interaction that can be achieved while the robot is communicating with a designated individual.

Figure 1-6: Domo [14].

The assistive robot KASPAR (Kinesics And Synchronization in Personal Assistant Robotics) is designed to promote social interaction via a realistic humanoid form [4]. Its primary application at this point is as a research platform for human-robot interaction where its expressions are used to encourage interaction. Although a few simple expressions can be expressed (i.e. happiness, displeasure, surprise), it is designed for minimal expressive features. The small size and minimal facial actuation gives it the appearance of an animated toy or doll, as seen in Figure 1-7.

Figure 1-7: KASPAR [4].

As can be seen from the given examples, there are many different types of socially interactive assistive robots in existence. Each one of these robots has a similar function in that they are in one way or another involved with human-robot interaction. Unfortunately few possess any type of receptive facial expressions to promote the interaction they were designed for. Moreover, the robots that do have the capabilities of expressing themselves in some method do so in a very limited manner. This lack of reciprocation of emotions in human-robot interaction, which seems to be a common occurrence, indicates that there is a need for a communication interface, such as a robotic head, that possesses these characteristics during assistive interactions.

1.4 Proposed Methodology and Research Tasks

The overall proposed methodology comprises the following components with corresponding reference to the Dissertation Chapters to develop a believable human-like robotic head for assistive applications:

1. *Expressive Human-Robot Interaction*

   In Chapter 2, a detailed literature review of the three main research topics of this work is presented: (i) Human-like Robotic Faces, (ii) Emotion-Based Human-Robot Interaction and (iii) Mimicking of Human Expressions. These topics present the necessary parameters needed to promote believable social interaction with a robot.

2. *Architecture of Robotic Head*

   In Chapter 3, the developed robotic head is described focusing on the skeletal structure. The dimensions and degrees of freedom used to design the structure are determined to be analogous to that of a human head to create a sense of human embodiment. The motors used to create the necessary movements are also explicitly described. This chapter ultimately demonstrates how the structure and mobility of the robot head is laid out in a manner that resembles the size, shape and movement of a human head.

3. *Muscle-based Robotic Expressions*

   In Chapter 4, the proposed novel facial expression actuation mechanism is described. In particular, the design of a robotic face that will utilize the modeling of human facial muscles utilizing a minimum number of control points is presented.

4. *Implementation*

Chapter 5 will present all the experimental results pertaining to how accurately the robot portrays the desired expressions. The proposed methods will be used to encourage human-robot interaction on a socially comfortable level.

Finally, Chapter 6 presents conclusions on this research work, highlighting its potential applications and future work.

Chapter 2 Literature Review

2.1 Robotic Heads

Many robots that are developed are designed to interact with humans on a regular basis. These robots are also known as Robotic User Interfaces (RUI), where the robot acts as an interface to another system, in this case a human [15]. This type of interaction is only effective if the interface is sufficient. Many RUI possess a head-like unit to interact with humans in a social manner. As when humans interact with one another, the head is the main interface for verbal and non-verbal communication. In general, when a person interacts with someone, they watch the other individual's face for a physical reaction expressing their feelings about what is being heard or seen. It has been found that the embodiment aspect of a robot head is important for believable interaction. Therefore it is vital to develop and investigate a believable and visually appealing robot head for an assistive robot whose purpose is to aid elderly patients. Three types of robotic heads used in assistive robot applications are either: (i) an LCD monitor with video display of an actual human-face or 2D graphic/avatar, (ii) virtual animated 3D human-like graphic/avatar, or (iii) physically embodied human-like robotic head.

2.1.1 LCD Monitor Display

The use of an LCD monitor to display video of a human face or a virtual agent has several advantages and disadvantages to their utilization. This type of social interface allows virtually any video or 2-Dimensional image to be displayed, making this a very versatile platform. This is a very adaptive system that has the capability to change its face/display avatar based on the individual it is interacting with. For example, if a child patient were interacting with the robot, it could take on the appearance of a child as well in order to make the patient feel more comfortable. Unfortunately, the drawbacks to this system seem to outweigh the advantages. LCD monitors, when viewed from an angle, may cause the image being displayed on the screen to appear dimmer or even disappear completely. Also, the color accuracy varies from monitor to monitor, which indicates that the image may not be displayed as an accurate representation as desired. Another potential issue is that these types of monitors commonly experience a ghosting effect when fast motion is displayed [16]. This could potentially cause a problem when the face being displayed is moving.

This type of robotic head is commonly used with telepresence robots such as PEBBLES (Providing Education By Bringing Learning Environments to Students,) as seen in Figure 2-1 [17]. This robot's main function is allow to hospitalized children to attend class via a remotely controlled videoconferencing robot. Although this system proved to be successful in a classroom setting where it is used as an interface between the student and a teacher, it has been developed for a display for tele-presence and hence does not incorporate features for one-to-one interaction with. The screen can only be seen from one angle and the video image displayed on the LCD cannot effectively look around its environment in 3D space [18]. Another example of telepresence based robots is the robot named Companion, developed by In Touch Inc. for geriatric care. It allows communication between individuals in remote locations, however the patients had trouble identifying the sex of the person they were speaking to and recognizing who they are [19]. Unfortunately this lack of recognition could lead to many drawbacks, such as the patient not communicating all information regarding a specific situation because of a lack of comfort.

Figure 2-1: PEBBLES [17].

2.1.2 Virtual 3D Graphics

Another type of robotic head developed integrates both physical and virtual components in order to generate a Mixed Reality Agent (MiRA) [18]. This involves a 3D virtual head that can be seen on a physical robot via a Head Mounted Display (HMD). The physical robot will travel in and receive feedback from its real environment and express its reactions via a 3D virtual head. Although this allows the user to feel like they are interacting with a 3D head rather than a 2D image, it lacks physical embodiment. Another crucial limitation is that the head can only be seen while wearing the HMD which is bulky and may be uncomfortable, as seen in Figure 2-2.

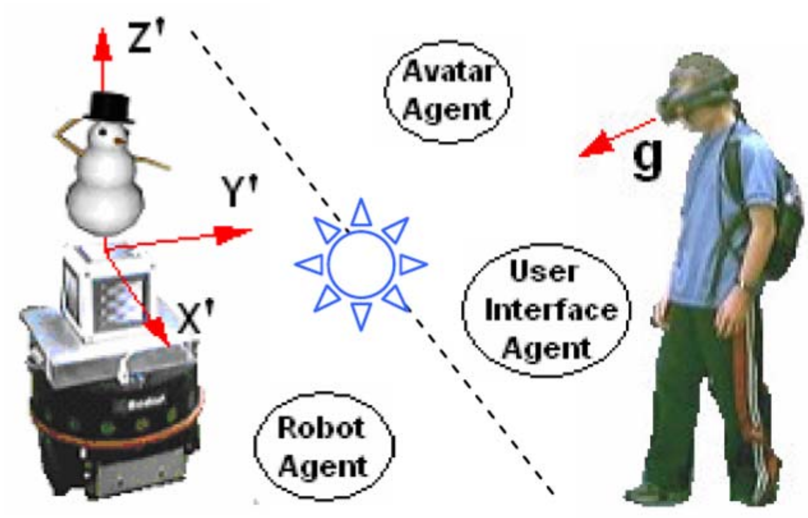

Figure 2-2: Mixed Reality Agent and Head Mounted Display [18].

2.1.3 Physical Embodied Human-Like 3D Head

Another type of robotic head used is a physical 3-Dimensional human-like robotic head. These robotic heads usually consist of at least eyes and a mouth such as Kismet [20]. This is the bare minimum of physical components necessary to facilitate a satisfactory conversation between a human and the robot. Eyes are important, because they allow the individual to form eye contact with the robot while speaking or listening to it, which is common during human-human interaction [21]. The mouth component is necessary in a socially interactive robot, since one of its main functions is to speak with people. The mouth is usually controlled to mimic the movement of a human mouth based on the audio output. Even though the sound of the voice is actually being projected through a speaker, this gives the illusion that the robot is actually annunciating each word via its mouth. Some of these robots possess skin to cover the internal components and give a much more life-like appearance, such as SAYA, as seen in Figure 2-3 [22]. Once again, the concept of a physically embodied human-like 3D robotic head gives a very life-like appearance and encourages social interaction between the individual it is interacting with and itself [23].

Figure 2-3: SAYA [22].

2.2 Emotion-Based Human-Robot Interaction

Human-Robot Interaction (HRI) research is typically focused on developing the social functionality of a robot in such a way that direct social engagement will be encouraged between the robot and human participants [18]. Effective social interaction is the key to successful HRI, as research has shown that computers that behave in a socially competent manner are treated as equal social partners by humans [24]. Although the research is based on Human Computer Interaction (HCI), interactions in both HCI and HRI are closely related, often providing insight to one another [25].

It is vital that the person interacting with the robot feel comfortable during communication. Emotion is extremely important, because this is what separates humans from machines. Giving the robot a means to show emotions, allows humans to interact with the robot on an emotional and social level. Mori indicated in “The Uncanny Valley” that an emotional affection can be generated between a robot and a human by possessing the robot with human-like communication references [26]. It has been proven that humans interact well and create a social bond with systems that resemble humans. For example, it has been demonstrated that people are more willing to cooperate better with software agents that have human faces [27] and mechanical robots with a more human-like appearance [23]. The development of such robots could be effective in situations where obtaining a patient’s compliance is necessary for important treatments and exercise routines, for which expressed anger or deep concern should be used, whereas cheerfulness and enthusiasm can be used in less serious interactions. Such traits can be especially advantageous when interacting with young and elderly patients.

Animal/pet-like robots were developed in order to foster this emotional bond between a human and a machine. These types of robots were developed due to the benefits revealed from animal-assisted therapy as an alternative therapeutic modality, which is used to promote the quality of life and positive health benefits of patients [28]. Researchers have found that people tend to identify with these types of assistive robots since many take on the form of household pets. People tend to develop a strong psychological attachment with animals, also known as an animal-human bond [29]. This bond has been proven by analyzing the neurochemicals before and after a human subject interacts with a specific animal. After a positive interaction, these neurochemicals increased, which scientifically proved the psychological benefits associated with this type of therapy [30]. This is the reason that these types of robots substantially encourage emotion-based human-robot interaction. Two of these types of robots are Paro [7], which resembles a seal, and Yume Neko [9], which resembles a cat. Their soft furry bodies and subtle facial expressions are modeled to mimic an amicable pet.

2.3 Mimicking of Human Expressions

Current robotic research platforms used to mimic human expressions have several different methods. One of the simplest forms is by a combination of LEDs and motorized eyes [31]. This method involves a grid of LEDs that light up in specific patterns in order to mimic actuation of the mouth and cheeks. Although this method replicates human expressions in a manner that the emotion they are portraying can be recognized with ease, it is far from realistic. This gives a toy/cartoonish appearance to the face as seen in Figure 2-4.

Figure 2-4: Ifbot [31].

Another method of actuation recreates the expressions of the eyes and mouth on a robot-like face. These faces typically have the actuating mechanism exposed and lack skin [20]. Unfortunately the lack of skin does not allow actuation of cheek muscles, which is very important to effectively mimic human facial expressions. Some of the current applications have incorporated a skin-like layer to cover the facial mechanisms and allow full actuation of the face. The skin material usually consists of either urethane sponge or silicone rubber [32]. For example, KASPAR uses a child CPR training manikin mask for the face, which is only attached to the face mechanism at the ears and mouth [33]. This drastically limits the number of nodes that can be actuated on the skin to the mouth and cheek region of the face, since the only facial expressions displayed are due to opening and closing of the jaw. There have been some developments that focus on imitating the human facial muscle structure [22, 32, 39-42]. The complexity of the human facial muscle structure is very difficult to recreate in a precise manner. This is typically done by individually recreating the motion of each of the 41 parallel and sphincter muscles in the human face, in turn requiring a fairly complex actuation system.

Usually the movement of each muscle node is mimicked by a servo motor. Since there are so many nodes, many motors are needed for an accurate representation, as seen in Figure 2-5. This leads to a massive power draw, which as mentioned earlier, can have a substantial toll on the battery life of a mobile assistive robot. In addition to this issue, a large amount of space is required to store all of these motors in the head. This usually ends up occupying most of the available space in the end, which ultimately interferes with the other vital components (i.e. frame structure, sensory system, etc.) stored in that region.

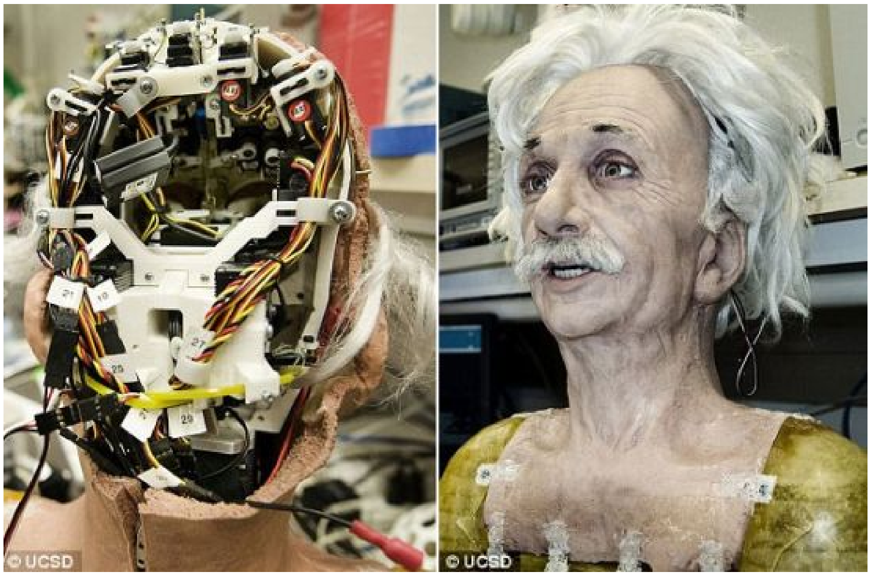

Figure 2-5: Albert Einstein Face Robot by Hanson Robotics.

Facial expressions are key in the design of the robot's ability to emulate emotions and hence, play a central role in human-robot interaction. The six basic expressions that people identify with are happy, surprise, angry, disgust, sad and fear [34]. According to Ekman, there are characteristics associated with each emotional expression that humans identify with to indicate the emotional state of one another. These characteristics include rapid onset, short duration, unbidden occurrence, automatic appraisal, and coherence among responses. Although some of these characteristics are shared between some emotions, there is a unique combination of them to form each emotional expression. This allows humans to distinguish each emotional state. Most of the current robotic systems out there aim to mimic these characteristics and create emotional expressions in a believable manner, in order to encourage a truly interactive conversation where the person involved feels that they are receiving receptive feedback.

2.4 Concluding Remarks

Based on the literature review the physical emobodied human-like head appears to be the best design, which was verified by the literature review of emotion-based human-robot interaction. This indicated that the more human-like a robot is the more comfortable people are interacting with it socially. A physically emobodied human-like robotic head must also possess the ability to mimic human expressions. This literature review indicated that there are many different types of actuation systems, but the most accurate are the ones that mimic the human facial muscle structure. These muscle actuation systems are usually designed to express the six basic emotions of happy, surprise, angry, disgust, sad and fear. Overall, this literature review indicates that the best design of a robotic head for social interaction should embody that of a human head and be capable of expressing the six basic emotions via an actuation system based on the human muscle structure.

Chapter 3 Architecture of Skeletal Structure

The preliminary design of the robotic head, which is presented herein, consists of a human-like demeanor having similar functionalities as a human. The head unit has been designed to encourage natural interactions between a person and itself. The objective herein, is to design the robotic head as simple and as cost effective as possible for its application. It is designed utilizing dimensions from a male human volunteer, in order to keep the size and proportions as life-like as possible. In this chapter the design of the skeletal structure of the robotic head will be outlined.

3.1 Structural Design

3.1.1 Skeletal Structure

The objective of the robotic head design is to make it socially appealing and look as human-like as possible, while keeping it functional. In order to accomplish this task, approximate dimensions and joint locations were measured from a male volunteer. This aided in determining the placement of the eyes and teeth as well as the location of the neck and jaw joints, Figure 3-1.

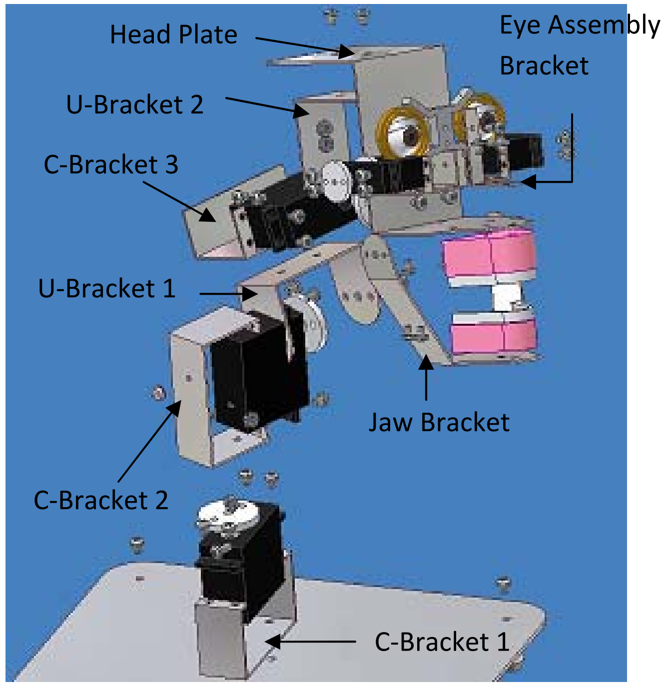

Figure 3-1: Mechanical design of the robot head.

To provide the rigidity needed for the head and to structurally support all the weight of the components in the head, as well as keeping the head lightweight, the skull of the robot was constructed out of 1.588 mm aluminum weighing only 2.860 N in total. The skull structure was designed to have similar support aspects as a human skull, as can be seen in the pivot points and structure of the jaw, Figure 3-2. The overall dimensions of the robotic head are 262 mm tall, 113 mm wide and 171 mm deep.

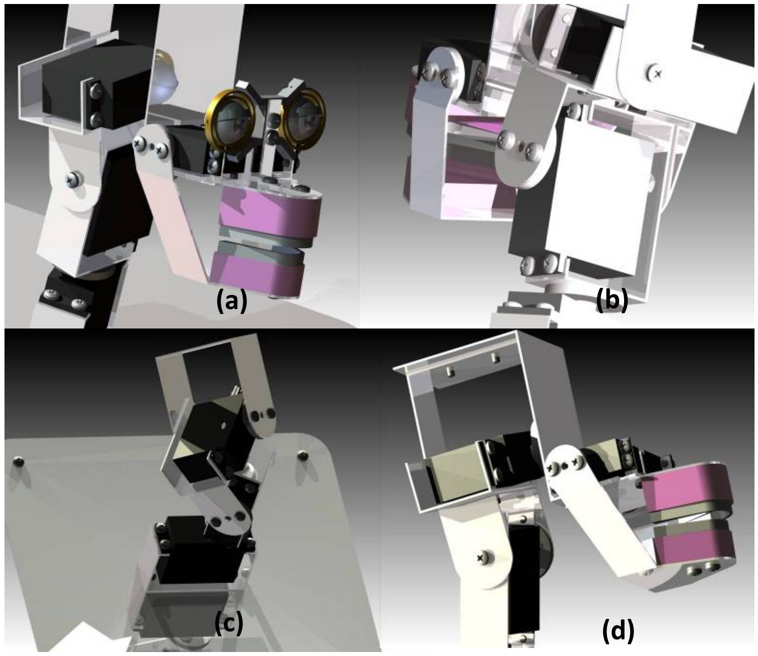

Figure 3-2: CAD renderings of (a) front view of complete robotic head, (b) rear view of complete robotic head, (c) neck assembly, (d) jaw assembly.

It is critical that the structure have the approximate dimensions of a human head, since the face structure that will be attached to it will also be modeled after an adult human male. In addition, the teeth and eyes are separate components that match the dimensions of an adult human and the structure must be to the same proportions or else it may cause a slightly deformed appearance, which would in effect discourage social interaction.

3.1.2 Eye Mechanism

The eyes were a very important component, as eye contact is crucial in natural interactions, therefore making it equally important in human-robot interaction. Eye contact is a common and effective method of initiating conversation [21]. This obviously stresses the need for an accurate-to-life and visually appealing set of eyes. For this reason a very realistic, eye-mechanism was chosen and integrated into the robotic head, as seen in Figure 3-3. The structure was designed to have the eyes spaced the same distance as that of an average human male.

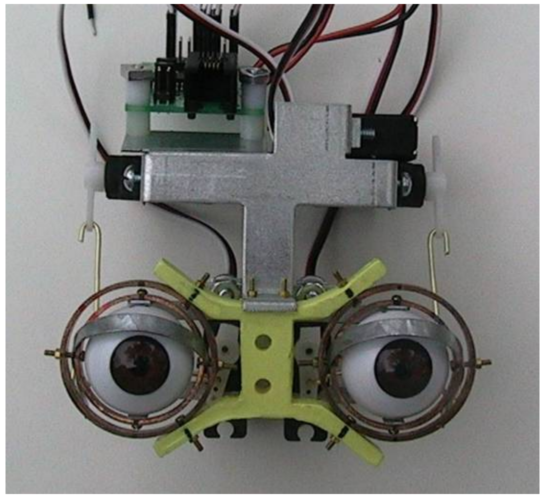

Figure 3-3: Mechanical design of animatronic eyes [www.androidworld.com].

3.1.3 Teeth

The teeth are another important part of the overall structure of the head. Although the teeth are not being used to pronounce words as with a human, their presence is necessary in order to ensure the head is as human-like as possible. The teeth, seen in Figure 3-4, are generally used as an orthodontics demonstration kit. These teeth were created from a dental mold from an actual human volunteer to verify that it is as accurate as possible.

Figure 3-4: Mechanical design of teeth [www.evansorthodontics.com].

3.1.4 Skeletal Frame

Once the teeth, eye mechanism and overall design of the robotic head were determined, the detailed design of the structural brackets was performed. First the placement of the eyes and teeth had to be established in relation to one another on the robotic head. Front and side 2D images were taken of a human male subject to determine the appropriate location of the eye mechanism and teeth as well as the approximate locations of the pivot points of the neck and jaw, Figure 3-5. Critical pivot joints were located on the human subject by inspection and then indicated on the image. A grid was placed over the images to allow coordinates to be used to indicate critical locations. This grid also provided limitations to the overall size of the structure, to ensure that it was within the boundaries of a human head.

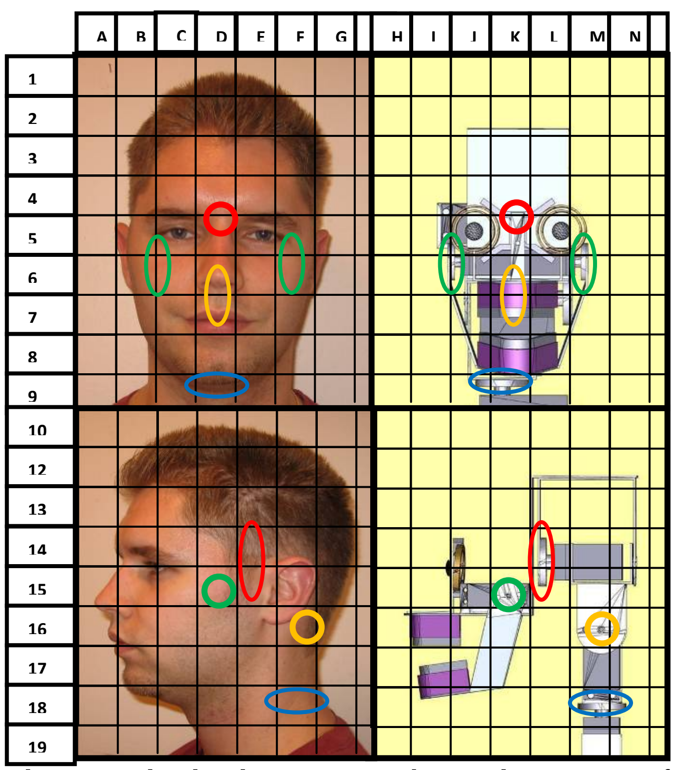

Figure 3-5: Grid pattern utilized to determine size, shape and pivot points of structure frame.

The focus of the actual bracket design was to provide motion at each pivot point. C-Bracket and U-Bracket designs were generated to create the desired movement. The C-Bracket is designed to house a rotary actuator to provide motion to the head. Three types of C-Brackets were generated to create the desired mounting position for each actuator. The U-Bracket is designed to connect to each of the actuators to act as a linkage. Two types of these brackets were generated in order to create the desired motion and not interfere with other components. *C-Bracket 1*, Figure 3-6, is the base bracket designed to house a rotary actuator in a horizontal position to allow left-right rotation at the center of the base of the neck as indicated by the grid. *C-Bracket 2*, Figure 3-7, is designed to attach to the top of the rotary actuator housed in *C-Bracket 1*. *C-Bracket 2* also houses a rotary actuator, except in the vertical position. *U-Bracket 1*, Figure 3-8, is attached to this actuator to create the forward and backward nodding of the head, pivoting about the back of the head where the neck meets the base of the head as indicated by the grid. *C-Bracket 3*, Figure 3-9, attaches to the top of *U-Bracket 1* and houses a rotary actuator that attaches to *U-Bracket 2*, Figure 3-10, to provide the left-right tilting of the head, pivoting at the center of the head as indicated by the grid. These brackets previously mentioned make up the neck structure.

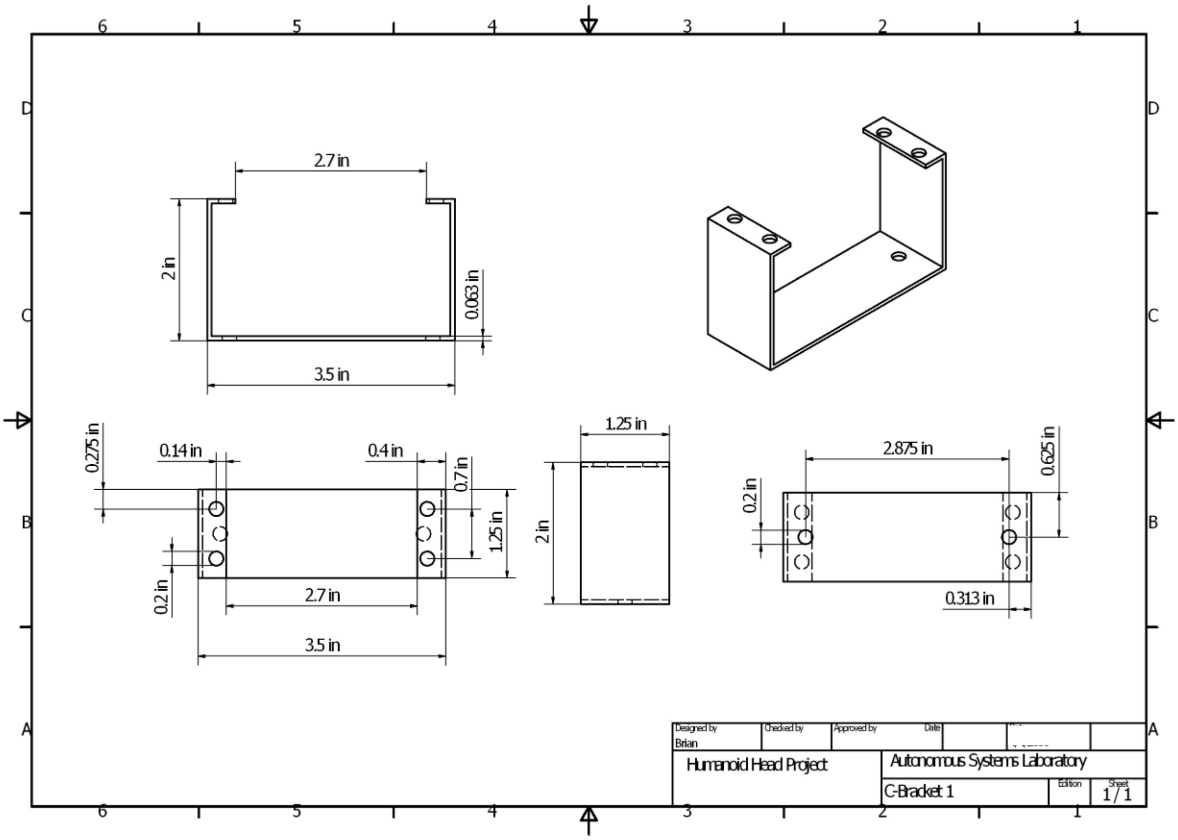

Figure 3-6: Dimensions of C-Bracket 1.

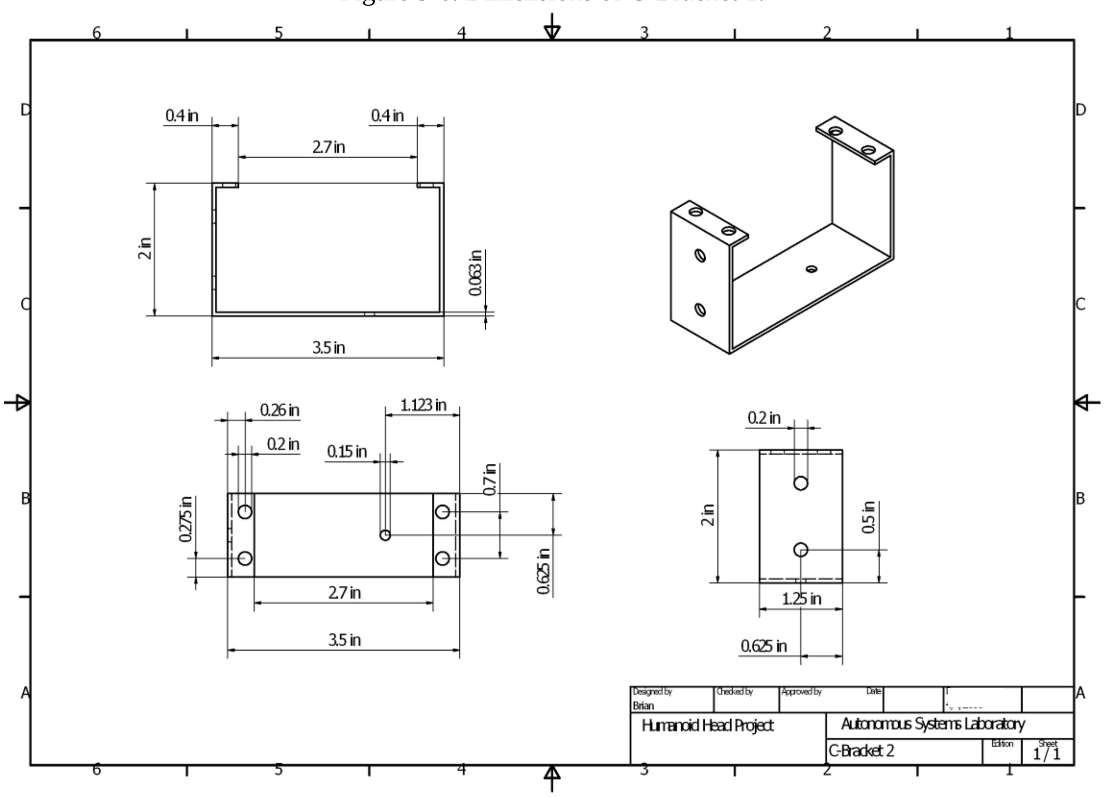

Figure 3-7: Dimensions of C-Bracket 2.

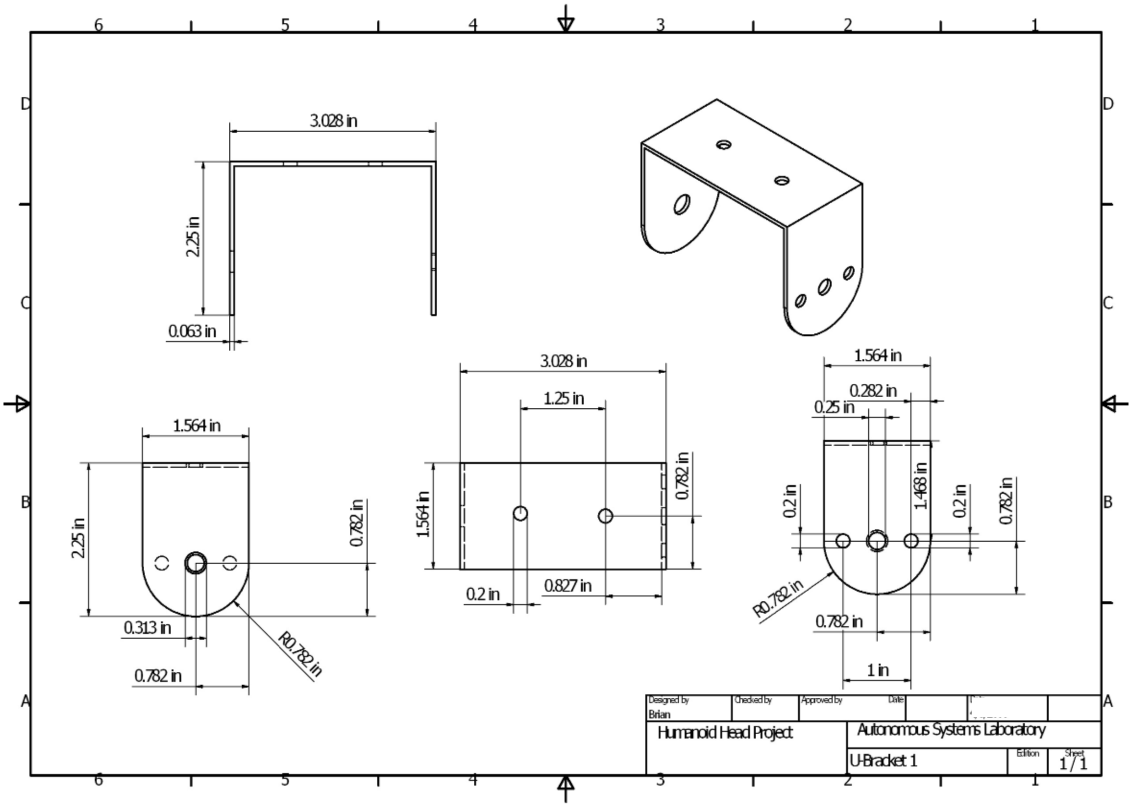

Figure 3-8: Dimensions of U-Bracket 1.

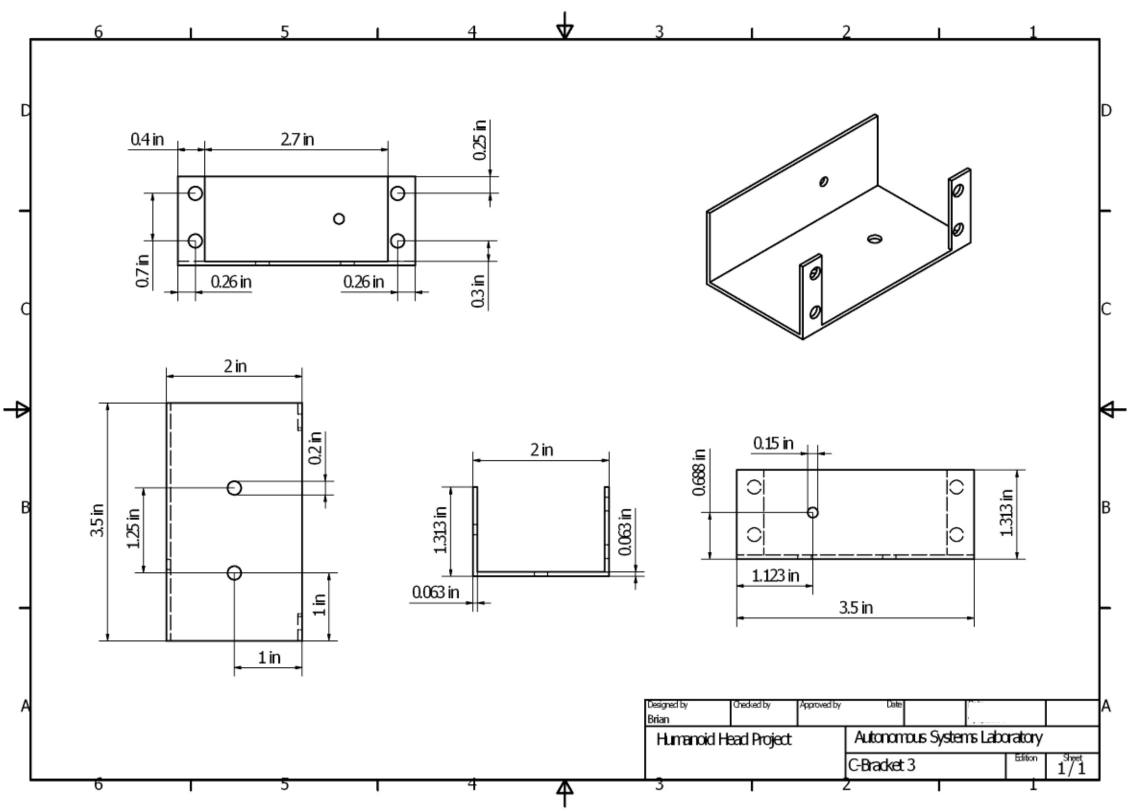

Figure 3-9: Dimensions of C-Bracket 3.

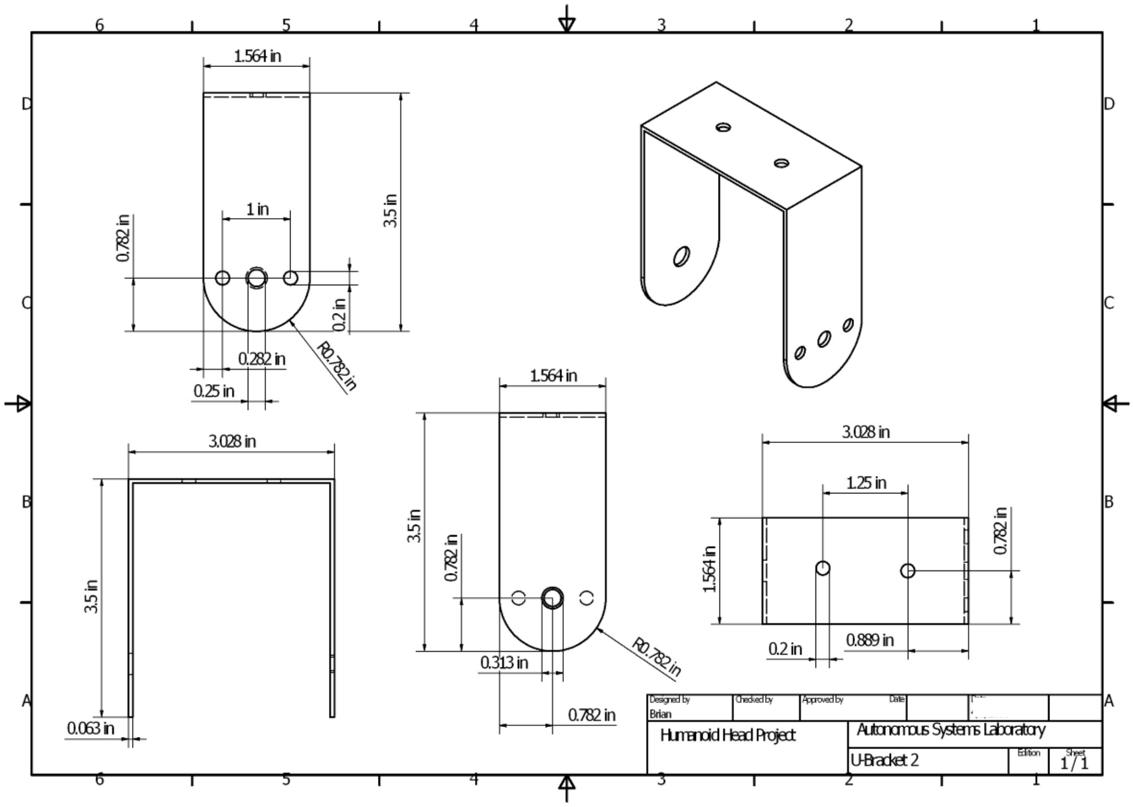

Figure 3-10: Dimensions of U-Bracket 2.

The next structure component is the *Head Plate*, Figure 3-11, which is where the *Eye Assembly Bracket*, Figure 3-12, and *Jaw Bracket*, Figure 3-13, are attached. The *Head Plate* is designed to attach to the top of the neck, bend 90 degrees down, then bend 90 degrees out toward the front of the head at the level of the top of the teeth, as indicated by the grid. The plate then extends forward until it reaches the front of the teeth, as indicated by the grid. Then the *Eye Assembly Bracket* is a simple L-bracket design that is attached to the *Head Plate* in a manner that ensures that the Eye Mechanism is placed properly as indicated by the grid. The *Jaw Bracket* is designed to act as a linkage between the bottom teeth and the jaw pivot point as indicated by the grid. The combination of these brackets gives an attachment provision for the eye mechanism and teeth, which gives the human-like appearance that is ultimately desired.

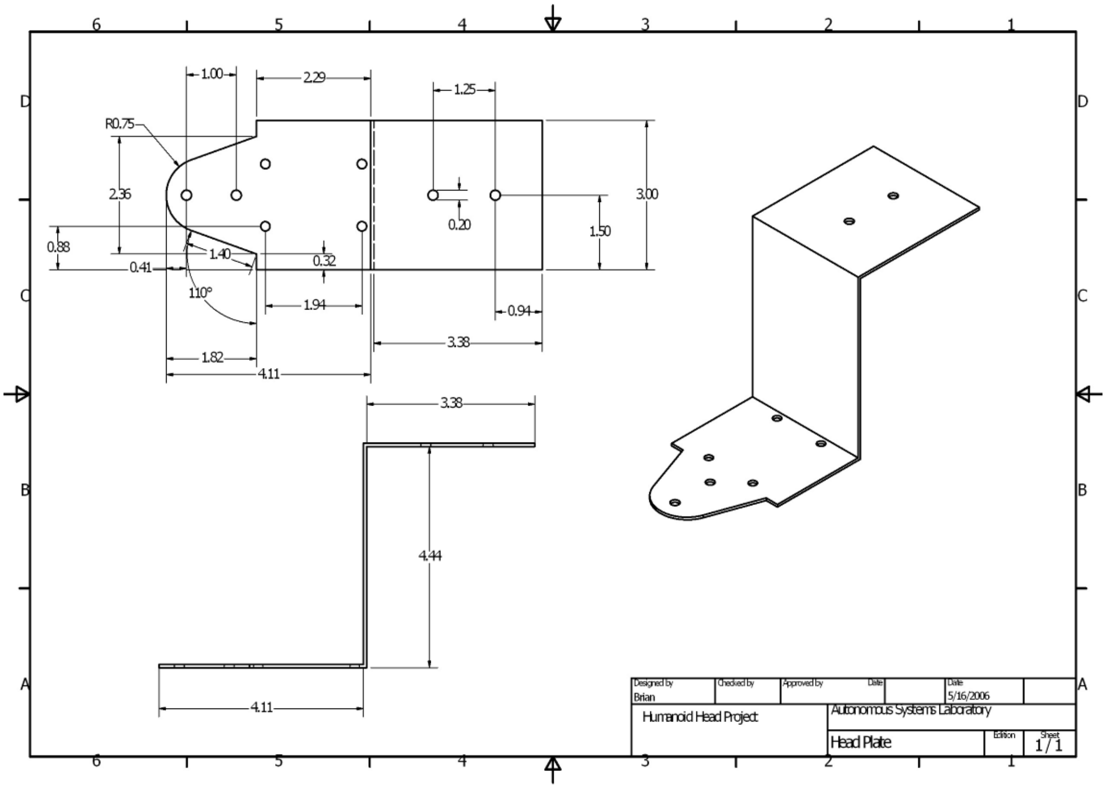

Figure 3-11: Dimensions of Head Plate.

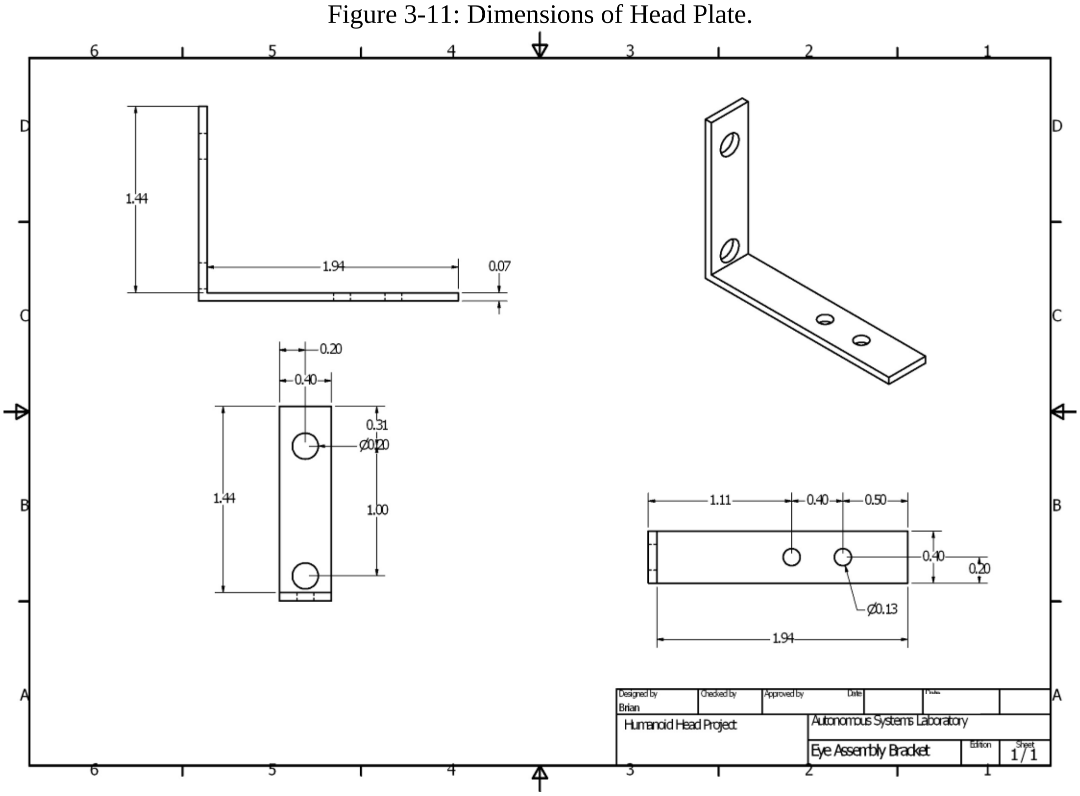

Figure 3-12: Dimensions of Eye Assembly Bracket.

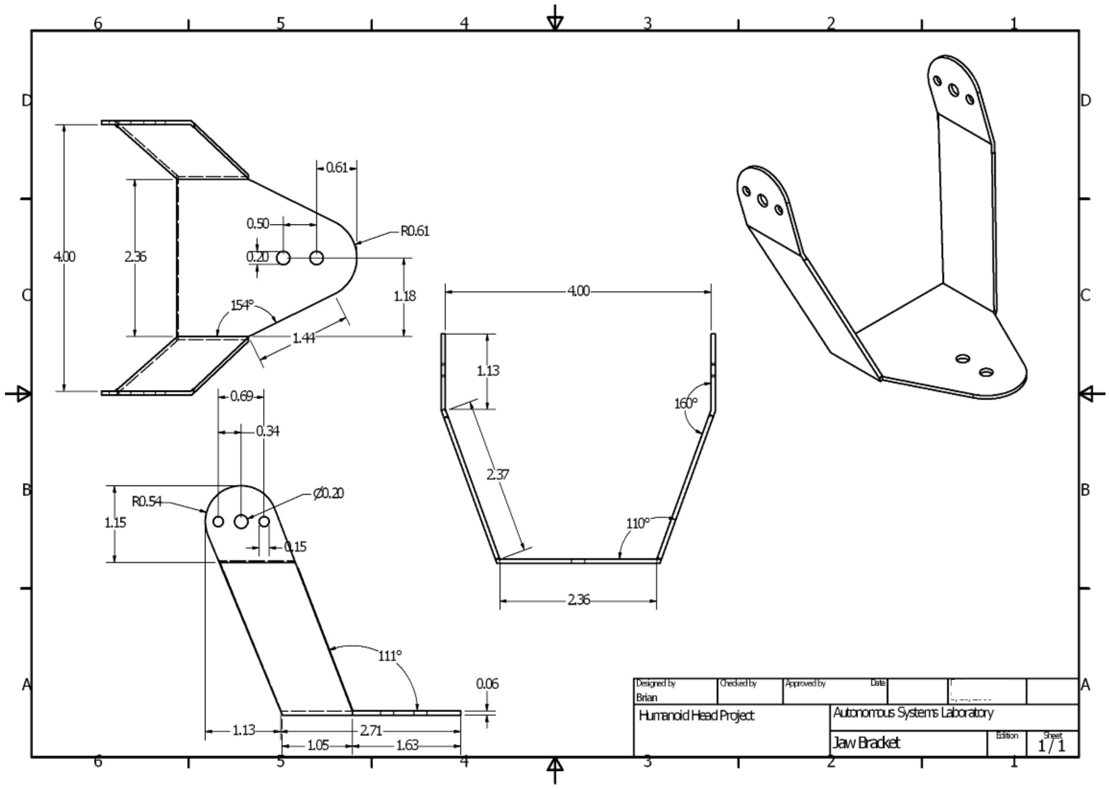

Figure 3-13: Dimensions of Jaw Bracket.

The location of each of the structure brackets mentioned can be seen in Figure 3-1. As previously mentioned 1.588 mm 6061-O aluminum alloy was chosen as the most appropriate material for the structure brackets due to its strength and light weight properties, as seen in Table 3-1.

Table 3-1: Skeletal Structure Bracket Weight Analysis

Skeletal Structure Bracket	Weight (N)
C-Bracket 1	0.269
C-Bracket 2	0.268
C-Bracket 3	0.331
U-Bracket 1	0.299
U-Bracket 2	0.406
Head Plate	0.905
Eye Assembly Bracket	0.036
Jaw Bracket	0.346

In order to verify that the aluminum material chosen would be sufficient for this application, a Finite Element Analysis (FEA) was performed. The *Head Plate* was selected for the analysis since this acts as a central structural support for most of the components being attached to the robotic head. The CAD model was imported into Pro/ENGINEER 3D modeling software to be analyzed by the Mechanica module used for FEA. Initially a Free Body Diagram (FBD) was created to determine how to subject the loads and constraints to the model. The ground constraint was determined to be the surface region where the *Head Plate* is attached to *U-Bracket 2*, Figure 3-1. Then the weight load of each structure component connected to the bracket, (i.e. *Eye Assembly Bracket*, Eye Mechanism, *Jaw Bracket,* and Teeth) was subjected on the model in the appropriate location. Once the load and constraints were properly set, the analysis was performed. Two sets of results were generated for the displacement and stress acting on the *Head Plate*. According to the data, the maximum displacement of 4.5 mm occurred at the unconstrained edge of the plate, as seen in Figure 3-14. The results also indicated that the maximum von mises stress of 27 N/mm^2 occurred at the bend located at the lower section of the *Head Plate*, as seen in Figure 3-15. The maximum displacement is minimal and the maximum von mises stress is below the yield stress of 6061-O aluminum alloy of 55 N/mm^2, verifying the structural integrity of this design.

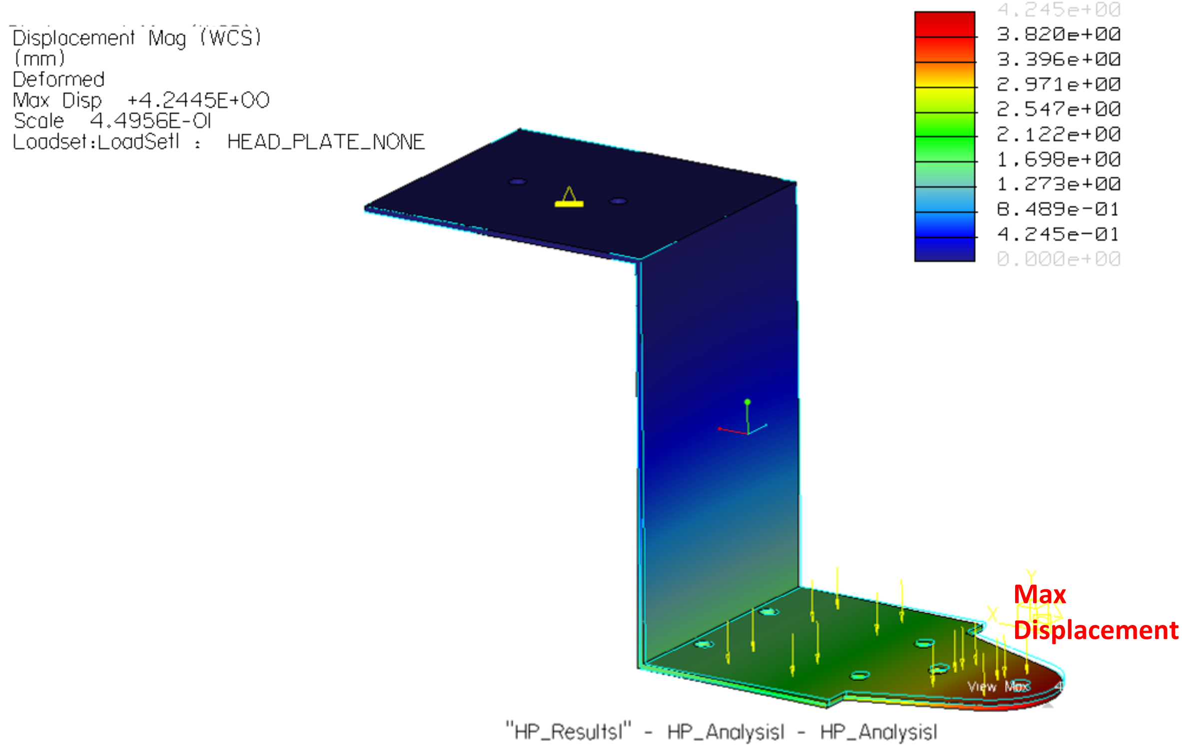

Figure 3-14: FEA Displacement Results of Head Plate.

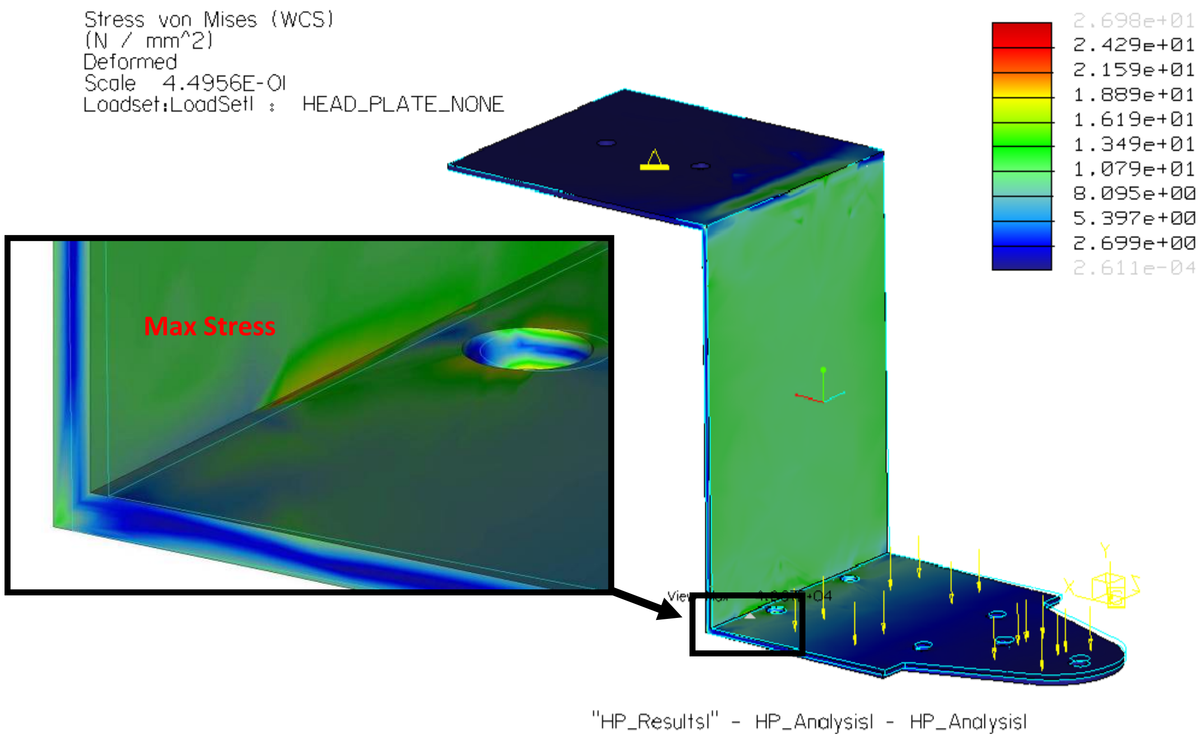

Figure 3-15: FEA Stress Results of Head Plate.

3.1.5 Face Structure

The face structure is composed of a face mask attached to the aluminum skeletal structure of the robot. The mask ultimately serves two main functions: (i) to create the shape desired for the skin, and (ii) to provide support to the muscles and skin. A generic human-like mask was obtained, seen in Figure 3-16. The mask was selected as the face structure for several reasons. The function of the mask is to fit on to a person's face, therefore it can be inferred that it will be approximately the same size as a human face. In addition, this would confirm that it will fit perfectly on the skeletal structure since this was designed to the same dimensions as that of a human head.

Figure 3-16: Face mask [www.costumeholidayhouse.com].

After determining that a mask would be appropriate to create a structural surface, the type of mask was selected. Although many types exist, most are designed to mimic a particular face type or character. A generic mask with a neutral facial expression was determined to be the most appropriate for this application as to not constrict the skin by any pre-existing expressions present on the structure that may show through. Another issue was the material of the mask, which can range from rubber to plastic typically. Since this is being used for a structural application, plastic is a much more rigid platform. Although the plastic used for the mask selected is thin, minimal support is necessary for the skin and the light-weight property of this particular material is highly desirable for this application. The size was the final deciding factor for this type of mask, as masks vary from partial face coverage to full head coverage. For this application a full-face-only mask was desired. A partial-face mask would not give enough support for the skin and a full-head mask could potentially interfere with the overall motion of the head. Since the overall shape, size and contours of this surface are very close to those of the layer of skin that will be applied, it acts as the perfect structural support for the face.

3.2 Mobility and Movement

The head of the robot has been designed to have a wide range of motion, allowing the robot to make head gestures in conjunction with facial expressions. Once again the mobility of the head was based on that of a human. The neck has 3 degrees-of-freedom (DOF) which includes turning left and right, up and down and tilting left and right, i.e., yaw, pitch and roll. In addition there is 1 DOF in the jaw and 3 DOF for the overall eye system, which allow the eyes to look left and right, up and down and the eyelids to blink. Not including the actuation of the skin, there are 7 DOF in the robot's head, Figure 3-17. This method of expression gives a substantially more realistic sense of the emotion being displayed.

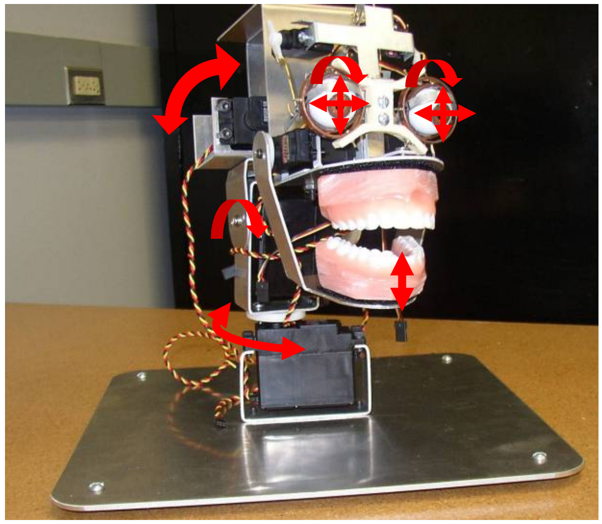

Figure 3-17: Skeletal structure with motion of each DOF indicated.

After the overall dimensions and joint placement of the structure were designed, the actuation components were selected. Several parameters must be considered when making this selection including: (i) size, (ii) weight, (iii) power requirements and (iv) control precision. When considering the size of the actuator, it is necessary that it is small enough to fit within the given dimensions of the skeletal structure. The weight of the actuator is also extremely critical in this situation as all the actuators are mounted within the head structure. In addition to this the power draw must be considered, as it is highly desired to keep this to a minimum in this type of application. One of the most important aspects, in regards to this design, is that it is necessary to have precise control of the actuators. Ultimately this robot will be computer controlled; therefore actuators that are easily integrated and can be controlled with computer software are most appropriate. In reality, virtually any motor can be controlled by a computer with the right combination of circuits and relays. For the purpose of this thesis, it is necessary that the motors have a signal feedback so that the exact position can be controlled. For situations where a particular head gesture must be made, this is vital in order to get a recognizable movement. Usually in applications that require position feedback of a rotating shaft, a potentiometer is used.

There are many types of actuators that could be used in this application, but the most appropriate one must be selected. Some options are hydraulic and pneumatic actuators which are within the size constraints and provide plenty of torque. The main disadvantage of these systems is that they are usually fairly heavy, which would add substantial weight to the head. Furthermore, they can be quite costly. Another disadvantage is that although these types of actuators can be small in size to fit within the head, they require a reservoir to hold the air/hydraulic fluid necessary to actuate them. These can be mounted remotely, but still adds additional undesired complexity to the design. In addition to this, they usually have high power requirements and lack the precision necessary to move the head as required.

Fortunately there is a type of motor that possesses many desirable aspects of the parameters being considered for this application, also known as a servomotor. One of the major benefits of using this type of motor is that it allows the user to simply input the desired degree and the servo will move to that position and hold it under load. Another advantage of using servomotors is that they are fairly standard components in many hobbyist applications, making it readily available. For these reasons, servomotors were selected to control the head.

Once selecting the appropriate type of motor, the exact model servomotor had to be selected for each part of the head. There are generally three different sized motors depending on the torque required. For this application, with the size constraints given, large ¼ scale servos could be used for the neck as this part will require the most torque, standard servos can be used for actuation of the jaw as this will not require as much torque, and finally micro-servos for the eye-mechanism as small-size is necessary and minimal torque is necessary. To determine the exact model, a simple minimum torque requirement calculation was performed, i.e.:

$$\mathbf{T} = \mathbf{F}L \quad , \tag{3.1}$$

where F is the weight of the body being actuated and L is equal to the length from the motor shaft to the center of gravity (COG) of the body being actuated by the motor.

Based on the calculations performed the following motors were determined to be sufficient for the size and torque specifications required. Three Hitec HS-805BB servos with 2422 N-mm of torque each are used to provide the motion of the neck, two Hitec HS-5645MG servos with 1186 N-mm of torque each are used to provide the jaw motion and smaller Hitec HS-85BB micro-servos with 346 N-mm of torque each provide the required motion for the eyes.

Table 3-2: Hitec Servo Specifications

Hitec Model	HS-805BB	HS-5645MG	HS-85BB
Head Component(s) Used to Actuate	Neck	Jaw	Eyes
Hitec Part#	31805S	35645S	31085S
Description	Mega Giant Scale	High Torque Digital	Premium Micro
Torque (4.8V/6.0V) N-mm	1942/2422	1010/1186	297/346
Speed (4.8V/6.0V) sec/90 degrees	0.19/0.14	0.23/0.18	0.16/0.14
Bearing	Dual BB	Dual BB	Top BB
Gear Type	Nylon	Metal	Nylon
Length (mm)	65.79	40.39	28.96
Width (mm)	29.97	19.56	12.95
Height (mm)	57.40	37.59	29.972
Weight (N)	1.50	0.59	0.19

Now that the motors have been selected, it is necessary to select a control system. As mentioned earlier, control of the motors needs to be via a computer. Allowing control from a PC will make the robot head easier to integrate into the overall robotic body and control motion via a single program. There are many servo controllers commercially available that allow control utilizing a Windows supported PC. Since this robotic head has motors with several different torque requirements, it was necessary to find a servo controller capable of controlling many servos simultaneously, while being able to support different power requirements. The best choice for this application was the SSC-32 servo controller, which can control up to 32 servos simultaneously and has multiple power inputs.

Table 3-3: SSC-32 Servo Controller Specifications

Microcontroller	Atmel ATMEGA168-20PU
EEPROM	24LC32P (Required for 2.01GP)
Speed	14.75 MHz
Internal Sequencer	12 Servo Hexapod (Alternating Tripod)
Serial Input	True RS-232 or TTL, 2400, 9600, 38.4k, 115.2k, N81
Outputs	32 (Servo or TTL)
Inputs	4 (Static or Latching, Analog or Digital)
Current Requirements	31mA
PC Interface	DB9F
Microcontroller Interface	Header posts
Servo Control	Up to 32 servos plug in directly
Servo Type Supported	Futaba or Hitec
Servo Travel Range	180 degrees
Servo Resolution	1uS, .09 degrees
Servo Motion Control	Immediate, Timed, Speed or Synchronized.
PC Board Size	76.2mm x 58.4mm
VS Current Capacity	15 amps per side, 30 amps max

Chapter 4 Facial Expressions

One of the most challenging factors in developing an effective facial expressions actuation mechanism for a robot is the ability to determine appropriate actuation nodes on the face and to be able to properly actuate these nodes in 3D or 2D space. In order to generate life-like facial expressions for the robotic head, this work has consisted of developing a robotic face that will utilize the modeling of expression muscles of a human face [35]. The human face consists of two main types of muscles: parallel muscles that pull and sphincter muscles that squeeze [36]. Parallel muscles have fibers that are parallel to their applied force. A sphincter muscle is a ring-like muscle that normally maintains constriction of a body passage or orifice, such as the mouth, and relaxes as required by normal physiological functioning [37]. These muscles have been successfully used by Choe et al. for computer animation of a human face [36], and herein, their use is extended for a physical robotic face. In the proposed face model, 11 of 19 parallel expression muscles and 1 of 3 sphincter expression muscles that exist in a human face are utilized, Figure 4-1. To keep the muscle model as simple as possible, the minimum number of parallel muscles necessary to actuate the face was used. For example, there are sphincter expression muscles surrounding each eye that are not considered in this model. Instead only the blinking of the eyes will be considered kinematically. The numbers in Figure 4-1 correspond to the different parallel muscles; 1) Frontalis, 2) Corrugator, 3) Procerus, 4)

Levator Labii Superioris alaeque nasi, 5) Levator Labii Superioris, 6) Zygomaticus Major, 7) Risorius, 8) Depressor Labii Inferioris, 9) Depressor Anguli Oris, 10) Mentalis, and 12) Orbicularis Oculi, and the sphincter muscle; 11) Orbicularis Oris. All muscles, except for muscles 3 and 11, exist in pairs.

This model is utilized to provide the information needed to determine the location of the actuation nodes on the robotic face for the muscle-induced motion of the skin. The advantage of utilizing this approach is that it is a generic representation of muscle actuation and hence, can be applied to a variety of robotic faces.

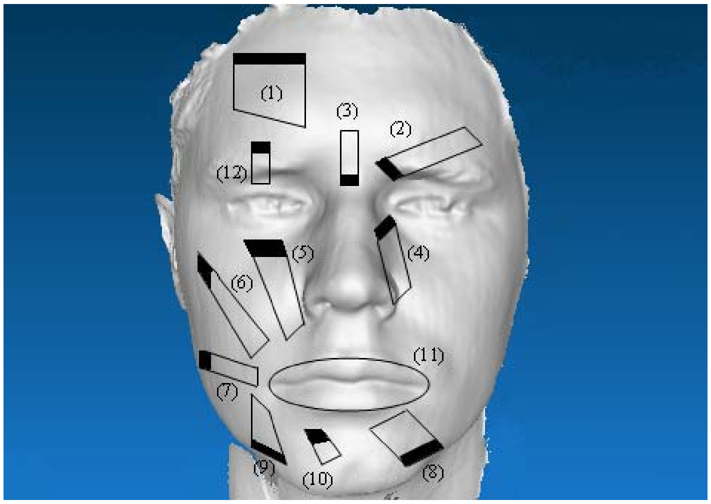

Figure 4-1: Facial Muscles.

4.1 Facial Muscles

In general, muscles in the human face work cooperatively and simultaneously in groups. Each area of the face has a specific muscle group, i.e., mouth, nose or eye, which performs specific functions. Very few people can actually cause the individual muscles to act independently. This association of movement allows for us to achieve various facial expressions. For example, when a volition is directed to the Orbicularis Oculi muscle

(Figure 4-1, muscle 12) to contract, it directly affects the muscles in the surrounding area: The Frontalis muscle (Figure 4-1, muscle 1) and the Corrugator muscle (Figure 4-1, muscle 2) will also contract, working cooperatively with the Orbicularis Oculi to deform the whole eyebrow region. This work consists of developing an integrated cooperating mechanism system to simulate respective groups of muscles of the face. Utilizing this information from human face anatomy, four corresponding hybrid muscle groups have been determined. With respect to their location on the human face, Figure 4-2: (i) eyes and eyelids (muscles: 1-3 and 12), (ii) upper portion of the mouth and nasal (muscles: 4-6), (iii) surrounding muscles of the mouth (muscles: 7 and 11), and (iv) lower mouth (muscles: 8-10) which are grouped with the jaw muscles. These hybrid muscle groups allow the face to achieve its multiple facial functions. Control nodes within these muscle groups have been identified to actuate in order to generate believable facial expressions. Each muscle group is designed to have at least one control node. This allows for the linking of certain nodes that are dependent on one another, yet allowing for enough independent nodal combinations in order to create a sufficient variety of facial expressions. Figure 4-2 details the location of the control nodes for each muscle group and the direction of travel. The muscles are created from thin rigid plastic and translate in space along tracks defined in the face mask to mimic muscle actuation.

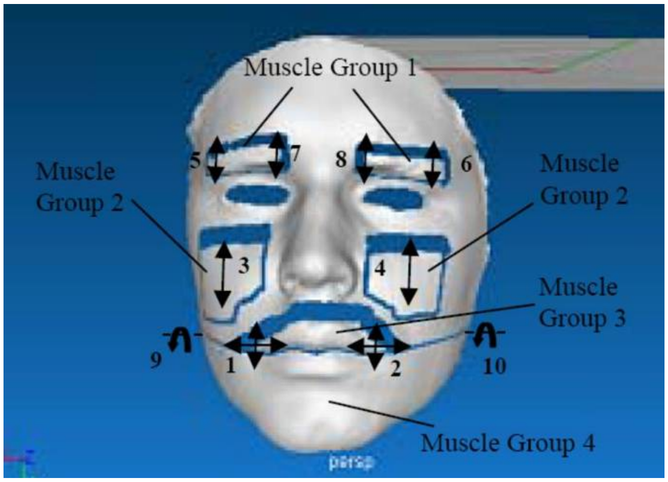

Figure 4-2: Muscle Group Locations and Direction of Motion.

4.2 Facial Control Nodes

Ekman identified happiness, sadness, fear, anger, disgust and surprise as six basic universal emotions among humans [34]. This work consists of designing the robotic face in order for the face to be able to initially display these six emotions through the appropriate control of the facial control nodes of each muscle group.

Several experiments were initially performed utilizing 3D model-based software to observe and analyze how the identified control nodes move on a natural human face under the influence of each of the six emotions. A male volunteer's face was scanned utilizing a 3D scanner system in order to create a 3D point cloud. This point cloud provided the data required to generate a mesh surface of the face. The model was then imported into Pro/ENGINEER 3D modeling software to allow for muscle manipulation. The locations of the facial control nodes depicted in Figure 4-2 were identified on the 3D face model. The red circles in Figure 4-3 depict the location of the control nodes on the face model. Then several 2D images of a variety of faces displaying a neutral expression and the six basic emotions were taken, i.e. Figure 4-4. These images were used to obtain the direction of translation and necessary displacement to modify the 3D model to accurately depict each emotion. The facial control nodes depicted in Figure 4-2 were also identified on a CANDIDE-3 wireframe human face model developed by Ahlberg, Figure 4-3 [38]. CANDIDE-3 is a parameterized face model containing 3D description of the facial shape in coordinate information.

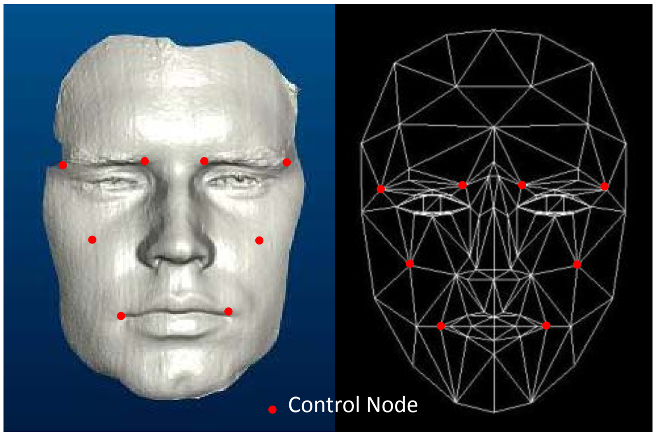

Figure 4-3: Initial 3D Face Model and CANDIDE-3 Wire Model with Neutral Control Nodes Indicated.

The 2D image of a person depicting a neutral facial expressions was adapted to the 3D wireframe model and then manually adapted to match the expression, Figure 4-4. Then each of these wireframe models were imported into the Pro/ENGINEER software and projected on to the surface of the 3D face model in the neutral position. Utilizing the Interactive Surface Design Extension (ISDX) module of Pro/ENGINEER, the 3D face model was manually adapted to these images utilizing a mesh-surface altering feature of the software, Figure 4-5. This feature allowed the initial neutral face to be altered into each of the basic emotions. The skin in the face model was stretched from the initial neutral position of each control node to its final position based on the equivalent direction and displacement as the 2D images. The respective control points were identified on each neutral position facial image as local motion (deformation) parameters to track the activation and motion of the defined muscle groups during the display of each of the basic emotions, Figure 4-5.

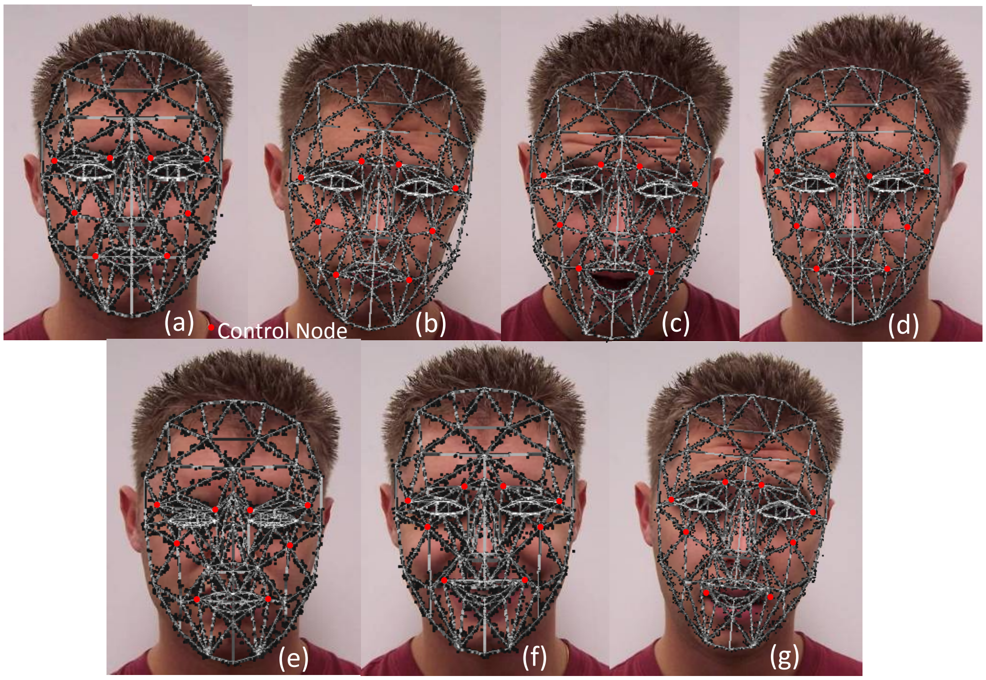

Figure 4-4: Six basic expressions: (a) neutral, (b) sad, (c) surprise, (d) angry, (e) disgust, (f) happy, and (g) fear.

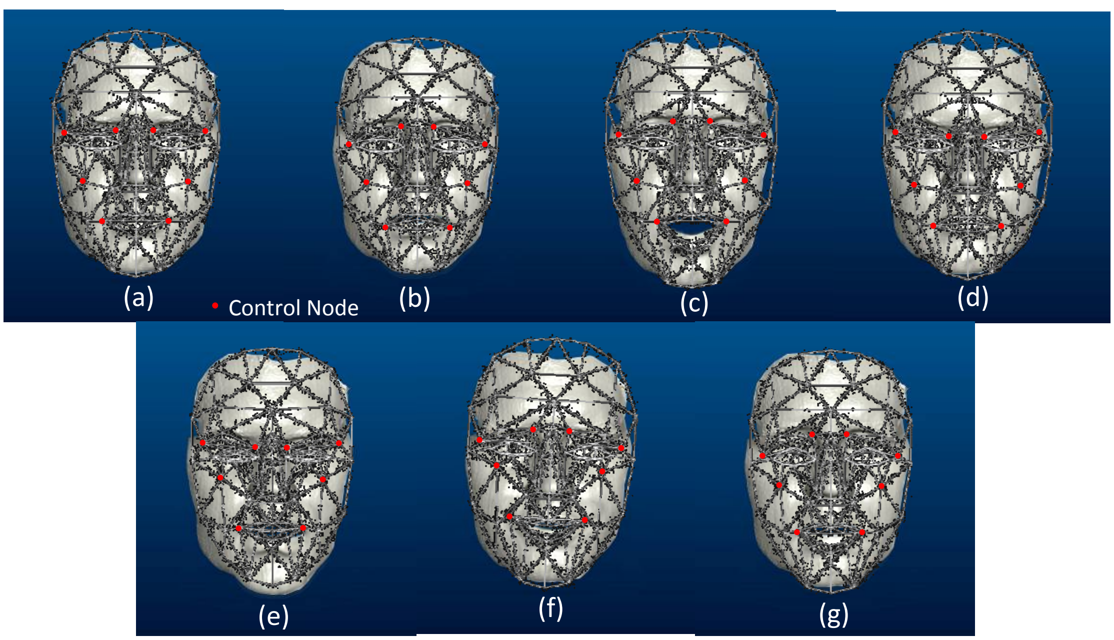

Figure 4-5: 3-D CAD Simulations Based on Measured Control Node Placement: (a) neutral, (b) sad, (c) surprise, (d) angry, (e) disgust, (f) happy, and (g) fear.

The observed *average* human facial motion was utilized to determine the corresponding nodal movements for the human-like robotic face by calibrating the global and local motion parameters of the robotic head to the observed human heads. Since the robot's main purpose is to interact with humans from varying age groups, it is important to ensure that its facial expressions are clearly implemented. In this work, the determined nodal displacements are multiplied by a safety factor to allow for the distinction between the different facial expressions. The calculated nodal displacements for the six emotions are summarized for each pair of nodes in Table 4-1.

Table 4-1: Required Displacements of Control Nodes

Facial Expression	**Control Node**	**Required Displacement (cm)**
Happy	1,2(up)	0.37
	3,4(up)	0.72
	5,6(down)	0.23
	7,8 (up)	0.29
	9,10(open)	0.18
Sad	1,2(down)	0.23
	3,4 (down)	0.03
	5,6 (down)	0.29
	7,8(up)	0.29
	9,10 (open)	0.03
Angry	1,2 (down)	0.11
	3,4 (down)	0.06
	5,6 (up)	0.07
	7,8 (down)	0.18
	9,10(open)	0.00
Surprise	1,2 (up)	0.00
	3,4 (up)	0.00
	5,6 (down)	0.20
	7,8(up)	0.29
	9,10(open)	0.72
Fear	1,2 (up)	0.09
	3,4 (up)	0.29
	5,6 (down)	0.29

	7,8(up) 9,10(open)	0.40 0.40
Disgust	1,2 (up) 3,4 (up) 5,6 (up) 7,8 (down) 9,10(open)	0.20 0.57 0.11 0.18 0.06

4.3 Actuation Mechanism

Since muscle groups 1-3 have similar translational motion, they utilize the same type of actuation mechanism, whereas muscle group 4 is actuated together with the jaw muscles. Figure 4-6 shows these muscle groups and their corresponding control nodes on the physical robotic face. In this section the developed actuation mechanism will be described.

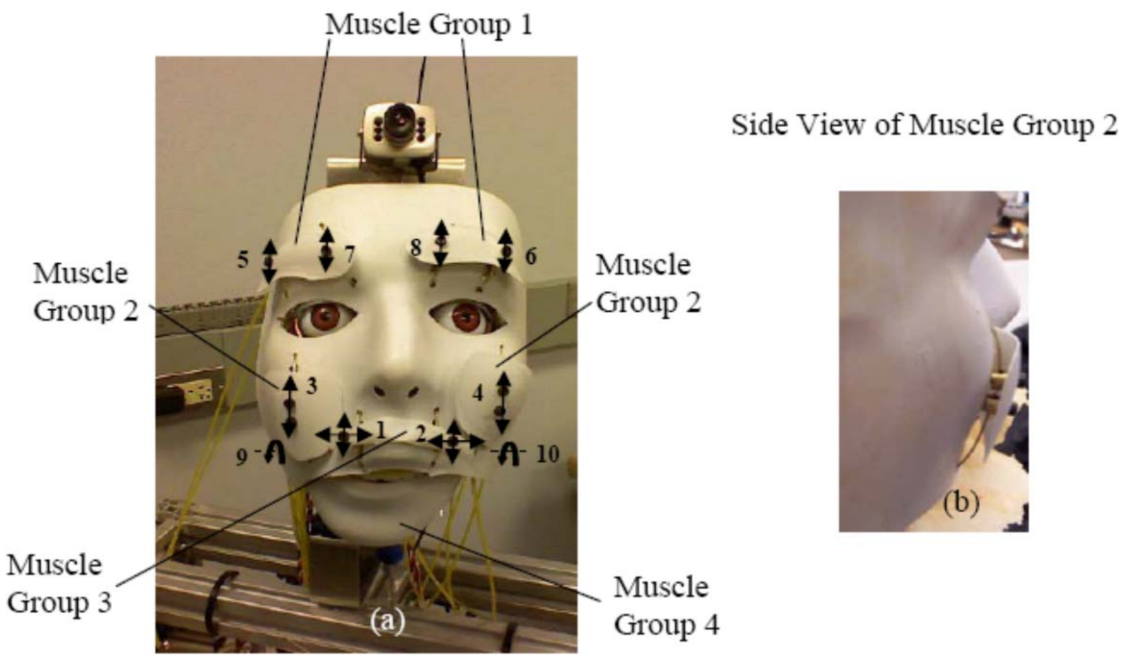

Figure 4-6: Robot Muscle Structure and Corresponding Control Nodes.

Muscle Groups 1-3: The actuation mechanism for these muscles consists of a pivoting cable linkage system. The cables are attached to each control node and to both sides of a double arm lever which pivots at its center via a servomotor, Figure 4-7(a).

This lever mechanism is utilized to provide the necessary actuation of a control node. Each control node is further attached to a muscle guide (a bolt) which moves the muscle in the direction of the desired actuation along a slotted track in the face mask, Figure 4-7(b) and (c). This ensures that the muscle will move in the appropriate direction in a controlled manner and not exceed the desired maximum displacement.

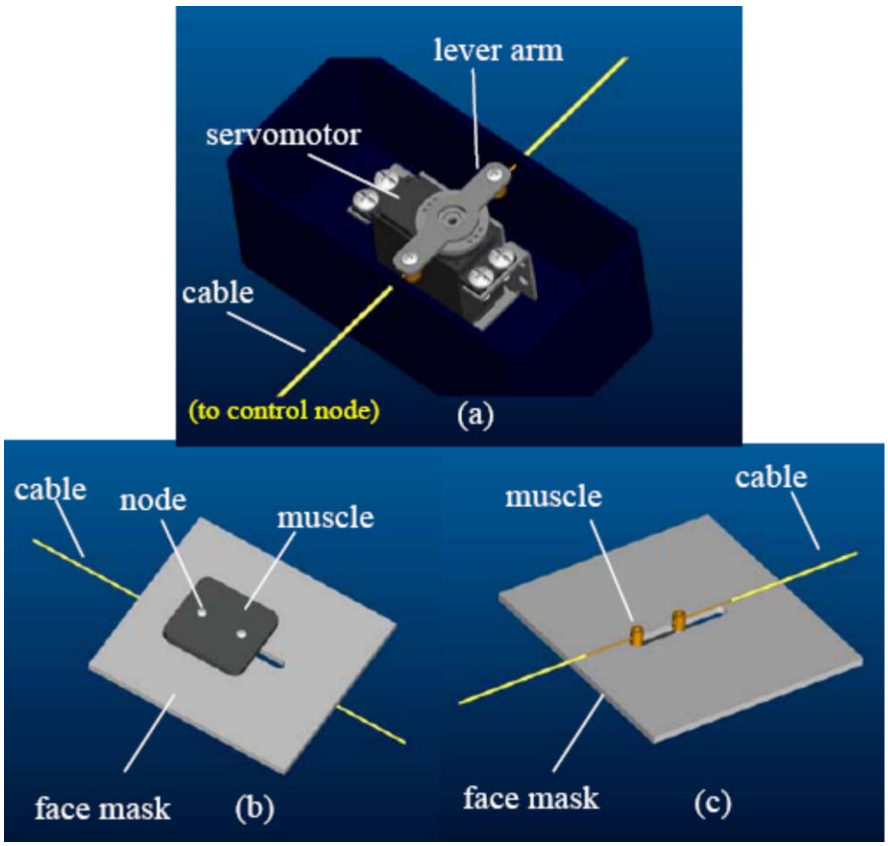

Figure 4-7: Actuation Mechanism: (a) lever mechanism, (b) top view of track system, and (c) bottom view of track system.

Utilizing the nodal displacement (magnitude and direction) results in Table 4-1 and the location of nodes on the face, a dependency relationship has been determined between nodes 1 to 4 and 5 to 8, namely:

$$\boldsymbol{x}_{1,2} = f(\boldsymbol{x}_{3,4}), \text{ and} \tag{4.1}$$

$$\boldsymbol{x}_{5,6} = f(\boldsymbol{x}_{7,8}) \quad . \qquad (4.2)$$

Each lever actuation mechanism is capable of controlling a set of four control nodes and is used to provide actuation in 2D or 3D space. The overall actuation system consists of a total of four lever mechanisms. Mechanisms 1 and 2 actuate nodes 1 through 4 and Mechanisms 3 and 4 actuate nodes 5 through 8. The configuration for Mechanisms 1 and 2 consists of the actuation of symmetric nodes 1 and 2 by one lever arm and the actuation of symmetric nodes 3 and 4 by the other lever arm. Similarly for Mechanisms 3 and 4, actuation of symmetric nodes 5 and 6 is by one lever arm, while actuation of symmetric nodes 7 and 8 is by the other lever arm. For all mechanisms, symmetric nodes on the face are connected to one lever arm due to the fact that in order to generate the six basic emotions, these nodes need to be actuated in the same direction for the same amount of displacement. Two mechanisms are utilized to control each node in order to mimic expansion and contraction of the muscles and are attached to each node in an opposite directional configuration. Ideally, when one mechanism pulls a control node in an upward direction, the other pushes in the same direction. This allows a push/pull motion at each node due to both mechanisms acting simultaneously, and ensures smooth realistic movements, prevents binding and provides more natural expressions of the face.

There are several benefits in utilizing the proposed mechanism configuration, in particular: (i) the actuation dependency of respective control nodes allows for a more realistic/lifelike human expression, (ii) controlling four nodes simultaneously via one mechanism minimizes the complexity of the overall hardware design, and (iii) having only four actuation mechanisms in total reduces the size and power requirements of the actuation system.

In comparison to the robotic face actuation techniques presented in the literature, the proposed design is the *only one* that utilizes the dependency of muscle activity to minimize the number of actuators. The majority of robotic faces developed in the literature have mainly consisted of using a separate actuator for each node on the face where motions of the nodes have only been linked via programming [22, 32, 35, 39-42].

Muscle Group 4: The control nodes of the lower mouth (9, 10) are actuated with the jaw in a pivoting manner in order to allow for movement in 3D space. In particular, when the jaw rotates to an open mouth position, it does so by utilizing two servo motors connected at its pivoting points.

4.4 Control of Nodal Displacements

In order to achieve the desired nodal displacements for each emotion utilizing the proposed actuation mechanism for muscle groups 1-3, the required lengths of each lever arm, *L*, need to be specified, Figure 4-8. As can be deduced from Table 4-1, in general, dependent nodal pairs (i.e., 1, 2 and 3, 4) attached through cables to a lever arm on each side of the servo horn do not move the same distance to generate a specific emotion. By defining non-symmetric lever arm lengths on either side of the servo horn, both pairs of control nodes may be controlled from one servomotor. The length of each corresponding lever arm is a function of the average node displacements and their dependency, i.e:

$$L_{i,j} = avg\left(\frac{\boldsymbol{x}_{i,j}}{\boldsymbol{x}_{m,n}}\right) \times L_{m,n}, \qquad (4.3)$$

where i, j, m and n represent the dependent nodes and x represents the required displacements of these nodes.

The actual linkage length, L, is based on the maximum required displacement, $x_{\max}$, of each node set, i,j and m,n, and the maximum actuation angle of the motor, $\gamma_{\max}$, i.e.:

$$L_{i,j} = \sqrt{\frac{x_{i,j\max}^2}{2 - 2\cos\gamma_{\max}}} \quad (4.4)$$

$$L_{m,n} = \sqrt{\frac{x_{m,n\max}^2}{2 - 2\cos\gamma_{\max}}} \quad (4.5)$$

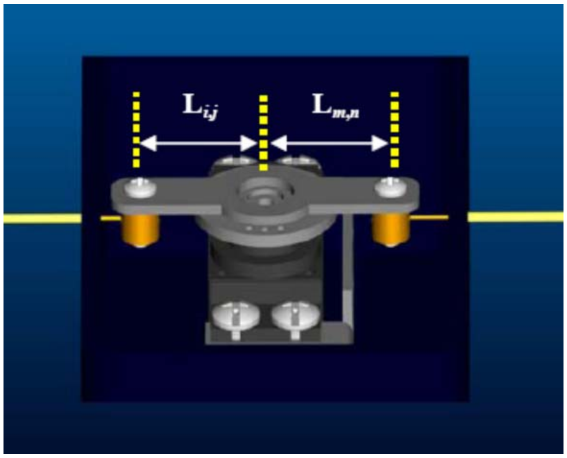

Figure 4-8: Lever Arms of the Actuation Mechanism.

Another important design parameter is the required torque needed to deform the skin by the maximum nodal displacements. This torque is the minimum torque required to actuate the skin and is defined as:

$$\mathbf{T} = \mathbf{F}_{\mathbf{max}} L_{\max} \quad , \quad (4.6)$$

where F_{max} is the maximum required actuation force and L_{max} is equal to the maximum lever arm length.

As can be denoted from Figure 4-9, when x is at point x_o the skin element is in its fully relaxed state. The displacement dx is dependent on the angular rotation of the lever arm L:

$$dx = Ld\theta \quad , \qquad (4.7)$$

where dθ is the change in the angle of rotation of the lever arm attached to servomotor i. Since the material of the skin exhibits elastic behavior, Hooke's Law is utilized to approximate the change in applied force, dF, to the skin:

$$d\mathbf{F} = kLd\theta \quad , \qquad (4.8)$$

where k is the elastic constant of the skin material.

F_{max} is then defined to be:

$$\mathbf{F}_{max} = \int_0^{\theta_{max}} d\mathbf{F} = kL_{max} \int_0^{\theta_{max}} d\theta \quad , \qquad (4.9)$$

where θ_{max} is the pre-determined value that depends on the desired nodal displacement.

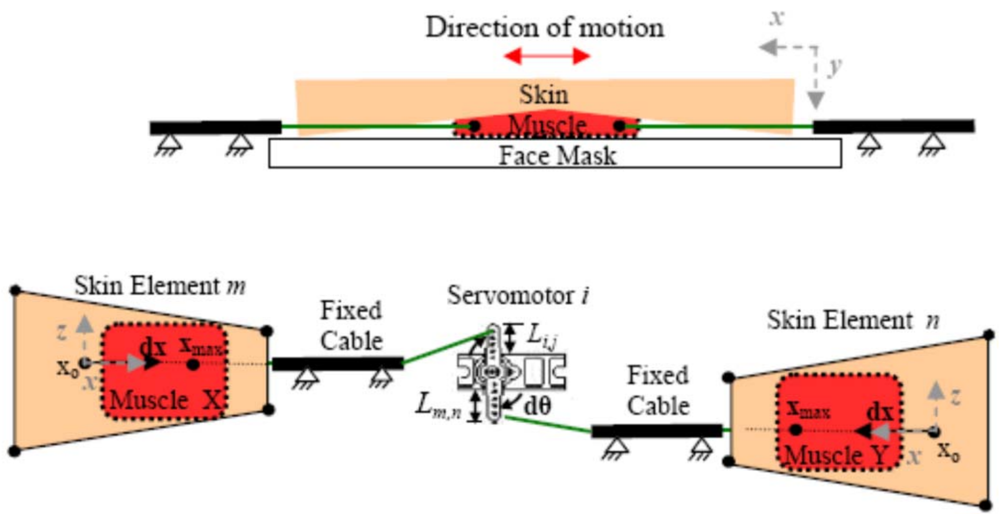

Figure 4-9: Muscle Actuation.

By utilizing the aforementioned model, the minimum torque required to fully actuate the skin was determined to be approximately 850 N-mm. Next, the most appropriate type of actuator had to be selected, which required the consideration of several parameters. The main parameters considered were: (i) size, (ii) power requirements and (iii) control precision. When considering the size of the actuator, although the mechanism design allows remote mounting, it still must be able to fit within the torso. The power must also be considered, as it is desired to keep power draw to a minimum. Finally, control of the actuator must be considered, since it is necessary to actuate the linkage at specific angles in order to display the emotions desired accurately. According to these requirements there are not many options as hydraulic and pneumatic can provide the necessary torque, but their cost, bulky size and high power requirements make them undesirable. Smaller linear actuators were another option, as they are commonly used in this type of application. Usually they are selected because their small size allows them to fit behind the face. Although these are fairly precise and within the size constraints, they lack the torque required to actuate multiple nodes simultaneously as this mechanism is designed to do. Unfortunately these actuators are typically used to actuate one node each. This leads to the consideration of the servomotor, which was the type selected earlier to actuate the head structure. The parameters required for the face mechanism actuator are similar to that of the structure actuator, therefore making this type of motor appear to be the ideal candidate. As mentioned earlier, servomotors are compact, include feedback position sensors for precise motion, require little power and are capable of providing sufficient torque for this application. Since this appears to be the best option, a Hitec HS-5645MG servomotor was chosen of the mechanism, which can provide up to 1186 N-mm of torque (well beyond the minimum torque required).

Table 4-2: Hitec Servo Specifications

Hitec Model	HS-5645MG
Head Component(s) Used to Actuate	Skin
Hitec Part#	35645S
Description	High Torque Digital
Torque (4.8V/6.0V) N-mm	1010/1186
Speed (4.8V/6.0V) sec/90 degrees	0.23/0.18
Bearing	Dual BB
Gear Type	Metal
Length (mm)	40.39
Width (mm)	19.56
Height (mm)	37.59
Weight (N)	0.59

The overall mechanism design can be seen in Figure 4-10, demonstrating the function of the mechanical dependency between node sets.

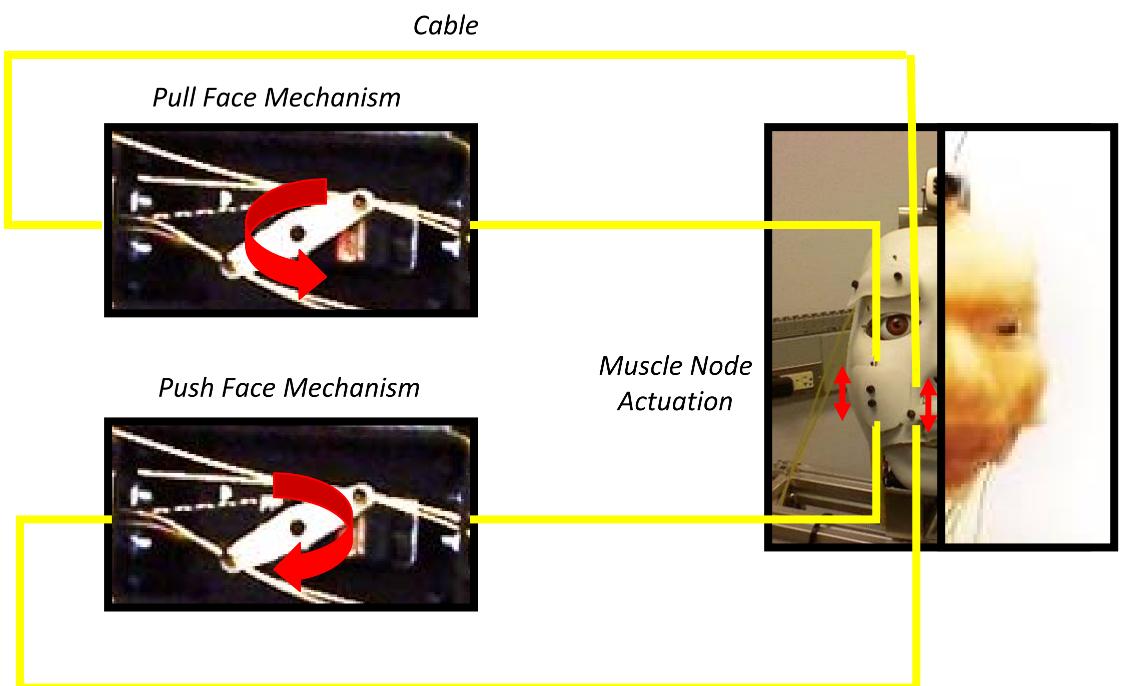

Figure 4-10: Diagram of Face Actuation System Actuating Nodes 1 and 3.

Chapter 5 Experiments

5.1 Experimental Set-Up

The preliminary experiments consisted of an evaluation of the performance of the overall anthromorphic robotic face. For the purposes of the experiments the head was installed on a human-like robot body. Several experiments were performed including these which involved: (i) the physical motion of the control nodes that were experimentally observed and compared to those determined in Section 4.2, and (ii) an interaction scenario between a human and the robotic head that was created, where the human was asked to identify the emotions that the face was displaying during a one-on-one conversation.

5.2 Analysis of Robot Expressions

During these experiments the robotic face displayed each of the six basic facial expressions, Figure 5-1, via actuation of the appropriate control nodes, as seen in Figure 4-3. The SSC-32 servo controller was connected to a PC via a RS232 cable allowing independent control of each servo simultaneously. Visual Studio Automation (VSA), graphical servo programming software, was used to program the servos in the head and face to display each emotion.

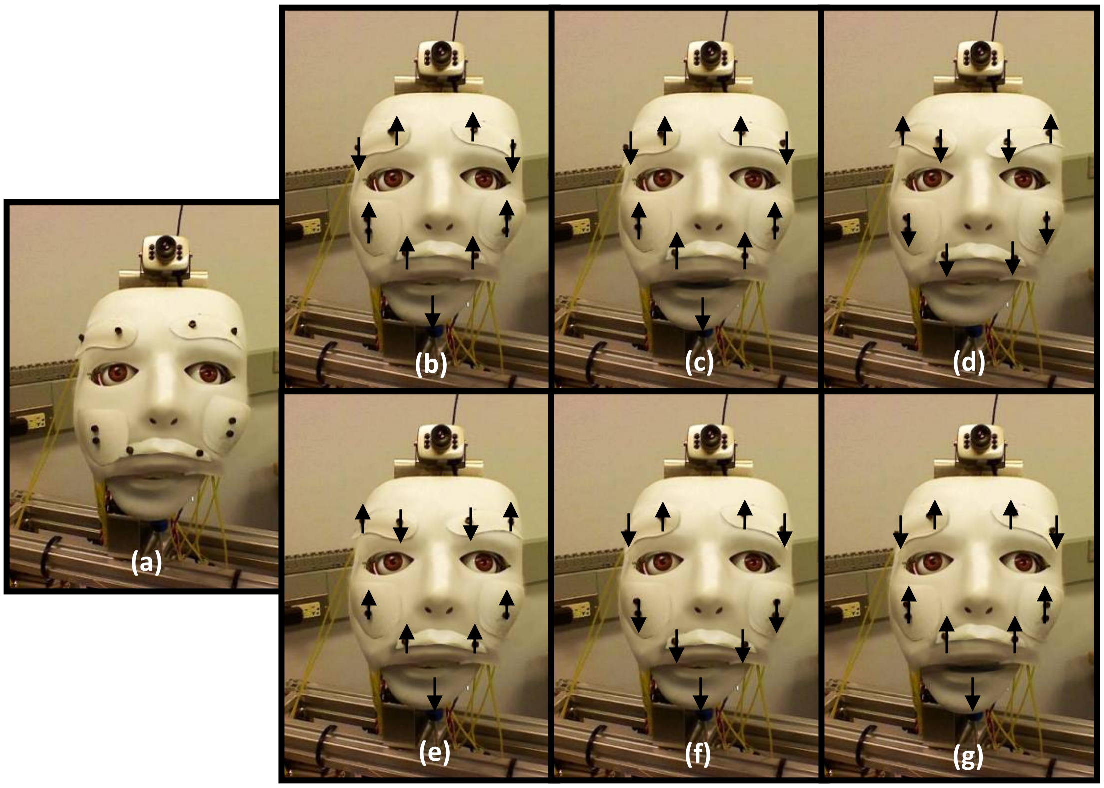

Figure 5-1: Robot Emotional State (w/o skin) with Direction of Node Movement Indicated (a) neutral, (b) happy, (c) surprise, (d) angry, (e) disgust, (f) sad, and (g) fear.

The servomotors used in each face actuation mechanism are initially in a neutral position. From this neutral position, each servo has a range of 45 degrees of rotation in either direction. The appropriate actuation angle, γ, for each node set was calculated for each emotion via the following formulas:

$$\gamma_{i,j} = \cos^{-1}\left[1 - \frac{\left(\frac{x_{i,j}}{L_{i,j}}\right)^2}{2}\right] \qquad (5.1)$$

$$\gamma_{m,n} = \cos^{-1}\left[1 - \frac{\left(\frac{x_{m,n}}{L_{m,n}}\right)^2}{2}\right] \qquad (5.2)$$

where x is the required distance traveled for each node set obtained from Table 4-1, L is the linkage length for each node set, while $_{i,j}$ and $_{m,n}$ represent the two sets of nodes actuated by each mechanism. This calculation provides the exact angle necessary for the required displacement of each node set. Since both sets of nodes are actuated by the same mechanism, they are mechanically linked and must actuate at the same angle for the given emotion. The actuation angle, θ_x, for each face actuation mechanism for each emotion was then calculated by taking an average between the actuation angle of each node set, Table 5-1.

$$\theta_x = \frac{\gamma_{i,j} + \gamma_{m,n}}{2} \qquad (5.3)$$

Table 5-1: Actuation angle of each face mechanism servo.

Emotion Displayed	**Mechanism 1 Actuation Angle**	**Mechanism 2 Actuation Angle**	**Mechanism 3 Actuation Angle**	**Mechanism 4 Actuation Angle**
Happy	+45.00°	-45.00°	+33.78°	-33.78°
Sad	-14.68°	+14.68°	+38.61°	-38.61°
Angry	-8.36°	+8.36°	-15.22°	+15.22°
Surprise	0.00°	0.00°	+31.41°	-31.41°
Fear	+14.21°	-14.21°	+45.00°	-45.00°
Disgust	+29.57°	-29.57°	-18.26°	+18.26°

The appropriate angles were then entered into the VSA software for each servo for each emotion desired. The displacement of each node was determined by measuring the distance traveled by each muscle. In order to accurately make the appropriate measurements, the experiment was performed prior to installation of the skin, Figure 5-1. The actual displacement of each node was then compared to the required displacement determined in Table 5-2.

Table 5-2: Comparison of Required and Measured Displacements of Control Nodes

Facial Expression	Control Node	Required Displacement (cm)	Actual Displacement (cm)
Happy	1,2(up)	0.37	0.37
	3,4(up)	0.72	0.72
	5,6(down)	0.23	0.22
	7,8 (up)	0.29	0.30
	9,10(open)	0.18	0.18
Sad	1,2(down)	0.23	0.12
	3,4 (down)	0.30	0.24
	5,6 (down)	0.29	0.25
	7,8(up)	0.29	0.35
	9,10 (open)	0.03	0.03
Angry	1,2 (down)	0.11	0.07
	3,4 (down)	0.06	0.14
	5,6 (up)	0.07	0.10
	7,8 (down)	0.18	0.14
	9,10(open)	0.00	0.00
Surprise	1,2 (up)	0.00	0.0
	3,4 (up)	0.00	0.0
	5,6 (down)	0.20	0.21
	7,8(up)	0.29	0.28
	9,10(open)	0.72	0.72
Fear	1,2 (up)	0.09	0.12
	3,4 (up)	0.29	0.23
	5,6 (down)	0.29	0.29
	7,8(up)	0.40	0.40
	9,10(open)	0.40	0.40
Disgust	1,2 (up)	0.20	0.25
	3,4 (up)	0.57	0.48
	5,6 (up)	0.11	0.12
	7,8 (down)	0.18	0.17
	9,10(open)	0.06	0.06

As can be seen from Table 5-2, the actual nodal displacements are comparable to the required displacements. The actual nodal displacement for Happy, Fear, Disgust and Surprise facial expressions were the closest to the required displacement. The actual node displacements for Happy, Fear, Disgust and Surprise facial expressions were within an average percent error of +/- 0.18%, +/- 2.53%, +/- 2.55%, +/- 0.31%, respectively. This is due partially to the fact that the linkage lengths were calculated based on the maximum displacement of nodes. For these particular expressions, the maximum displacement of node sets 1,2 and 3,4 are required simultaneously for Happy, while the maximum displacement of node sets 5,6 and 7,8 are required simultaneously for Fear. In addition, there is zero displacement of node sets 1,2 and 3,4 for Surprise, which is mimicked by not actuating those mechanisms. As a result, the actual displacements were comparable to the required displacements for these node sets. In addition, it may be observed that the actual and required displacement of node set 9,10 is always comparable as well. This is due to the individual control of the jaw mechanism, which actuates independent of mechanisms 1 through 4. These are the only nodes on the face that actuate independently.

The actual nodal displacements for the emotions Angry and Sad were slightly less accurate than the previously mentioned emotions. In particular, the actual nodal displacements for the emotions Angry and Sad were within an average percent error of

+/- 23.52% and +/- 12.19% of the required nodal displacements. Due to the mechanical dependency between specific node sets, some discrepancies are to be expected within reason. The proportion established in equation (4.3) of chapter 4 indicates that node set 1,2 will always have a lower displacement than node set 3,4, while node set 5,6 will always have a lower displacement than node set 7,8. The reverse of this relationship is required by the node displacement of the expression for Sad, therefore resulting in the least accurate actual node displacement. Overall, the average percent error for the actual nodal displacements is +/- 26.76% of the required nodal displacements. Most of the results are either identical or fairly close to one another as indicated in Table 5-2. This demonstrates the effectiveness of the proposed muscle actuation system based on nodal dependence.

5.3 Robot Emotion Interpretation

In this experiment, the robotic head displayed several facial expressions to convey its emotions during one-to-one interaction with a human, Figure 5-2. Although the focus of the experiment is on the head, in order to facilitate a more natural interaction the robot also made body gestures that correlated with the face expressions. 10 students in our lab participated in the experiments ranging in age from 16 to 30 years old. During interaction, each person was asked to interpret and identify the robot's overall expressions into the six basic emotions. The objective of this experiment was to determine if the robot's intended expressions could be directly interpreted by a human.

Figure 5-2 depicts the robot’s neutral facial expression (which was used as the reference point) and the robot’s facial expressions as it displays the six basic emotions during interaction. Table 5-3 summarizes the recognition results.

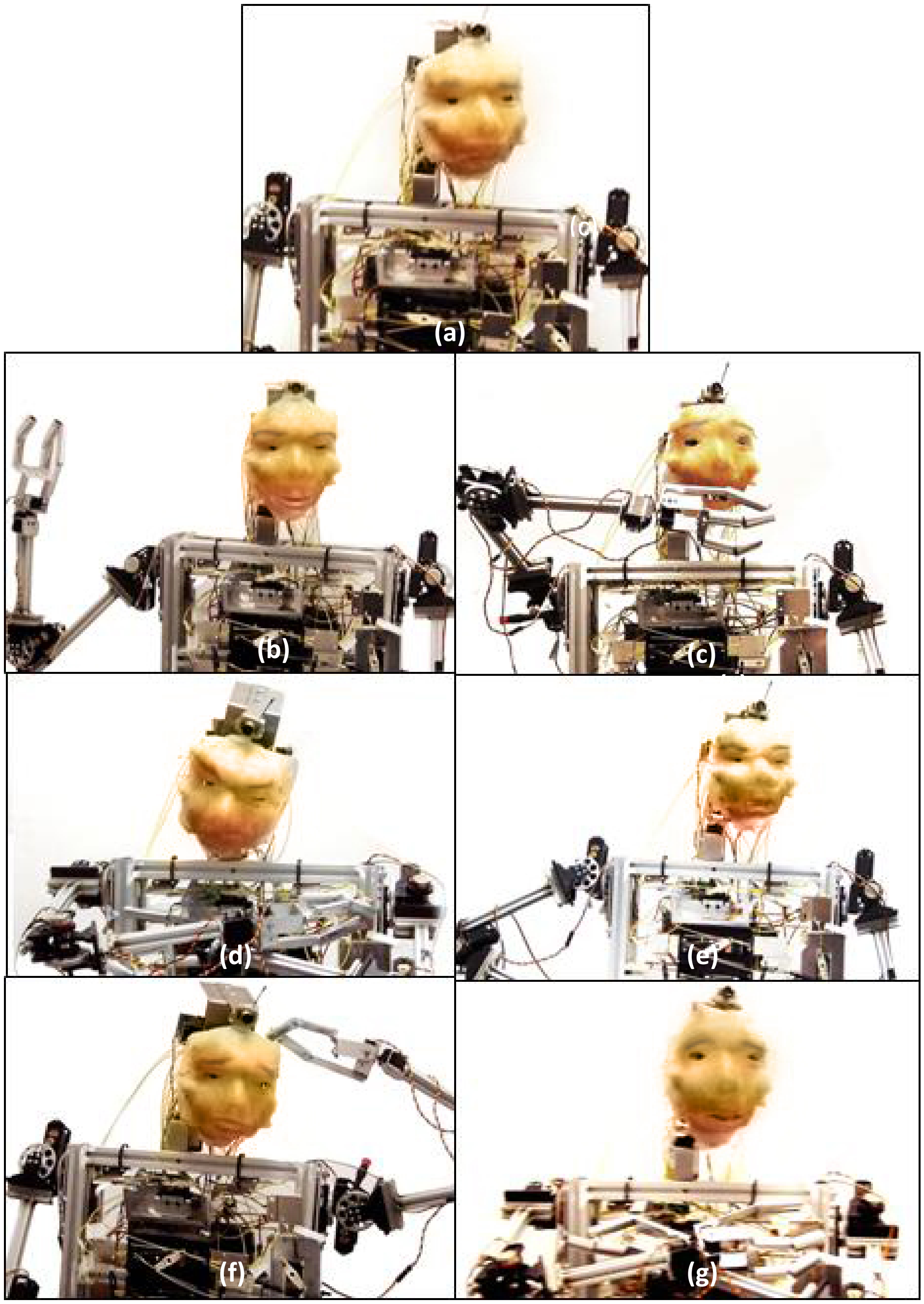

Figure 5-2: Robot Emotional State (w/ skin) (a) neutral, (b) happy, (c) surprise, (d) angry, (e) disgust, (f) sad, and (g) fear.

Table 5-3: Recognition Results from Human-Robot Interaction

	Recognized Emotions					
Implemented Emotions	Happy	Sad	Angry	Surprise	Fear	Disgust
Happy	10					
Sad		10				
Angry			8			2
Surprise				10		
Fear					10	
Disgust			2			8

The results demonstrate that during interaction with the robot, the humans were able to identify the robot's emotions with a 93% recognition rate. These results verified that when this type of head is paired up with an expressive human-like robotic body, the expressions of each emotion are highly recognizable. The only small discrepancy was between the two emotions of angry and disgust. In general, on synthetic faces, these two emotions have been shown to be difficult to tell apart [i.e., 22, 43]. The reason for this confusion can be seen slightly clearer when observing the actual and required displacements for these expressions in Table 5-2. The actual and required displacements for node sets 5,6, 7,8 and 9,10 for each emotion are within 0.06 cm of one another. The close proximity in node displacement of three out of five of the node sets for these particular expressions is more than likely responsible for their confusion with one another. Due to these factors demonstrating the similarities between the two expressions, it is understandable to have results of this nature.

Chapter 6 Conclusions

6.1 Summary of Contributions

The primary contributions of this work are summarized below.

6.1.1 Architecture of Skeletal Structure

Chapter 3 presents the unique design of the basic components of a robotic head structure. The main components of the robotic head are the skeletal frame, face mask and actuation mechanisms. The skeletal frame is the basic supporting structure for all other components within the head. This frame is designed based on the joint placement and dimensions of an average male human head. The design of the skeletal frame is to serve two purposes: (i) support the weight of the overall robot head, and (ii) provide an overall shape to the head that is life-like. This strategy ensures that the mounting of the eye mechanism and teeth, two critical components of the head, will be in the appropriate location to achieve the most anthromorphic appearance possible. The next component is the face structure, which is composed of a face mask. The mask consists of a rigid, light-weight, plastic material which acts as a support for the face muscles and skin. The contours of the mask allow the skin to rest in a manner so that the face maintains a human-like demeanor even after it is stretched across it. The final component that is responsible for the life-like movement of the head are the servo motors. To keep movement as realistic as possible the head possesses 7 DOF. The head can turn left and right, up and down, and tilt left and right. In addition to this the jaw can open and close and the eyes can turn left and right, up and down, and blink. Each of these DOF are actuated by a servo motor. Each servomotor is attached to a Lynxmotion SSC-32 servo controller board, which receives signals from a PC.

6.1.2 Facial Expressions

In this thesis, human face muscles are utilized to develop an effective robotic facial expressions actuation system. The human face consists of many muscle groups in a complex manner. The novelty of this design involves developing a simplification of the human muscle structure as well as indicating similarities in motion between muscle groups and then in turn using this model to create a new type of face actuation system.

In order to simplify the muscle structure of the robotic face, muscles were grouped together based on their location and function. In particular, four muscle groups, eyebrows, checks, mouth and jaw were determined to be needed to actuate the face appropriately to display the six basic emotions that humans express happy, sad, surprise, fear, angry and disgust. The former 3 groups exist in pairs on the robotic face. Control nodes within these muscle groups were identified and actuated in combination to display the required expression.

A unique muscle actuation system was developed to mimic the necessary human facial expressions. Based on a dependency between the movement of the control nodes within the muscle groups, a simplified unique actuation system was proposed consisting of four servomotors and a lever-cable actuation mechanism.

6.1.3 Implementation

Preliminary experiments were conducted to verify the effectiveness of the design of the robotic head. For the first experiment, the actual displacement of each muscle node was determined. These results were compared to the required measurements determined based on the 2D images of each of the basic emotions. The proximity of the actual node displacement to the required node displacement verifies the performance of the facial expression mechanism. The second experiment involved one on one interaction between a human and the robot, where the robot expressed each of the six basic emotions. Ten students in our laboratory interacted with the robot and were then asked to identify each emotion. Overall there was a 93% recognition rate of the implemented emotions. Disgust and fear were the most commonly confused, but overall results verified the effectiveness of the design.

6.2 Discussion and Future Work

This design of a robotic head has potential for use in many assistive robot applications. The slotted face mechanism used to mimic muscle actuation, as well as the remotely mounted servomotor based actuators linked by cables, worked as intended.

This design proved effective with an average +/- 26.76% error between the actual and required node displacement, as well as a 93% facial expression recognition rate overall. These experimental results verify the effectiveness of this unique design. Although this robotic head has met the standards desired by its original design, a few issues were indicated by the results of the experimental phase. This data can be used to improve the overall robotic head design and efficiency of the experiments to ensure that future versions are optimized for the performance required.

In the first experiment presented, only the difference in displacement between the actual motion and required motion of each node was considered to evaluate the performance of the mechanism. Although this performed as expected, the results of the second experiment established a slight lack of recognition by a couple students between angry and disgust, as the muscle node direction and displacement is very close for these two emotions. Even with the muscle node displacement exaggerated slightly by a safety factor. There are a couple items that may be responsible for this lack of actuation. One issue may be that the muscle actuation is not translating completely through the silicone-rubber skin. If the outer surface of the skin is ultimately not moving as much as the muscle, the subject interacting with the robot does not observe the actual performance of the mechanism, therefore decreasing the recognition rate. Another possible issue is that there is some loss of muscle actuation via the cable between the face actuation mechanism and muscle node. This may be creating an additional lack of displacement of the muscle group.

Future work should focus on further development of the skin material. Use of a more elastic material that is more form fitting to the contours of the face structure and muscle nodes would aid in the visible performance of the face. The method by which the skin is adhered to the face structure could also be improved to allow creasing of the face in particular areas to emphasize specific emotions. Overall the mechanical design of the robotic head and face mechanism, which is the focus of this thesis, performed as intended. After some improvement of the skin material, the displacement that is lost through the skin per unit length must be considered. Another potential improvement to the design of the mechanism is to determine a closer mounting location of the actuation mechanism. Although the current location of the actuation mechanism is most convenient for mounting within the torso of the robot used for the experiment, future robots that the head is mounted to should be designed to allow closer mounting. This will allow use of shorter cables between the actuation mechanism and muscle node, therefore decreasing the loss of actuation. In addition to this, the loss of actuation per unit length of cable must be taken into consideration. Bearing this in mind will allow a more accurate recalculation of the required displacements, which could then be used to recalculate the linkage lengths via the same method as presented in this thesis. Once the skin and actuation mechanism location is redesigned, future experiments should also take into consideration the amount of time it takes the subject to recognize each emotion. This would give a better evaluation of the performance of each emotion by the robotic head.

6.3 Final Concluding Statement

In this thesis, an anthromorphic robot head was developed as a potential social interface for human-robot interaction. The novelty of the robotic head is the mechanism designed for actuation of the facial muscle control nodes. Its design is based on an observed relationship between certain facial muscle groups on the face and their interaction together to display certain facial expressions. In order to keep the complexity of the overall design as simple as possible, the minimum number of actuating mechanisms was used. Based on the similarities in motion between certain muscle groups, it was determined that no more than four actuating mechanisms were required to actuate the entire face as necessary. Experiments show that the mechanism actuates the muscle nodes as intended generating a highly recognizable human-like robot expression. Future work will include further development of the skin material and attachment method, as well as consideration of the loss of muscle node displacement through the thickness of the skin and cable length, in-turn optimizing the recognition performance of the mechanism.

References

[1] S. R. Kunkel and R. A. Applebaum, “Long-term Care For The Boomers: A Public Policy Challenge for the Twenty-first Century,” Prepared for the Office of the Assistant Secretary for Planning and Evaluation, U.S. Department of Health and Human Services, pp. 1-18, 1991.

[2] M. Nies, G. Nejat, Y. Sun, and T. Sexton, “A Multidisciplinary Team Program of Research with Interactive Nurse Robots to Enhance Elderly Health,” Sigma Theta Tau Int. Nursing Research Congress Focusing on Evidence-Based Practice, Vienna, Austria, 2007.

[3] M. Montemerlo, J. Pineau, N. Roy, S. Thrun, V. Verma, “Experiences with a mobile robotic guide for the elderly,” in Proceedings of the National Conference on Artificial Intelligence, Vol. 18. pp 587-592, 2002.

[4] M. Blow, K. Dautenhahn, A. Appleby, C.L. Nehaniv, and D. C. Lee, “Perception of Robot Smiles and Dimensions for Human-Robot Interaction Design,’ International Conference on Rehabilitation Robotics, 337-340, 2005.

[5] K. Freedman, S. Mataric, M.J. Cunningham, and M.J. Lopez, "A Hands-off Physical Therapy Assistance Robot for Cardiac Patients," IEEE International Conference on Rehabilitation Robotics, pp. 337-340, Chicago, IL, 2005.

[6] A. Libin, E. Libin, “Person–robot interaction from the robopsychologists point of view: The robotic psychology and robotherapy approach,” Proceedings of Institute of Electrical and Electronics Engineers, Vol. 92, pp. 1789–1803, 2004.

[7] T. Shibata, “An overview of human interactive robots for psychological enrichment,” in *Proceedings of Institute of Electrical and Electronics Engineers*, November 2004.

[8] T. Shibata, K.Wada, T. Saito, K. Tanie, “Robot assisted activity for senior people at day service center,” in Proceedings of the International Conference on Information Technology in Mechatronics, pp. 71–76, 2001.

[9] J. Koehn. "Trend: Robo Pets." CScout 12 January 2007. <http://www.cscout.com/blog/2007/01/12/trend-robo-pets.html>.

[10] M. Heerink, B. Kröse, B. Wielinga, V. Evers, “Human-Robot User Studies in Eldercare: Lessons Learned,” Assistive Technology Research Series, Vol. 19, 2006.

[11] K. Sato, M. Ishii, H. Madokoro, “Testing and Evaluation of a Patrol Robot System for Hospitals,” Electronics and Communications in Japan (Part III: Fundamental Electronic Science), Vol. 86, Iss. 12, pp. 14-26, 2003.

[12] M. López, R. Barea, L. Bergasa, M. Escudero, "A Human-Robot Cooperative Learning System for Easy Installation of Assistant Robots in New Working Environments," Journal of Intelligent and Robotic Systems, Vol. 40, No. 3, pp. 233-265, 2004.

[13] N. Roy, G. Baltus, D. Fox, F. Gemperle, J. Goetz, T. Hirsch, D. Magaritis, M. Montemerlo, J. Pineau, J. Schulte, S. Thrun, "Towards personal service robots for the elderly," in Proceedings of the Workshop on Interactive Robotics and Entertainment (WIRE), Pittsburgh, PA, 2000.

[14] Massachusetts Institute of Technology. "Futuristic Robot Adapts To People, New Places." ScienceDaily 11 April 2007. 4 April 2009 <http://www.sciencedaily.com /releases/2007/04/070411124418.htm>.

[15] C. Bartneck, M. Okada, " Robotic User Interfaces," Proceedings of the Human and Computer Conference (HC2001), Aizu pp. 130-140, 2001.

[16] LCD Monitor. "LCD Monitor Disadvantages," <http://www.lcdmonitor.org/article/general-information/lcd-monitor-disadvantages.html>.

[17] J. Yeung, D. I. Fels, "A Remote Telepresence System for High School Classrooms," Canadian conference on Electrical and Computer Engineering, Vol. 1, Iss. 4, pp. 1465-1468, 2005.

[18] M. Dragone, B.R. Duffy, T. Holz, G.M.P. O'Hare, "Fusing Realities in Human-Robot Social Interaction," Proccedings of the Joint Conference of the 37th International Symposium on Robotics (ISR 2006), Munich, Germany, 2006.

[19] N. Luna. "Robot a new face on geriatric care." OCRegister.com 6 August 2003. <http://www.ocregister.com>.

[20] C. Breazeal, "Robot in Society: Friend or Appliance?" In Agents 99 Workshop on Emotion-Based Agent Architectures, Seattle, pp. 18-26, 1999.

[21] D. Miyauchi, A. Sakurai, A. Nakamura, Y. Kuno, "Active Eye Contact for Human-Robot Communication," Conference on Human Factors in Computing Systems, Vienna, Austria, pp. 1099-1102, 2004.

[22] T. Hashimoto, S. Hitramatsu, T. Tsuji and H. Kobayashi, "Development of the Face Robot SAYA for Rich Facial Expressions," SICE-ICASE International Joint Conference, Bexco, Korea, pp. 5423-5428, 2006.

[23] P. J. Hinds, T. L. Roberts, H. Jones, "Whose Job is it Anyway? A Study of Human-Robot Interaction in a Collaborative Task," Human-Computer Interaction, Vol. 19, Iss. 1, pp. 151-181, 2004.

[24] B. Reeves, C. Nass, "The Media Equation: How People Treat Computers, Television, and New Media Like Real People and Places." Cambridge University Press, 1998.

[25] C. Breazeal, "Social Interactions in HRI: The Robot View," Transactions on Systems, Man, and Cybernetics, pp. 81-186, 2004.

[26] M. Mori, "The Buddha in the Robot," Charles E. Tuttle Co., ISBN 4333010020, 1982.

[27] T. Koda and P. Maes, "Agents with faces: The effects of personification of agents," Proc. HCI'96, pp.239–245, 1996.

[28] K. M. Cole RN, MN, CCRN and A. Gawlinski RN, DNSc, CS-ACNP, "Animal-Assisted Therapy: The Human-Animal Bond," Complementary and Alternative Therapies, Vol. 11, Iss. 1, pp. 139-149, 2000.

[29] J. Gammonley, J. Yates, "Pet Projects: Animal Assisted Therapy in Nursing Homes," 17(1):12-5, Jan 1991.

[30] J. S. J. Odendaal, "Animal-Assisted Therapy: Magic or Medicine?" Journal of Psychosomatic Research, Vol. 49, Iss. 4, pp. 275-280, 2000.

[31] M. Kanoh, S. Iwata, S. Kato, H. Itoh, "Emotive Facial Expressions of Sensitivity Communication Robot Ifbot," IEEE/RSJ International Conference on Intelligent Robots and Systems, Vol. 2, Iss. 28, pp. 1586-1591, 2004.

[32] M. Hashimoto, C. Yokogawa and T. Sadoyama "Development and Control of a Face Robot Imitating Human Muscular Structures," IEEE International Conference on Intelligent Robots and Systems, Beijing, China, pp. 1855-1860, 2006.

[33] M. Blow, K. Dautenhahn, A. Appleby, C. L. Nehaniv, D. Lee, "The Art of Designing Robot Faces – Dimensions for Human-Robot Interaction," Human Robot Interaction, Salt Lake City, 2006.

[34] P. Ekman, "An argument for basic emotions," Cognition and Emotion, Vol. 6, pp. 169-200, 1992.

[35] G. Nejat, B. Allison, N. Gomez, and A. Rosenfeld, "The Design of an Interactive Socially Assistive Robot for Patient Care," ASME Int. Mechanical Engineering Congress and Expo, Seattle, WA, IMECE2007-41811, 2007.

[36] B. Choe, H. Lee, and H. Ko. "*Performance-Driven Muscle based Facial Animation*," The Journal of Visualization and Computer Animation, vol 12, no. 2, pp. 67–79, 2001.

[37] G. Spalding, *Gray's Anatomy*, Vintage Books, New York, 1994.

[38] J. Ahlberg, CANDIDE-3 -- an updated parameterized face, Report No. LiTH-ISY-R-2326, Dept. of Electrical Engineering, Linköping University, Sweden, 2001.

[39] W. Weiguo, M. Qingmei and Wang Yu “Development of the humanoid head portrait robot system with flexible face and expression,” IEEE International Conference on Robotics and Biomimetics, Shenyang, China, pp. 757-762, 2004.

[40] H. Kobayashi, T. Tsuji, K. Kikuchi, “Study on face robot platform as a KANSEI medium,” IEEE Conference of Industrial Electronics Society, Nagoya, Japan, pp. 481 – 486, 2000.

[41] T. Hashimoto, M. Senda, and H. Kobayashi, “Realization of Realistic and Rich Facial Expressions by Face Robot,” IEEE Technical Exhibition Based Conference on Robotics and Automation, Tokyo, Japan, pp. 37 – 38, 2004.

[42] K. Itoh, H. Miwa, Y. Nukariya, K. Imanishi, D. Takeda, M. Saito, K. Hayashi, M. Shoji, and A. Takanishi, “Development of Face Robot to Express the Individual Face by optimizing the Facial Features,” IEEE-RAS International Conference on Humanoid Robots, Tsukuba, Japan, pp. 347-352, 2005.

[43] S. Noël, S. Dumoulin, T. Whalen, J. Stewart, “Recognizing Emotions on Static and Animated Avatar Faces,” IEEE International Workshop on Haptic Audio Visual Environments and their Applications, Ottawa, Canada, pp. 99-104, 2006.