

A Pragmatic Production of Cost-Efficient Controllable Humanoid Robot Head with Realistic Reproduction of Human Facial Expressions

Isaac Nwachukwu Chimeka
Southern University and A & M College, College of Sciences and Engineering,
Department of Computer Science, Baton Rouge, Louisiana

Abstract
This study explores all viable methods and techniques for the production of a responsive humanoid robot which would be both practically feasible and economically efficient. In the past few decades, scientists have been highly interested in the development of life-like humanoid robots. Some of these robots were used mostly in transporting heavy objects of accessing regions that were unreachable by humans. Between 1980's and the 1990's, engineers and scientists shifted their interest to the development of humanoid robots. These types of robots were able to stand, walk, and even pick up objects with mechanical hands. The introduction of humanoid robots greatly increased the interests of ordinary people in humanoid robots in particular. However, with the interest in these robots came the issue of communication. Majority of these robot have little or no recognizable facial features and would have to communicate with an external user by the use of audible sounds or visual symbols. This issue brought up the idea of creating robots that have recognizable facial features and are capable of carrying a conversation with humans. This project will develop a responsive and controllable humanoid robot head which would be capable of recreating basic movements of the human neck (such as rotate and pitch) as well as some basic and widely recognizable human facial expressions. This project focuses on developing a cost efficient, and practical process of creating animatronic robotic protype which will serve as a springboard for researcher, students, academia, and robot developers. The study further conducts a biomechanical analysis of the human head with specific emphasis on facial features including skeletal and muscular tissue structure to assist readers to learn and replicate the process. Above all, the project will enable researchers, scholars, students, and robot making companies to produce an animatronic humanoid robot head which can recreate basic human facial expressions that are easily recognizable to the average human such as happiness, anger, fear, sadness etc. to assist smooth communication, and business transaction. Also, the robot would be capable of recreating basic human neck and head movements like tilting of the head upwards and downwards and rotating of the head from side to side to follow human instructions.
Keywords: Robots, Humans, Interactions, Humanoids, Robotic, Production, Automated, Facial-Expression, Skin, Animatronic, Skeletal, Artificial- Intelligence (AI)
DOI: 10.7176/CEIS/14-2-02
Publication date: March 31st 2023

INTRODUCTION

Robotics is a diverse sector with many moving parts. The modern term *robot* was derived from the Czech word *robota* (meaning "forced labor"), used in Karel Capek's play "Rossum's Universal Robots" (R.U.R) (Goodrich & Schultz, 2007; Lassig et al., 2021; Ashok & Menon, 2018). The play's robots were manufactured humans, heartlessly exploited by factory owners until they revolted and ultimately destroyed humanity. Surprisingly, whether they were biological, like the monster in Mary Shelly's *Frankenstein* (1818), or mechanical was not specified, but the mechanical alternative inspired generations of inventors to build electrical humanoids. Meanwhile, the word *robotics* first appeared in Isaac Asimov's science-fiction story Runaround (1942) (Moravec, n.d.; Ashok & Menon, 2018; Lassig et al., 2021). Along with Asimov's later robot stories, it set a new standard of plausibility about the likely difficulty of developing intelligent robots and the technical and social problems that might result (Moravec, n.d.). *Runaround* also contained Asimov's famous Three Laws of Robotics which includes the following: (a) a robot may not injure a human being, or through inaction, allow a human being to come to harm; (b) a robot must obey the orders given it by human beings except where such orders would conflict with the First Law; and (c) a robot must protect its own existence as long as such protection does not conflict with the First or Second Law (Moravec, n.d.).

As the concept of robotic emerged in the 20th century, scientists have continued to improve upon the initial ideas and capabilities of the first types of humanoid robots over the next two decades (Lassig et al., 2021; Ashok & Menon, 2018; Nocks, 2006). These improvements led to the second generation of humanoid robots which were developed between the 50's and 70's. In the late 90's and into the early 2000's, the development of humanoid robots continued to improve leading to the creation of robots like Honda's ASIMO, and more recently PETMAN by DARPA (Lassig et al., 2021). Following the expansion of the robotic industry, it is important for readers to note that robotics is a crowded industry of more than 500 companies making products that can be best broken down into four categories (Lassig et al., 2021): conventional industrial robots and cobots, stationary professional services (such as those with medical and agricultural applications), mobile professional services (such as professional cleaning, construction, and underwater activities), and automated guided vehicles (AGVs) for transporting large and small loads in logistics or assembly lines (Lassig et al., 2021).

As a result, it has been theorized in the literature by Lassig et al. (2021) that companies of all types should focus on seven unfolding developments that will influence the direction of robotics in the next ten years. The seven unfolding developments includes the following: (1) Professional services robots will dominate the sector, (2) Changing consumer preferences and social trends will accelerate the need for advanced robotics solutions, (3) Robots will increasingly take over traditionally lower-paying and less skill-intensive jobs, (4) Artificial intelligence and other technological advances will enhance human-to-robot interactions, (5) Robot capabilities will include the ability to learn, (6) Semiautonomous mobile machines will increasingly manage tasks in pre-mapped environments, and (7) Asian robotics companies, currently a small slice of the market, will be competitive with US and European manufacturers.

Currently only a bare sliver of the market, professional services robots will have sales that may be more than double those of conventional and logistics robots. We expect the global robotics market to climb from about $25 billion this year to between $160 billion and $260 billion by 2030, with market share for professional services robots hitting up to $170 billion and industrial and logistics robot sales topping off at about $80 billion (see Figure 1 for more details).

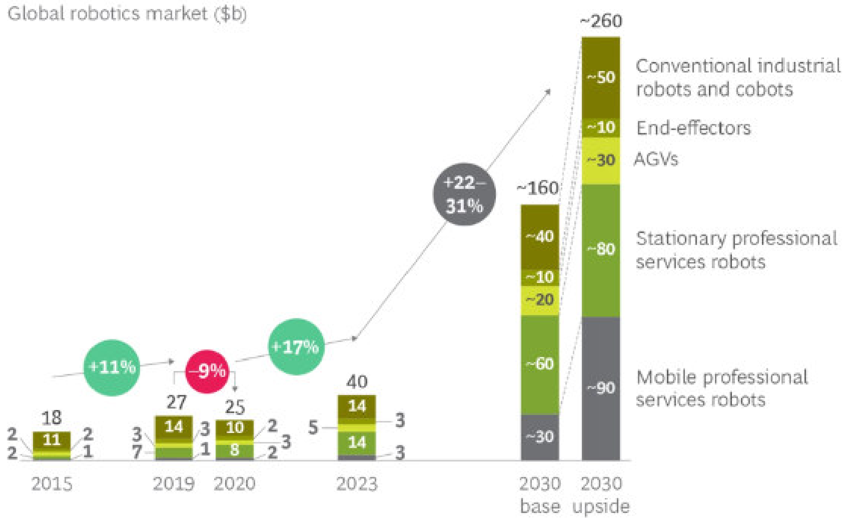

Figure 1: Trends that Shape the Robotic World
Source: IFR: Markets and Markets-BCG Market Model
Note: AGVs- means automated guided vehicles

According to Lassig et al. (2021), the consumer-driven demand for quicker deliveries of customized products has contributed to the expansion of robot capacity in manufacturing individualization and logistics applications. Additionally, the aging demographics has also resulted in a greater need for the use of mobile services robots to assist in personal hygiene, exercise, meal delivery, and other jobs. Also, there has been an increasing emphasis on recycling and other sustainability measures that requires robots to take on complex disassembly and sorting tasks (Lassig et al., 2021). Lately, there has been a rapid increase of interest in the area of consumer targeted robotics with humanoid robots being a major attraction. It is an undeniable fact that the high demand of robotic services has led to the development of these types of robots that would be the creation of mechanisms capable of mimicking and/or replicating basic human emotions and expressions. Nevertheless, the development of these type of robots has been quite daunting a task as they are often restricted to state-of-the-art robotics companies or research groups at higher institutions and polytechnics funded by external organizations. Even though there has been somewhat of a reasonable amount of progress in the development of life-like humanoid robots capable of mimicking human facial expressions, but they are often rudimentary or limited in nature. Recently, some of the very few rudimentary or limited studies on the development of flexible artificial skins that has given rise to more realistic kinds of humanoid robots which can recreate facial expressions with striking resemblance to that of an average human include the following: (a) For instance, *Hanson and Sophia* developed by Hanson Robotics are some of the best examples of this technology. Both robots are capable of replicating several human emotions including joy, sadness, even confusion. They were developed using a special type of artificial skin created by Hanson Robotics called

Frubber [9] which contains a bed of embedded electric wires within the layers of the silicone which actuates the artificial skin to create the expressions on the faces of the robots. (b) The *Jia Jia fembot* developed by the University of Technology of China in Hefei, and (c) the *Geminoid F robot* developed by Dr. Hiroshi Ishiguro at the Osaka University in Japan are also notable examples of humanoid robots capable of replicating human facial expressions.

Toward this end, as rightfully observed from the literature humanoid robots are steadily gaining more popularity in the field of consumer technology and robotics. Therefore, human interaction with these types of robots is highly anticipated to increase in the near future. Humans naturally respond more comfortably to visual stimuli rather than other forms of stimuli. That is why developing robots that can replicate human expressions is very important in order to improve the interaction between humans and humanoid robots. Therefore, this study tends to fill-in the literature gap by contributing to the very few literature on the creation of flexible artificial skins to develop robots that can replicate human expressions.

LITERATURE REVIEW

The development of facial expressions in humanoid robots is an area of modern robotics that is being studied intensely by various researchers. There have been various attempts presented in response to the issue. In order to successfully recreate or mimic human facial expressions, it is important to study the characteristics of the average human face and how its muscles work together to create the various expressions conveyed by humans regularly.

Skeletal Structure: First of all, the basic structure of the human head and face have to be taken into consideration. The average human head has a length ranging between 19.5 and 23.3 cm and has a width ranging between 15.4 and 15.9 cm (Alfayad et al., 2016). Alfayad et al. (2016) also states that the average human neck has a height which ranges between 22.3 and 23.3 cm. Consequently Prendergast (2013) states that the human face sits upon an intrinsic network of skeletal, fatty, and muscular tissue each of which combine their various functions to produce a recognizable emotional expression. Bellavia (2013) clearly discloses in the literature that the skeletal frame of the average human facial structure consists of the Frontal bone; this serves as the cover to the sensitive frontal lobe of the human brain. It also forms the top of the eye socket (Bellavia, 2013; Prendergast, 2013). The next major bone is the Maxilla which houses both the bottom of the nostrils and the top half of the teeth and jaw it also carries part of the top lip (Bellavia, 2013). Following the Maxilla, is the Mandible which contains the lower half of the teeth as well as the bottom of the jaw and the chin (Bellavia, 2013; Prendergast, 2013). Finally, we also have the nasal bone which gives the nose its shape and forms the top of the nostrils (see Figure 2 for more details).

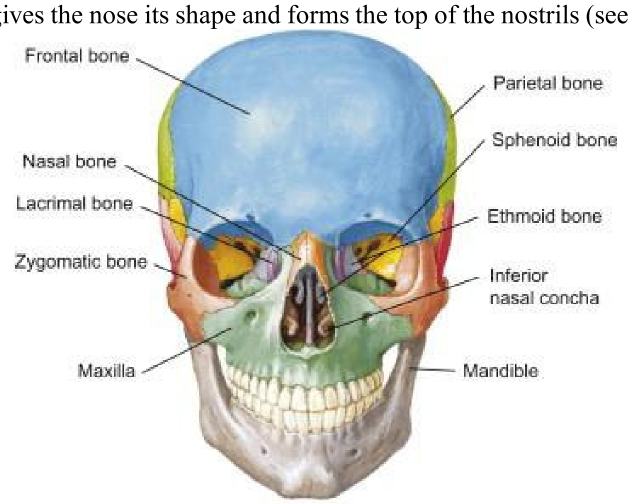

Figure 2: Human skull bone diagram
(Source: Prendergast, 2013)

Along the surface of the skull, there are several points where tissues and muscles connect to the skull. This helps keep part of the face connected to the skull and also define the structure of certain physical features of the face. For instance, the tissues and muscles of the top of the nose are connected to the procerus (Prendergast, 2013) which is the outer most tip of the nasal bone while those in the nostrils are connected to the nasalis (see Figure 3 for more details). We find also, that those muscles which are responsible for chewing and controlling the movement of the jaw are connected to the temporalis and masseter points of the skull (Prendergast, 2013).

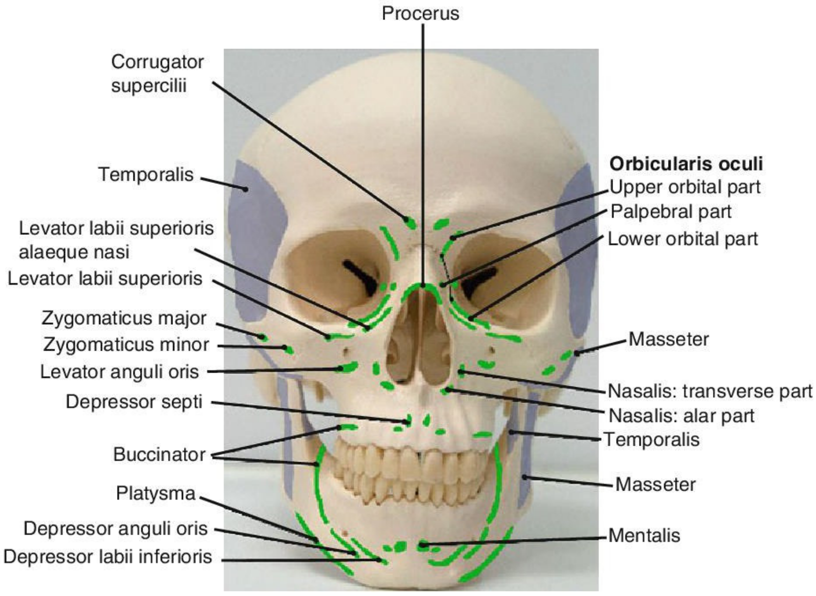

Figure 3: Facial connection nodes
(Source: Prendergast, 2013)

According to Prendergast's statements in the "Anatomy of the Face and Neck", we can also agree that the muscles which control the ability to smile on an average human face are connected to three points along the zygomatic bone which are namely: zygomaticus major, zygomaticus minor, and levator anguli oris (see Figure 3).

Facial Expression in Humans: In order to recreate facial expressions, it would be helpful to first obtain a functional understanding of how the average human makes these expressions and why. Humans mainly use expressions to convey an emotional message to a recipient or in reaction to a particular situation or occurrence. For instance, people often give a joyful expression after receiving some good news and frown when aggravated by something. Research from Du and Martinez (2014) also states that human facial expressions can be classified in six basic categories namely: happiness, surprise, fear, sadness, disgust, and anger (see Figure 4 for more details). Apart from a neutral expression, these are the expressions most used by humans on a regular daily basis. Work done by Du and Martinez (2014) also shows that the six basic facial expressions can be further combined resulting in the creation of compound expressions. These types of facial expressions occur when humans are experiencing a mixture of two of more emotions at the same time thereby creating one condensed expression on the face. As portrayed in Figure 4, the human facial expression has a total range of twenty-two expressions made of six basic and fifteen compound expressions which are happily surprised, happily disgusted, sadly fearful, sadly angry, sadly surprised, sadly disgusted, fearfully angry, fearfully surprised, fearfully disgusted, angrily surprised, angrily disgusted, disgustedly surprised, appalled, hatred, and awed.

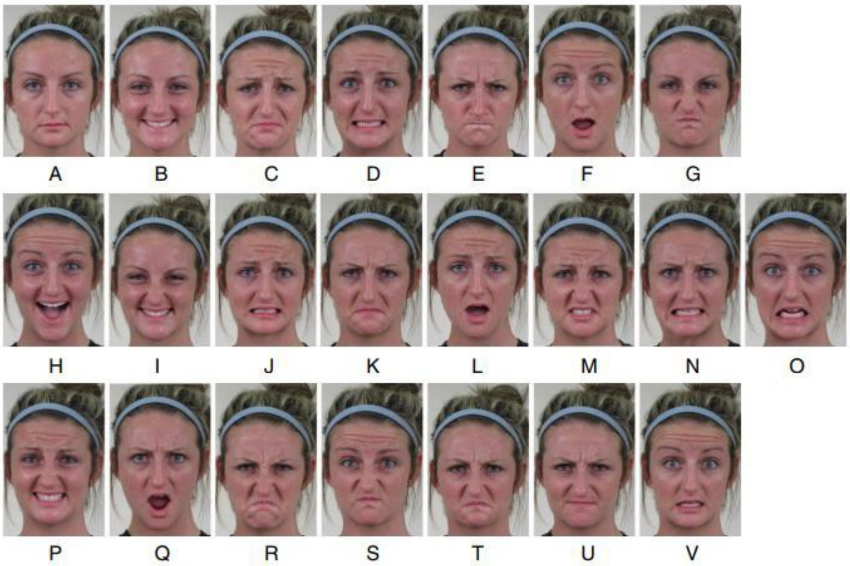

Figure 4: Images of the 22 Categories of Facial Expressions.
(Source: Du & Martinez, 2014)

Mechanical Structure: The ability of a robot to successfully recreate human facial expressions depends greatly upon the mechanism which would be used to drive the actuation and motion of its facial covering. In earlier attempts, robotics scientists utilized a combination of bare mechanical parts in a manner that gave a robot some resemblance of human facial features. These being circular orbs for eyes which were later replaced by cameras, often adding a pointed or rounded nose, and a speaker grill or an LED strip for the mouth and lips of the robot's face.

With enhanced study and research of anatomy and biomechanics, scientists began to design robots which have a more accurate representation of the human facial features. Along with the basic features they had, these types of robots include servo actuated parts like eye brows, jaws, eyes, and lips. Subsequently, modern humanoid robots have since surpassed these preliminary attempts proving that robots could be even capable of co-existing functionally within the same physical environment as humans. This is shown by recent humanoids like Sophia by Hanson Robotics, Geminoid-DK and Geminoid-F by Dr. Hiroshi Ishiguro of the Osaka University in Japan, and a host of other humanoid robots. These modern robots combine years of collaboration between, scientists, artists, and developers to create robots with striking realism and accuracy in their replication of facial features and expressions. An instance of this can be seen in Figure 6.

Mechanical Animation and Replication of Facial Expressions: The complexity of all the muscles, tissues, tendon, and skeletal elements of the average human's face, make the process of copying human facial expressions nearly impossible. However, the introduction of machine learning and artificial intelligence in robots has greatly reduced some of the challenges associated with the process. In the early phases of humanoid robot development, some robots were capable of vocal communication often by using pre-recorded audio files but were unable to make facial expressions. This led to the work done by Paul Ekman as discussed in Wu et al. (2009) publication titled, "Learning to Make Facial Expression". The creation of emotional expressions is a naturally occurring reflex of humans meaning that, humans don't require much thought to react emotionally to external stimuli.

Robots on the other hand require specialized programs that receive a command and translate it to a form of data that can be processed by computer software. In response to this issue, Ekman developed the Facial Action Coding System (FACS). This system categorizes the various muscular movements of the face into groups known as facial Action Units (AU) which detailed the movements of the eyebrows, cheeks, nose, lips, chin, and eye lids. Ekman was able to derive the conclusion that human facial expressions consist of a combination of these units to make a visible expression. Based upon this system Wu et al. (2009) expanded the concept in research carried out in the publication of "Learning to Make Facial Expression". Using Ekman's system, they created a robotic replica of Prof. Albert Einstein which could identify and reproducing facial expressions (See Figures 5 & 6 for more details). The robot uses a facial recognition software combined with a Computer Expression Recognition tool (CERT) program to identify facial expression on a subject. The image is then processed for AUs to determine what expression is being made by the subject. The units are translated to machine language which is used by the robot's servos to mirror the particular expression.

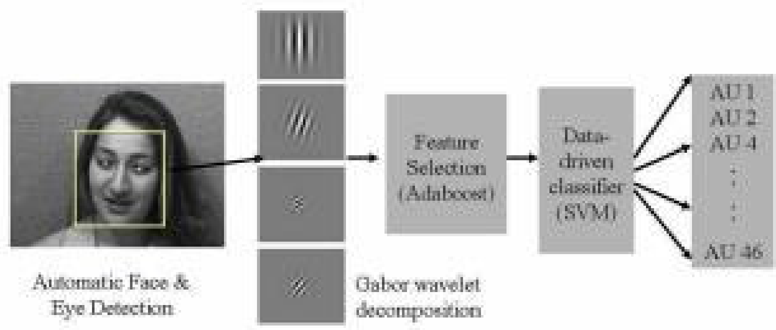

Figure 5: Computer Expression Recognition Tool (CERT) Program (Source: Wu et al., 2009)

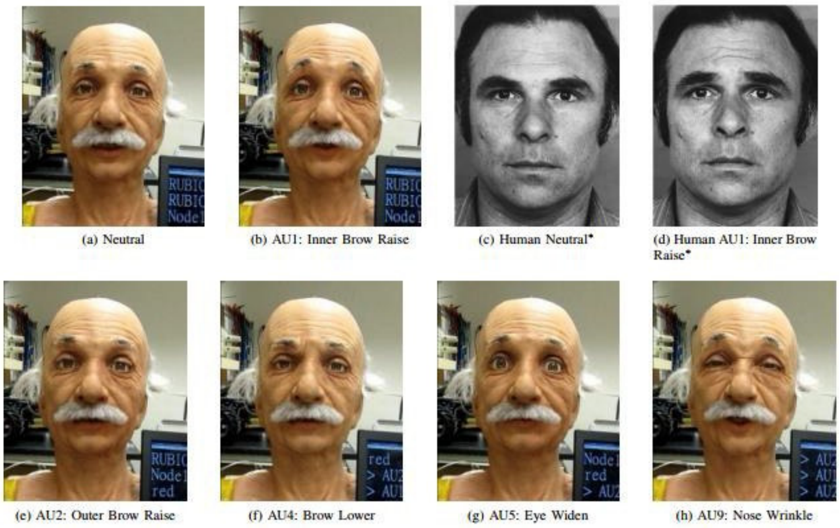

Figure 6: Einstein Robot Learning Facial Expressions
(Source: Wu et al., 2009)

METHODS AND MATERIALS

The intended result of the project is to produce an animatronic humanoid robot head which can recreate basic human facial expressions that are easily recognizable to the average human such as happiness, anger, fear, sadness etc. Using information gained from a study of human bio- mechanical features of the skull, facial tissues, muscles and skeletal kinetics, the relation of the motions of the motors incorporated within the mechanical skull of the robot would then be similar to that of actual facial muscles and tissues of the human face. Therefore, the robot's design is made up of a combination of structural and actuating mechanisms under a synthetic skin cover which would display animated facial expressions using the motion of the actuation mechanism below it. The structural mechanisms proposed for this robot comprises of 3D printed mechanisms which would act as the robot's structural core. This core would then be covered by a layer or artificial skin which would provide both the facial features and emotional expressions of the robot.

Resources: In order to successfully create the prototype, the following tools, materials, and resources would be required: (1) *3D Printer:* This tool is used in the creation of structural pieces which would house the robot's mechanical parts and control board. (2) *3D Printer Filament*: This is the material required in order to print the plastic structural parts which would act as both a supporting structure for the external skin and a housing for its mechanical parts. (3) *Computer:* This tool is used to control the center of the finished robot and would carry required software and programming needed to operate the robot. It would also be used to create 3d models of the robot's mechanical parts. (4) *Micro controller:* This is an electrical circuit board which acts as the main driver of the servos and actuators being used in the robot. (5) *Servo motors:* These are used to actuate the robot's artificial skin cover thereby giving it the ability to recreate facial expressions. These motors would be placed at specific locations within the skull replica of the robot. (7) *Linear actuators (optional):* These will be used along with the servo motors to actuate parts of the artificial skin that are actuated by the facial muscles of a human. (8) *Silicone Rubber:* This is a thick rubber which would be used to create an artificial skin for the robot. The finished rubber mask would act both as a covering for the structural and mechanical parts of the robot as well as provide the robot's humanoid facial characteristics i.e., eyebrows, nose, lips etc.

Procedure and Production Design: In order to create the required parts for the structural base of the robot, they first have to be physically sketched and designed by hand according to the information from the biomechanical study of the features of an average human's head. These designs are then digitally recreated and rendered using an applicable 3D modeling software (some good instances being Google SketchUp, Autodesk Inventor etc.). After the rendering of the models to digital 3-dimensional models, they are then converted to G-CODE format which is readable by a 3D printer. With this format, a physical part of the model can be printed using printable plastic therefore creating a physical part that can be assembled into a mechanism. After printing all the 3D parts for the robot, they can be gathered and grouped into separated sections in preparation for the production of mechanical sections and parts of the robot. These sections are then combined into their respective mechanisms which are then combined to make parts of the robot's face and head. The proposed mechanisms include servo actuated mechanisms to facilitate the movement of the eyes, jaws, and neck of the robot's head. These mechanisms will then be covered with a 3D printed skull replica which would be comprised mainly of the major bones that make up the human face. This replica will serve as the base for the robot's artificial skin cover which would be laid over the skull replica thereby giving the robot a more natural human appearance.

The artificial skin which would be used to create the robot's human-like face, would be made from silicone. This is achieved by using relative measurements for an average human's skull/facial features to create a snug fitting layered covering which would bring forth the desired motions on the face. The proposed facial characteristics are derived from a face cast mainly obtained from a subject being used as a source for the features. These features are then imprinted onto a cast using mold making material to store the characteristics of the source's face. After this process is completed, the silicone material is poured into the face cast mold thereby recreating the features of the source's face. With silicone being a soft and stretchable material, it would greatly allow for the underlying actuating mechanisms to actuate the skin covering in a manner that would recreate human facial expressions thereby giving the researcher the intended result of a robot mechanically recreating human facial expressions.

THE ANALYSIS OF THE ROBOTIC PRODUCTION AND ACTUAL IMPLEMENTATION OF THE PROCEDURES

The production of the robot begins with the design of the 3D printed skull parts. This is achieved with the use of information gathered from the bio-mechanical study of the human head, and design drawings of the proposed parts. After the drawings have been finalized, they can then be recreated within a 3D design software to create the gcode required by the 3D printer to create the parts. Using a 3D printer, the parts can then be transferred and printed thereby creating the physical parts of the skull (see Figure 7 for more details). After all parts required to create the robot have been acquired, the process of assembly can begin. This starts with the assembly of the parts for the robot's skull. These are split into two halves of 3D printed components which include the top cover and the base of the skull.

Figure 7: Plastic 3D printed parts

The top consists of three interlocking pieces namely: skull cover front which provides the shape of the robot's forehead and also houses the actuating mechanism of the eyebrow, skull middle plate, and skull rear plate which provide the curvature from the middle of the skull to its rear. These are printed in pairs of left and right which when combined, produce the top of the skull. The skull's base consists of the same interlocking printed parts as well. These include skull base front which like the skull cover front, houses the actuating mechanism of the robot's cheeks and upper lip. The next part to focus on is the jaw/ teeth base of the robot.

This attaches a life-size typodont model of natural human teeth to the bottom of the skull. It also provides the robot with the ability to replicate some basic expressions such as delight, surprise, and fear. After the base of the skull and jaw have been connected, the neck mechanism can then be connected to it (see Figure 8 for more details).

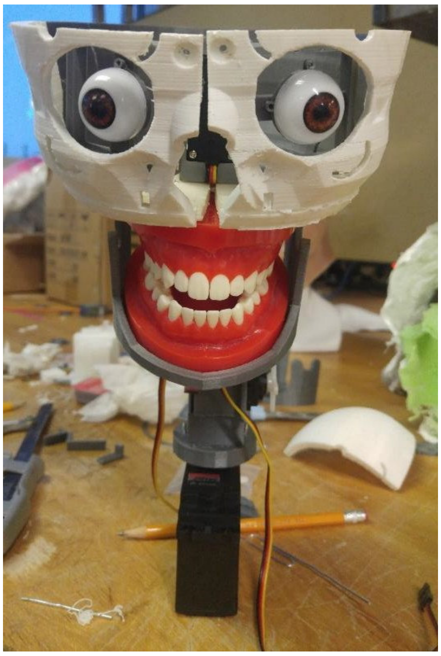

Figure 8: Skull base and neck assembly

This mechanism controls axes of motion within the robot. These are the rotation of the robot from left to right, tilting upwards or downwards, and flexion from the left to right. When the base parts and neck have been put together, the top cover of the skull can then be attached to the base thereby creating a finished skull for the robot.

Within the skull, servo motors can be attached to the varying mechanisms which control the movement of the robot's eyes, teeth, jaw and facial features like its eyebrows and cheeks (see Figure 9 for more details). The artificial skin covering can then be placed over the skull after it has been assembled and can then be tested for the various expressions it is required to replicate.

(a) (b)

Figure 9: (a) Skull with internal servo motor, (b) Finished animatronic skull

RESULTS AND DISCUSSION OF THE ROBOTIC PRODUCTION

The result of this procedure is a humanoid robot head, which bears a striking resemblance to a human's head and face in terms of facial features and aesthetics. The resulting aesthetic features being a product of the robot's external silicone covering and the actuating mechanisms on which it rests upon (see Figure 10 for more details).

Figure 10: Final robot prototype with external skin

The robot is capable of replicating basic human facial emotional expression i.e., happiness, anger, fear, disgust etc. making it physically appear to possess the ability to visually express emotional feelings. The underlying servo motors and actuating mechanisms, coupled with the robot's motion control code would work together to give the robot multiple range of motion as it will be able to tilt and drop its head, open and close its mouth, and turn its neck from side to side. Actuating mechanism in the robot's eyebrows and jaw, give it the ability to recreate basic motions of human facial muscles which enables humans to create facial expression. Therefore, it would be able to mimic emotional poses such as smiling, frowning, shock, fear etc.

CONCLUSION AND PROSPECTS OF THE PROTOTYPE

This prototype will greatly inspire more interest in the study of human and robot interaction in both scientists and enthusiast alike because, it would provide a viable robot which can be studied and observed to further develop mechanisms which continue to improve the features of the robot's ability to recreate realistic emotions. The prototype would provide a cost-efficient process that would require relatively basic or rudimentary knowledge of electrical wiring and computer programing to create a functional robot. By developing this prototype, manufacturers may become more interested in developing assistant robots that can communicate both verbally and emotionally with humans.

REFERENCES

Alfayad, S., El-Asswad, M., Abdellatif, A., Ouezdou, F.B., Blanchard, A., Beaussé, N., & Gaussier, P. (2016). "HYDROID Humanoid Robot Head with Perception and Emotion Capabilities: Modeling, Design, and Experimental Results" *J. Frontiers in Robotics and AI,* Apr. 2016.

Ashok, K. H., & Menon, M. (2018). Robotics in Genitourinary Surgery. *Springer. pp. 8–9. ISBN 978-3-319-20645-5.*

Bellavia, W. (2013). "*Review of Basic Anatomy: Treatment of TMJ,"* St Paul, MN: Academy of Dental Learning & OSHA Training, 2013.

Du, S., Y. Tao, Y. & Martinez, A. M. (2014). "Compound facial expressions of emotion," *Proceedings of The National academy of Sciences of The United States of America,* vol. 111, no. 15, pp. E1454-E1462, 2014.

Goodrich, M. & Schultz, A. (2007). "Human- Robot Interaction: A Survey," *J. Foundations and Trends in Human-Computer Interaction*, Vol. 1, No. 3, pp. 203-275, 2007.

Hanson, D. (2019). "Creating value with human-like robots," [Online]. Available: https://www.hansonrobotics.com/hanson-robots/. [Accessed 23 February 2019].

Hanson, D. (2018). "Robots with human faces by David Hanson," [Online]. Available: https://forcetoknow.com/hi-tech/robots-human-faces-david-hanson.html. [Accessed 15 April 2018].

History-Computer.com. "The Robots of Westinghouse". History of Computers. Available [Online].

Lassig, R., Lorenz, M., Sisimatos, E., Wicker, I., & Buchner, T. (2021). Robotics Outlook 2030: How Intelligence and Mobility will shape the Future. Understanding The Robotics Industry Outlook | BCG

Moravec, P. H. (n.d.). Robot Technology. Britannica. Robot | Definition, History, Uses, Types, & Facts | Britannica

Nocks, L. (2006). The Robot: The Life Story of a Technology. *Greenwood Publishing Group. p. 64. ISBN 978-0-313-33168-8.*

Pasek, A. (2015). "Renaissance Robotics: Leonardo da Vinci's Lost Knight and Enlivened Materiality". Available [Online]. Sep. 2015.

Prendergast, P. (2013). "Anatomy of The Face and Neck," in *Cosmetic Surgery: Art and Techniques*, Berlin, Springer, 2013, pp. 29-45.

RichardsRobots.com. "Eric Robot, 1928". Richards Family Robot Archive. Available [Online].

Wu, T., Butko, N. J., Ruvulo, P., Bartlett, M. S., & Movellan, J. R. (2009). "Learning to Make Facial Expressions," in *2009 IEEE 8th International Conference on Development and Learning*, San Diego, 72009.