Design and motion control of bioinspired humanoid robot head from servo motors toward artificial muscles

Yara Almubarak and Yonas Tadesse
yara.almubarak@utdallas.edu, yonas.tadesse@utdallas.edu
Humanoid, Biorobotics and Smart Systems (HBS) Laboratory, Mechanical Engineering Department

The University of Texas at Dallas, Richardson, TX 75080, USA

Abstract

The potential applications of humanoid robots in social environments, motivates researchers to design, and control biomimetic humanoid robots. Generally, people are more interested to interact with robots that have similar attributes and movements to humans. The head is one of most important part of any social robot. Currently, most humanoid heads use electrical motors, pneumatic actuators, and shape memory alloy (SMA) actuators for actuation. Electrical and pneumatic actuators take most of the space and would cause unsmooth motions. SMAs are expensive to use in humanoids. Recently, in many robotic projects, Twisted and Coiled Polymer (TCP) artificial muscles are used as linear actuators which take up little space compared to the motors. In this paper, we will demonstrate the designing process and motion control of a robotic head with TCP muscles. Servo motors and artificial muscles are used for actuating the head motion, which have been controlled by a cost efficient ARM Cortex-M7 based development board. A complete comparison between the two actuators is presented.

Keywords: Bioinspired Head, Soft Actuators, Humanoid Robot, Social Robot, Motion Control

1. Introduction

Humanoid robots have been studied for the past four decades. Humanoids are robots which use different types of sensors to acquire information and perform certain tasks through facial expressions, body and hand movements with or without locomotion [1]. Today, the application of robots, especially humanoids, are beyond that imagination which we see in movies [2]. Researchers and investors try to bring robots in social environments including homes, schools, hotels, etc. Hence, there are many popular topics that focus on manufacturing humanoid robots such as path planning[3, 4], navigation in human crowds [5], generating human-like motion [6], visual servoing [7], and learning social behaviors[8]. Besides speech, humans use facial expression and body gestures to communicate. Thus, a humanoid should mimic facial expressions as human beings. One of the most common problem in the field of social humanoid robotics, is to design a head mechanism and motion controller that is able to translate robotic to human like emotions . Therefore, many scientific research has been introduced such as Buddy [9], baby [10], SAYA[11], Actroid-F [12], ROMAN [13], Hubo [14], Geminoid DK [15], Kaspar [16], and Zeno [17]. Mimicking human qualities in robots has different factors such as control of actuator, optimized design, mechanical parameters for different joint movements, and deformation analysis for skin elongation. The facial expression (motion) should be continuous and not discrete. However, some research claims that the facial expression perception is a categorical one [18]. Naturally humans are affected by language and culture [19]. There are six main facial features which are disgust, happiness, sadness, anger, fear, and surprise. These six facial expressions serve as the base for all other expressions which are different level combinations of these six [20]. To better understand how to create robot facial features, studies of emotions and emotional detection were conducted. Ekman's theory, developed the "atlas of emotions" which has hundreds of facial expressions based on these six main facial features [21]. Moreover, emotions can also be studied as a vector model. In 1992, the vector model of emotions was created, this 3-dimensional model includes three axis. The x axis "serotonin" that is responsible for mood balance. The y axis "noradrenaline" that is the rate measure of heart's contractions. The z axis "dopamine" that controls blood pressure and is affected by startling movements [22]. These different emotional detection methods allow researchers to conduct different experiments in order to achieve the most realistic human-robot interaction. Different type of actuators are used in humanoid heads. For example, Buddy and ROMAN used electrical servo motor. Tadasse et al and Hara et al [23] used SMA to control motion of head. The Actroid-F use pneumatic actuators. The SAYA use McKibben actuators. Each actuator has its own advantage and disadvantage. For example, electrical motors are energy efficient and can be controlled easily; while, they are bulky and expensive. The SMA is fast and light weight in size; however they are fragile. Pneumatic actuators require an air pump which is not applicable in many practical situations. Recently, Haines et al. made a new artificial muscle which uses fishing line and silver coated nylon [24]. This muscle is an inexpensive (~$5/kg) high-strength polymer fiber. Thermal contraction of nylon 6,6 fibers is about 4%. The polymer's fibers have been twisted to change to chiral. The twist enables polymer fibers to work as torsional muscles. By adding more twist such that the twisted fiber converts to a coiled fiber. The extra twist amplifies the tensile stroke of the twisted polymer fiber. These muscles can untwist, especially when under a load. Thermal annealing solves this problem by forming a torque-balanced structure. By wrapping a highly twisted polymer fiber around a mandrel and stabilizing the coils by thermal annealing, a twisted and coiled polymer muscle can be fabricated. The main contribution of this paper is the twisted and coiled polymer muscle as actuators for humanoid face. The comparison of a simple smile generated by electrical servomotors and twisted and coiled polymeric muscles is demonstrated. In this paper; we explain fabrication in detail, the design process, the circuit and controller design for both the servo and muscles and discussion of both experiments conducted on the head with the two different actuators.

2. Fabrication

Firstly the mold fabrication is described followed by the process of creating skin is explained. The 3D head model was fabricated using computer facial recognition program FaceGen. FaceGen creates faces from multiple 2D photos. By uploading the photos, front and side views, the program will instruct the user to click on significant points on the picture such as identifying the midpoints of the eyes, edge of the nose, edge of the lips, and chin as shown in **Fig1.(a)**. It will then regenerate the 2D picture into a 3D model which can be then saved, edited, and 3D printed as shown in **Fig1.(b).**

Figure 1: GenFace face scanning (a) program instructions and layout (b) 3D head model using GenFace

2.1 Mold fabrication

The mold consists of polyurethane materials that was a mix of 2:1 ratio of part A and part B. Polyurethane(PMC 746) has a shore hardness of 60A which makes it extra rigid and will allow us to create multiple skin samples from the same mold. The mold was created by pouring the polyurethane on the 3D printed head and allowing it to dry for 24 hours, schematics of fabrication is shown in **Fig2.(c)**. The printed head was screwed into place while keeping a distance of 5mm between the nose and the bottom plate of the enclosure. Several items were also added to reduce the amount of material needed to make the mold as demonstrated in **Fig2.(b)**.

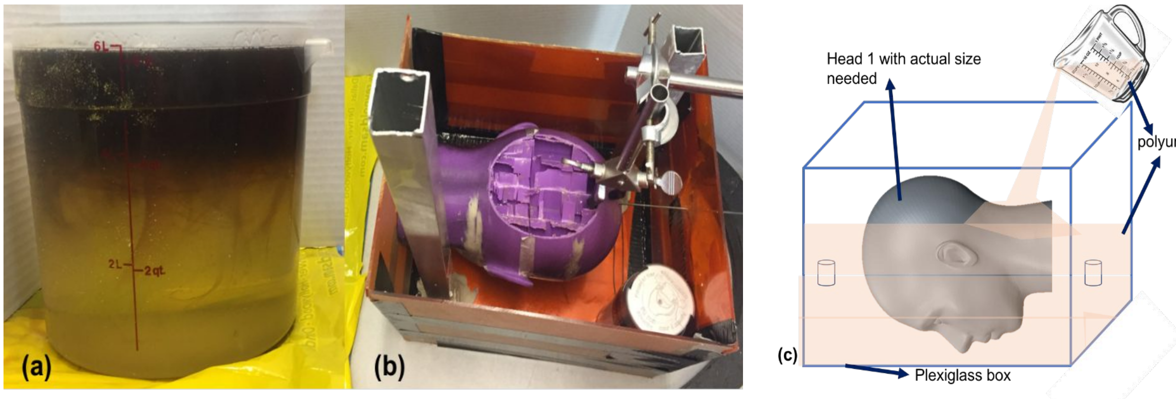


Figure 2: (a) Polyurethane mix of A and B, (b) Mold Fabrication, and (c) Schematics of mold fabrication

2.2 Skin fabrication

Silicone elastomer material (Ecoflex-30) is used as the artificial skin for the robotic head. This silicone consists of a 1:1 ratio mix of part A and part B, it has a shore hardness of 00-30A, up to 900% elongation, and tensile strength of 200psi (1379kPa). To achieve flexible fast movement within the face the skin is required to have less force requirements than the original ecoflex-30 mix while still maintaining the other physical characteristics such as color and texture. As a result, in addition to the Ecoflex part A (400ml) and part B (400ml) we have added a mix of sodium bicarbonate (210ml of vinegar and 120ml baking soda by volume). The addition of baking soda and vinegar will create gas bubbles that will create a porous material [25]. The silicone was added into the polyurethane mold and pressed using a 3D head smaller by 4% from the initial head used to achieve a gap of 4mm giving a uniform skin thickness.

2.3 TCP muscle preparation

Twisted and Coiled Polymeric muscles were fabricated using an automated fabrication method by suspending a dead weight on the bottom end of the muscles while connecting the top end to the motor. The twist was achieved by applying a counter clockwise rotation using the motor. This coiling process is allowed to occur until the entire length of the thread is coiled which results in 1-ply muscle [24]. In order to make 2-ply muscle, we folded the 1-ply in half and due to the initial rotation tension the second coiling process is done manually. The muscles were then annealed by suspending 350 g dead weight and applying an increasing voltage proportional to the length of the TCP muscle using (~1.2 x length of the muscle in inches) until the muscle reaches steady state. The muscles were then trained by applying a voltage equal to the last annealing voltage and suspending a weight of 200g. **Fig3** shows schematics of the annealing and training process for the 2-Ply muscle. The 2 TCP muscles had a strain average of 17%.

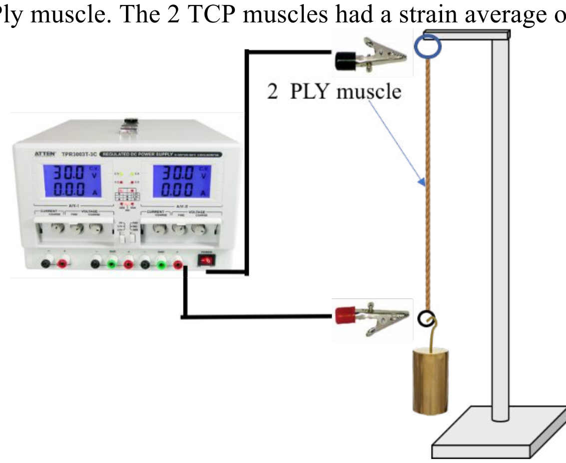


Figure 3: Schematics of TCP muscle annealing and training

3. Analytical design

Lace fabric was embedded to the inside of the skin in order to achieve uniform actuation, seen in **Fig4.(a)**. This method will help get uniform equal actuations in the desired sections of the skin. The lacy material covers different surface areas and can either connect with the TCP muscle and servos either directly or through a tendon. During the actuation the whole surface area of that skin will move in the direction of the actuation rather than a single point. For the two cases we connected a stiff wire to the lace material on one end and the actuation mechanism on the other. By pulling the stiff wire in any direction linear deformation would occur throughout the whole surface area of the embedded lace material. Moreover, this method will also help in the reduction of the number of actuators needed to create deformation for one expression. **Fig4.(b)** demonstrates actuators connections with the lace material embedded in the silicone.

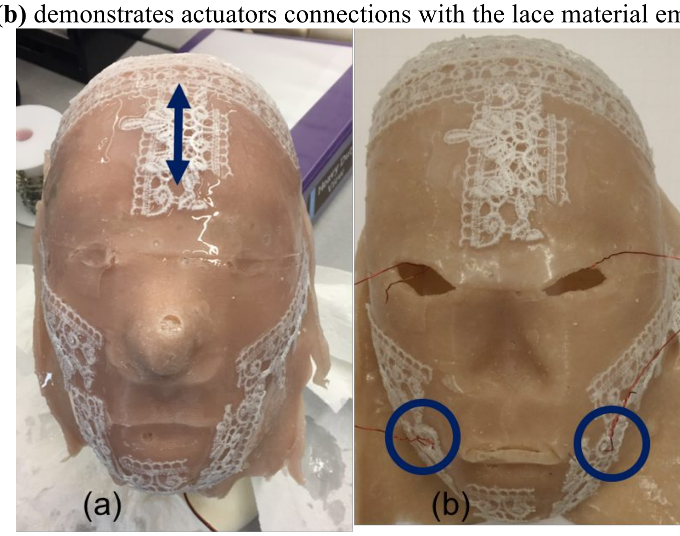
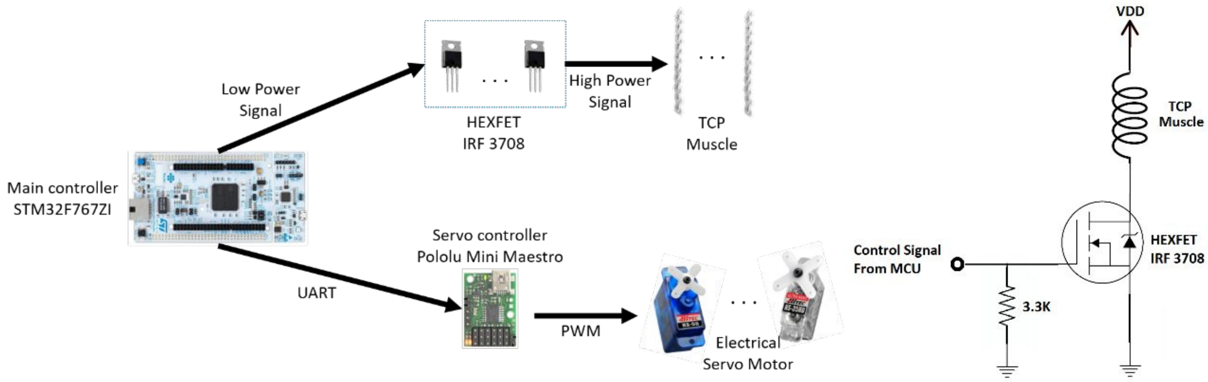


Figure 4: (a) Lace material embedded in silicone, (b) Embedded wires for actuation connections

4. Circuits and Control

In this paper we are comparing the deformation resulting from electrical servo motors and twisted and coiled polymer muscles for a simple smile. **Fig5** shows the circuit which we used. A STM32 Nucleo-144 development board with STM32F767ZI microcontroller unit is used as main controller. The STM32F767ZI is a high-performance ARM Cortex-M7 microcontroller with digital signal processor (DSP) and a floating point unit (FPU) which supports ARM® double-precision and single-precision data-processing instructions and data types. The program was written in C language in Atollic TrueSTUDIO IDE which use GNU ARM Embedded Toolchain (GCC compiler). A Pololu Mini Maestro Servo controller board is used as interface between the main controller and electrical servo motors. The Nucleo board sends command through Universal asynchronous receiver/transmitter (UART) protocol to the Pololu Mini Maestro Servo controller board. Logic high voltage level of the STM32F767ZI is 3.3v. Therefore, IRF3708 is selected as HEXFET (power N-channel enhancement type MOSFET) which can work as switch in 3.3v. The IRF3708 can works up to 30v, 51A and 62w. This feature makes IRF3708 completely proper for twisted and coiled polymer muscles.



(a) (b)

Figure 5: Schematics of circuit design and control (a) Controller and interface (b) Muscle Circuits schematic (detail)

5. Experiment

A smile is tested. Two servo and two TCP muscles were used, one placed on the right side of the edge of the lips and the other placed on the left side. These placements will allow the lips to deform in a direction outwards of the mouth creating a smile. The muscle and servo placements are exactly identical as the same connecting wires are used. The wire is embedded into the silicone on one end and the other end is either connected to a servo or muscle.

5.1 Force required to deform the skin

Tests were done in order to find the minimum force required to deform the skin a distance of 5mm or larger. These results are important as they will define the number of actuators needed to deform a specific section of the head. The test was conducted by tying a wire to a section and applying weights via pulley system in order to find the total weight needed to create a deformation. After finding the total weight in grams the value was converted to Newton.**Table 1** below shows the different forces needed to deform each section of the face.

Table 1: Data obtain for force required to deform each section in the face as shown in Fig6

Section	Weight (g)	Force (N)
1	600	5.886
2	490	4.809
3	200	1.962
4	300	2.943

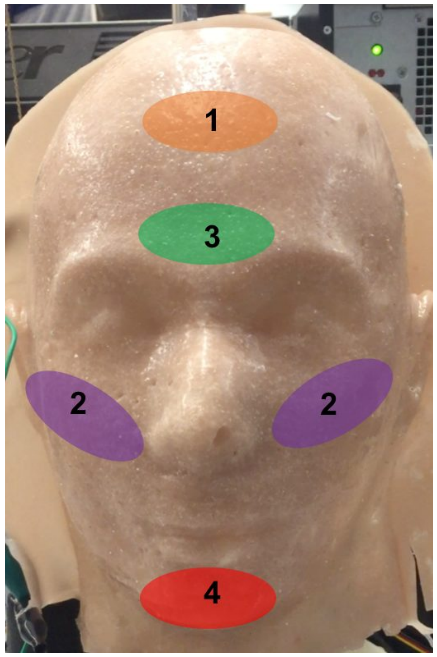


Figure 6: Section of face for force analysis

6. Results and discussion

This experiment was done using both the TCP muscles and servo motors to create a smile in the face. **Fig7** shows a comparison between initial position (before the deformation) and the final position (maximum deformation for TCP and servo motor). **Fig 7.(a)** show TCP muscle actuation at 1.2A while **Fig7.(b)** shows the servo motor actuation at 5V. **Fig7** shows the results of creating a smile using artificial muscles and servo motors. **Table 2** demonstrates data comparison between servos and TCP muscles. The deformation using motors was quick compared to the deformation using artificial muscles. The muscles required a lot more time to fully create the actuation needed. Only two actuators for each were used to form a smile. Servo motors used in this experiment were HS81 which operate at variable range of voltages 4-6V while the use of TCP muscles is controlled by current range of 0.6A-0.8A for each TCP. The muscles are much more cost effective than servos as they are almost 6 times cheaper than the servomotors used.

Table 2: Comparison data between servo motors and TCP muscles

Characteristic	**Servo Motor**	**Twisted and Coiler Polymer Muscle (TCP)**
Time for Actuation	2 seconds	30 seconds
Number of Actuators	2	2
Voltage required	5V	24.93V
Maximum current	0.449A	1.2A
Price	$26.00	$4 for 240 cm used

Although the TCP muscle was slower than the servo in actuation it still produced very similar deformation as shown in **Fig7.(a)** at a lower cost**.** The TCP muscles are flexible, small, light in weight, and cheaper compared to the servos which are significantly heavy and take up a lot of space. This means that we can increase the number of muscles used in the face to create more detailed facial expressions easily without worrying about size, weight , and cost of the full humanoid head. Using servo motors is still beneficial if the desired facial features needed are simple. Smaller servo motors such as HS35 can be used but typically they cannot handle the minimum force required to deform the skin. Therefore, using smaller servos will mean that the number of servos would increase to achieve the force required to create any type of deformation. As a result, it will also cause an increase in price of building the humanoid head.

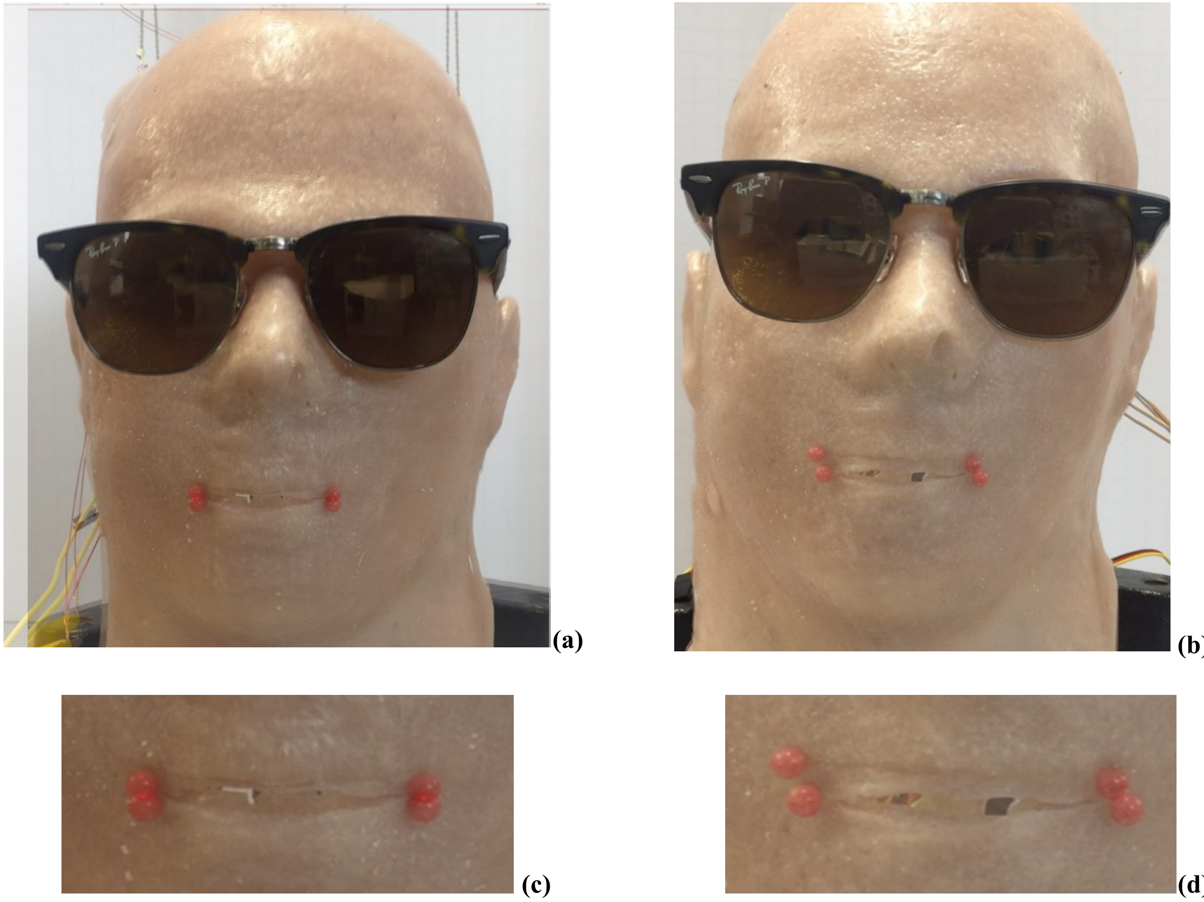


Figure 7: (a) Smile using TCP muscle actuator (b)Smile using servo motor actuator (c) Zoomed in pictures of TCP muscle actuations (d) Zoomed in picture of servo motor actuation

7. Conclusion

This paper presents a 3D printed affordable humanoid face. Polyurethane is used to create mold for casting the skin. Ecoflex-30 is used for skin material. A cost-efficient ARM Cortex-M7 based development board with STM32F767ZI is used as main controller. The development board is connected through UART with servo motor controller. Power N-channel enhancement type MOSFETs are used as switch for Twisted and Coiled Polymer artificial muscles. The servo motors and muscles have been actuated at the same position to create a simple smile. Results show that servomotors and TCP muscles will give the same actuation with various time intervals. Electrical servo motors are power efficient in compare to artificial muscles; however, they take more physical space and are much more expensive. It can be concluded that a lot more TCP muscles can be used to create a humanoid head that is capable to perform very detailed facial expressions at a lower cost compared to the electrical servo motors.

Acknowledgments
Part of this work is supported by the Office of Naval Research under the grant number N00014-15-1-2503

References

1. Ting, C.-H., et al., *Humanoid robot: A review of the architecture, applications and future trend.* Res. J. Appl. Sci. Eng. Technol, 2014. **7**: p. 1364-1369.
2. Fakoor, M., A. Kosari, and M. Jafarzadeh, *Revision on fuzzy artificial potential field for humanoid robot path planning in unknown environment.* International Journal of Advanced Mechatronic Systems, 2015. **6**(4): p. 174-183.
3. Stone, R. and M. Lavine, *The social life of robots.* Science, 2014. **346**(6206): p. 178-179.
4. Fakoor, M., A. Kosari, and M. Jafarzadeh, *Humanoid robot path planning with fuzzy Markov decision processes.* Journal of Applied Research and Technology, 2016. **14**(5): p. 300-310.
5. Trautman, P., et al., *Robot navigation in dense human crowds: Statistical models and experimental studies of human–robot cooperation.* The International Journal of Robotics Research, 2015. **34**(3): p. 335-356.
6. Gielniak, M.J., C.K. Liu, and A.L. Thomaz, *Generating human-like motion for robots.* The International Journal of Robotics Research, 2013. **32**(11): p. 1275-1301.
7. Cai, C., N. Somani, and A. Knoll, *Orthogonal Image Features for Visual Servoing of a 6-DOF Manipulator With Uncalibrated Stereo Cameras.* IEEE Transactions on Robotics, 2016. **32**(2): p. 452-461.
8. Liu, P., et al., *Data-Driven HRI: Learning Social Behaviors by Example From Human–Human Interaction.* IEEE Transactions on Robotics, 2016. **32**(4): p. 988-1008.
9. Potnuru, A., M. Jafarzadeh, and Y. Tadesse. *3D printed dancing humanoid robot "Buddy" for homecare*. in *Automation Science and Engineering (CASE), 2016 IEEE International Conference on*. 2016. IEEE.
10. Tadesse, Y., D. Hong, and S. Priya, *Twelve degree of freedom baby humanoid head using shape memory alloy actuators.* Journal of Mechanisms and Robotics, 2011. **3**(1): p. 011008.
11. Hashimoto, T., et al. *Development of the face robot SAYA for rich facial expressions*. in *SICE-ICASE, 2006. International Joint Conference*. 2006. IEEE.
12. Yoshikawa, M., et al. *Development of an android robot for psychological support in medical and welfare fields*. in *Robotics and Biomimetics (ROBIO), 2011 IEEE International Conference on*. 2011. IEEE.
13. Berns, K. and J. Hirth. *Control of facial expressions of the humanoid robot head ROMAN*. in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*. 2006. IEEE.
14. Oh, J.-H., et al. *Design of android type humanoid robot Albert HUBO*. in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*. 2006. IEEE.
15. Vlachos, E. and H. Schärfe. *The geminoid reality*. in *International Conference on Human-Computer Interaction*. 2013. Springer.
16. Dautenhahn, K., et al., *KASPAR–a minimally expressive humanoid robot for human–robot interaction research.* Applied Bionics and Biomechanics, 2009. **6**(3-4): p. 369-397.

17. Ranatunga, I., et al. *Enhanced therapeutic interactivity using social robot Zeno*. in *Proceedings of the 4th International Conference on PErvasive Technologies Related to Assistive Environments*. 2011. ACM.
18. Fugate, J.M., *Categorical perception for emotional faces.* Emotion Review, 2013. **5**(1): p. 84-89.
19. Jack, R.E., et al., *Cultural confusions show that facial expressions are not universal.* Current Biology, 2009. **19**(18): p. 1543-1548.
20. Asheber, W.T., C.-Y. Lin, and S.H. Yen, *Humanoid head face mechanism with expandable facial expressions.* International Journal of Advanced Robotic Systems, 2016. **13**(1): p. 29.
21. Ekman, P. and H. Oster, *Facial expressions of emotion.* Annual review of psychology, 1979. **30**(1): p. 527-554.
22. Bradley, M.M., et al., *Remembering pictures: Pleasure and arousal in memory.* Journal of experimental psychology: Learning, Memory, and Cognition, 1992. **18**(2): p. 379-390.
23. Hara, F., H. Akazawa, and H. Kobayashi. *Realistic facial expressions by SMA driven face robot*. in *Robot and Human Interactive Communication, 2001. Proceedings. 10th IEEE International Workshop on*. 2001. IEEE.
24. Haines, C.S., et al., *Artificial muscles from fishing line and sewing thread.* science, 2014. **343**(6173): p. 868-872.
25. Tadesse, Y., et al. *Silicone based artificial skin for humanoid facial expressions*. in *SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring*. 2009. International Society for Optics and Photonics.