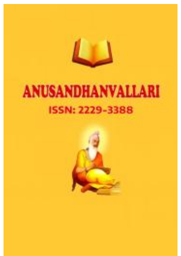

Anusandhanvallari
Vol 2024, No.1
May 2024
ISSN 2229-3388

Design and Fabrication of a Low-Cost Mechanical Humanoid Robot Head for Social Interaction (M.H.R.S.I.)

Ankush Kumar Rajput[1], Ambrish Pratap Singh[2], Khushi Gautam[3], Vikas Babu[4]

[1,2,3,4] Department of Mechanical Engineering, Rajkiya Engineering College Banda

Abstract

This paper presents the design, numerical analysis, fabrication, and system integration of a mechanical humanoid robot head intended for basic social interaction via facial expressions, eye motion, and speech-based question answering. The proposed prototype, named M.H.R.S.I. (Mechanical Humanoid Robot for Social Interaction), integrates a multi-servo facial actuation scheme, a linkage-based eye movement mechanism, and an embedded computing stack based on Raspberry Pi. The head is modeled in SolidWorks and its structural feasibility is evaluated through static simulation using gravity loading, a hinge torque case, and an external force case. A physical prototype is fabricated using fused deposition modeling (FDM) with PLA filament, followed by assembly and integration of seven SG90 micro servo motors, an ultrasonic sensor for proximity awareness, and audio I/O using a microphone and Bluetooth speaker. For interaction, a speech-to-text → question answering → text-to-speech pipeline is implemented, using a lightweight pretrained QA model (deepset/tinyroberta-squad2) adapted with a custom context database related to the robot and its environment. Results demonstrate the feasibility of a low-cost, interdisciplinary workflow for developing an expressive humanoid head prototype and provide a reusable methodology for future social robotics development.

Keywords: Social robots; Humanoid head; Facial expressions; Eye mechanism; FDM; Raspberry Pi; Human–robot interaction.

1. Introduction

Social robots are designed to interact with humans in everyday environments, and their acceptance often depends on how naturally they convey attention and emotion through the head and face. The robot head is particularly important because it is a primary channel for nonverbal communication, including gaze direction and facial expressions. At the same time, building an expressive humanoid head becomes challenging when constrained by low cost, limited actuators, manufacturability, and embedded compute limitations [1-2].

This work addresses these constraints through the design and prototyping of M.H.R.S.I., a mechanical humanoid robot head that combines (i) servo-driven jaw motion, (ii) a constrained eye movement linkage mechanism, (iii) a compact facial expression actuation strategy, and (iv) a Raspberry Pi–based interaction pipeline. The emphasis is on producing a reproducible design-to-fabrication workflow using commonly accessible tools (CAD + simulation, FDM printing, commodity servos, and open-source NLP libraries).

This paper makes the following contributions:

- A complete mechanical design of an expressive robot head with defined outer shell and inner mechanism architecture.
- A linkage-based eye movement design with supporting kinematic calculations derived from servo characteristics.
- A feasibility-focused structural simulation using SolidWorks static study with defined loads/fixtures.

- An embedded interaction stack using speech recognition, lightweight QA, and speech synthesis, integrated with proximity sensing and expression triggers.
-

2. Related work and motivation

Prior work in social robotics highlights that user acceptance can be influenced by human-likeness and expression quality, but also warns that poor design can produce discomfort (often discussed via the "uncanny valley" idea). David Hanson's research (2006) proposes research thinking of the idea of an "uncanny valley" in robots. This research describes a series of preliminary tests that attempt to map out human reaction to robots that are nearly human-looking in appearance [3]. In Gheorghe Asachi's (2012) research, he explored making social robots with a special emphasis on designing their eye system, mouth system, and neck system [4]. Jizheng Yan et al. (2014) systematically engineered an advanced intelligent control system and constructed an authentic robot head [5]. Wagshum Techane Asheber et al. (2015) crafted a robot with an efficient mechanism that can create more expressions without needing extra parts [6]. Varun B.L and Rohan B.L.'s research celebrates Sophia (2019), which is a humanoid robot, with groundbreaking impact, heralding a new societal era with her human-like psychological traits [7]. Anna Henschel et al. (2021) addressed the difference between scientific definitions of social robots and public expectations [8]. According to Anouk Neerincx et al. (2023) , in the Netherlands, the child and family centre takes care of kids' health, both physical (vaccines, check-ups) and mental (family coaching, school sessions) [9]. Motivated by this gap, M.H.R.S.I. focuses on an economical yet expressive head mechanism that can be manufactured with FDM and controlled using a single-board computer.

3. System overview

M.H.R.S.I. is organized into mechanical subsystems (outer shell and inner mechanisms) and an electronic/control subsystem centered on Raspberry Pi. The outer geometry includes upper face, lower jaw, back, detachable top, and a stand designed to support the internal assembly. The inner assembly includes an eye movement mechanism, a lower jaw motion mechanism, and servo-driven facial expression actuation.

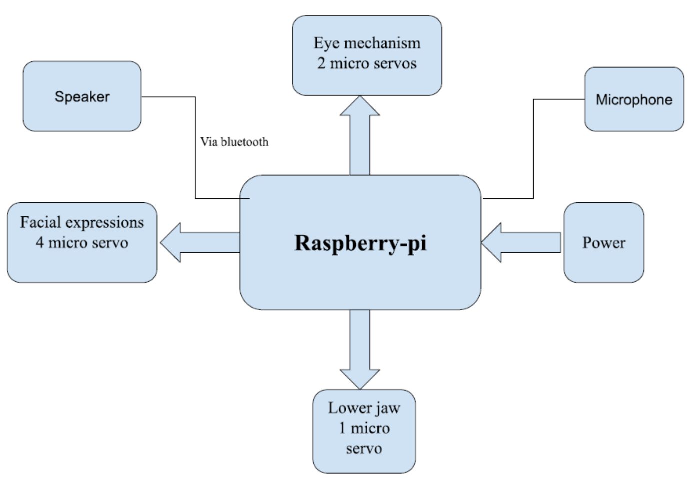

Fig. 3.2.1. Block Diagram of the Control Panel

A block diagram (see in fig.1) is a visual depiction of a system that shows how various Components are connected. A block-level electronic architecture uses seven SG90 micro servos, a microphone, a Bluetooth speaker, and an HC-SR04 ultrasonic sensor, all interfaced through Raspberry Pi GPIO/PWM and USB/Bluetooth connectivity. The intended interaction flow is: user speech captured by microphone → speech-to-text conversion → answer retrieval by a QA model → text-to-speech audio output via speaker, with optional expression triggers based on events and sensor input.

3.1 Hardware components

Key components and specifications used in the prototype are summarized in Table 1.

Table 1. Core hardware used

Component	Role in system	Specification (used/mentioned)
SG90 micro servo motors	Jaw, eye actuation, facial expression actuation	~180° rotation, 4.8–5 V, stall torque ~1.8 kgf·cm; 7 servos used.
Raspberry Pi 4 Model B	Main controller for sensing, audio, and QA pipeline	Quad-core Cortex-A72 (1.5 GHz), dual-band Wi-Fi, Bluetooth 5.0, USB ports.
Microphone (REES52 PC mic)	Speech input	Used as Raspberry Pi–compatible microphone (effective distance noted as >2 m in thesis).
Bluetooth speaker	Speech output	Connected to Raspberry Pi via Bluetooth for audio output.
HC-SR04 ultrasonic sensor	Proximity detection	Used to detect nearby users and trigger behaviors (e.g., greeting/anger distance logic).

4. Mechanical design methodology

The mechanical design is implemented in SolidWorks using a combination of sketching, surface modeling, thickening, splitting, and part assembly. The face geometry is created by tracing front and side reference views and generating surfaces that are later thickened, with reported face thickness around ~2 mm (varying locally due to geometry). The lower jaw is separated from the upper face using the split operation and connected via hinges so that the jaw rotates relative to the upper face.

The back portion is modeled using a similar approach, while the detachable top is created by sketching, extrusion, and shelling to form a hollow part that can be pinned onto the back. A stand and adjustable back supporter are designed to carry the load of the mechanism and to maintain alignment between inner mechanisms and outer shell parts.

4.1 Inner mechanisms

Jaw plate and mounts. A lower jaw plate is designed to mount onto the stand, with provisions for servo placement and supports for the eye mechanism.

Eye mechanism. The eye movement mechanism consists of a base plate, links for motion transfer, a servo holder, and eyeball/holder parts, with two servos used to generate left–right and up–down eye motion. The eyeballs are attached to the eyeball holder and coupled to specific linkage elements so that servo rotation produces constrained eye movement.

5. Kinematic calculations (eye motion)

The analysis derives eye motion calculations by using SG90 servo speed characteristics and linkage geometry simplified into kinematic chains. Using a servo speed of 60° per 0.1 s, the analysis computes an angular velocity of approximately 10.47198 rad/s for the servo arm. For up–down eye motion, the instantaneous center (I-center) method is used to compute an output angular velocity of approximately 7.0523 rad/s for the output link and an eye angular displacement around 0.6734. For left–right motion, the analysis indicates a simplified case where input and output links have the same angular velocity due to the 90° geometry relationship between adjacent links in the simplified mechanism diagram.

The servo pulse positions (1 ms, 1.5 ms, 2 ms) is also analysis corresponding to angular extremes/middle and estimates a pulse increment per degree (reported via a unitary method). These calculations are used primarily for feasibility and motion planning rather than closed-loop gaze control.

6. Structural simulation (SolidWorks)

Before fabrication, a SolidWorks static simulation study is used to check feasibility under representative loads and boundary conditions. The simulation defines fixtures including a fixed stand and a hinged lower jaw, then applies gravity, a hinge torque of 0.1 kgf·cm, and an external force totaling 4 N. The study then meshes the body as shown in fig. 2 and evaluates stress and strain distributions.

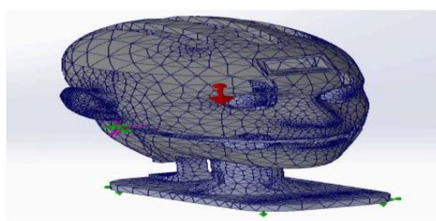

Fig. 2. Meshed Body using SolidWorks

Table 2. Static study loads

Load type	Value (as used)
Gravity	9.81 m/s²
Hinge torque	0.1 kgf·cm
External force	4 N

The paper includes von Mises stress visualization and notes a yield strength reference of 66,780,000 N/m² within the stress plot legend. Strain plots are displayed in fig. 3, with a maximum strain scale on the order of 2.300×10^{-4} in the displayed legend. These outputs support a feasibility claim that the structure remains within acceptable limits for the modeled loading scenario.

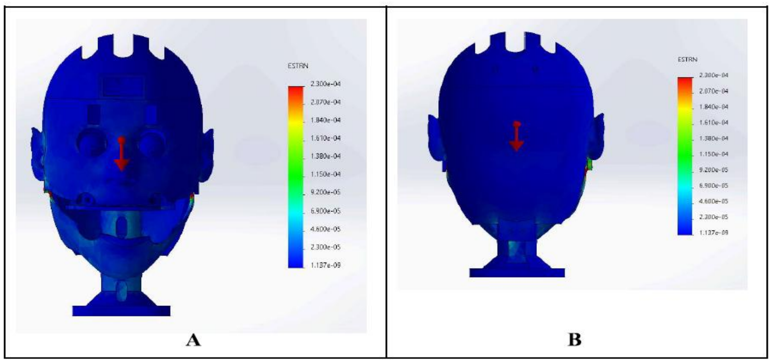

Fig. 3. A. Front view of strain analysis of robot, B. Back view of strain analysis of robot.

7. Facial expression actuation and triggers

Facial expressions are generated by commanding predefined servo positions to emulate common affective cues (smile, sadness, surprise, anger). The paper maps expression "effects" to specific servo numbers and small angular offsets relative to a mean position. Table 3 summarizes the expression trigger logic and servo mapping.

Table 3. Expression mapping used

Expression	Servos involved	Commanded motion (reported)	Intended effect (reported)
Happy	1, 2	Both ~2° outwards	Widens lips (smile cue).
Sad	1, 2, 6, 7	All ~2° inwards	Lowers eyebrows + shortens lips.
Surprised	6, 7	Both ~4° outwards	Raises eyebrow.
Angry	6, 7	Both ~4° inwards	Shrinks forehead / warning cue.

The proximity-based "anger" behavior is tied to ultrasonic sensing, where a distance threshold (30 cm) is used to trigger the response. This mapping is designed as a simple behavior layer to create expressive feedback even when the verbal pipeline fails or when users are too close to the device.

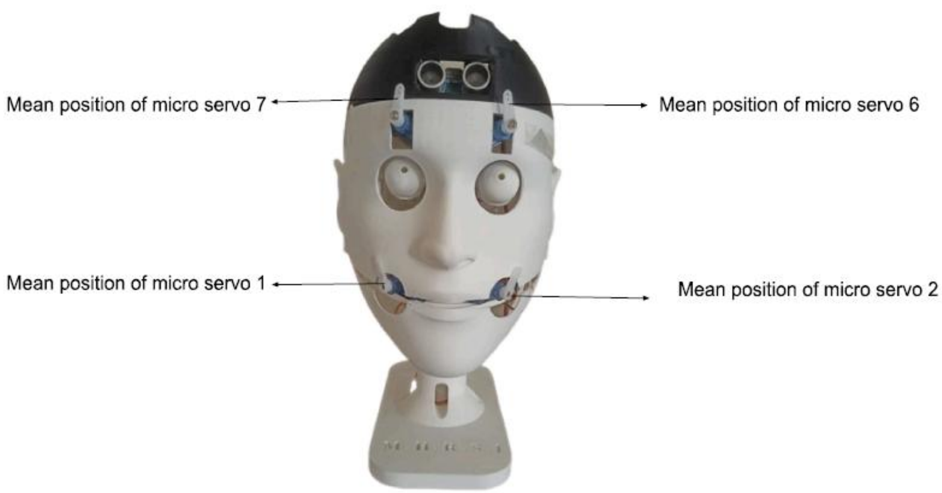

Fig. 4. Mean position of micro servo motor

8. Results and feasibility outcomes

The paper reports successful completion of a humanoid robotic head prototype capable of producing facial expressions and interacting with humans, with the design executed in SolidWorks for 3D modeling and simulation. It reports additive manufacturing completion using FDM with PLA and claims that the process supported structural integrity through material selection and printing. It further reports successful integration of the jaw, eye mechanism, and expression generation, with stability and motion constraints supported by SolidWorks simulation.

At the system level, the head is equipped with speech recognition and speech generation capabilities, environmental awareness via sensors, and Raspberry Pi–based control enabling communication and response to stimuli. The “pilot study insights” are primarily feasibility-oriented, emphasizing the interdisciplinary integration of design engineering, computer science, and electronics, and positioning the project as a reusable methodology for future humanoid robot development.

The current prototype focuses on feasibility and reproducibility rather than full human-robot interaction validation in complex social settings. The expression mapping uses small-angle servo offsets with event-based triggers, which is simple to implement but may be limited in expressiveness compared to high-DoF actuation systems. The QA approach is dependent on the provided context database and therefore behaves as a constrained-domain assistant unless the knowledge base is expanded.

9. Conclusion and future work

This paper presented the design, simulation, fabrication, and integration of M.H.R.S.I., a mechanical humanoid robot head intended for social interaction through facial expressions, eye movement, and speech-based question answering. The design combines a CAD-driven mechanical workflow with an embedded Raspberry Pi controller and a lightweight QA model adapted by a predefined context database. Future work includes enhanced humanoid features, richer sensory integration, improved speech recognition/NLP, emotional intelligence behaviors, expanded applications (healthcare/education), formal HRI user studies, and potential integration with smart home/IoT systems.

Reference

[1]. J. A. Rojas-Quintero and M. C. Rodriguez-Liñán, "A literature review of sensor heads for humanoid robots", Rob. Auton. Syst., vol. 143, no. 103834, p. 103834, Sep. 2021.

[2]. M. Akhtaruzzaman and A. A. Shafie, "Evolution of Humanoid Robot and contribution of various countries in advancing the research and development of the platform", in ICCAS 2010, Gyeonggi-do, 2010.

[3]. L. V. Ho et al., "A hybrid computational intelligence approach for structural damage detection using marine predator algorithm and feedforward neural networks", Comput. Struct., vol. 252, no. 106568, p. 106568, Aug. 2021.

[4]. F. Adăscăliței and I. Doroftei, "Expressing emotions in social robotics - A schematic overview concerning the mechatronics aspects and design concepts", IFAC Proc. Vol., vol. 45, no. 6, pp. 823–828, May 2012.

[5]. J. Yan, Z. Wang, and Y. Yan, "Humanoid robot head design based on uncanny valley in facial expressions", J. Robot., vol. 2014, pp. 1–5, 2014.

[6]. W. T. Asheber, C.-Y. Lin, and S. H. Yen, "Humanoid head face mechanism with adaptable facial expressions", Int. J. Adv. Robot. Syst., vol. 13, no. 1, p. 29, Jan. 2016.

[7]. Y. Bai, D. C. Nardi, X. Zhou, R. A. Picón, and J. Flórez-López, "A new comprehensive model of damage for flexural subassemblies prone to fatigue", Comput. Struct., vol. 256, no. 106639, p. 106639, Nov. 2021.

[8]. A. Henschel, G. Laban, and E. S. Cross, "What makes a robot social? A review of social robots from science fiction to a home or hospital near you", Curr. Robot. Rep., vol. 2, no. 1, pp. 9–19, Feb. 2021.

[9]. A. Neerincx, D. Veldhuis, J. M. F. Masthoff, and M. M. A. de Graaf, "Co-designing a social robot for child health care", Interact., vol. 38, no. 100615, p. 100615, Dec. 2023.