Robotic Eye System for Animatronic Faces in Human-Robot Interaction

Marina Z. Rocha
Centro de Ciências Computacionais
Universidade Federal do Rio Grande
Rio Grande, Brasil
ORCID: 0009-0007-7048-429X

Igor P. Maurell
Centro de Ciências Computacionais
Universidade Federal do Rio Grande
Rio Grande, Brasil
ORCID: 0000-0002-4376-9544

Kristofer S. Kappel
Centro de Ciências Computacionais
Universidade Federal do Rio Grande
Rio Grande, Brasil
ORCID: 0000-0002-9124-8540

Paulo L. J. Drews-Jr
Centro de Ciências Computacionais
Universidade Federal do Rio Grande
Rio Grande, Brasil
ORCID: 0000-0002-7519-0502

Rodrigo S. Guerra
Centro de Ciências Computacionais
Universidade Federal do Rio Grande
Rio Grande, Brasil
ORCID: 0000-0003-4011-0901

***Abstract*—Anthropomorphism plays a crucial role in Human-Robot Interaction (HRI), as nonverbal cues, such as eye gaze and facial expressions, significantly influence social perception. Among facial features, the eyes are particularly important, as they convey emotion and indicate the focus of attention. This work presents the development of a compact and functional animatronic eye system designed to improve an existing mechanism integrated into the robotic face of a domestic service robot. The current system, which mechanically links both eyes, limits expressiveness and restricts natural movement. To address these issues, two alternative mechanisms were explored: ABENICS and a system inspired by the HITSZ-Snakebot II robot. These were developed through CAD modeling and fabricated using both FDM and DLP 3D printing techniques. Three prototypes were created—two based on ABENICS and one on the snakebot design. The final prototype, based on the snakebot model, proved to be the most effective, offering a greater angular range, size reduction, and smoother, more natural movements. Its modular, compact structure makes it suitable for integration into expressive robotic faces, contributing to the development of more relatable and socially capable robots.**

***Index Terms*—robotic face, anthropomorphism, 3D modeling, social robotics**

I. Introduction

Anthropomorphism is a relevant topic in the field of Human-Robot Interaction (HRI). As Mori's Uncanny Valley theory from 1970 [1], people tend to prefer interacting with elements that they can relate to. The presence of human traces usually has a positive impact on HRI. However, if the robot's similarity to humans is excessive, it often causes discomfort to the users. Studies suggest that emotions are mainly communicated through non-verbal signals in social interactions [2].

One can notice that eyes are key elements in social communication, as they denote one's region of attention. This is emphasized by facial pareidolia, a phenomenon in which humans identify faces in faceless objects. Usually, the pattern consists of two parallel, symmetrical traces with a third one in the middle, vertically displaced. The lower trace can be seen as a mouth or a nose; either way, the other two are recognizable as eyes, [3].

The eyes enable most emotional expressions, and through eye gaze, it is possible to indicate an area of interest. A robot with this ability can be perceived as a predictable agent, which can reduce the level of discomfort experienced by users. Hence, facial expression reproducibility is a relevant feature in the HRI area [4].

The human eye has 3 DoF, being able to rotate in the axis: roll, pitch and yaw, as shown in Fig. 1. Main movements are vertical, looking up and down, and horizontal, which is perceived as pupil dislocation from the closest to the furthest lateral points to the nose. Pitch and yaw rotation ranges are approximately 75° and 90°, respectively, as roll angular amplitude is very small; this axis is usually disregarded in mechanical faces [5].

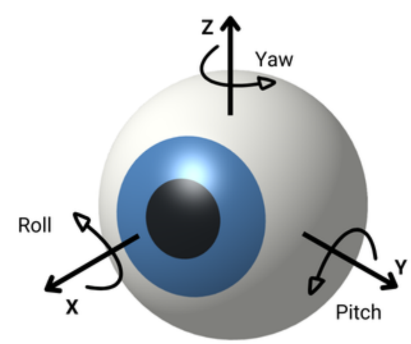

Fig. 1: Human eye axis of rotation

Therefore, this work proposes a model capable of achieving wider and more robust movements compared to the existing systems. The range of human eye movement was used as a reference, approximately 90^o of yaw rotation and 75^o of pitch.

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By achieving an angular range equal to or greater than that of the human eye, the model can reproduce expressions in a way that resembles natural movement. Despite mimicking human motion, it is expected that the model's cartoonish appearance and materials prevent the Uncanny Valley effect.

The current eye system limitations were mapped, with the main features to improve being angular amplitude for both axes and detached structure for each eyeball. The development of this project involved CAD modeling and 3D printing of two prototypes inspired by the ABENICS and HITSZ-Snakebot II mechanisms. The resulting models were assembled with the 3D-manufactured parts and micro motors as actuators.

This paper is organized as follows: Section II presents related works; Section III describes the mechanisms studied; Section IV details the methodology of the prototype developments; Section V discuss the projects results, highlighting the features improved comparing with the original system; Lastly, Section VI concludes the paper and summarize possible future work.

II. Related Work

In the context of service robots, it is desirable for people to feel at ease in their presence. Thus, it is expected that these robots should display a high level of sympathy. Advancements in the HRI area have enabled the development of anthropomorphic robotic interfaces capable of emulating human facial expressions.

Animatronic faces can be defined as a mechanical system integrated with an electronic circuit, designed to replicate the facial expressions of humans, animals, or fictional creatures [2]. Although this paper focus on this category of social interface, it is worth mentioning other types of robotic faces seen in the literature.

A. Non-mechanical robotic interfaces

Non-mechanical robotic interfaces can be subdivided into Static or Digital faces. The first, relates to robots that present a fixed expression, in this cases this feature is employed mostly to create the impression of another social agent. Example of robots with static interfaces include: Robovie-V4; Pepper; and Romeo.

Facial expressions can be emulated without mechanical parts, the common alternatives for those are light projection or the use of digital screens. In the first approach, a translucent material mask covers the front of the head and a projector is positioned inside this structure, in order for the image to appear in the facial region. Some of the robots utilizing this method are Taban [6]; SociBot™; and Furhat [7].

Virtual faces can be assembled with digital screens, which can vary from simple facial structures such as EyePi; BEO; and PALbator [8]–[10], to more complex ones like CHARMIE; HERA; [11], [12] and Robio. Those models can present advantages, as they are usually lightweight and easily adaptable, compared to other facial structures. Nonetheless, their visibility can be reduced depending on light conditions and on the user's viewing angle of the robot's front. Furthermore, due to the flat design of most virtual faces it is difficult to achieve an anthropomorphic face shape [2].

B. Mechanical robotic faces

Certain robotics faces combine mechanical parts with LEDs (Light Emitting Diode) for simulating facial expressions. Examples of robots in this category include iCub; MARKO; and Twente humanoid head [5], [13], [14]. Other hybrid models employ this features to expand human facial expressions, resembling cartoonish gestures, such as Robothespian; KOBIAN; and Flobi [15], [16].

Entirely mechanical robotic faces are found in the literature in a range of styles, from high humanoid resemblance to even fictional low realism models. Robots like Sophia, Little Sophia and Zeno by Hanson Robotics©; Erica; Geminoid; and HRP-4C [17]–[19], were designed with convincing human appearance, and combine their mechanical structure to replicate facial expressions as natural as possible. Even though the mentioned robots are reference in the area, due their high similarity to humans, they tend to fall into Uncanny Valley [1].

Animatronic faces commonly embrace mechanical faces characterized by their anthropomorphic, zoomorphic or fictional aspects, presenting unrealistic style [20]. The models analyzed in this project were selected based on the presence of eyes system, humanoid traces, low realism features and available descriptions.

Kismet [21], features expressive eye control with independent yaw movement and synchronized pitch movement, allowing it to simulate natural gaze behaviors. The robot also includes independent upper eyelids, which enable varied blinking patterns, enhancing emotional expressiveness. However, it lacks lower eyelids, limiting the full range of eye-based expression.

KOBIAN [15], supports pitch-synchronized and yaw-independent eye movement, enabling its ability to simulate natural gaze shifts. It includes blinking eyelids, that contribute to basic visual behaviors and to the display of emotions. The eye system relies on a pulley-based mechanism, which adds mechanical complexity and increases the risk of failure.

Muecas [22], allows the eyes to move independently in yaw and together in pitch via a linear screw mechanism. Unlike others, it does not feature eyelids, which can cause users discomfort and diminish realism in emotional interactions. The exposed eye mechanisms, also present challenges for durability and aesthetics.

InMoov, in its original version, lacked eyelids and eyebrows, reducing its ability to convey emotions through the eyes [23]. A second version introduced these features to improve expressiveness. The robot's eye system remains simple, prioritizing accessibility and ease of replication, and intentionally embraces a robotic appearance to avoid the Uncanny Valley.

https://robots.ros.org/robovie-r4/
https://us.softbankrobotics.com/pepper
http://doc.aldebaran.com/2-5/home_romeo.html
https://www.humanrobotics.ai
https://engineeredarts.com/robot/robothespian

Eva 2.0 provides independent eye movement, though with a restricted angular range, limiting the expressiveness of gaze shifts. Its face is covered with a silicone mask featuring ten control points, which contributes to more lifelike facial expressions [24]. The design prioritizes accessibility and open-source adaptability, balancing functionality with ease of replication.

MARKO [5], employs 4-bar mechanisms for its eyes, eyebrows, and eyelids, allowing coordinated movement that supports both gaze and emotional expression. However, the inclusion of LEDs for enhancing facial expression and the absence of a movable mouth limit its ability to synchronize visual and verbal communication.

Open Robot, uses 4- and 5-bar linkages to reproduce eye movements as part of a larger system capable of expressing up to 94% of human facial actions, [25]. Despite the mechanical range, the lack of material variation and the exposure of internal mechanisms may cause discomfort in users during interaction, affecting the perception of eye realism.

Jubileo [26], incorporates independent movement of eyelids and eyebrows, allowing basic emotional expression. The eye system, uses lightweight and unconventional materials, which may affect long-term stability and precision. Though not highly durable, this design reflects a low-cost, adaptable approach for exploring facial expression in HRI contexts, making it a valuable platform for experimentation and research.

Adam [27], features eyes mounted on ball joints, that closely mimics human gaze shifts. However, it lacks eyelids entirely, which limits its emotional range. Additionally, the presence of a central hole in the forehead for a camera and the complexity of its ocular system may reduce user's comfort and increase the likelihood of mechanical failure.

III. Sphere Rotating Mechanisms

A. Current System

The base of this project is an animatronic face of a domestic service robot, which integrates eyes, eyelids, eyebrows, and jaw movements. Those systems are assembled with 3D-printed parts and utilize servomotors as actuators. The current eye mechanism possesses 2 DoF, capable of moving the eyes simultaneously horizontally or vertically.

Horizontal system works by indirect movement of both eyes, as presented in Fig. 2. The clockwise rotation of the servo motor (red arrows) causes the orange piece to shift leftward, moving the eyes in the opposite direction, as indicated by the dashed arrows. It can be observed that the central axes of both eyes (highlighted in pink) are connected to the pink piece. This results in limited movements due to the length of the connecting parts and the limited internal space within the eyes. It also impedes adduction and abduction gestures, for example, looking at the nose.

The vertical range of movement is significantly lower than human eye limits, being 30^o, while the natural pitch range is 75°. The eyes are also linked to each other in this axis rotation, as shown in Fig. 3. The blue base, where both eyes are interconnected, is attached to the pink rod, which is actuated by the servo motor. The movement limitation is highlighted

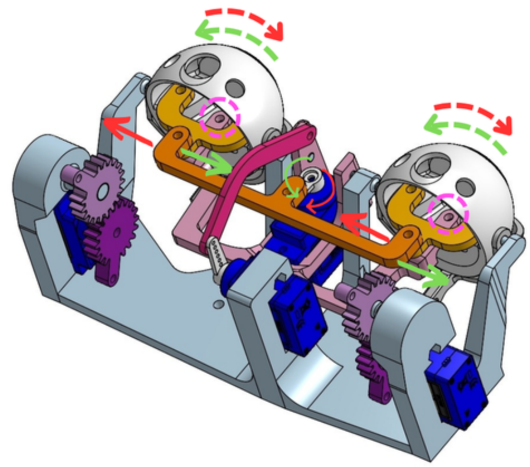


Fig. 2: Horizontal movement diagram

by the red arrows, indicating the contact points between the system's components.

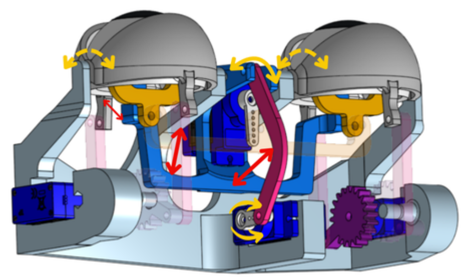


Fig. 3: Vertical movement diagram

From this literature review, it was estimated that independent mechanisms for each eyeball would enhance movement range and stability. Therefore, the studied models were focused on rotating sphere systems, which could be adapted into a single robotic eye structure with 2 DoF.

B. ABENICS Mechanism

Based on the analysis of the current eye mechanism, it is proposed to develop an independent mechanism for each eye. One study that proved particularly relevant for orbital movement is the ABENICS model [28]. This model features a 3 DoF rotational system composed of a spherical gear paired with two monopolar gears, as shown in Fig. 4. The sphere is attached to a fixed support, while the other gears are connected to the motors. Their shape enables motion similar to that of conventional spur gears. Additionally, the design allows the spherical gear to slide passively between the others.

C. Snake Robots

The second mechanism studied is based on Snake Robots, bio-mimetic robots inspired by snakes' mobility. An example

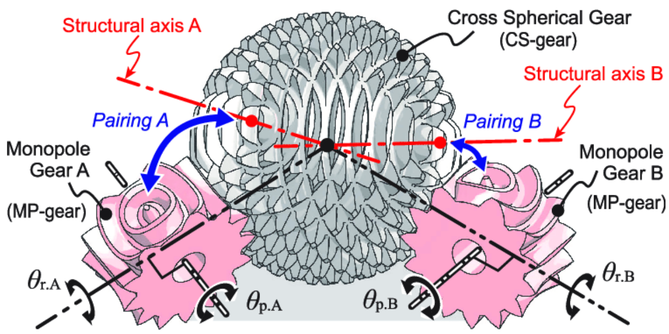
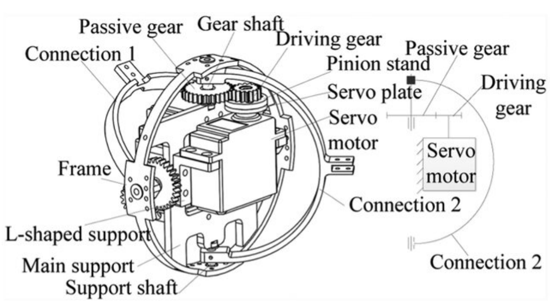
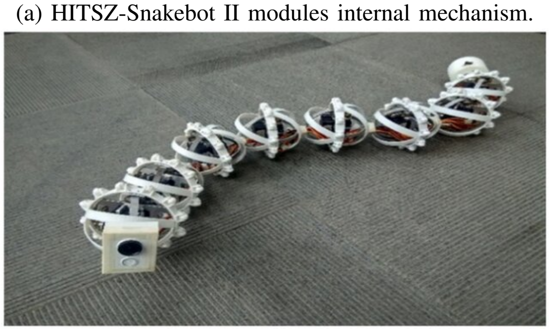


Fig. 4: Structure of an ABENICS system. Source: [28].

of a snake robot found in the literature is the HITSZ-Snakebot II [29]. Its system consists of a combination of eight spherical modules, each with two degrees of freedom (2 DoF) and equipped with two motors. Fig. 5 illustrates the snake robot mechanism analyzed in this study. In which, Fig. 5a presents the internal structure of each module of the HITSZ-Snakebot II. And Fig. 5b shows this robot's prototype assembly of the eight spherical modules. The angular range of this model is estimated to be approximately 90° in both pitch and yaw. This exceeds the rotational capacity of the human eyeball, making the system suitable for adaptation in this project. Each module has a diameter of 103 mm, and due to its metallic structure, it weighs 335g. Considering these characteristics, it was necessary to scale the system down to ensure the eyes proportion to the robotic face. Additionally, the mechanism had to be lighter to maintain stability in the overall system.



(a) HITSZ-Snakebot II modules internal mechanism.



(b) HITSZ-Snakebot II prototype.

Fig. 5: Design and physical model of HITSZ-Snakebot II. Adapted from [29].

IV. Proposed Eye System

To develop a functional and compact animatronic eye system, this work involved designing, modeling, and fabricating different prototypes based on two distinct mechanisms: ABENICS and the HITSZ-Snakebot II. The models were developed through CAD modeling and physical prototyping, with a focus on achieving a lightweight structure that allows for a wide range of motion in both pitch and yaw axes.

The components were manufactured using two 3D printing techniques. Fused Deposition Modeling (FDM), with PLA (Polylactic Acid), was used for parts requiring greater toughness and resistance to impact, as well as for pieces that benefited from easier and more cost-effective printing. Digital Light Processing (DLP), using dental resin, was employed for components requiring higher precision and finer detail, such as complex gears and small connectors, where dimensional accuracy and surface quality were critical [30].

This methodology enabled the construction of compact prototypes that preserved functional integrity while allowing fast iterations. Moreover, the compactness and modularity of the snakebot-based design ultimately proved more suitable for integration into the robotic face, given its greater angular range and reduced volume.

A. ABENICS Inspired Version

The first design was adapted from the ABENICS mechanism by reducing it to 2 DoF: rotation axes, pitch, and yaw. The structure consisted of two orthogonal spur gears linked to a cross spherical gear, as shown in Fig. 6.

Due to inconsistencies between the 3D model and the physical pieces, friction occurred, causing the sphere to dislocate from its axis. To correct this, printing quality was improved, and a third passive spur gear was added to help stabilize the spherical gear.

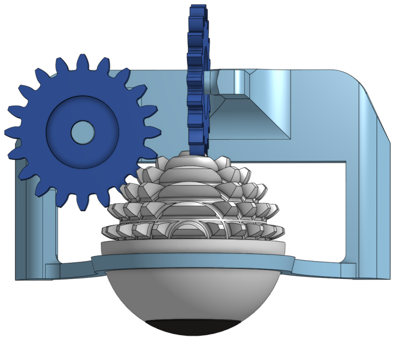
Another challenge faced was the fragility of the main axis (white ring). To improve its resistance, the width of this part would need to be increased to the point where most of the visible part of the sphere would be covered. As an alternative, a transparent semi-sphere was considered as the axis of rotation. This widened the contact area, making the mechanism steadier while still allowing the frontal side of the sphere to remain visible.

Fig. 7 presents the second version of the ABENICS-based model, already equipped with servomotors as actuators. It is worth noting that the spur gear ratio is 1:1, designed to avoid a reduction in motor rotation.

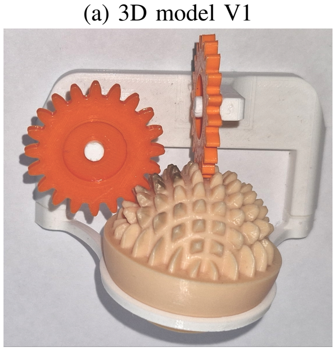
B. Snakebot Inspired Version

To adapt the HITSZ-Snakebot II modules to an eye model that fits into a robot head, the servo motors were replaced with micro-stepper motors. These smaller, lighter actuators are more suitable for the application. Additionally, using 3D-printed parts helped reduce the overall weight of the system.

Alongside improvements to the second version of the ABENICS model, a new design was developed based on the HITSZ-Snakebot II mechanism, illustrated in Fig. 8 The

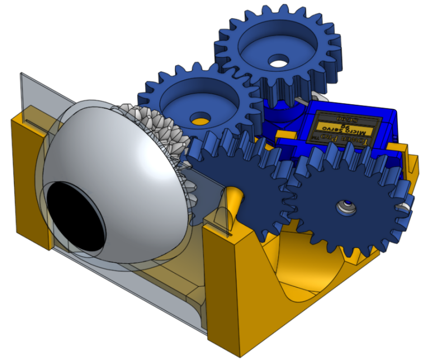


(a) 3D model V1

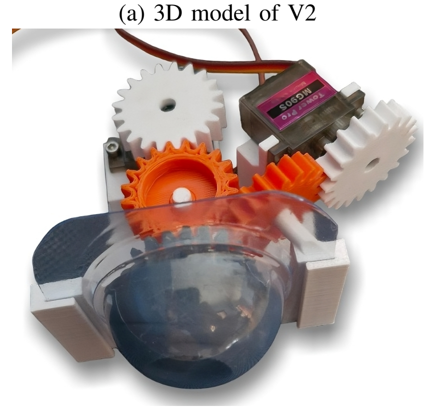


(b) Physical prototype of model V1

Fig. 6: Version 1 of ABENICS model.



(a) 3D model of V2



(b) Physical prototype of model V2

Fig. 7: Version 2 of ABENICS model.

system includes a rotating base (yaw axis) that holds two micro stepper motors, and a fixed base with bearings for pitch movement. The mechanism uses two gear systems:

- Vertical: Features a 1:2.5 gear ratio. The passive gear is aligned vertically with the sphere, while the motor is placed on the front face of the rotating base.
- Horizontal: Due to space constraints, a 1:1 gear ratio was used. The motor is mounted at the rear of the rotating base, with the passive gear directly fitted into an opening in the sphere. To avoid part overlap, the yellow component includes a notch aligned with the motor shaft.

The size reduction from the original HITSZ-Snakebot II model was a challenging part of the development. Although the replacement with the micro stepper motors was sufficient, designing pieces to fit inside the eyeball demanded precision and high-quality 3D printing. The spur gears fabricated through the FDM process were adequate. For the gyratory base, DLP manufacturing was opted for to ensure accurate measures. The fixed base and external eye parts were also printed in FDM, due to their low complexity.

V. Results

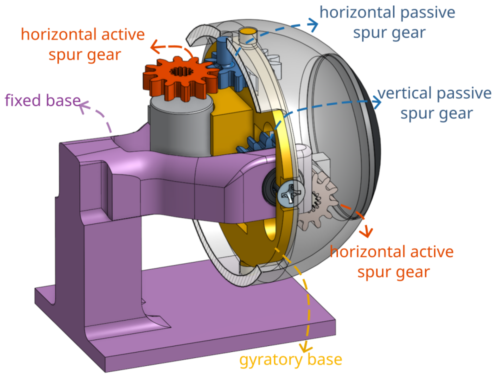
Three prototype versions were developed in this project, two based on the ABENICS mechanism and the third was inspired by the HITSZ-Snakebot II model, as shown in Figs. 6b, 7b and 8b, respectively. The ABENICS-based systems combine spur gears and spherical gears, enabling 2 DoFs: pitch and yaw. Although the second version presented itself as steadier than V1, with thicker spur gears and with the sphere positioned on its axis, there were still points of friction. This restrained the range of rotation and resulted in uneven movements.

The third prototype, based on snakebots, proved to be more suitable for this project's demands. Compared to V1 and V2, this version is approximately 54% smaller, easier to replicate, and offers greater stability. The snakebot eye design presented an approximately 73^o amplitude in yaw and 95^o in pitch, which is a movement range higher than that of the human eye. With these features, the developed prototype is more robust than the current eye system, enabling smoother and more natural movements.

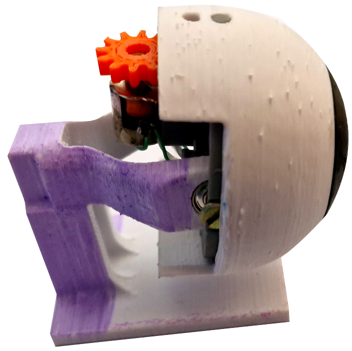
VI. Conclusion

This work presents the development of a prototype for an animatronic eye system. Two main mechanisms were studied: ABENICS and the snake robot combined with 3D modeling and printing techniques. The resulting structure, based on the HITSZ-Snakebot II model, addresses the limitations of the original eye system in a compact and accessible way. Therefore, the project achieved its objective of redesigning a more robust robotic eye system.

One of the next steps is to integrate the eye system into the complete animatronic face, incorporating eyelids, eyebrows, and jaw to validate the mechanism's robustness in a more realistic setup. Additionally, the models developed here open opportunities for comparative studies and validation analyses,



(a) 3D model of snakebot model version



(b) Physical prototype of snakebot model version

Fig. 8: Model based on snakebot

which can further improve the design and performance. Ultimately, this prototype lays the groundwork for qualitative research into the social impact of animatronic faces in service robots, potentially yielding valuable insights for the field of social robotics.

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