
Extra-ocular Muscles for Robotic Eye and its Control Design for Real-Time Stimulus Tracking

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Abstract:

For coordination and communication in human-robot interaction within a social environment, fast camera sensor movement is crucial for stimulus tracking. This paper proposes bio-inspired extra-ocular muscles for humanoid robotic eyes to achieve a high decoupling ratio between the camera sensor and the robotic head skeleton. The extra-ocular muscles, based on a gimbal system, offer effective decoupling and enable the camera sensor (ESP32 CAM) to be mounted within the inner channel, resembling the human eyeball in the extra-ocular muscles. The high decoupling ratio provided by the gimbal system makes the robotic eye more suitable for fast real-time stimulus tracking. The implemented control system allows for both automatic target tracking and manual control using commands. A comparison between the human and robotic eyes, including structure, mechanical design, and tracking mechanism, demonstrates the suitability of the proposed extra-ocular muscles for humanoid robots. A short video demonstrating real-time stimulus tracking by the robotic eye is provided as well.

Keywords: Extra-ocular Muscles; Control Design; Tracking Stimulus; Humanoid Robotic Eye

I. INTRODUCTION

Human-Robot Interaction (HRI) is a multidisciplinary field focused on the interaction between robots and humans. Human beings depend on their visual sensory input, with the eyes processing up to 80% of environmental data in the context of a constantly evolving social setting. In such a dynamic environment, the task of data perception presents significant challenges for robots. The perception of data within a dynamic environment necessitates a high degree of decoupling between the robotic eyeball and the underlying head skeleton. This substantial decoupling plays a crucial role in enabling effective stimulus tracking and, consequently, the acquisition of a greater volume of data. Analogous to human eyes, which employ extraocular muscles to achieve this decoupling ratio, researchers in the field of robotics have tackled this challenge through various technological advancements. The primary objective within this domain is to enhance information acquisition concerning a given stimulus through precise tracking mechanisms. Comparative overview of bionic and robotic eye systems vision systems restoration vs. industrial and motion tracking applications is provided here.

Bionic Vision Australia has demonstrated success in restoring vision through an implanted chip connected wirelessly to a camera on glasses [22]. Although it has proven effective for vision restoration, its resolution is limited compared to natural vision, and it focuses mainly on restoring vision rather than offering advanced functionalities like high-speed tracking. Second Sight's Argus II stands out as one of the most advanced bionic eye systems, aiding patients with severe vision loss by employing a retinal implant linked to a camera on glasses [23]. Despite its advancements, the Argus II is constrained by limited visual resolution, a narrow field of view, high costs, and a complex surgical implantation process. On Robot Eyes are tailored for industrial applications, providing 2.5D vision capabilities suitable for sorting, CNC machine tending, and pick-and-place tasks. While effective in these contexts, they are not designed for vision restoration or humanoid robotics and exhibit moderate tracking speed and accuracy

compared to more sophisticated systems. The Insect-Inspired Compound Eye features an impressive 220° field of view and motion-tracking capabilities, inspired by the wide-angle vision of insect eyes [24]. However, its lower resolution compared to human-like artificial eyes limits its applicability to scenarios requiring broad vision rather than detailed image analysis.

The researchers have directed their efforts toward advancing robotic eye technology in three key domains: camera sensors, vision control, and actuators. The camera sensors serve the purpose of acquiring information much like the eyeball in the human eye, vision control emulates the role of the brain, and actuators are employed to mimic the functions of extra-ocular muscles. In the realm of camera sensors, researchers have endeavored to replicate the functionality of the human eyeball by utilizing movable cameras [1-4]. On the other hand, a significant challenge that persists in this research is the presence of a low decoupling ratio, rendering it less effective for humanoid robots operating in dynamically changing social environments. To address the concern of vision control or brain emulation, Artificial Intelligence (AI)-based vision controllers have been proposed and implemented within the literature. These vision controllers encompass a variety of algorithms, including tracking algorithms [5,6], scanning algorithms [7], and recognition algorithms [8]. These algorithms are designed to simulate the functioning of the human brain. It is noticed that a critical challenge arises in their implementation within a continuously evolving environment, necessitating a high decoupling ratio for rapid tracking to allow for extensive training. To implement control laws effectively on camera sensors, quality actuators, and a substantial decoupling ratio are essential. Researchers have dedicated their efforts to achieving this goal and have implemented control laws through mechanisms such as soft pulleys [9, 10] and pneumatic control systems [12]. While these actuation systems have succeeded in achieving some degree of

decoupling, they contribute to the complexity of robotic eyes, increase their cost, size, and weight, and elevate their power consumption during stimulus tracking. A similar challenge is encountered in [13], where researchers experimentally confirmed that gimbal camera movements result in minimal changes in viewpoint, particularly within the context of vestibular ocular reflex movements. In [14], gimbal control was implemented for vision-based target tracking; however, it introduced complexities, weight, size, and cost concerns.

To achieve a high decoupling ratio with lower weight and cost, small-size researchers proposed an actual gimbal system for the robotic eye [15]. The proposed idea of gimbal-based tracking is verified by simulating the stabilization control using mathematically modeled state space equations with the help of MATLAB/SIMULINK [16], [17]. As per the author's knowledge, experimental implementation of the aforementioned proposed and simulated tracking control for humanoid robots for faster tracking received zero attention till now. The focus of this paper is to first compare the proposed extra-ocular muscles with the human eye to prove that a gimbal-based robotic eye can perform the functionality of extra-ocular muscles. The second objective is to experimentally implement the gimbal-based tracking control for real-time tracking. The key features are the structural simplicity, light weight, and lower cost providing a high decoupling between the camera and robotic head skeleton. These features make this eye more suitable to be used as extra-ocular muscles in humanoid robots.

In pursuit of achieving a high decoupling ratio while minimizing weight and cost, researchers have introduced the concept of a gimbal system for robotic eyes [15], [19]–[21]. The proposed idea of gimbal-based tracking is validated through the simulation of stabilization control. This simulation uses mathematically modeled state-space equations and is facilitated by MATLAB/SIMULINK [16], [17]. To the best of the author's knowledge, there has been no experimental implementation of this proposed and simulated tracking control for humanoid robots, particularly focusing on enhancing tracking speed. The primary objective of this paper is twofold. Firstly, it aims to draw a comparative analysis between the proposed bio-inspired extra-ocular muscles and their human counterparts, scrutinizing their physical structure, mechanical design, and operational mechanisms. The intention is to demonstrate that the gimbal-based robotic eye can effectively replicate the functions of human extra-ocular muscles, thereby establishing its suitability for humanoid robots. Secondly, this research endeavors to experimentally implement gimbal-based tracking control for real-time stimulus tracking. Notable features of this robotic eye include its structural simplicity, lightweight construction, and cost-effectiveness, all contributing to a robust decoupling between the camera and the underlying robotic head skeleton. These attributes position it as a viable substitute for human extra-ocular muscles within humanoid robots.

The contributions made in this paper are outlined as follows: First, the introduction of bio-inspired extra-ocular muscles for humanoid robotic eyes, followed by a comprehensive comparison with the corresponding structures, mechanical designs, and working mechanisms found in human eyes. This substantiates the potential of

the gimbal system, equipped with servo motors, to emulate the functionality of human extra-ocular muscles within robotic eyes, reinforcing its applicability for humanoid robots. Secondly, the implementation of a low-cost, ESP32-CAM-based automatic and manual control system for real-time stimulus tracking. This achievement underscores the practicality and versatility of the proposed robotic eye muscles. Additionally, the article explores the features of the robotic eye with the proposed muscles and offers recommendations for future research directions. To provide a visual demonstration of real-time stimulus tracking, a brief video has been uploaded with the link provided in the references.

The remaining paper is structured as follows: Section 2 provides the proposed method of newly proposed extra-ocular muscles and an in-depth comparison between the human extra-ocular muscles and the newly proposed extra-ocular muscles. Section 3 presents the discussion of automatic and manual control of proposed Extra-Ocular Muscles. The section discusses the distinctive features of the proposed muscles and offers recommendations for future research directions. Furthermore, we explore the real-time tracking mechanism. Finally, the paper concludes by summarizing the key findings and contributions presented throughout the document.

II. METHOD AND MATERIALS

A) The Human Eye's Extra-Ocular Muscles

From a pointing and tracking perspective, the human visual system comprises three primary components: the eyeball, extra-ocular muscles, and the brain. The eyeball serves as the optical instrument, capturing visual stimuli and relaying them to the brain via intricate networks of neurons. In response to the received visual data, the brain formulates precise commands based on stimulus positions, which are then transmitted to the extra-ocular muscles through neuronal pathways for precise actuation. These extra-ocular muscles, in turn, orchestrate horizontal and vertical movements of the eyeball, adhering to the prescribed control law. This intricate feedback mechanism within the human eye is depicted in Fig. 1. The actuator muscles, commonly referred to as extra-ocular muscles, assume a pivotal role in stabilizing, safeguarding, and orienting the eyeball. These specialized muscles effectively decouple the eyeball from the head skeleton, as visually represented in Fig. 2. Distinct pairs of extra-ocular muscles are engaged to facilitate horizontal and vertical ocular movements. The key advantage of such decoupled ocular mobility lies in its capacity to enable humans to track stimuli

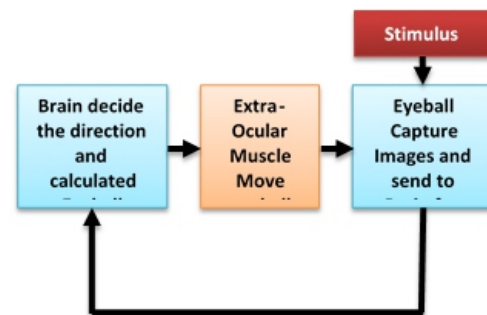


Fig. 1 The Human Eye Feedback Mechanism

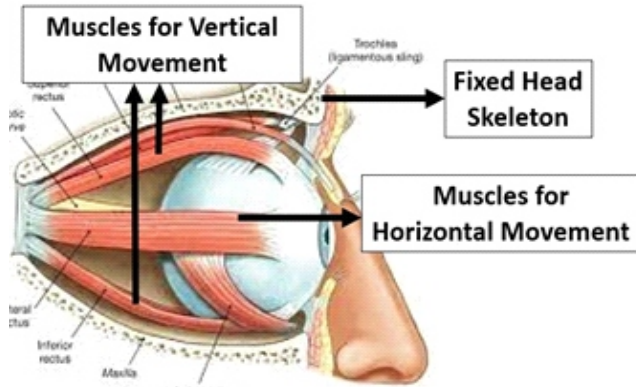


Fig. 2 The Human Eye Extra-Ocular Muscles

eyeball, adhering to the prescribed control law. This intricate feedback mechanism within the human eye is depicted in Fig. 1. The actuator muscles, commonly referred to as extra-ocular muscles, assume a pivotal role in stabilizing, safeguarding, and orienting the eyeball. These specialized muscles effectively decouple the eyeball from the head skeleton, as visually represented in Fig. 2. Distinct pairs of extra-ocular muscles are engaged to facilitate horizontal and vertical ocular movements. The key advantage of such decoupled ocular mobility lies in its capacity to enable humans to track stimuli without necessitating concurrent head movements. This efficient mechanism demands minimal energy expenditure while affording swift and precise tracking of objects within dynamic and ever-changing environments. The ability to track stimuli without head movement empowers individuals to maintain focus during activities like walking, riding, hiking, jumping, or engaging in physically turbulent conditions. In the realm of robotics, tracking stimulus without a dedicated head skeleton has posed a terrible challenge. Drawing inspiration from the highly efficient functioning of human extra-ocular muscles, researchers have endeavored to introduce similar decoupled movement capabilities in robots. Despite the fact some progress has been made in realizing stimulus tracking without head movement in robotic systems, these efforts have frequently led to intricate mechanical designs, increased weight, and elevated costs. To address these challenges, we propose a bio-inspired gimbal-based extra-ocular system for robotic eyes, offering a pragmatic solution to these concerns.

B) Proposed Extra-Ocular Muscles for a Robotic Eye

The proposed extra-ocular muscles are similar to the human eye's extra-ocular muscles in their actuation, feedback mechanism, physical structure, and mechanical design. The similarity in the actuation process is due to the gimbal system, shown in Fig. 3. For this process, the gimbal system and the two servo motors are used to hold and rotate the camera sensor of the inner channel. In human eyes, these functions are performed by the extraocular muscles. Due to this reason, we call it extra-ocular muscles for a humanoid robotic eye. The gimbal system has the property of decoupling anything mounted on its inner channel from the fixed holder. We used this decoupling property of the gimbal system for the actuation of the robotic camera sensor. For this purpose, we mounted ESP32 CAM in the inner channel of the gimbal system along with two servo motors

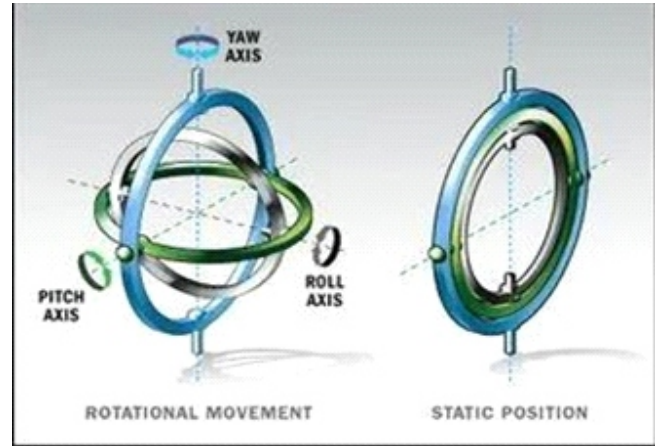


Fig. 3 The gimbal system

(one for the inner channel and one for the outer channel). The ESP32 CAM has a camera sensor that is used for the collection of information about stimuli. The acquired information is provided back to the controller which calculates a control law accordingly. The control law is then implemented using the servo motors. The feedback process is demonstrated in Fig. 4. From the physical structure and mechanical design point of view, the robotic eye with proposed extra-ocular muscles consists of a fixed holder and two rotating inner channels. The fixed holder is the part of the robotic head skeleton that remains fixed during stimulus tracking, like the human head skeleton shown in Fig. 2. The inner channels rotate in pitch and yaw axis and hold and rotate the camera sensors as the human eye's extra-ocular muscles do. We designed a CAD model shown in Fig. 5 for demonstration and implementation. This design helps us define where to mount the servo motors for actuation. The CAD design demonstrates the simplicity of the physical structure. There are just two rotating channels with a fixed holder. Simplicity from the electrical point of view can be observed in Fig. 6, which are just two servo motors connected to the ESP32 CAM. The complete design of the robotic eye with proposed bio-inspired extra-ocular muscles is provided in Fig. 6

C) Electrical Connection:

The inner and outer channels of the gimbal system are electrically connected to the controller as shown in Fig. 7. Two SG90 micro servo motors for inner and outer channels are connected through H-Bridge with ESP32 Cam where the main control code is uploaded for executions. The camera sensor tracks the target and provides information to the controller where control law decides the control command to actuate the servo motors for rotating the inner and outer channel.

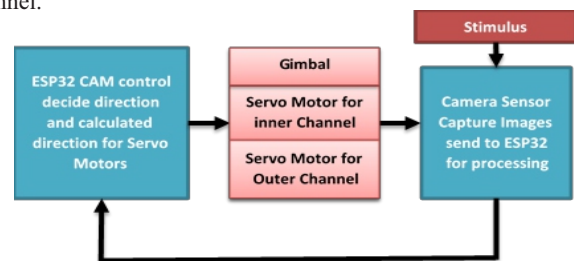


Fig. 4 The Robotic Eye Feedback Mechanism

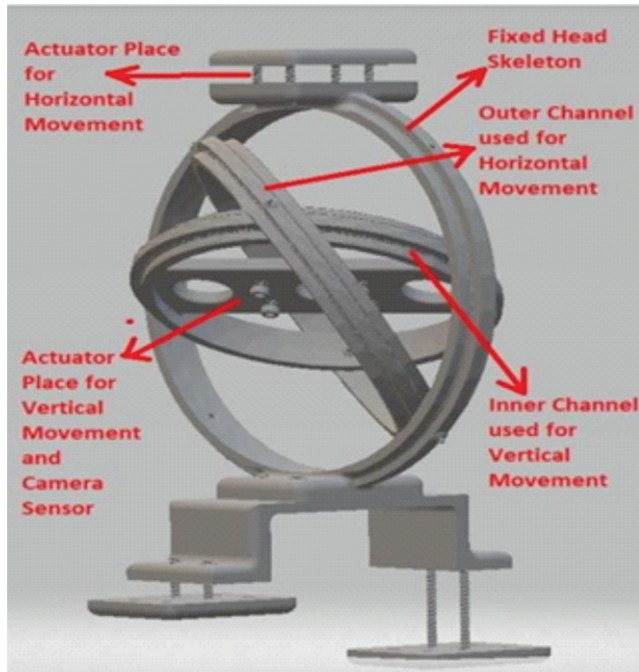


Fig. 5 CAD 3D model of robotic eye

D) Control Design:

Control of the proposed extra-ocular muscles for a robotic eye have two choices Manual Control and automatic control as shown in Fig. 8. GUI is developed for manual control to track a stimulus while the PI controller automatically control the proposed muscles. Details of both controls are given below.

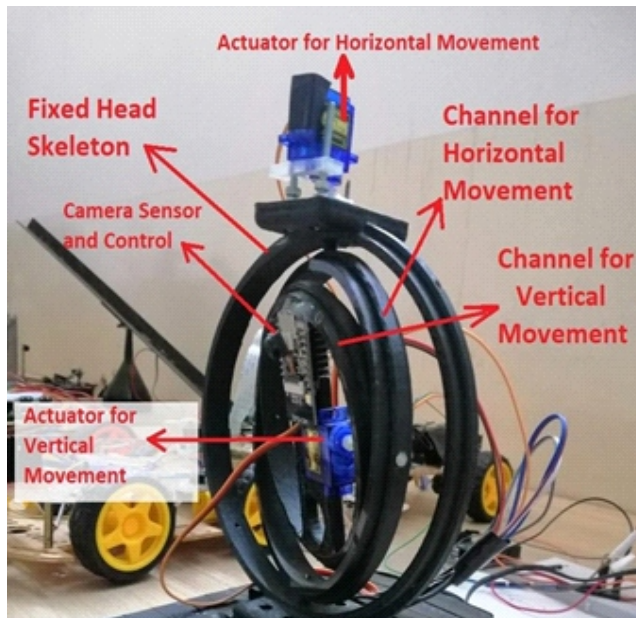


Fig. 6 Proposed Robotic Eye looking downward

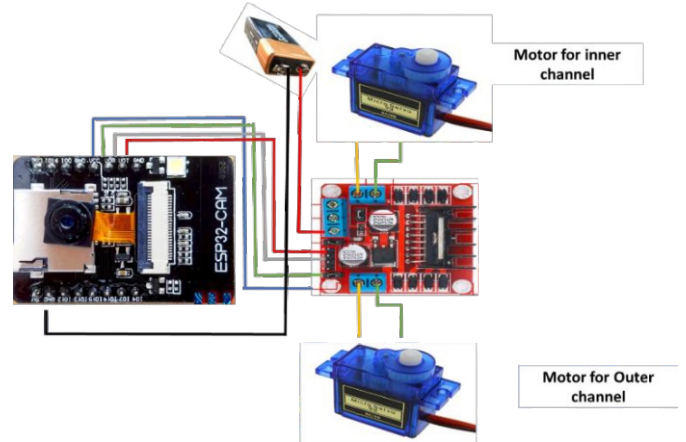


Fig. 7 Electrical connections

A) Automatic Control

We use two micro servo motors (SG90) that actuate the gimbal system. One motor is mounted on the outer channel for horizontal movement and the one mounted on the inner channel is for vertical movement. These servo motors, together with a gimbal system, replace the functionality of extra-ocular muscles in the robotic eye. A camera sensor is mounted on the inner channel that collects information about the stimulus. To actuate the camera sensor for automatic stimulus tracking, we control the shaft of the servo motors. Both the SG90 micro servo motors are controlled using Electrical Pulse Width Modulation (PWM). Initially, both the servos motors are at the neutral position from where they can move in both directions, i.e. 90-degree clockwise and 90-degree anti-clockwise. The proposed robotic eye muscles can be set to rotate the camera sensor at 360 degrees, like the chameleon. The PWM is implemented at 50Hz (Time period=20 ms). Within this 20 ms, a series of electrical pulses with variable widths are sent to control the motor's shaft. The shaft moves according to the commands provided by the ESP32 controller. In this way, the ESP323 CAM controls the tracking mechanism of the extra-ocular muscles.

The robotic eye collects the stimulus information is collected using ESP32 CAM. The information is then sent to the web page using Wi-Fi communication, enabling a live stream of the stimulus on our web page. There are four buttons left, right, up, and down on the web page, as shown in Fig. 9. When a user presses a button on the webpage, a request is sent to the ESP32 CAM. The back-end coding handles these requests and sends a control signal to the SG90 micro servo motors. In this way, the SG90 micro servo motors control the camera sensor. In this way, the servo motors actuate the camera sensor according to the user demand from a remote location.

III. Results and Discussion

A) Stimulus Tracking in a Changing Environment

For human-robot interaction in a social environment, robots may require riding, walking, or sudden direction changes and may face shakes and jerks that disturb the field of view. A stable

It can be seen in the proposed robotic eye that the Frame (head skeleton inhuman eye) is fixed while the inner and outer channels are rotating the camera sensors for tracking like extra-ocular muscles in a human eye.

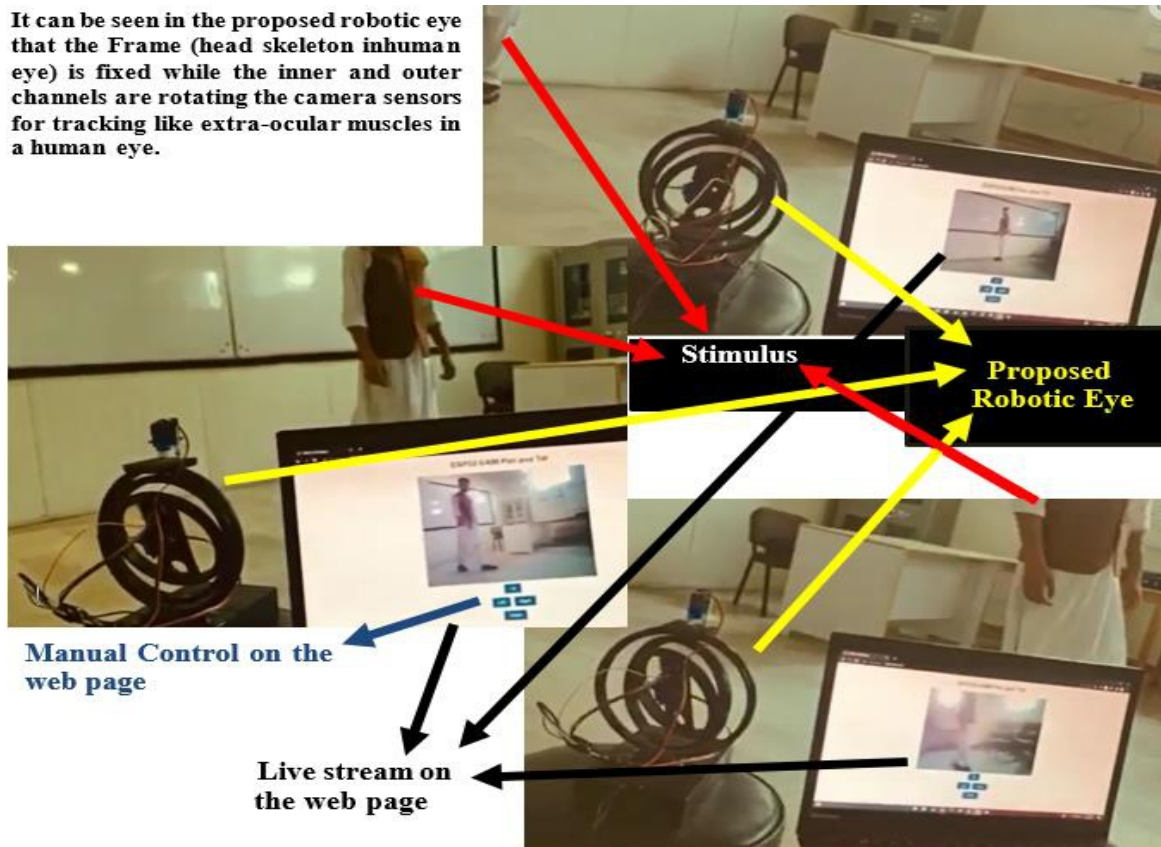


Fig. 8 Stimulus Live Tracking

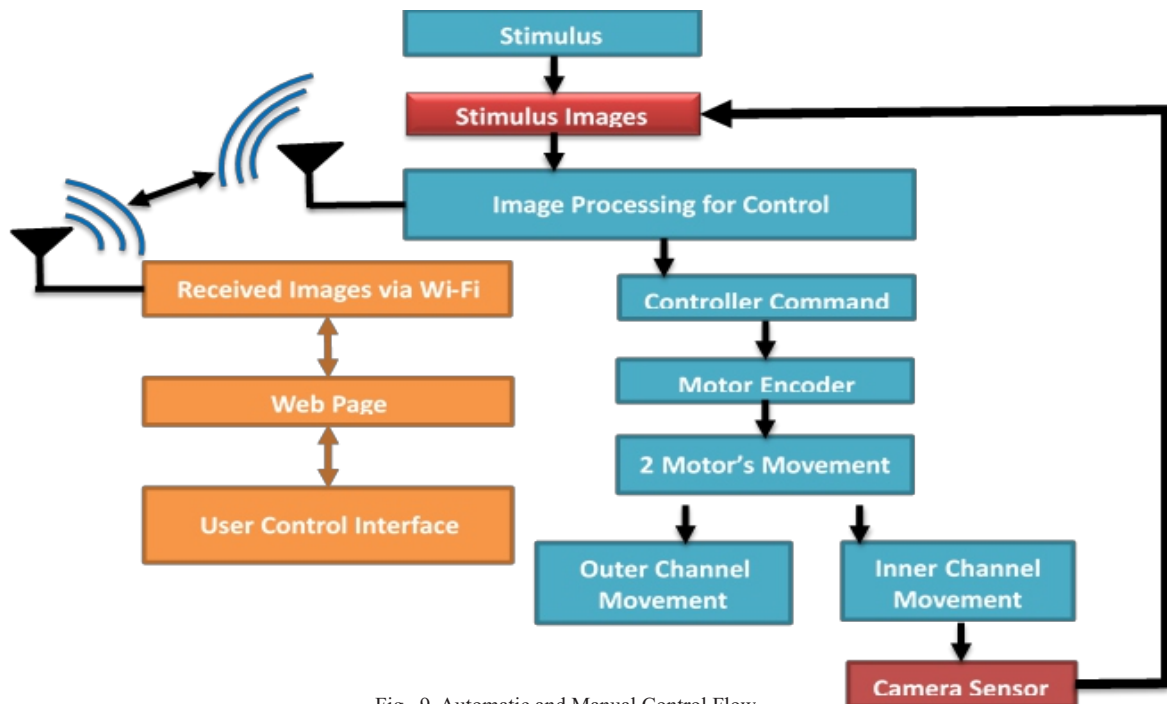


Fig. 9 Automatic and Manual Control Flow

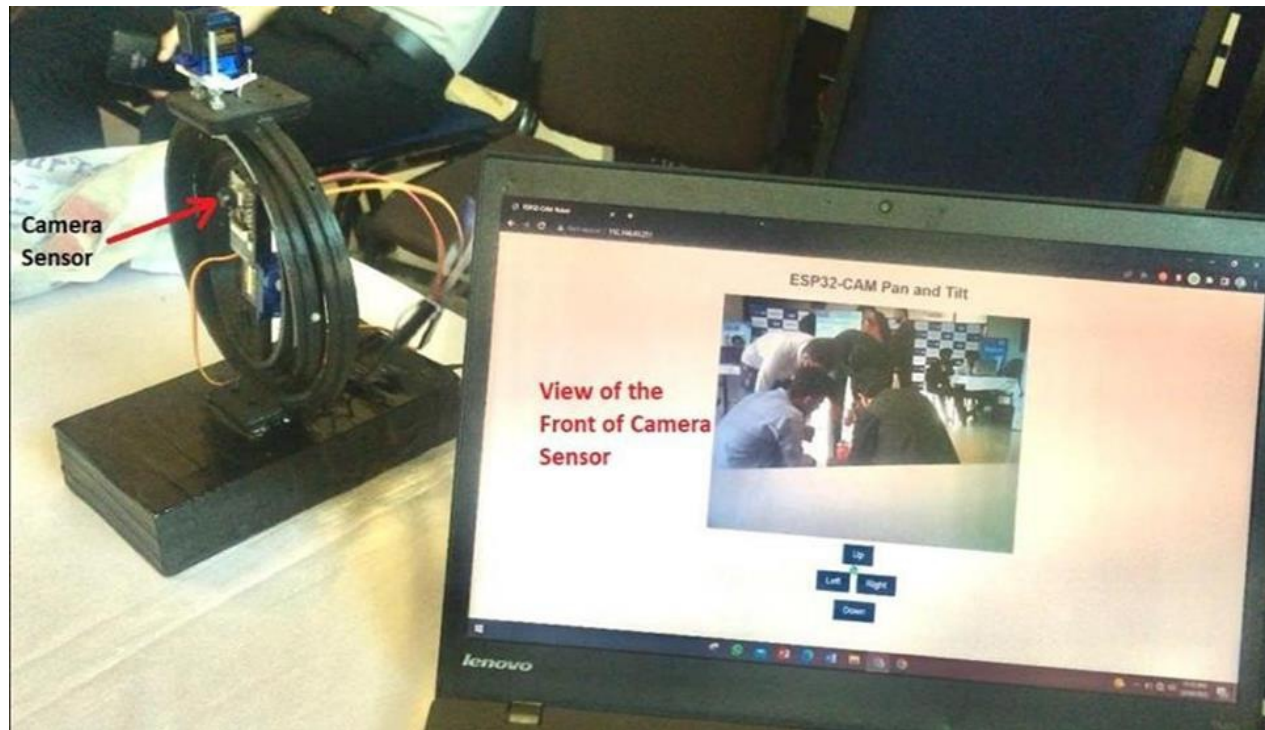


Fig. 10 User Interface for Manual Control

field of view is essential for pointing, tracking, and recognition. It provides more time to see the stimulus for the perception of more information. There may be another case where the robot is stationary, and the target continuously changes location. In both cases, robots require a stable field of view that is easily achieved using the proposed extra-ocular muscles. The beauty is that robots require no head movement for real-time stimulus tracking. The movement without head movement is because of the decoupling property of the gimbal system that decouples the camera sensor from the robotic head skeleton. This feature saves power consumption. The camera sensor creates a field of view to see a stimulus, as shown in Fig. 8-10, and feedback on the information to the ESP32 CAM. The controller calculates a gain according to the provided information. This gain is implemented using two servo motors that actuate the pitch and yaw channel for camera adjustment in the desired direction. A short video clip is uploaded on youtube.com to show the real-time stimulus tracking of the proposed robotic eye [18].

B) Features and Future Recommendations

The robotic eye with proposed extra-ocular muscles has multiple features discussed below with some future recommendations.

- The decoupling property of the gimbal system in the proposed extra-ocular muscles enables the robotic eye to track a stimulus like humans. The camera sensor tracks the stimulus independently from the head skeleton. The feature of the eye reduces power consumption as only the camera sensor moves instead of the whole head. It also provides decoupled movement for fast-tracking objects in a changing environment. It helps the robots focus while walking, riding, hiking, jumping, or in other shaking conditions. Robots will be able to see like humans. In this way, it would perceive more information for the training of any AI-based control.
- The weight of the robotic eye with proposed extra-ocular muscles is light due to the Nylon plastic frame. The use of plastic material also reduces the cost. One of the key features is the simplicity of its electrical connections and mechanical structure. Electrically it consists of just two servo motors connected with ESP32 CAM and its power connections for activation. Mechanically, the robotic eye with proposed extra-ocular muscles consists of three rings of Nylon plastic, i.e., a fixed holder and two rotating channels. With plastic in its design, the tracking performance is still match-able with existing robotic eyes. The additional features like simplicity, low cost, and less weight make it superior for humanoid robots. The plastic frame has more friction which reduces the tracking speed. Increasing the tracking speed, other materials with low friction components can be used.
- This will also increase the weight and cost of the robotic eye. There should be a trade-off between the tracking performance and the weight and cost of the robotic eye.
- The proposed robotic eye can be set to rotate at 360 degrees like a Chameleon eye. Our design and applications have limitations. When we fix it in a robotic body, it can rotate up to 80 degrees clockwise and anti-clockwise in both pitch and yaw directions.

The human eye's monocular Field of View (FOV) is around 114 degrees of view horizontally.

- To address the limitation that "the 80-degree rotation limit in each direction falls short of the human eye's field of view" in a gimbal-based robotic eye, several approaches can be considered. One solution is to redesign the gimbal mechanism to allow for a greater range of motion, potentially increasing the rotation limit to 90 or even 120 degrees per direction. This can be achieved by using more advanced servomotors or multi-axis gimbals that offer higher flexibility and precision in movement.

IV. Comparison of Tracking Speed, Accuracy, and Power Consumption in Robotic Eye Systems

The Gimbal-Based Robotic Eye achieves high tracking speeds in the range of milliseconds and excels in accuracy, though it comes with higher power consumption, typically around 10-20 watts. In contrast, the Electrochemical Eye (EC-Eye) and Insect-Inspired Compound Eye demonstrate strong potential in accuracy and speed with lower power consumption, though specific tracking speed data for the EC-Eye is not available. Bionic Vision Australia and Second Sight's Argus II, both focused on vision restoration, have limited tracking speed and moderate accuracy, with lower power demands suitable for wearable devices. On Robot Eyes, designed for industrial automation, offers moderate tracking speed and accuracy, alongside moderate power consumption. Overall, this comparison shows a trade-off between high performance and power efficiency, depending on the system's design and intended application.

V. LIMITATIONS OF USING A NYLON PLASTIC FRAME AND ALTERNATIVE MATERIALS

Materials like aluminum offer a high strength-to-weight ratio and improved tracking speed, but come at a higher cost and moderate weight. Carbon fiber, with its excellent strength, low friction, and light weight, could significantly enhance tracking accuracy, though it involves high costs and complex manufacturing. Polyether Ether Ketone (PEEK) presents a balance between strength, low friction, and durability, but is more expensive than Nylon. Titanium, while offering exceptional strength and biocompatibility, is costly and challenging to machine. Advanced polymers such as polycarbonate provide a lightweight, cost-effective option, but may lack the mechanical strength and durability of metals. A comparative analysis of these materials highlights their respective trade-offs in terms of tracking speed, friction, cost, and manufacturing ease, allowing for a more informed discussion on optimizing performance.

VI. CONCLUSION

The paper introduces bio-inspired extra-ocular muscles for robotic eyes and successfully implementing them for real-time stimulus tracking. The robotic eye demonstrates automatic and manual control capabilities, tracking stimuli without head movement. Notably, it exhibits advantages such as a high decoupling ratio with the head skeleton, compactness, lightweight design, and cost-effectiveness, while consuming minimal electrical power. Tracking control is achieved using the ESP32 CAM. The proposed robotic eye

with extra-ocular muscles offers features including decoupling for independent stimulus tracking, reduced power consumption, lightweight design, and structural simplicity. It ensures stability in changing environments and eliminates the need for head movement.

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