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Vision-Based Bionic Hand

Hrushikesh g nadig[1], Mohammed Ehtesham Khan[2], Sharath Kumar H[3], Mahesh S Meti [4] ,Prajwal R M[5] , N.Sivakamasundari[6]

1(Dept Of Mechatronics, Hindustan Institute Of Technology And Science, Chennai Padur
Email: hrushikeshnadig@gmail.com)
2(Dept Of Mechatronics, Hindustan Institute Of Technology And Science, Chennai Padur
Email: mdehteshamkhan11@gmail.com)
3(Dept Of Mechatronics, Hindustan Institute Of Technology And Science, Chennai Padur
Email: sharathkumarh389@gmail.com)
4(Dept Of Mechatronics, Hindustan Institute Of Technology And Science, Chennai Padur
Email: maheshmeti941@gmail.com)
5(Dept Of Mechatronics, Hindustan Institute Of Technology And Science, Chennai Padur
Email: prajuprajwal2004@gmail.com)
6(Dept Of Mechatronics, Hindustan Institute Of Technology And Science, Chennai Padur
Email: sksundari@hindustanuniv.ac.in)

***Abstract*— This research outlines the development of a Bionic hands designed to emulate the way we use our fingers in a simplified and economical manner, through the use of computer vision as a means of capturing data. The development of the system utilizes real-time computer vision technology, allowing for hands-free recognition of hand gestures by using a camera to detect finger movements, with the data being analyzed by an image processing algorithm and provided to a microcontroller, thus controlling the movements of the servo motors which are located in each of the individual fingers. The design of the Bionic includes the construction via a 3D printer, which will result in a Bionic that will be light and can be custom made for each user. Each finger is actuated by means of a single-DOF linkage and is driven by a common multi-channel PWM (pulse width modulation) driver. The prototype exhibits excellent appearance and functionality (including finger movement accuracy) while also having fast response time and providing no need for complex calibration of sensors. Future improvements will include hybrid EMG signal integration, tactile feedback to the user, and adaptive learning so the user can better interact with their environment**

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***KEYWORDS*— Vision-Based Bionic Hand, Computer Vision, Gesture Recognition, Bionic Design, 3D Printing.**

I. INTRODUCTION

In recent years Bionics have advanced dramatically thanks to robotics technology, embedded systems, and artificial intelligence. As a result, there are now many new types of devices that behave almost like real human limbs. Bionic hands are one of the most important types of Bionics because they can help people do routine tasks that involve multiple steps, including grasping, holding, and manipulating items. Achieving natural and intuitive control over the movement of a hand is one of the biggest challenges for designers developing prostheses.

Standard Bionic hands use sensor inputs like electromyography (or EMG) to determine user intent through electrical activity in the muscles or use of flex sensors or pressure sensors for tactile input. These methods provide some degree of control, but their complexity makes them inconvenient they typically require many steps before they can be used effectively and take time to calibrate properly. The requirement for the user to have some type of physical contact with the sensor creates discomfort and further decreases usability over extended periods of time.

In order to tackle some of these limitations, this research is proposing a vision-based Bionic hand that is not reliant upon contact-based sensing at all. This system uses real-time computer vision technology from a single camera to capture and interpret the movements of your hands while analysing the positions and movements of your fingers, subsequently transferring this data into establishing control signals which allow for intuitive, non-invasive operation of the Bionic.

The Bionic hand is designed based on the movement of the human hand, with a linkage mechanism designed to allow multiple joints to be operated with one actuator per finger. This results in decreased mechanical complexity while still allowing for a coordinated and natural finger movement. The material used to create the structure is created using a 3D Printing Technology, providing the Bionic hand with a lightweight, compact, and customizable design, making it suitable for practical application.

The control portion of the system integrates image processing algorithms, a microcontroller-based processing unit, and a multi-channel PWM driver for synchronous actuation of servo motors. The overall architecture of the system has been designed with the goal of reducing latency and providing smooth responses in real time.

This study focuses on designing a low-cost, efficient, and simple Bionic hand to provide an option of a more traditional Bionic for users in developing countries. The Bionic will be developed using a combination of computer vision and Bionic mechanical design, thus offering a novel direction for future assistive technology.

II. LITERATURE REVIEW

In the field of Bionic technology, robotic and intelligent control systems are continuously improving the efficiency and functionality of artificial hands. One of the major challenges in Bionic hand development is achieving natural finger movement with high accuracy, low cost, and simple control methods. Researchers are focusing on the use of EMG signals, computer vision, and machine learning techniques to improve the performance of Bionic devices. AI-based signal analysis has been used to improve EMG signal interpretation for better force control in Bionic hands, where anthropometric data helps to increase control accuracy and adaptability [1]. Hybrid control methods that combine EMG signals with visual information have also been introduced to produce human-like grasping motions, improving precision and stability in Bionic operation [2]. Real-time EMG-controlled Bionic hands have been tested to study latency, response time, and signal accuracy, which are important factors for comfortable and reliable usage in practical conditions [3].Several studies also focused on developing low-cost and mechanically efficient Bionic hands to make the system affordable and easy to use. Machine learning algorithms with EMG signals have been used to design cost-effective Bionic hands with good control performance while reducing hardware complexity [4]. Myoelectric control systems tested with amputee users provided information about real-time interaction, rehabilitation support, and user-oriented control strategies for dexterous Bionic hands [5]. Different mechanical gripper and underactuated finger mechanisms have been studied to achieve a balance between simplicity and functionality, allowing natural finger motion with fewer actuators [6]. Low-cost mechanical Bionic hands have been fabricated using simple materials and compact mechanisms to reduce weight and manufacturing cost [7]. The use of 3D printing technology has also been introduced to design lightweight and customizable Bionic hands with optimized structure and improved durability [8]. These developments show that combining intelligent control, efficient mechanical design, and low-cost fabrication methods can improve the performance and accessibility of modern Bionic hand systems.

III. BLOCK DIAGRAM

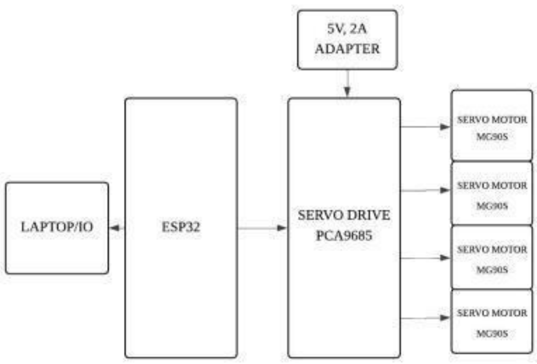

Fig. 1. Block Diagram of the System

The block diagram in Figure 1 describes an electrical control system for the Vision Based Bionic Hand. The Vision Based Bionic Hand is powered by a 5V, 2A adapter that provides power to the PCA9685 servo driver and MG90S servo motors. Visual information is processed by the laptop/PC and control signals are transmitted from the laptop/PC to the ESP32 microcontroller. The ESP32 receives the control signals and processes the data received from the laptop/PC; this data is then communicated from the ESP32 to the PCA9685 via the I2C communication protocol. The PCA9685 produces PWM signals to control the movement of multiple MG90S servo motors which act as fingers for the Bionic hand. Because of this configuration, accurate, real time, synchronized movements of the Bionic hand's fingers can take place as a result of visual inputs.

IV. CIRCUIT DIAGRAM

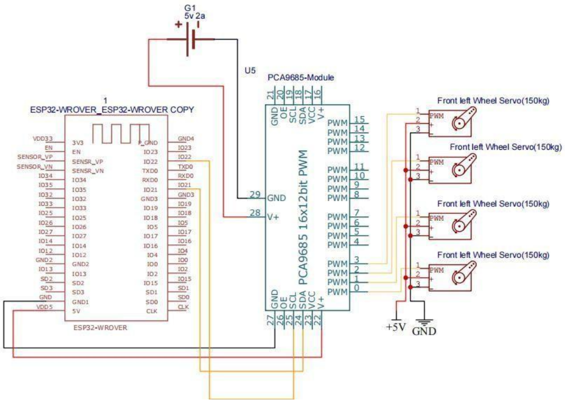

Fig. 2. Circuit diagram of system

In this schematic of the electrical and control systems of the Vision-Based Bionic Hand Bionic is shown ... the ESP32 controller, PCA9685 PWM Driver and the multiple servo motors that create the movement of the fingers. The ESP32-WROVER is the main processing unit and communicates with the PCA9685 module using I2C communications lines (SDA- SCL). The PCA9685 generates the precise PWM signals needed to control the multiple High-Torque Servo Motors simultaneously. The PWM Driver and Servo Motors receive power from an external 5V Power Source and are connected to a common Ground to provide stable and reliable operation of the complete system.

Every finger of the robotic hand represented by an individual motor can be moved through PWM output that is provided to each motor from the PCA9685, allowing the motors to produce coordinated human-like movements with a single mobilization direction through each finger. In addition, the Bionic hand itself is constructed from lightweight materials which permit the motor control signals to be created from a vision-based gesture detection system that is processed by the ESP32. This combination of design and control result in smooth, accurate, low delay movements without requiring any type of contact-based sensing technology, like EMG or flex sensors. Furthermore, the system is able to provide a reduced cost, high efficacy approach to Bionic control that provides increased accessibility through a more precise and natural actuation of the fingers.

V. HARDWARE COMPONENTS

A) ESP32 Microcontroller:

The ESP32 microcontroller serves as the primary processor in the Vision-based Bionic Hand and is responsible for processing gesture data and controlling finger movement. The ESP32 communicates with a PCA9685 PWM driver over I2C to generate control signals for servo actuation. As the ESP32 receives data from the vision-based system, it processes the data and generates positional commands for the Bionic fingers. The ESP32's high-speed processing capabilities, Wi-Fi/Bluetooth connectivity, and numerous GPIO pins make it a very good candidate for use in a real-time control system. The ESP32 plays an important role in providing smooth, accurate, and synchronized movement of the Bionic fingers.

B) PCA9685 PWM Driver Module:

To control various servo motors at the same time, a PCA9685 driver (16-channel PWM) module is needed to communicate with the ESP32 microcontroller over the I2C bus (SDA/SCL). The PCA9685 then produces the PWM signal that drives each of the servo motors appropriately. The PCA9685 offloads a number of computations from the microcontroller and provides consistent timing (i.e., stable PWM). This means that each finger motor will receive unique driving commands and will be able to produce natural and coordinated motion of the Bionic hand. The PCA9685 also allows the user to control a number of actuators using only two communication connections, making the overall system small and efficient.

C) Servo Motors:

The servo motors within the Bionic hand act as actuators for the Bionic finger and transfer motion from each servo to one of the five fingers via a series of linkages to make it possible for each finger to move and bend like a human hand. The scissors mechanism allows the servo to turn and rotate based on the PWM signal it receives from the PCA9685 module. The servos rotate to the correct angle needed to perform the same motion detected by the vision system (i.e., the gesture of an object) using a high-torque servo to provide enough force to grip an object while allowing for a smoother operation of the Bionic hand. The servo motors are critical to provide the accurate, repeatable and coordinated finger movements needed for performing tasks with the Bionic hand.

D) External 5V Power Supply:

A 5V external power source will provide enough current to run both the servo motors and the pulse width modulation (PWM) driver module. The servo motors draw more current than the ESP32 microcontroller can provide, so a separate regulated power source is required in order to ensure stable operation of the servos. The external power supply is connected to the V+ and GND pins on the PCA9685 driver module; thus, it shares a common ground with the ESP32 microcontroller. This is critical to the performance of this entire system, as it eliminates any possibility of voltage drops occurring when the servos are being operated simultaneously.

VI. DESIGN

In Figure 3 appears the front view of a Bionic Bionic; this view indicates the appearance of the item in question from its leading edge as well as demonstrating its configuration regarding each of its five digits and also how the palm is created. This view is helpful to provide an individual with the ability to assess the position of each digit around the overall height of this type of device, as well as how the front view interacts with the visual aspects of the overall item.

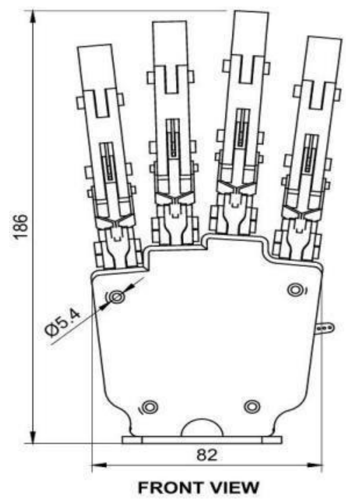

Fig. 3. front view of system

Figure 4 displays the rear view of a bio-inspired robotic hand. The rear view enables us to observe and understand the back side shape of the hand, along with the locations of the internal parts that were used to create the hand (i.e., gears, actuators, and attachment points on both sides of the hand). In addition, it provides information regarding how the components are secured within the hand, as well as how each actuator transmits movement through each finger of the hand.

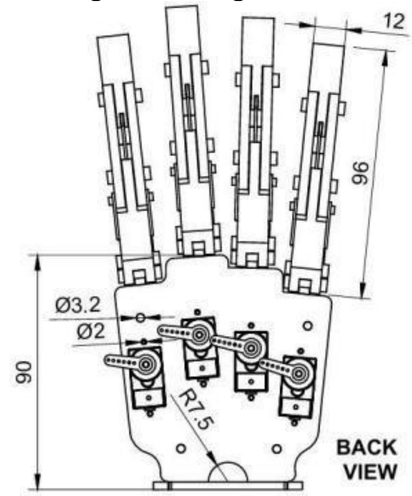

Fig. 4. back view of system

A side view of the Bionic hand is provided in Figure 5, where its height and thickness, as well as the bending mechanisms of each individual finger are displayed. The side view of the Bionic provides an overview of its overall shape and function as well as how the servo motor housings, linkages, and the finger joints are situated relative to one another to provide a clearer understanding of how the Bionic functions from a side view perspective.

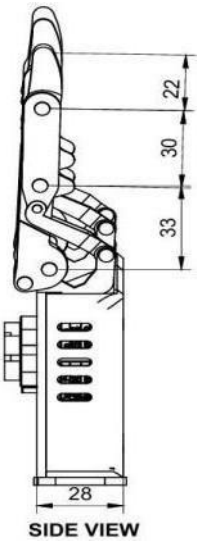

Fig. 5. side view of system

VII. VISION IMPLEMENTATION

For developing control systems for the Bionic hand a firmware program was created using a microcontroller working with defined gesture inputs to generate accurate actuator command outputs for controlling finger movements. The algorithm used to control the Bionic hand was designed to create mappings from finger bending values received from the vision system to specific servo positions. The control logic for the servos was modified and tuned to ensure that all the servos operate accurately with respect to each other thereby ensuring reproducible and accurate movements of each finger.

The control algorithm was designed to provide smooth transitions in all different hand gesture types, thereby providing fluid and coordinated movement of each finger while performing gripping or releasing motions. The vision processing unit utilizes real-time information about hand gestures to collect and output relevant positions to the controller to allow for execution of the appropriate command to control motion of the Bionic hand according to the gesture performed. The combination of embedded control and vision-based input allows for very responsive and realistic motion of the Bionic hand without the need of any physical sensors.

The central element for the production of very precise (PWM) signals necessary for accurate operation of servo motors is a microcontroller-based control system. As well, this system allows independent motion of each finger, allowing smooth and coordinated finger movements of the Bionic hand. The finger joint actuation (movement of the finger) occurs through proper placement (positioning) of the servos to achieve a natural/synchronized motion of the fingers. Through processing the gesture data from the vision processing module, the control system translates the gesture data into a corresponding motor command to enable real-time reproduction of human-like movements of the hand.

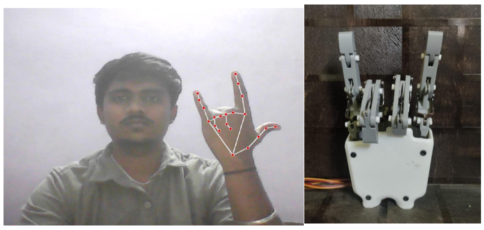

Fig. 6. Working of vision system and Bionic hand

VIII. RESULT AND DISCUSSION

The hand Bionic known as the Vision-Based Bionic Hand exhibits accurate, smooth, and robust movement of all fingers through computer vision and embedded control. The use of an ESP32 microcontroller combined with a PCA9685 servo driver allowed for precise and coordinated control of several servo motors, resulting in coordinated movement of all fingers. The use of MG90S servos in conjunction with a single degree-of-freedom linkage mechanism resulted in stability while providing a natural bending motion for each finger. This vision-based control system has also been able to eliminate the need for electromyographic (EMG) or contact-based sensors, which reduces overall costs and simplifies system complexity while providing acceptable response time and movement accuracy.

As demonstrated in Figure 7 the prototype Vision-Based Bionic Hand unit was composed of three pieces: 1) hand frame; 2) servo system; and 3) the control electronics (the ESP32 microcontroller and PCA9685 servo driver). The hand frame component was fabricated using 3D printing and designed for lightweight, compact construction. The ESP32 microcontroller and PCA9685 servo driver were assembled inside the bottom housing and secured in place to ensure a stable subsystem. The servo motors were attached to the finger linkage system to maintain stability and were routed and connected to the battery for reliable operation during testing.

Fig. 7. Prototype of Bionic hand

A prototype was made, assembled, and tested in order to examine motor movement of hand fingers, response times (RT) from vision to finger servo response times, and overall movement and speed with eye to finger servo activity. The Bionic hand performed both fast (low-latency) and slow (high-latency) finger gestures by producing smooth, precise movements of each finger one after another. No significant lag occurred between vision and finger movement characteristics. There were only minor issues regarding finger bending accuracy due to minor adjustments made in the linkage mechanism.

IX. CONCLUSION

This paper discusses the creation of a Bionic hand that uses vision to improve natural hand movement with less complexity, more cost effectively, and with higher accuracy of control. The system uses computer vision, an ESP32 microcontroller, and a PCA9685 servo driver for controlling the hand via servos connected through a single degree of freedom linkage to perform the grip/human-like movements of the fingers. The Bionic uses gesture detection through vision instead of using EMG- or contact-based sensing methods to provide smooth and precise motion while simplifying the control system. Because this Bionic is 3D printed, it has a lightweight, compact and configurable design, making it an appropriate solution for being a low-cost Bionic device.

Future enhancements to system performance will be focused on integrating EMG and vision controlling in hybrid control techniques to provide increased accuracy and responsiveness of fingers. The presence of tactile feedback will provide increased control over gripping and handling items. Additionally, adaptive learning algorithms can provide a more individualized response from the Bionic device based on user needs. Currently, the system is limited by requiring external vision processing, and by incorporating onboard AI modules that will enable faster and fully independent operation, improvements can be made.

The development of new Bionic hands will incorporate more advanced features, including multi-degree-of-freedom (MDF) finger mechanisms, improved actuator designs (i.e., electromagnetic-actuated) for providing actuation to the MDF fingers/tips through the manipulation of an external signal, and wireless communication that allows using the Bionic hand in a portable manner. Additionally, these added capabilities can be extended to use within a variety of applications, including robotic manipulators, rehabilitation devices, and human-machine interaction research. All enhancements will provide increased flexibility and usability during real-time application.

Consequently, the Vision-Based Bionic Hand has shown that integrating computer vision, embedded systems, and 3D printed mechanical design can produce a more affordable and more effective replacement for existing Bionic hand control options. By reducing the complexity of systems, improving access to systems, and showing great promise for future intelligent Bionic devices that provide increased user comfort, safety, and functional capability, this solution is an innovative approach to improving the lives of amputees.

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