Kinect-Driven Humanoid Robot for Mimetic Interaction

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Abstract

This paper presents an innovative approach to human-robot interaction through the use of a Kinect-type device for capturing the movement of a human operator, which is then accurately reproduced by a humanoid robot. The robot, standing at 110 cm, mimics a reduced-sized human and is crafted utilizing advanced 3D printing technology. The core of this system lies in its ability to capture human limb movements via the Kinect device, analyse the angular movements, and process this data to control the robot to replicate these movements identically. This methodology not only enhances the fidelity of movement replication but also broadens the scope of applications for such technology. Potential applications include but are not limited to rehabilitation, where the robot can assist or guide physical therapy exercises, entertainment, through performances or interactive displays, and educational settings, where it can serve as a tool for learning about robotics and human anatomy. This research marks a significant step forward in the development of humanoid robots that can seamlessly integrate into various aspects of human life, offering both functional and educational benefits.

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Introduction

The integration of human-computer interaction (HCI) technologies with robotic systems has opened new avenues in the development of assistive devices, particularly in the realm of robotic manipulators. Among the various technologies employed, the Microsoft KinectV2 sensor stands out for its ability to provide real-time 3D motion capture without the need for physical contact. This capability, when harnessed alongside versatile microcontroller platforms such as Arduino UNO and Arduino Nano, can lead to the development of highly responsive and intuitive robotic arms. This paper presents a novel approach to controlling a robotic arm using the KinectV2 sensor for motion capture, with Arduino UNO serving as the main controller. The system architecture also incorporates an Arduino Nano, which acts as a secondary controller that sends commands to a PCA9685 servo driver to actuate the servomotors based on the data received from the Arduino UNO. The communication between the KinectV2 sensor and the Arduino platform is facilitated through MatLab, with an FTDI232 module transmitting the interpreted data to the Arduino Software's Serial Monitor for real-time control and feedback.

The primary motivation behind this work is to explore the potential of KinectV2 in robotic arm control, leveraging its high precision in tracking human gestures to create a more natural and intuitive interface for users. By integrating this technology with the Arduino ecosystem, we aim to develop a cost-effective and accessible solution that can be adapted for various applications, from educational tools to assistive devices for individuals with mobility impairments. The use of MatLab as an intermediary software not only simplifies the data processing and transmission but also provides a flexible platform for further development and integration with other technologies.

This paper is structured as follows: Section II provides a detailed overview of the system architecture, including the hardware setup and the communication protocol between the KinectV2 sensor, Arduino UNO, Arduino Nano, and the PCA9685 servo driver. Section III describes the methodology for capturing and processing motion data using the KinectV2 sensor and Matlab2016b, as well as the algorithm for translating these data into servo commands. Section IV presents the results of preliminary tests conducted to evaluate the system's performance in terms of responsiveness, accuracy, and usability. Finally, Section V discusses the implications of our findings and outlines future directions for research and development in this area.

Literature review

The literature review section has been meticulously examined to incorporate advancements in the field of robotics, specifically focusing on innovative control mechanisms for robotic arms and hands, as well as broader applications in teleoperation and human-robot interaction (HRI). Recent studies have highlighted a range of methodologies, including the use of gesture recognition, eye gaze tracking, sensor fusion, and more, to enhance the intuitiveness and efficiency of controlling robotic systems.

One stream of research, represented by studies such as those by (Paterson & Aldabbagh, 2021; Gourob et al., 2021; Rathika et al., 2021; Sihombing et al., 2020) explores the development of gesture-controlled robotic arms and hands, leveraging technologies like computer vision, machine learning, and the OpenCV library to interpret human gestures for robotic manipulation. This approach aims to facilitate more natural and intuitive human-computer interactions by eliminating the need for physical controllers. These studies tackle various challenges associated with gesture recognition, including background interference and the 3-dimensional representation of gestures, and employ different hardware components like USB cameras, Raspberry Pis, and 3D printers.

Another notable direction, as discussed in (Sharma et al., 2020; Syakir et al., 2019; Bunkum et al., 2019) involves the design of systems to assist individuals with severe speech and motor impairments (SSMI) or to provide medical assistance remotely. These systems use eye gaze tracking, Kinect cameras, and internet connectivity for teleoperation, allowing users to perform physical tasks and access medical consultations without direct physical interaction with the robotic system.

Research has also delved into the integration of sensor fusion technology (Yang et al., 2023) and the application of Kinect devices for human posture estimation (Rosca et al., 2022) and control of robotic arms (Syakir et al., 2019). These approaches enhance the precision and reliability of robot control, closely replicating human motions and enabling contactless operation, which is particularly beneficial in teleoperation and rehabilitation scenarios.

Further innovation is seen in the utilization of mixed reality (MR) and augmented reality (AR) for robot control (Su et al., 2022; Walker et al., 2019), offering immersive environments that significantly improve the efficiency and user experience in telemanipulation tasks. Studies have also demonstrated the potential of acoustic gesture recognition (Ai et al., 2019), showcasing advancements in human-computer interaction through novel methodologies like the Doppler effect for humanoid robot control.

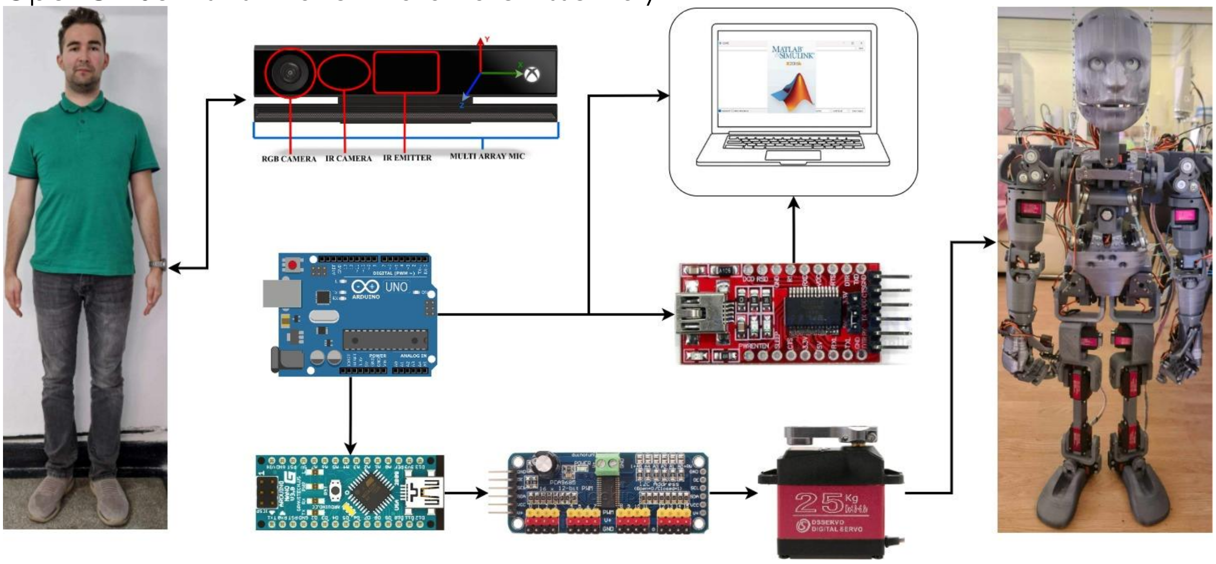
Moreover, advancements in neural networks and artificial intelligence are leveraged for force sensorless control schemes (Yang et al., 2019) and the classification of electromyography (sEMG) signals (Schabron et al., 2019; Rosca et all., 2020), pushing the boundaries of intuitive and adaptive robot manipulation.

In teleoperation systems, research (Cerón et al., 2023; Hirschmanner et al., 2019; Li et al., 2020; Škulj et al., 2021; Bakri et al., 2019) has introduced innovative solutions combining VR/AR technologies, wearable sensors, and wireless communication to enable more flexible and intuitive control of robotic systems. These contributions are significant in contexts ranging from educational and therapeutic applications to industrial environments and hazardous scenarios, where safety and efficiency are paramount.
In summary, the body of research encapsulates a multi-faceted approach to enhancing human-robot interaction through innovative control mechanisms and technologies. These advancements not only promise to make robotic systems more accessible and intuitive for users across various applications but also aim to extend the capabilities of robots to perform complex tasks with higher precision and reliability.

Methodology

According to Figure 1 Microsoft's KinectV2, a sophisticated motion sensing input device primarily designed for the Xbox One console but also compatible with PCs, integrates an advanced depth sensor, RGB camera, and microphone array, enabling full-body 3D motion capture, facial recognition, and voice recognition, thus serving as a pivotal tool for capturing human gestures and translating them into commands for the robotic arm; within this setup, the Arduino UNO acts as the main controller, processing data from the KinectV2 and transmitting commands to the Arduino Nano, which functions as a secondary controller by receiving commands from the Arduino UNO via serial communication and forwarding them to the PCA9685 servo driver, a 16-channel, 12-bit PWM servo driver controlled via the I2C-bus, thereby allowing for precise movements and positioning of the servomotors of the robotic arm; additionally, the FTDI232 module facilitates data transmission from MatLab on a mputer to the Arduino UNO, ensuring that data received through MatLab can be easily interpreted by the Serial Monitor in the Arduino Software, thus enabling real-time control and feedback for the robotic arm, with MatLab playing an important role in processing the data captured by the KinectV2 sensor, interpreting the gestures and movements captured by the KinectV2, and translating them into commands understandable by the Arduino UNO.

Figure 1
OpenCV Joints Estimation Hardware Assembly



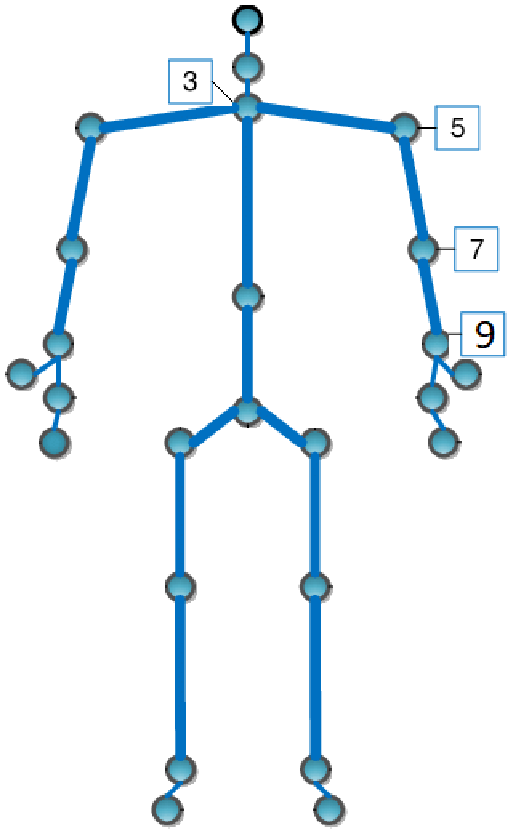
Source: Author's illustration

The provided Figure 2 depicts a human skeletal structure captured and analysed by the Kinect V2 sensor, which employs an advanced depth sensor, RGB camera, and microphone array to generate a real-time, detailed three-dimensional map of the human body, allowing for the identification and tracking of various joints and points of articulation within the skeletal system; the image features a blue wireframe figure with numbered joints, indicating key points detected by the Kinect V2, such as the Spine Shoulder (point 3), serving as a central node for upper body movement and orientation, the Right Shoulder (point 5), pivotal for detecting arm movements, the Right Elbow (point 7), enabling tracking of forearm bending and extending motions, and the Right Wrist (point 9), facilitating detection of hand and finger movements; the Kinect's software algorithms utilize visual and depth information to infer joint positions in three-dimensional space, recognizing anatomical patterns and predicting joint locations even when partially occluded or not directly visible to the sensor.

In order to estimate the upper limb human posture, we studied the anatomical structure that offers 5 degrees of freedom through shoulder and elbow joints. First joint possesses three degrees of freedom being composed of a spherical joint, while the latter possesses only two degrees of freedom, both forming a kinematic chain. The first joint also, in terms of the skeletal system, consists of three bones that form four joints, independently of each other, as presented in Figure 3.

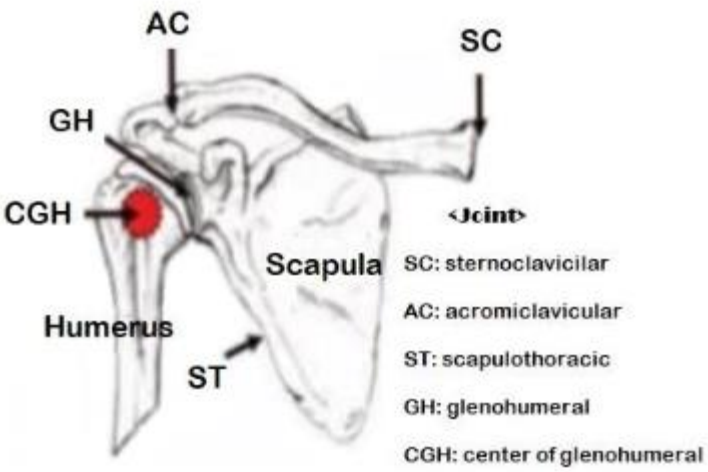
The first joint sternoclavicular, noted as SC in Figure 3, form a connection between thorax and the clavicle bone. The second joint, acromioclavicular, note as AC in Figure 3, interconnect the scapula to clavicle bones, the third one, scapulothoracic, note as ST in Fig. 1, create the movement between scapula bone and thorax. The last one, glenohumeral joint, name as GH, connects the humerus to the scapula bones. The most important joint is the glenohumeral joint which allows a variety of movements conducted by an unstable bone structure: abduction between 150-180°, flexion with a limit of 180°, extension limited to 45-60°, but also external rotation up to 90° (Rosca et al., 2020).

Figure 2
Human body Right Arm Key Points



Source: Author's illustration

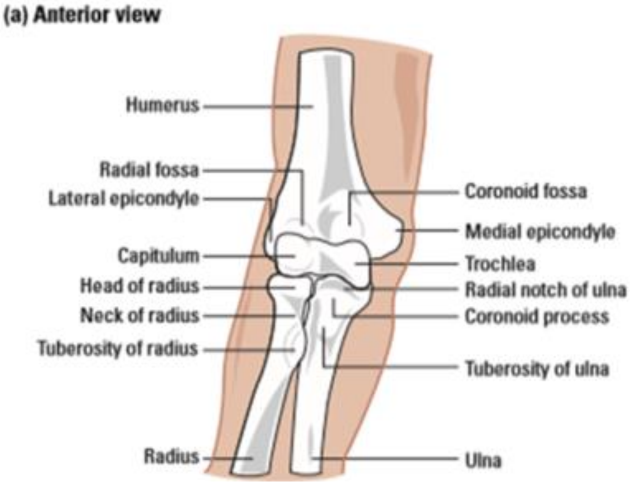
Figure 3
Shoulder joint anatomy



Source: Internet

Regarding the anatomical structure of the elbow, it is composed of two additional bones related to the humerus, ulna and radius, as presented in Figure 4.

Figure 4
Shoulder joint anatomy



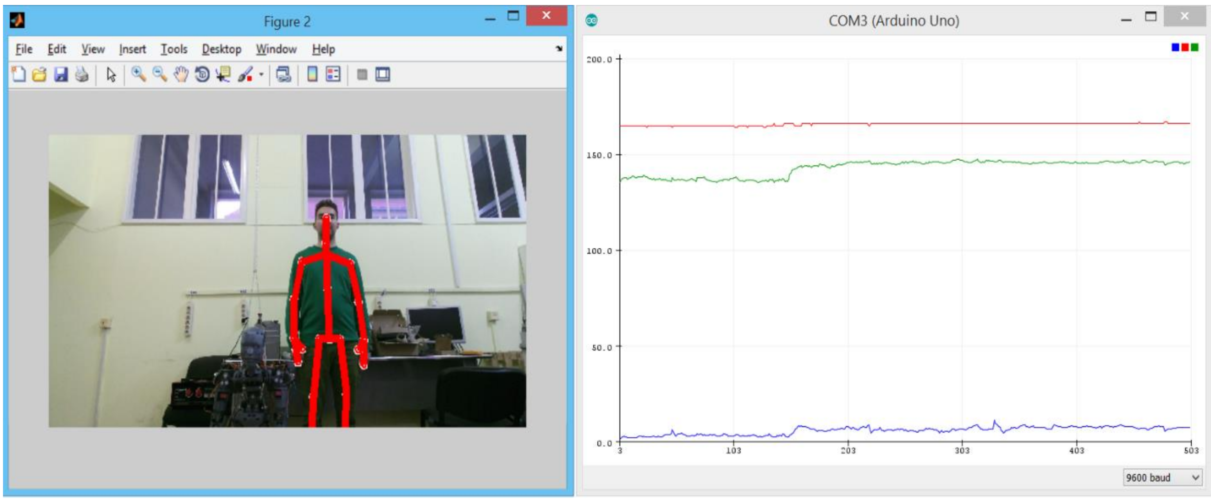
Source: Internet

Regarding the movements allowed in the case of the elbow, we have a group of four main movements. The first two are flexion movements with a maximum range of 140° and extension limited to 10°. However, to perform common tasks the usual range of motion of the elbow is between 30-130°. Regarding the last two movements, supination and pronation, the maximum range of movement is around 90°. Also, additionally lateral and medial angle is limited in case of abduction and adduction movements (Rosca et al., 2020).

Results

In order to validate our model, we implemented a scenario in three steps applying computer vision method on four phases to recognize the upper limb rest state, a movement that imply only one degrees of freedom applied alternately to the elbow and shoulder joints and finally a more complex movement executed based on the shoulder-elbow complex.

Figure 5
Rest Position

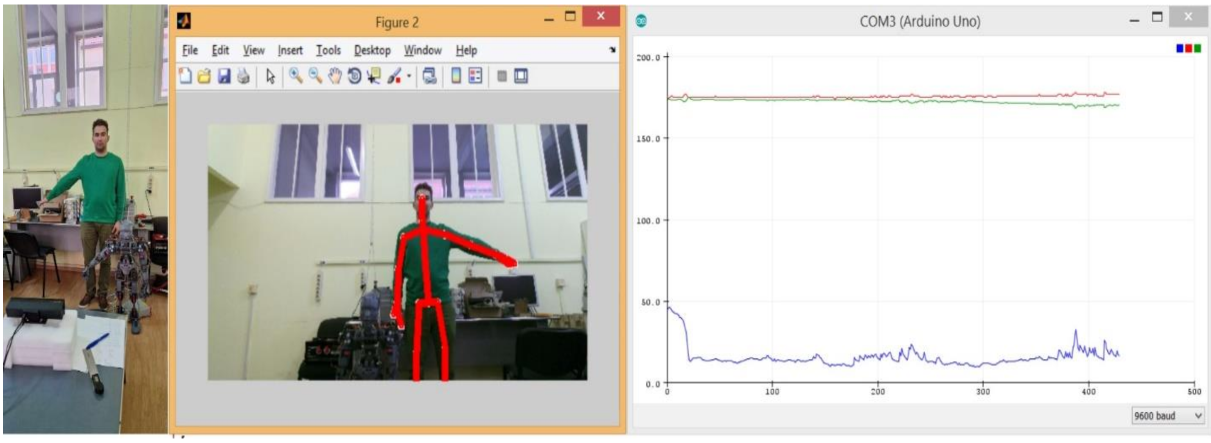


Source: Author's illustration

In the Figure 5 we start to capture the rest state motion of a subject through Kinect V2 skeleton that measuring in real time the human posture. The first window shows the image generated by the RGB camera of the device generated by superimposing the skeleton over the anatomical joints and the image on the right represents the graph generated by the Serial Plotter on the XYZ axis, where blue color line means the shoulder movement on vertical axis, green one, the elbow and red shoulder movement on horizontal axis.

In the Figure 6 there is captured the abduction/adduction movement from the same subject, where the first maximum abduction movement has a lower limit of 10 degrees, while the latter is imposed at a maximum angle of 130 degrees. In terms of angular values distribution in this case the x axis is represented by blue color line means the shoulder movement on vertical axis, green one, the elbow and red shoulder movement on horizontal axis.

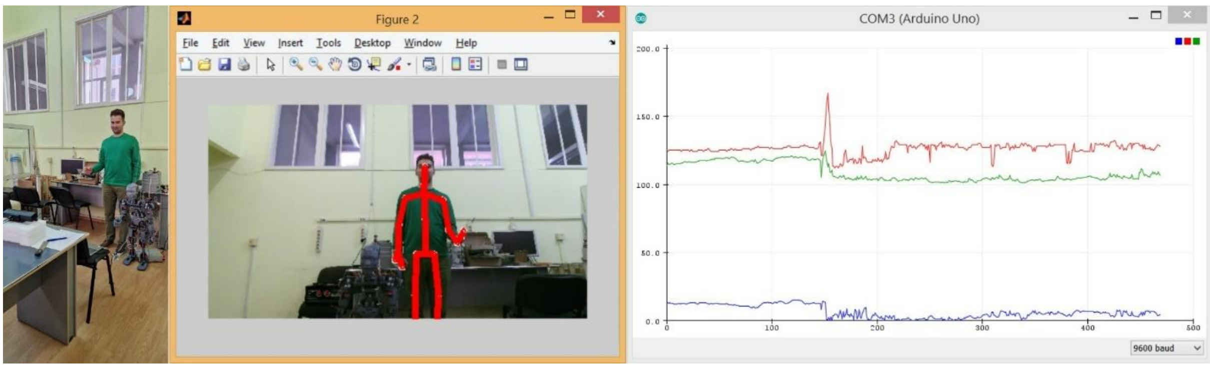
Figure 6
Horizontal Position



Source: Author's illustration

The flexion/extension movement, presented in Figure 7 using same method interpret the limit of 80 degrees to the first one, and to 170 degrees limit for the last one. In this case reported to angular values the axis changed, the x one is represented by blue line that correspond to shoulder movements on vertical axis, the y one is represented by green line on horizontal shoulder movement and last one on z axis represented by red line to elbow movement.

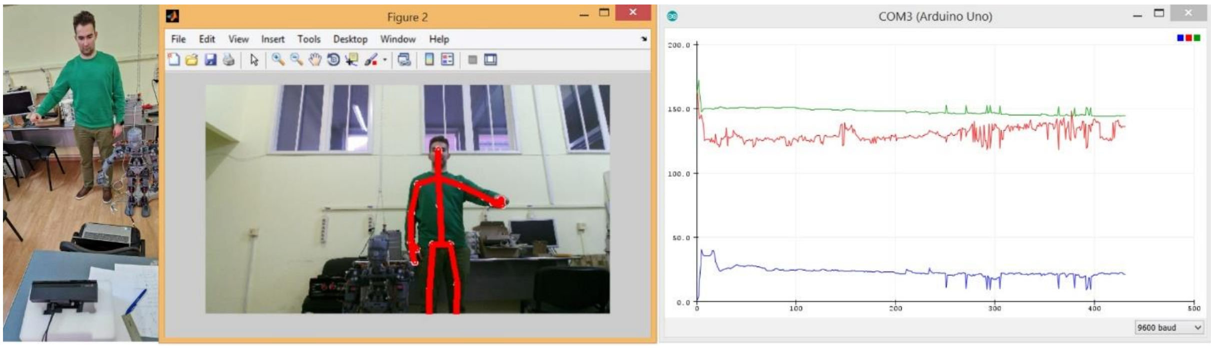
Figure 7
Elbow Position



Source: Author's illustration

In Figure 8 we present a complex movement that imply the movement of Shoulder on 2 axis and elbow in one axis. In terms of colors representation of each axis, corresponds with previous plot of the elbow. The angles limit identified from calculus it the same as previous presented together with cartesian representation.

Figure 8
Horizontal Elbow Position



Source: Author's illustration

Conclusion

In this study, we have successfully demonstrated a novel approach to controlling a robotic arm using the KinectV2 sensor for motion capture, with the Arduino UNO serving as the main controller. The integration of the Arduino Nano as a secondary controller to relay commands to the PCA9685 servo driver for actuating the servomotors, facilitated by serial communication and an FTDI232 module for data transmission through MatLab, represents a significant advancement in the field of robotic manipulation. Our system showcases the potential of combining motion capture technology with microcontroller platforms to create a highly responsive and intuitive control system for robotic arms. The use of KinectV2 for capturing human gestures and translating them into robotic movements has proven to be highly effective, offering a natural and user-friendly interface for controlling robotic devices. The Arduino platform, with its versatility and accessibility, has enabled the seamless integration of various components, including the PCA9685 servo driver and servomotors, to achieve precise and fluid motion of the robotic arm. The employment of MatLab as an intermediary for processing and transmitting data has further enhanced the system's performance, allowing for real-time control and feedback.

Throughout the development and testing phases, we encountered several challenges, including optimizing the data transmission rate and ensuring the accuracy of gesture recognition. However, through iterative testing and refinement, we have addressed these issues, resulting in a robust and reliable control system. The lessons learned from this project underscore the importance of careful component selection, system integration, and the potential impact of real-time control systems on the field of robotics. Future work will focus on expanding the capabilities of the system, including the integration of additional sensors for enhanced gesture recognition, improving the system's scalability, and exploring its applications in various domains such as teleoperation, education, and rehabilitation. The potential for further optimization and customization of the control algorithms also presents an exciting avenue for research, with the aim of achieving even more nuanced and complex robotic movements.

In conclusion, this study contributes to the growing body of knowledge in robotic control systems, offering insights into the integration of motion capture technology, microcontroller platforms, and software tools for the development of intuitive and accessible robotic arms. The success of this project paves the way for future innovations in the field, with the potential to significantly impact the way we interact with and utilize robotic systems in our daily lives.

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