

Wearable Data Glove Design Based on Strain Sensors for Bionic Manipulator Control

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Abstract. To address the challenges associated with remote manipulation in complex environments, this study presents a remote control system for bionic manipulators utilizing a strain-sensor-based data glove. The system captures joint angle data from five-finger grasps and thumb-index opposition gestures, which are then processed through limit filtering, Kalman filtering, and range mapping to improve control robustness. A vibration feedback module delivers tactile force information from the bionic fingers back to the user's hand, enhancing grip accuracy and preventing structural damage caused by excessive manipulator motion. Experimental results confirm that the data glove enables reliable remote control of the bionic hand when handling fragile objects, thereby validating the system's effectiveness and precision.

Keywords: Strain Sensors; Bionic Manipulators; Vibration Feedback; Data Gloves.

1. Introduction

The bionic manipulator, characterized by multiple degrees of freedom and high flexibility, is capable of mimicking human hand movements to perform complex tasks. This functionality enables it to substitute for humans in hazardous and complex environments. Accurately detecting human hand motion and precisely controlling the bionic manipulator remain key challenges in practical applications [1]. Among the available technologies, data gloves are considered one of the most effective tools for capturing hand gestures and postures. One of the earliest commercial data gloves, the Power Glove, was released in 1989 by Mattel for the Nintendo Entertainment System, based on the earlier DataGlove developed by VPL Research [2]. Although it enabled users to control virtual objects and games using hand gestures, it exhibited low precision and caused user discomfort during prolonged use.

In recent years, advanced data gloves have been developed to improve gesture recognition accuracy and reduce user fatigue. For instance, the Gest smart glove by Apotact Labs emphasizes lightweight design and precise motion tracking [3], while the PowerClaw glove enhances haptic feedback to increase immersion in virtual environments [4]. Modern data gloves are widely applied in VR gaming, human-computer interaction, and gesture recognition systems [5]. Researchers have also designed flexible data gloves using space-division multiplexed optical fiber sensors. These gloves are thin, lightweight, and attachable to the hand, allowing tactile sensation to be retained during daily activities. Such designs have found applications in gaming, virtual reality interaction, telemedicine, and augmented reality. For example, Guo et al. integrated a PC, DSP, and MCU to collect EMG signals, enabling synchronized grasp control of a robotic manipulator [6]. Data gloves offer significant advantages in human-computer interaction, monitoring, and motion analysis. Compared with other control strategies for bionic manipulators, those based on data gloves typically provide lower latency, reduced error rates, and better representation of human motion intent [7]. As such, research into data glove design continues to be of practical and academic value.

Meanwhile, technological advances have increased attention on both intelligent and bionic manipulators. Gong proposed a manipulator featuring a synchronous bionic palm, capable of issuing control commands based on brain intentions [8]. Similarly, Yan developed a robotic gripping system based on cloud computing, enabling dynamic gripping and efficient processing of object data [9]. The development of such manipulators allows operators to avoid dangerous environments by remotely

executing complex tasks. As a result, the design and application of bionic manipulators have become a prominent research focus.

In this study, a strain-sensor-based data glove is designed to achieve follow-up control of a bionic manipulator. By analyzing human joint angle data during five-finger and lateral thumb-base grasping, the manipulator is enabled to imitate hand gestures. Additionally, a pressure feedback module is incorporated to regulate the manipulator’s gripping force, enhancing the precision and safety of remote manipulation.

2. Overall Design

In this paper, a joint angle measurement and bionic hand control method based on strain sensors is proposed. The physical system consists of two parts: a data glove and a bionic manipulator. As the core component for controlling the bionic manipulator, the data glove includes an operational amplifier module, a vibration module, a controller, a wireless transmission module, and a bending measurement module. The bionic manipulator, as the controlled object, is capable of performing actions such as grasping and lateral gripping. The system workflow is illustrated in Figure 1.

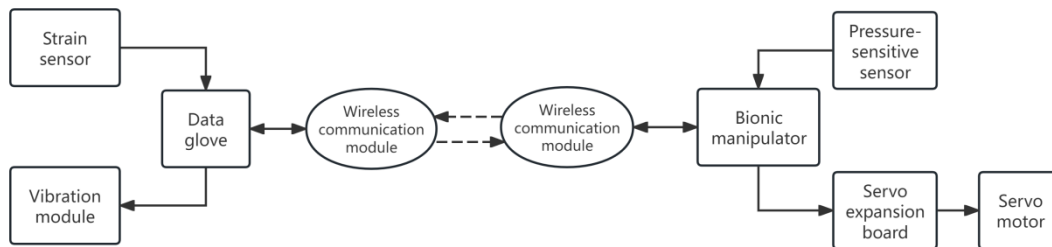


Fig. 1 System workflow

2.1. Design of the Data Glove

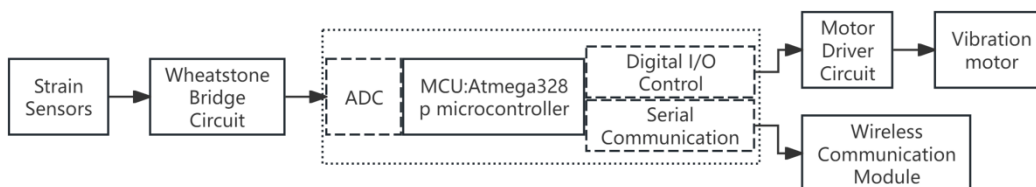


Fig. 2 Data glove design

Once the data glove is worn and powered on, it begins collecting curvature data from the hand. Six FLEX curvature sensors are embedded at the second joints of each finger and at the base of the thumb, enabling the acquisition of both grasping angles and the lateral grip angle of the thumb [10]. To improve data quality, the glove applies filtering processes: limit filtering is used to suppress signal spikes, while Kalman filtering enhances signal smoothness and reduces the effects of finger tremors. The design of the data glove is illustrated in Figure 2.

2.2. Design of the Manipulator

After data processing is completed, the extracted joint angle information is converted into motor control signals and transmitted to the slave unit of the bionic manipulator through the wireless communication module, thereby enabling remote manipulation. The structural design of the manipulator is presented in Figure 3.

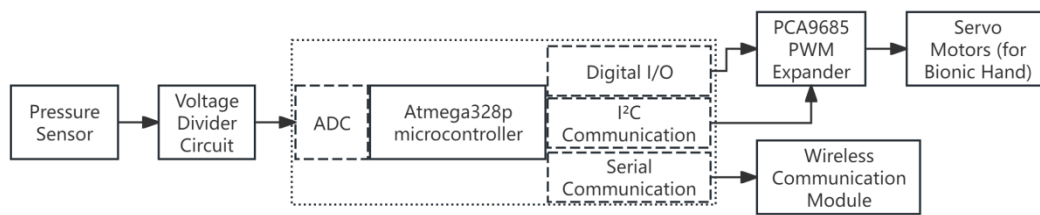


Fig. 3 Manipulator design

3. Hardware Design

3.1. Data Gloves

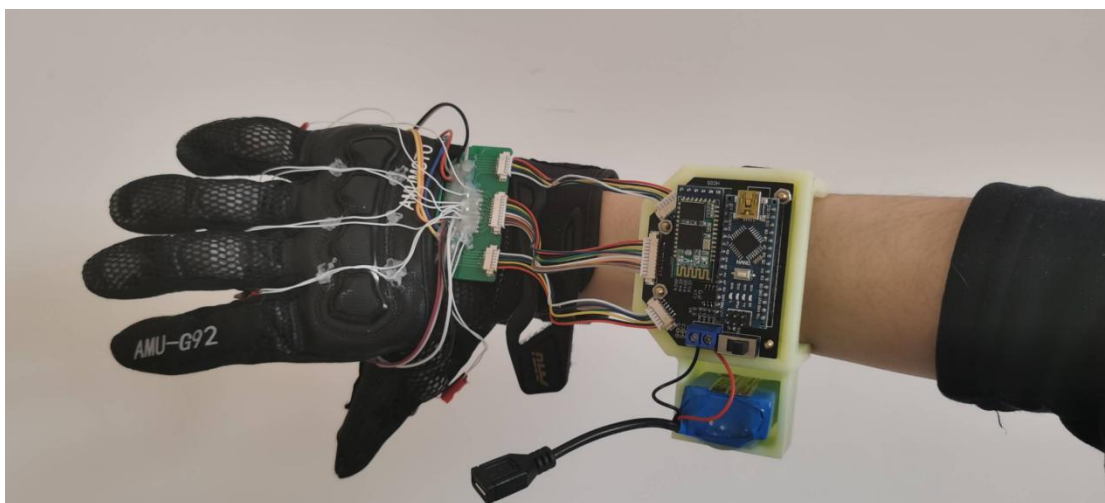


Fig. 4 Physical view of the data glove

The hardware of the data glove comprises a 2.2-inch Flex strain sensor, an operational amplifier module, a vibration feedback module, a controller, a wireless transmission unit, and the glove body. A physical representation of the data glove is presented in Figure 4.

The Flex 2.2" sensor is a 2.2-inch curvature sensor that was previously utilized in an electronic glove developed by Nintendo. When the metal side of the sensor bends outward, its electrical resistance changes, enabling the detection of joint movement [11]. The relationship between resistance and joint bending angle is illustrated in Figure 5.

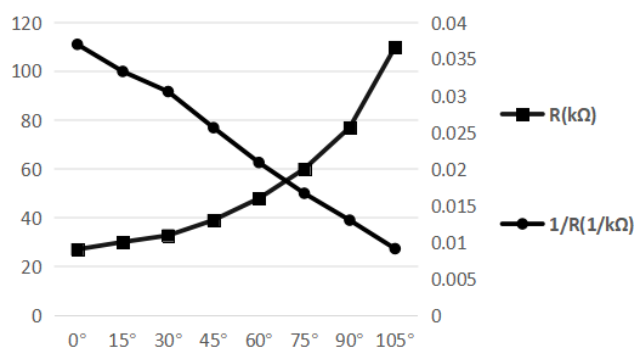


Fig. 5 Relationship between joint bending angle and resistance

Six Flex 2.2" strain sensors are employed as the primary sensing elements for measuring the bending angles of finger joints. Five sensors are installed between the middle and proximal phalanges of the five fingers, while one sensor is positioned between the metacarpal bones of the thumb and the little finger. The sensor layout is illustrated in Figure 6.

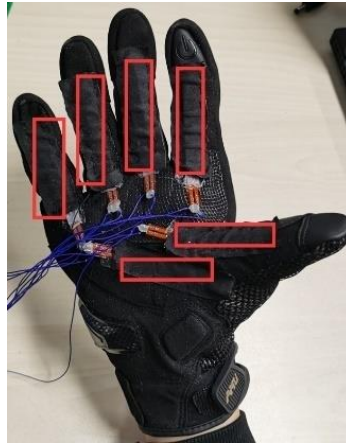


Fig. 6 Layout of flex sensors on the hand

The strain sensor is a resistive type that initially adopts a traditional voltage divider circuit, which limits the utilization of the microcontroller’s ADC to approximately one-third of its full range. To overcome this limitation, a dedicated balanced-bridge operational amplifier module was implemented. This module converts the curvature sensor’s resistance (ranging from 25 k Ω to 130 k Ω) into a voltage signal spanning from 0.024 V to 4.796 V, thereby fully utilizing the ADC input range and significantly enhancing control accuracy and signal smoothness. A physical view of the amplifier module is illustrated in Figure 7.

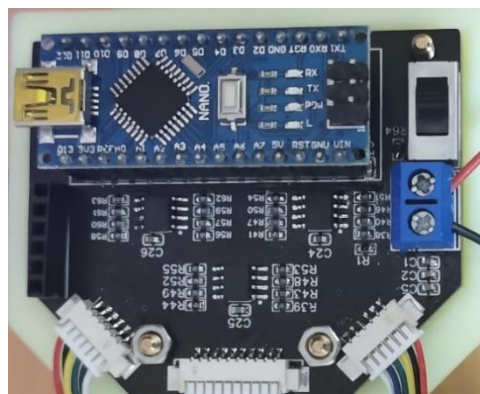


Fig. 7 Physical view of the bridge amplifier module

To enable the data glove to provide force feedback from the bionic manipulator, five 0827 DC vibration modules were embedded within the glove, each positioned at the middle phalanx of a finger. The startup current of each module is approximately 90 mA, which exceeds the microcontroller’s direct drive capacity. To address this, an amplifier transistor was integrated into the output stage of the main controller. A high-level signal from the control pin activates the transistor, allowing a higher current to drive the rotor and generate vibration.

There are no specific performance requirements for the microcontroller unit (MCU) in this study. For convenience during testing, the ATmega328p was selected. The Arduino Nano development board based on this chip was employed in both the somatosensory glove and the bionic manipulator.

The wireless transmission module was selected based on transmission range considerations. Options include Bluetooth, Wi-Fi, and RF-based serial modules. In this study, the HC-05 Bluetooth module was chosen for indoor communication. This module supports both master and slave modes and once powered on, can be discovered by any Bluetooth-enabled device, such as a smartphone. In addition to enabling the basic functionalities of the bionic hand, the module also supports smartphone-based control and real-time data monitoring from the somatosensory glove.

3.2. Bionic Manipulator

The bionic manipulator utilizes Youbionic’s fully actuated 11-degree-of-freedom control scheme, incorporating eleven SG90 servo motors. These motors are vertically embedded within the fingers and operate via horizontal connecting rods, which convert horizontal rotational torque into longitudinal gripping force at the finger joints. The structural design is illustrated in Figure 8.

The bionic hand is modeled on the skeletal structure of the human hand. Each of the five fingers features two degrees of freedom, enabling segmented joint-based grasping. Additionally, a horizontally mounted motor is installed at the base of the thumb to achieve lateral thumb movement, facilitating opposition and grasping motions. This design enhances the naturalness and diversity of the hand’s movements.

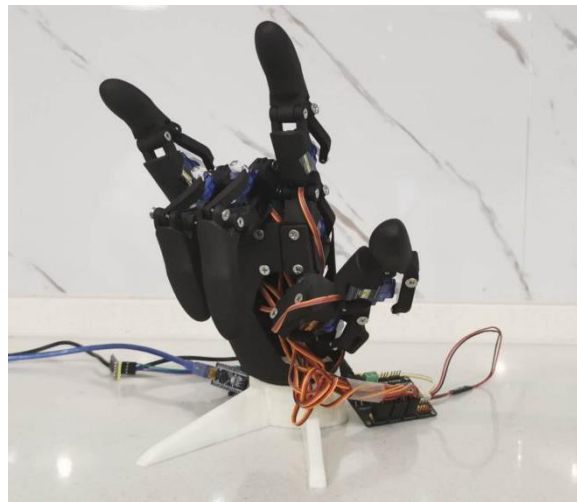


Fig. 8 Mechanical structure of the bionic manipulator

The PCA9685 chip is employed to generate eleven PWM signals for servo motor control via the I²C bus, significantly reducing the computational burden on the microcontroller.

To enable force feedback and measure the gripping force of each finger, five pressure-sensitive sensors are embedded at the second joints of the fingers. A 2 mm thick silicone layer is applied to the surface of each sensor to enhance surface friction and evenly distribute point loads across the sensing area. This modification expands the effective sensing range and yields smoother and more accurate pressure readings.

As precise control is not required for the pressure-sensitive sensors in this study, the signal acquisition circuit is simplified to a voltage divider combined with a basic operational amplifier. The relationship between applied pressure and sensor resistance is illustrated in Figure 9.

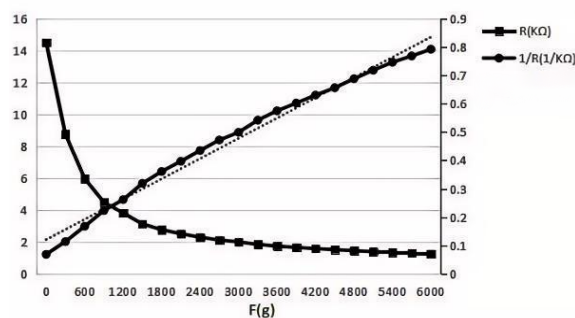


Fig. 9 Relationship between pressure and resistance of the sensor

4. Software Design

4.1. Program Flow

The control algorithm in this design comprises two main components: gesture and pressure detection, and actuator control. In the somatosensory glove, once the microcontroller's ADC acquires voltage data from the strain sensors, the corresponding resistance is computed based on the amplifier circuit parameters. Using a resistance-to-curvature mapping function, the bending angle of each finger is then determined.

Due to imperfect glove fit and involuntary finger tremors, the calculated angles may exhibit fluctuations and noise. To mitigate this, a combination of dynamic range adaptive mapping and Kalman filtering is applied to reduce error and smooth the signal, yielding theoretical angle values for the servo motors [12]. Similarly, the target intensity of each vibration module is derived from the readings of the pressure-sensitive sensors embedded in the bionic manipulator.

The processed data is transmitted between the glove and manipulator via the Bluetooth module. Upon receiving the angular data, the manipulator's controller performs segmented quantization and applies anti-chatter zones to suppress servo jitter, subsequently determining the target PWM values. These signals are then transmitted to the PCA9685 chip via I²C communication to control the bionic hand.

Concurrently, the somatosensory glove receives pressure feedback signals from the bionic manipulator and adjusts the PWM outputs sent to the vibration modules accordingly, generating varying vibration intensities. The overall software control flow is illustrated in Figure 10.

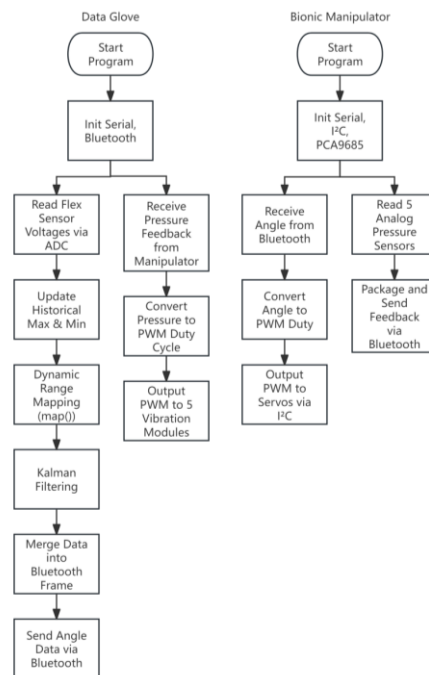


Fig. 10 Program flow chart

4.2. Somatosensory Detection Algorithm

In this design, six strain sensors are employed to measure the bending of all five fingers and the inward curvature of the palm. Due to the high sensitivity of these sensors, normal finger tremors and circuit noise can significantly affect the readings. To mitigate this, Kalman filtering is applied to smooth the signal.

Additionally, during wireless transmission, issues such as frame loss or data corruption may occur. To address this, the received data is filtered according to the communication protocol, and limit filtering is used to eliminate outliers.

Owing to differences in gloves, finger sizes, and individual users, the voltage range measured by the strain sensors may vary. To ensure algorithmic generalization and consistency, a range mapping method is adopted. This approach continuously detects the maximum and minimum voltages and linearly maps the input values to a predefined fixed range, thereby normalizing the input for universal control [13].

Let the measurement of joint 1 be denoted as x . After initialization, the voltage range is defined as $x \in [x_0, x_1]$, where x_0 is the initial value. As the system runs, new extremum values may appear. If a new value $x_1 < x_0$ is detected, the range is updated to $x \in [x_1, x_0]$; likewise, if a new maximum $x_2 > x_0$ occurs, the range becomes $x \in [x_1, x_2]$.

If the standard output range is defined as $x \in [200, 600]$, each input is linearly mapped into this fixed range in real-time while updating the measurement range. The corresponding conversion formula is:

$$200 + (x - x_1) * \frac{600 - 200}{x_2 - x_1} \tag{1}$$

At this stage, all processed data groups are smooth signals with uniform variation within the range of 200 to 600, making them suitable for use in any control system.

5. System Control Experiment

5.1. Grasping Test and Feedback Evaluation

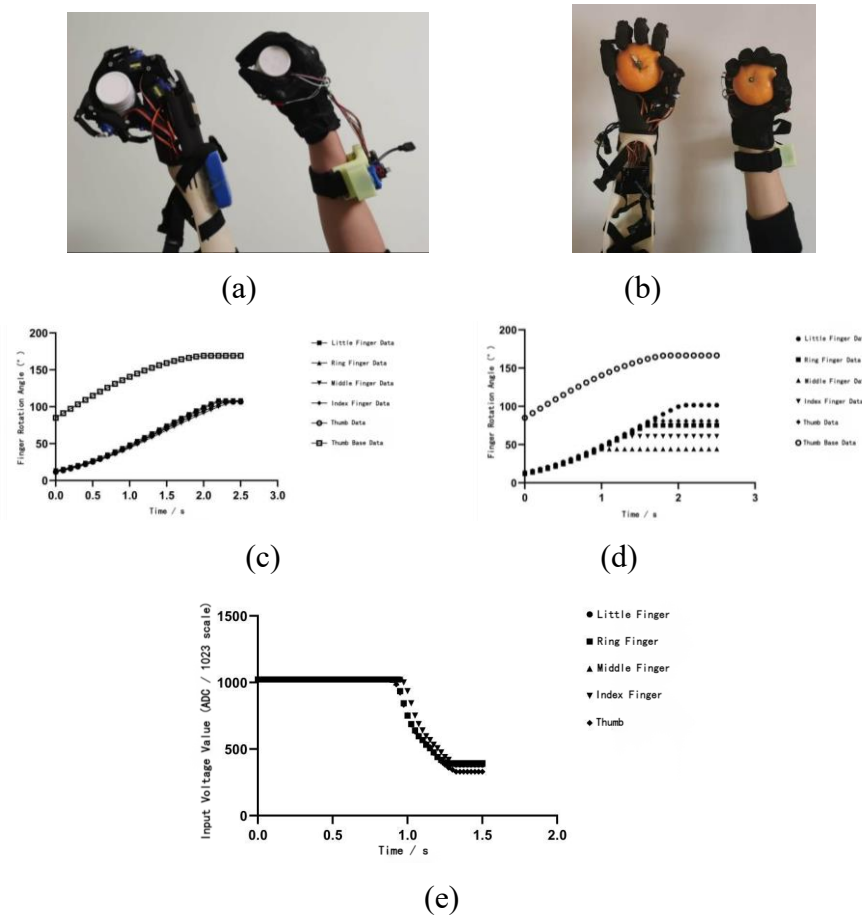


Fig. 11 Grasping process and sensor signal group. (a) Actual grasping of a cylindrical object; (b) Actual grasping of a soft spherical object; (c) Joint angle variation during cylindrical grasping; (d) Joint angle variation during soft spherical object grasping; (e) Input voltage change from pressure sensors during grasping

To evaluate the system's capability in grasping various objects, experiments were conducted using cylindrical and soft spherical items. The five fingers and the thumb base of the bionic hand transitioned from a relaxed position to complete the grasping task within 1-2.5 seconds, depending on the object type.

The grasping process for cylindrical and soft spherical objects is illustrated in Figure 11(a) and (b), which depict the final grasping postures. The corresponding joint position signals are shown in Figure 11(c) and (d). Cylindrical objects, due to their regular geometry, were grasped smoothly with coordinated joint actuation. In contrast, soft spherical objects required more adaptive responses; nonetheless, the system completed the grasp within 2 seconds.

To assess the effectiveness of force feedback, pressure sensors were used to monitor contact force during the grasping process. As shown in Figure 11(e), a distinct voltage drop was observed between 1.0 s and 1.5 s following contact with the cylinder, indicating successful force feedback detection.

6. Conclusion

To achieve high-precision and low-latency control of a bionic manipulator, this paper proposes a control system based on strain sensors. A data glove is used to collect human hand motion signals in real time, with wireless transmission enabling both data sending and feedback. As the actuator of the system, the bionic hand reproduces human hand movements in real time. When the fingers of the bionic hand experience force, the feedback is transmitted back to the human hand via the data glove. In the data processing pipeline, techniques such as limit filtering, Kalman filtering, range mapping, and PID control are applied to produce smooth and stable control signals, effectively improving system responsiveness. To enhance system robustness, pressure sensors are used to monitor the grip force of the bionic hand, enabling better handling of fragile objects and preventing excessive motor rotation when grasping hard objects, thereby extending the service life of the manipulator.

Grasping experiments demonstrate that the system enables remote, real-time control of an 11-degree-of-freedom fully actuated bionic hand with low latency, accurately replicating gestures and grasping actions. In the future, the system holds promise for remote manipulation tasks in complex environments such as bomb disposal and mine clearance.

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