International Journal of Robotics and Control Systems
Vol. 4, No. 4, 2024, pp. 1641-1655
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

Development of a Sensor-Based Glove-Controlled Mobile Robot for Firefighting and Rescue Operations

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ARTICLE INFO

Article history
Received August 06, 2024
Revised September 19, 2024
Accepted October 01, 2024

Keywords
Microcontroller;
Arduino;
Bluetooth;
Sensor-Based Glove Control;
Robotic Control Systems;
Firefighting Robot

ABSTRACT

Robots are important in preventing hazards. This paper presents the construction and testing of a mobile robot equipped with a sensor-based glove for firefighting and rescue operations. The main idea is based on the ability to control the mobile robot through the movement of a gloved hand. The glove circuit is connected to the robot circuit through Bluetooth. The MPU6050 gyroscope sensor detects the movement of a gloved hand and sends the direction of the hand's inclination to the microcontroller, which in turn uses this information to direct the mobile robot' movement in the desired direction. Experiments were conducted to test the mobile robot and its control system. Results showed that the robot prototype works effectively with satisfactory response to the intended direction of robot movement. An increase in safety level and a reduction in firefighting risks were also observed. The proposed robot can assist effectively in rescue operations, creating opportunities for future improvements.

1. Introduction

The field of robotics has achieved significant developments, expanding the applications for robots to surveillance, services, industry, hazardous environment safety applications and even robot-assisted rehabilitation [1]-[4]. In addition, robots have been recently applied in medicine [5]. Such design has been implemented in hazardous environments where human lives are at a significant risk; one example is firefighting. Owing to the frequent occurrence of fire-related accidents that pose significant risks to human safety, a strong emphasis is placed on fire prevention and control [6]. A variety of robots equipped with the necessary firefighting tools and other tools to aid civil defense workers have been designed to fulfill this responsibility [7], [8].

The invention of different types of controllers with user-friendly interface has advanced the development of real control systems [9], [10]. A microcontroller can be used for controlling the movement of a specific task completion of a robot system [11]-[14]. Robot control can be considered a result of the early applications of various human motion recognition systems, particularly the integration of advanced sensors including gyroscopes, accelerometers, and elastic sensors [15]-[17]. These sensors can follow hand movements, making the robot control interface dynamic and diverse.

The development of interactive control systems for robots has attracted research attention [11]-[13]. An example is the use of sensor-based gloves to control mobile robots, which are sensors built within the glove that detect the direction of the hand's inclination or bending of each finger depending on the technology used [14]. Several hand gloves that control the robot have been developed [18]-[20]. Most of them were developed to help patients support their weak hands depending on the strength and direction of the movement of their fingertips so they can perform specific tasks [21], [22]. Studies on these gloves focused on the material of manufacture, the dimensions of the hand, and the external structure of the gloves. These robotic control gloves have greatly improved the lives of people with weak hands, increased hand function, and provided support throughout the medical treatment [18]-[30].

One study presented an electronic glove comprising a flex sensor on each finger that recognizes finger bending and controls a mobile robot [24]. The fuzzy logic technique was employed to identify the required command through the bending of different fingers. Another work designed a robotic glove that has a flex sensor on each finger [25]. This glove was further developed to support patients' weak hands during treatment and rehabilitation so they can perform specific tasks [31]. Another design of a robot glove with a simple and easy-to-assemble structure was introduced [26]; however, this design features rigid links that require careful fittings at the finger joints, and the glove is heavy and bulky and thus hard to carry.

Adopting robots in the execution of tasks involving potentially hazardous chemical materials will aid in the mitigation of potential hazards [32]-[34]. The same approach applies to the management of heavy materials to save time and effort [35]-[37]. Some studies used a pneumatic actuator to develop a soft robotic glove that contains two sensors [28], [29]. The disadvantage of using a pneumatic actuator is that it requires a large external supply system to achieve good response, making the portability of the pneumatic glove difficult.

Robotics has contributed to the improvement of healthcare by providing precise designs of robotic arms and facilitating their widespread medical applications where treatments are handled remotely [38]. Examples include high-risk treatment situations, such as treating patients in quarantine rooms during the COVID-19 pandemic [39]-[43]. Advances in new technologies have also helped in achieving efficient automated applications and adopting microcontrollers in industrial processes [44]-[46]. Moreover, robots are usually in medical applications that often require a high level of precision [47]-[49]. Monitoring applications in healthcare have also been improved through the use of robots based on machine learning technology and other advanced AI applications [50]-[52].

In this study, a simple wool glove was used to achieve user-friendly robot control. This method was adopted to control the movement of a mobile robot, not to support weak hands as in previous research. The proposed control method with the mobile robot can minimize risks for humans, especially those in hazardous working environments. It also provides alternative options for people with special needs who have limitations in using traditional control methods due to disability. This technology is expected to have many applications, including bomb removal, rescue operations in dangerous areas, and remote surgery. However, this research mainly focused on the adoption of this robot in firefighting and rescue operations.

Compared with earlier designs that employ carbon dioxide and water, the proposed robot prototype uses only water in firefighting [53], [54] and is controlled within the operator's viewing distance at a close range. Therefore, this design revels the need for camera or obstacle avoidance tools which save to cost and provide real-time control for flexible operation [32], [55]. In addition, the prototype uses wheels for mobility which limited its movement to flat areas preventing it from moving on stairs and uneven areas compared to others that had a chain track belt [56], [57].

This research aims to employ a new technique for controlling mobile robots using a sensor-based glove. A gyroscope sensor is utilized for capturing the change in the angle of hand movement to control the robot accordingly. The use of mobile robots in hazardous environments, especially in firefighting and rescue operations, greatly aids rescuers exposed to harmful risks.

2. Hardware Implementation

The main components of the proposed system and its control are described as follows. It consists of two parts: the glove circuit, which acts as a transmitter, and the mobile robot, which receives and executes user commands. These components are specifically chosen because they are low cost, commercially available, sufficient to fulfill required duty satisfactory, and are compatible with the microcontroller.

2.1. Transmitter Hardware

The main components of the transmitter are mounted on the hand glove to control the robot through a defined hand movement.

2.1.1. Arduino Nano Microcontroller

As shown in Fig. 1, Arduino Nano with ATmega328 microcontroller has 22 digital inputs/outputs, 8 analog inputs/outputs, 2KB of RAM, 32KB of memory for program storage, and a Mini-B USB connector for power. In this project, this microcontroller is used to determine the inclination angles of the user's hand (the glove and its sensor) after receiving data from the MPU 6050 sensor. Signals are sent via Bluetooth to the robot control unit (Arduino Uno) to drive the mobile robot in the desired directions.

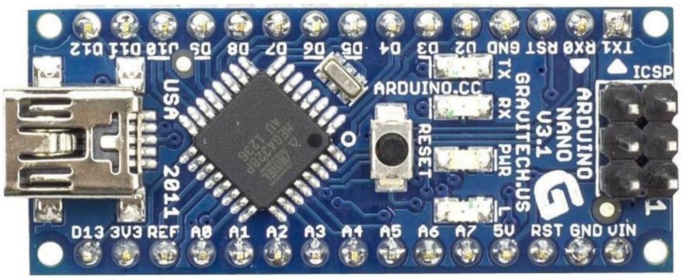

Fig. 1. Arduino nano microcontroller

2.1.2. MPU 6050 Sensor

As shown in Fig. 2, the MPU 6050 sensor is a 6-axis motion tracker accelerometer gyroscope chip with high sensory accuracy. It has many different applications, including mobile phones, satellites, spacecraft, drones, and robots for motion tracking, orientation, and position detection [58].

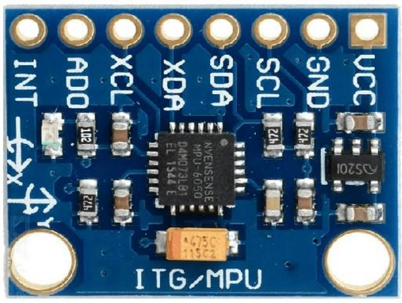

Fig. 2. MPU 6050 gyroscope sensor

2.1.3. Bluetooth Module

Bluetooth module HC-05 (Fig. 3) is capable of two-way wireless communication. It can be used to connect with any Bluetooth-enabled device or with two microcontrollers, such as Arduinos [59]. Data can be wirelessly sent and received at a baud rate of 9600 using the Universal Synchronous/Asynchronous Receiver/Transmitter (USART) protocol, which also supports additional baud rates. Outdoor, its range is fewer than 100 meters. It functions as a receiver in the robot's control unit but is always employed as a transmitter in the glove's electronic circuit. A password is required when connecting the Bluetooth module to the microcontroller. This password can be programmed using the microcontroller software to provide security to the communication between the glove and robot.

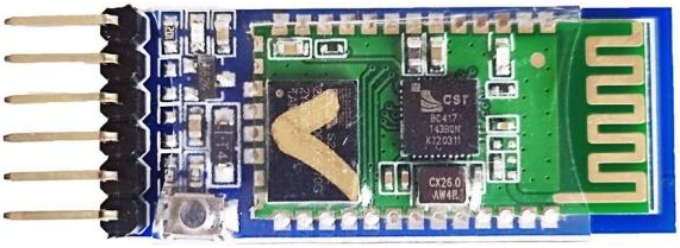

Fig. 3. Bluetooth module HC-05

2.2. Receiver Hardware

The receiver part is the robot to be controlled remotely. The main components of the mobile robot are the communication circuit mounted on it and the components driving its movement.

2.2.1. Arduino Uno Microcontroller

Arduino Uno has 14 digital inputs/outputs, 6 analog inputs/outputs, 2KB of RAM, 32KB of memory for program storage, and a USB connector for power. This microcontroller receives the inclination angles of the glove from the Bluetooth module HC-05 (receiver) and sends the control instructions to the motors to move to the desired direction. The Arduino microcontroller is programmed in C++.

2.2.2. L298N Module

L298N (Fig. 4) is an integrated circuit containing a dual H-bridge motor driver that controls the rotational speed and direction of two dc motors [60]. It is a small motor driver with a robust heatsink that can run motors with voltages ranging from 5 V to 35 V and a maximum current of 2 A.

Fig. 4. L298N dual H-bridge driver module

2.2.3. Water Level Sensor

The water level sensor measures the water level and detects any leaks in the tank. The sensor has 10 exposed copper traces, five of which are power traces and the other five are sensing traces. One sense trace is placed between two power traces due to the parallel interlacing of these traces. These traces are usually disconnected unless they are submerged come into contact with water as shown in Fig. 5. The aforementioned components are the main components of the mobile robot prototype. The other electrical and mechanical components of the robot are described in the following section.

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Fig. 5. Water level sensor

3. Implementation and Assembly of the Mobile Robot

The mechanical parts of the proposed robot are assembled as shown in Fig. 6. It consists of a base, which is a 2WD robot car kit containing two DC motors with voltage (3–6 V) and a speed encoder (1:48) that moves on three wheels mobilized by the DC motors. Fixed on this base is the robot body, a wooden structure covered by reinforced plastic from the outside. The water tank and the rest of the mechanical and electronic parts are placed inside the body of the robot. As shown in the Fig. 6, the robot dimensions are 21×13.5 cm for the base and 30 cm for the robot height.

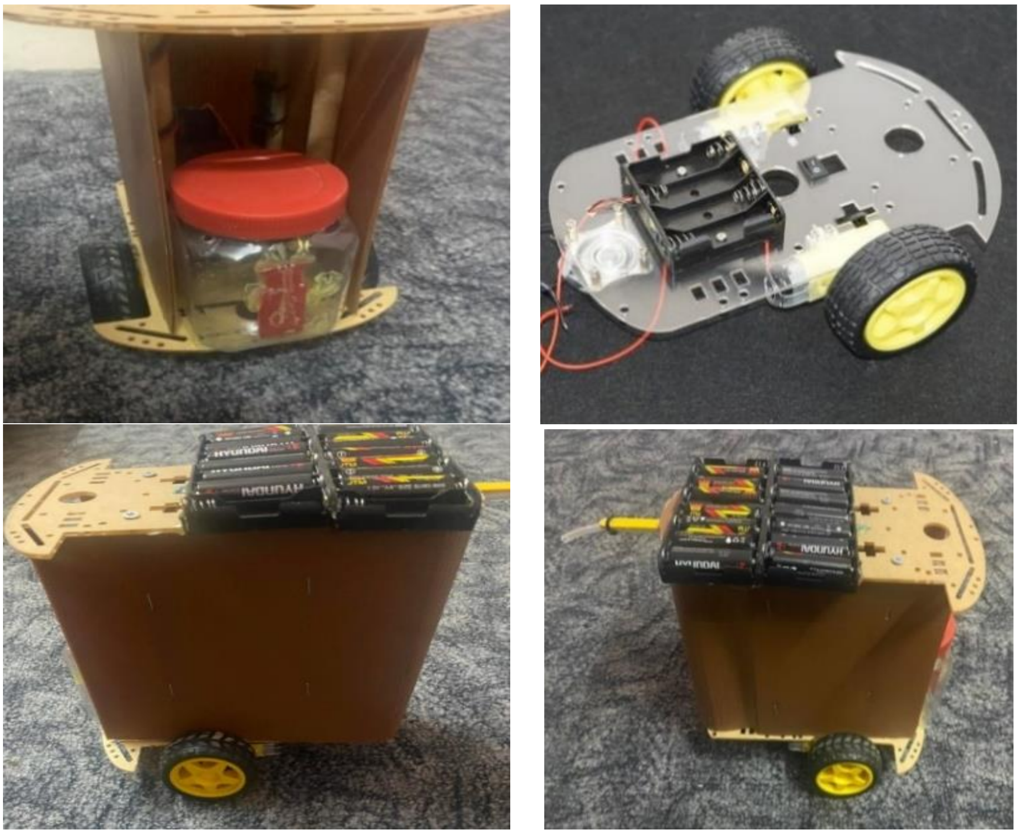

Fig. 6. Mechanical parts of the mobile robot

For the electronic circuits, the outputs and inputs are identified, and connections are made among the sensors, Arduino, and other components of the electronic circuits. The electronic circuits for the glove circuit transmitter of the proposed robot are shown in Fig. 7.

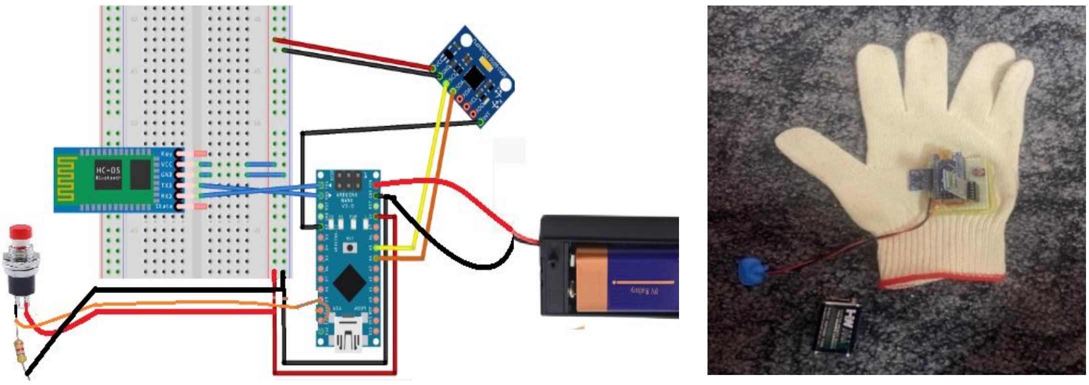

Fig. 7. Final glove circuit transmitter

The electronic circuit for the receiver and the robot control system of the proposed robot is shown in Fig. 8. For the prototype, the requirements voltages and currents are approximately 12 V and 50 mA for both Arduino boards, 6V and 220 mA for both DC motors, 6V and 200 mA for the water pump, and 5 V and 250 mA for all the other components, respectively. Sixteen units of lithium rechargeable batteries with 1.5 V and 2200 mAh are used to power the motor drivers, sensors, relays, and microcontrollers.

At no-load: battery life=battery capacity/total current =16×2200 mAh/(2×50 mA+2×220 mA+200 mA+250 mA)≈35 hours. At full-load, the system consumes around eight times this power. Therefore, its battery life is more than 4 hours, which is satisfactory.

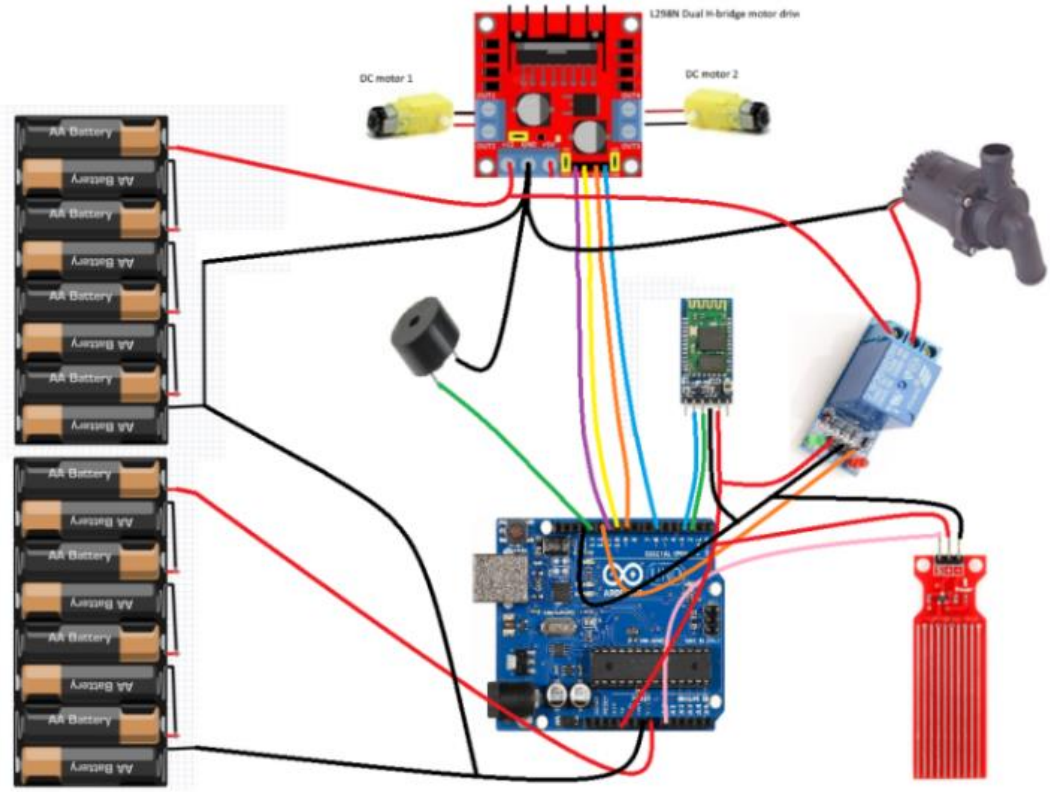

Fig. 8. Circuit of robot control system

4. Methodology

This section provides a detailed explanation of how to use the glove-controlled mobile robot and how to detect changes in the tilt angle of the glove-covered hand and send it to the microcontroller to move the robot in the desired direction for firefighting and rescue operations. Fig. 9 shows the block diagram of the proposed mobile robot, where a gloved hand controls its motion. The user's hand movements captured by the MPU 6050 gyroscope sensor, which is mounted on the hand glove. The captured coordinates are then sent to Arduino Nano microcontroller for further processing. In the implemented prototype, Bluetooth module HC-05 is used for communication between the hand glove and microcontroller board. Two HC-05 Bluetooth modules are assembled on both parts of the system, one as a transmitter from the hand glove and the other as a receiver at the mobile robot part. Arduino Nano transmits the captured coordinates to Arduino Uno, which subsequently employs the received data to direct the mobile robot to execute the required tasks.

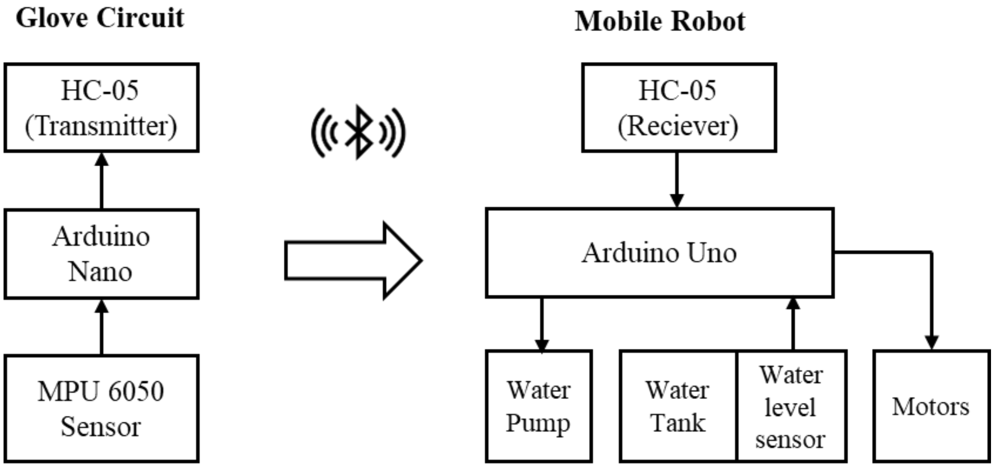

Fig. 9. Block diagram of proposed mobile robot

Fig. 10 shows the details on the functionality of the glove circuit. The flowchart illustrates the process of changing the hand position and tilt angle so that the robot can imitate this action to attain the desired location. The gyroscope sensor captures the current orientation of the hand. The Arduino Nano microcontroller identifies the location of the hand and provides the mobile robot with instructions to move in a certain direction.

Fig. 11 shows the flowchart for executing the required movement commands at the robot receiver circuit. The following movements can trigger the mobile robot: first is the hand angle tilting downward, which prompts the robot to move forward; second is the hand angle tilting upward, which prompts the robot to move backward; third is the hand tilting downward and deviating slightly to the right, causing the robot to turn clockwise while moving forward; fourth is the hand tilting upward and deviating slightly to the right, causing the robot to move backward while turning counterclockwise; fifth is the hand tilting downward and deviating slightly to the left, causing the robot to move forward while turning counterclockwise; and lastly is the hand tilting upward and deviating slightly to the left, causing the robot to move backward while turning clockwise.

If the gyroscope sensor provides inaccurate data, the user can stop the robot's progress and change the glove angle again to obtain the desired result. In the future, this robot may need another gyroscope sensor so that the data from the two sensors can be compared to accurately determine the desired direction without errors. When the Bluetooth is disconnected, the communication system must be restarted before the robot can resume its movement.

The proposed mobile robot can be used in hazardous conditions, such as rescue operations and firefighting. The flowchart in Fig. 12 illustrates the execution of firefighting commands. In the event of a fire, especially in places where humans cannot reach, the user can move the mobile robot to the desired position. The firefighting system placed on the mobile robot, which is composed of a water pump, is activated using the button mounted on the glove. If the tank runs out of water, the control system automatically stops the water pump and activates the buzzer alert so that the rescuer can refill the water tank. When the fire ceases, the user can withdraw the mobile robot out of the hazard region.

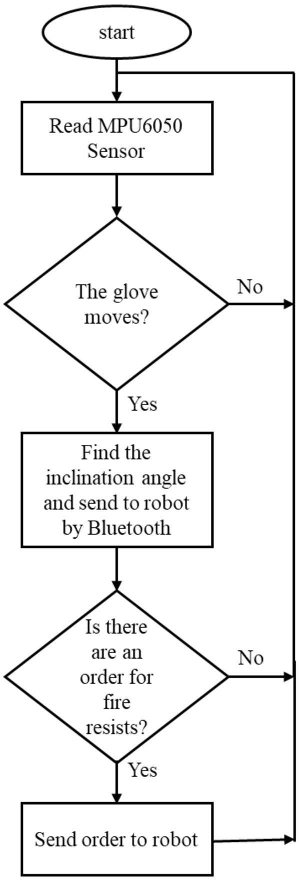

Fig. 10. Glove circuit transmitter flowchart

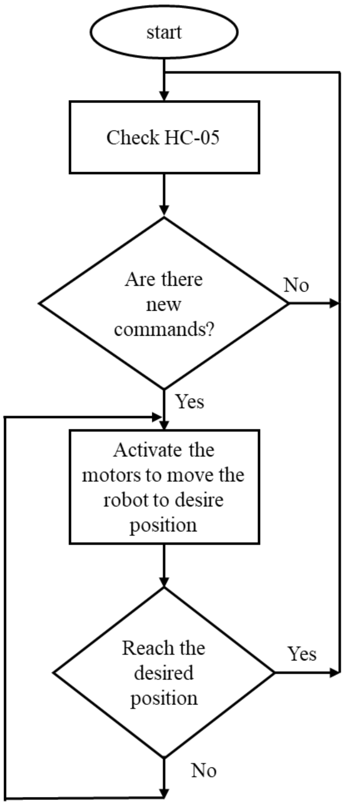

Fig. 11. Flowchart of the mobile robot movement commands: receive and execute

5. Results

Following the complete construction of the mobile robot prototype, the connections for the electronic circuits were established. The two Arduino microcontrollers were programmed and conFig.d, and the mobile robot and gloved hand were linked through Bluetooth. Practical tests were then carried out, and the following outcomes show how the mobile robot responded to the proposed control system.

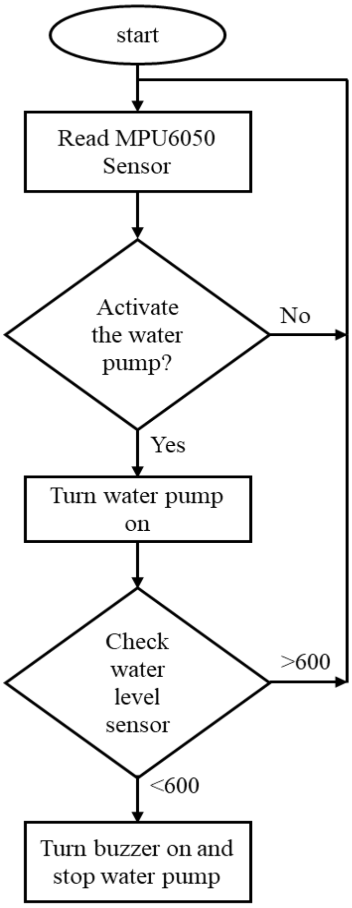

Fig. 12. Firefighting unit flowchart

The mobile robot is controlled by the movement of a gloved hand. In the first experiment, the hand was tilted downward to prompt the robot to move in a forward direction. As shown in Fig. 13, the mobile robot moved forward as long as the gloved hand remained sloped downward.

In the second test, the hand was tilted upward to prompt the robot to move in a backward direction. Fig. 14 shows that the mobile robot moved backward in response to the upward-leaning hand. In the last trial, the hand was tilted upward and deviated slightly to the right to prompt the robot to move backward while turning counterclockwise. Fig. 15 shows that the mobile robot moved backward while rotating counterclockwise as the hand tilted upward with a slight deviation to the right.

In the previous experiments, the distance between the glove and the mobile robot was no more than 40 meters due to the limited Bluetooth communication distance. The speed of the robot was adjusted to 2 m/s. When the desired location was 20 meters away from the mobile robot, the robot reached the exact target within 40 seconds at most. This response time is deemed adequate for accurate movement necessary to achieve the intended position. Therefore, the prototype of the mobile robot and the glove control system functions properly. The developed system is lightweight, flexible, user friendly, and low cost, and the glove utilizes one gyroscope sensor.

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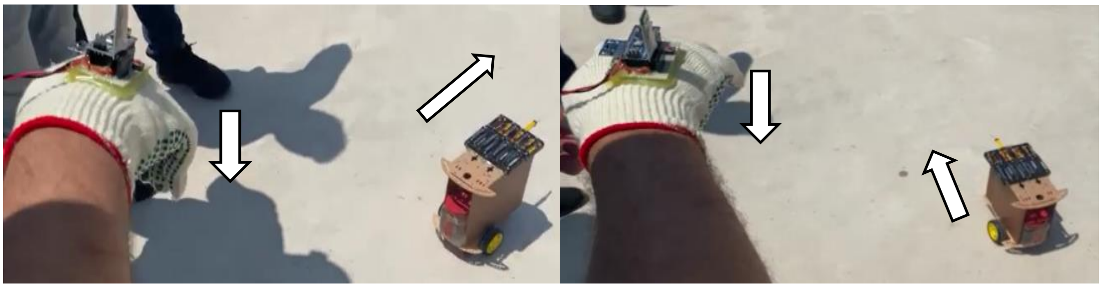

Fig. 13. The hand angle is downward, and the robot moves in the forward direction

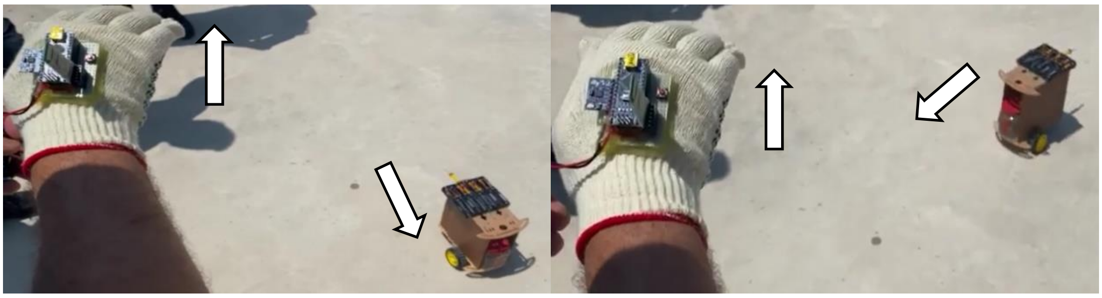

Fig. 14. The hand angle is upward, and the robot moves in the backward direction

A comparison of the proposed mobile with other prenoted models is presented in Table 1. The prototype found to be less complex; its gloved control system is composed of only one gyroscope sensor, which provides acceptable accuracy in such application. It is also light weight, which realizes the advantage of portability and easy handling and transferring to the required place. In addition, its flexibility is superior to other developed glove controls. The controller technology (Arduino microcontroller) used in the proposed system is commercially available, and the use of Bluetooth module for communication makes it suitable for hazardous environments, such as firefighting.

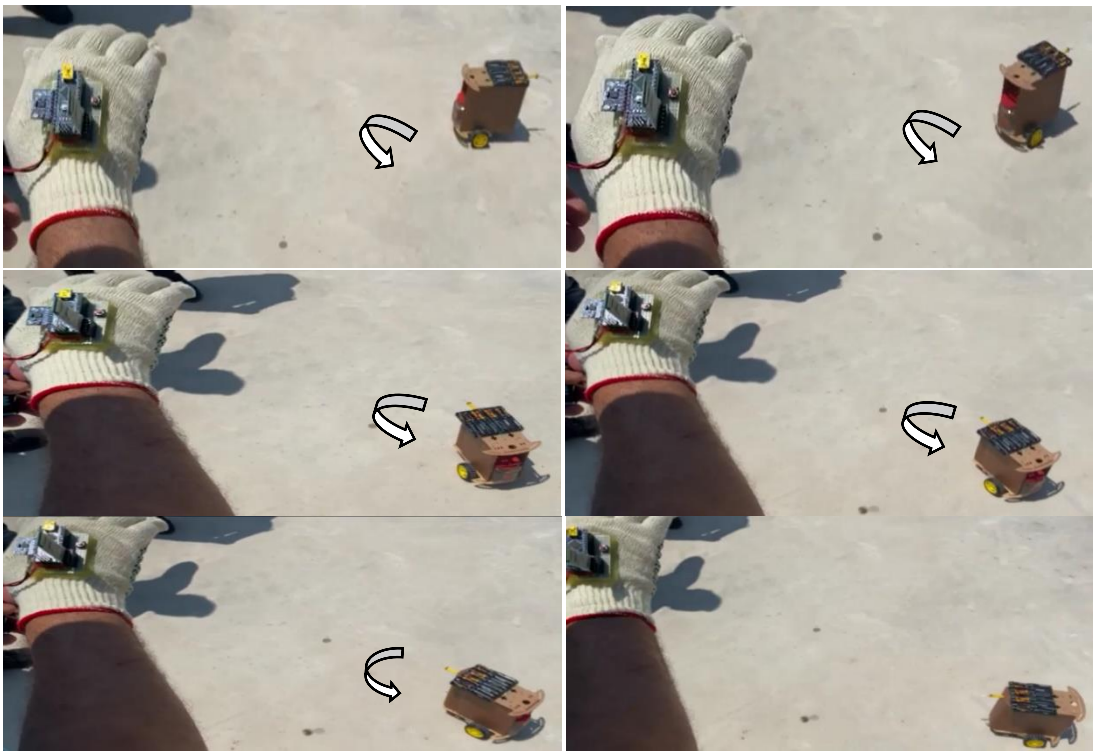

Fig. 15. The hand bends upward slightly to the right, and the robot rotates CCW backwards

Table 1. Comparison with other developed glove control mobile robots

Reference study	Sensors	Flexibly to use	Wight	Technology / Communication	Application
[24]	flex sensor on each finger	Medium Flexibly	Medium weight	Microprocessor/ RF	Mobile robot remote control
[25]	flex sensor on each finger	Medium Flexibly	Medium weight	Arduino/RF	Control robotic gripper
[27]	two pressure sensors	soft robotic gloves	portability is difficult	Arduino/wired	Rehabilitation
Proposed Robot	One gyroscope sensor	Flexible	Very light	Arduino / Bluetooth	Control firefighting mobile robot

6. Conclusion

This paper presents the development of a sensor-based glove for mobile robot control to deal with risky conditions. The mechanical and electronic control systems of the prototype are detailed. The idea is based on the ability to control a mobile robot through the movement of a gloved hand. Bluetooth is utilized for communication between the glove circuit and the mobile robot. The developed prototype has the following advantages: the glove is a lightweight wool glove that easily fits any hand size and contains a single gyroscope sensor. Meanwhile, real-time control of the mobile robot is realized because of the limited distance between the gloved hand and the mobile robot. Tests of the mobile robot were carried out, and the outcomes showed that the mobile robot can be accurately controlled to deal with dangerous conditions, such as firefighting and rescue operations. However, the developed system can only be used within a distance of 100 meters due to the limitation of Bluetooth and can only move in flat areas due to the lack of a chain track belt.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Acknowledgment: The authors are grateful to Palestine Technical University - Kadoorie for the financial support for this research and for providing the needed laboratory facilities to conduct this project. The authors also thank the technicians and undergraduate students who provided technical assistance and supported the work in the laboratory.

Conflicts of Interest: The authors declare no conflict of interest.

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