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Smartphone-Controlled Robotic Arm for Remote Throat Swab Collection in Pandemic Healthcare Applications

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Abstract

Pandemic healthcare circumstances have emphasized the importance of minimizing direct contact between healthcare personnel and potentially infected patients during diagnostic procedures such as throat swab collection. This paper presents the design and implementation of a low-cost smartphone-controlled robotic arm system for remote throat swab sampling using an Arduino-based embedded platform. The proposed system integrates servo motors, Bluetooth communication, a camera module, and a flexible robotic structure to enable controlled remote operation through a smartphone interface. The robotic platform was developed to reduce exposure risks to medical personnel while maintaining simple and user-friendly operation. Experimental testing demonstrated stable wireless control, acceptable robotic movement flexibility, and effective remote operation capability during simulated sampling procedures. The use of low-cost embedded hardware and wireless communication makes the system suitable for resource-limited healthcare environments and preliminary remote medical assistance applications. Although the current implementation depends mainly on manual control and lacks advanced sensing and autonomous positioning mechanisms, the proposed platform provides a feasible foundation for future remote healthcare robotic systems. Future improvements may include force-feedback control, intelligent image processing, automated positioning, and extended wireless communication technologies to enhance safety, precision, and operational reliability.

Keywords:

Robotic arm, Arduino Uno, Bluetooth control, Medical robotics, Throat swab collection.

I. INTRODUCTION

THE rapid spread of infectious diseases during global pandemic circumstances has highlighted the critical importance of minimizing direct physical interaction between healthcare workers and infected patients. Medical personnel involved in diagnostic procedures are often exposed to elevated risks of infection transmission, particularly during close-contact sampling operations such as throat and nasal swab collection. These procedures require healthcare workers to remain near patients, increasing the probability of cross-contamination and occupational exposure to airborne pathogens. Consequently, the development of safer and more intelligent healthcare technologies has become an important research priority in modern medical engineering.

Recent advances in robotics, embedded systems, wireless communication, and remote healthcare technologies have enabled the development of automated medical assistance systems capable of reducing human exposure in hazardous clinical environments. Robotic platforms have demonstrated significant potential in supporting healthcare operations through contactless interaction, remote monitoring, autonomous assistance, and telemedicine applications. Robotic arms equipped with precise motion control mechanisms can perform repetitive and delicate tasks with improved safety and operational consistency.

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During pandemic conditions, remote robotic systems can play an essential role in reducing infection risks associated with diagnostic sampling procedures. Traditional throat swab collection methods require healthcare workers to manually insert swabs into the patient's oral cavity while maintaining a short physical distance. Such procedures expose medical staff to respiratory droplets and aerosol particles generated during coughing, sneezing, or breathing. Therefore, integrating robotic technologies into diagnostic sampling operations can significantly improve healthcare safety while preserving procedural effectiveness.

The integration of smartphone control technologies with robotic systems further enhances operational flexibility and ease of use. Smartphones provide user-friendly interfaces, wireless communication capability, portability, and real-time control functionality. Bluetooth communication offers a low-cost and reliable solution for short-range wireless robotic control without requiring complex networking infrastructure. Combined with microcontroller-based embedded platforms such as Arduino, smartphone-controlled robotic systems can provide accessible and affordable solutions for medical applications, especially in emergency healthcare environments and resource-limited facilities.

Several studies have investigated robotic assistance systems for medical and healthcare applications, including robotic surgery, patient monitoring, automated medicine delivery, rehabilitation support, and teleoperated diagnostic systems. However, many existing healthcare robotic platforms involve complex mechanical structures, expensive control systems, or advanced industrial hardware that may limit practical deployment in low-cost healthcare environments. Furthermore, relatively limited research has focused specifically on compact robotic systems designed for remote throat swab collection using simple embedded hardware and wireless smartphone control.

To address these challenges, this paper presents the design and implementation of a smartphone-controlled robotic arm system for remote throat swab collection under pandemic healthcare conditions. The proposed system utilizes an Arduino-based embedded control platform integrated with servo motors, Bluetooth communication, and a camera-assisted monitoring mechanism to enable controlled and flexible robotic movement during the swab collection process. The robotic structure is designed to provide stable positioning and smooth motion control while allowing healthcare personnel to remotely operate the system from a safer distance. The primary objectives of this research are:

- Develop a robotic arm capable of collecting throat swabs remotely.
- Reduce direct contact between healthcare workers and infected patients.
- Provide an economical and easy-to-use medical robotic system.
- Create a platform that can be expanded for future medical applications such as dental and eye examinations.

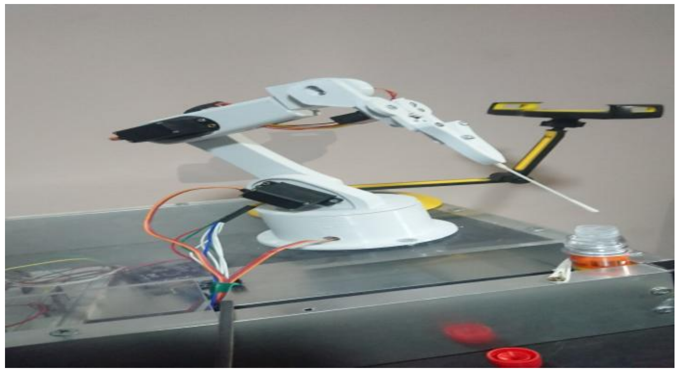

Fig. 1. The robotic arm.

Experimental implementation and testing were conducted to evaluate the movement capability, wireless control performance, and operational feasibility of the proposed robotic system. The obtained results demonstrate that the developed platform can effectively support remote throat swab collection while minimizing exposure risks to healthcare personnel. Figure 1 shows a photographic view of the robotic arm.

The remainder of this paper is organized as follows. Section 2 reviews related works and recent developments in healthcare robotics and remote medical systems. Section 3 presents the hardware and software architecture of the proposed robotic platform. Section 4 discusses system implementation and experimental testing procedures. Section 5 presents the obtained results and performance analysis, while Section 6 concludes the paper and outlines future research directions.

II. LITERATURE REVIEW

Recent pandemic conditions accelerated the use of robotics in healthcare to reduce direct contact between medical staff and potentially infected patients. Robotics has been identified as a practical solution for infection control, remote diagnosis, disinfection, sample handling, and clinical assistance, particularly when healthcare workers face high exposure risk [1]–[3]. Early pandemic-related studies emphasized that robots could function as a protective barrier between patients and medical personnel, supporting safer clinical workflows and reducing contamination risk [1], [2]. Broader reviews on robotics for infectious disease management also confirmed the relevance of robotic systems in diagnosis, logistics, disinfection, and remote medical interaction [3].

Robotic swab collection has received research attention because throat and nasal swab procedures require close contact with patients. Chen et al. developed a tele-operated oropharyngeal swab robot using a soft robotic mechanism to improve sampling safety and reduce healthcare worker exposure [4]. Another collaborative robot for oropharyngeal swabbing employed a snake-like manipulator, haptic devices, and visual guidance to support remote sampling tasks [5]. These systems demonstrated the feasibility of robotic swab sampling but generally required more complex mechanical structures and control interfaces than low-cost embedded platforms.

Autonomous swab sampling has also been investigated.

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Haddadin et al. developed and clinically tested an autonomous robot station for naso- and oropharyngeal screening, showing that robotic sampling can reduce transmission risk while maintaining sampling feasibility [6]. More recently, Dong et al. proposed a flexible transoral swab sampling robot using visual–tactile fusion, combining camera-based oral image recognition with force feedback for safer autonomous sampling [7]. Lee et al. further examined force-compliant robotic control for nasopharyngeal swab collection, emphasizing the importance of force sensing and compliant motion during medical sampling [8].

In addition to swab-specific systems, recent studies highlight the wider role of medical robots in pandemic healthcare environments. Zemmar et al. discussed how surgical and healthcare robots can reduce infectious exposure while maintaining clinical service continuity [9]. Cresswell et al. reviewed robotic testing technologies and argued that robots could improve testing capacity while reducing risk to healthcare staff [10]. Similarly, recent studies on robotic disinfection, hospital assistance, and intensive care applications show increasing acceptance of robotic systems for noncomplex but high-risk or repetitive medical tasks [11]–[13]. Low-cost embedded robotic platforms are also relevant to healthcare and remote operation. Arduino-based systems have been widely used because they offer low cost, simple programming, flexible hardware integration, and compatibility with servo motors and wireless communication modules. Recent Arduino-based healthcare and biosensing studies indicate that open-source microcontroller platforms can support affordable medical and diagnostic applications [14]. Bluetooth-enabled Arduino robotic systems have also been developed for remote manipulation and navigation in hazardous environments, demonstrating the practicality of smartphone or Android-based control for low-cost robotic operation [15].

Smartphone-controlled and Bluetooth-controlled robotic arms have been increasingly explored for remote manipulation, object handling, and hazardous task execution. Recent robotic arm studies show that Arduino, servo motors, Bluetooth modules, and mobile applications can provide accessible control solutions for educational, industrial, and assistive applications [16]–[18]. Although many of these systems focus on pick-and-place operations rather than medical sampling, their hardware principles are directly applicable to low-cost medical robotic platforms where precise, remote, and user-friendly control is required.

Overall, the reviewed literature shows that robotic swab collection is technically feasible and clinically relevant, but many existing systems depend on expensive robotic arms, force sensors, complex vision systems, or advanced teleoperation interfaces. Therefore, there remains a clear need for simpler, low-cost, smartphone-controlled robotic systems that can assist throat swab collection under pandemic healthcare circumstances. The proposed Arduino-based Bluetooth-controlled robotic arm contributes to this direction by emphasizing affordability, ease of operation, remote control, and reduced exposure risk for healthcare personnel. A comparative review of recent robotic healthcare systems and remote swab collection approaches is summarized in Table 1.

III. SYSTEM DESIGN AND IMPLEMENTATION

The proposed system consists of a smartphone-controlled robotic arm designed to remotely perform throat swab collection under pandemic healthcare conditions. The system integrates an Arduino-based embedded controller, servo motors, Bluetooth communication, and a camera-assisted monitoring mechanism to provide flexible and controlled robotic movement during the sampling process.

The overall hardware architecture includes:

- an Arduino Uno microcontroller,
- multiple servo motors for robotic arm motion,
- an HC-05 Bluetooth communication module,
- a smartphone control application,
- a camera module for visual monitoring,
- and a lightweight mechanical robotic structure.

The Arduino microcontroller functions as the central control unit responsible for processing wireless commands received from the smartphone through Bluetooth communication. Based on the received control signals, the Arduino generates pulse-width modulation (PWM) signals to control the angular movement of the servo motors. The robotic arm provides multiple degrees of freedom to support flexible positioning and controlled throat swab movement.

The smartphone application serves as a wireless user interface that allows healthcare personnel to remotely control the robotic arm from a safer distance. Bluetooth communication was selected because of its low cost, ease of implementation, low power consumption, and compatibility with mobile devices.

A camera module was integrated into the system to assist visual monitoring during the swab collection process. The camera enables the operator to observe robotic arm positioning and improve movement precision during sampling operations.

The software implementation was developed using the Arduino Integrated Development Environment (IDE). The control algorithm manages servo motor movement according to directional commands transmitted from the smartphone interface. Smooth robotic motion and controlled positioning were considered during implementation to improve operational stability and patient safety. The proposed robotic platform was designed with emphasis on low implementation cost, operational simplicity, flexible wireless control, and reduced healthcare worker exposure risk. Figures 2 to 5 show the schematic system design, the Arduino Uno board, the Bluetooth communication electronic parts, and the servo motor parts, respectively.

The characteristics mentioned make the system suitable for remote healthcare support and diagnostic assistance under pandemic healthcare circumstances.

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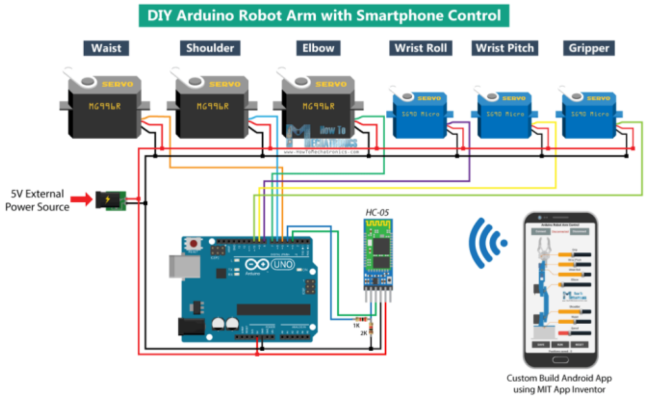

Fig. 2. Robotic Arm System Design.

Fig. 3. Arduino Uno microcontroller.

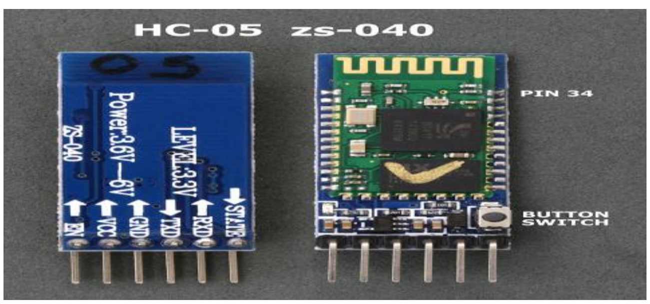

Fig. 4. Bluetooth communication electronics.

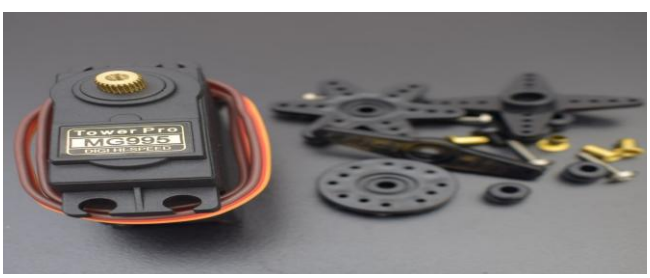

Fig. 5. Servo motors auxiliaries.

IV. EXPERIMENTAL TESTING AND RESULTS

Experimental testing was conducted to evaluate the operational performance and feasibility of the proposed smartphone-controlled robotic arm system for remote throat swab collection. The experiments focused on wireless control performance, robotic arm movement accuracy, response stability, and the ability to reduce direct interaction between healthcare personnel and patients during sampling procedures.

The robotic platform was assembled using an Arduino Uno controller, servo motors, Bluetooth communication module, camera module, and a lightweight robotic arm structure. The smartphone interface was used to remotely control the movement of the robotic arm through Bluetooth communication. Multiple motion tests were performed to verify the responsiveness and stability of the robotic system during remote operation.

The experimental implementation demonstrated that the robotic arm successfully performed controlled movement in multiple directions with acceptable positioning flexibility. The servo motors provided smooth angular motion, enabling gradual positioning of the swab mechanism during operation. Bluetooth communication maintained stable connectivity within the operational range, allowing reliable real-time control using the smartphone interface.

The integrated camera module improved visual monitoring during robotic operation by assisting the operator in positioning the robotic arm more accurately. This feature contributed to safer and more controlled movement during simulated throat swab procedures.

The proposed system also demonstrated several practical advantages, including reduced direct physical interaction, low implementation cost, simple hardware integration, and ease of operation.

Compared to more complex robotic healthcare systems, the proposed platform provides a lightweight and affordable solution suitable for basic remote medical assistance applications.

Although the developed system successfully demonstrated remote robotic control capability, several limitations were identified during testing. The robotic arm positioning accuracy remained dependent on manual operator control, and the absence of advanced force-feedback sensing limited fully autonomous operation. In addition, Bluetooth communication range constraints may affect operation in larger healthcare environments.

Overall, the experimental results confirmed the feasibility of using low-cost embedded robotic systems for remote healthcare support under pandemic circumstances. The proposed robotic arm successfully demonstrated remote throat swab collection capability while reducing potential exposure risks to healthcare personnel.

V. DISCUSSION

The experimental implementation demonstrates that the proposed smartphone-controlled robotic arm can provide a practical low-cost solution for remote throat swab collection under pandemic healthcare circumstances. The system successfully integrates Arduino-based control, Bluetooth communication, servo-driven robotic movement, and camera-assisted monitoring into a compact platform that can be operated from a safer distance. This supports the main objective of reducing direct exposure between healthcare workers and potentially infected patients.

Compared with advanced robotic swab collection systems reported in the literature, the proposed system prioritizes simplicity, affordability, and ease of implementation rather than full autonomy or highly precise medical-grade manipulation. Existing teleoperated and autonomous swab robots often

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provide better motion precision, force control, and safety feedback, but they usually require complex robotic hardware, advanced sensing systems, and expensive control platforms. In contrast, the proposed system uses accessible components such as Arduino, servo motors, Bluetooth modules, and a smartphone interface, making it more suitable for educational prototypes, low-resource environments, and preliminary pandemic-response applications.

VI. CONCLUSION

This paper presented the design and implementation of a smartphone-controlled robotic arm system for remote throat swab collection under pandemic healthcare circumstances. The proposed system successfully demonstrated the feasibility of using a low-cost Arduino-based robotic platform integrated with Bluetooth communication, servo motors, and camera-assisted monitoring to reduce direct physical interaction between healthcare personnel and patients during sampling procedures. The developed robotic system provided simple and flexible remote operation through a smartphone interface while maintaining acceptable movement control and operational functionality. The use of low-cost embedded hardware makes the proposed platform suitable for healthcare environments where advanced commercial medical robots may not be economically accessible. Although the system demonstrated practical potential for remote medical assistance, several limitations remain. The current implementation depends primarily on manual operator control and lacks advanced sensing mechanisms such as force feedback and intelligent autonomous positioning. In addition, Bluetooth communication range limitations restrict operation to short-distance environments, and the system has not yet undergone clinical validation. Overall, the proposed robotic platform provides a practical foundation for future remote medical sampling systems. Future work should focus on integrating force sensors, intelligent image processing, automated motion control, extended wireless communication technologies, and supervised clinical evaluation to improve operational safety, precision, and real-world healthcare applicability.

TABLE I
COMPARATIVE REVIEW OF RECENT ROBOTIC SYSTEMS FOR PANDEMIC HEALTHCARE APPLICATIONS

Ref.	System / Approach	Main Technology	Application	Merits	Limitations
[1]	Healthcare robotics framework	Mobile and autonomous robots	Pandemic healthcare support	Reduces human exposure risk	Conceptual review without implementation
[4]	Tele-operated swab robot	Teleoperation with robotic manipulator	Remote throat swab collection	Improves sampling safety	Complex control mechanism
[5]	Collaborative swab robot	Vision-guided compliant robot	Oropharyngeal sampling	Accurate motion guidance	High hardware complexity
[6]	Autonomous swab station	Autonomous medical robotics	Nasopharyngeal/oropharyngeal testing	Minimize healthcare contact	Expensive robotic infrastructure
[7]	Visual–tactile swab robot	Sensor fusion and robotics	Automated swab sampling	Improved sampling precision	Requires advanced sensors
[8]	Force-compliant robotic sampling	Force-feedback control	Nasopharyngeal swabbing	Enhanced patient safety	Increased control complexity
[11]	Hospital assistance robot	Autonomous service robotics	Healthcare support and disinfection	Reduces manual intervention	Limited diagnostic capability
[12]	Intelligent healthcare robot	AI-assisted robotics	Pandemic healthcare operations	Supports remote healthcare tasks	High implementation cost
[14]	Arduino-based healthcare platform	Embedded systems and sensors	Medical monitoring	Low-cost and flexible	Limited computational capability
[15]	Bluetooth robotic system	Wireless embedded robotics	Hazardous remote operation	Simple remote control	Limited communication range
[16]	Smartphone-controlled robotic arm	Arduino and Bluetooth	Remote robotic manipulation	Easy operation and affordability	Moderate positioning accuracy
Proposed Work	Smartphone-controlled robotic arm for throat swab collection	Arduino, Bluetooth, servo motors, camera module	Remote medical swab collection	Low cost, flexible control, reduced exposure risk, simple implementation	Limited automation and sensing capability

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TABLE II

COMPARATIVE RESULTS OF THE PROPOSED SYSTEM WITH RELATED ROBOTIC HEALTHCARE WORKS

Ref.	Robotic System / Approach	Control Method	Application	Main Reported Result	Limitation
[4]	Tele-operated swab robot	Remote teleoperation	Oropharyngeal swab sampling	Demonstrated safer remote sampling with reduced staff exposure	Complex robotic structure and control
[5]	Collaborative swab robot	Vision-guided compliant control	Throat swab collection	Improved guidance and sampling precision	Requires advanced vision and compliant hardware
[6]	Autonomous swab station	Autonomous robotic control	Naso-/oropharyngeal screening	Reduced direct healthcare worker contact during sampling	High system cost and complex infrastructure
[7]	Visual–tactile swab robot	Visual and tactile sensor fusion	Transoral swab sampling	Improved safety through sensing-based guidance	Requires advanced sensors and processing
[8]	Force-compliant swab robot	Force-feedback control	Nasopharyngeal sampling	Enhanced patient safety through compliant motion	Increased hardware and control complexity
[14]	Arduino-based healthcare platform	Embedded microcontroller control	Healthcare monitoring	Demonstrated low-cost healthcare system feasibility	Limited robotic manipulation capability
[15]	Bluetooth robotic system	Bluetooth wireless control	Remote hazardous operation	Simple and low-cost remote control	Limited communication range
[16]	Smartphone-controlled robotic arm	Arduino and Bluetooth	Remote robotic manipulation	Easy operation and affordable implementation	Moderate positioning accuracy
Proposed Work	Smartphone-controlled robotic arm	Arduino, Bluetooth, servo motors, camera monitoring	Remote throat swab collection	Low-cost remote sampling prototype that reduces direct exposure risk	Manual control, limited sensing, and no clinical validation

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