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Design and Experimental Validation of a Voice Controlled 3D-Printed Dental Chair Model

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Abstract

This research presents a small-scale, desktop educational proof-of-concept prototype of a voice-controlled and 3D (three-dimensional)-printed dental chair model designed to improve the clinical work environment by reducing direct manual interaction. The system integrates a microcontroller, four servo motors, and a smartphone application, enabling touchless chair position changes via predefined voice commands. Ten functional chair positions are developed, ranging from 0° to 90° for four chair situations. The mechanical model is designed in SolidWorks, and a 3D-printed model is generated to visualize the actual chair. The system is evaluated through practical tests, which demonstrate an average execution accuracy of 84% across all voice commands. The system is under development and operates in both Arabic and English, making it available to local and international users. Future proposals include advanced voice recognition models and noise-filtering techniques, with the scope of application expanding to encompass variations in voice tone and accents across users.

Keywords: accuracy, voice recognition, medical dental chair, servo motor, 3D printing, microcontroller

1. Introduction

Voice control (VC) of devices is a field that has evolved significantly over the past decades and combines voice technologies and artificial intelligence to make interacting with devices easier and more convenient. With the continuous advancement of VC, it will become more powerful, accurate, and integrated into various aspects of our lives, making them easier and more efficient. Early voice-control systems focused on simple word recognition, with examples including Bell Labs' "Audrey" device [1]. In the 1960s, the IBM Shoebox program appeared [2], which demonstrated early advances in voice recognition. Subsequent advances enabled the recognition of more words and complex expressions. More advanced algorithms, such as simple neural networks, began to be used to improve the accuracy of voice recognition. Commercial products such as Dragon NaturallySpeaking became available [3], making voice controls a practical tool for personal use. The advent of smartphones provided a major boost to VC technologies. Improved microphone quality and Internet connectivity have made voice recognition and analysis faster. Intelligent voice assistants such as Apple's Siri [4], Google Assistant, and Amazon's Alexa [5] further expanded the practical applications of VC. The integration of VC with the internet of things (IoT) [6] has enabled home appliances, such as lighting, televisions, to become compatible with voice commands. VC will be available on almost all devices, from phones and cars to wearables and even home appliances.

Previous studies have also demonstrated the application of VC in various fields. A study developed voice commands for a home aid robot with an offline service for processing spoken instructions in real-time [7]. Other studies explored bluetooth- and Wi-Fi-based voice control for home appliances [8] and an Arduino UNO voice command platform [9]. Another study used

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voice instructions to perform various functions and interact with users through responses to their inquiries, with an emphasis on system simplification and design formulation and estimation [10]. These showed the feasibility of using voice commands with embedded systems for various functions and applications. They also demonstrated the flexibility of voice-depend interfaces across robotic and interactive applications. However, the reviewed studies mainly concentrated on general-purpose applications, underscoring the necessity for further exploration into voice-control systems specifically designed for medical devices, where reliable operation, ease of use, and accurate execution of commands are particularly important [7-10].

In recent years, the rapid development of the internet of medical things (IoMT) and smart healthcare systems has a substantial effect on clinical workflows and patient care delivery [11]. Modern clinical environments increasingly give priority to touchless automation, ergonomics, and intelligent devices to minimize cross-contamination and operator fatigue [12].

Within dentistry, the combination of smart sensors, robotic motors, and hands-free control (such as voice recognition and gesture movement) has gained considerable impetus [13]. Recent studies highlight that replacing traditional manual controls with voice-mechanisms not only improves infection control protocols in dental operatories but also enhances ergonomic efficiency for practitioners during complex procedures [14]. Despite these advancements in high-end commercial systems, there remains a critical research gap in developing accessible, low-cost, bilingual (Arabic-English) voice-controlled physical models that bridge low-cost automation with real-time clinical position adjustments.

Although significant progress has been achieved in voice control technologies and intelligent assistants, most previous studies have focused on general-purpose voice-controlled systems, smart home applications, robotic assistants, and wheelchairs. Existing research has primarily addressed speech recognition algorithms, IoT-based control, or Arduino-based implementations as independent solutions. However, limited attention has been given to integrating real-time voice control with a 3D (three-dimensional)-printed dental chair that combines mechanical actuation, servo motor control, and embedded systems within a single platform. Furthermore, there is a lack of comprehensive studies involving real-time modeling, prototype development, and experimental validation of voice-controlled dental equipment. Therefore, this study aims to bridge this gap by designing, simulating, fabricating, and experimentally evaluating a smart 3D-printed dental chair controlled through voice commands, providing a low-cost and intelligent solution for modern dental clinics.

Voice-controlled dental chairs may facilitate hands-free operation, reduce manual adjustments, and improve clinical workflow efficiency. Saving time by replacing chair adjustments contributes to improving the workflow in the clinic. For VC applications, the system can include commands such as “up the chair,” “down the chair,” and other commands that facilitate the dentist’s work. For these issues, there has not been a significant amount of scientific research focusing specifically on the benefits of the VC of a dental chair. However, there are general studies related to VC technologies in different fields, including healthcare, which can support the idea of the benefits of this technology in medical clinics. The main contributions of the design and experimental investigation of the voice-controlled 3D-printed dental chair are as follows:

(1) Introducing a modified design of a voice-controlled 3D-printed dental chair to reduce manual contact and improve regimens in healthcare environments.

(2) Integrating four servomotors, Arduino Nano, and a smartphone application to provide a smooth and continuous touchless control system.

(3) Implementing ten functional positions with a voice recognition system for both Arabic and English, ensuring applicability for both local and international users.

The remainder of this manuscript is organized as follows. Section 2 presents the materials and methods, including the design, modeling, simulation, hardware implementation, and voice control system. Section 3 presents the experimental results and performance evaluation. Section 4 discusses the obtained results and compares them with previous studies. Finally, Section 5 summarizes the main conclusions of this study and outlines potential directions for future work.

2. Design Methodology

This study builds a small-scale, desktop educational proof-of-concept prototype of a VC [15] model based on the microcontroller. This research introduces a general framework with ten functional orders: zero-degree position, 90-degree position, 45-degree position, up position, middle position, down position, head test position, head 90-degree position, leg test position, and leg 90-degree position. The design is structured using SolidWorks software [16] with a photo of a dental chair that is adopted in the design of the chair for the model using a 3D printer [17-19]. The model consists of a microcontroller [20]. Four servo motors [21] are illustrated in the block diagram in Fig. 1. In addition, for more details, Fig. 2 demonstrates a schematic diagram and a printed circuit board with a 3D design using the Proteus software [22-24]. Furthermore, Fig. 3 depicts the actual framework, including its components, for additional information. For more details and explanation, Fig. 4 shows the 3D printed components, which presents the mechanical design specifications. The material used for the design is Nylon (Polyamide), which is a very hard material with slight flexibility and high resistance to friction.

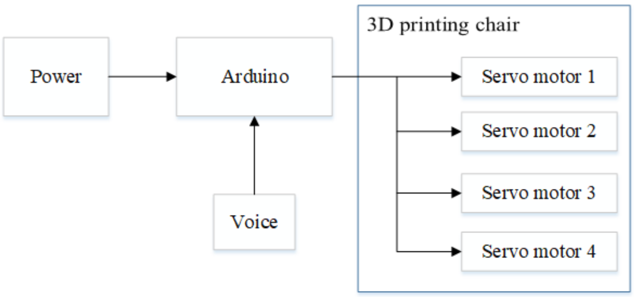
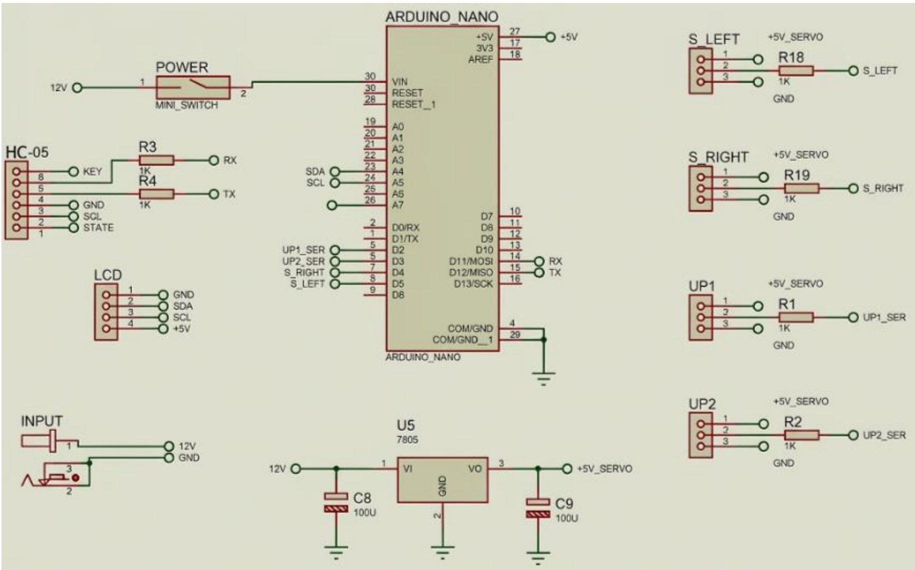
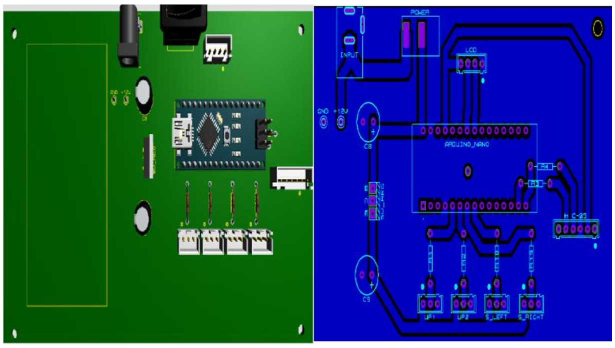


Fig. 1 Block diagram of the voice control prototype dental chair-based microcontroller



(a) Schematic diagram



(b) Printed circuit board

Fig. 2 Proposed system architecture and its physical implementation

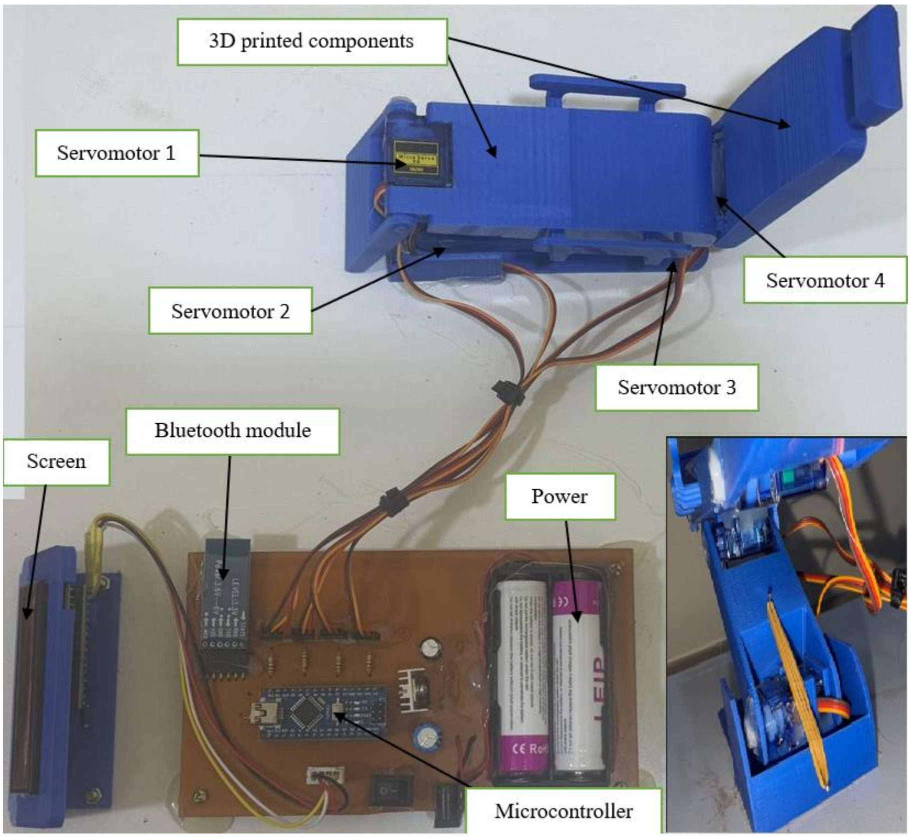
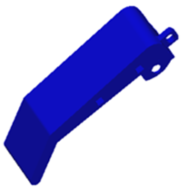
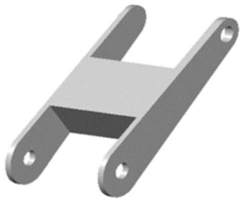


Fig. 3 Components of the prototype with its components

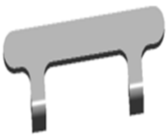
(a) Head stand



(b) Leg stand

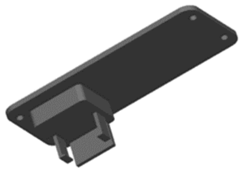


(c) Connect base



(d) Arm stand

(e) Base cover



(f) Bed base

Fig. 4 Mechanical design specifications

The system uses an Arduino Bluetooth [25] alongside Android application to control devices remotely. This type of technology is used to maintain audio clarity and to prevent noise interference because using a microphone typically requires additional work, such as creating filters to exclude noise, especially in a medical clinic or hospital. It allows the user to send commands to the Arduino using specific control buttons within the application, making it suitable for controlling various devices, such as robots, electrical switches, and even a dental chair. As shown in Fig. 5, the flow chart illustrates the system workflow. The system starts up and activates the voice reception system to prepare to receive user commands and it then verifies whether the input audio matches predefined commands. If so, the signal is sent to the microcontroller; otherwise, the system re-initialize. Next, the microcontroller analyzes the voice command, converts it into an electrical control signal, and sends commands to the motors based on the analyzed audio. The chair moves in the specified direction depending on the voice command. Finally, the process is completed after the movement is successfully executed. The programming settings and technical considerations proposed in terms of interference and response time are evaluated through repeated testing in noisy environments. The device is successfully operated under these conditions.

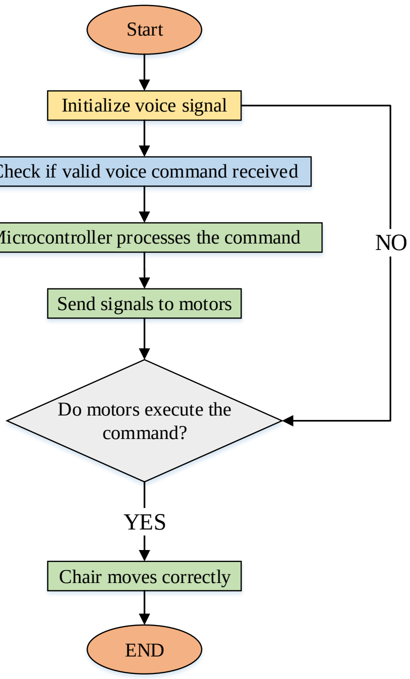


Fig. 5 Flowchart of the voice control prototype dental chair-based microcontroller

The algorithm for speech processing and the process of recognizing commands are presented in Fig. 6 to clearly illustrate the speech processing and command recognition procedure, showing how voice commands are captured, recognized, validated, transmitted, and executed to control the dental chair. This improves the readability and reproducibility of the proposed system.

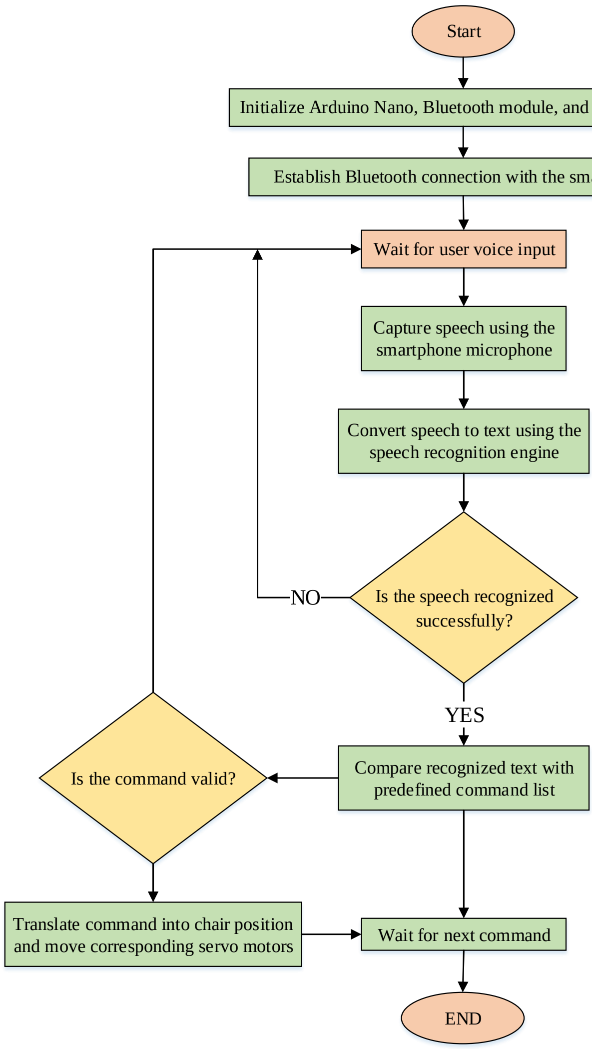


Fig. 6 Flowchart of the speech processing and command recognition

3. Experimental Results

VC of the dental chair is a modern technology that aims to facilitate dentists' work and improve the patient experience. This technology allows the chair to be turned on or off, adjusted in height, and repositioned through simple voice commands. The experimental results demonstrate that the system can operate and change position in real-time, and the practical tests demonstrate its applicability. It is capable of performing the following tasks: zero-degree position, 90-degree position, 45-degree position, up position, middle position, down position, head test position, head 90-degree position, leg test position, and leg 90-degree position.

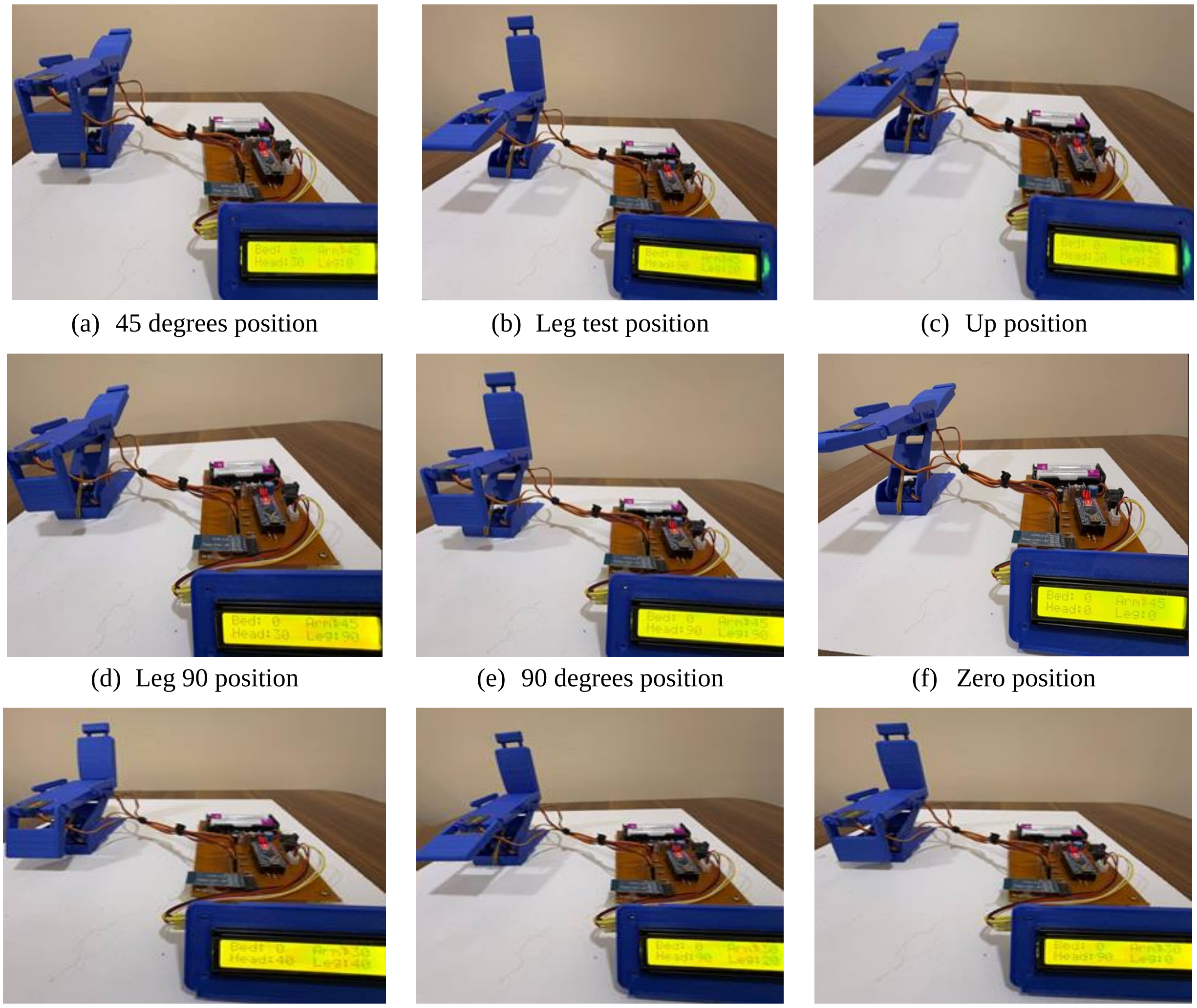
The commands are displayed on the screen: the leg (servomotor 1), the arm (servomotor 2), the bed (servomotor 3), and the head (servomotor 4) instructions. The purpose of the screen is to provide visual feedback, support education, and ensure that instructions are executed correctly. Since the model is a prototype, the screen is used not only by the doctor but also to improve operational accuracy.

Table 1 shows the approved angles for moving the dental chair in different directions. Each angle is carefully selected based on functional requirements and patient anatomical comfort. These angles are adjusted based on preliminary experiments to ensure smooth movement and effective response to voice commands. Servomotor 3 operates in coordination with servomotor 2 in a dual-actuator setup. This configuration is used to balance the 3D-printed backrest mechanism on both sides and distribute dynamic physical loads. In the tested positions, servomotor 3, which controls the bed mechanism, remains at 0°, while servomotor 2 controls the arm movement according to the programmed commands. The dental chair movement angles are distributed according to the optimal positions, and Fig. 7 shows a snapshot of the exact values for each angle.

For designing a hydraulic or mechanical system for a dental chair, the choice of angles depends on various factors, such as the dentist's needs for different procedures. A 90° angle (upright) is proposed for easy patient entry and exit from the chair, initial examination, and communication with the dentist. A 0° angle (supinate) provides a fully supine position for the patient and is the ideal angle for maxillary arch treatment, allowing the dentist direct vision without neck bending. A 30°-45° angle (rectlined) provides the best viewing and illumination angle for mandibular arch treatment while maintaining patient comfort. Also, the servo motors and 3D-printed joints have geometric limits in rotation (0°-90°). Choosing these angles ensures smooth movement that prevents excessive friction between printed parts or overloading of the motors.

Table 1 Positions and angles for moving the dental chair in different positions

Positions	Leg (Servomotor 1)	Arm (Servomotor 2)	Bed (Servomotor 3)	Head (Servomotor 4)
45°	0°	45°	0°	30°
Leg test	20°	45°	0°	90°
Up	20°	45°	0°	30°
Leg 90°	90°	45°	0°	30°
90°	90°	45°	0°	90°
0°	0°	45°	0°	0°
Head test	40°	30°	0°	40°
Head 90°	20°	30°	0°	90°
Middle	0°	40°	0°	30°
Down	0°	30°	0°	90°



(a) 45 degrees position (b) Leg test position (c) Up position

(d) Leg 90 position (e) 90 degrees position (f) Zero position

(g) Head test position (h) Head 90 position (i) Down position

Fig. 7 Snapshots of the angles for the voice control prototype dental chair

The system accuracy is calculated as defined below [26-27], based on the number of correct attempts relative to the total number of attempts:

$$\textit{Accuracy}\ (\textit{Acc.}) = [\textit{Correct attempts/ total attempts}] \times 100\% \quad (1)$$

A total of 10 attempts is conducted for each command. Table 2 demonstrates the testing trials and accuracy for each command.

Table 2 Testing trials for the dental chair movements

Trials \ Position	0°	90°	45°	Up	Middle	Down	Head Test	Head 90°	Leg Test	Leg 90°
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	✓	✓	×	✓	×	×	✓	✓	✓	✓
4	×	✓	✓	✓	✓	✓	×	✓	✓	✓
5	✓	×	✓	✓	×	✓	✓	✓	✓	×
6	✓	✓	✓	×	✓	×	✓	✓	✓	✓
7	✓	✓	✓	✓	✓	✓	×	✓	×	✓
8	✓	✓	✓	✓	✓	✓	✓	×	✓	×
9	×	✓	✓	✓	✓	✓	✓	✓	×	✓
10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ACC. (%)	80	90	90	90	80	80	80	90	80	80

Note: correct :✓; incorrect : ×

For statistical analysis of the experimental results, with five participants, ten voice commands, and five repetitions per command per participant, the sample size is $N = 5 \times 10 \times 5 = 250$. The successful tests are 210 and failed tests are 40, yielding the overall accuracy of 84%. A scientific comparison between the proposed voice control system and manual control of a dental chair is presented in Table 3. The comparison indicates that the voice-controlled system offers significant improvements in performance efficiency, comfort, and reduced contact, making it a promising future option in dental clinics. However, it remains necessary to enhance the accuracy of voice recognition and rely on extensive testing to ensure complete reliability in real clinical settings.

Table 3 Comparison between the proposed voice control system and manual control system

Comparative feature	Manual control	Voice control (Proposed system)
Flexibility during examination	The doctor has to use his hands to adjust the position of the chair, which may interrupt the examination or contaminate the instruments.	Allows the physician to adjust the chair position without touching, maintaining their focus and the cleanliness of the clinical environment.
Response speed	It depends on the availability of the doctor or assistant to adjust the positions.	Commands are executed almost instantly via voice commands.
Accuracy in adjusting angles	Depends on user experience and manual discretion.	Angles are set with a pre-defined digital precision (e.g., 45°, 90°).
Patient comfort	The patient may feel anxious or uncomfortable about the repetitive hand movement.	Provides smooth and convenient navigation to pre-defined voice commands.

Table 4 Experiment parameters of voice recognition

Parameter	Specification	Description
Number of participants	Five	Three male and two female aged (23-55) years
Language	Arabic and English	Iraqi dialect
Testing environment	Controlled indoor laboratory	Quiet room setting to simulate a baseline clinical room

For more details about the voice recognition and performance experiments such as the number of participants, testing conditions with different accents are evaluated in Table 4, which is conducted with a group of five participants (three males, two females). The testing evaluated both Arabic (local dialect) to test bilingual responsiveness. All trials are performed in a controlled laboratory environment with low ambient noise.

To evaluate the real-time performance of the system, the total time latency (T_{total}) is measured from the moment a voice command is uttered until the mechanical chair reaches the target position. As detailed in Table 5, the total response time is expressed as as follows:

$$T_{total} = T_{voice} + T_{command} + T_{microcontroller\ processing} + T_{motor\ actuating} \tag{2}$$

where T_{voice}, $T_{command}$, $T_{microcontroller\ processing}$, and $T_{motor\ actuating}$ denote the voice recognition time, command transmission time, microcontroller processing time, and motor actuation time, respectively.

Table 5 Real-time performance of the system for total time latency

Stage	Description	Time latency (ms)
Time for voice processing (T_{voice})	Speech-to-Text recognition via smartphone app.	800±125
Time for transmission ($T_{command}$)	Bluetooth data transfer to microcontroller	140±40
Time for microcontroller processing ($T_{microcontroller\ processing}$)	Microcontroller processing	55±5
Time for motor actuating ($T_{motor\ actuating}$)	Servo motors moving 3D printed chair model	1150±200
Total time latency (T_{total})	End-to-end delay from voice command to motion completion	≈ 2.20 seconds

The average total time is measured at approximately 2.20 seconds. These results confirm that the system provides an acceptable real-time response for clinical environments without introducing hazardous movement delays.

To assess the mechanical ability of the proposed prototype for a full-scale clinical chair, a theoretical static torque technique is performed considering worst-test loading conditions. The total required torque ($T_{required}$) at the backrest axis is estimated as a behavior of the integrated gravitational load of the patient ($G_{patient}$), evaluated within a standard clinical range of 70 to 120 kg as well as the structural backrest (B_{frame}), multiplied by the adequate center of mass lever arm (l_{mass}) and a safety factor ($S_f = 1.5$).

Based on this balance, standard servo motors are replaced in the full-scale deployment system by an industrial 24V DC heavy-duty linear motor. Linear motors are providing a rated push/pull force capacity of ≥ 6 kN are preferred as the optimal actuation structure. This arrangement integrates directly with the recommended microcontroller command via high-current relay drivers, supporting smoothly continuous integration without altering the underlying voice-recognition.

4. Discussion

The performance of the proposed prototype model is assessed according to 10 execution trials that are conducted per voice command under controlled laboratory conditions. As 10 trials are tailored for evaluating the initial physical feasibility and repeatability of the proof-of-concept prototype, comprehensive evaluations involving broader user demographics and noisy clinical settings are planned for future work.

The low accuracy rate in executing some voice commands (reaching 80% in a number of cases) is attributed to several potential technical and human factors, the most important of which are the similarity of the tone or pronunciation of voice commands; some commands may be similar in pronunciation or contain similar sounds, making it difficult for a voice recognition system to distinguish between them, especially in the absence of advanced natural language processing models. Voice pitch and speech rate vary between users, or even within the same person from one attempt to the next, which can affect the microphone or software's ability to interpret the command correctly. The testing environment may not be soundproof, meaning that external noises interfere with the target audio signal, which can lead to command recognition errors. When relying on a limited number of voice recordings or only one user, the system is not trained to adapt to differences in voices and accents, which reduces accuracy in recognizing different commands. Based on these findings, it is recommended to improve the testing environment, use professional microphones, expand the training dataset to include multiple voices, and adopt more advanced voice recognition algorithms.

However, the physical constraints that prevent building a real medical dental chair are as follows: the miniature model is made of plastic, while the actual chair needs a steel or aluminum structure to withstand weights of up to 150-200 kg while preventing structural deflection. The actual chair has a large mass and therefore possesses high inertia. This requires motors with mechanical brakes and a manual emergency stop switch to prevent unintended movement in case of audible delay or command error. Transitioning from small servo motors operating at 5V/2A to industrial linear motors operating at 24V or 220V and drawing high current requires cooling circuitry and thermal overload protection. Dental equipment is exposed to water, liquids, and chemical materials; therefore, motors and electronic parts must be sealed to international protection standards to facilitate clinical sterilization.

Any medical or hydraulic/mechanical device dealing with humans requires high safety standards. First, the proposed system is a 3D-printed, small desktop prototype that operates at very low voltage, low-torque servo motors that pose no physical risk or potential for damage during laboratory testing. Second, the software algorithm already includes an automatic cancellation mechanism; if the sound does not match the ten predefined commands, the system rejects the command entirely and does not execute any random movement. Finally, mechanical emergency stop mechanisms (such as a physical stop button and limit switches are typically integrated with high-power industrial motors in clinical trials, not in proof-of-concept models.

While traditional commercial chairs offer rapid mechanical execution (< 1.0 s) and complete mechanical reliability, they necessitate direct physical contact via foot pedals or manual touchpads, thereby posing a high risk of cross-contamination. Monolingual voice-controlled systems make no need for physical contact and achieve speech recognition accuracies between 85% and 90%; however, they are limited to English commands and frequently depend on cloud-based application programming interfaces, resulting in greater processing latencies (3.0-4.5 s). Moreover, Computer vision and gesture-based control systems present hands-free operation with response latencies ranging from 1.8 to 2.5 s, with recognition rates (80 % - 86%) due to ambient lighting sensitivity and limited positional flexibility (3-4 preset positions). In contrast, the proposed framework achieves a balanced operational trade-off, providing dual-language support (Arabic and English), accommodating 10 predefined clinical positions, operating with an end-to-end response latency of approximately 2.20 s, and maintaining an overall execution accuracy of 84% using accessible, low-cost microcontroller hardware.

5. Conclusions

This study presented the design, implementation, and experimental evaluation of a real-time voice-controlled dental chair prototype based on a microcontroller architecture. The proposed system integrates an Arduino controller, four servo motors, a smartphone application, and programmed voice commands to provide touchless adjustment of dental chair positions. The developed prototype was designed to improve clinical workflow, enhance patient comfort, and reduce direct physical contact during chair operation. The main conclusions of this study are summarized as follows:

(1) The proposed voice-controlled dental chair successfully executed ten predefined chair positions through spoken commands in both Arabic and English.

(2) The developed system achieved an average voice command recognition accuracy of 84%, demonstrating reliable performance under the experimental conditions.

(3) The integration of Arduino-based control, servo motors, and mobile application technology provided a simple, low-cost, and practical solution for smart dental chair automation.

(4) The touchless operation reduced the need for manual chair adjustments, which can contribute to minimizing cross-contamination risks and improving infection control in dental clinics.

(5) The proposed prototype demonstrated the feasibility of applying voice control technology in dental equipment while improving operational efficiency for both dentists and patients.

Future work will focus on enhancing speech recognition accuracy using advanced AI (artificial intelligence)-driven models and voice pre-processing techniques, incorporating robust real-time noise suppression methods for clinical environments, accommodating a wider range of accents and speech patterns, and integrating additional smart functions such as IoT connectivity and intelligent patient management.

Conflicts of Interest

Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. If there is no conflict of interest, please state "The authors declare no conflict of interest."

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