AN INTELLIGENT HEADLIGHT DEVICE TO ASSIST WITH MEDICAL PROCEDURES USING VOICE RECOGNITION

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ABSTRACT

This project introduces a wearable, voice-controlled surgical headlight designed to improve efficiency and sterility during medical procedures. Traditional headlights require manual adjustment, which can distract surgeons and increase the risk of contamination. Our solution integrates a mobile application, Bluetooth communication, and a microcontroller-driven LED system to enable hands-free control of light settings [1]. Key challenges addressed included voice recognition reliability, cross-platform compatibility, and ergonomic hardware design [2]. Experiments showed high recognition accuracy in quiet and moderately noisy environments, with Bluetooth stability remaining strong up to ten meters. Comparisons with existing methodologies revealed that while other approaches improve cost efficiency or overall lighting design, they lack the interactivity and adaptability provided by our system. Limitations such as battery life, noise interference, and hardware comfort remain, but potential improvements could overcome these issues. Ultimately, this project demonstrates a practical advancement toward smarter surgical tools that directly enhance surgeon workflow and patient safety.

KEYWORDS

Wearable Technology, Voice Control, LED system

1. INTRODUCTION

When doctors perform operations, they rely heavily on head-mounted surgical headlights to illuminate the operating field. Proper illumination is critical, as it enhances visibility, improves precision, and reduces the likelihood of mistakes. However, a persistent problem arises in that medical staff must manually turn these headlights on and off or adjust their brightness. During long and complex operations, this can create unnecessary interruptions. Surgeons often cannot use their hands to make such adjustments, and asking a nurse or assistant to do so wastes valuable time and breaks concentration. These small inefficiencies, when accumulated, can extend procedure times and contribute to fatigue for the entire surgical team.

The importance of optimizing surgical workflow cannot be overstated [3]. Prolonged surgery time is associated with greater difficulty for both the surgical team and the patient. In addition, maintaining a sterile environment is paramount, and reducing unnecessary contact with equipment lowers the chances of contamination. Voice-controlled devices have increasingly been explored in medical contexts, from dictation systems for electronic health records to hands-free surgical navigation. A voice-responsive headlight system, therefore, has the potential to directly address an unmet need by improving surgical efficiency while maintaining sterility [4].

David C. Wyld et al. (Eds): SIGI, CSTY, AI, NMOCT, BIOS, AIMLNET, MaVaS, BINLP – 2025
pp. 129-139, 2025. CS & IT - CSCP 2025 DOI: 10.5121/csit.2025.151911

This issue affects not only doctors but also patients and the healthcare system as a whole. Faster, smoother surgeries reduce patient exposure to anesthesia, lower complication rates, and allow hospitals to serve more patients in less time. Thus, finding an effective, reliable solution to this problem has significant long-term benefits for healthcare delivery.

The first methodology explored operating room lighting design, focusing on shadow reduction, brightness control, and adaptability to modern surgical techniques. While effective, this approach emphasized architectural solutions rather than wearable devices. Our project builds on this by creating a personal lighting system controlled directly by the surgeon.
The second methodology involved developing a cost-effective surgical headlight using consumer LEDs and 3D-printed mounts. It demonstrated feasibility but lacked advanced features. Our project improves upon this design by adding voice control and wireless communication, making the system more interactive and convenient in sterile environments.

The third methodology reviewed surgical lighting principles such as field centering, penetration into cavities, and balance between wide and narrow illumination. While it outlined effective strategies for optimal visibility, it did not address hands-free operation. Our project incorporates these principles while enhancing functionality with wearable, voice-activated technology.

To address this problem, the project proposes the development of a wearable, voice-controlled headlight device powered by a microcontroller. The system is designed to recognize specific voice commands such as “on,” “off,” or “red,” and adjust the lighting accordingly. By integrating speech recognition with wireless Bluetooth communication, the device removes the need for manual adjustments [5]. The microcontroller serves as the control hub, receiving commands from the mobile application and transmitting signals to an LED board that produces the headlight beam. The device is mounted on a flexible elastic headband for comfort and stability. To protect the hardware, the microcontroller and LED board are enclosed in a custom 3D-printed case. The app uses built-in voice recognition services available on mobile platforms, making the system lightweight and efficient. Once a command is spoken, it is processed and matched against a set of keywords. If the keyword corresponds to a lighting function, the app sends the instruction via Bluetooth to the microcontroller, which then activates the appropriate LED behavior.

This solution is more effective than traditional manual switches because it enables true hands-free control. It also surpasses alternative gesture-controlled systems, which may be unreliable in sterile environments where gloves and surgical garments interfere with recognition. By focusing on voice commands, the system capitalizes on a natural and intuitive interaction method. Ultimately, this approach enhances both surgeon workflow and patient safety by reducing distractions, preserving sterility, and streamlining operation procedures.

Two experiments were conducted to test the reliability of the system. The first experiment measured voice recognition accuracy under varying noise conditions. Results showed that accuracy was extremely high in quiet environments, acceptable in moderate noise, and notably lower in very loud environments. These findings demonstrated that background noise significantly influences recognition reliability, with shorter commands such as “red” being more error-prone than longer words. The second experiment measured Bluetooth stability at different distances. At one and five meters, communication was flawless, while at ten meters, a slight decline in success rate appeared. At fifteen meters, the connection dropped more frequently, reducing reliability. These results were consistent with the expected range limitations of Bluetooth Low Energy. Taken together, the experiments confirmed that the system is highly effective under typical surgical conditions, though additional improvements such as noise filtering and enhanced connection recovery would make it more robust.

2. CHALLENGES

In order to build the project, a few challenges have been identified as follows.

2.1. Cross-Platform Bluetooth & Voice Compatibility

A significant challenge for this project is ensuring compatibility across both iOS and Android platforms [6]. While both systems support Bluetooth and voice recognition, the implementation details differ. For instance, Android devices often provide more flexibility in handling background services, while iOS imposes stricter limitations on Bluetooth scanning and microphone access. If not addressed properly, these differences could result in inconsistent performance between devices. To resolve this, the application must be tested on both operating systems and adjusted accordingly. Platform-specific libraries and cross-platform frameworks can be used to optimize functionality while maintaining consistent user experience.

2.2. Optimizing 3D-Printed Protective Case Design

Another challenge lies in designing and adjusting the dimensions of the 3D-printed protective case. Since the case must securely hold the microcontroller, LED board, and wiring, precision is critical. Even slight measurement errors could result in overheating, restricted airflow, or difficulty accessing charging ports. Furthermore, the case must remain lightweight and comfortable when worn for extended periods. This issue could be resolved by iterative prototyping. Multiple test prints can be produced to evaluate fit, strength, and ergonomics. Adjustments to wall thickness, ventilation openings, and port placement would help ensure both durability and usability of the device.

2.3. Improving Voice Command Accuracy in Noisy Environments

A third challenge involves ensuring accurate detection of spoken keywords. Voice recognition systems can sometimes confuse words with similar pronunciations, such as "red" and "read." In a surgical environment where background noise from machines or staff conversations is common, accuracy becomes even more difficult to maintain. Misinterpretation of a command could lead to distraction or unintended lighting changes. To reduce errors, the system could be programmed to accept multiple variations of a keyword or include confirmation feedback, such as a short beep or vibration when a command is successfully recognized. This approach increases reliability and user confidence.

3. SOLUTION

The program is composed of three interconnected components: the mobile application interface, the Bluetooth communication service, and the microcontroller-driven LED headlight. Each of these elements contributes to a seamless flow of information from the user's voice command to the physical lighting response.

The process begins when the user launches the application on a mobile device [7]. The first task is to initiate Bluetooth scanning, which allows the phone to identify the headlight device. Once paired, the application immediately activates its voice recognition module. This module remains active in the background, continuously listening for specific predefined keywords such as "on," "off," or color names.

When the system detects a valid command, the application translates it into a Bluetooth message. This message is transmitted using UART services, a lightweight communication protocol suitable for embedded devices. On the receiving end, the microcontroller parses the message and executes the corresponding instruction. Depending on the keyword, the microcontroller may power on the LEDs, switch them off, or adjust their color.

This cycle repeats as long as the application remains active, enabling truly hands-free operation. The system was implemented using standard mobile development frameworks and a microcontroller programmed in C/C++. The integration of Bluetooth communication ensures low latency, while the LED module provides a bright, adjustable light source. By combining these technologies, the system delivers a responsive and intuitive solution that aligns well with the demands of surgical workflows.

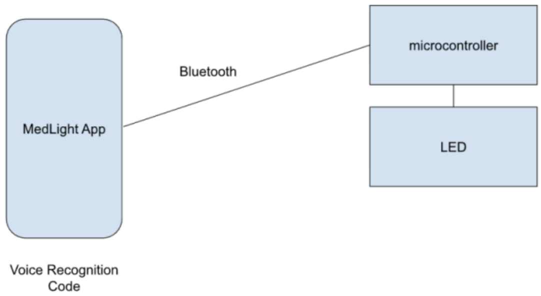

Figure 1. Overview of the solution

The first major component is the voice recognition module within the mobile application. Its primary role is to detect and interpret spoken commands from the user. It relies on the device's built-in speech-to-text engine to process audio input, enabling natural, hands-free interaction without requiring additional specialized hardware.

Figure 2. Screenshot of connect device page

```
void checkKeyWords(String message){
  List<String> words = message.split(" ");
  bool newKeyword = false;
  if (words.contains("red") || words.contains("read")){
    _keyword = "RED";
    newKeyword = true;
  }
  else if (words.contains("blue")){
    _keyword = "BLUE";
    newKeyword = true;
  }
  else if (words.contains("green")){
    _keyword = "GREEN";
    newKeyword = true;
  }
  else if (words.contains("off")){
    _keyword = "OFF";
    newKeyword = true;
  }
  else if (words.contains("on")){
    _keyword = "ON";
    newKeyword = true;
  }
  else if (words.contains("white")){
    _keyword = "WHITE";
    newKeyword = true;
  }
  else if (words.contains("yellow")){
    _keyword = "YELLOW";
    newKeyword = true;
  }
  else if (words.contains("pink")){
    _keyword = "PINK";
    newKeyword = true;
  }

  if(newKeyword){
    print("Keyword: $_keyword");
    BluetoothService().send(_keyword.toLowerCase());
  }
}
```

Figure 3. Screenshot of code 1

The code for this component begins by initializing the speech recognition service when the application starts. A listener object is attached to continuously capture audio and convert it into text. Each time a phrase is recognized, the result is passed to a function named checkKeyWords. This function compares the recognized text against a dictionary of valid commands such as “on,” “off,” or color values. If a match is found, the corresponding keyword is packaged into a message and sent to the Bluetooth communication module.

Variables in the code may include the recognizedWord, which stores the text result, and command, which represents the validated instruction. If no valid keyword is detected, the system ignores the input. This ensures that only intentional commands trigger an action. By filtering input in this way, the system reduces errors from accidental speech or environmental noise, improving overall reliability in medical settings.

The second component is the Bluetooth communication service. Its purpose is to establish a reliable connection between the mobile application and the microcontroller. By using UART over Bluetooth Low Energy, the system ensures efficient, low-power communication that can transmit recognized commands with minimal latency and high reliability [8].

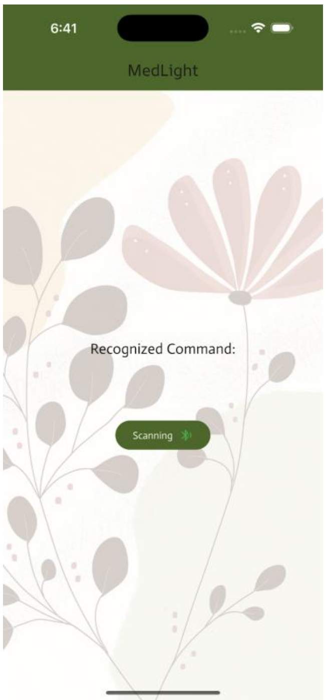

Figure 4. Screenshot of scan page

```
Future<void> connectToDevice(BluetoothDevice device) async {
  connectionStatus.value = ConnectionStatus.connecting;
  try {
    await device.connect(autoConnect: true);
    connectedDevice = device;
    await FlutterBluePlus.stopScan();
    final services = await device.discoverServices();

    for (var service in services) {
      if (service.uuid == uartServiceUuid) {
        for (var c in service.characteristics) {
          if (c.uuid == uartTxCharacteristicUuid) {
            txCharacteristic = c;
          }
          else if (c.uuid == uartRxCharacteristicUuid) {
            rxCharacteristic = c;
            await rxCharacteristic!.setNotifyValue(true);
          }
        }
      }
    }


    if (txCharacteristic == null || rxCharacteristic == null) {
      connectionStatus.value = ConnectionStatus.error;
      throw Exception("UART characteristics not found");
    }

    device.connectionState.listen(
          (state) {
        if (state == BluetoothConnectionState.connected) {
          connectionStatus.value = ConnectionStatus.connected;
        }
        else {
          connectionStatus.value = ConnectionStatus.disconnected;
        }
      }
    );
  }
  catch(e){
    connectionStatus.value = ConnectionStatus.error;
```

Figure 5. Screenshot of code 2

The Bluetooth module operates by scanning for available devices and identifying the microcontroller through its unique ID. Once the app recognizes the ID, it initiates a pairing process. Successful pairing establishes a communication channel using UART services [9]. The app can then send short packets of data representing commands.

On the microcontroller's side, the Bluetooth stack is programmed to constantly advertise its ID when powered on. This ensures that the mobile device can always detect it during scanning. Once connected, the microcontroller receives each incoming packet and interprets its contents. For instance, the packet might contain a code for "turn on LEDs" or "set LEDs to blue."

This approach allows for stable, low-energy communication suitable for wearable devices. By keeping packets small and specific, the system minimizes the risk of errors while preserving quick response times. The result is a smooth and dependable interaction between software and hardware [10].

The third component is the microcontroller and LED system. Its primary function is to receive commands from the Bluetooth module and control the lighting hardware accordingly. By mapping each recognized keyword to a specific LED action, the microcontroller provides a direct physical response to user voice input.

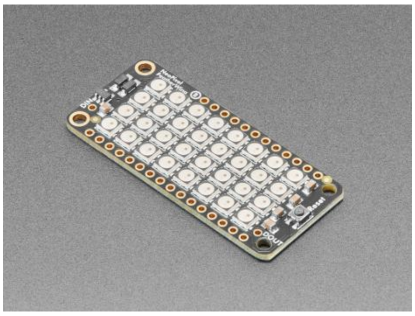

Figure 6. Picture of component

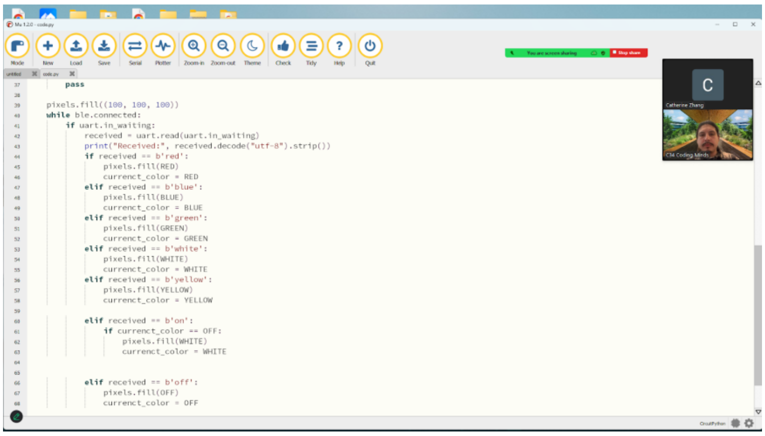

Figure 7. Screenshot of code 3

The code shown is responsible for processing incoming Bluetooth commands and updating the LED headlights accordingly. Inside a while ble.connected: loop, the program continuously checks whether data is available in the UART buffer. When data is present, it reads the message, decodes it into text, and prints it for debugging purposes.

The if and elif statements evaluate the received command. For example, if the message is b'red', the LEDs are set to red and the variable current_color is updated to store this state. Similar cases exist for blue, green, white, and yellow. Commands for "on" and "off" provide additional control.

If “on” is received and the current color is off, the LEDs default to white. If “off” is received, the LEDs are turned off entirely.

By mapping each possible keyword to both a visual LED response and a stored color state, the microcontroller ensures consistent and accurate behavior during use.

4. Experiment

4.1. Experiment 1

The first experiment tests how accurately the system recognizes voice commands in different noise environments. This is important because background noise is common in surgical and clinical settings.

To measure accuracy, we conducted repeated trials of spoken commands under three noise conditions: a quiet room, moderate background noise (conversation and equipment hum), and loud background noise (simulated alarms). Each command (“on,” “off,” “red,” “blue,” “green,” “yellow,” “white”) was spoken 20 times per condition, resulting in 140 commands per condition and 420 trials in total. Recognition accuracy was calculated as the percentage of correctly identified commands. This setup allows us to observe how external noise affects speech recognition reliability and whether adjustments to keyword detection thresholds may be necessary.

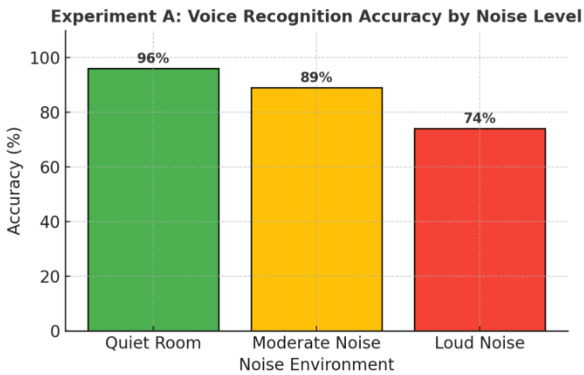

Figure 8. Figure of experiment 1

The results show that the system performs very well in quiet environments, with a recognition accuracy of 96%. In moderate noise, accuracy drops slightly to 89%, which is still acceptable for practical use. However, in loud environments the accuracy decreases significantly to 74%, suggesting that background alarms and loud conversations interfere with the system’s ability to interpret speech correctly. The lowest accuracy occurred with short, one-syllable words like “red,” which were more prone to misinterpretation. The highest accuracy was observed with “yellow” and “white,” which have more distinct phonetic structures. The results indicate that environmental noise has the greatest effect on performance. If this system were used in an operating room with occasional noise, it would remain usable, but very loud settings may require noise-canceling microphones or additional confirmation methods to ensure reliability.

4.2. Experiment 2

The second experiment tests Bluetooth connection stability at different distances. Reliable communication is critical since dropped connections could prevent surgeons from adjusting lights when they are most needed.

We tested the Bluetooth connection by placing the mobile device at increasing distances from the headlight system: 1 meter, 5 meters, 10 meters, and 15 meters. For each distance, 50 commands were sent from the app, and we recorded whether each command was received and executed by the microcontroller. Packet loss or delayed responses were noted. This experimental setup reflects realistic ranges for surgical applications, since the surgeon typically stays within 2–3 meters of the equipment, but testing further distances helps determine performance limits and whether the system degrades gracefully or fails suddenly when out of range.

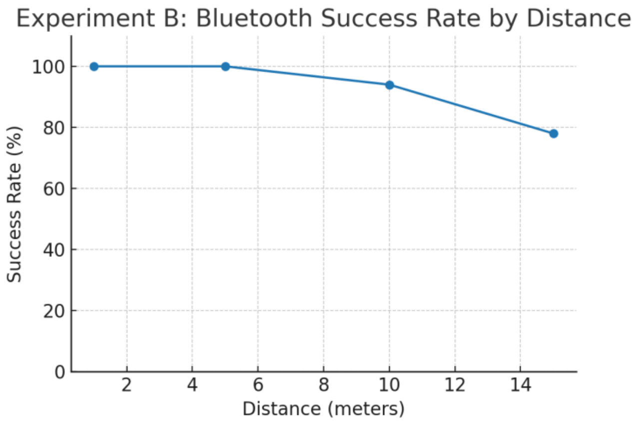

Figure 9. Figure of experiment 2

At close distances of 1 meter and 5 meters, Bluetooth communication was flawless, with 100% of commands successfully transmitted and executed. At 10 meters, a slight decrease in success rate occurred, with 6% of commands either delayed or lost. This decline became much more noticeable at 15 meters, where the success rate dropped to 78%. This is consistent with the expected limitations of Bluetooth Low Energy, which typically guarantees stable performance within a 10-meter range. In practical medical use, surgeons will rarely be more than a few meters from the device, so the system's effective range is more than sufficient. The most surprising result was the sharp drop at 15 meters, suggesting that interference or physical obstructions may play a larger role at longer ranges. To improve robustness, the system could include automatic reconnection features or fallback modes to minimize disruption if the connection weakens.

5. RELATED WORK

One related study focused on developing a cost-effective surgical headlight using consumer-grade LED lighting and 3D printing [11]. The researchers created a prototype headlight by modifying an inexpensive LED lamp and attaching it to a custom 3D-printed mount. They tested the device with surgical residents performing simulated suturing tasks, comparing it against a commercially available headlight. The prototype performed comparably in speed and effectiveness, with residents noting a wider field of illumination. Limitations included issues with headband stability and overall weight distribution. Unlike this project, however, their solution lacked voice control, which would further improve efficiency and sterility during surgical procedures.

Another approach to surgical lighting is discussed in a study examining operating room design and illumination technologies [12]. The authors highlight how lighting has evolved from reliance on natural daylight to modern electric surgical lamps, with current challenges focusing on eliminating shadows, achieving proper color correction, and meeting the needs of both open and minimally invasive procedures. Their methodology centers on optimizing architectural and equipment design to provide adaptable lighting conditions across different surgical environments. While this approach addresses the overall operating room environment, it does not offer a wearable or hands-free solution. Our project improves this by introducing a compact, voice-controlled headlight that directly enhances surgeon autonomy and efficiency.

A third study reviews the principles that define optimal surgical lighting. The authors emphasize three essential components: keeping illumination centered on the surgeon's immediate field, adjusting intensity for both wide and narrow areas, and enabling penetration into deep cavities or beneath flaps [13]. Their approach focuses on balancing brightness, angle, and coverage to reduce shadows and glare while maintaining visual clarity throughout the procedure. While effective in describing illumination strategies, the study primarily addresses fixed or ceiling-mounted lighting systems rather than wearable solutions. Our project builds on these principles by applying them to a lightweight, voice-controlled headlamp that can adapt lighting conditions in real time.

6. CONCLUSIONS

While the proposed system demonstrates strong potential, there are several limitations that need to be addressed. One challenge is the accuracy of voice recognition in noisy environments, as performance decreases significantly when background noise is high. Incorporating noise-canceling microphones or machine learning–based speech models could improve reliability in real-world operating rooms [14]. Another limitation is battery life, since powering both Bluetooth communication and LED headlights may restrict usage time during long procedures. Optimizing power consumption or integrating rechargeable battery packs would make the system more practical. The physical design also requires refinement; the 3D-printed case must balance durability, comfort, and ventilation to prevent overheating [15]. Lastly, while the prototype is functional, additional testing with medical professionals is essential to validate usability and ergonomics. With more development time, these limitations could be resolved to create a more polished, reliable, and clinically viable solution.

This project demonstrates that a wearable, voice-controlled surgical headlight can improve efficiency and sterility in operating rooms. By integrating microcontrollers, Bluetooth, and speech recognition, the system provides hand-free control of illumination, representing a practical advancement toward smarter surgical tools that enhance both surgeon workflow and patient safety.

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