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# EVA: An Intelligent Voice-Controlled Quadruped Assistant for the Visually Impaired

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***Abstract: Visually impaired individuals face significant challenges in safe navigation due to static and dynamic obstacles, uneven terrains, and slippery surfaces. Con- ventional assistive solutions such as white canes and guide dogs are constrained by limited range, adaptability, and high costs [1, 2]. Recent advancements in intelligent quadruped robots have highlighted the potential of legged mobility combined with artificial intelligence to improve assistive navigation for visually impaired users [1, 3]. This paper presents EVA, an intelligent quadruped robotic assistant designed as an assistive robotics platform that integrates ultra- sonic sensors for reliable obstacle detection and supports voice-based commands with real-time audio feedback. The system leverages embedded systems and Internet of Things (IoT) technologies to enable distributed control, voice-based human–robot interaction, and adaptive locomotion. Building upon prior assis- tive robotic systems such as DogSurf, SRAVIP, and CaBot [1–3], the proposed platform combines sensor-based perception, speech-driven human–robot interac- tion, and adaptive quadruped locomotion strategies to enhance navigation safety while maintaining affordability, robustness, and a user-centric design.***

***Keywords: Quadruped robot, Visual impairment, Ultrasonic sensor, Obstacle detection, Voice control, Human–robot interaction, Assistive robotics, Embedded Systems, Internet of Things (IoT), Voice-Based Human–Robot Interaction***

## I. INTRODUCTION

### *A. Background and Motivation*

According to the World Health Organization (WHO), approximately 2.2 billion people worldwide experience some form of visual impairment, including millions who are com- pletely blind [2]. Traditional assistive tools such as white canes and guide dogs remain effective but are limited by restricted sensing range, minimal environmental awareness, and high maintenance costs [1].

These limitations have driven research toward intel- ligent robotic guide systems capable of perceiving surroundings and communicating effectively with users [3, 4].

Quadruped robots have emerged as strong candidates for assistive navigation due to their inherent stability and ability to traverse uneven terrain, closely resembling the functionality of guide animals [1, 7]. Systems such as DogSurf employ learning- based surface classification to improve walking safety [1], while SRAVIP demonstrates speech-based interaction for indoor navigation [2]. CaBot further integrates mapping and localization techniques to provide reliable guidance cues [3].

### *B. Evolution of Assistive Robotic Systems*

The evolution of assistive robots emphasizes natural human–robot interaction (HRI). Audio-based feedback systems have been refined to enhance clarity, personalization, and user acceptance [4, 5]. Early systems relied on microcontroller-based architectures with ultrasonic sensors to enable basic obstacle detection and warning mechanisms [6]. More recent low-cost platforms leverage Raspberry Pi and ESP32 controllers to support conversational interfaces and modular control architectures [7].

Advanced navigation systems such as BlindPilot employ sensor fusion techniques, combining depth sensing and LiDAR to improve spatial awareness [8]. Meanwhile, research in quadruped locomotion has progressed toward rhythmic gait learning and reinforcement learning-based adaptation [11, 12]. Although such approaches offer high adaptability, they often require significant computational resources, making edge-based, lightweight solutions more suitable for affordable assistive devices.

### *C. Proposed Work*

This paper proposes a 12-degree-of-freedom quadruped robotic guide featuring a hierarchical, distributed control architecture. The system utilizes an Arduino Nano for low-level motion control and a Raspberry Pi 4B for high-level processing and human–robot interaction. Unlike cloud-dependent solutions, the robot implements offline wake-word detection and speech recognition, ensuring low latency and privacy- preserving interaction. The quadruped structure enhances mobility on irregular terrain, while real-time audio feedback ensures user safety and confidence during navigation.

Unlike existing systems, the proposed work focuses on a low-cost, fully offline assistive quadruped platform with distributed intelligence, making it suitable for real- world deployment in resource-constrained environments. As shown in Table 1, the proposed system achieves a balance between cost, mobility, and offline intelligence compared to existing solutions.

Table 1 Comparison of existing systems with the proposed EVA system

| System | Sensors | Accuracy (%) | Response Time (ms) | Cost | Mobility | Offline |
|---|---|---|---|---|---|---|
| DogSurf | LiDAR | 97 | 200 | High | High | No |
| SRAVIP | Camera | 90 | 300 | Medium | Low | No |
| CaBot | LiDAR + Camera | 98 | 180 | High | Medium | No |
| EVA (Proposed) | Ultrasonic | 95 | 320 | Low | High | Yes |

## II. METHODOLOGY

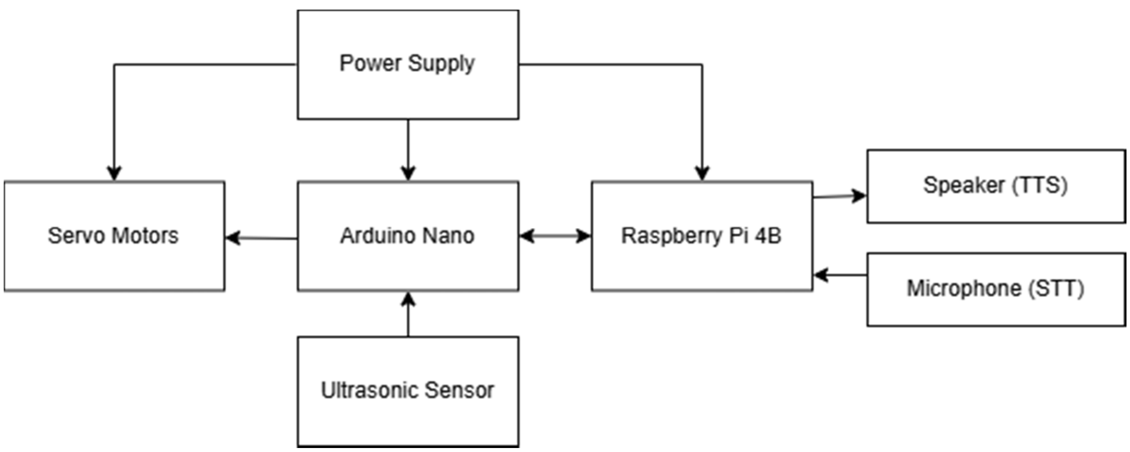


Fig. 1 System block diagram of the proposed EVA quadruped assistant

The proposed quadruped robot consists of four legs, each actuated by three servo motors, resulting in a total of twelve degrees of freedom. These motors are controlled by an Arduino Nano, which is responsible for precise locomotion control and gait generation.

An ultrasonic sensor is integrated for real-time obstacle detection. Distance mea- surements are processed by the Arduino Nano, and when an obstacle is detected within a predefined threshold range, a notification is sent to the Raspberry Pi 4B through serial communication.

The Raspberry Pi interfaces with a microphone and speaker module to enable voice-based interaction. A wake-word detection mechanism activates the system, after which speech recognition is used to interpret user commands. The robot can respond to navigation-related commands as well as simple informational queries such as the current day or date. Audio feedback is generated to warn users of obstacles and confirm received commands. This distributed architecture ensures real-time responsiveness, efficient processing, and robust human–robot interaction.

Table 2 System components and their functions

| Sr. No. | Components | Type | Function |
|---|---|---|---|
| 1 | Raspberry Pi 4 | Main Controller | Handles STT, NLP, TTS, and overall decision-making |
| 2 | Arduino Nano | Motion Controller | Controls servo motors and processes sensor data |
| 3 | Ultrasonic Sensor | HC-SR04 | Detects obstacles and surface variations |
| 4 | Microphone | USB Mic | Captures user voice commands |
| 5 | Speaker | 8 Ω/1 W | Provides audio feedback to users |
| 6 | Servo Motors | MG90S Servo | Controls leg movement of the quadruped |
| 7 | Power Supply | 8 V, 5 A Li-ion Battery | Provides regulated power to all components |

### *D. Quadruped Locomotion Control*

The quadruped robot employs a twelve-degree-of-freedom (12-DOF) locomotion sys- tem, comprising four legs with three servo-actuated joints per leg corresponding to the coxa, femur, and tibia. All servo motors are directly controlled by an Arduino Nano using the Servo.h library.

Leg motion is governed by a software-based inverse kinematics framework, where desired foot positions in Cartesian space $(x, y, z)$ are transformed into joint angles through geometric computations. The functions cartesian to polar() and polar to servo() compute the required joint orientations based on limb dimensions and target coordinates. Linear interpolation between current and target foot positions ensures smooth trajectory generation.

Locomotion behaviors such as forward walking, turning, sitting, and standing are implemented using a static crawl gait, which maintains stability by ensuring that at least three legs remain in contact with the ground at all times. A 50 Hz timer interrupt implemented using the FlexiTimer2 library synchronizes real-time servo updates, enabling coordinated and stable movement across all joints.

### *E. Obstacle Detection and Avoidance*

Obstacle detection is implemented using an HC-SR04 ultrasonic distance sensor inter- faced with the Arduino Nano via dedicated trigger and echo pins. The sensor emits an ultrasonic pulse, and the echo return time is measured to compute distance using the speed of sound:

$$\text{Distance (cm)} = \frac{\text{Time} \times 0.034}{2} \quad (1)$$

A reactive obstacle avoidance strategy is integrated directly into the locomotion control loop. When an object is detected within a 30 cm threshold, the robot initiates an avoidance maneuver by executing a spot left turn. To prevent repeated triggering caused by stationary obstacles or sensor noise, a 5-second cooldown interval is enforced using time-based logic. Upon detection, a serial message labeled OBJECT is transmitted for monitoring and higher-level processing. In the absence of obstacles, the robot resumes forward locomotion. This closed-loop sensing and actuation mechanism enables autonomous navigation in dynamic environments.

### *F. Voice Command Recognition*

The high-level human–robot interaction layer is implemented on a Raspberry Pi 4B, which handles voice-based control and system-level decision-making. A far-field microphone module continuously captures environmental audio input.

Wake-word detection is achieved using the Picovoice Porcupine engine, which oper- ates entirely offline to ensure low latency and privacy. Upon detection of the predefined keyword *"Hey Eva"*, the system activates speech recognition. Natural language pro- cessing is performed using the Vosk speech recognition framework, which employs lightweight offline acoustic models based on Kaldi. Recognized speech is parsed to identify user intents such as system status queries or general informational requests (e.g., time and date). These commands are mapped to corresponding system actions or verbal responses, enabling intuitive and hands-free interaction.

### *G. Audio Feedback System*

Audio feedback is provided through a MAX98357A $I^2S$ digital-to-analog converter connected to a speaker module, enabling real-time auditory responses. Text-to-speech conversion is performed using the eSpeak-ng speech synthesis engine.

The system adopts an interrupt-driven, multi-threaded architecture on the Rasp- berry Pi. A background thread continuously monitors serial data received from the Arduino Nano. When an OBJECT alert is received, the system immediately priori- tizes and outputs an emergency audio warning (e.g., "Object detected, turning left"), pre-empting any ongoing non-critical processes. For general user queries, contextual responses are generated using system-level data such as the real-time clock and delivered in a conversational format. This audio feed- back mechanism enhances situational awareness and supports seamless human–robot interaction for visually impaired users.

## III.RESULTS

The proposed EVA quadruped assistant was evaluated in real-world indoor environ- ments, including corridors and obstacle-rich pathways. The system was tested to assess obstacle detection reliability, locomotion stability, and real-time responsiveness. The robot successfully detected obstacles, executed avoidance maneuvers, and responded to voice commands under varying environmental conditions. The results demonstrate the effectiveness of the proposed system for assistive navigation applications.

### *A. Response Time Analysis*

The response time of the system was evaluated by measuring the delay between user voice command input and corresponding robot action execution. The average response latency was observed to be approximately **320 ms**, which includes wake-word detection, speech recognition, command processing, and actuation. This low latency ensures real-time responsiveness, making the system suitable for assistive navigation where timely reactions are critical for user safety.

### *B. Obstacle Detection Performance*

Fig. 2 illustrates the real-time distance measurements obtained from the ultrasonic sensor as the robot approaches an obstacle. A gradual reduction in measured distance is observed until the predefined threshold of 30 cm is reached. Once the threshold is crossed, the obstacle avoidance behavior is triggered, validating the responsiveness and reliability of the sensing subsystem.

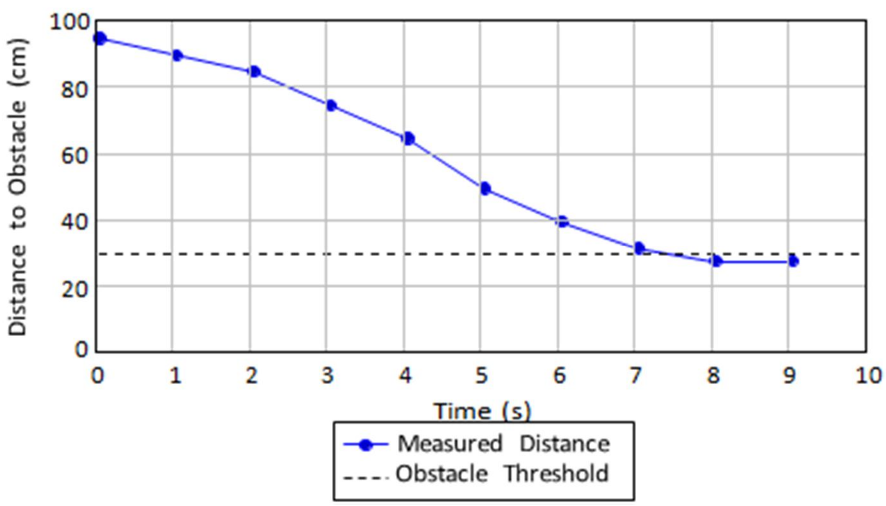


Fig. 2 Ultrasonic sensor distance measurement and obstacle detection threshold

The obstacle detection accuracy at varying distances is summarized in Fig. 3 and Table 3.

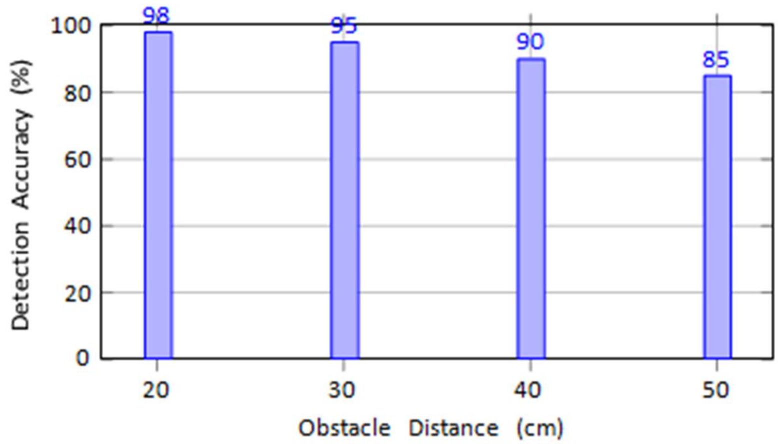


Fig. 3 Obstacle detection accuracy at varying distances

Table 3 Obstacle detection accuracy at different distances

| Distance (cm) | Detection Accuracy (%) |
|---|---|
| 20 | 98 |
| 30 | 95 |
| 40 | 90 |
| 50 | 85 |

As shown, the ultrasonic sensor achieves high detection accuracy at closer dis- tances, with performance gradually decreasing as distance increases due to signal attenuation and environmental noise. However, within the operational range of 30 cm, the system maintains reliable detection suitable for assistive navigation.

*C. Locomotion Stability Analysis*

Fig. 4 presents the variation of hip joint angles for the front left and rear right legs during crawl gait locomotion.

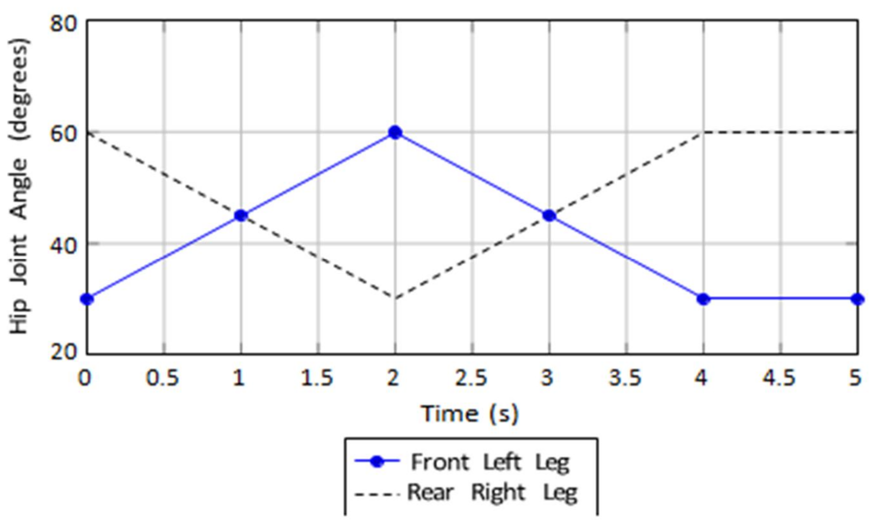


Fig. 4 Hip joint angle variation during crawl gait locomotion

The smooth and periodic angular transitions indicate coordinated servo actua- tion and stable gait generation. The complementary motion between diagonal legs ensures that at least three legs maintain ground contact at all times, thereby enhancing stability.

*D. Processing Load Distribution*

Fig. 5 shows the processing load distribution across the control units.

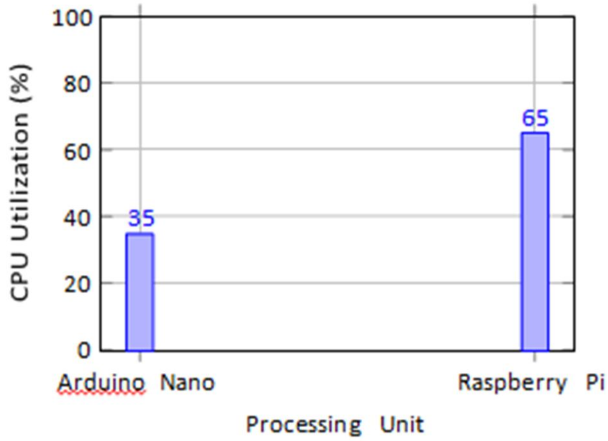


Fig. 5 Processing load distribution across control units

The results demonstrate effective separation of low-level motion control and high- level interaction tasks, ensuring efficient system performance.

*E. Navigation Performance Evaluation*

To evaluate real-world performance, the robot was tested in an indoor obstacle-rich environment across 10 independent trials. The system successfully navigated the envi- ronment without collision in 9 out of 10 trials, achieving a navigation success rate of 90%.

The failure case was primarily due to delayed detection at larger distances, high- lighting the limitations of ultrasonic sensing in extended range scenarios. Despite this, the overall performance demonstrates the reliability and effectiveness of the proposed system for assistive navigation.

*F. Load Calculations*

Before designing the power system, it is important to calculate the total load to under- stand the current and power requirements of the system. Each component operates at a specific voltage and current rating, and these values are used to estimate the over- all power consumption. This ensures proper selection of the power source and reliable system performance.

Table 4 Power Specifications of System Components

| Sr. No. | Components | Operating Voltage (V) | Current Consumption (A) |
|---|---|---|---|
| 1 | Raspberry Pi 4 | 5 | 2.00 |
| 2 | Arduino Nano | 5 | 0.20 |
| 3 | Ultrasonic Sensor | 5 | 0.015 |
| 4 | Microphone | 5 | 0.003 |
| 5 | Speaker | 5 | 0.20 |
| 6 | Servo Motors (12 total) | 5 | 2.00 |

*G. Nominal Power Calculation*

$I_{\text{nominal}} = 2.00 + 0.20 + 0.015 + 0.003 + 0.20 + 2.00 = 4.418$ A

$P_{\text{nominal}} = V \times I = 5.00 \times 4.418 = 22.09$ W

Nominal Result: 4.418 A at 5 V → 22.09 W

### *H. Peak Power Calculation*

$I_{peak} = 2.50 + 0.20 + 0.015 + 0.003 + 0.20 + 2.50 = 5.418$ A

$P_{peak} = 5.00 \times 5.418 = 27.09$ W

**Peak Result:** 5.418 A at 5 V → 27.09 W

### *I. Power System Analysis*

The system requires approximately 22.09 W under normal operation and can reach up to 27.09 W during peak load conditions. Considering a standard engineering safety margin of 20–30%, the estimated power requirement is approximately 26–30 W.

To ensure stable operation, a regulated 5 V, 6 A (30 W) DC power supply is recommended. This configuration supports transient current spikes, maintains voltage stability for critical components such as the Raspberry Pi and servo motors, and allows for future system expansion.

### *J. Battery Selection*

The system is powered using a Lithium-Polymer (Li-Po) battery due to its lightweight structure, compact size, and high energy density. These characteristics make it suitable for portable robotic applications while ensuring stable and efficient power delivery under varying load conditions. Additionally, its rechargeable nature enhances system usability and operational lifespan.

## IV. CONCLUSION

This paper presented EVA, an intelligent voice-controlled quadruped robotic assistant designed to support safe navigation for visually impaired individuals. The system integrates a distributed architecture using an Arduino Nano for real-time locomotion control and a Raspberry Pi 4B for high-level voice interaction and decision-making.

Experimental results demonstrate that the proposed system achieves reliable obsta- cle detection with an accuracy of up to 95% within the operational range, along with an average response latency of 320 ms. The system also achieved a navigation success rate of 90% in real-world indoor environments, validating its effectiveness for assistive applications.

The proposed approach offers a practical balance between performance, affordabil- ity, and offline capability, making it suitable for deployment in resource-constrained environments. Future work will focus on enhancing system intelligence through sensor fusion, vision-based navigation, and adaptive learning techniques to further improve robustness and autonomy.

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