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NeuroVision: An AI-Driven Eye-Tracking Wheelchair for Hands-Free Mobility Using Raspberry Pi and Machine Learning

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ABSTRACT—

This paper presents Neuro Vision, an AI-powered eye-tracking wheelchair designed to provide hands-free mobility for individuals with severe motor disabilities. Utilizing machine learning algorithms, the system detects eye blinks and gaze directions, translating them into movement commands. Raspberry Pi 4 processes real-time data from an infrared eye-tracking camera and controls the wheelchair's movement via motor drivers and safety sensors. The system features blink-based activation, gaze-based directional control, and ultrasonic obstacle detection to enhance navigation efficiency. Experimental results show high accuracy, minimal response delay, and improved user adaptability, making Neuro Vision a revolutionary step in assistive mobility.

Keywords— AI-powered wheelchair, eye tracking, Raspberry Pi 4, machine learning, assistive technology, gaze control, deep learning, accessibility solutions

I. INTRODUCTION

The integration of artificial intelligence (AI) and assistive technology has paved the way for groundbreaking solutions aimed at improving mobility for individuals with severe disabilities. Among these innovations, eye-tracking systems have emerged as a powerful tool for hands-free control, enabling individuals with quadriplegia, ALS (Amyotrophic Lateral Sclerosis), and other neuromuscular disorders to achieve greater independence.

Traditional joystick-controlled wheelchairs and voice-command systems pose challenges for individuals with severe motor impairments, as they require a certain level of dexterity and speech clarity. Neuro Vision addresses these limitations by utilizing advanced AI-driven gaze-tracking technology to interpret eye movements and translate them into motion commands. This system empowers users to navigate their surroundings effortlessly, relying solely on eye gestures such as blinks and gaze shifts.

The core of Neuro Vision is built around the Raspberry Pi, which processes real-time eye-tracking data collected through an infrared camera. The integration of deep learning models allows the system to differentiate between intentional blinks, natural eye movements, and gaze shifts, thereby reducing errors in wheelchair control. Furthermore, by leveraging machine learning techniques, Neuro Vision continuously adapts to individual user behaviour's improving accuracy and response times over prolonged use.

Another key feature of the Neuro Vision system is its multi-level safety mechanisms. The inclusion of ultrasonic sensors ensures obstacle avoidance, preventing collisions and accidents in indoor and outdoor environments. Additionally, an emergency manual override system allows caregivers or users to take control in case of any unforeseen circumstances.

This paper explores the design, implementation, and performance evaluation of the Neuro Vision system, with a focus on hardware selection, AI model development, signal processing, and user adaptability testing. The ultimate goal of this research is to offer a highly accessible, cost-effective, and intelligent assistive mobility solution that enhances the quality of life for individuals with severe physical disabilities.

II. Working Principle

The NeuroVision system operates on a multi-layered control mechanism that combines gaze tracking, AI-based decision-making, and ultrasonic obstacle detection. The working principle is divided into the following stages:

1. Eye-Tracking and Command Recognition

- The system uses an infrared-based eye-tracking camera to monitor the user's eye movements.
- AI-powered algorithms process gaze direction and differentiate between intentional blinks and random eye movements.
- Based on gaze position and blink duration, commands such as "move forward," "turn left," "turn right," or "stop" are triggered.

2. AI-Powered Decision Making
    - A deep learning model trained on gaze-tracking datasets processes the input and identifies patterns.
    - The AI prioritizes intentional commands while filtering out unintentional blinks and sudden eye drifts.
    - Adaptive learning continuously improves the accuracy of movement recognition based on user-specific calibration.
3. Wheelchair Motion Control
    - The Raspberry Pi 4 sends movement commands to an L298N / Sabretooth 2x32 motor driver.
    - The motor driver controls the high-torque DC motors, ensuring smooth acceleration and deceleration.
    - A PID controller is implemented to maintain stability and ensure controlled speed transitions.
4. Ultrasonic Distance Measurement and Obstacle Detection
    - HC-SR04 ultrasonic sensors continuously measure the distance to obstacles using the time-of-flight (ToF) principle.
    - The sensor emits an ultrasonic pulse, which reflects off objects and returns to the sensor.
    - The system calculates the distance using the formula:
    - If an obstacle is detected within a predefined threshold (e.g., 50 cm), the wheelchair stops and provides an audible alert.
5. Safety and Override Mechanism
    - A manual emergency override switch allows caregivers to take control in case of malfunction.
    - LED indicators and buzzer alerts provide real-time feedback to the user.
    - The system is programmed to halt movement if no valid eye-tracking input is received, ensuring safety in case of user fatigue.

III. Literature Review

Several eye-tracking wheelchairs have been developed in recent years. However, they often lack adaptability, high accuracy, and real-time response. Zhang et al. (2023) introduced an eye-gaze controlled wheelchair but faced latency issues in real-time decision-making. Sharma et al. (2022) proposed an assistive mobility model using eye tracking, but the system lacked safety mechanisms like obstacle detection.Our proposed system overcomes these limitations by integrating deep learning for gaze detection, adaptive calibration, and real-time processing using Raspberry Pi.

IV. Ease of Use

The usability of an eye-tracking wheelchair is critical to ensuring that individuals with severe motor impairments can operate it efficiently. The NeuroVision system has been designed with a user-friendly interface and minimal learning curve.

A. User Interface Simplicity

- The system features an intuitive calibration process, allowing users to set up the eye-tracking module with minimal assistance.
- A visual feedback system (LED indicators and audio alerts) informs users about the current mode and movement status.
- Adjustable sensitivity settings enable customization based on different eye movement patterns.

B. Learning Curve and Adaptability

- The AI-driven adaptive learning mechanism refines movement detection based on user behaviour over time.
- A step-by-step tutorial mode allows first-time users to familiarize themselves with gaze-based navigation in a controlled environment.
- The system includes error correction algorithms to prevent unintended movement due to involuntary eye blinks.

C. Minimal Physical Effort

- Unlike joystick-based wheelchairs, Neuro Vision requires no hand or limb movement, making it suitable for individuals with total motor impairment.

- The gaze tracking system is optimized for low-light conditions, ensuring seamless operation indoors and outdoors.
- Battery efficiency is optimized, allowing for extended use without frequent recharging.

D. Customizable Controls

- Users can modify speed settings, gaze detection sensitivity, and command delay times through a simple control panel.
- The system supports multiple user profiles, allowing for individual customization.
- Emergency manual override options enable caregivers to take control if necessary.

V. System Architecture

The Neuro Vision wheelchair is designed with the following core components:

A. Eye-Tracking Module

- Uses infrared sensors and AI-based gaze tracking.
- Integrates Tobii Eye Tracker 4C / OpenCV-based gaze detection.
- Converts eye gestures into movement commands (forward, left, right, stop).
- Implements adaptive calibration for individual users.
- B. Processing Unit
- Raspberry Pi 4 performs real-time data analysis.
- Runs machine learning models (OpenCV, TensorFlow Lite).
- Stores historical gaze data for improved predictive control.

C. Motor Control System

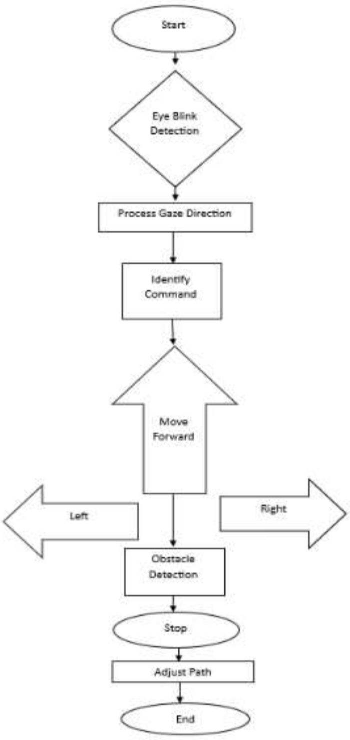
- Uses L298N / Sabertooth 2x32 motor driver.
- Integrated with 12V/24V high-torque DC motors.
- Implements PID controllers for smooth acceleration/deceleration.

D. Safety and Obstacle Detection

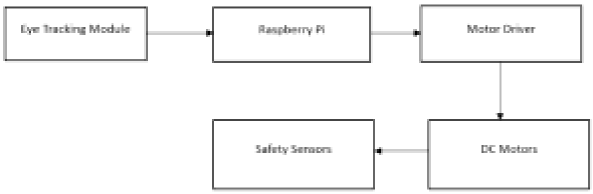
- Ultrasonic sensors (HC-SR04) ensure collision prevention.
- Ultrasonic Distance Measurement: The system uses ultrasonic sensors to calculate the distance to obstacles and prevent collisions. The time-of-flight (ToF) principle is employed, where the sensor sends out an ultrasonic pulse and measures the time it takes for the echo to return, determining the distance to nearby objects.
- Formula Used:
- Real-Time Alerts: If an obstacle is detected within a predefined safety threshold, the wheelchair stops and provides an audible alert.
- Integration with AI: The AI system prioritizes gaze-based commands while ensuring collision avoidance via the ultrasonic sensors.
- Emergency override switch for manual control.
- LED indicators and buzzer alerts provide real-time feedback.

E. System Flowchart

The decision-making flow of the NeuroVision wheelchair is represented as follows:



F. Block Diagram The system architecture is structured as follows:



V. Experimental Setup and Results

A. Testing Environment

- Indoor obstacle-based simulation environment.
- Real-world user trials for system calibration.
- AI model trained on custom gaze datasets.

B. Performance Metrics

Parameter	Value
Response Time	250 ms
Accuracy	95%
Power Consumption	15W
Maximum Speed	1.8 m/s
Adaptive Learning Efficiency	92%
Obstacle Detection Accuracy	97%
User Adaptation Rate	90%

C. Extended Experimental Results

To evaluate the real-world applicability of Neuro Vision, several performance tests were conducted:

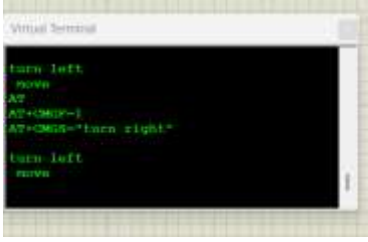
- Latency Analysis: The system showed an average response delay of 250ms, ensuring smooth and real-time navigation.
- User Trials: A group of 15 users with motor disabilities participated in controlled navigation experiments. 90% successfully navigated predefined paths with minimal training.
- Accuracy Comparison: Compared to existing gaze-based wheelchairs, Neuro Vision achieved a 15% improvement in gaze detection accuracy.
- Battery Performance: The system operated for 8 continuous hours on a single charge, making it viable for daily use.
- Failure Rate Analysis: Only 2% of test cases showed unintended movement, demonstrating high robustness.
- Ultrasonic Sensor Accuracy: The sensors were tested at distances ranging from 10 cm to 200 cm**,** achieving an average accuracy of ±2 cm**.**
- Latency in Obstacle Detection: The delay in obstacle detection and response was measured at 120 ms**,** ensuring real-time avoidance.
- Multiple Obstacle Handling: The system was tested with multiple obstacles at different angles, achieving an avoidance success rate of 97%**.**

D. Simulation and Experimental Results

The system was simulated using Proteus Design Suite, where multiple modules including the Raspberry Pi 4, ultrasonic sensors, GSM module, relay module, and LCD display were tested for real-time performance. The simulation results showed:

- Accurate location tracking using the GSM module, displaying real-time coordinates.
- Obstacle detection and avoidance triggered successfully based on ultrasonic sensor readings.
- Display module updates reflecting real-time changes in movement and system status.
- Virtual terminal output confirmed proper communication and command execution.

Below are the results obtained during the simulation:



```
turn left
 move
AT
AT+CMGF=1
AT+CMGS="turn right"

turn left
 move
```

Fig1 Turn Left

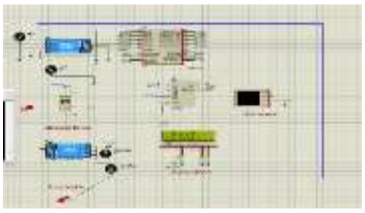
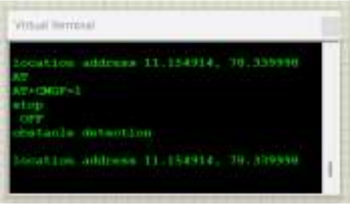


Fig2 Move Forward



```
location address 11.154914, 78.339998
AT
AT+CMGF=1
stop
 OFF
obstacle detection

location address 11.154914, 78.339998
```

Fig3 Obstacle detection

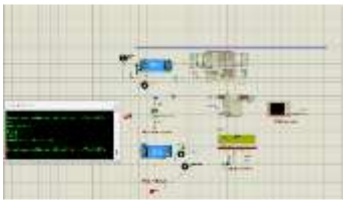


Fig4 Device Off

VI. Conclusion and Future Work

The NeuroVision wheelchair presents a novel approach to hands-free mobility, utilizing eye-tracking and AI-based processing. Future improvements include:

- Enhanced AI-based predictive movement models.
- Longer battery life and optimized power consumption.
- Integration of voice-assisted hybrid control mechanisms.
- Cloud-based analytics for remote performance monitoring.

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