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# Design and Development of a Hybrid Eye and Mobile Controlled Wheelchair Prototype using Haar cascade Classifier: A Proof of Concept

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**Abstract.** According to the wheelchair foundation, about 1.86% of the world's population requires a functional wheelchair. Most of these wheelchairs have manual control systems which puts millions of people with total paralyzes (total loss of muscle control including the head) at a disadvantage. However, the majority of those who suffer from muscular and neurological disorders still retain the ability to move their eyes. Hence the concept of eye-controlled wheelchair. This paper focused on the design and development of a hybrid control system (eye and mobile interface) for a wheelchair prototype as a proof of concept. The system was implemented using the pre-trained Haar cascade ML classifier in open CV. Focus was shifted from high accuracy common to lab-based studies to deployment and power consumption which are critical to usability. The system consists of a motor chassis that takes the place of a wheelchair, a raspberry pi4 module which acts as a mini-computer for image and information processing, and a laser sensor to achieve obstacle avoidance. The Bluetooth module enables serial communication between the motor chassis and the raspberry pi, while the power supply feeds the raspberry pi and the camera. The system performance evaluation was carried out using obstacle avoidance and navigation tests. An accuracy of 100% and 89% were achieved for obstacle avoidance and navigation, respectively, which shows that the system would be helpful for wheelchair users facing autonomous mobility issues.

**Keywords:** Paralysis · Wheelchair · Eye control · Obstacles avoidance · Camera

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# 1 Introduction

Paralysis is a total or partial loss of physiological functions in some part of the human body [1]. Paralysis is often characterized by either motor or sensory loss or both in the affected area. Common causes of paralysis include Stroke, Multiple sclerosis, Spinal cord injury, Cerebral palsy among others [1, 2]. An age-adjusted comparison of results from the 1980 and 1990, National Health Interview Survey (NHIS) found a 26% increase in the use of canes and a 57% and 65% increase in the use of walkers and wheelchairs, respectively, among all ages which increased to 83% by 1994 [3]. Besides, the latest study has reported that 1.86% of the world population need functional wheelchair [4]. The design of wheelchairs for paralyzed patients has witnessed advances from conventional manually powered to electrical wheelchairs [5]. The population of elderly citizens in the world is also increasing, with this increase, there is a need to design welfare robotic devices for such people. A conventional wheelchair tends to focus exclusively on manual use which assumes users are still able to use their hands and excludes those unable to do so. Many of those suffering from complete paralysis usually still retain the ability to control eye movements, which inspired the development of an eye-controlled electric wheelchair. There are in existence different modes of eye-controlled wheelchair such as EOG – control, gaze estimation control and video based control systems. However, most of them only have one control system (the eye) and few who incorporated an auxiliary control system employed manual gear steering (joy stick) which requires some form of energy and skill to use.

In order to increase versatility and ease of use, a dual-controlled eye tracking system for wheelchair navigation is proposed, which uses eye gaze as the primary control system and mobile interface as an auxiliary. The proposed system uses an off-the-shelf webcam for eye image acquisition using Open CV/CV2 library to process the signal in a raspberry pi 4 device which has improved functions and uses Linux based operating system. Going by the ubiquity of mobile phone users, the auxiliary control module is implemented on a mobile phone interface such that instead of a joystick, the users' phone is connected by Bluetooth to the Arduino Uno control board to steer the motors of the wheelchair. Hence, increasing the system's usability for patients with either complete or partial paralysis and the elderly. A wheelchair prototype is employed in the form of a robotic car, and the obstacle avoidance mechanism is achieved using a laser sensor

## 1.1 Literature Review

Over the years, research works have been using different control applications on wheelchair systems aside from manual control approaches. The common physiological signals often adopted include Electrooculography (EOG) signal, Electromyography (EMG) signal, and Electroencephalography (EEG) signal [2, 4]. The EOG signal and video-based control systems have been extensively studied for eye control applications in a wheelchair [6]. When the eye moves, the EOG signal is generated from the changing potential difference between the cornea and the retina. This change is registered as a potential difference useful in detecting the location or gaze of the eye. This system often requires the direct attachment of electrodes to the face/forehead of the user, as in Fahim *et al.* [1]. Some EOG-based studies developed better eye movement tracking algorithms

and wheelchair control [7–9]. [1, 9, 10] adopted EOG and EMG signals in the control system design, while Naeem and Qadar [11] used voice control. The major drawback of EOG-based design is that it often constitutes a physical burden on the user besides the heavy noise attributed to the signal [4] and the high level of cognition required. Voice control is often plagued with interference in a sound wave from the environment coupled with its high voice energy demands [11].

A few works on video-based eye control include the work of Mani *et al.* [12]. His work processed the image of the eye captured by a head-mounted camera to activate the direction of motion in 3 dimensions (left, right, and forward). However, the performance evaluation of the system was not wholly reported.

Another design by Patel *et al.* [13] was built around Raspberry pi using an open CV library for image processing of the acquired face image for eye location. The system activates and deactivates in 3 seconds; eye closure and directional motion are initiated with the eye's blinking. The procedure was adequately explained, but the system's performance was not assessed using accuracy and response latency which are vital tools for such systems evaluation.

Lately, machine learning algorithms/models [14] have been employed in the image processing of eye-controlled wheelchairs with a significant increase in accuracy [15, 16]. George *et al.* [16] implemented a convolution neural network (CNN) model using a webcam image for real-time gaze classification in seven directions: right, left, center, forward, upright, up left, down left, and down right. Localization of facial regions was carried out by a modified Viola-Jones algorithm. The CNN model for combined eyes (left and right eye) was observed to yield better accuracy than training each eye separately. It gave good accuracy, but it's computationally complex. Krafka *et al.* [15] also proposed an eye tracking system using deep end-to-end CNN with a larger data set obtained from 1450 participants. To check computational time and high complexity, dark knowledge was used with a simpler network, however, the frame rate is less than the standard 20-25 FPS needed for smooth real-time application.

## 2 Methodology

### 2.1 Material

Material selection was a key part of this project. Before the development of the project, certain factors were considered for the design to meet technical specifications while minimizing cost and increasing easy movement [17, 18]. The important materials selected are the Web camera, Raspberry pi board, Arduino Uno, H-bridge Motor driver (L298), Bluetooth module, and Motor chassis.

### 2.2 System Design and Description

The system is divided into three modules: the image data acquisition module, the wheelchair control/steering module, and the wheelchair. Fig. 1 shows the block diagram of the eye-controlled wheelchair system. The web camera captures the eye image data which is sent to the Raspberry-pi. The Raspberry-pi serves as the mini processor

for synthesizing the pupil location [19]. The location identified by the raspberry–pi is fed to the Arduino Uno board where different eye positions are programmed into left, right, and forward movement commands. These commands are fed to the motor driver of the wheelchair for navigation in the desired direction. The auxiliary control module involves the mobile App with a control interface connected by Bluetooth to the Arduino board [20]. This can also be used to navigate the wheelchair aside the eye control. The laser sensor feedback mechanism for obstacle avoidance takes care of system safety.

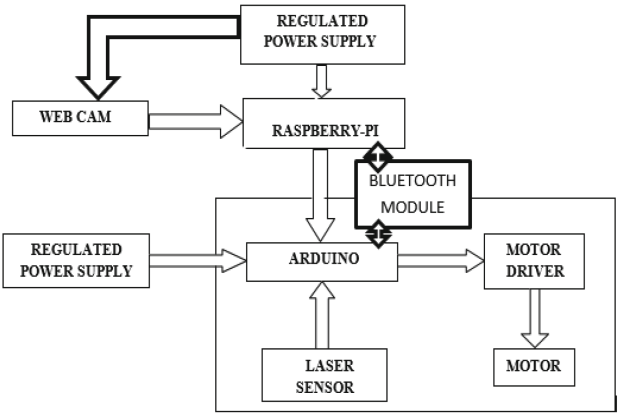



**Fig. 1.** System block diagram

### 2.2.1 Image Data Acquisition System

An off-the-shelf raspberry pi camera is wired to the raspberry pi board with an extended cable. The camera is placed at a distance of 5cm from the face and at eye level such that it can capture the facial images from which eye/pupil location would be extracted.

The dynamics of navigation proposed for the wheelchair includes forward, left, right, and backward movement with a start and stop process initiated by the blinking of the eye. The first left eye winking starts the image acquisition and subsequent movement of the wheelchair, while any second left eye winking would automatically stop data acquisition and, subsequently, the wheelchair stops, as implemented in [4]. Hence, four (4) eye states are employed in the navigation process.

Haar cascade was used in the gaze tracking algorithm for pupil detection because of its simplicity and fast processing time, making it useful in real-time applications. This method uses the concept of features and classifiers in machine learning (ML) for its detection scheme. The fundamental idea behind Haar cascades is that they employ a collection of salient "features" that can be computed from an image, including the intensity, difference between neighboring pixels or tiny areas of the image [21–24].

The Haar-like features in Haar cascade are calculated using the following equation:

$$f(x, y) = \sum_{i=x}^{x+w-1} \sum_{j=y}^{y+h-1} I(i, j) \tag{1}$$

where I(i,j) represents the intensity of the pixel located at position (i,j). The Haar-like feature is calculated as the difference between the sum of intensity of pixels in two rectangular regions, defined as:

$$f(x,y) = \sum_{i=x}^{x+w/2-1} \sum_{j=y}^{y+h-1} I(i,j) - \sum_{i=x}^{x+w/2} \sum_{j=y}^{y+h-1} I(i,j) \tag{2}$$

The Haar cascade uses an Adaboost classifier, which is a type of machine learning classifier that combines multiple simple classifiers to form a strong classifier. The Adaboost classifier makes its decision using the following equation:

$$h(x) = \begin{cases} 1 \sum_{t=1}^{T} \propto_t h_t(x) \geq \frac{1}{2} \sum_{t=1}^{T} \propto_t \\ 0 \; otherwise \end{cases} \tag{3}$$

where T is the number of weak classifiers, $\propto_t$ represents the weight associated with each weak classifier, $h_t$ (x) represents the decision made by the tth weak classifier, and sign(x) is the sign function, which returns 1 if x is positive and -1 if x is negative

A classifier is therefore trained using these characteristics to differentiate between the pupil and the background. The trained classifier is used by the Haar cascade to assess the characteristics of several eye regions, including the eye lid, iris, and cornea, and determine whether or not the eye frame is likely to contain the object of interest. This procedure is repeated for several eye regions and points most likely to contain the pupil is marked "detection". However, the frame illumination often changes with the nature of the environment; hence Histogram Equalization is used to change the probability distribution of the image to a uniform distribution for better image contrast [25].

### 2.2.2 Wheelchair Control/Steering System

The decision/output of the pupil data acquisition system is used to navigate the wheelchair. These decisions are coded in form of left, right, forward, backward, and start/stop modes such that when fed to the H-bridge motor driver, it steers according to the code in the received signal.

#### 2.2.2.1 Mobile Control Interface

The primary control system for the wheelchair prototype is the eye gaze detection system. However, a secondary control system is incorporated in an RC-controlled mobile interface to improve the versatility of the device for both tetraplegic and non-tetraplegic patients, such as the elderly. This uses a Bluetooth module to communicate between the app interface and the H-bridge Arduino motor driver to achieve motion control. The H-bridge motor driver is responsible for steering the wheels' directions. An open-access RC controller program was adapted to achieve forward, backward, left, and right movements and other sub-directions (Fig.3). Two DC motors were installed in the prototype and linked with the front wheels.

### 2.2.3 Safety Subsystem: Laser Sensors

For safety precautions, the wheelchair is designed to have an automated stopping mechanism that will disconnect the gaze-based controller and stop the chair as soon as it

approaches any nearby object. A proximity sensor quantitively measures how close an object is to the sensor. It has a range, and a flag is raised whenever an object enters this threshold region. The sensor sends out electromagnetic waves, which are picked up after being reflected off nearby objects. The procedure is quite similar to how radar works. A laser proximity sensor is adopted in this work.

### 2.2.4 Mobile Application

The Bluetooth RC controller is a mobile application that connects with the Bluetooth attached to the wheelchair (prototype) and is used to send commands serially to the Bluetooth, which in turn controls the motors, as an alternate method of control for partially paralyzed subjects (lower limbs) to aid easy control of the wheelchair. Fig. 2 (c) shows the Bluetooth RC controller mobile application interface.

### 2.2.5 Wheelchair

A motor chassis serves as a prototype for a wheelchair and necessary components and modules are attached to it.

## 2.3 Overall Design Outlook

The various modules are interconnected to form the complete system. Fig. 2 describe the complete system in more details. The device operational flow chart is shown in Fig. 3. The web camera picks the face and eye image frames and the algorithm checks if the eye is open or closed. If closed, the loop returns and check again for eye status. If open, the gaze direction is identified by template matching and accurate direction is detected before obstacle avoidance is checked. The obstacle avoidance is set at a threshold (stopping

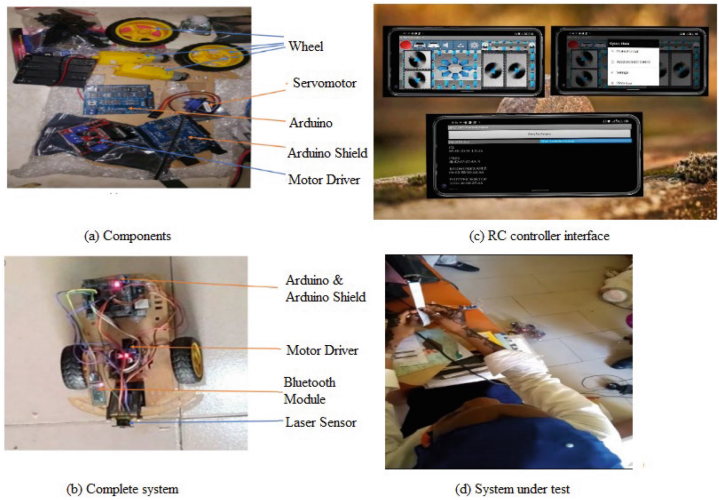



**Fig. 2.** Pictorial description of the system

distance) of 1m as used in [4]. If an obstacle is detected at a distance <=1 m, the device stops abruptly or would not move if detected at the point of start; else, it moves in the determined direction.

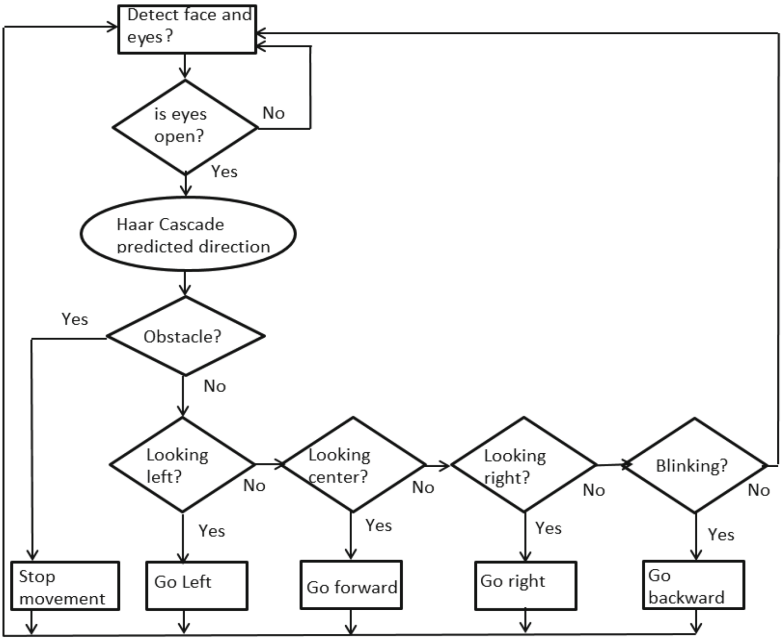



**Fig. 3.** Flowchart of the navigation control algorithm

## 3 Results and Discussion

### 3.1 Performance Evaluation

Testing the whole design is carried out to certify that the constructed design is in its proper working condition and ensure that operating expectations are achieved. Thus, tests carried out include the following: Test for the output voltage of the power supply and charging unit using a digital multimeter, test for the right connection of components with Arduino, components like the motor driver, Bluetooth module, laser sensor, servo motor, testing the functionality of the serial connection between the Bluetooth module and the Raspberry pi, testing for accuracy in the detection of various eye gaze by the camera as seen in Fig. 2(d), and testing for the effectiveness of the detected eye gaze's condition transmission and what is received by the motors.

From the tests carried out, it was confirmed that the camera detects certain eye gazes, including: blinking, looking center, looking left, and looking right, and by clicking buttons right, left, up, and down on the mobile application, the motors carried out the respective appropriate commands. It was also observed that the laser sensor detects obstructing obstacles within a 1m radius and stops movement to avoid collision with the detected obstacle. When the device stops because of an obstacle, a backward movement (given by blinking), leftward, rightward movements can be initiated for a new path. It was also confirmed that the prototype's Bluetooth module automatically connects with the Raspberry pi for effective receiving/transmitting of information upon powering ON the device.

Twenty different obstacles of different shapes and sizes were put in front of the device. All the twenty obstacles were detected, causing the wheelchair (prototype) to stop forward movements when a distance of 1m to the obstacle was reached. Therefore, the accuracy is 100% as given by Eq. (4).

$$\text{Accuracy} = \frac{\text{No of obstacles detected}--\text{No of obstacles undetected}}{\text{Total number of tests carried out}} = \frac{20-0}{20} \times 100 = 100\% \tag{4}$$

### 3.2 Navigation Evaluation

Another important test carried out was to monitor the design for seamless navigation and response time, and it was observed that there is a slow response time after the command has been given compared to when the motor carries out its appropriate commands, and this is due to the low random access memory (RAM) of the raspberry pi4 model being used in this design. Therefore, obtained average navigation/direction accuracy was 89.16 %. This accuracy was calculated using equation 5.

$$accuracy = \frac{No\ of\ \ correct\ predictions}{Total\ no\ of\ \ predictions} \times 100 \tag{5}$$

In turn, the speed of the motors was reduced to compensate for this setback so that more distance is not covered before another command is received. Table 1 shows the average accuracy (%) from the movement of the wheelchair for four (4) different directions after five (5) trials for each subject experimented with a total of three (3) subjects. Two different kind of average accuracies were calculated: the average navigation/directional accuracy and the average accuracy/person. The average accuracy per person showed how each participants performed on the overall task. Subject 1 had the best score of 90, suggesting that he was slightly able to direct is eye better than others. Table 2 showed the score from the mobile interface test and overall score was 100%. Hence, navigation was smooth with the mobile interface.

**Table 1.** Average accuracy (%) from the movement of the wheelchair for four different directions after five trials for each subject experimented with a total of 3 subjects using eye control.

| Direction of movement | Subject 1 | Subject 2 | Subject 3 | Average accuracy per direction (%) |
|---|---|---|---|---|
| Right | 85 | 90 | 90 | 88.3 |
| Left | 90 | 85 | 85 | 86.67 |
| Forward | 85 | 85 | 85 | 85 |
| Backward | 100 | 95 | 95 | 96.67 |
| Average accuracy per subject (%) | 90 | 88.75 | 88.75 | 89.16 / 89.16 |

**Table 2.** Average accuracy (%) from the movement of the wheelchair for four different directions after five trials for each subject experimented with a total of 3 subjects using the mobile interface.

| Direction of movement | Subject 1 | Subject 2 | Subject 3 | Average accuracy per direction (%) |
|---|---|---|---|---|
| Right | 100 | 100 | 100 | 100 |
| Left | 100 | 100 | 100 | 100 |
| Forward | 100 | 100 | 100 | 100 |
| Backward | 100 | 100 | 100 | 100 |
| Average accuracy per subject (%) | 100 | 100 | 100 | 100 / 100 |

## 4 Summary and Conclusion

The paper is centered on the design and development of a prototype electric-powered wheelchair that has an eye-controlled navigation system with obstacle avoidance technology for safety. The system provides navigation autonomy for people with total paralysis by using the eye to drive the wheelchair and even extended the research by incorporating a mobile control interface instead of the common joystick auxiliary control to extend the system's usability to the elderly and people with hemiplegia. Haar cascade ML algorithm with Histogram Equalization (for illumination control) was adopted in the design for its simplicity, high perception rate and fast processing time. Four movement directions were achieved from the eye image frames, while more directional movements were obtainable from the auxiliary mobile control interface. Hence, the system is versatile enough to accommodate persons with total and partial paralysis. The average navigation accuracy of the device/person is 89.16%; this is slightly low because of the low computation power of Raspberry Pi4, and better accuracy could be achieved when the eye detection algorithm is fine-tuned, or deep learning classification is introduced. However, using CNN often require GPU which makes implementation and deployment on edge devices like raspberry pi impractical. The obstacle avoidance score was 100%. The paper provided an extensive review of state-of-the-art technology in this domain, identifying that most studies are lab-based focusing more on accuracy rather than deployment and power consumption which are critical to usability. This work also put into consideration

implementation in low-resource settings. Future recommendations to enable optimum satisfaction of this design should include: the implementation of the project on a typical wheelchair and utilization of the necessary components for the effective running of the wheelchair, the usage of the latest model of Raspberry pi with higher random access memory(RAM) to ensure swift navigation of the wheelchair, a tracking device using a motion sensor can be incorporated in the design for emergency tracking of patient's whereabouts, the utilization of an infrared webcam for night gaze detection. Finally, more laser sensors can be incorporated to cater to the whole range of motion of the device.

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