كرسي متحرك مقاد بحركة العين بالزمن الحقيقي باستخدام معالجة الصور وشبكة SSD لتحسين تصنيف الاتجاه

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الملخص:

خلّفت الحرب التي اجتاحت البلاد العديد من الإصابات، مما أدى إلى بتر الأطراف أو الشلل الرباعي. نتيجةً لذلك، نشأت حاجة ملحة لاستخدام الكراسي المتحركة، مما دفعنا إلى معالجة مشكلة أتمتة كرسي متحرك كهربائي وتحسين تنقل الأشخاص ذوي الاحتياجات الخاصة.

في هذا العمل، تم استخدام تقسيم الصور وتحويل هاف (Hough Transform) لمعالجة صور حركة العين مسبقًا، مما يحسّن دقة اكتشاف الميزات. ثم تم استخدام هذه الصور المقطعية لتدريب شبكة عصبية من نوع (SSD) لتصنيف مواضع العين إلى ثلاث فئات: يمين، يسار، ومحايد. يساعد هذا التصنيف على التحكم في حركة الكرسي المتحرك من خلال اكتشاف نية المستخدم بناءً على اتجاه العين.

تم تصميم نموذج وواجهة برمجية باستخدام بيئة MATLAB. وتم اختبار النظام على خمسة أفراد (ثلاثة رجال وامرأتان)، تتراوح أعمارهم بين 30–45 عامًا ووزنهم بين 65–85 كجم، في ظروف النهار وعلى سطح مستوٍ. أجري كل مشارك الاختبار ثلاث مرات على الأقل. بلغ معدل النجاح في اكتشاف اتجاه حركة العين وتوجيه الكرسي المتحرك حوالي 85% بعد دمج تقنيات معالجة الصور المحسّنة.

تاريخ الايداع

تاريخ القبول

الكلمات المفتاحية: التحكم بكرسي المريض، خوارزمية فيولا–جونز، شبكة SSD

Real-Time Eye Movement-Controlled Wheelchair Using Image Processing and SSD Network for Enhanced Directional Classification

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Abstract

The war that passed through the country left many injuries, resulting in limb amputations or bilateral or quadriplegic paralysis. Consequently, there became an urgent need to use wheelchairs, which led us to address the problem of automating a motorized wheelchair and enhancing the mobility of people with special needs. This research focuses on utilizing eye movement to control and steer a wheelchair using advanced image processing techniques.

In this work, image segmentation and the Hough Transform were employed to preprocess eye movement images, improving the precision of feature detection. These segmented images were then used to train a Single Shot Detector (SSD) neural network to classify eye positions into three categories: Right, Left, and Neutral. This classification helps control the wheelchair's movement by detecting the user's intent based on eye direction.

The motorized wheelchair was converted into an electric wheelchair using two DC motors with carefully calculated power to withstand the weight of the chair and the expected user. Two specially designed control loops were used to manage the motors, while the Viola-Jones algorithm was adopted for initial face and eye detection. The image processing pipeline was then enhanced by combining Hough Transform for feature detection and segmentation, followed by training the SSD network for classification.

A model and software interface were designed using the MATLAB environment. The system was tested on five individuals (three males and two females), aged between 30-45 years and weighing between 65-85 kg, under daylight conditions and on a level surface. Each participant performed the test at least three times. The success rate for detecting eye movement direction and steering the wheelchair was approximately 85% after incorporating the enhanced image processing techniques.

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1. Introduction

The wheelchair is a device that assists people with physical disabilities or chronic illnesses, as well as the elderly, in mobility.[1]

1.1 General Introduction

The aftermath of the war left a significant number of individuals with severe injuries, many of which resulted in permanent disabilities, such as quadriplegia, that impair mobility. Globally, statistics show an average of 40 new cases of quadriplegia per year per million people [1]. This highlights the urgent need for assistive mobility devices like wheelchairs. However, traditional wheelchair control mechanisms, such as joysticks, are challenging for those with quadriplegia [2-3].

As a result, there has been a growing trend toward automating wheelchair control, with various technological solutions proposed. These include voice command control [1], eye movement tracking [1,3,4].

Facial expression monitoring (such as smiling or eyebrow movement) [2], brain signal interpretation [5] and mouth or tongue movement control [6]. Additionally, innovative solutions like head movement control [19], EEG-based brain-computer interfaces [21], hand gesture control [32], and gaze-based navigation systems [15, 30] have gained attention for their potential to improve the lives of individuals with limited mobility.

In this research, we propose controlling an electric wheelchair using eye gaze. Eye-gaze tracking offers a non-invasive, intuitive solution for individuals who cannot use other methods. Numerous algorithms have been developed to facilitate eye movement-based control, including image processing techniques such as the Viola-Jones algorithm for face and eye detection, Hough Transform for geometric feature detection, and deep learning approaches like Single Shot Detector (SSD) networks for accurate eye movement classification. By integrating these advanced methods, our approach aims to provide a reliable and efficient control system for electric wheelchairs.

1.2 Theoretical Background

Digital image processing involves multiple stages, summarized as image preprocessing, image analysis, and visualization. Image preprocessing is a fundamental step before image analysis, crucial for extracting relevant features from an image. Both preprocessing and analysis are essential stages before displaying results on the computer or utilizing the extracted data for control commands [1].

Figure 1 illustrates several commonly used methods for detecting a body or an object in a specific image. These methods vary in effectiveness, mathematical approaches, and transformation techniques that apply image processing operations to derive coefficients for detecting the desired object [2]

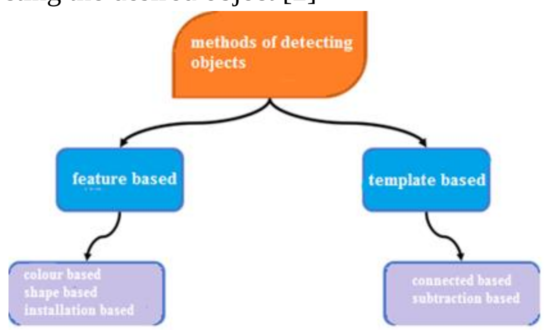

Figure 1- methods of object detection.

In digital images, each pixel is represented by three numerical values, corresponding to the Red, Green, and Blue (RGB) color channels. This color information is stored in three numerical arrays representing the pixel intensities of the image. A colored image can be interpreted as a three-dimensional function (intensity with spatial coordinates), where each matrix corresponds to a slice of the image at different intensity levels. In object detection tasks, high-contrast regions are preferred, enabling more accurate detection under varying lighting conditions.

Traditional detection methods, such as the Fixed Template Matching Technique, process all target images within a video stream. Although this method is fast, its effectiveness is limited compared to more adaptive techniques like Updated Template Matching[7]. The Log-Polar Transformation method[8], inspired by the human eye's retinal network, reduces the amount of information in an image by focusing on high-resolution details at the center while reducing resolution toward the edges. This method helps mitigate the effects of rotation and scaling in Cartesian coordinates.

For more precise detection and tracking of objects, advanced image processing techniques like the Hough Transform and SSD (Single Shot Detector) networks have been integrated into this

study. The Hough Transform is applied to detect geometric shapes, such as circular features, enhancing the accuracy of identifying critical elements in the eye region. Segmentation techniques are used to preprocess the image by isolating these features before feeding them into the SSD network.

The Viola-Jones algorithm, known for its reliable face detection capabilities, is employed as the first step in isolating facial regions. Its high detection rate and relatively low error rate make it suitable for real-time applications, particularly when detecting and tracking faces in dynamic environments. However, to improve the classification of eye movements (left, right, neutral), the SSD network is trained on segmented images processed through the Hough Transform. This combination allows for more accurate classification by leveraging deep learning's ability to detect and classify features across a range of image variations[9].[10]

Face detection serves as the entry point for further analysis and classification of eye movements, which is critical in systems designed to control devices, such as motorized wheelchairs, based on eye direction.

Digital image processing involves multiple stages, summarized as image processing, image analysis, and computer display. Image processing is a fundamental step before image analysis, and image processing and analysis are essential stages before displaying them on the computer or using their data for control commands .[1]

Figure (1) shows several commonly used methods for detecting a body or an object in a specific image, differing in their effectiveness, mathematical approach, and transformation derivatives that perform image processing operations to obtain coefficients for detecting the desired object.[2]

Representation of colored images within the computer involves three numerical arrays. Each pixel in the image is described by three numerical values, each indicating one of the three RGB components. There are also methods for storing a colored image in the computer memory based on the color space used. Each matrix of a colored image is interpreted as a three-dimensional function (intensity with spatial coordinates). Another level is placed parallel to the coordinate level of the image, and it is sliced into slices in the intersection area [7]. In this method, it is preferred that the color of the body to be detected has high and distinctive contrast up to a certain threshold to confront changes in light intensity. On the other hand, the matching method (Fixed Template Matching Technique) processes all target images making up the video, and although this method is fast, its detection effectiveness is usually lower compared to the Updated Template Matching technique [7]. The Log-Polar Transformation [8] method is widely used to reduce the amount of information in the image by relying on its location in the same frame. It is inspired by the operation of the eye retina network, where high resolution is in the center and decreases as we approach the peripheral edges. This method also helps to eliminate the effects of rotation and changes in size that may occur in the template in Cartesian coordinates.[8]

The Viola-Jones algorithm followed in this research for face detection features reliable Viola-Jones algorithm characteristics, as it has a high detection rate and relatively low error rate [9]. It is also configured to work in real-time, especially in applications where face detection is essential, and at a rate not exceeding two frames per second [10]. Face detection plays a crucial role in isolating faces in images from other objects, serving as the first step in face recognition, which requires high computational capabilities at the hardware level [9], [11].

1.4 Literature Review:

Recent advancements in assistive technologies have significantly improved the mobility and independence of individuals with physical disabilities. A particular focus has been on developing innovative wheelchair control systems that leverage eye gaze movement, head motion, and brain-computer interfaces. These systems employ various algorithms and sensors to interpret user intentions and translate them into actionable commands, thereby enhancing the usability of motorized wheelchairs.

Dahmani et al. (2020) presented a cost-effective eye-tracking system that uses Convolutional Neural Networks (CNN) for feature extraction from images, allowing for precise wheelchair control even when the user's head is tilted. This approach ensures high accuracy in detecting eye positions and transmitting the corresponding motion commands to the motor drive circuit . Similarly, Dinh, Alnusairi, and Rehman (2022) introduced a smart wheelchair control system based on electrooculography (EOG) specifically designed for quadriplegic patients. Their system captures eye movements to enable wheelchair navigation, offering a non-invasive solution for individuals with severe mobility impairments .
Moreover, voice-controlled wheelchairs have also been explored as an alternative to traditional control methods. Kumar, Rani, and Sharma (2021) implemented a voice-controlled system that allows users to navigate their wheelchair through spoken commands, providing a hands-free experience that is particularly beneficial for those with limited hand mobility . In a related study, Khanna and Chauhan (2018) developed a gaze-based control system that utilizes computer vision techniques to interpret eye movements, offering another viable option for quadriplegic patients .
Furthermore, Iqbal, Rahman, and Islam (2022) proposed a low-cost brain-computer interface (BCI)-based wheelchair for disabled individuals. This system translates brain signals into control commands, enabling users to operate their wheelchairs solely through mental effort . Al-Husban and Aboud (2020) also contributed to this field by designing a face and eye detection system using the Haar Cascade algorithm, which accurately identifies the user's gaze direction for controlling wheelchair movement .

Additionally, researchers have explored the integration of multiple control modalities to enhance system reliability and user comfort. For example, Kumar, Agarwal, and Sharma (2021) developed an intelligent gaze-tracking system that combines eye-tracking with advanced image processing techniques, providing a more intuitive and responsive control method . Similarly, Nayak, Biswas, and Das (2020) designed a head movement-based control system that leverages accelerometers to detect user intent and navigate the wheelchair accordingly .

2. Research Methods and Materials:

Descriptive and experimental methods were adopted to describe the problems, procedures, and tools necessary for conducting the research. All necessary experiments to implement a prototype model and test it were described.

2.1 working principle

We did number of experiments and tested the Algorithm and the designed system on five users three of them are male and two of them are female their ages between 30 to 45 years and their weight between 65 to 85 kg and the experiments done by using webcam with daylight conditions on flat land after that we had the results، The results were discussed and compared with international research findings, leading to conclusions based on the following stages:

Initially, electric motors were selected based on their efficiency and the power required by the wheelchair in relation to the expected user weight. Electrical and mechanical components were then assembled, including electric motors, electrical and electronic circuits to control and drive the motors, and the design of the communication circuit with the computer. Figure (3) shows a simulation of the motor drive circuit placed under the chair. The control method involved moving the seat's eye because it was more effective than other methods such as using voice or placing sensors for electrical signals around the eye, allowing the seat to move freely without constraints. After investigating several algorithms, the Viola-Jones algorithm was chosen for its efficiency. This algorithm issues commands to the motor drive circuits based on eye gaze movement. Converting the modified wheelchair into an electric wheelchair was done by adding two 12-volt DC motors with a power of 50 watts and designing two control circuits controlled by an Arduino chip with low cost suitable for low-income individuals. The system was tested by several individuals, 70% of whom reported that the system worked well and had no difficulty controlling the eye to determine the direction of movement, even under daylight conditions and on a level surface.

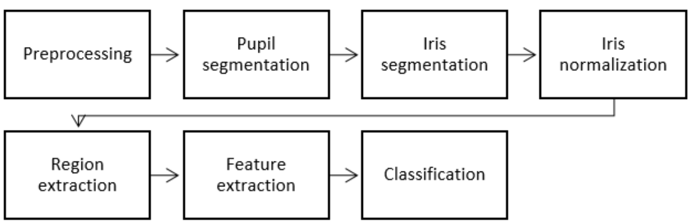

Figure 2. Iris Recognition System Workflow. This Figure shows the various steps involved in processing the captured eye image to obtain a normalized representation of the iris. The process includes pre-processing, iris segmentation, pupil detection, iris detection, iris normalization, and region extraction.

2.2 Eye Blink Detection:

The algorithm proceeds through the subsequent steps in detecting eye blinks:

2.2.1 Image Feature Extraction

There are some common characteristics in human faces that form matchable features between faces, including: the area around the eyes is darker than the area around the cheeks, the area around the nose bridge is brighter than the area around the eyes, the location and size of the eyes, mouth, and nose bridge, and the values of pixel density gradients [11]. Figure (4) illustrates the distinctive features of the Haar cascade.

The algorithm searches in an image for the presence of a human face using the aforementioned features [9], [11].

Rectangular Haar-like features are given by the relationship:

Feature value = Sum of pixels in the bright area - Sum of pixels in the dark area

There are three patterns of rectangular features: two-rectangle, three-rectangle, and four-rectangle.

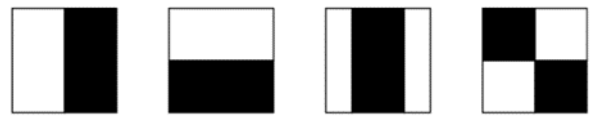

Figure 3- Basic Haar-like features.

2.2.2 Integral Image Creation

The integral table evaluates rectangular features over a fixed time period. This algorithm gives a significant advantage in execution speed compared to alternative algorithms with more complex structures. Since each rectangular patch is always adjacent to another rectangular patch, we can say that any two rectangular patches following a certain feature can be calculated through six relational matrices, and any three rectangular patches are calculated through eight relational matrices, meaning that any four rectangular patches related to a feature can be calculated through nine relational matrices [12].

2.2.3 Application of the AdaBoost Algorithm

The speed at which feature evaluation occurs is proving to be inadequate, particularly when considering the vast number of features involved. To illustrate, let's consider a subwindow of dimensions 24 pixels by 24 pixels. Within this relatively small area, the estimated count of potential features amounts to a staggering 162,336 [12]. Attempting to evaluate each of these features individually when testing a specific image becomes virtually impossible from a computational standpoint.

This challenge is where an enhanced iteration of the AdaBoost algorithm in the realm of machine learning comes into play. This improved algorithm is instrumental in identifying a subset of features that exhibit superior discriminatory power. Moreover, it facilitates the training of classifiers to effectively detect these selected features within new images.[12]

The core mechanism of this algorithm involves the construction of a high-performance classifier. This classifier is formed by amalgamating multiple weighted classifiers, each of which may individually be weaker in performance [10]. During the training phase, these classifiers establish threshold functions based on features, where parameters like the threshold value (θ_j), polarity (s_j), and coefficient (a_j) are determined [10]. This process is guided by the minimization of the weighted classification error.
Practically, during the training phase, a set of N images is provided, each labeled as either positive or negative based on whether they contain the desired features or not [9]. These images are then subjected to iterative adjustments, where weights are assigned based on their classification errors. Ultimately, this iterative process aims to refine the classifiers' performance, improving their ability to discern relevant features within images .[9]
Eventually, the final classifier is derived based on a predefined set of criteria, providing a robust mechanism for feature detection within images [12].

2.2.4 Processing Using SSD network

The distinctive features extracted after detection through previous stages include the sum of pixel intensities within rectangular regions. These features bear a resemblance to the Haar-like functions, which are widely used in object detection within image processing. The features employed in the Viola-Jones algorithm rely on multiple rectangular regions, often resulting in more complex patterns [12]. While the Viola-Jones algorithm uses these features to detect objects like faces, modern object detection has seen significant advancements with deep learning approaches such as the Single Shot Detector (SSD) network.

The SSD network, as shown in Figure 4, enhances detection by using a convolutional neural network (CNN) to perform object localization and classification in a single forward pass, making it highly efficient for real-time applications. In this stage, sequential classifiers are employed, allowing the system to detect features across varying scales and positions. The SSD network structure integrates multi-scale feature extraction, improving accuracy for small and large objects alike .

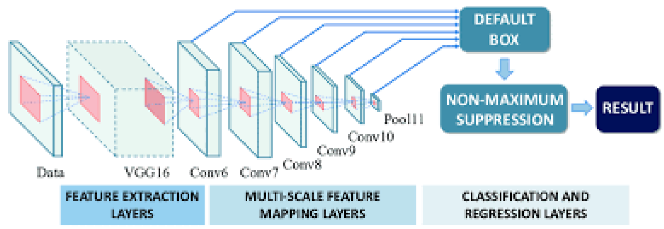

Figure 4- SSD network structure

In every subwindow analyzed, the probability of detecting a real face or object is calculated, with an initial probability of 0.01%. The architecture balances computational operations across these subwindows, prioritizing those with higher probabilities of containing a face. This improves detection speed and reduces the need for unnecessary processing in irrelevant areas of the image.
By leveraging the SSD network, the system improves detection performance, achieving higher accuracy and lower false-positive rates. For instance, a simplified classifier with only two dimensions might achieve a detection rate of 100%, but with a false positive rate of 50%. However, by using SSD, which evaluates multiple feature maps and scales in parallel, detection is more precise, reducing false positives while maintaining a high detection rate.

3. Results and Discussion:

After applying the algorithm and the designed system on the participants and testing the two driving circuits placed under the modified wheelchair, the following results were obtained:

3.1 Eye Pupil Detection:

The Viola-Jones algorithm goes through several stages to achieve the goal of detecting the presence of the eye pupil and determining its direction. The first stage involves using the Haar feature.

3.1.1 Haar Feature Application Results:

Figure (9) demonstrates a practical application of the Haar feature, which relies on the contrast between the white and black rectangles in a specific region of the image. Each feature is associated with a specific location within the sub-window (the sub-window is a part of the original image on which the features are applied).

Figure 5. The process of creating a mask for pupil detection involves several steps. First, the pupil is captured, and its center is calculated. Subsequently, a mask is applied to exclude the upper portion of the eye, effectively eliminating the interference caused by eyelashes. This mask is circular and centered around the pupil, aiding in the isolation of the pupil from the surrounding image elements

3.1.2 Eye Pupil Localization:

Figure (10) illustrates that the algorithm first recognizes the face and identifies it within a specific frame. Then, the eye image is isolated, converted from RGB to grayscale, divided into 33 sectors, and the density level is adjusted. The pupil (black) should be visible, and the sector containing the pupil determines the desired direction, thus indicating the direction to move (right, front, left).

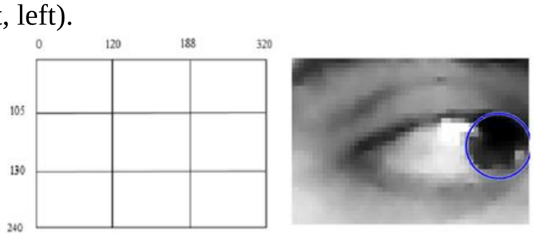

Figure 10- Eye Pupil Localization.

3.1.3 User Interface Design:

Figure (11) shows the interface of the face detection, eye detection, and pupil tracking program, programmed using the MATLAB environment. The program includes the implementation of the Viola-Jones algorithm. A detailed explanation of the program and the user interface follows.

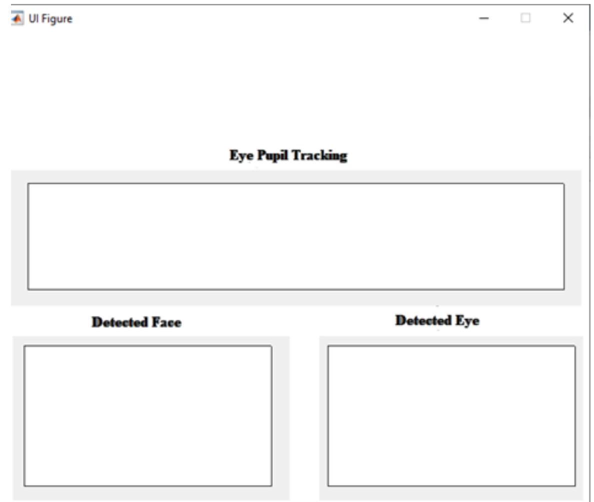

Figure 11- Main Interface of the Program.

3.1.4 Program Testing:

The program underwent testing, divided into four sections according to cases:

1. Testing the program's ability to detect eye movement to the right while determining the pupil's location and displaying it.

3.1.5 Reliability test:

eye movement to the right, left, front, and inability to track pupil movement.

[Figure 12 illustrates different tests conducted on the system.]

This figure represents various tests conducted on the system to evaluate its reliability in tracking eye movement in different directions and its ability to determine the absence of eye movement.

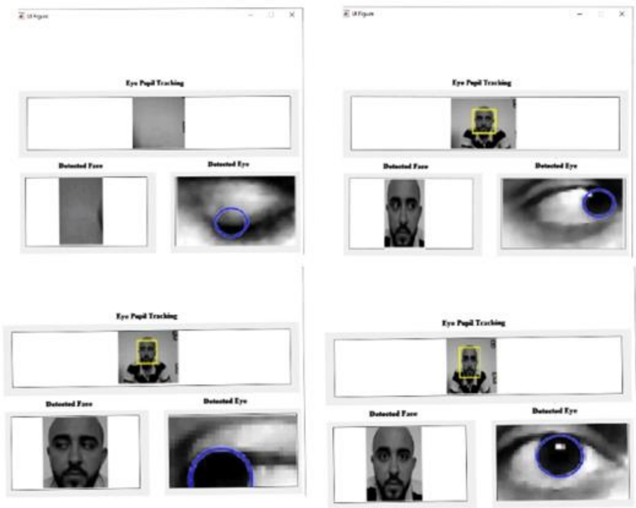

Figure 12- test(1).

4.Conclusions and Recommendations:

Conclusions

- Eye movement-based control systems significantly enhance mobility for wheelchair users and individuals with special needs, allowing them to navigate independently without external assistance.
- The Viola-Jones algorithm proved effective for face detection, feature extraction, and eye tracking, contributing to reliable wheelchair control. However, by integrating advanced techniques like the Single Shot Detector (SSD) network, accuracy and real-time performance in classifying eye movements (right, left, and neutral) were further improved.
- Any standard wheelchair can be converted into an electric wheelchair with the necessary mechanical and electronic modifications, making it a flexible and scalable solution for various users.

Recommendations

- Explore additional facial or head gestures to introduce more control functions, enhancing user interaction with the wheelchair.
- Investigate the application of the Viola-Jones algorithm not only for face detection but also for face recognition, person identification, or other advanced applications.
- Leverage artificial intelligence techniques, such as deep learning models and neural networks, to enhance the system's control, monitoring, and safety functions, making the wheelchair more responsive and secure in real-world environments.

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