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Design and Development of an Assistive System Based on Eye Tracking

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Abstract: This research concerns the design and development of an assistive system based on eye tracking, which can be used to improve the quality of life of disabled patients. With the use of their eye movement, whose function is not affected by their illness, patients are capable of communicating with and sending notifications to caretakers, controlling various appliances, including wheelchairs. The designed system is divided into two subsystems: stationary and mobile assistive systems. Both systems provide a graphic user interface (GUI) that is used to link the eye tracker with the appliance control. There are six GUI pages for the stationary assistive system and seven for the mobile assistive system. GUI pages for the stationary assistive system include the home page, smart appliance page, eye-controlled television page, eye-controlled air conditional page, i-speak page and entertainment page. GUI pages for the mobile assistive system are similar to the GUI pages for the stationary assistive system, with the additional eye-controlled wheelchair page. To provide hand-free secure access, an authentication based on facial landmarks is developed. The operational test of the proposed assistive system provides successful and promising results.

Keywords: eye tracking; wheelchair; people with disabilities; elderly people; Raspberry Pi; image processing

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1. Introduction

A disabled person is a person who suffers from a physical or mental impairment that makes the person's life and living conditions such that it is difficult to do certain activities or effectively interact with the world. The World Health Organization (WHO) and the World Bank estimate that one billion people experience some form of disability [1], 20% of whom live with great functional difficulties in their day-to-day lives. Disability can be classified into four categories, including disabilities related to visual impairments, hearing impairments, motor impairments, and cognitive impairments [2]. Among the four categories, a disability related to severe motor impairments results in mostly a bed-ridden patient whose quality of life is degraded significantly.

An attempt to develop an assistive system for a severe motor-impaired disable patients has seen increasing interest over the last few decades. Rivera et al. [3] presented a new robotic assistant for disabled patients. Robot capabilities are easily integrated with existing computer interfaces. The independence from any specific input device makes it possible to use the system without special training, even for completely disabled patients suffering from the severe stages of amyotrophic lateral sclerosis (ALS). However, the limitation of the designed system by Rivera et al. is too bulky to be portable. Matthew [4], a master's degree student at Massachusetts Institute of Technology (MIT), developed a wearable, silent-speech device called AlterEgo, using an electromyogram electrode to detect an attempt to say words. Using eight detection electrodes attached to the chin and neck area, the device uses an artificial neural network (ANN) to determine the 10-word probabilities of the input.

The classified ANN output can then be linked to create usable applications for patients with speech impediments or speech loss and can be used as an assistive technology for ALS patients. However, in order for the device to be fully functional as a real-time speech technology substitute, a more extensive vocabulary would be required, and promising work is already being done to greatly increase the vocabulary of the devices. Mccane et al. [5] captured brain signals (Electroencephalography, EEG) using a 16-channel electrode cap that is placed on the patient scalp and further analyzed for the brain–computer interface (BCI). The system can achieve and average accuracy of 92.9% and can be applied to provide communication with ALS patients. The disadvantages of BCI are the long setup time, expensive cost, and slow response.

Eye-gaze tracking is one of the most challenging problems in computer vision. Eye-gaze tracking systems use devices that measure eye movement/activity and gaze (point of regard) tracking, which is later processed to be used as a human–machine interface. Eye-gaze tracking has been used in various applications [6], including drowsiness detection [7], iris recognition [8], behavioral therapy [9], and Human Computer Interaction (HCI) [10,11]. A human–machine interface for ALS patients based on eye-gaze tracking has recently captured researchers' attention. Bissoli et al. [12] developed a new assistive system based on eye tracking for controlling and monitoring a smart home, based on the Internet of Things. The proposed system uses a low-cost eye tracker to control the position of the mouse in a software application that performs various events, including appliance control and lamp control. By gazing at the point for a few seconds, the tool generates the corresponding event, resembling the left-button mouse click. The system was evaluated on 29 healthy subjects. The end-users evaluated the assistive system with mean scores of 92.5%. Klaib et al. [13] utilized the video oculography approach through Tobii technology with added voice interfaces using Azure cloud to help control home appliances in a smart home for elderly and special needs users through Internet of Things technology (IoT). Tested on 20 volunteers, the system demonstrated a high accuracy in tracking the eye gaze and movement through how responsive the pointer on the interface was. The response time of the system had an acceptable delay. Pai et al. [14] designed an eye control device based on image processing to assist mobility for handicapped patients suffering from quadriplegia and paraplegia. Eye-gaze tracking is measured by attaching a non-slipping contact lens over a corneal bulge and affixing a sensing magnetic coil or mirror to the lens. The system is used to guide and control the powered wheelchair. Extending the system to control the equipment around fans, lights, etc., and voice-activated functions are left for future work. Eid et al. [15] proposed an eye-gaze control system for people with motor disabilities. The system consists of eye-tracking glasses, a depth camera to capture the geometry of the ambient space, a set of ultrasound and infrared sensors to detect an obstacle, a laptop placed on a flexible mount, and a safety switch to turn off the system in case of emergency. An N-cell grid-based graphical user interface that adapts to input/output interface specifications is introduced to navigate unknown environments in a continuous, real-time fashion. The system was evaluated on a Permobile M400 wheelchair with a participant with ALS. The participant reported a higher level of confidence driving the wheelchair and experienced no collisions throughout the experiment. Additional research on eye-gaze tracking applications to assist ALS and handicapped patients can be found in [16–18].

With the recent improvements in technology, the state-of-the-art research on autonomous wheelchairs tends to use modern deep learning technologies to improve the quality of detection systems and controllability of the wheelchair. For example, Dahmani et al. [19] developed a motorized wheelchair that can be controlled via eye movements. They applied Convolutional Neural Networks (CNN) for gaze estimations. Similarly, in the study of Amer et al. [20], deep learning–based face and eye detections were applied to control wheelchairs. In addition, Luo et al. [21] applied CNN for eye blink detection and used this as a practical human–computer interaction system for wheelchair motion control. Although deep learning–based methods provide a promising technology for wheelchair control, they are customized for each individual, and the performance is degraded when used with subjects who were not trained. Moreover, due to cutting-edge technologies, the original purpose of human computer interface (HCI) (i.e., to control devices, to communicate commands) is now broadened to automatically recognize users' behavioral activities for better communication and performance. For instance, a Brazilian start-up, HOOBOX Robotics, collaborated with Intel to launch Wheelie 7 [22], an adapter kit that can be plugged into any motorized chair. It applies artificial intelligence (AI) technology to detect the real-time facial expressions of users to control the movement of the chair.

This research concerns a smart eye-tracking system that is designed for people with disabilities. The concept of the research is to apply eye movement to control appliances and wheelchairs and to communicate with caretakers. The salient aspects and/or contributions of this paper are as follows.

1. A limitation of a camera-based eye-gaze tracking is that it requires the user to maintain the head in a static position. When the subject is in upright position, the head always moves from the calibration position and hence frequently requires re-calibration. To solve the problem, we proposed a dual eye-tracking system consisting of (i) a mobile system and (ii) a stationary system. For the stationary system, we used a commercial Gazepoint eye tracker to measure eye gaze when a patient lies in bed. For the mobile system, we designed a glasses frame installed with an infrared camera to estimate the eye location when the patient sits on a wheelchair.
2. We proposed patient authentication in a stationary eye-tracking system based on facial landmarks. This provides convenient and secure access to the system.
3. Our eye-tracking system is used to control appliances, including lamps, air conditioners, and televisions. The system is also designed to communicate with the caretaker through i-speak, which can convert some programmed text to speech.

2. Materials and Methods

Our assistive system based on eye tracking is divided into two subsystems: (i) a stationary assistive system and (ii) a mobile assistive system, as shown in Figure 1a,b, respectively. With the mobile assistive system and stationary assistive system, a disabled patient is capable of controlling appliances and communicating with caretakers using eye tracking. The mobile assistive system is used when the patient is on a wheelchair, whereas the stationary assistive system is used when the patient lies in a bed. The additional feature of the mobile assistive system is that it includes an eye-tracking wheelchair controller. The details of both systems are as follows.

2.1. Stationary Assistive System

A stationary assistive system is used when a disabled patient stays in bed. The system consists mainly of a notebook installed with a commercial eye tracker and a built-in universal serial bus (USB) camera. The commercial eye tracker is used to estimate the gaze of the patient, and the USB camera is used for smart authentication using facial landmark extraction. The provided application program interface (API) and software development kit (SDK) of the commercial eye tracker allows the developer to use gaze location on the notebook screen to control various appliances and to communicate with the caretaker. There exist six graphic user interfaces (GUIs) for the stationary assistive system. Two of the GUIs are related to the appliance controller, which are for television and air condition. These can be accessed by using an actuator module controlled by Arduino, which is in turn interfaced with the notebook via serial communication. Details of the GUIs are provided in Section 2.3.

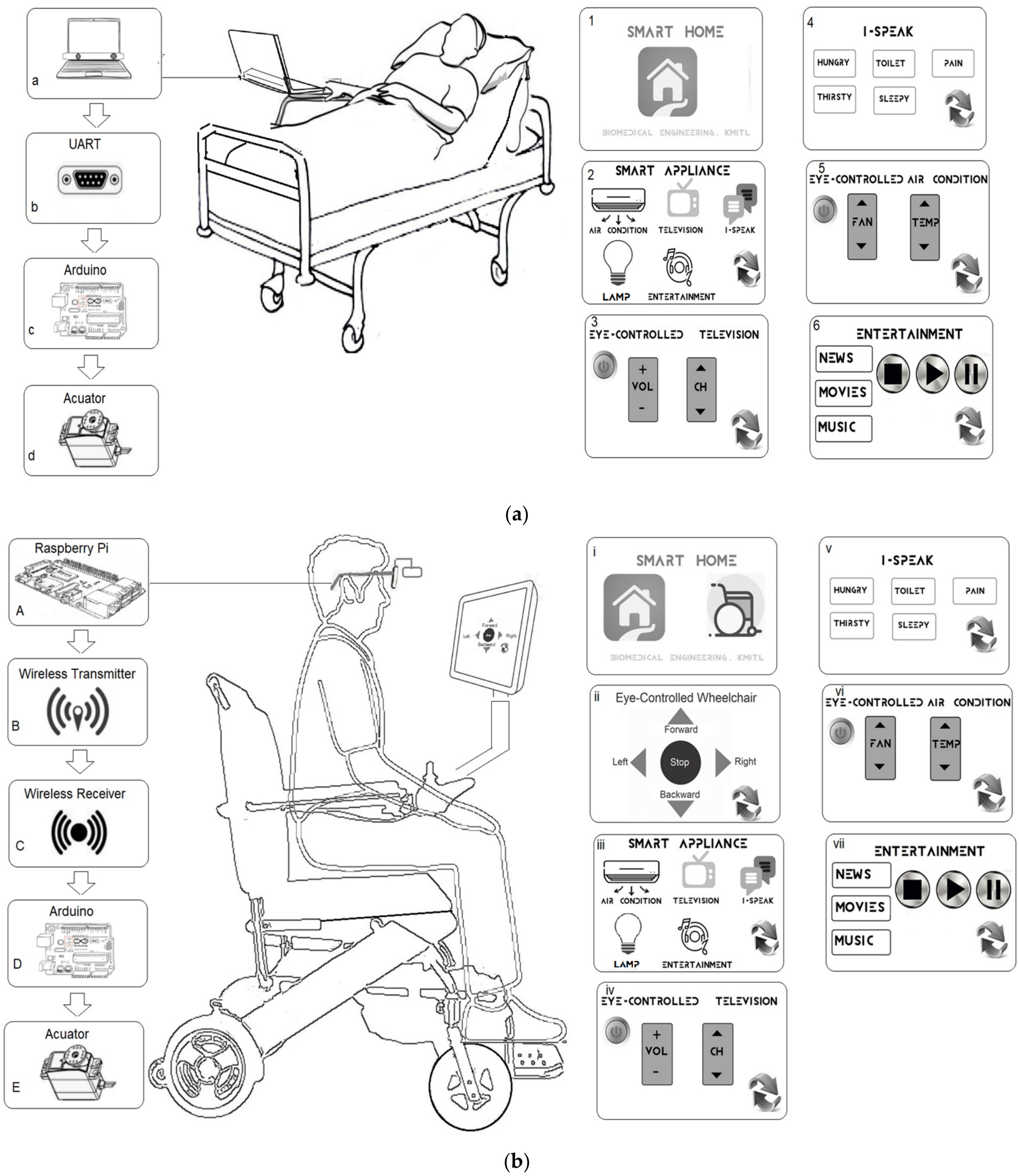


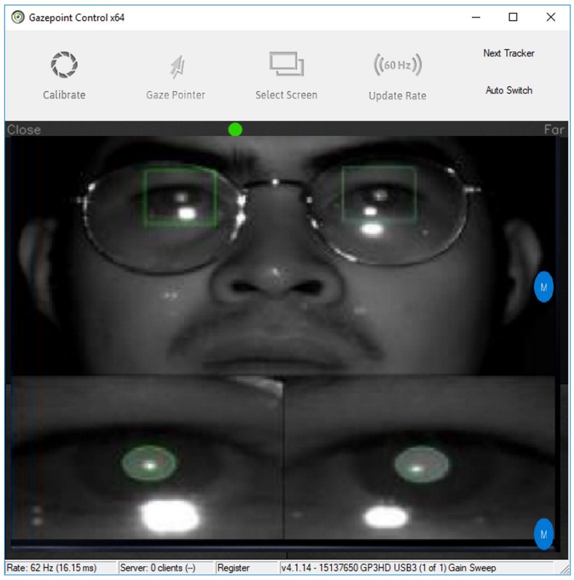
Figure 1. Smart home based on eye tracking: (**a**) stationary system and (**b**) remote system.

2.1.1. Eye Tracker for Stationary Assistive System

The eye tracker used in the stationary assistive system is Gazepoint model GP3 [20], as shown in Figure 2. It is based on infrared oculography, in which a source of invisible near-infrared or infrared light illuminates the pupil, causing detectable reflections in both the pupil and the cornea. These reflections are tracked by an infrared camera, which is used to estimate the center of the pupil, deduce eye rotation, and determine gaze direction. Prior to using the Gaze point model GP3, the system must be calibrated with the user staring at the screen and following five to nine moving landmarks on the screen to normalize the distance between the user and the eye tracker. Once calibrated, the marker will be bound, covering the eye areas as shown in Figure 2b. The system is now ready to be applied for eye tracking. The specifications of the Gazepoint model GP3 are listed below.

- 0.5–1.0 degree of visual angle accuracy
- 60 Hz or 150 Hz sampling rate
- 5- or 9-point calibration needed
- Easy to use
- Open standard API
- 35 cm (horizontal) × 22 cm (vertical) movement
- ±15 cm range of depth movement
- Ultra-portable—235 × 45 × 47 mm (125 g)
- Compatible with 24” displays or smaller

(**a**)



(**b**)

Figure 2. Gazepoint GP3 eye tracker [23]: (**a**) Gazepoint GP3 eye tracker mounted on notebook; (**b**) calibration software.

2.1.2. Smart Authentication for Assistive System

Security is one of the main concerns of smart systems, to prevent unauthorized access of the system for an individual patient. To provide hands-free secure access, smart authentication based on facial landmarks is proposed. The Haar cascade algorithm is used to detect the region of interest (ROI) of facial components, which consists of the eyes, nose, and mouth. Facial landmarks related to the eyes, nose, and mouth are defined by radon transform. Distance features associated with each facial landmark are then computed and used to identify patients.

(i) Define facial region of interest using Haar cascade algorithm.

Facial component detection using a Haar feature-based cascade classifier is an object detection method proposed by Paula Viola and Michael Jones [24]. Haar cascade is a set of Haar-like Features that are combined to form a classifier consisting of dark regions and light regions. The process of the Haar cascade classifier computes the difference of the sum of the intensities of the dark regions and the sum of the intensities of the light regions, selects the best features from all features, and combines increasingly more complex classifiers in a cascade, which allows negative input (non-face) to be quickly discarded while spending more computation on promising or positive face-like regions. The first goal of our hands-free authentication was to define the region of interest, the 2D face image, using the Haar cascade algorithm, as shown in Figure 3a, following determination of both eyes, the nose, and the mouth, as shown in Figure 3b,c.

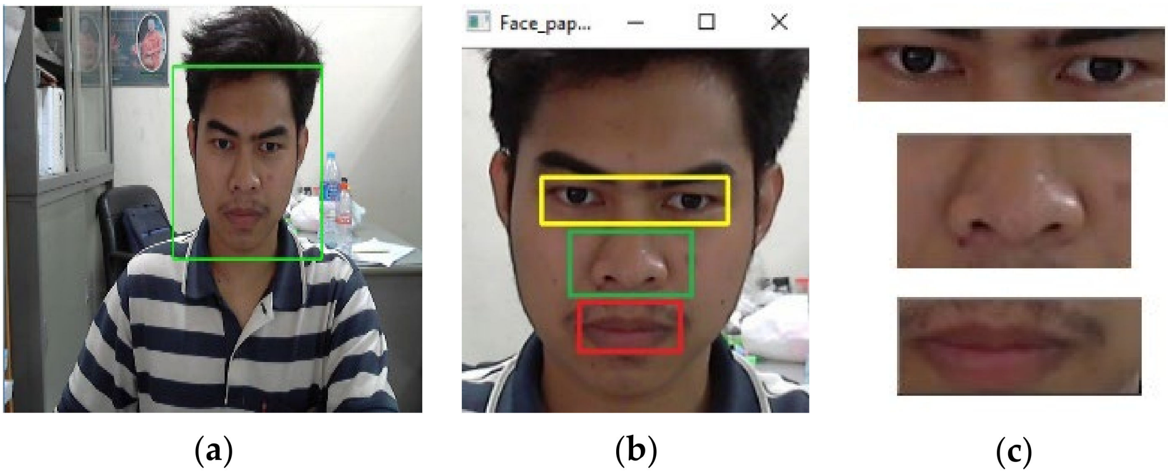


Figure 3. Defined ROI of facial components by the Haar cascade algorithm: (**a**) face detection; (**b**) eye, mouth, nose and detection; (**c**) extracted ROI of eye, nose and mouth.

(ii) Facial landmark extraction based on projection technique.

To find landmarks associated with the eye, we converted eye ROI images to binary images using a thresholding algorithm. The result is illustrated in Figure 4c, which includes the binary region associated with the eye and eyebrow. To exclude the eyebrow region, the horizontal projection shown in Figure 4c, which is the sum of pixel values horizontally, was performed. The projection data can then be used to differentiate between the eye region and eyebrow region. To detect eye-related landmarks, vertical projection was applied. The outermost pixel could be identified as the associated eye landmark, shown as a yellow dot in Figure 4b.

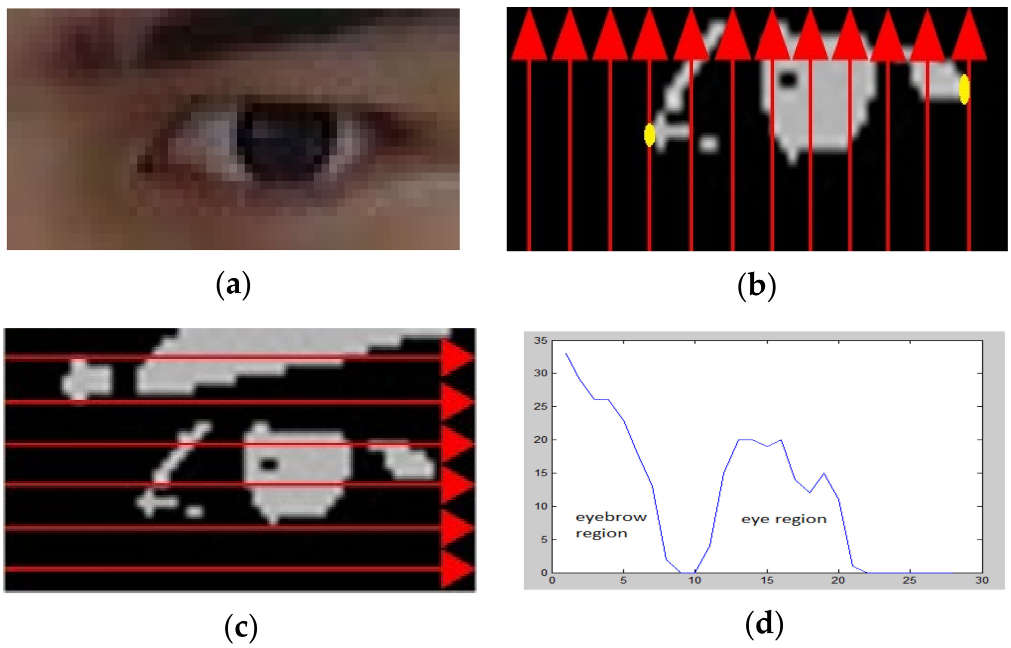


Figure 4. Projection technique to find landmarks of eye; (**a**) extracted eye ROI; (**b**) vertical projection; (**c**) horizontal projection; (**d**) projection data of (**c**).

To extract the nose-related landmarks, the nose ROI was converted to a binary image and vertical projection was applied. The outermost pixel could be identified, and the associated nose landmark could be detected, as denoted by the yellow dots in Figure 5. Figure 6 shows a similar algorithm applied to detect mouth-related landmarks.

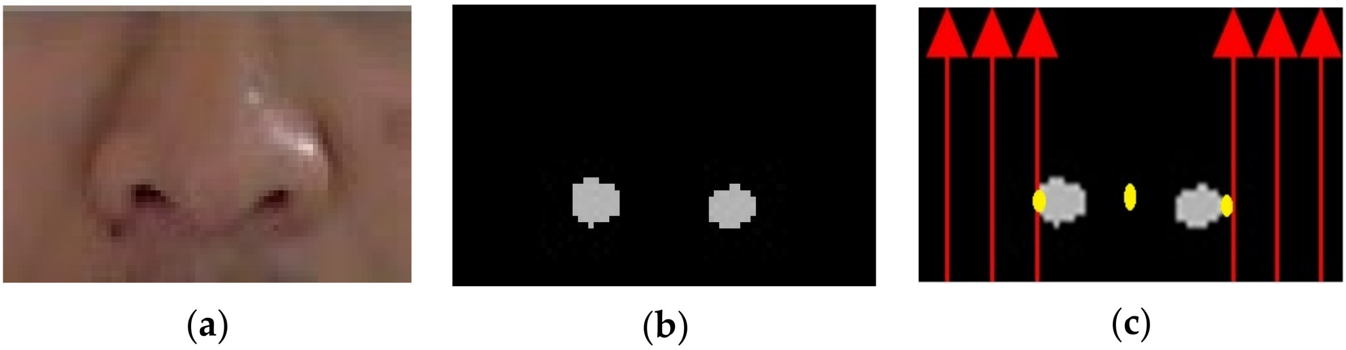


Figure 5. Projection technique to find landmarks of the nose: (**a**) extracted nose ROI; (**b**) binarized nose ROI; (**c**) vertical projection.

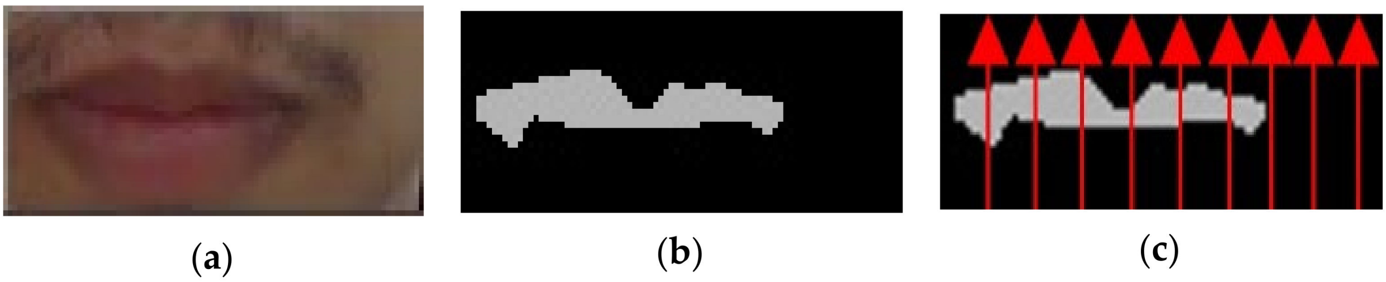


Figure 6. Projection technique to find landmarks of the mouth. (**a**) extracted mouth ROI; (**b**) binarized mouth ROI; (**c**) vertical projection.

(iii) Person authentication.

To authenticate a person based on extracted fiducial points, the facial border point is used to align the reference with the inquiry image. Facial border points P1, P2, P3, P4, P5, and P6 are shown in Figure 7. The definitions of facial border points are as follows:

P1 is defined by the coordinates

$$(X1 - \frac{X5 - X1}{2}, Y1) \tag{1}$$

P2 is defined by the coordinates

$$(X6 - \frac{X5 - X6}{2}, Y6) \tag{2}$$

P3 is defined by the coordinates

$$(\frac{X5 + X6}{2}, \frac{Y6 + Y7}{2} + 1.3 \times (\frac{Y6 + Y7}{2} - Y5)) \tag{3}$$

P4 is defined by the coordinates

$$(X7 + \frac{X7 - X5}{2}, Y7) \tag{4}$$

P5 is defined by the coordinates

$$(X4 + (\frac{X4 - X5}{2}), Y4) \tag{5}$$

P6 is defined by the coordinates

$$(\frac{X2 + X3}{2}, \frac{Y2 + Y3}{2.5}) \tag{6}$$

where

$X1$, $Y1$ are the coordinates of the left eye outer landmark point (LE1),
$X2$, $Y2$ are the coordinates of the left eye inner landmark point (LE2),
$X3$, $Y3$ are the coordinates of the right eye outer landmark point (RE1),
$X4$, $Y4$ are the coordinates of the right eye inner landmark point (RE2),
$X5$, $Y5$ are the coordinates of nose landmark point (N),
$X6$, $Y6$ are the coordinates of mouth right landmark point (M1),
$X7$, $Y7$ are the coordinates of mouth left landmark point (M2).

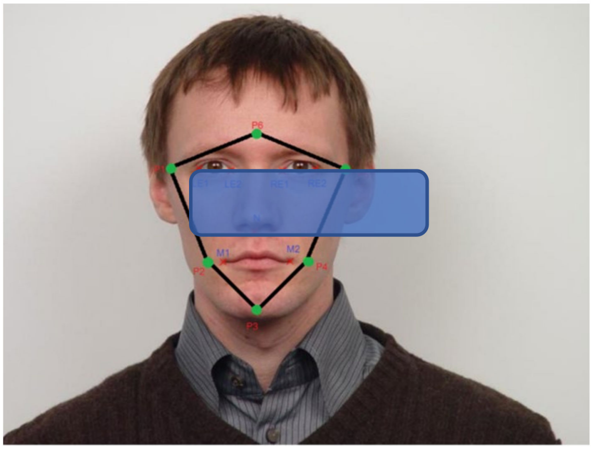
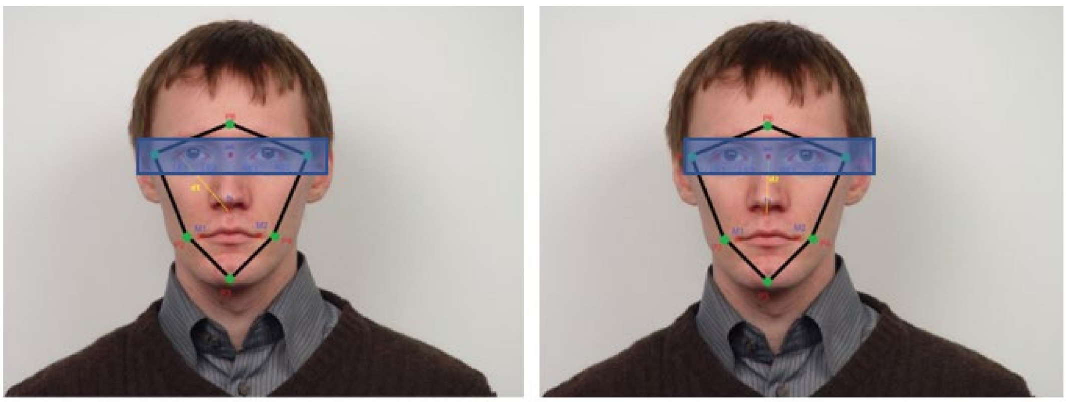


Figure 7. Facial border points defined by facial landmarks [25].

Furthermore, seven vectors were formed as feature vectors. The feature vectors are defined in Figure 8a–h.

A feature vector for the seven distance features can then be formed and used as a quantitative measure to authenticate the patients.



(**a**) (**b**)

Figure 8. *Cont.*

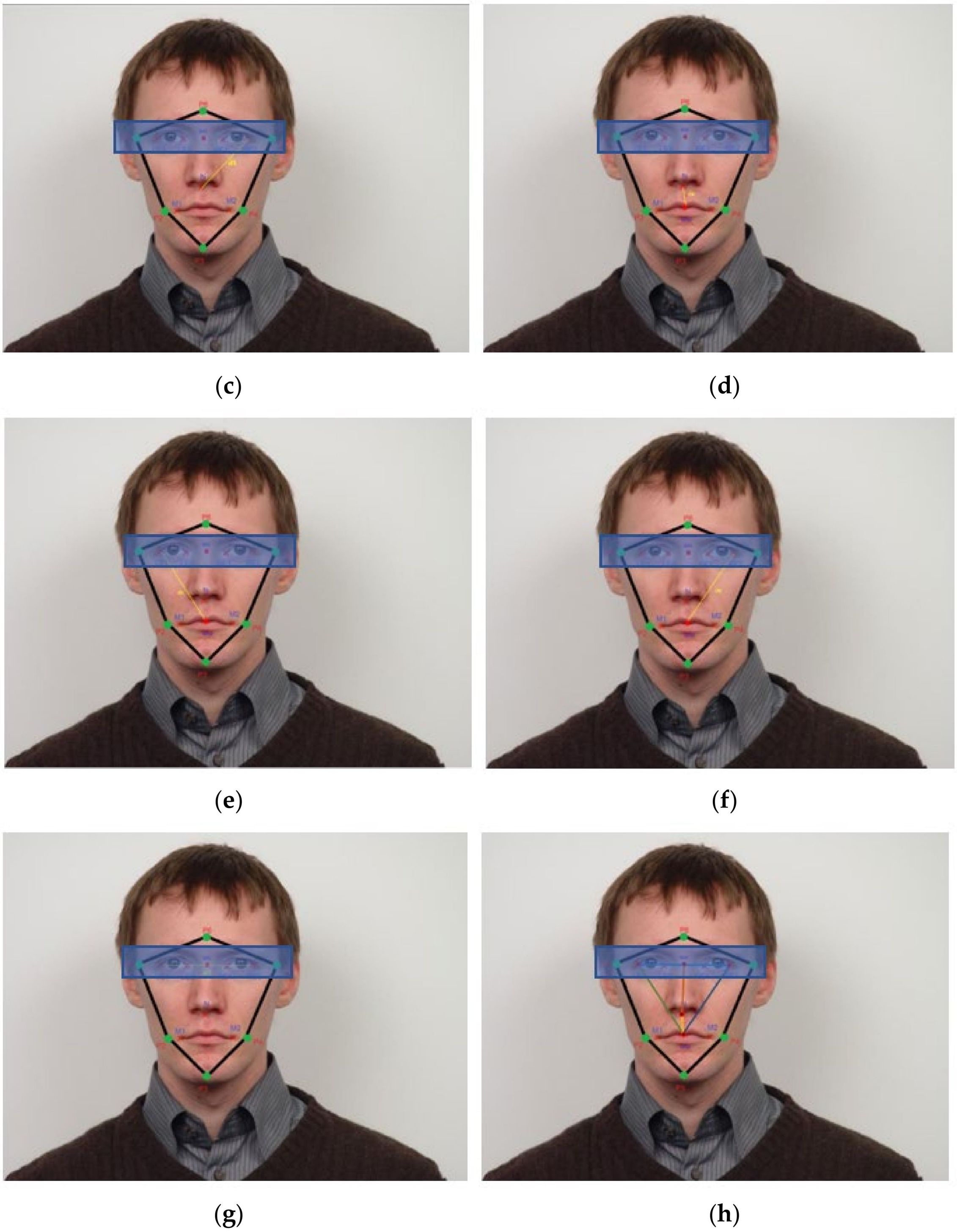


Figure 8. Distance of facial landmarks: (**a**) d1 is the distance from the outer corner of the right eye to the center of the mouth landmarks, (**b**) d2 is the distance from middle point between the center of both eyes to the nose landmark; (**c**) d3 is the distance from the outer corner of the left eye to center of the mouth landmark; (**d**) d4 is the distance from the nose landmark to center of the mouth landmark; (**e**) d5 is the distance from the outer corner of the right eye to the center of the mouth landmark; (**f**) d6 is the distance from outer right eye to the center of the mouth landmark, (**g**) d7 is the distance from outer right eye to outer left eye landmark; (**h**) all distance features.

(iv) Image registration using facial landmarks and affine transformation.

Image registration is used for identification of a person. To align the query face image against the reference image in the database, facial border points were extracted. The facial border points on the query face and the reference face were then used to estimate the affine transformation matrix based on the corresponding key points using the following equation:

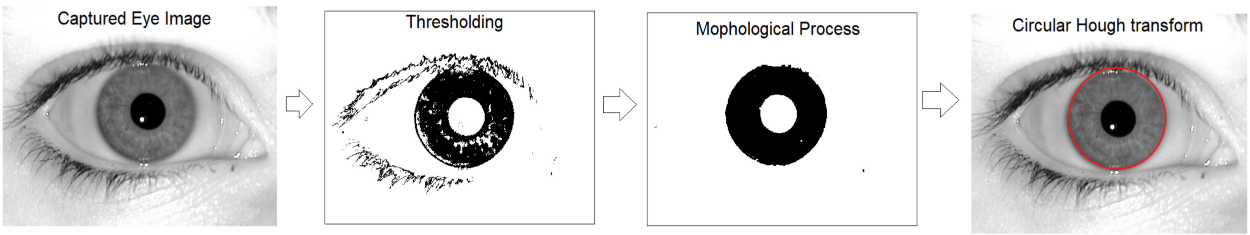
$$Z = \left(X^T X\right)^{-1}\left(X^T Y\right) \tag{7}$$

where Z is the affine transformation matrix, and X and Y are the corresponding key points of reference and inquiry facial image, respectively. Once transformation Z was determined, the inquiry image was registered with the reference image. Combined with the distance feature vector, a distance map [26] was computed and used as a quantitative measure to identify the person.

2.2. Mobile Assistive System

The disadvantage of the stationary assistive system using the Gazepoint GP3 eye tracker is the requirement of calibration. Performance is sensitive to head motion. The head cannot be excessively moved, otherwise the user must re-calibrate the system. In a mobile assistive system, the head position is subjected to movement due to the motion of the wheelchair. We proposed to use an eye glass installed with an infrared USB camera as eye tracking in the mobile assistive system, as illustrated in Figure 9a. Real-time images from the USB camera were processed on Raspberry Pi using OpenCV to obtain the position of the eyeball and define eye blink. The eye movement was also employed as the cursor control on the Raspberry Pi screen eye blink and used for entering the command to control several applications.

(**a**)



(**b**)

Figure 9. (**a**) Mobile assistive system eye tracker; (**b**) gaze estimation using the image processing module.

2.2.1. Gaze Estimation Using Image Processing Module

To estimate gaze on the mobile assistive system, we opted to use the image processing module based on the C++ OpenCV library [27]. As the eyeball is in a circular shape, we proposed to use circular Hough transform (CHT) to detect eyeball position. The circular Hough transform (CHT) is an algorithm to detect circles. In the algorithm, edge detection is first applied by using the Hough gradient method. At each pixel location on the edge, a circle with a determined radius is created. The existing circle with the radius equal to the to-be-detected circle will have the most pixel accumulation from this circle creation. The point with the highest pixel accumulation is denoted as the detected location of the interested circle. To achieve the best performance for CHT, preprocessing is required, as shown in Figure 9b. The captured image from the USB camera is converted to a binary image using the thresholding technique. Morphological processing, including opening and closing, is applied to the binary image to remove the irrelevant pixels, and only the pixels related to the eyeball are kept as a result. CHT is then applied to the resulting image from morphological processing to detect the eyeball and its location. The location of the eyeball is linked with the cursor position on the Raspberry Pi screen to control various functions of the mobile assistive system. The image processing module is also applied to simulate the keyboard enter key using eye blink detection. To detect the eye blink, the number of dark pixels in the pupil area is measured. The change from high to low of the dark pixel number (eye-blink pulse) is designated for the eye-blink detection, i.e., the enter key. To ensure the intentional eye blinking, a few consecutive eye-blink pulses are required to be counted as the enter key. Combined with the eye blink detection, the system is featured with toggle mode, where the previous command and parameters are stored. When the subject wants to change a command, he/she can stare at the specific location for some period of time and blink the eyes. The system then updates the command and parameters. The toggle mode provides more comfortable operation and less eye strain for the subject.

2.2.2. Eye Position Controlling Wheelchair Coding

The eyeball position is used to control the mouse cursor position and finally control the powered wheelchair. The algorithm for eyeball position and control of the wheelchair is as follows.

(I) Determine the average position of the eyeball. The average position, denoted as AVGX and AVGY, is the average of position of the eyeball in a relaxed position, i.e., eyeball looking forward.

(II) Detect the current position from the Hough circle detection. Compute the deviation of the current position from the average point, denoted as the deviation as x and y.

(III) Classify the motion direction shown on Figure 10 based on the following criterion:

Turning left if -AVGX-60 < x < AVGX-30, AGVY-10 <y < AGVY+10
Turning right if -AVGX+30 < x < AVGX+60, AGVY-10 <y < AGVY+10
Forward if -AVGX-10 < x < AVGX+10, AGVY-50 <y < AGVY-30
Backward if -AVGX-10 < x < AVGX+10, AGVY+30 <y < AGVY+50

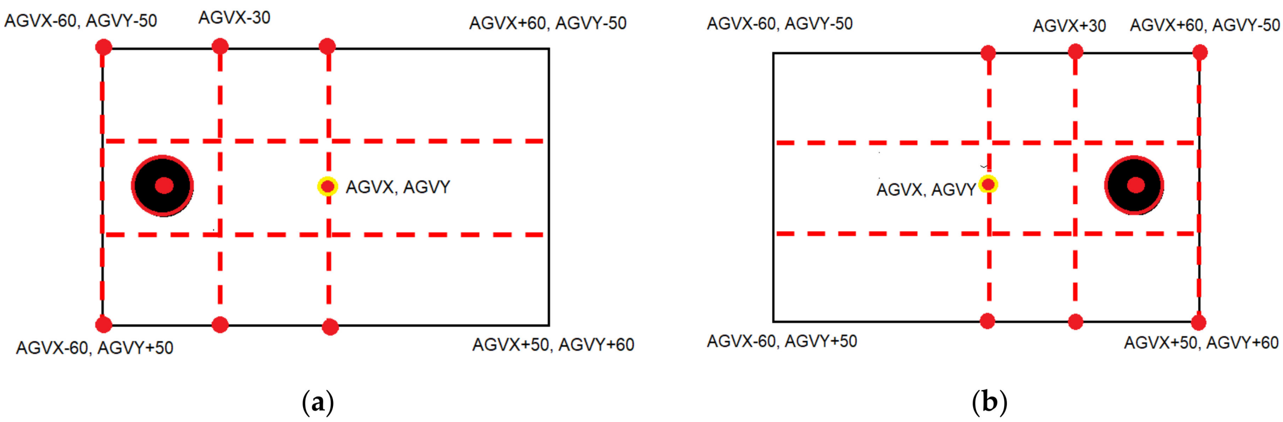
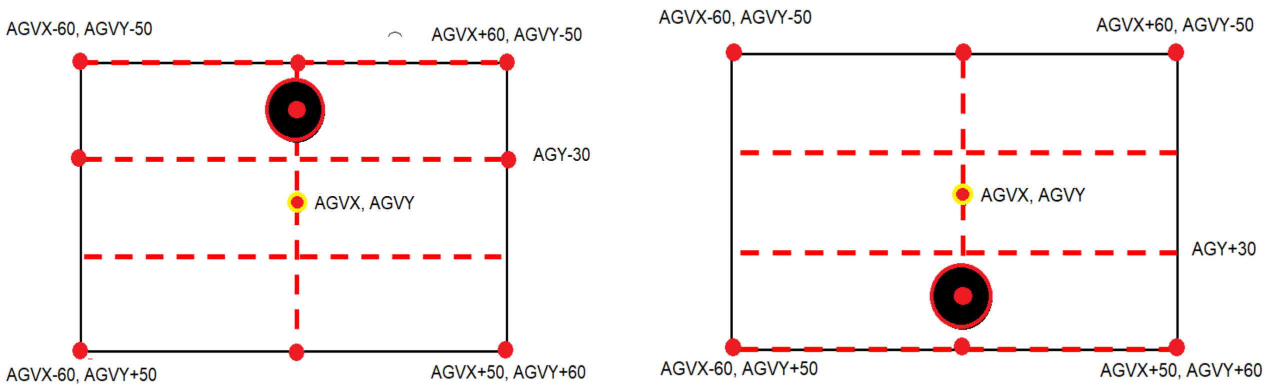


Figure 10. *Cont.*

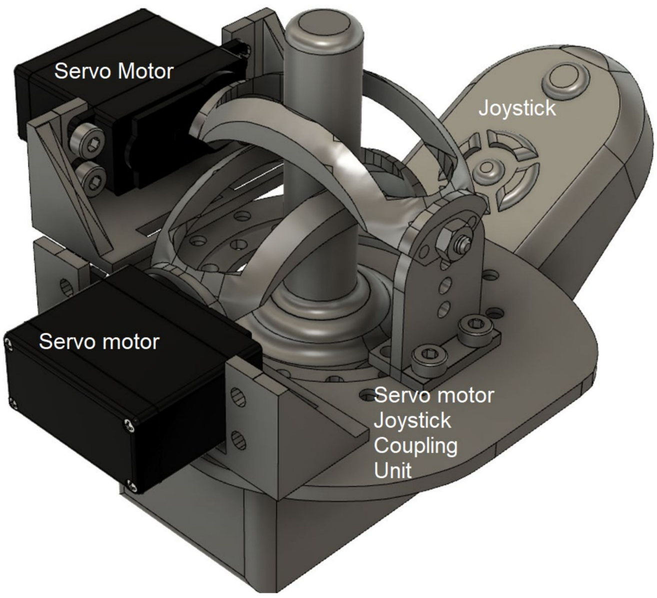


(**c**) (**d**)

Figure 10. Eyeball direction encoding: (**a**) turn left, (**b**) turn right, (**c**) forward, and (**d**) backward.

2.2.3. Joystick Servo Motor Coupling Unit

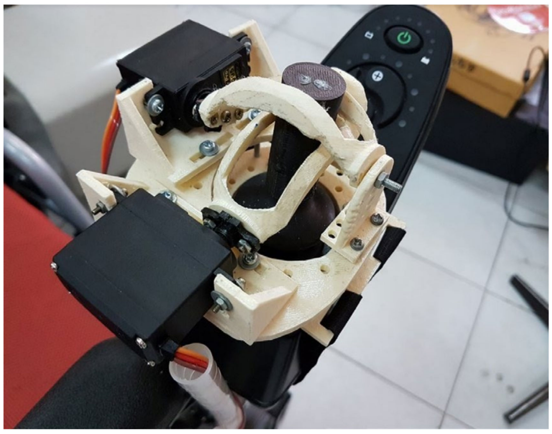
Eye position coding, including left, right, forward, backward and stop codes, is used to control the powered wheelchair. There exist two alternatives to link eye position code with the powered wheelchair. The first alternative is to redesign the wheelchair motor drive and then interface Arduino with the wheelchair motor drive directly. The second alternative is to design a joystick servo motor coupling unit where two servo motors are mounted on the coupling unit, mimicking the omni-directional control of the wheelchair with a joystick. We opted to use the second option due to the following three reasons. First, built-in optimal-design wheelchair motor drives are already being tested to meet medical device standards. Second, the wheelchair joystick control provides a natural and familiar control that is not overly sensitive. Third, this method is both low-cost and convenient. Figure 11a shows the design of the joystick servo motor coupling unit, consisting of two servo motors controlling the joystick in two directions. Figure 11b–e shows the joystick servo motor coupling unit operating in stop, forward, right, and left position codes.



(**a**)

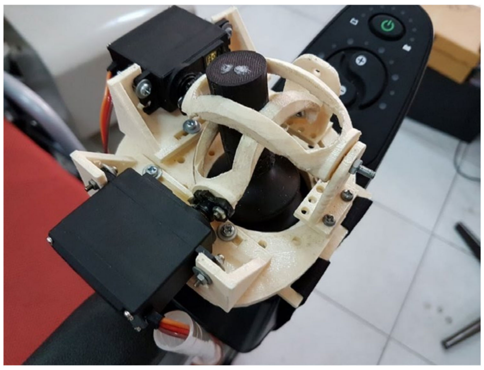
Figure 11. *Cont.*

(**b**)



(**c**)

(**d**)

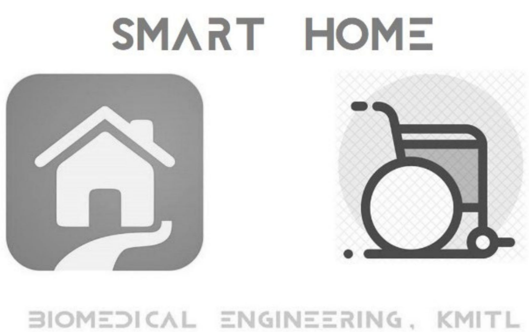


(**e**)

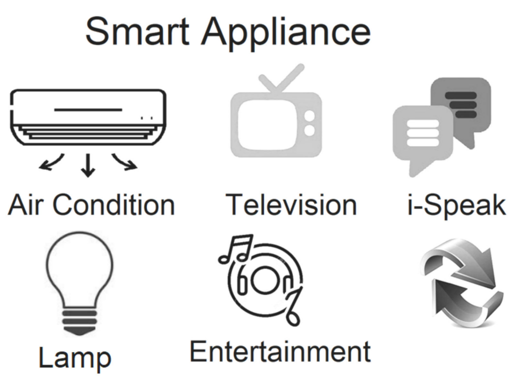
Figure 11. Joystick servo motor coupling unit: (**a**) design, (**b**) stop, (**c**) forward, (**d**) turning right, and (**e**) turning left operation.

2.3. Graphic User Interface

Graphic user interface (GUI) is used to link the eye tracker and the appliance control. There are six GUI pages for the stationary assistive system and seven for the mobile assistive system. The GUI pages for the stationary assistive system include the home page, smart appliance page, eye-controlled television page, eye-controlled air condition page, i-speak page, and entertainment page. The GUI pages for the mobile assistive system are similar to the GUI pages for the stationary assistive system, with the additional eye-controlled wheelchair page. The seven GUIs of the mobile assistive system are shown in Figure 12.



(**a**)



(**b**)

Figure 12. *Cont.*

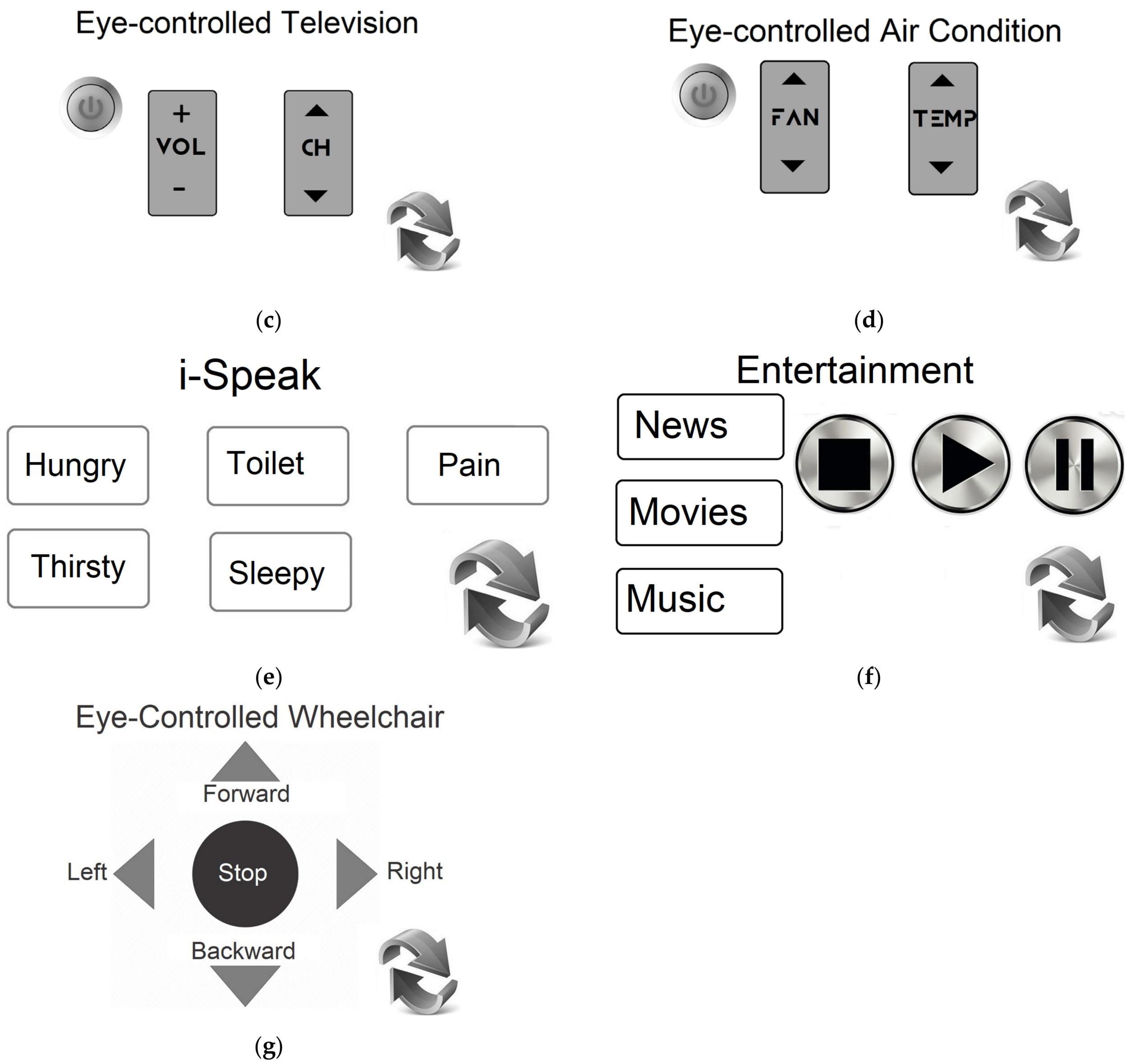


Figure 12. Graphic user interface: (**a**) home page; (**b**) smart appliance page; (**c**) eye-controlled television page;(**d**) eye-controlled air condition page; (**e**) i-speak page; (**f**) and entertainment page; (**g**) eye-controlled wheelchair page.

The home page is the starting page of the assistive system. There are two icons for the mobile assistive system, which are a smart appliance icon and a wheelchair icon. The user can enter the selected mode by gazing at the icon for a specific time, for example, a few seconds. When selecting the smart appliance mode, the system will direct to the smart appliance page (Figure 12b). When selecting the wheelchair mode, the system will direct the user to the eye-controlled wheelchair page, as shown in Figure 12g, which contains four icons associated with moving the wheelchair in the forward direction, backward direction, left direction, right direction, and stopping.

The smart appliance page is the main control page for appliance control and communication. There are six icons on this page, including an icon for the eye-controlled television page, eye-controlled air conditioning page, i-speak page, entertainment page, lamp control, and the return icon. The lamp icon is used to control turning on and off of the lamp. It is operated in a toggle fashion. Once turned on, when the individual stares at the lamp icon, it will turn the lamp off, and vice versa. The eye-controlled television page and eye-controlled air conditioning page are shown in Figure 12c,d, respectively. For the eye-controlled television page, the user can control the channel change, volume change, and the on/off power by gazing at the associated icon. Similarly, for the eye-controlled air conditioning page, the user can control fan speed change, temperature change, and on/off power by gazing at the associated icon. The interface between the selected icon on the eye-controlled television page or the eye-controlled air conditioning page uses an IR transmitter to send the control operation code to the IR receiver of the television or air conditioning unit [28]. The i-speak page applies the text-to-speech library [29] to convert most-used words to sound and sends the sounds to the speaker to let the caretaker know the basic needs of the patient. In case that the caretaker is not nearby, i-speak can also send a notification to the smartphone using the Blynk application [30]. To use the Blynk application, the ESP31 microcontroller of the WIFI Module is required to work with Arduino. The i-speak page is shown in Figure 12e, with the five most-used words. The entertainment page links the recorded movie clip or sound clip to the notebook. There are three icons on the entertainment page, which are the movie, music, and news icon. When any of the icons is selected, the system will show a list of recorded items associated with the selected icon. Once an item is selected, it will run the video clip on the media player. Note that all graphic user interfaces contain a common return icon, which is used to return to the previous page.

3. Experiments and Results

We conducted three experiments. First, we demonstrated the high accuracy of the person identification used in our hands-free person authentication. In the second experiment, we compared the robustness of gaze estimation between the eye tracker used in the mobile assistive system and the stationary system. The last experiment concerned the operational test for eye-controlled wheelchairs and eye-controlled appliances.

3.1. Person Identification Test

We tested the accuracy of the person identification used in our hands-free person authentication using face images from the database [25]. We performed two experiments, including intra-subject and inter-subject experiments. The intra-subject experiment was used to verify the robustness of the purpose technique, with the facial images from nine different geometric transformations. The inter-subject experiment applied our technique to face recognition. The results of the inter-subject and intra-subject experiment are shown in Tables 1 and 2, respectively. The results of the inter-subject authentication show that the objective function is minimum for the same subject and hence provides 100% accuracy. For the intra-subject authentication test, the maximum objective function still ensures the correct authentication, as shown in Table 1.

Table 1. Inter-subject authentication test.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
R1	**68.8**	169.1	137.8	183.7	117.8	118.2	146.9	304.8	143.2	257.2	200.6	216.8
R2	234.71	**86.9**	258.6	320.4	185.4	240.8	294.5	470.5	162.57	339.7	319.2	374.4
R3	213.9	261.3	**37.67**	247.7	209.3	195.6	173.4	294.3	220.7	291.5	243.5	263.4
R4	150	201.9	142.49	**55.28**	171.76	126.2	115.8	185	150.6	174.7	155	142
R5	292.7	266.4	258.7	417.2	**67.4**	268.85	309.2	467.8	199.5	386.5	271.2	465.9
R6	203.4	228.7	186.1	263.6	144.3	**80**	183.447	298.05	152.3	270.87	252.2	312.9
R7	148.6	209.5	122.9	157.3	164.9	152.7	**58.9**	152.5	151.7	150.9	136.7	155.6
R8	239	422.9	183	185.1	250.7	234.8	139.5	**40.1**	260.9	159	151.3	255.5
R9	216.7	209.7	188.7	288.5	146.6	174.3	255	327.7	**89.7**	253.9	217.9	352.7
R10	204.4	304.9	174.2	250.8	203.9	204.9	134	173.3	171.5	**46.5**	165.4	237.6

Table 1. *Cont.*

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
R11	498.9	516	384.1	506.5	318.7	464.9	385.2	526.2	422.3	465.3	**94.4**	451.2
R12	173.3	254.2	151.3	142	208.3	194.9	128.5	182.7	207.9	182.4	150.3	**92.4**

Rx is reference face image, Sx is iniquity face image.

Table 2. Subject 1 intra-subject authentication test.

	S1 (2)	S1 (3)	S1 (4)	S1 (5)	S1 (6)	S1 (7)	S1 (8)	S1 (9)
R1 (1)	68.8	93.3	78.8	80.9	57.2	81.6	76.6	85.4

STD = 10.8881. Rx is reference face image, Sx is inquiry face image.

3.2. Robustness of Gaze Estimation

To test the robustness of gaze estimation, we designed a phantom consisting of five red dots at various locations, as shown in Figure 13. The subject was asked to stare at the red dots for 10 s. The same position was used ten times. The subject was asked to turn the eyes away for each position detection. The robustness of gaze estimation was measured by deviation of the position from the ten-time data collection. A system with good robustness will provide less deviation when the subject is staring at the same position ten times. The deviation was measured by computing average and standard deviation from ten data collections. The average and standard deviation was computed and tabulated. The results are shown in Table 3. The results demonstrate the compatible tracking performance when compared with the commercial one.

Figure 13. Five-point pattern used in the robustness test.

Table 3. Robustness results for gaze estimation.

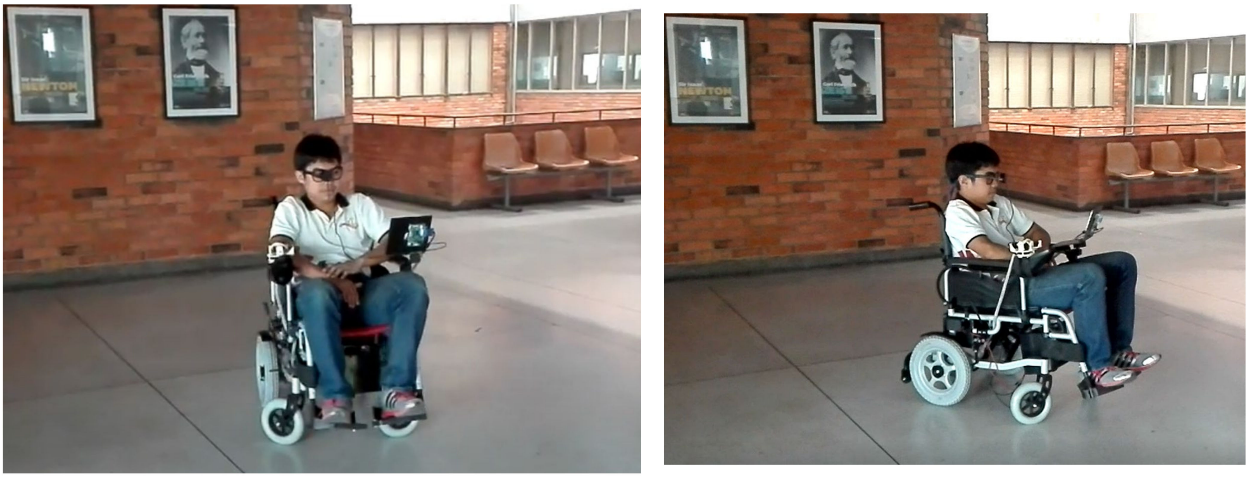
Zone		Eye Tracking Based on Circle Hough Transform (CHT)		Eye Tracking Using Commercial Eye Tracker Module	
		x-Axis (cm)	y-Axis (cm)	x-Axis (cm)	y-Axis (cm)
Central Middle	Average	20.587	16.357	19.625	17.698
	STD	17.589	16.215	12.990	12.742
Upper Right	Average	16.547	15.479	15.258	16.528
	STD	18.265	19.527	22.369	25.288
Upper Left	Average	16.528	19.478	18.485	18.598
	STD	21.560	17.235	20.597	21.633
Lower Right	Average	17.587	18.568	16.436	16.147
	STD	16.415	22.987	22.156	21.879
Lower Left	Average	18.568	17.568	15.879	17.418
	STD	24.526	22.597	23.256	21.579

3.3. Operational Test on Mobile Assistive System and Stationary Assistive System

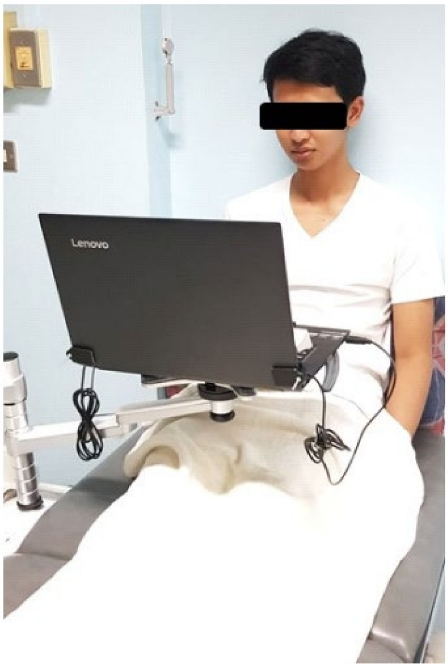
We tested the mobile assistive system and the stationary assistive system on two subjects. Subject A was a 24-year-old male with a weight of about 60 kg. Subject B was a 22-year-old male with a weight of 58 kg. Prior to the mobile assistive test, the system setup required as the following:

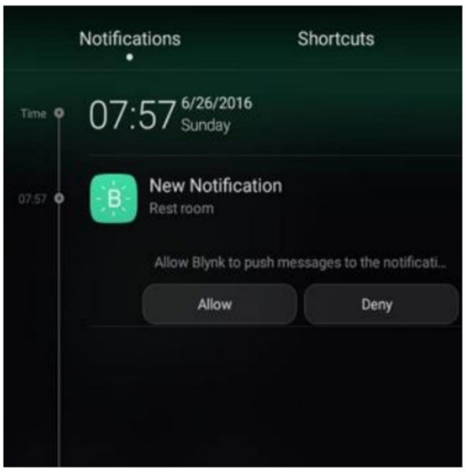
(i) Charge wheelchair until it is fully charged.
(ii) Manually set speed of wheelchair to medium speed (5 km/h).
(iii) Let the subject be seated in a comfortable position.
(iv) Put on an eye tracker (eyeglasses).
(v) Let the subject stare forward and turn on acquisition software on the Raspberry Pi to compute the reference AVGX and AVGY for a period of time.
(vi) The subject is now ready to use the mobile assistive system.

Figure 14a shows subject A controlling the wheelchair using eye tracking.



(**a**)





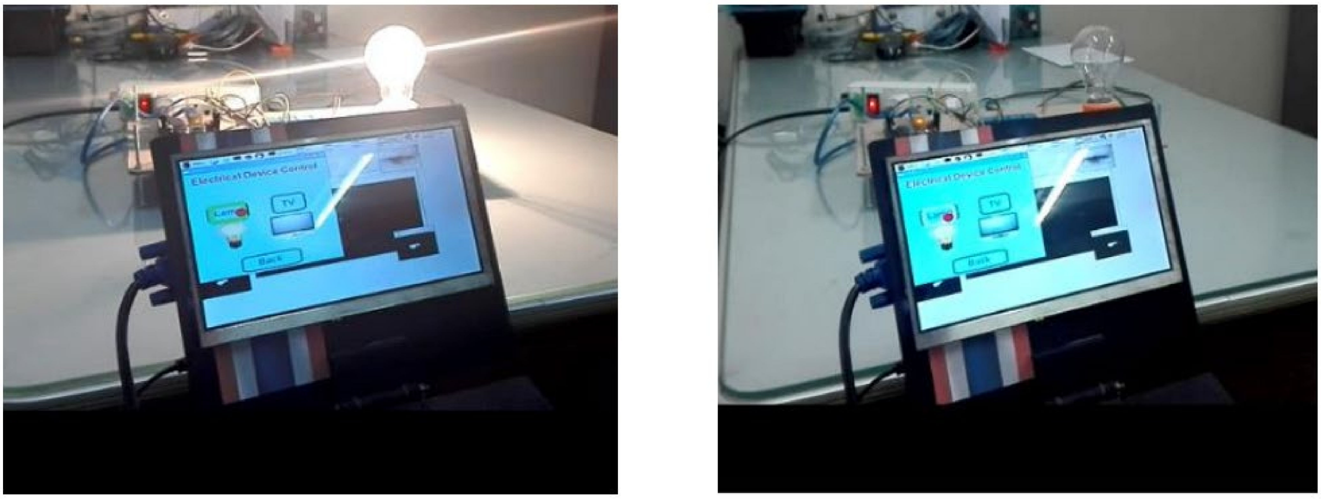
(**b**) (**c**)

Figure 14. Operational test for (**a**) mobile assistive system (eye-controlled wheelchair); (**b**) stationary assistive system; (**c**) nurse calling notification.

To test the stationary assistive system, put the subject in a stable pose in front of the stationary system. The system setup is proceeded as follows:

(i) Turn on commercial calibration software for Gazepoint eye tracker. The software will display five-point patterns for the subject to stare at.
(ii) Turn on stationary assistive software. The program will proceed to the authentication process. If facial landmarks of the subject have been collected, the program will verify and approve access to the system.
(iii) The program will display the home page of the stationary assistive system. The subject is now ready to operate the system with eye tracking.

Figure 14b shows subject B operating the stationary assistive system. Subject B is asked to use all features for smart appliances, including eye-controlled television, entertainment, i-speak, and nurse calling. The operation is successful as designed. The results of i-speak are shown in Figure 14b, where subject B requests the restroom. The notification is sent to the nurse's mobile phone. Figure 15 demonstrates the mobile assistive system used to turn the lamp on and off. The lamp icon appears on the main page, as it is frequently used. The lamp control is operated in toggle fashion. To turn on the lamp, the subject stares at the lamp icon for 3 s and blinks the eyes. The lamp will turn on even if the subject moves the eye location away.



(**a**) (**b**)

Figure 15. Mobile assistive system controlling appliance. (**a**) Turning on lamp; (**b**) turning off lamp.

4. Discussion

An assistive system based on eye tracking that can be used for disabled persons is proposed in this study. The objective of this research is to design a system that can control appliances and communicate with caretakers with the use of eye movement. Despite the promising results, there are a number of issues that need to be discussed. Hands-free authentication using facial landmarks is used when the system has not been used for some time, i.e., no eyeball is detected. The screen will be locked, and this is to provide secure access for the registered patients. To register, facial landmarks of patients must be acquired and saved in the system. When the system is in an idle state, by moving the eyeball, the system will be activated, and the hands-free authentication using facial landmarks will operate to allow registered patients to enter the system.

(i) For the inter-subject authentication test in Table 1, the objective function is defined as the average error of the feature vector and the distance map between the inquiry image and the reference image. The objective function along the diagonal cell will be less than the off-diagonal cell, as it compares the feature vector and distance map of the same person. The minimum and maximum objective function along the diagonal cell is 40.1 and 94.4, respectively. The minimum and maximum objective function of the off-diagonal cell is 115.8 and 516, respectively. The objective function of 100 can be used as a threshold to identify the person.

(ii) The robustness result of gaze estimation as shown in Table 3 concludes that the designed eye tracker using eyeglasses installed with infrared camera performs comparable to the commercial Gazepoint GP3 eye tracker. The disadvantage of the Gazepoint GP3 eye tracker is the requirement of calibration, which must be done every time subjects move or change location. The problem worsens for patients that can still move the upper part of their body, such as the elderly and recovery patients. For the eye tracker using eyeglasses installed with an infrared camera, the problem is less severe, as the eyeglasses are attached to the head, and the relative motion of the eyeglasses with respect to the head is insignificant. It is recommended, however, that the infrared camera be lightweight and compact in shape and size so that the eye tracker will be comfortable for use by the patient.

(iii) The prototype model of the assistive system based on eye tracking was successfully tested with the normal subject. Further investigation in the future will be the test for real patients, which requires electric safety and standard tests. This will be left for future work.

5. Conclusions

This research concerns a design and development of an assistive system based on smart eye tracking that can be used for disabled person. The concept of the research is to apply eye movement to control appliances and wheelchairs and communicate with caretakers. The assistive system is divided into two subsystems: (i) the stationary assistive system and (ii) the mobile assistive system. The mobile assistive system is used when the patient is in a wheelchair, whereas the stationary the assistive system is used when the patient lies on a bed. Both systems provide a graphic user interface, where a cursor position is controlled by gazing. To simulate the enter key, intentional eye blinking and intentional staring are used for the mobile and stationary systems, respectively. Hands-free authentication based on facial landmarks is included in the stationary assistive system to provide secure access. The mobile assistive system includes an eye-tracking wheelchair controller. Three experiments were conducted, including an accuracy test for person identification used for hands-free person authentication, the robustness of gaze estimation between the eye tracker used in the mobile assistive system and stationary system, and an operational test for eye-controlled wheelchairs and eye-controlled appliances. The operational test demonstrates a successful and satisfactory result for the users.

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References

1. World Health Organization. Report of Disability. Available online: https://www.who.int/disabilities/world_report/2011/report.pdf (accessed on 12 January 2022).
2. Kevin, C.L. Four Types of Disabilities: Their Impact on Online Learning. *TechTrends* **2008**, *52*, 51–55. [CrossRef]
3. Rivera, G.P.; Eichmann, C.; Scherzinger, S.; Puck, L.; Roennau, A.; Dillmann, R. Flexible, Personal Service Robot for ALS Patients. In Proceedings of the 2019 IEEE International Conference on Robotics and Biomimetics (ROBIO), Dali, China, 6–8 December 2019; pp. 1595–1600. [CrossRef]
4. Matthew, W. AlterEgo as a Speech Interface for ALS Patients. Master's Thesis, Electrical Engineering and Computer Science, Cambridge, MA, USA, May 2019.

5. Mccane, L.; Sellers, E.W.; Dennis, M.; Carmack, C.S.; Wolpaw, J.; Vaughan, T.M. Brain-computer interface (BCI) evaluation in people with amyotrophic lateral sclerosis. *Amyotroph. Lateral Scler. Front. Degener.* **2014**, *15*, 207–215. [CrossRef] [PubMed]
6. Chennamma, H.R.; Yaun, X. A survey on eye-gaze tracking technique. *Indian J. Comput. Sci. Eng.* **2013**, *4*, 388–393.
7. Picot, A.; Charbonnier, S.; Caplier, A. Drowsiness Detection Based on Visual Signs: Blinking Analysis Based on High Frame Rate Video. In Proceedings of the 2010 IEEE Instrumentation and Measurement Technology Conference, Austin, TX, USA, 3–6 May 2010.
8. Xu, G.; Zhang, Z.; Ma, Y. Improving the Performance of Iris Recognition System Using Eyelids and Eyelashes Detection and Iris Image Enhancement. In Proceedings of the 2006 5th IEEE International Conference on Cognitive Informatics (ICCI), Beijing, China, 17–19 July 2006; pp. 871–876.
9. Riquier, F.; Herbelin, B.; Grillon, H.; Thalmann, D. Use of Virtual Reality as Therapeutic Tool for Behavioral Exposure in the Ambit of Social Anxiety Disorder Treatment. In Proceedings of the International Conference on Disability, Virtual Reality & Associated Technologies, Esbjerg, Denmark, 18–20 September 2006; pp. 105–112.
10. Goldberg, J.; Stimson, M.; Lewnstein, M.; Scott, N.; Wichansky, A.M. Eye Tracking in Web Search Tasks: Design Implications. In Proceedings of the ETRA02: Eye Tracking Research & Applications (ETRA) Symposium, New Orleans, LA, USA, 25–27 March 2022.
11. Jacob, R.J. What You Look at is What You Get: Eye Movement-Based Interaction Techniques. In Human Factors in Computing Systems. In Proceedings of the CHI 90: Conference on Human Factors in Computing, Seattle, WA, USA, 1–5 April 1990; ACM Press: New York, NY, USA, 1990; pp. 11–18.
12. Bissoli, A.; Lavino-Junior, D.; Sime, M.; Encarnação, L.; Bastos-Filho, T. A Human–Machine Interface Based on Eye Tracking for Controlling and Monitoring a Smart Home Using the Internet of Things. *Sensors* **2019**, *19*, 859. [CrossRef] [PubMed]
13. Klaib, A.F.; Alsrehin, N.O.; Melhem, W.Y.; Bashtawi, H.O. IoT Smart Home Using Eye Tracking and Voice Interfaces for Elderly and Special Needs People. *J. Commun.* **2019**, *14*, 614–621. [CrossRef]
14. Pai, S.; Ayare, S.; Kapadia, R. Eye Controlled Wheelchair. *Int. J. Sci. Eng. Res.* **2012**, *3*, 1–5.
15. Eid, M.A.; Giakoumidis, N.; El Saddik, A. A Novel Eye-Gaze-Controlled Wheelchair System for Navigating Unknown Environments: Case Study with a Person With ALS. *IEEE Access* **2016**, *4*, 558–573. [CrossRef]
16. Verma, S.; Pillai, P.; Hu, Y.F. An Eye-Tracking Based Wireless Control System. In Proceedings of the 26th International Conference on CAD/CAM, Robotics and Factories of the Future, Kuala Lumpur, Malaysia, 26–28 July 2011.
17. Karibasavaraju, T.S.; Niranjan, S.H.; Sushma, K.S.; Veena, E.; Pavan kumar, P.J.; Vinay, K.C. Intelligent Eye Ball Controlled Wheelchair for Paralyzed Patients using Arduino. *Int. J. Eng. Sci. Comput.* **2020**, *10*, 26174–26176.
18. Chee, F.P.; Duinong, M.; Chang, H.W.J.; Awang, A.; Francis, A.S.; Dayou, J. Eye Tracking Electronic Wheelchair for physically challenged person. *J. Eng. Appl. Sci.* **2017**, *12*, 4078–4083.
19. Dahmani, M.; Chowdhury, M.E.H.; Khandakar, A.; Rahman, T.; Al-Jayyousi, K.; Hefny, A.; Kiranyaz, S. An Intelligent and Low-Cost Eye-Tracking System for Motorized Wheelchair Control. *Sensors* **2020**, *20*, 3936. [CrossRef]
20. Amer, S.G.; Ramadan, R.A.; Kamh, S.A.; Elshahed, M.A. Wheelchair Control System based Eye Gaze. *Int. J. Adv. Comput. Sci. Appl.* **2021**, *12*, 889–894. [CrossRef]
21. Luo, W.; Cao, J.; Ishikawa, K.; Ju, D. A Human-Computer Control System Based on Intelligent Recognition of Eye Movements and Its Application in Wheelchair Driving. *Multimodal Technol. Interact.* **2021**, *5*, 50. [CrossRef]
22. Intel AI Builder. Available online: https://builders.intel.com/ai/social-hub/video/hoobox-the-wheelie-7 (accessed on 19 January 2022).
23. GP3 Eyetracker. Available online: https://www.gazept.com/product/gazepoint-gp3-eye-tracker/ (accessed on 15 December 2021).
24. Viola, P.; Jones, M.J. Robust Real-Time Face Detection. *Int. J. Comput. Vis.* **2004**, *57*, 137–154. [CrossRef]
25. Database of Face Images. Available online: https://www2.imm.dtu.dk/pubdb/views/publication_details.php?id=394 (accessed on 15 December 2021).
26. Pintavirooj, C.; Cohen, F.S.; Iampa, W. Fingerprint Verification and Identification Based on Local Geometric Invariants Constructed from Minutiae Points and Augmented with Global Directional Filter Bank Features. *IEICE Trans. Inf. Syst.* **2014**, *97*, 1599–1613. [CrossRef]
27. OpenCV. Available online: https://opencv.org/ (accessed on 15 December 2021).
28. Project Hub. Available online: https://create.arduino.cc/projecthub/akarsh98/automatic-arduino-based-ir-remote-control-temperature-driven-99d1d7 (accessed on 15 December 2021).
29. CPlusPlus. Available online: http://www.cplusplus.com/forum/general/78128/ (accessed on 15 December 2021).
30. Blynk IoT Platform. Available online: https://blynk.io/ (accessed on 15 December 2021).