Development of EOG and EMG-Based Multimodal Assistive Systems

Biswajeet Champaty, D.N. Tibarewala, Biswajit Mohapatra and Kunal Pal

Abstract This study discusses a human-computer interface (HCI)- based novel approach for designing a computer-aided control and communication system using electrooculogram (EOG) and electromyogram (EMG) signals for people with severe hindrance to motor activities and communication. The EOG and EMG signals were attributed to eye movements and voluntary eye blinks, respectively. The acquired signals were processed and classified in a MATLAB-based graphical user interface (GUI) to detect different eye movements. A couple of Hall-effect sensors were conditioned to be used concurrently with multidirectional eye movements or voluntary eye blinks to generate multipurpose serial commands to control the movement of a robotic vehicle (representative assistive aid) and communications support systems. The user details were registered and the system operability was monitored in the same GUI. Due to multitasking and ease of use of the proposed device, the quality of life of the incapacitated individuals can be improved with greater independence.

Keywords Human-computer interface · Incapacitated patients · Electrooculogram · Electromyogram · Graphical user interface · Hall-effect sensor · MATLAB

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1 Introduction

1.1 Motivation

In recent years, there has been an enormous rise in the research on the development of assistive technologies for providing support to the individuals with severe disabilities. This has been made possible due to the advancements in the field of control and communication technologies, which has facilitated the improvement of the quality of the human-machine interface (HMI) or human-computer interface (HCI) devices [1]. This discipline of technology has a great potential to enable the severely disabled persons to operate computer and other assistive gadgets directly by biopotentials (e.g. electroencephalogram (EEG) [2–4], electrooculogram (EOG) [5, 6], electromyogram (EMG) [7, 8] etc.). These biopotentials are also used for wireless tele-monitoring [9, 10]. Individuals suffering from amyotrophic lateral sclerosis (ALS), brain or spinal cord injury, multiple sclerosis and muscular dystrophies have been reported to have severe inabilities to perform speech and/or motor activities [11, 12]. Therefore, they face difficulties in locomotion as well as conveying their intentions. This significantly reduces their ability to interact, which in turn, compromises the quality of life of such individuals. Due to this reason, these individuals are forced to rely on the peripheral aids like computer-aided assistive and augmentative communication systems for conveying their intentions to others and to perform other daily activities. In these individuals, it has been found that the functionality of the muscles responsible for ocular movement remains intact [13]. These muscles are responsible for the significant voluntary activity associated with the eye movement. The biopotential generated due to the movement of the eyes regarded as EOG. Hence, EOG has been used as the input signal for control and communication interactive assistive devices.

1.2 Literature Review

Several methods, based on EOG controlled man-machine interfaces (multimode controller communication assistive devices), have been reported [11–23]. EOG has been employed to control the prosthesis for footdrop correction [24]. Robotic prosthetic arms have also been guided by EOG signals [23, 25]. A lot of research has been carried out in the movement of wheelchairs, a major mobility aid for the motor disabled individuals [5, 15, 26–29]. Additionally, EOG has found tremendous applications in facilitating communications by controlling keyboards, mouse and joystick functions [6, 13, 18, 19, 30–32]. In the last decade, home automation using EOG has also found substantial attention [20, 31, 33–36]. Though different technologies are available for expressing the intentions of the severely disabled individuals using EOG based HCIs, many of them are quite expensive [37], unreliable, inaccurate [38] and are complex to operate [38]. Further, none of the studies has reported the concurrent use of the assistive devices for both control and communication purposes.

1.3 Contribution and Benefit Over Existing System

Taking inspiration from the above, in this paper, we propose a novel real-time EOG based computer assistive technology to develop a robust hardware-software system that combines the control activities with communication activities. The device can be effectively used by the severely disabled individuals having volitional eye movement and minimum finger movements. In this study, EOG signal was acquired from a dual channel (horizontal and vertical) bioamplifier and was band-limited (0.16–33.88 Hz). The band-limited signal was acquired in a computer, processed and finally classified using a MATLAB program. The classification of the EOG signals helped in detecting various eye movements. As a representative mobility aid, an electromechanical robotic vehicle was designed. The first-stage activation and the end-stage deactivation of the robotic vehicle were achieved using voluntary eye blink. The functioning (movements) of the robotic vehicle was controlled by up, down, left and right movements of the eye. To avoid any accidental initiation of the tasks, a switching system was introduced using a couple of HE sensors, attached to the index and middle fingers. The signals obtained from the eye movements, voluntary blink and triggering of the HE sensors were used in different combinations to control either the functioning of the robotic vehicle or initiating communication (making calls and sending emails). A GPRS shield, piggybacked on Arduino Mega ADK, was used to facilitate the control of the communication unit for making voice calls through serial communication. The control signals were generated with the help of a customized graphical user interface (GUI) designed in MATLAB. Conscious efforts were made to make the device robust, partially intricate and user-friendly to render a disabled individual to lead an independent lifestyle for social integration. The implementation of the multimodal control systems, i.e., controlling the assistive device (robotic vehicle) and alerting the attendant or the health caregivers through mobile and internet communication system is the key advantage of the proposed study over existing similar studies.

1.4 Organization of the Paper

The paper has been organized into five different thematic sections. Following the first introductory sections, the second section briefly presents the generation of electrooculogram signal. Section three describes the materials and methods. Section four discusses the results of the study. Finally, section five provides a closing discussion and conclusion. All the referred research works are cited in the text and are listed under the reference section.

2 Electrooculogram: A Brief Introduction

Human eye can be depicted as a fixed dipole that allows the generation of electric field. The cornea behaves as the positive pole, whereas the retina behaves as the negative pole. The relative electric potential in the retina is due to the higher metabolic rate rather than its excitable nature. This corneo-retinal potential, which gives rise to a fixed dipole, is in the range 0.4–1.0 mV [39]. This difference in potential, due to the rotation of the eye, can be acquired by surface electrodes placed around the eye at specific locations. This signal is known as electrooculogram (EOG). The EOG can be generated both in darkness and closing the eyes. The EOG signal can be employed by the researchers for developing real-time assistive devices. The EOG signals can also be recorded and analyzed by the optometrists to diagnose different ophthalmic disorders.

3 Materials and Methods

3.1 Materials

AD-620 (Analog Devices, India) [5], NI USB-6008 (National Instruments, USA) [40], Arduino ADK Mega (Arduino, Italy) [41], Arduino UNO (Arduino, Italy) [5], Arduino wireless proto shield (Arduino, Italy) [42], Xbee-S1 wireless transceiver module (Digi International, USA) [42], GPRS Shield V1.0 (Seeed Technology Limited, China) [41], AH-34 Hall effect sensor (Triax Corporation, Japan) [41], Ag/AgCl disposable electrodes (BPL, India) with connecting clips [24], freeware EAGLE PCB Design Software (CadSoft Inc., USA) and licensed MATLAB® R2014a (MathWorks, USA) were used in this study. A laptop, with processor specification Intel (R) Core (TM) i7-2600 CPU @ 3.40 GHz, was used in this study.

3.2 Informed Consent

15 volunteers from National Institute of Technology Rourkela, India, of either sex, were selected for this study. All the volunteers were in the age group of 22–30 years. Prior to experimental involvement, all the volunteers were verbally made aware of the study and the experimental procedure. The volunteers had to sign an informed consent form to participate in the experiment. None of the volunteers was suffering from any health issues or had any adversity to the experimental conditions. A prior ethical clearance was obtained from the Institute ethical clearance committee vide order No. (NITR/IEC/FORM/2/25/4/11/002).

3.3 Development of EOG Acquisition System

The EOG biopotential amplifier reported in [5] was modified for the present study. The improvement in the circuit was achieved through modifications in the power supply section. The circuit was developed using the commercially available instrumentation amplifier IC AD-620. A resistor of 560Ω (gain resistor) was used to achieve a 1st stage gain of 90. Like EEG [43] and EMG [44], the EOG signal is also a random process. Hence, the presence of unpredictable noise is obvious. It has been reported that the frequency range of the EOG signal is 0.1–30 Hz [45]. Hence, the amplified signal was filtered using a 1st order passive band-pass filter with lower and upper cut-off frequencies of 0.16 and 33.88 Hz [46], respectively. Subsequently, the pre-amplified signal was smoothened using a 2nd order low-pass filter with cut-off frequency of 33.88 Hz. The smoothened band limited EOG signal was further amplified using AD-620 with a gain of 12. The signal was further processed through a 2nd order low-pass filter with a cut-off frequency of 33.88 Hz. This constituted the first EOG amplifier (EOG-I). Similar to the EOG-I amplifier, EOG-II amplifier was designed having similar specifications.

EOG-I amplifier was used for recording the vertical eye movements (up and down) by placing the electrodes in the orbital position. EOG-II amplifier was used to record the horizontal eye movements (left and right) by placing the electrodes in the canthi position. The output of both the amplifiers was acquired into a laptop (operating in battery mode) using a NI USB-6008 data acquisition system. The sampling rate of the USB-6008 was set at 10 KS/s. The output of the EOG-I amplifier was acquired from the AI0 input terminal, whereas, the output of the EOG-II amplifier was acquired from the AI1 input terminal. The biopotential amplifier circuit was powered by a ±12 V power supply. The power supply was developed using a DC-DC converter (IC MAU-108) [47]. The MAU-108 accepts an input voltage of +5 V and generates an output of ±12 V. The MAU-108 was powered from the USB-6008. The circuit diagram of the biopotential amplifiers (EOG-I and EOG-II) and the functioning circuit of MAU-108 to generate ±12 V have been shown in Fig. 1. The V-channel in the Fig. 1, signifies the conditioned output of the vertical (up-down) eye movements. Similarly, the H-channel denotes the conditioned output of the horizontal (left-right) eye movements.

3.4 Acquisition of the EOG Signals

A 5-marker panel was designed. It has been reported that the accommodation of the eye up to a distance of 2 m produces important cues that influences the space perception [48]. Hence, based on the space availability, the distance between the patient and the panel was fixed to 150 cm. The central marker was at the level of the

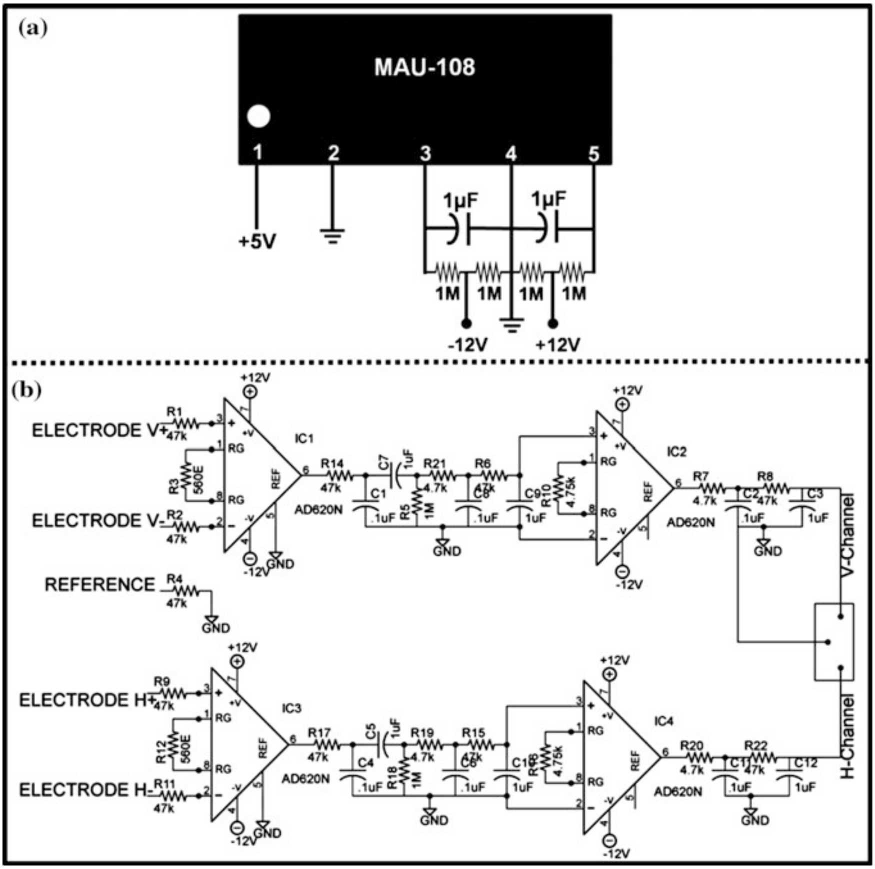


Fig. 1 Circuitry assemblage **a** power supply circuit, and **b** EOG biopotential *amplifier*

eyes of the volunteers. The horizontal markers were at a distance of 140 cm on either side of the central marker. The vertical markers were 75 cm apart on either side of the central marker. This arrangement (Fig. 2) created an angel of ±30° and ±50° [13] in the vertical and horizontal directions, respectively. The volunteers were verbally commanded to look at the specific markers and the corresponding EOG signals were recorded. By default, the volunteers were pre-advised to always look at the central marker always. If only the distance between the central marker and the subject will increase (fixing the distance of the peripheral markers), there will be a significant change in the height and width of the signal.

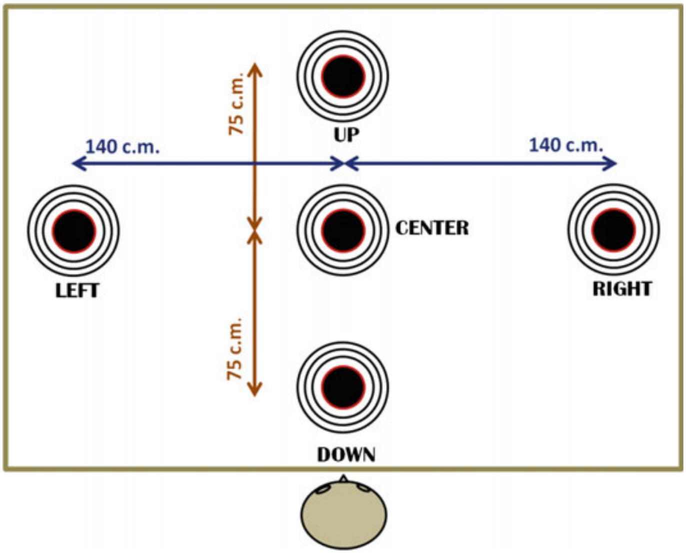


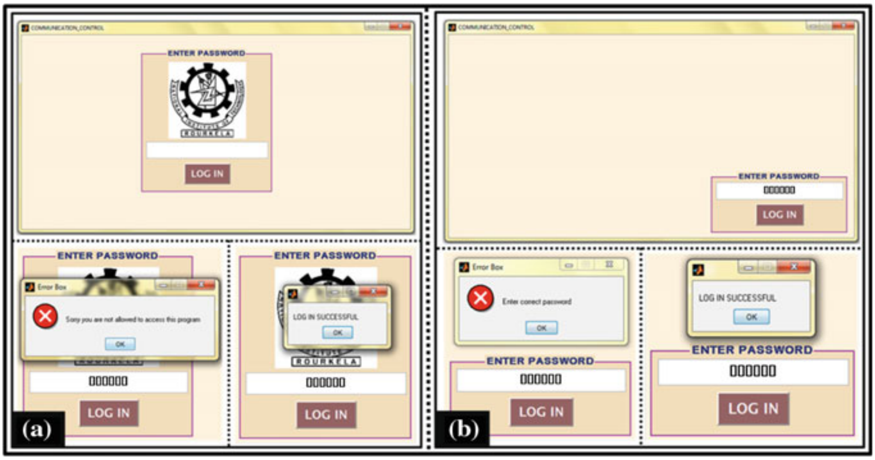
Fig. 2 Markers location for EOG recording

3.5 Processing of EOG Signal for Generation of Control Signals

500 samples of the EOG signals were used for processing. The acquired EOG signals were initially processed to remove the baseline drift by subtracting the mean of the acquired signal from the original signal. Thereafter, the signal was processed using a moving averager (triangular method). The width of the moving average was 10. Subsequently, the averaged signal was filtered using a moving-average filter which was implemented as a direct from II transposed structure. This filter was used to calculate the rolling average of the moving averaged EOG signal using a window size of 500. The filtered signal was used for further classification of the eye movements. Dual threshold comparison logic was employed to detect the movement of the eye. The signals from EOG-I was used for the detection of voluntary blink and up-down movements of the eye. The signal from EOG-II was used for detecting the left -right movement of the eye.

3.6 Development of GUI

The graphical user interface design environment (GUIDE) in MATLAB provided a way to design customized user interfaces using the in-built interactive tools. All the user interfaces, used in this study, were graphically designed in the GUIDE Layout



Sorry you are not allowed to access this program

LOG IN SUCCESSFUL

Enter correct password

Fig. 3 Password protection for the GUIs **a** password protected primary GUI, and **b** password protected sub-GUI

Editor. As per the layout construction, MATLAB codes were generated automatically. The auto-generated MATLAB codes were edited and modified to behave as per the desired applications. A password protected GUI was designed to avoid any unauthorized access (Fig. 3a). Provisions were made to save the patient history in an Excel file and to save the contact details of the persons to whom the patient may make calls and send emails. The above functions were implemented through two sub-GUIs. The sub GUI for saving communication details was also password protected (Fig. 3b). The primary GUI contains two major sections, namely, control unit and communication unit (Fig. 4). The control unit showed the generation of the control signals used for controlling the functionality of the robotic vehicle. The

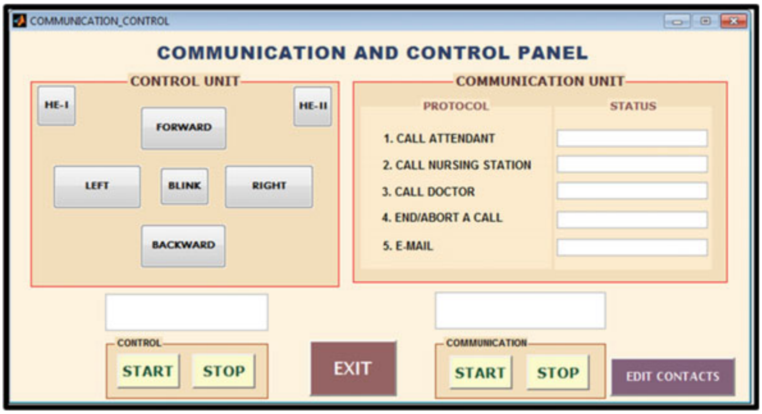


Fig. 4 Primary GUI showing the entire user interface controls

detailed explanation to the demonstration of Fig. 4 has been given in the result section via Figs. 12, 13, 14, 15, 16, 17 and 18. On the other hand, the control signals generated for the communication unit was used for sending emails and making voice calls to particular persons. Also, provisions were made to abort a call if anybody calls to the patient.

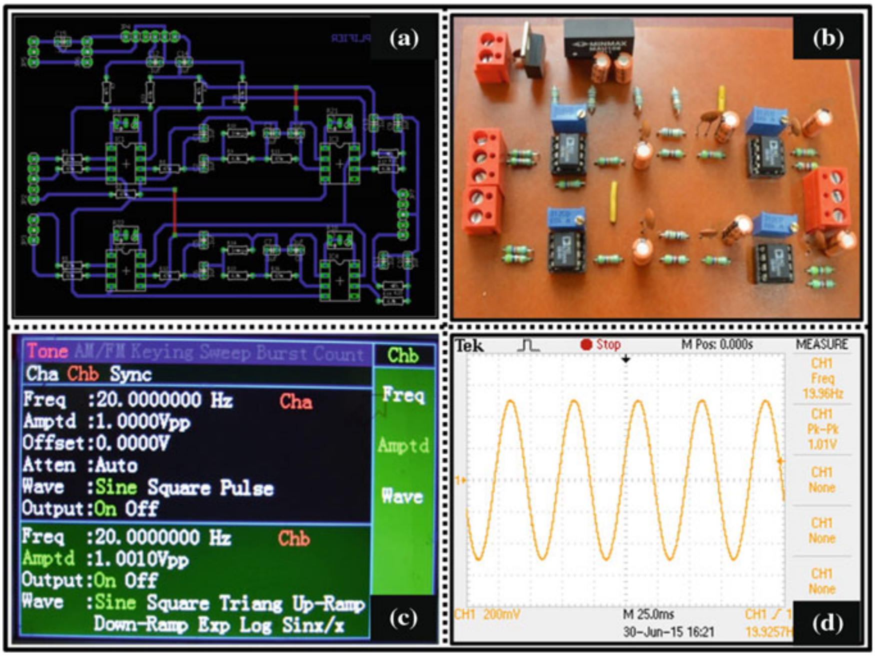
3.7 Development of Control System

The generated classified eye movement signals, in combination with the HE sensors, were used to control the functioning of the robotic vehicle and to initiate communication. The control unit for the robotic vehicle was activated by simultaneous voluntary blink and activation of the HE-I sensors at a time. During the process of activation, the inputs of the two H-bridges of the motor shield were enabled. Thereafter, the movement of the eye in the specific directions helped in generating the control signal for specific functions of the robotic vehicle. The control signals were generated only if the HE-I sensor was triggered within 10 s of activating the device. Otherwise, the control unit was deactivated, i.e., the inputs of the two H-bridges of the motor shield were disabled. The movement of the eye, in addition to an activated HE-I sensor, initiated the functioning of the robotic vehicle. The deactivation of the HE-I sensor for more than 10 s deactivated the control unit as well. Similar to the program made for the movement of the control unit, a program was made for controlling the communication unit under the primary GUI. The HE-I sensor was used as a supplementary switch for operating the control unit, whereas, HE-II sensor was used as the supplementary switching device for the functioning of the communication unit. The developed system needs a laptop to process the EOG signals and to generate the control commands.

4 Results

4.1 Development of EOG Acquisition System

The EOG acquisition system was developed as per the circuit given in Fig. 1. A PCB was designed on a copper clad board by carbon transfer and etching of the copper layer. The PCB layout was designed using the freeware Eagle software (version 7.3.0). The designed PCB layout has been shown in Fig. 5a. A PCB was designed from the layout, and the picture of the designed PCB has been shown in Fig. 5b. The designed circuit had a theoretical combined gain of 1080 ($A_{1st\ stage} = 90$ and $A_{2nd\ stage} = 12$). A differential sinusoidal signal of 1 $mV_{P\text{-}P}$ was used as the input and the output of the EOG amplifier was measured to be 1.01 $V_{P\text{-}P}$ with an error of 6.48 %. This confirmed the practical gain of the amplifier to be



Freq :20.0000000 Hz
Amptd :1.0000Vpp
Offset:0.0000V
Atten :Auto
Wave :Sine Square Pulse
Output:On Off

Freq :20.0000000 Hz
Amptd :1.0010Vpp
Output:On Off
Wave :Sine Square Triang Up-Ramp Down-Ramp Exp Log Sinx/x

CH1 Freq 19.96Hz
CH1 Pk-Pk 1.01V
CH1 None
CH1 None
CH1 None

Fig. 5 EOG bioamplifier design and analysis **a** PCB layout diagram in Eagle **b** developed PCB **c** differential input to the circuit, and **d** amplified output

~1000. The picture of the input and the output signals, as observed on the oscilloscope, has been shown in Fig. 5c, d. From the results, it can be concluded that the circuit was functioning as desired.

4.2 Acquisition of the EOG Signals

The EOG signals were acquired using the developed EOG amplifier. The output of the signal was taken into a laptop using USB-6008 data acquisition system. The complete setup of the EOG signal acquisition system which was used for the acquisition of the signal into the system has been shown in Fig. 6a. The orbital electrodes were placed on the either side of the right orbit. The canthi electrodes were placed at the lateral side of each eye. The reference electrode was placed on the left-hand side of the forehead [15]. The placement of the electrodes has been shown in Fig. 6b. The placement of the HE sensors and their functional activation has been shown in Figs. 6c1–c4. The volunteers were asked to sit on a chair in a relaxed position and were instructed to look at the central marker in the 5-marker panel without any head movement. Subsequently, they were advised to move the eyes in different directions as per the verbal instructions. The corresponding EOG

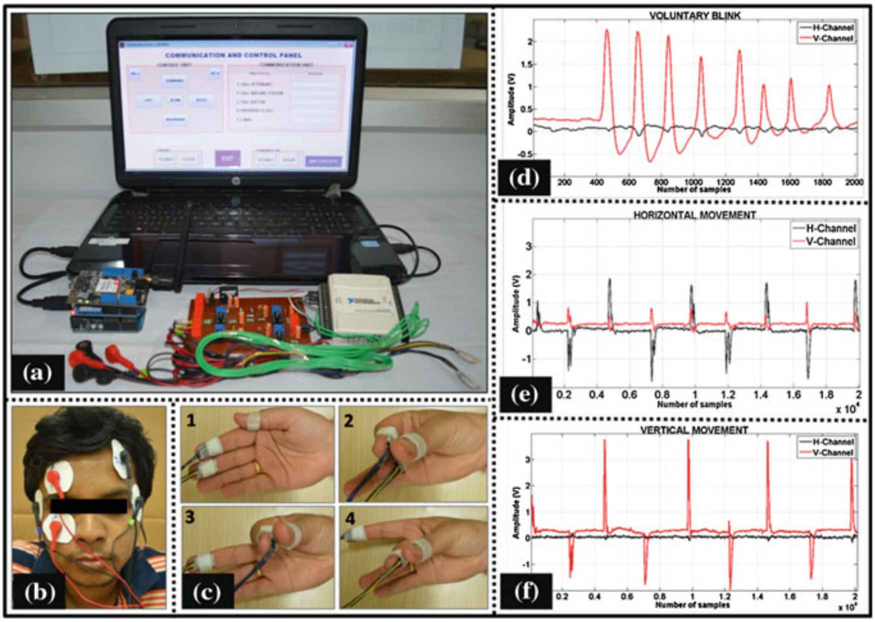


Fig. 6 Experimental compilation **a** setup of the EOG signal acquisition system, processing and control unit **b** electrode placement **c** HE sensor placement and functional activation **d** unprocessed voluntary blink signal **e** unprocessed horizontal signal, and **f** unprocessed vertical signal

signals were recorded. Figure 6d–f shows a representative output from EOG-I and EOG-II amplifiers when the volunteers were asked to move their eyes left, right, up, down and voluntary blink.

4.3 *Processing of EOG Signals for Generation of Control Signals*

The baseline of the EOG signal varies due to imperfect electrode-skin interface during electrode placement and movement of body parts [49, 50], which degrades the biosignals [51]. The acquired EOG signal was processed so as to remove the baseline drift, which appeared in the acquired EOG signal. Baseline drift was eliminated by the conventional baseline drift elimination method, i.e., subtracting the mean of the signal from the acquired signal. Thereafter, the signal was averaged using a moving average (triangular method). The triangular moving average (TMA) is a simple moving average (SMA) that has been averaged again, i.e., averaging the average. It produces an extra smooth moving average plot. The small ripples superimposed on the EOG signals were abolished after smoothening [52]. The equations of the averaging process are given below:

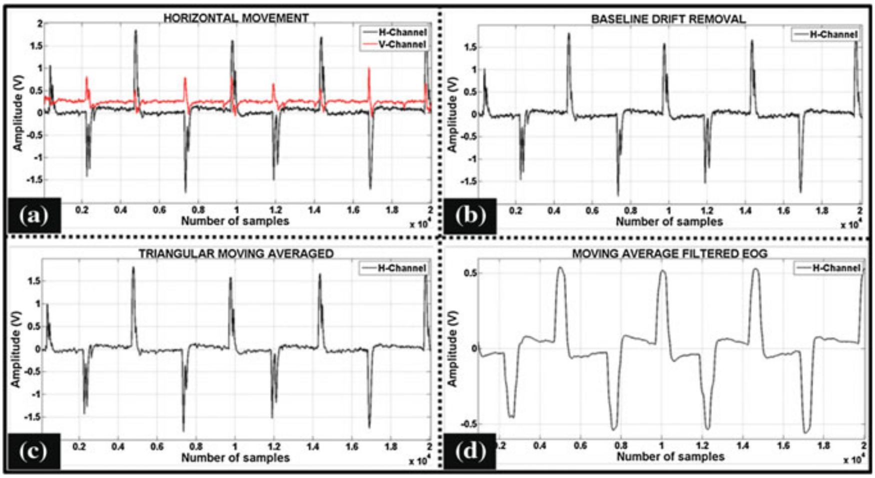


Fig. 7 EOG signal processing **a** unprocessed horizontal signal with vertical channel response **b** horizontal signal isolation and baseline drift removal **c** triangular moving averaged signal, and **d** moving average filtered signal

$$\mathrm{SMA} = (x_1 + x_2 + x_3 + \cdots x_N)/N \tag{1}$$

$$\mathrm{TMA} = (\mathrm{SMA}_1 + \mathrm{SMA}_2 + \mathrm{SMA}_3 + \cdots + \mathrm{SMA}_N)/N. \tag{2}$$

where

N	No. of periods
$x_1 \ldots\ldots x_N$	‘N’ number of data samples
$\mathrm{SMA}_1 \ldots\ldots \mathrm{SMA}_N$	Simple moving average of $x_1 \ldots\ldots x_N$ number of samples

Subsequently, the signal was filtered using a moving average filter having a window size of 500. Figure 7 shows the output of the processed signal at different stages of processing. The final processed EOG signals has been showed in Fig. 8 and the flowchart for classifying the up, down, left, right and voluntary blink using the threshold limits has been showed in Fig. 9. Each kind of eye movements and voluntary blink were associated with specific control commands (numerical values). These commands were used to activate a specific function in the control unit and were serially transmitted to the Arduino Mega ADK to achieve particular communication tasks through the GPRS shield. The multidirectional eye movements and HE sensor triggering in logical combination with voluntary eye blinks concurrently produced a set of commands responsible for accomplishing control and communication protocols. Tasks like making voice calls, aborting a call, and sending emails were programmed under communication protocol. The control unit guided the direction of the robotic vehicle in four different directions. The logical combination for activation of the control and the communication protocols has been given in Table 1.

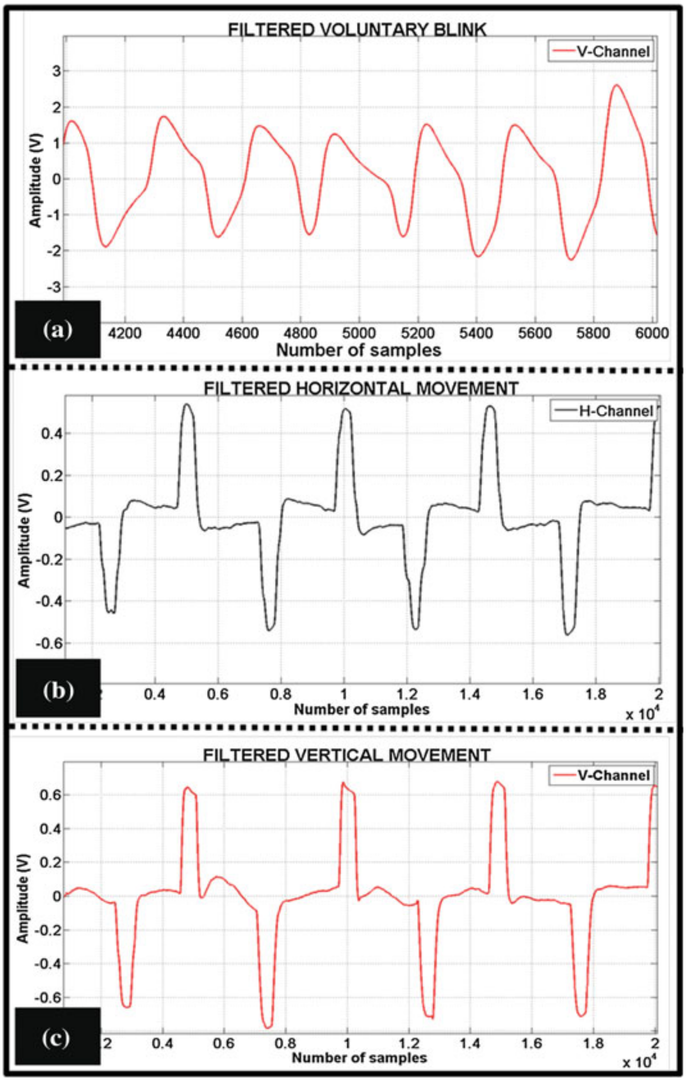


Fig. 8 Final processed EOG signals **a** voluntary blink **b** horizontal movement, and **c** vertical movement

4.4 Functionality of the Developed GUI

A MATLAB based password protected GUI was developed such that only the authorized personnel can access the GUI by entering a correct password. After the successful login, a patient history GUI will automatically pops-up. It allows to save the address, contact and official (ward name and bed no.) details are entered in the GUI. Clicking the *continue* button in the GUI allows the user to save the patient

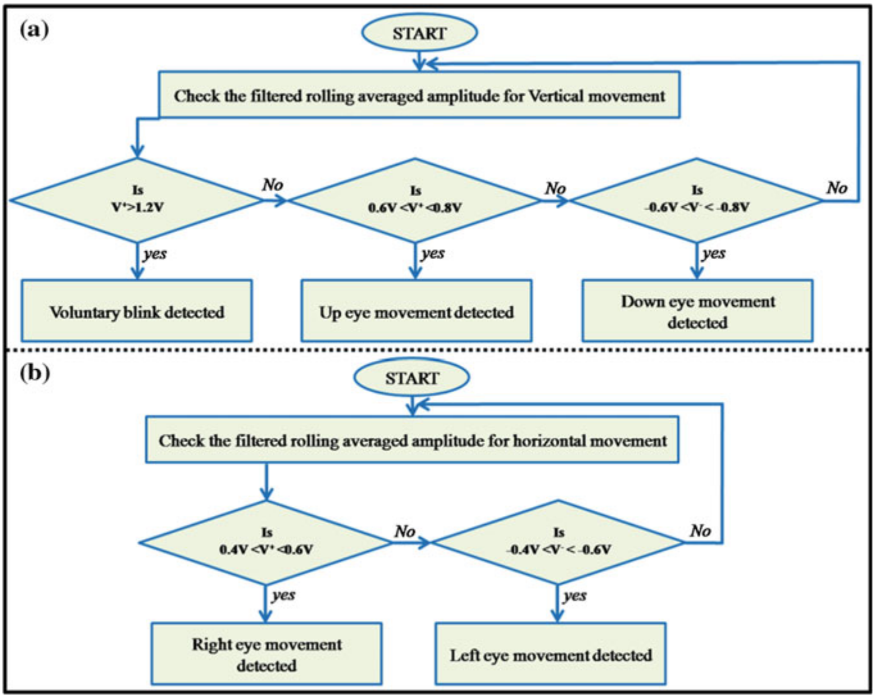
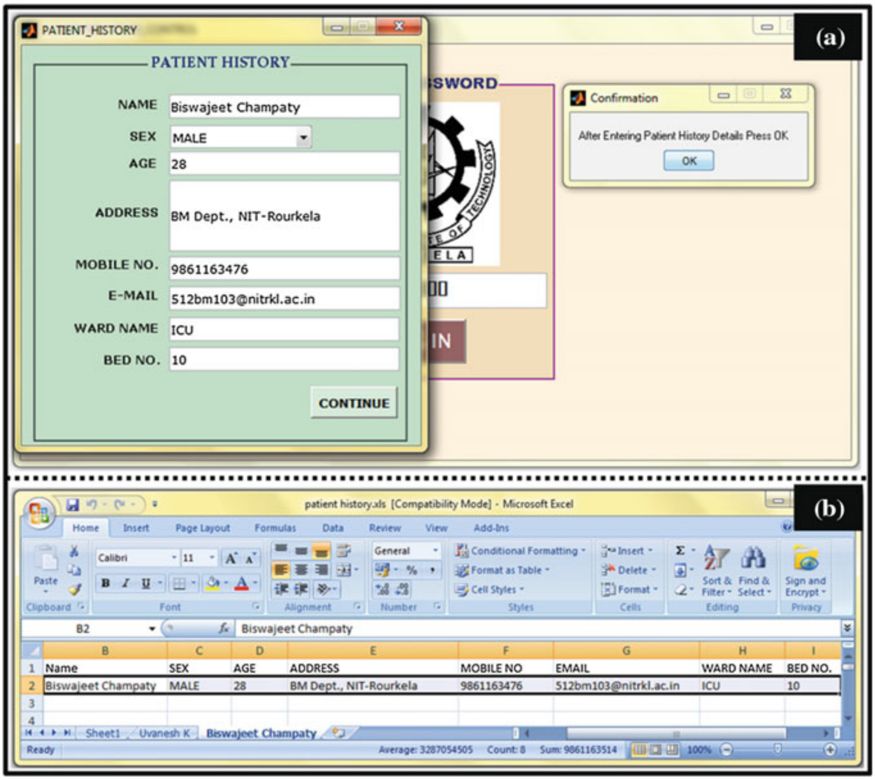


Fig. 9 Analogy for eye movement classification **a** flowchart for voluntary blink, up and down eye movement detection **b** flowchart for left and right eye movement detection

Table 1 Logical combination of eye movements and HE sensors in control and communication protocol activation

HE-I sensor	HE-II sensor	Types of eye movements	Proposed tasks	Figure demonstration
√	√	Voluntary blink	Activates the motor shield	12a
x	–	–	Deactivate the motor shield	12b
√	x	Left	Left movement	13a
√	x	Right	Right movement	13b
√	x	Up	Forward movement	13c
√	x	Down	Backward movement	13d
x	√	Up	Call to attendant	14
x	√	Right	Call to nursing station	15
x	√	Left	Call to doctor	16
x	√	Down	Email to doctor, nursing station and attendant	17
x	√	Voluntary blink	Abort a call	18b

√ = activated; x = deactivated; – = idle



PATIENT HISTORY

NAME Biswajeet Champaty
SEX MALE
AGE 28
ADDRESS BM Dept., NIT-Rourkela
MOBILE NO. 9861163476
E-MAIL 512bm103@nitrkl.ac.in
WARD NAME ICU
BED NO. 10

After Entering Patient History Details Press OK

patient history.xls [Compatibility Mode] - Microsoft Excel

B2 Biswajeet Champaty

Name	SEX	AGE	ADDRESS	MOBILE NO	EMAIL	WARD NAME	BED NO.
Biswajeet Champaty	MALE	28	BM Dept., NIT-Rourkela	9861163476	512bm103@nitrkl.ac.in	ICU	10

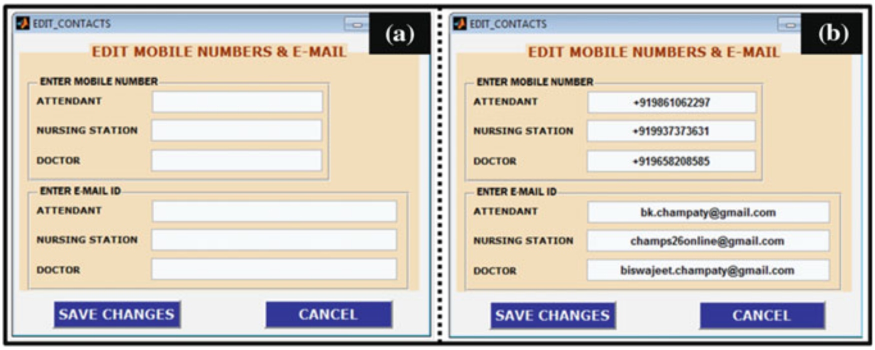
Sheet1 Uvanesh K Biswajeet Champaty

Average: 3287054505 Count: 8 Sum: 9861163514

Fig. 10 Sub-GUI-I **a** patient history entered **b** history saved in a separate tab as per the patient name in an excel sheet "patient history"

history in a particular excel file (under a new tab). Subsequently, the GUI is opened. The sub-GUI for saving patient history has been shown in Fig. 10. The main GUI contains two segments, namely, control unit and communication unit. The communication segment includes an *edit contact* button. Clicking the edit contact button results in the opening of another sub-GUI, which allows the users to change and save the contact details of the person to whom the communication to be made (Fig. 11). This GUI is also password protected for authorized access only.

The control unit has seven virtual indicators (virtual LEDs) displaying left, right, forward, backward, stop, HE-I sensor and HE-II sensor. A couple of pushbuttons at the bottom of the GUI are intended for activating (ON) and deactivating (OFF) the unit. The unit is activated just by a by pressing th START button but does not initiate the tasks. The unit does not start functioning unless a simultaneous signal from HE-I and HE-II sensors and a voluntary blink is detected. The activation is confirmed by a display note ("ACTIVATED...!!!") in the same unit (Fig. 12). As per Table 1, the virtual indicators are activated (change in background color) during specific operations associated with different eye movements, voluntary blink and



(a)

EDIT MOBILE NUMBERS & E-MAIL

ENTER MOBILE NUMBER

ATTENDANT

NURSING STATION

DOCTOR

ENTER E-MAIL ID

ATTENDANT

NURSING STATION

DOCTOR

(b)

EDIT MOBILE NUMBERS & E-MAIL

ENTER MOBILE NUMBER

ATTENDANT +919861062297

NURSING STATION +919937373631

DOCTOR +919658208585

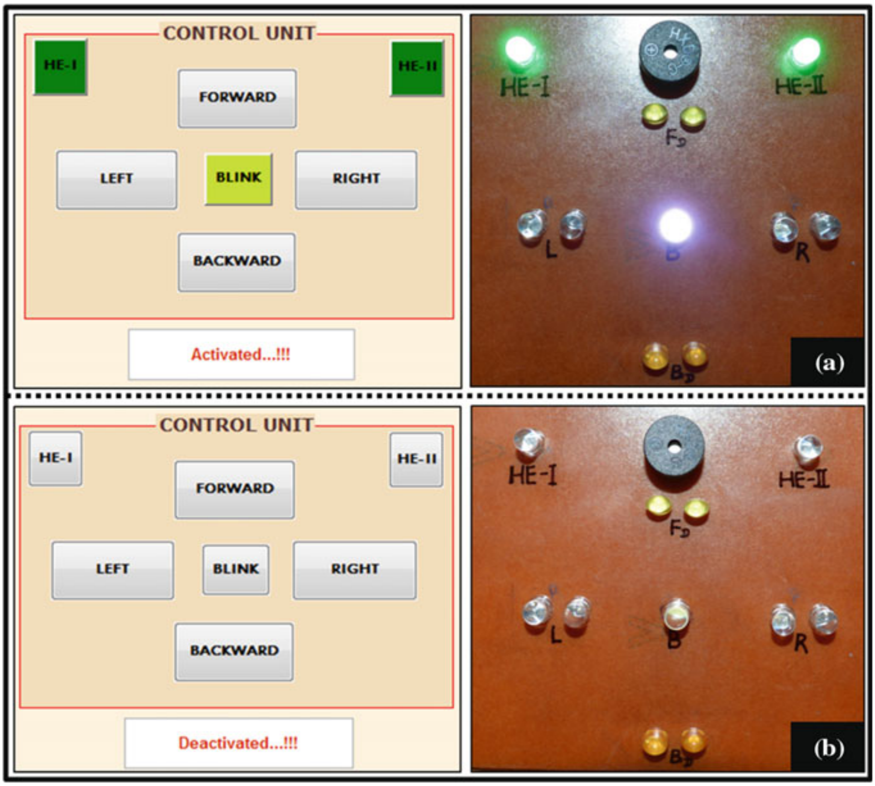
ENTER E-MAIL ID

ATTENDANT bk.champaty@gmail.com

NURSING STATION champs26online@gmail.com

DOCTOR biswajeet.champaty@gmail.com

Fig. 11 Sub-GUI-II **a** contact options, and **b** enter contact details and save



Activated...!!!

Deactivated...!!!

Fig. 12 **a** Activation of control unit, and **b** deactivation of control unit

triggering of HE sensors (Fig. 13). STOP button makes the unit dormant. Due to line-of-sight communication, the duration lapse between the initiations of the control signal to the actual response/action time for the robotic vehicle is 117 ms.

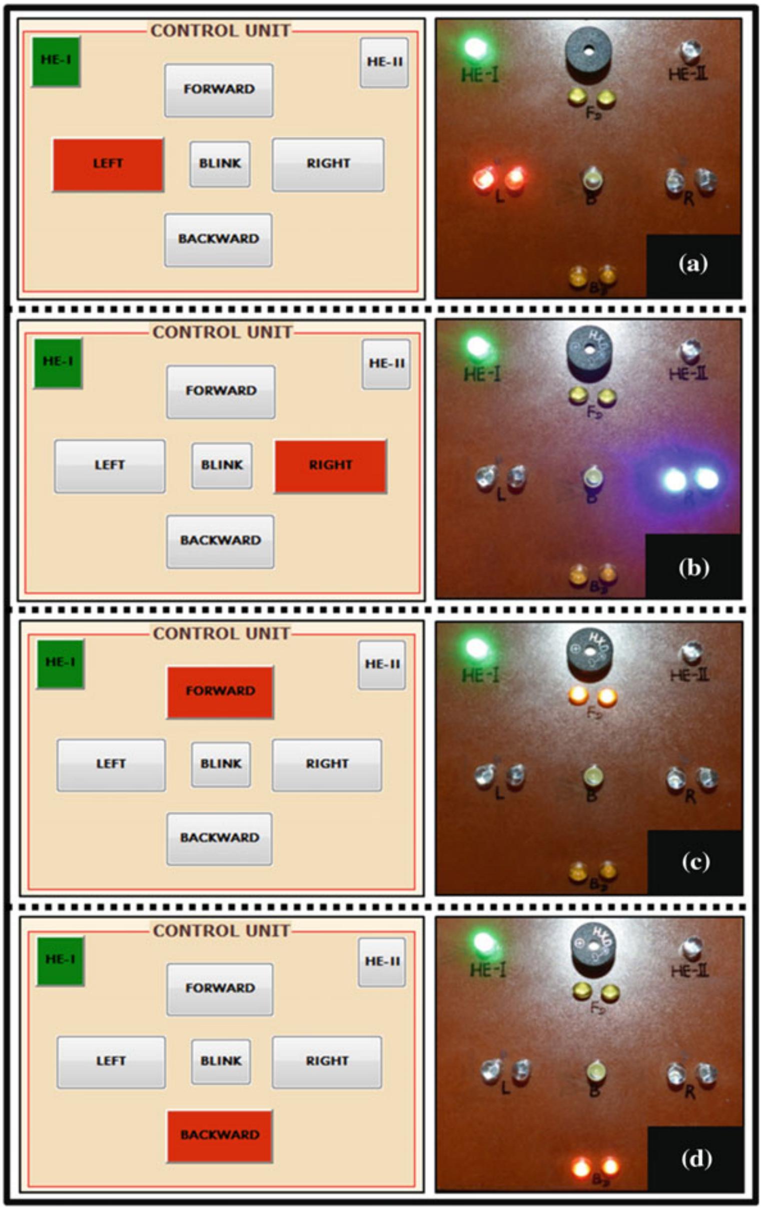
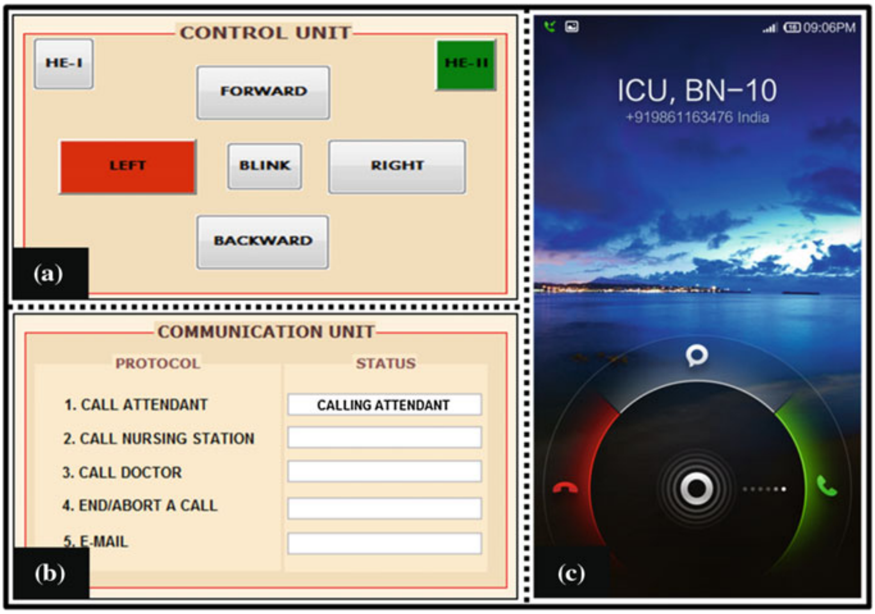


Fig. 13 Control task execution and hardware realization **a** left eye movement-left command **b** right eye movement-right command **c** up eye movement- forward command, and **d** down eye movement- backward command

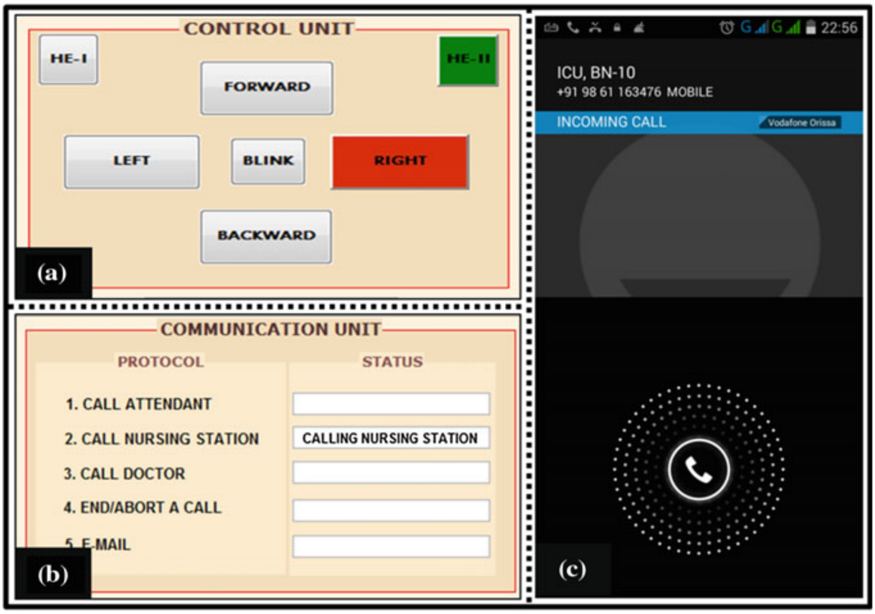
Like control unit, the communication unit too has activation and deactivation processes. The communication operations are set off by software switches. A GPRS Shield V1.0 instilled into the Arduino Mega ADK provides a way to use the GSM cell phone network. It is controlled via AT commands (GSM 07.07, 07.05 and SIMCOM enhanced AT Commands). Each communication protocol in the GUI generates a specific serial data which gets transmitted to the microcontroller. The GSM shield starts doing particular functions like making voice calls, abort a call, etc. when a specific serial command reaches the Arduino Mega ADK. All the voice calls were directed to the saved contacts. The patient mobile number should be saved in the recipients' (attendant, nursing station and doctor) mobile as <Ward Name>, <Bed No. (BN)> during the process of patient registration. Due to the vast usage of smartphones, email facility was employed as one of the prime communication protocols in our study. All the emails are programmed to be sent through NIT-RKL Cyberoam server client that supports Post Office Protocol (POP). The content of subject in the mail is like—"Please attend the patient—<Patient Name>, <Ward Name> <Bed No. (BN)>". The content is sent in the subject line for quick viewing. The patient name, ward name and bed number were accessed from the patient history saved earlier. As per Table-1, all the communication tasks were carried out in the GUI. Figures 14, 15, 16 show the incoming call to the attendant, nursing station and doctor and their respective GUI demonstration, respectively.



PROTOCOL	STATUS
1. CALL ATTENDANT	CALLING ATTENDANT
2. CALL NURSING STATION	
3. CALL DOCTOR	
4. END/ABORT A CALL	
5. E-MAIL	

ICU, BN−10
+919861163476 India

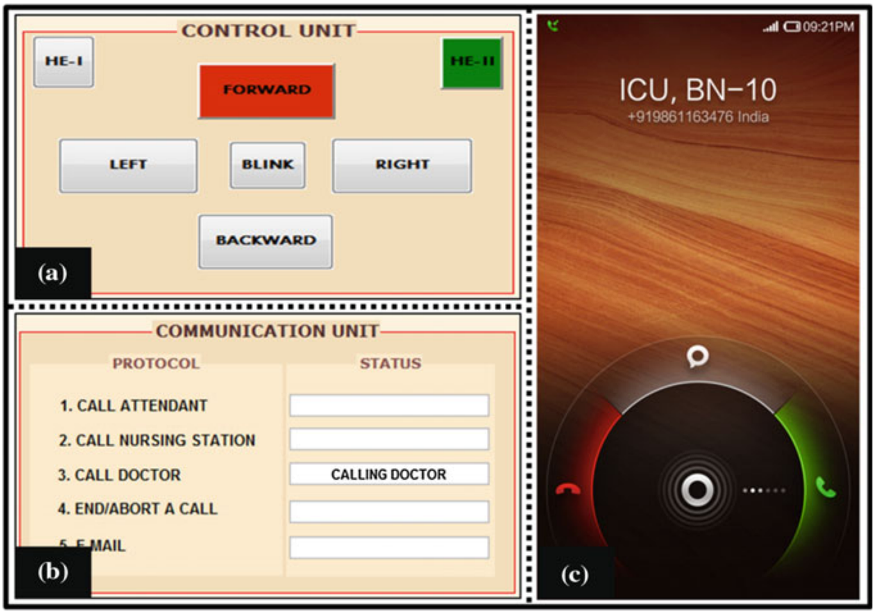
Fig. 14 Calling attendant **a**, **b** GUI demonstration, and **b** an incoming call on the attendant's mobile



CALLING NURSING STATION

ICU, BN-10
+91 98 61 163476 MOBILE

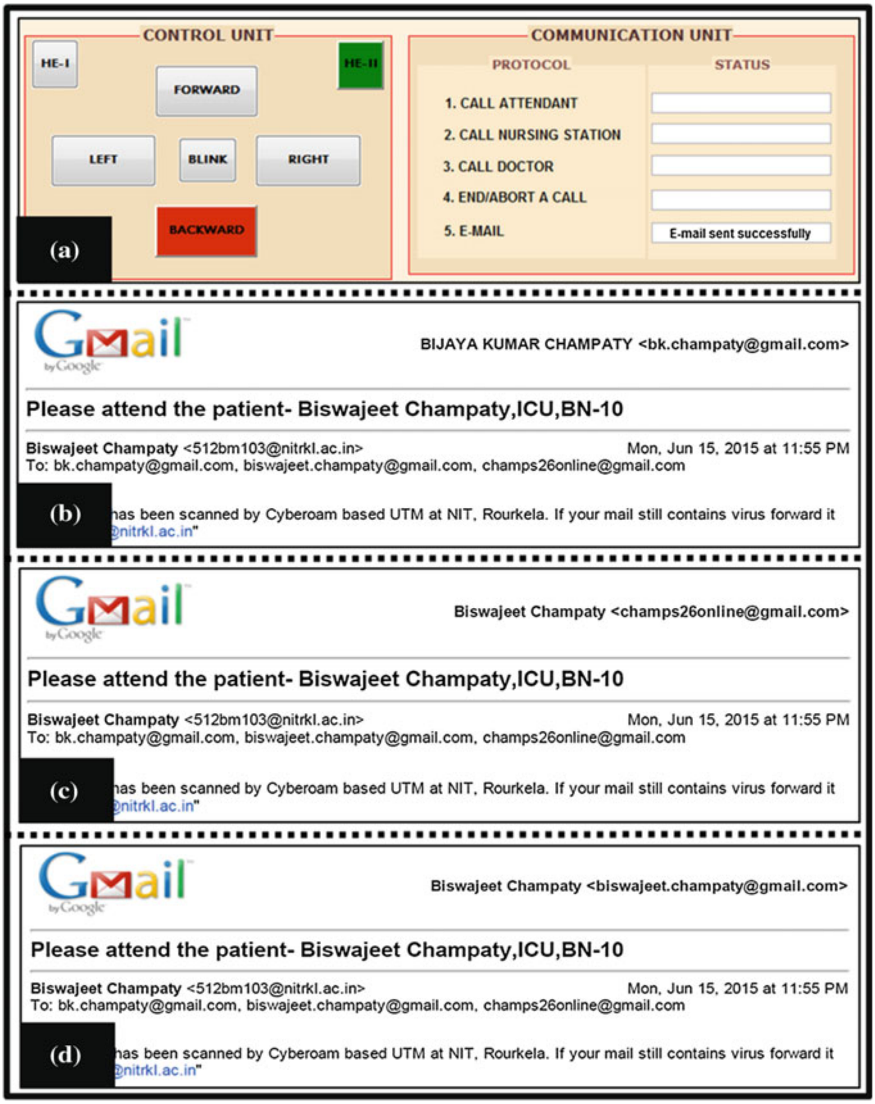
Fig. 15 Calling nursing station **a**, **b** GUI demonstration, and **b** an incoming call on the nursing station mobile



CALLING DOCTOR

ICU, BN−10
+919861163476 India

Fig. 16 Calling doctor **a**, **b** GUI demonstration, and **b** an incoming call on the doctor's mobile



1. CALL ATTENDANT
2. CALL NURSING STATION
3. CALL DOCTOR
4. END/ABORT A CALL
5. E-MAIL — E-mail sent successfully

BIJAYA KUMAR CHAMPATY <bk.champaty@gmail.com>

Please attend the patient- Biswajeet Champaty,ICU,BN-10

Biswajeet Champaty <512bm103@nitrkl.ac.in> Mon, Jun 15, 2015 at 11:55 PM
To: bk.champaty@gmail.com, biswajeet.champaty@gmail.com, champs26online@gmail.com

has been scanned by Cyberoam based UTM at NIT, Rourkela. If your mail still contains virus forward it
@nitrkl.ac.in"

Biswajeet Champaty <champs26online@gmail.com>

Please attend the patient- Biswajeet Champaty,ICU,BN-10

Biswajeet Champaty <512bm103@nitrkl.ac.in> Mon, Jun 15, 2015 at 11:55 PM
To: bk.champaty@gmail.com, biswajeet.champaty@gmail.com, champs26online@gmail.com

has been scanned by Cyberoam based UTM at NIT, Rourkela. If your mail still contains virus forward it
@nitrkl.ac.in"

Biswajeet Champaty <biswajeet.champaty@gmail.com>

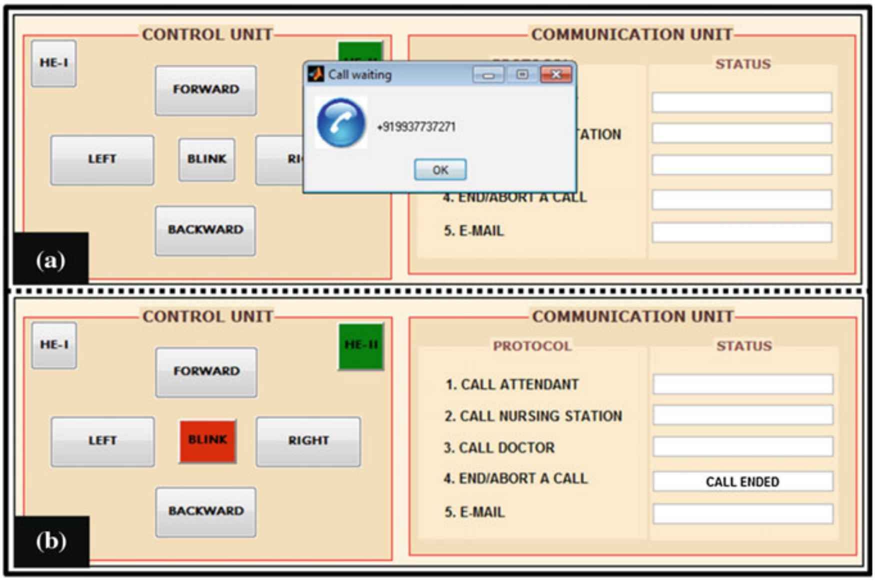
Please attend the patient- Biswajeet Champaty,ICU,BN-10

Biswajeet Champaty <512bm103@nitrkl.ac.in> Mon, Jun 15, 2015 at 11:55 PM
To: bk.champaty@gmail.com, biswajeet.champaty@gmail.com, champs26online@gmail.com

has been scanned by Cyberoam based UTM at NIT, Rourkela. If your mail still contains virus forward it
@nitrkl.ac.in"

Fig. 17 E-mail delivery **a** delivered to attendant **b** delivered to nursing station, and **c** delivered to doctor

Figure 17 shows the email delivery to the attendant, nursing station and the doctor. An incoming call to the patient's mobile number and the aborting the call has been shown in Fig. 18.



+919937737271

CALL ENDED

Fig. 18 **a** Incoming call to the patient's mobile number, and **b** aborting the call

4.5 Development of Control System

A control system was developed using the five control signals produced as a result of eye movements. Signals from the two HE sensors were acquired into the laptop and were integrated with the program for doing specific tasks (control and communication tasks). The HE-I sensor (accompanied by eye movements) was used to control the control unit, whereas, HE-II sensor (attached to the middle finger) was used to initiate tasks in control unit. In this study, a robotic vehicle was used as the representative assistive device. After switching on the HE-I sensor, a voluntary eye blink activated the control unit. The movement of the eye in different directions was detected by the EOG signal processing program, which in turn, generated control signals. The generated control signals were visualized in the control unit segment of the GUI. Virtual indicators like left, right, forward, backward, stop, HE-I sensor activation and HE-II sensor activation were activated (change in background color). This segment can be used by the patients for proper training from time to time. It has been reported that visual feedback of biosignals helped the disabled persons to strengthen their ocular activities. Also, the control signals were transmitted to a robotic vehicle via a pair of wireless XBee shields. The various control signals were used to control the movement of the robotic vehicle. As mentioned earlier, after the activation of the control unit (switching on the HE-I sensor and voluntary blink concurrently), the movement of the eye to the right, left, up and down directed the

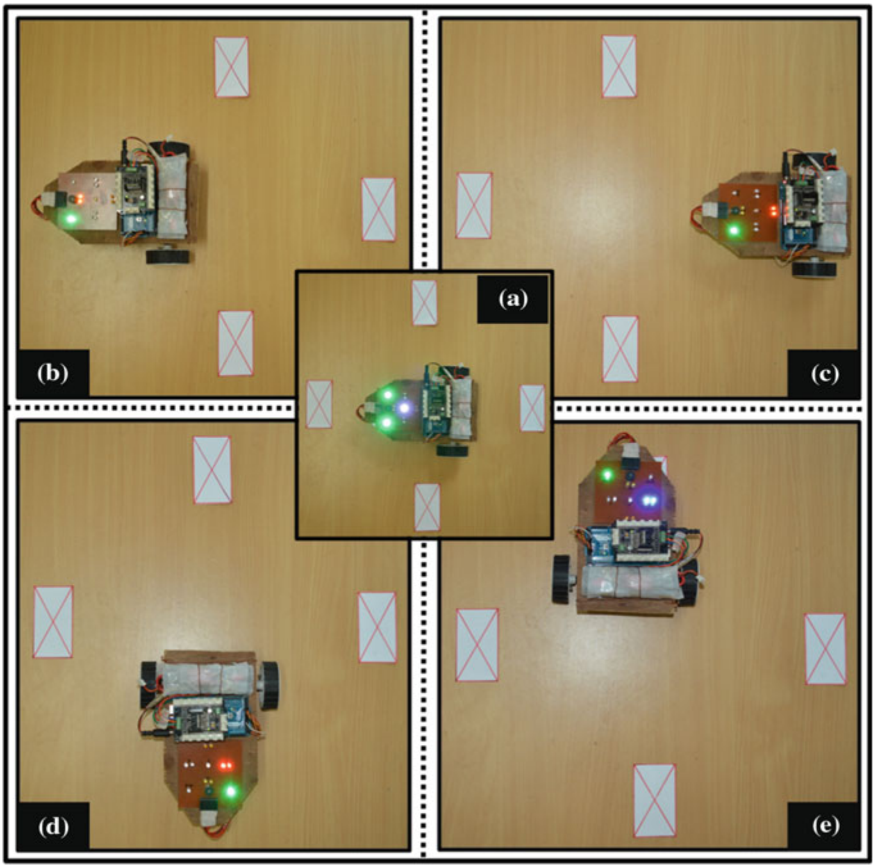


Fig. 19 Robotic vehicle movements **a** activated at the centre **b** forward **c** backward **d** left, and **e** right

robotic vehicle to move right, left, forward and backward, respectively. The switching-off of the HE-I sensor halts the movement of the robotic vehicle. If the HE-I sensor is in the switched off condition for more than 10 s, the control unit is deactivated. The functioning of the control unit for controlling the movement of the robotic vehicle was successfully tested. The activation and the movement of the robotic vehicle in different directions have been showed in Fig. 19. All the 15 volunteers were trained for 20 min to get familiar with the working of the device. Therefore, all of them were able to complete the tasks without any false positive result. No movement was observed in the robotic vehicle, if the eye motion wasn't one of the specified five cases reported in the control unit.

5 Conclusion

The purpose of the study was to develop a robust EOG based HCI device, which can be diversified both as a control system for the functioning of the assistive devices and for initiating communication with the healthcare and non-healthcare personnel in case of any emergency and need. The proposed hardware-software device can be used for the severely disabled persons who have limited motor activity. Excluding the cost of the laptop, the total cost of the system is nearly $267. This has been reported that the energy required for moving the eyes are much lower as compared to the other motor activities in the disabled person. Also, the individuals suffering from neuromuscular diseases are left with the activities of the ocular muscles even in the late stages of the disease. Due to these reasons, EOG based HCIs gained much importance in the development of assistive devices. In this study, as a representative assistive device, the robotic vehicle was directed to different directions using the EOG signal and helped in testing of the developed control system. The successful testing of the control of the robotic vehicle throughout the study concluded that the control system developed using the EOG signals may be used for controlling robotic arms, wheelchairs, home automation systems etc. in future. In addition to the existing control commands, more control commands can be generated by moving the eyes in diagonal directions like up-right, up-left, down-right and down-left. The developed EOG biopotential amplifier has the capability to record these additional eye movements. Additionally, by slightly modifying the hardware components, it was possible to initiate various communication protocols for the severely disabled persons.

In gist, in this study, EOG signals were used to manipulate a robotic vehicle and a communicationdevice suggesting that the proposed device can be used for multi-tasking.

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