EyeAssist: A Communication Aid through Gaze Tracking for Patients with Neuro-Motor Disabilities

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Abstract—The paper presents EyeAssist, a low cost, user friendly communication aid developed specifically for individuals suffering from neuro-motor problems. Existing gaze based typing systems encounter problems of unintentional key presses, extensive calibration process and inbuilt noise of eye trackers. We tried to solve these problems in the EyeAssist system by employing accurate gaze tracking. Fixation information are derived from the acquired gaze data. The systematic and variable noises of the eye tracker are being removed by graph signal processing based filters, Kalman filter and linear transformation. A unique one-time calibration which is subject and session independent has made the system easy to use without compromising its efficacy. The system has provision for setting variable dwell time according to users’ preferences. EyeAssist also provides some unique features like text to speech conversion of typed sentences, predictive word and sentence entry etc. Results show that the average typing rate is 11.8 words per minute with an average error rate of 6.6%. Moreover the error rate reduces drastically with some practice. The system is user friendly, easy to use which makes it a perfect choice for patients suffering with neuro-motor disabilities.

Keywords—Eye tracking; virtual keyboard; communication aid; fixation detection; graph signal processing; Kalman filtering; Linear transformation

I. INTRODUCTION

Neuro-motor disabilities like Amyotrophic Lateral Sclerosis (ALS), multiple sclerosis (MS), cerebral palsy, ataxia to name a few, make people unable to carry out even simple daily chores [1-2]. With progression of disease, they sometimes lose the capability to communicate with the outside world. Sometimes accident or trauma causes damage to the neuro-muscular system of an individual. These disabled people are unable to move their limbs, walk or maneuver the objects around them, and sometimes they are unable to speak also. However, in most of these cases their cognitive abilities remain intact. Developing means to help these people to communicate is a major challenge that the scientific community is currently facing. There exists various ways of communication for neuro-motor disabled patients’ viz., communication through only head movement, only eye movement, based on vibrations/movement of larynx and brain computer interfaces (BCI) [3-4] and the like. BCI utilizes motor imagery to communicate or control devices relying on brain signals, which are highly non-stationary, non-linear in nature. Deciphering the brain signals precisely and implementing them as a communication means is quite difficult [5]. Moreover, different types of noises, as well as various cognitive processes in mind pose hindrance in utilizing them in real life scenarios outside the controlled lab environment. In most of the cases the head movement, larynx movement cease to exist as the disease advances. The eye movements remain intact even in the severe cases of locked-in state [6]. Thus the eye movement based communication aids can prove to be beneficial for the neuro-motor disabled persons who have not yet entered into the complete locked-in state.

Eye movement based communication technique can find its application in several areas, viz. virtual games, analyzing cognitive abilities, cognitive load, in tele-navigation, tele-operation to name a few [7-10]. Eye movements can be detected by eye tracker devices, by webcams through computer vision analysis as well as by electrooculography (EOG) [11]. EOG measures the potential difference between the cornea and the retina. Different directional eye ball movements as well as blinks can be detected by EOG. EOG is an obtrusive means of eye signal acquisitions, since the electrodes are placed around the eye cavity. This can lead to user discomfort. Moreover, EOG signals can tack the gaze direction, but computation of exact gaze coordinates from EOG signals have not been achieved to date. The performance of the eye tracking using web cam depends on the environmental illuminations and the image analysis is highly computationally complex. In this regard, eye tracking from infrared (IR) based approach seems to be a good alternative. Additionally, coordinates of the screen corresponding to eye gaze are obtained from the eye trackers. Thus IR based eye-tracking approach is one of the best modus to achieve pervasive, unobtrusive and alternative communication aid for neuro-motor disabled people [12], [20].

Infrared (IR) eye trackers are the popular means in nearable eye tracking devices owing to their cost-effectiveness [20]. These sensors use either dark-pupil or bright-pupil approach to track the eyes [23]. In the former method, the eyes are illuminated with an off-axis source in order to have the pupil as the darkest region in the obtained image; whereas the
iris, sclera and eye lids reflect more illumination relatively. The bright pupil method illuminates the eyes with a source that is very nearby to the axis of the camera. However, both these techniques suffer from low signal to noise ratio and low resolution which degrades their overall performance.

Eye movements consist of fixations, smooth pursuits and saccades. During fixations the eye gaze remain stationary in a particular position for certain amount of time [13]. Whereas saccades are the fast eye movements, i.e. when the eye gaze traverses very quickly from one location to another. Most of the eye tracker based keyboard control systems depend on the dwell time for key press selection. Panwar et.al [14] had developed Eyeboard, which utilizes adaptive dwell time based on eye gaze for text entry in an onscreen keyboard. They have also tested various configurations of on-screen keyboards. Vertnanen [15] has presented a dwell time free eye tracking based text entry system. Majaranta and Raiha [16] have stated that the dwell time between 450-1000 ms works suitably even for novice users. In all of these dwell time based text entry systems, the problem of Midas Touch [17] introduces unintentional erroneous texts. Midas touch refers to the unintentional key presses. This problem degrades the accuracy of the text entry system as well as increases the user fatigue and stress. The eye-typing system developed by Mackenzie and Zhang [13] has implemented both letter and word prediction to increase the text entry rate and to minimize the eye movements for search and key presses. Prabhu and Prasad [18] designed a virtual keyboard that can be accessed through eye gaze, by BCI or by some muscular activity. Eye-S [19] exploited usage of eye-graffiti to write alphabets and numbers on computer screen. All of these state of the art systems are dependent upon an initial calibration process as most of the eye tracking devices possess some inherent noises [21-22]. The calibration process is time consuming and is required to be performed for each user individually before each trial.

In this paper a low cost, easy to use communication aid, EyeAssist, is proposed which is controlled by fixations of the eye gaze. Most of the state of the art approaches use the raw eye gaze data instead of the fixation for cursor control which makes typing erroneous. Our developed system employs unique approach which extracts the fixations, then applies noise removal techniques to ultimately control the cursors movement on an onscreen keyboard. A novel noise removal technique utilizing graph signal processing, Kalman filter, and linear transformation removes both variable and systematic errors of the eye tracker. A unique calibration process has been developed and implemented which is not elaborate and, time consuming. Each user can use the system without any prior training and calibration. The system also predicts words and sentences to increase the text entry speed and reduce the effort required by the user. Some predefined phrases can be chosen based on user’s preference and frequency of uses. There is also a provision for text to speech output of the selected phrase, or word. The EyeAssist system has been primarily developed as an augmented assistive aid for those who have lost their motor as well as speech capacity.

The paper is organized as follows. Section II elaborates the methodology of preprocessing, error removal and implementation of the EyeAssist, Section III describes the experimental setup and the layout of the virtual communication interface. Results depicting the performance of EyeAssist are enlisted in section IV, followed by concluding remarks in the section V.

II. METHODOLOGY

This section explains the details of EyeAssist system. The overall system is depicted in Fig.1. Eye gaze coordinates \(\{x,y\}\) are acquired from the EyeTribe [36] eye tracker. Initially fixations on the virtual keyboard (V.K) are detected and the gaze coordinates corresponding to fixation of maximum duration are selected for further analysis. Next blinks are eliminated from these fixation data. The blink free fixation data are then processed to remove systematic and variable noise by applying Kalman filter(KF), graph signal processing (GSP) and linear transformation. The screen transformation matrix (T.M) generated in the calibration phase is used to map the fixation data to the exact location on the screen and is used to perform key presses.

![Fig. 1. EyeAssist: Overall system design](image)

A. Fixation Detection and blink elimination

During eye movements when eyes pause for certain time, those gaze points are referred to as fixations. In present scenario, fixations are the vital parameters since fixations are obtained whenever eye focusses on a particular key of the keyboard in order to select the same. Moreover, instead of carrying out the further analysis on total number of gaze points, fixations are computed first and rest of the analysis is done over that to reduce the computational complexity of the protocol. Most of the visual processing takes place during the fixations which is another reason of extracting the fixations from raw data. In the current work, velocity threshold based fixation detection has been applied [26]. First the eye tracking data for certain window of time is buffered. Next the point to point velocities of every gaze points are computed. Usually, fixations show very low velocities (<100 deg/sec) [26], whereas saccades being the very fast eye movements show high velocities (>300deg/ sec). The data points which are below the threshold velocity are treated as the fixations, and the rest are the saccades. The saccades are eliminated, and the fixations are used further. During fixations there can be very slight eye movements such as drifts, flicks and tremors. To
extract relevant fixation information, the fixation points are grouped together and the centroid is calculated to map that particular fixation. Setting up the velocity threshold value is the crucial part of this algorithm. Sen and Megaw [27] utilized the velocity threshold of 20 degrees/second. In this work, experimentally and depending upon the sampling rate of the EyeTribe i.e. 30Hz, the velocity threshold is set as 20 degrees/second.

When blinks are encountered, the eye tracker returns null values which might be problematic for further analysis. Thus if blinks occur, our proposed algorithm replaces the blinks by a value obtained by interpolation based on the values just prior to the blinks.

B. Removal of variable error

There are mainly two types of errors associated with the eye trackers [21], variable error and systematic error as shown in Fig.2. If the gaze coordinates disperse considerably from the point of interest, it is referred to as the variable error. This error occurs due to lack of precision and is mainly related to physiological characteristics of a users’ head/eye motion and fatigue [24]. We have eliminated this by graph signal processing (GSP) based filtering [28] and Kalman filter [29].

GSP is applied on the noisy x,y coordinates acquired from EyeTribe to obtain a smooth signal. The incoming EyeTribe signal has been buffered for a certain window of duration 1.2 sec. The vertex set is then formed by set of \((x_i, y_i)\) of a particular window. Edges are formed if the Euclidean distance between two vertices are less than a threshold. The graph signal in each window is a combination of clean signal and the variable error. To obtain a clean signal and in order to smooth it, a multi-objective optimization is built. The graph signal in each window is denoised by the solving this multi-objective optimization. After GSP filtering, the variable error is removed, however, owing to the natural fluctuations of eye balls, the signals appears to be a bit noisy resulting in jerky cursor movement. Hence smoothing is necessary which is achieved using Kalman filter.

C. Removal of Systematic Error

The systematic error is the drift or the disparity in the fixation data from the desired gaze location occurring due to lack of accuracy as shown in Fig.2. Changes in screen illumination, participants' ethnicity, viewing distance from the screen, fatigue of the participants, etc. also add to the degradation of the eye tracker accuracy [25]. In order to eliminate this error, linear transformation approach has been utilized. During the one-time calibration phase, as explained in section III, subjects are asked to look at 9 known points on the screen while visually tracking a ball as shown in Fig. 3(b). The ball moves on the screen in such a manner that both static and dynamic eye tracking data is acquired. The data obtained after applying GSP and Kalman filter is subjected to spatial transformation by minimizing the cost function between the ground truth and the obtained filtered gaze data [22], to derive transformation matrices \( T_G \) based on a Gaussian weighing function. Thus, the corrected gaze data \( \hat{C} \) from test data \( \hat{S}_T \) is given by (1),

\[
\hat{C} = T_G \ast \hat{S}_T
\]

The corrected data is then used to control the cursor movement over the screen. After the extraction of the 9 transformation matrices, each of them is compared for correctness. Ideally, if the raw data and the ground truth data, were exactly the same, then \( T_G \) would be an identity matrix with determinant equal to 1. So the determinant of \( T_G \) is calculated and a threshold of 0.8 is set empirically. If the determinant of \( T_G \) is less than 0.8, then it is rejected and a fresh set of data is collected.

III. Experimental Paradigm

15 subjects (8 female and 7 male, age-30±7yrs) with normal or corrected to normal vision are selected. None had any prior experience of using eye tracking controlled interfaces. All have similar educational background and learnt English as a second language from early childhood. At the beginning, they are explained the objective and the experiments. Ethical clearance has been obtained from our Institutional Review Board and informed consents are taken. The subjects sat in a chair with armrest. A chin-rest is used to minimize the head movements. The stimulus is shown on a 15 inch TFT screen (1366 × 768) kept at a distance of 50 cm. The EyeTribe is placed below the screen as shown in Fig. 3(a).

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During calibration, the subject has been asked to track a ball (diameter 20 pixels, moving with a speed of 60 pixels/sec) that appeared on the screen. The ball moves along nine paths (D1 through D8) as shown in Fig. 3(b). The ball remains static in each nine locations (1 through 9) for 5 seconds. The fixations are extracted for all these locations. The preprocessing and eye tracker noise removal is performed on the acquired data. Transformation matrices are generated from this calibration phase data and saved. These transformation matrices are utilized for each subject who participated in the study. So it is one time calibration for generating the transformation matrices and reduces preparation time without compromising the accuracy.

Fig. 4 shows various EyeAssist interface. Fig. 4(a) is the first screen that appears when EyeAssist is launched. The subjects can choose the onscreen keyboard mode (Fig. 4(b)) or the quick phrase mode for communication, entertainment mode to listen music or watch movie, book mode to read and gaming mode. This work concentrates on controlling the onscreen keyboard with the eye movements tracked by the eye tracker. As seen in Fig. 4(b), the text box (width: 1145 pixels, height 60 pixels) where the typed texts are displayed is placed on the top of the screen. Below which the predictive text entry boxes are placed. Maximum eight predictions can appear during typing. The character (letter) keys are arranged in alphabetical order considering the fact that disabled/aged people are not well accustomed with the QWERTY keyboards. The number and letter keys are of width 55 pixels, height 70 pixels and text is of Helvetica font of size 30 pixels. There is a gap of 15 pixels in between the keys to reduce the unintentional selection of the nearby keys. “Delete”, “Speak”, “Reset” and “Exit” keys are present on both right and left side to minimize the time required to reach these keys depending on the current cursor position. For a key to be selected, the cursor needs to stay on that particular key for a minimum time referred to as the Dwell time. There is a provision in the EyeAssist to change the dwell time from the ‘settings’ option present on the initial window (Fig. 4(b)) depending upon disabilities, needs, learning rate and cognitive abilities of an individual.

The subjects are instructed to write 5 sentences selected from the Mckenzie phrases [33] in 5 consecutive trials (T1, T2, T3, T4 and T5). The phrases are so selected that the number of characters in each of them varies between 16-18 characters.

In the next phase, to assess the improvements after some practice, five subjects are chosen and are asked to type first four phrases (T1-T4) in five sessions (S1-S5). The sessions (S1-S5) are conducted at different times over two days.

**IV. RESULTS AND DISCUSSION**

The dwell time (DT) is varied from 400ms to 2000ms. Five subjects participated in this experimentation phase of finalizing DT. They are asked to type the 3rd phrase (T3) with varying dwell time. A Performance Index (PI), is computed as,

\[
P.I = \frac{NC - NTE}{Time} \times 100
\]

where, NC is the total number of characters in the phrase. For T3 it is 16. NTE is the total number of errors. Time is the total time taken to eye-type the phrase. Fig. 5 shows the variation of PI for five subjects for different DT. The PI is highest when DT is 1.2 seconds, providing minimum error rate and enhancing text entry rate simultaneously. Thus for all further experiments, the DT is kept as 1.2 seconds.

The performance of the EyeAssist system is evaluated qualitatively as well as quantitatively based on few metrics as explained next. Time taken (Time), in seconds, is the total time elapsed between eye-typing of the first character till the last character of each trial. Uncorrected errors (UnEr) are the erroneous typing that remained in the typed phrase. Corrected errors (CoEr) are the number of erroneous characters typed which were corrected by the user, i.e. the number of “DELETE” key presses. Total error is (UnEr + CoEr), expressed in %. The text entry rate is defined as number of words typed per minute (WPM). Number of characters typed per minute (CPM) is also been computed, which includes the erroneous key selections and the “DELETE” keys as well.

![Fig. 5. Performance index with variation in dwell time](image)

**TABLE I. PERFORMANCE IN TERMS OF TIME TAKEN, ERRORS AND CPM**

<table>
<thead>
<tr>
<th>Trials</th>
<th>Time</th>
<th>UnEr</th>
<th>CoEr</th>
<th>CPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>88.4</td>
<td>1.34</td>
<td>0.34</td>
<td>21.31</td>
</tr>
<tr>
<td>T2</td>
<td>77.06</td>
<td>1.267</td>
<td>0</td>
<td>31.71</td>
</tr>
<tr>
<td>T3</td>
<td>67.67</td>
<td>0.87</td>
<td>0.2</td>
<td>36.42</td>
</tr>
<tr>
<td>T4</td>
<td>73.07</td>
<td>0.54</td>
<td>0.3</td>
<td>31.34</td>
</tr>
<tr>
<td>T5</td>
<td>74.27</td>
<td>0.6</td>
<td>0.07</td>
<td>32.35</td>
</tr>
</tbody>
</table>

![Fig. 6. (a)Word per minute (WPM) and total error (%) averaged over all the subjects for five trials 1-5, and (b) Learning curve of five subjects over four sessions.](image)

Table I shows the time, UnEr, CoEr and CPM averaged over all 15 subjects for trials T1 through T5. It can be observed...
from that the Time, UnCr and CoEr decreases and CPM increases gradually from T1 to T5. For all the subjects CoEr is very less, which indicates that the subjects (even novices) are committing minimal errors while using EyeAssist.

There are several reasons why EyeAssist outperforms other existing approaches. First, EyeAssist has comparatively high WPM and CPM as well as that the number of corrected errors are much lower. Moreover, the users also found the facility of setting variable dwell time is another reason why EyeAssist is user-adaptive. The proposed system also includes unique features like text to speech conversion, predictive word and sentence entry etc. which makes it extremely helpful for individuals suffering from speech impairments.

In future, the system is intended to be tested on large number of subjects specifically patients and would like to include more functionalities in the system based on patient’s feedback.
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