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

Anwesha Khasnobish, Rahul Gavas, Debatri Chatterjee, Ved Raj, Sapna Naitam
TCS Research & Innovation, Tata Consultancy Services Ltd,
India
Email:(anwesha.khasnobish, rahul.gavas, debatri.chatterjee, vedraj.4, sapna.naitam)@tcs.com

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 Amyotropic 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

978-1-5090-4338-5/17/$31.00 ©2017 IEEE

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.

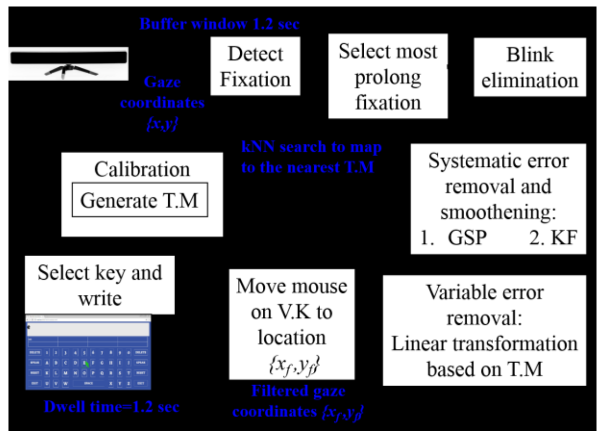

Fig. 1. EyeAssist: Overall system design

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].

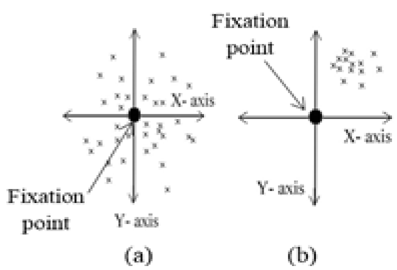

Fig. 2. Types of errors in eye-trackers (a) variable error (b) systematic error

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 $\vec{C}$ from test data $\vec{S}_T$ is given by (1),

$$\vec{C} = T_G * \vec{S}_T \qquad (1)$$

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).

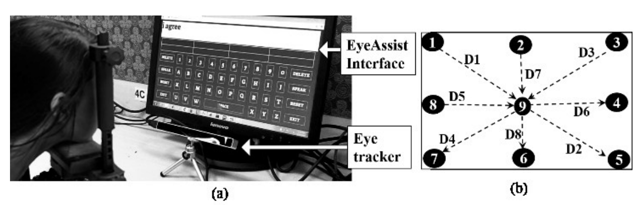

Fig. 3. (a)EyeAssist set up, (b)Calibration stimili of ball tracking.

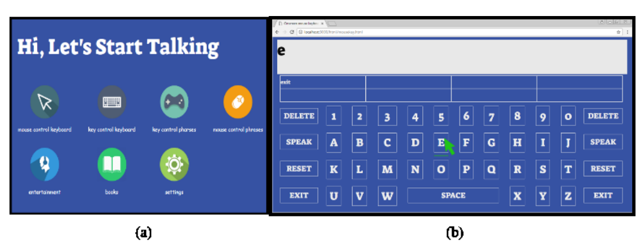

Fig. 4. EyeAssist user interfaces

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 30pixels. 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,

$$P.I = \frac{NC - NTE}{Time} \times 100 \tag{2}$$

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.

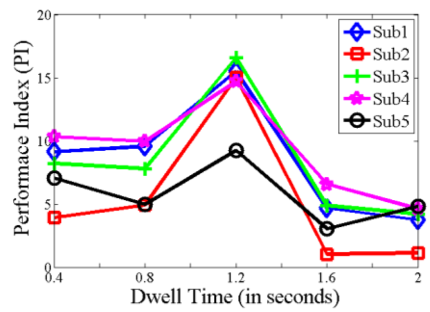

Fig. 5. Performance index with variation in dwell time

TABLE I. Perfomance in terms of time taken, errors and CPM

Trials	Time	UnEr	CoEr	CPM
T1	88.4	1.34	0.34	21.31
T2	77.06	1.267	0	31.71
T3	67.67	0.87	0.2	36.42
T4	73.07	0.54	0.3	31.34
T5	74.27	0.6	0.07	32.35

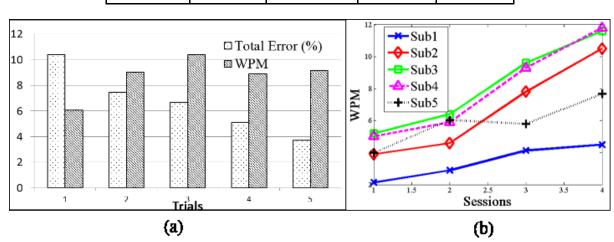

Fig. 6. (a)Word per minute (WPM) and toral error (%) averaged over all the subjects for five trials 1-5, and (b) Learning curve of five subjects over four sessions.

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.

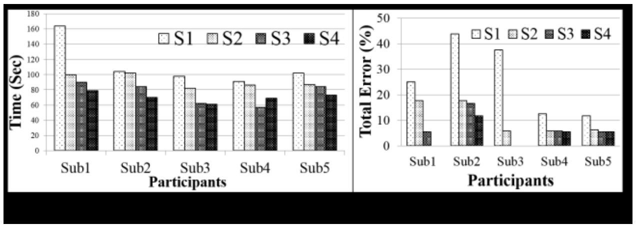

Fig. 7. (a) Time taken (in seconds) and (b) Total error rate of five subjects for four sessions

Fig. 6 (a) shows that the Total Error rate decreases from 1st to last trial, and hence the WPM increases. Maximum and average WPM have been computed to be 11.8 and 8.89 respectively. The minimum and average Total Error is found to be 0 and 6.6% respectively for all the subjects.

For presenting the detailed results, 5 subjects are chosen randomly, who performed four sessions (Session 1-4), where each session consisted of five trials. Fig. 7 (a) and (b) represents the change in Time and Total Error respectively. Maximum error rate is 44% for subject 2 in the 1st session, and is reduced to 10 % in the last session. Mean Total error for all 5 subjects, over 4 sessions is found to be 12%. For each subject, time has decreased from 1st till the last session. Thus the subjects are able to learn and adapt to the EyeAssist system with little practice. The learning curve portrayed in Fig. 6(b) shows that the text entry rate increases with time. These facts indicates that the EyeAssist performs well with novice users.

TABLE II. PERFORMANCE WITH RAW GAZE COORDINATE DATA

Trials	Time(sec)	Total Error (%)	WPM
T1	294	76.25	0.73
T2	363	81.25	0.860203
T3	324	64.47	1.21
T4	269	75	1.240948
T5	248	62.54	1.400914

Table II shows the performance of the system (mean of the metrics over all the subjects), when the raw gaze data are directly used typing, i.e without applying our proposed approach. It is evident that the raw gaze data is not suitable to be utilized for mouse cursor control. By implementing our proposed method, total error rate is reduced by 65% and WPM increases by 84%.

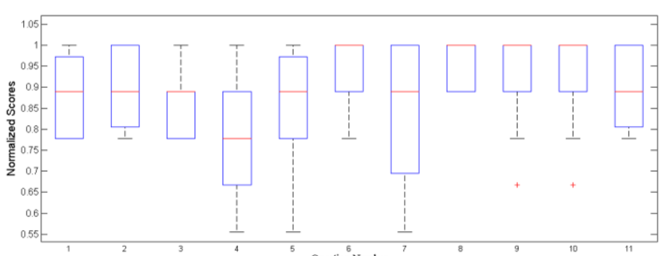

Fig. 8. Normalized scores given by all the subjects for the eleven questions in the IBM questionnaire.

After the typing sessions, the subjects are asked to rate their experiences with EyeAssist on IBM usability questionnaire [34]. The subject ratings for all 11 questions are averaged and normalized. Fig. 8 shows that mean score is more than 0.85 which substantiates the usability of the EyeAssist in terms of user experience.

Finally we compared the performance of EyeAssist, with existing state of the art systems. It is evident from Table III that EyeAssist has comparatively high WPM and CPM as well as that the number of corrected errors are much lower. Midas touch problem, which is highly faced in OptiKey [31], an available open source virtual interface, is not encountered in EyeAssist. This is due to usage of fixation data and selection of maximum prolonged fixation for noise removal and cursor control. Though the WPM of the system in [16] is more than EyeAssist, however, comparatively lower error rate and subject/trial independent calibration phase, makes EyeAssist more competent and user friendly. In terms of CPM also, EyeAssist outperforms other existing approaches.

TABLE III. COMPARISON WITH RELATED SYSTEMS

Approach	Remarks
EyeAssist	WPM=11.8(max),8.9 (mean), CPM= 30.6(mean) Time= 76.sec(mean),UnEr= 5.4%, CoEr= 1.07% Total Error= 6.6% (mean)
[14]	WPM=5.02, UnEr==1.88, CoEr= 11.27%, Total Error= 13.15%
[19]	Time= 188.5 sec, WPM=6.8
[13]	WPM= 12.3 (max), Error = 11.8%
[35]	CPM=9.3
[16]	WPM=9.8
[36]	WPM=7.99

V. CONCLUSION

This paper presents EyeAssist, a novel, low cost, unobtrusive, IR eye tracking based communication aid mainly designed for neuro-motor disabled people. The system utilizes EyeTribe eye tracker to acquire the gaze coordinates. Most prolonged fixations are detected from set of available gaze coordinates in a particular time window. The variable and systematic errors inherent to eye trackers are eliminated by novel GSP, Kalman Filtering and linear transformation techniques. This system requires one time calibration, which is independent of subjects over trials and sessions. In terms of the text entry rate and error rate, the system outperforms related state of the art approaches. Moreover, the users also found the system to be very user friendly, easy to understand and learn. 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.

ACKNOWLEDGMENT

We would like to thank all the subjects who enthusiastically participated in the study. Special thanks to Arpan Pal, Aniruddha Sinha, Kingshuk Chakravarty, Soumya Ranjan Tripathy, Arpit Viswakarma, Anagha Deshpande and Ratnamala Manna for helping us throughout the development and testing phase of EyeAssist.

REFERENCES

[1] H.I. Krebs, B.T. Volpe, M.L. Aisen, W. Hening, S. Adamovich, H. Poizner, K. Subrahmanyan, and N. Hogan, "Robotic applications in neuromotor rehabilitation," Robotica, vol. 21(01), pp.3-11, 2003.

[2] M. Sabbadini, R. Bonanni , G.A. Carlesimo, and C. Caltagirone, "Neuropsychological assessment of patients with severe neuromotor and verbal disabilities," J. Intell. Disability Res., vol.45(2), pp.169-79, 2001.

[3] T. Magnus, M. Beck, R. Giess, I. Puls, M. Naumann, and K.V. Toyka, "Disease progression in amyotrophic lateral sclerosis: predictors of survival," Muscle & Nerve, vol. 25(5), pp. 709-14, 2002.

[4] B. Wilhelm, M. Jordan, N. Birbaumer, "Communication in locked-in syndrome: effects of imagery on salivary pH," Neurology, vol. 67(3),pp. 534-5, 2006

[5] G. Dornhege, Toward brain-computer interfacing. MIT press, 2007.

[6] A.R.Murguialday, J. Hill, M. Bensch, S. Martens, S. Halder, F. Nijboer, B. Schoelkopf, N. Birbaumer, and A. Gharabaghi A, "Transition from the locked in to the completely locked-in state: a physiological analysis," Clinical Neurophys., vol.122(5), pp.925-33, 2011.

[7] U. Lahiri, Z. Warren and N. Sarkar, "Design of a Gaze-Sensitive Virtual Social Interactive System for Children With Autism," *IEEE Trans. Neural Sys. Rehab Engg.*, vol. 19(4), pp. 443-452, Aug, 2011.

[8] J.D. Smith and T.C. Graham TC, "Use of eye movements for video game control," Proc ACM SIGCHI Intl. Conf. Adv. Comp. Ent. Tech., pp. 20, 2006.

[9] O. Palinko, A.L. Kun, A. Shyrokov, and P. Heeman, "Estimating cognitive load using remote eye tracking in a driving simulator," Proc. Symp. Eye-tracking Res. & App., pp. 141-144, 2010.

[10] D. Zhu D, T. Gedeon, and K. Taylor, "Moving to the centre: A gaze-driven remote camera control for teleoperation," Interacting with Computers, vol. 23(1), pp. 85-95, 2011.

[11] A. Ubeda, E. Iañez and J. M. Azorin, "Wireless and Portable EOG-Based Interface for Assisting Disabled People," *IEEE/ASME Trans. Mechatron.*, vol. 16(5), pp. 870-873, Oct, 2011.

[12] A.M. Al-Rahayfeh, and M.I. Faezipour, "Eye tracking and head movement detection: A state-of-art survey," IEEE J. Transl. Engg. in Health and Medicine, pp.2100212, 2013.

[13] I. S. MacKenzie, and X. Zhang, "Eye typing using word and letter prediction and a fixation algorithm," Proc. ACM Symp. on Eye Tracking Res. and App., pp. 55-58. New York, 2008.

[14] P. Panwar, S. Sarcar, and D. Samanta D, "EyeBoard: A fast and accurate eye gaze-based text entry system," Proc. IEEE Intl. Conf. Intel. Human Comp. Interation, pp. 1-8, Dec 2012.

[15] P. O. Kristensson and K. Vertanen, "The Potential of Dwell-free Eyetyping for Fast Assistive Gaze Communication," Proc. ACM Symp. Eye Tracking Research and Applications, pp. 241–244, 2012.

[16] P. Majaranta and K. J. R¨aih¨a, "Text Entry Systems: Mobility, accessibility, universality," CA: Eds. Morgan Kaufmann, ch. Text Entry by Gaze: Utilizing Eye-tracking, San Francisco, 2007, pp. 175–187.

[17] H. Istance, R. Bates, A. Hyrskykari, and S. Vickers, "Snap Clutch, a Moded Approach to Solving the Midas Touch Problem," Proc. ACM Symp. on Eye tracking Res. & App., pp. 221–228, 2008.

[18] V. Prabhu, and G. Prasad, "Designing a virtual keyboard with multi-modal access for people with disabilities," Proc. IEEE World Congress on Info. and Comm. Tech. pp. 1133-1138, Dec 2011.

[19] M. Porta, and T. Matteo, "Eye-S: a full-screen input modality for pure eye-based communication," ," Proc. ACM Symp. on Eye tracking Res. & App., pp. 27-34, 2008.

[20] J. SuneAlstrup, J.S Agustin, H. Skovsgaard, J.P. Hansen, and M. Tall, "Low cost vs. high-end eye tracking for usability testing," ACM Extended Abstracts on Human Factors in Computing Systems, pp. 1177–1182, 2011.

[21] A.J. Hornof, and T. Halverson, "Cleaning up systematic error in eye-tracking data by using required fixation locations," Behavior Research Methods, Instruments, & Computers, vol. 34.4, pp. 592-604, 2002.

[22] M.A. Vadillo, C.N. Street, T. Beesley, and D.R. Shanks, "A simple algorithm for the offline recalibration of eye-tracking data through best-fitting linear transformation," Behavior Research Methods, vol. 47(4), pp. 1365-1376, 2015

[23] C. Morimoto, A. Amir, and M. Flickner, "Detecting eye position and gaze from a single camera and 2 light sources," Proc. Intl. Conf. on Pattern Recog., pp. 314–317, 2002.

[24] Z. Ramdane-Cherif, and Amine NaÏt-AliNait-Ali, "An adaptive algorithm for eye-gaze-tracking-device calibration," IEEE Trans. Instru. and Meas., vol. 57(4) pp.716-723, 2008.

[25] P. Blignaut, and D. Wium, "Eye-tracking data quality as affected by ethnicity and experimental design," Behavior Research Methods, vol.46(1), pp. 67-80, 2014.

[26] D.D.Salvucci, and J.H. Goldberg, "Identifying fixations and saccades in eye-tracking protocols," Proc. Symp. on Eye Tracking Res. & App. pp. 71-78, 2000.

[27] I. Sen, and T. Megaw, The effects of task variables and prolonged performance on saccadie eye movement parameters, A. G. Gale & F. Johnson (Eds.), Theoretical and Applied Aspects of Eye Movement Research, Amsterdam: Elsevier, 1984, pp. 103-111).

[28] D. I. Shuman, S. K. Narang, P. Frossard, A. Ortega, and P. Vandergheynst, "The emerging field of signal processing on graphs: Extending high dimensional data analysis to networks and other irregular domains," IEEE Signal Processing Magazine, vol.30(3), pp. 83–98, 2013.

[29] N. Obolensky, Kalman filtering methods for moving vehicle tracking, Ph.D. thesis, University of Florida, 2002

[30] T.C. Mills, Time series techniques for economists,Cambridge University Press, 1991.

[31] Availble at: https://github.com/OptiKey/OptiKey/wiki Available at: http://dev.theeyetribe.com/

[32] Available at: http://dev.theeyetribe.com/

[33] I.S. MacKenzie, and R.W. Soukoreff, "Phrase sets for evaluating text entry techniques," Extended Abstracts on Human Factors in Computing Systems, pp. 754-755, 2003.

[34] J.R. Lewis, "IBM computer usability satisfaction questionnaires: psychometric evaluation and instructions for use," Intl J. Human-Computer Interaction, vol. 7(1), pp. 57-78, 1995.

[35] H.A. Cecotti, "Multimodal Gaze-Controlled Virtual Keyboard," IEEE Trans. Human-Machine Systems, February 2016.

[36] Porta, Marco, and Matteo Turina. "Eye-S: a full-screen input modality for pure eye-based communication." Proceedings of the 2008 symposium on Eye tracking research & applications. ACM, 2008.

[37] J.O. Wobbrock, J. Rubinstein, J. Sawyer and A.T. Duchowski, "Not Typing but Writing: Eye-based Text Entry Using Letter-like Gestures," Proc. Conf. Comm. by Gaze Interaction, pp. 61-64,2007.