Investigating classification methods to improve eye-tracking systems operation

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Abstract: There are different problems with Eye-tracking systems such as users' head movements, multi-user compatibility and environment's light variation that reduce the accurately of these systems. The current research investigates the performance of using classifiers in the calibration stage of an infrared eye-tracking system on 10 subjects several times. The results show that classifiers can reduce the mentioned problems and improve the operation of the system to recognize the eye-gaze direction more accurately and furthermore give the system the ability to adjust with various interferential factors that will be interesting and important for a number of applications requiring human–computer interfaces.

Keywords: human computer interface; eye-tracking technology; classification, algorithm; infrared tracking; biomedical engineering.

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algorithms. Particular applications include: EEG signal processing in mental task activities, hypnosis, BCI and epileptic seizure prediction.

1 Introduction

Using eye gaze to create a practical eye-tracking system has long been a goal of human computer interaction research for either providing the usability of a computer or a system for handicapped people, or improving the human abilities in controlling an external system (Salvucci and Anderson, 2001; Rudman et al., 2003; Kim and Ramakrishna, 1999; Amarnag et al., 2003). Eye-tracking systems have also been used in developing equipment to help analyse human behaviour (Merten and Conati, 2006; Klinger, 2010) and in diagnostic procedures in the field of ophthalmology (Saraux, 1989; Hutton et al., 1987; Salz, 1999; Pinckers, 1979). Several methods and products were developed for tracking the eye gaze of humans such as Electro-Oculography (EOG), which relies on recordings of the electric potential differences of the skin surrounding the ocular cavity (Pinckers, 1979; François et al., 1956; Bulling et al., 2008; Sharifi and Masoomi, 2002; Norris and Wilson, 1997) that was the most widely applied technique during the mid-1970s (Young and Sheena, 1975). To improve accuracy, techniques using a contact lens were developed in the 1950s. Devices attached to the contact lens ranged from small mirrors to coils of wire. The obvious drawback of these devices is their invasive requirement of wearing the contact lens (Murphy et al., 2001; Geest and Frens, 2002; Houben et al., 2006; Träisk et al., 2005, 2007; Schmitt et al., 2006). The so-called non-invasive (sometimes called remote) eye trackers typically rely on the measurement of visible features of the eye, e.g., the pupil, iris–sclera boundary, or a corneal reflection of a closely positioned, directed light source (Aslin and Murray, 2004; Franchak et al., 2010; Ryan et al., 2008; Morimoto et al., 2000; Morimoto and Mimica, 2005). The next method called Video-Oculography (VOG) works with a camera sensor and capture the human face to detect and interpret the human gazes (Hirvonena and Aalto, 2009; Kujala et al., 2005); this method is non-invasive and contactless. Another non-invasive and contactless method that was employed in the current research is IR-tracking, which works based on the reflection of IR light by the area on both sides of the edge between the white sclera and the darker iris (Träisk et al., 2005; Nguyen et al., 2002; Nielsen and Pernice, 2009).

The mentioned prior art systems based on different eye movement measurement techniques suffer from changing the various interferential factors such as environment light, head movement and changing the user (with different sizes of head and eye) during the use. Because of these problems, the user cannot accurately select the correct targets and they have found it difficult to manipulate the interface without getting into difficulties. Therefore, the mentioned factors inhibited the use of promising and potentially highly enabling eye-tacking technologies.

In this research, it is tried to minimise the effect of these interferences and to optimise the performance of eye-tracking techniques, using classification algorithms in the software of the eye-tracking systems.

On the basis of different examination, we have found that considering a short-time calibration procedure, which is designed based on a classification algorithm, can improve the operation of the system to accurately identify the correct eye-gaze direction.

In this study, evaluating the effect of new algorithms was done based on the output signals of an IR-tracking system, but the result can be extended on the other introduced eye-tracking methods. In the next section, the system's hardware, its basic software, the detailed description of the testing procedure and the experimental result of non-improved system are presented. Section 3 describes the classification algorithms and their effect on the eye tracker system. The results of the improved system are discussed and a new eye-movement-based mouse control system that is designed based on the proposed algorithm is introduced. This system allows the user to type and also perform different games just with his or her eye movement. The last section includes the conclusion of the suggested algorithms' efficiency on the eye-tracking system's operation.

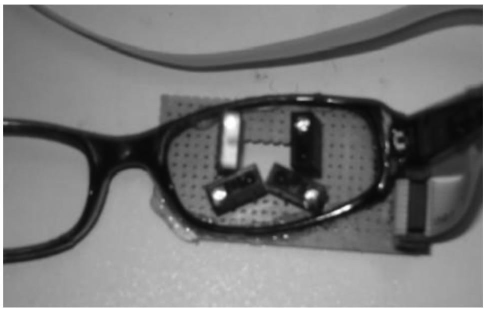
2 System overview

2.1 System's hardware

In our system, we have used IR photoelectric oculography (IR-Tracking) method that is contact-free and can be used for a long time without any discomfort for the subject (Sliney and Wolbarsht, 1980; Lin et al., 2005). This was important because the experiment lasted at least 1 h. The system works based on the principle of reflection of IR light by the sharp boundary between iris and sclera, the limbus.

Four IR Light Emitting Diodes (LEDs) and IR-sensitive detectors are mounted on the goggles worn by the subject (Figure 1), so that the receptive fields match the iris–sclera transition, both on the nasal and on the temporal side (Figure 2).

Figure 1 Four IR receivers and transmitters that were mounted on the goggles



Upon horizontal rotation of the eye, for example in the case of abduction, the nasally positioned detector will measure an increased scleral IR reflection, while the temporally placed detector measures a decreased iris reflection. Subtraction of the nasal and temporal detector signals gives a measure for horizontal eye movements. In vertical eye movements (as an example when the eye moves down), third and fourth detectors measure a decreased iris reflection. Because coloured part of the eye will situate opposite of these receivers, summation of these two detectors signals gives a measure for vertical eye movements.

Figure 2 The sighting position of four light transmitters and receivers

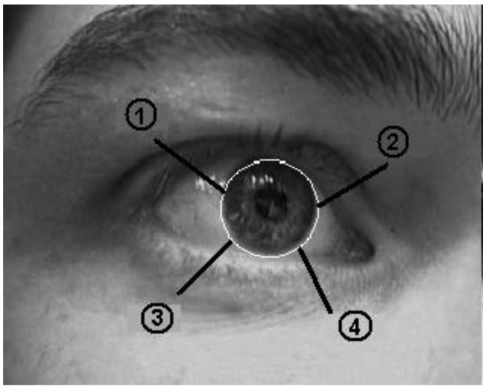
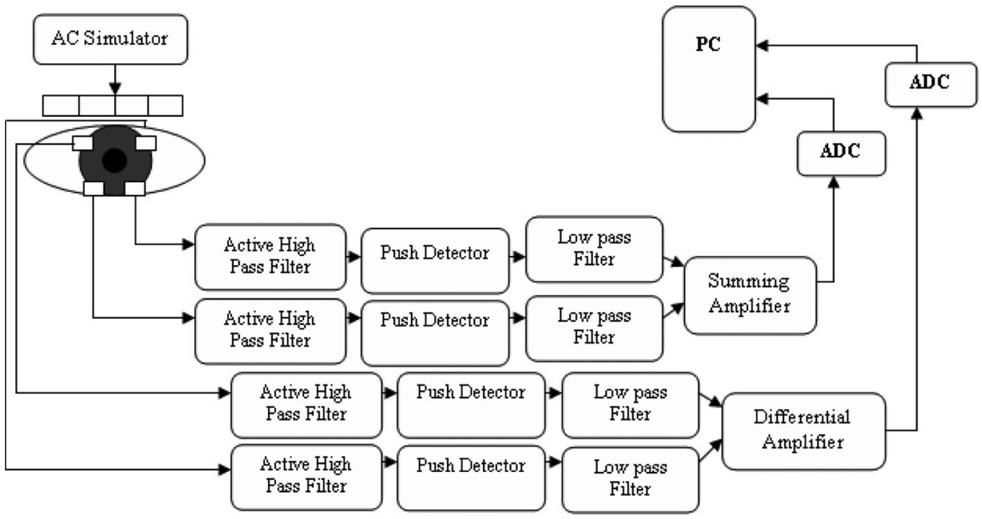


Figure 3 shows the system's block diagram. LEDs were stimulated with a pulse wave (250 Hz squared wave). Using pulse wave gives time to LEDs for cooling, so the IR LEDs can tolerate a higher level of current. Similarly, the eye tolerates higher illumination intensities when the illumination is pulsed.

Figure 3 Block diagram of the eye-tracking system



The detectors will collect a combination of three light sources:

- reflected light from eye movement that its frequency is about 1 Hz
- the light of LEDs
- IR light that exists in the environment.

The output signals of these detectors pass a high-pass filter, so the DC value that arises from photodiode's bias will be removed and we can have more amplification in next stages.

A simple push detector was used for separating the signal that arises from eye movements (its frequency is less than 1 Hz) from modulator pulse. A low-pass filter was considered for removing the variation of carrier signal. These operations are executed on each of these four detectors signals that are located around the eye. As it was mentioned before, summation of third and fourth detectors signals gives a measure of vertical eye movements and subtraction of first and second detectors signals gives a measure of horizontal eye movements; a summing and differential amplifier can implement these operations. Output of these two amplifiers enters to two microcontroller's A/D and after required processing in microcontroller, they will be sent to PC via serial port.

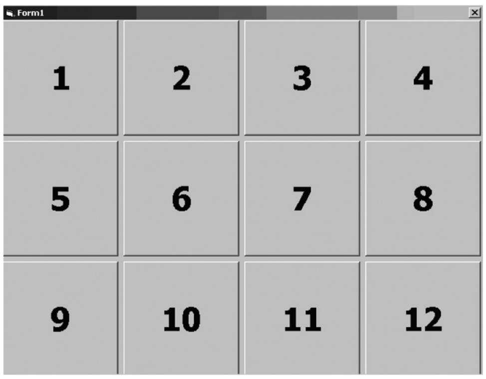
2.2 System's software

For the data acquisition and data analysis, a software was designed using visual basic language. This software includes two main parts, system's calibration (or training) stage and monitoring the eye-gaze point on the monitor screen.

Calibration stage was considered to set the system on new condition resulting from dissimilarity between recorded signals from different people. User can perform calibration by moving his or her eyes on calibration part on monitor's screen, in the start of using the system and also whenever the user feels the performance of the system falls owing to his or her unwanted head movements or other interferential factors.

Executing the calibration, first, a message appears on the monitor's screen that wants the user to gaze at a number of cells on monitor's screen, as an example Figure 4 shows calibration stages with 12 points, which each of them, respectively, starts to flashing for a few seconds (about 2 s) and the user should look at them until stop of flashing. It should be noted that the number of these cells will be increased by increasing the system's resolution. In other words, number of calibration points is equal to the number of points that are discernible by the eye-tracking system.

Figure 4 Twelve considered cells on monitor's screen



Software, respectively, receives the data that belongs to each cell. So, at the end of calibration stage, data range of x, y orientation is specified for each cell. Averaging the X values of each column and Y values of each row, an X and Y value is attributed to each column and row. Indeed, updating these X and Y values in each repetition of calibration stage, the system will set on new condition. After calibration stage, a page that includes different numbers will appear on screen. When user looks at a number, software compares the received data with *X* and *Y* value of each column and row and by this comparison, it recognises the number that is selected by user (eye-gaze point). Looking and staying for a few seconds on each cell (about 2 s), means as clicking the cell. The details of the system are summarised in Table 1. The system based on this simple algorithm was examined on different users that the details of the testing procedure and its results were reported in the following parts.

Table 1 System's specifications

Feature	*Value*
Measuring technique	Differential IR light reflection technique with amplitude modulation
Frequency of carrier wave	250 Hz
Eye Illumination diode	4 IR light diodes (ON2179)
IR light irradiance	within recommended safety limits (about 8.75 mW/cm2)
Distance between illumination diode and eye	The diodes are mounted on a goggles
Distance between eye and monitors	100 cm (can vary between 50 cm and 130 cm)
Recording range	Vertical: ±15° , Horizontal: ±35°
Recording configuration	Simultaneous horizontal or vertical eye movement recording of one eye(can be extended to two eyes)
PC Requirements	Windows, serial port

2.3 Testing procedure's details

To investigate the operation of the system with different algorithms, it was tested with 10 people with no disabilities, five men and five women. Before starting the test, necessary information about the system were given to the subjects. For more confidence and validating the results, the test was executed several times on each subject.

The testing procedure can be divided into the subject set-up, calibration and monitoring and measuring the system's resolution (the distance between two points on monitor's screen that are discernible by the system). In the subject set-up phase, the subject is seated in front of the monitor (15") by the distance of 100 cm and the goggles' of the eye-tracking system (Figure 1) are worn by the subject. To run the system, the communication cable of the system is attached to the PC's serial port and then the designed software is executed. Now, the system is ready to perform the calibration and then monitoring phase. After the execution, a massage appeared on the monitor that describes the calibration procedure for the user. Then in the calibration phase, a calibration pattern consisting of a number of calibration points is shown to the subject. The subject is asked to direct his or her gaze to each of the calibration points and the location of *X* and *Y* value for each calibration point is recorded as was described in details in the previous part. Finishing the calibration phase, the monitoring phase will start. The values from the calibration are used in calculating the locations of points of gaze from the values received from the eye-tracking system in the monitoring phase. In this phase for measuring the resolution of the system, a page with 192 cells (16 columns and 12 rows, the distance between each cell is about 2 cm) is presented on monitor's screen (Figure 5).

Figure 5 192 considered cells on monitor's screen

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112
113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160
161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176
177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192

Then, it is asked from the user to try to place the cursor on each cell by gazing at each cell, respectively, from 1 to 192. Then, the distance between a cell and the next cell that are distinguishable by the system (the user can correctly put the cursor on them by his or her eye gaze) is measured; an average of these distances is considered as the eye-tracking system's resolution.

Horizontal resolution is the average of the distances that are measured from two neighbour cells in a row and vertical resolution is the average of the distances that are measured from two neighbour cells in a column.

2.4 Experimental result of non-improved system

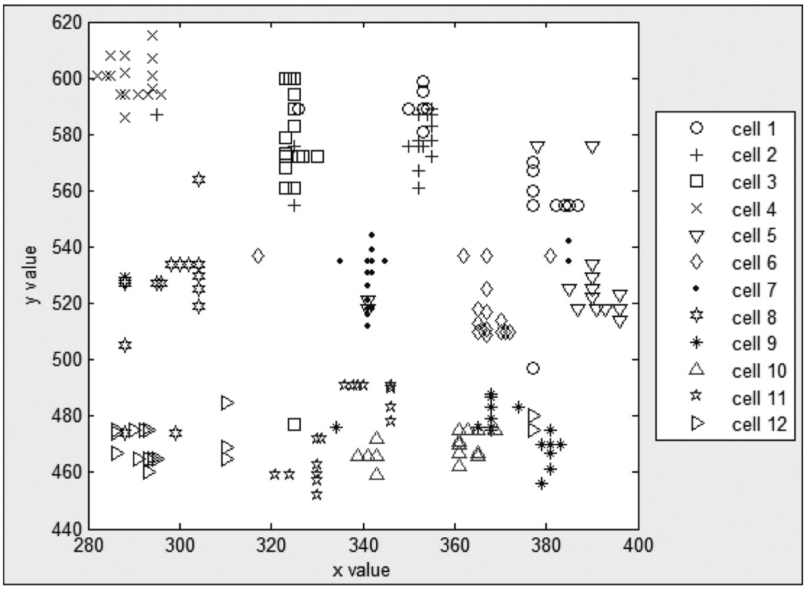
The examinations result shows that using the mentioned algorithm the vertical and horizontal resolutions of the system are, respectively, about 7.11 ± 1.3 cm and 6.13 ± 0.7 cm. The obtained resolution means that the current eye-tracking system with non-improved software can recognise 12 cells on monitor's screen, 4 columns and 3 rows (Figure 4). According to this result, the number of cells was reduced to 12 cells and the procedure was repeated and the X and Y values that belong to each of these 12 cells were collected and plotted when the user's eye gaze is on each of them (Figure 6).

According to Figure 6, it was seen that the related data of each of these 12 cells could be considered as a class of data. So, this idea is brought to mind that a classifier can recognise and separate the data of each class. Therefore, in our research we examined two classifying methods to improve the system's resolution.

3 Classification methods

It was shown that classification is one of the important parts of different studies, especially in developing diagnostic methods in medicine (Arigon et al., 2010). Two classifiers were

Figure 6 Collected data with the user eye gaze on each cell



investigated in this paper, Multi Layers Perceptron (MLP), neural network (Haykin, 1998) and K-Nearest Neighbourhood (KNN)-based classifier (Bubeck and Luxburg, 2009). Using a classifier needs some data for making the classifier model, which are called training data. In our suggested system, gathering the training data and making the classifier model is done in the calibration stage. Therefore, by finishing the calibration stage the classifier model is ready for use. In other words, in the calibration stage, it is wanted from the user to hold his or her eye gaze on each cell for a few seconds (until finishing the cell flashes). During this eye-gaze holding, the software gathers the data, which belongs to the cell that the user eye gaze is on it. Therefore, at the end of calibration stage the system has the related data of each cell (class). On the basis of these data, the classifier model will be made and whenever the user put his or her eye gaze on a cell, the software receives the data and gives it to the designed classifier to characterise that the data belong to which class (cell).

3.1 MLP neural network's result

The selected network in this study is a network with two hidden layers, where, respectively, there are five and four neurons in each layer (this structure is selected based on trial and error). Neurons function is tangent sigmoid. This network is trained using received data in calibration stage, so that the *X* and *Y* value of the received data is considered as the network input (each data belongs to a cell that the user put his or her eye gaze on it) and the cell's number is considered as the network output. According to the selected neurons function (tansig), network output extremely is between zero and one, so normalisation of the data is necessary. This is done by dividing the output of training data (the cell's number) by the number of cells. For renormalisation, network output is multiplied by the number of cells and the result is rounded off to obtain the cell's number that is predicted by the network. Gathered data in calibration stage (40 data for each cell) were considered as the training data for making the network and the data that are received after calibration were considered as the test data. Cross validation of the results shows that the resolution of the system with this new suggested algorithm is about 3.15 ± 0.8 cm for vertical and 3.10 ± 0.5 cm for horizontal movement. In other words, the number of cells that are distinguishable by the eye-tracking system has increased from 12 to 48 (8 columns and 6 rows). Therefore, the result shows that the operation of the system has improved in comparison with the previous algorithm (the system without classifier).

In the next stage of our study, we examined the operation of the system with a KNN-based classifier.

3.2 KNN-based classifier's result

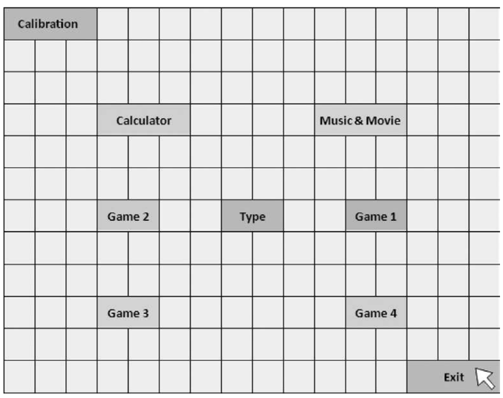
KNN algorithm is a method, which does not need to calculate any parameter for making a classifier, i.e., like the neural-network-based classifier; we need not estimate the classifier's parameters, for example, the weight of the neurons. We just select an appropriate K and start the classification. In this method, the proximity of neighbouring input (x) observations in the training data set and their corresponding output values (y) are used to predict (score) the output values of cases in the validation data set. Like the previous classifier, gathered data in calibration stage (40 data for each cell) were considered as the training data and the data that are received after calibration were considered as the test data. The measuring of the adjacency of neighbouring input (x) is done, using some distance function. In this project, Euclidean distance function was used and the selected value for K was five (selected based on trial and error).

Cross validation of the results shows that the resolution of the system based on the KNN algorithm is about 1.53 ± 0.5 cm for vertical and 1.3 ± 0.3 cm for horizontal movement, which means that all of the 192 points in Figure 5 can be approximately discerned by the eye-tracking system. This result shows more improvement compared with the previous algorithms.

On the basis of this result, we have suggested and designed an interface that allows the user to communicate with computer using his or her eye movement.

In this system after executing the designed software and passing from calibration phase, a graphical interface form, which is shown in Figure 7, is presented.

Figure 7 Graphical view of the designed interface based on the improved eye-tracking system (The empty cells can be considered for other future operations)



Nine procedures were considered in this interface form: calibration, type, calculator, music and movie, 4 games and exit. When the user gazes at the cells of each of these procedures and holds his or her gaze on the cell for about 2 s, the related procedure will execute.

- *Calibration*: One significant problem in eye tracking is the drift effect, which indicates a deterioration of the calibration over time (Tobii, 2003). The drift effect is because of the user's unwanted head movements and changes of the environment's light intensity between calibration stimuli and the experiment. Therefore in the current software we have considered the calibration cell, which allows the user to recalibrate the system by putting his or her gaze on this cell. When the user holds his or her gaze on this cell for about 2 s, the calibration procedure will start automatically and the system will adjust itself with the new condition. In fact, this readjustment will be done by changing the parameter of the classifier model. The user can repeat this procedure by his or her eye gaze without using external help whenever he or she feels that the system does not work as well as the first. Finishing the recalibration procedure, the first page of the program (Figure 7) will present automatically.
- *Type*: If the user wants to type with his or her eye movements, he or she should put his or her gaze on this cell. When the user holds his or her gaze on this cell, the cursor will jump from its previous position to this cell. If the user holds his or her gaze on this cell for about 2 s, a graphical interface form, which is shown in Figure 8, will be presented. This form will allow the user to type by putting and holding his or her eye gaze on each character for about 2 s. The selected character will be shown under the designed form. The user can remove the wrong characters, can recalibrate the system, can save the work or can return to the main page by putting his or her gaze, respectively, on 'Backspace', 'Calibration', 'Save' and 'Return' cells. The typed characters will be saved by '.txt' format.
- *Calculator*: If the user holds his or her gaze on this cell for about 2 s, a graphical interface form, which is shown in Figure 9, will be appeared that allows the user to calculate by putting and holding (about 2 s) his or her eye gaze on different numbers of operators.
- *Music and Movie*: If the user wants to listen to music or see a movie, he or she should hold his or her gaze on this cell for about 2 s. A graphical interface form, which contains different music and film, will be presented that allows the user to run each of them by putting and holding his or her eye gaze on them for about 2 s (number of music and films are restricted to 192).
- *Games*: Four games were considered in the current software. If the user holds his or her gaze on each of them, the graphical environment of each game will be presented. These games are easy and interesting and the user can play them just with his or her eye movement. In the main page of each game, as the same as previous options, there is a cell for 'Return'ing to the main page, a cell for 'Calibration' and a cell that 'Helps' the user to understand how to play the selected game.
- *Exit*: If the user wants to terminate the program, it is enough to put his or her gaze on this cell for about 2 s.

Therefore by this program that was designed based on a KNN-based classifier in its calibration procedure, the user can communicate by the computer with his or her eye movement. This program is just a suggestion that is designed for an IR-eye tracking system, but the introduced algorithm can be used and extended for other systems that work based on different eye-tracking methods.

Figure 8 Graphical view of the designed interface form for typing by eye movement

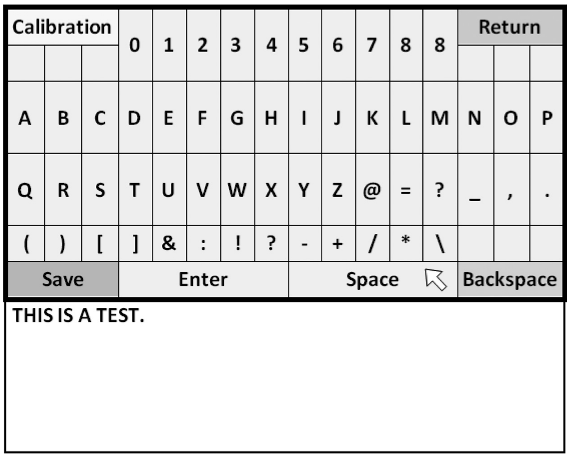
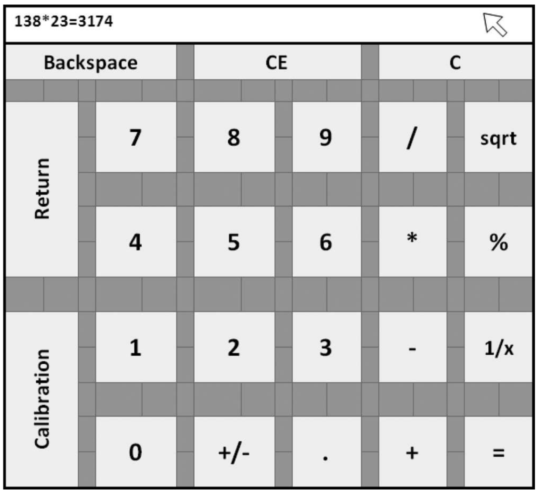


Figure 9 Graphical view of the designed interface form for calculating by eye movement



4 Discussion

Following the obtained result, it was shown that using the ability of classification method, an eye-tracking system can be designed that its performance is more acceptable than the tracking system without classifier. In fact, the classifier makes the system more resistant to the unexpected changes. The proposed method can also be used in other tracking systems (such as the system that (Hou et al., 2008) proposed in their study). The designed system, which works as an interface between computer and the user, could be useful to help handicapped people who because of some accidents (such as spinal cord injury) could not use their hand. These people often isolate themselves and feel depressed because they think they do not have the ability to communicate with the society. Therefore, such a system can provide a simple way to help these people to learn how to use the other ability of their body to overcome their problems. So this system can be one of the valuable systems in the rehabilitation field, which recently researchers put more attention on it (Petroni et al., 2010; Naik et al., 2011). Making a communication channel between the handicapped people and computer is one of the goals of the experts in the field of rehabilitation. On the basis of this goal, different studies were formed to design an interface between the users and computers, for example, Khan and Sepulveda (2011). The proposed system can also be categorised as a human computer interface.

Furthermore, by a little change in the software this system can be used in hospitals to help the patients to communicate with the doctor and nurses just with their eye movements that can be useful for the patients who can speak hard because of their severe disease.

The other application of this system is in ophthalmology. After an open or close eye surgery, the ophthalmologist should understand that the patient can move his or her eye in different directions correctly or not, so this system can be used to track eye movements in different directions.

Therefore, it can be claimed that the system with the proposed algorithm can be used in different fields of healthcare delivery by making some little changes in its application software.

To increase the resolution of the system, the authors propose recording the eye movements signals from both eyes. This may increase the ability of the system to identify more points on the monitor. The second suggestion is that the system be designed as a wireless system, which gives more freedom to the user.

5 Conclusion

In this study, the effect of using two different classifiers in an eye-tracking system was investigated. The results that are recorded in Table 2 show that by the use of the classification algorithms in eye-tracking system's software, the operation of the system in recognition of eye-gaze point on monitor screen can improve because the effects of introduced interferential factors are considered in the training stage and whenever the user feels the reduction of system's efficiency, recalibrating the system can adjust it with new condition.

Table 2 System's vertical and horizontal resolution

Method	*System vertical and horizontal resolution (cm)*
System without classifier algorithm	7.11 ± 1.3 and 6.13 ± 0.7
System with mlP neural network classifier	3.15 ± 0.8 and 3.10 ± 0.5
System with KNN-based classifier	1.53 ± 0.5 and 1.3 ± 0.3

On the basis of the obtained result, the KNN classifier was more effective than mlP network. Furthermore, KNN-based classifier has this advantage that it does not need to training procedure to estimate the classifier parameters such as neurons weight in neural networks, so it saves the time in the calibration stage.

In this research, 192 cells (classes) were considered on the monitor screen, but this number could be increased to cover more space on monitor screen. Increasing the number of cells (classes) may need to use a stronger classifier.

The suggestion of using classifier in eye-tracking system's software was investigated on an IR-tracking system's output. However, the eye-tracking systems that work based on the other tracking method can employ this suggestion in their system's software. For example, in an image-recording-based system, instead of tracking direction changes of considered features in the recorded images, it is suggested that in the calibration stage, the user puts his or her eye gaze on the considered cells on monitor screen for few seconds and the software records images that relate to the user eye gaze on different cells. Then, a classifier model is made based on these recorded images. After calibration, whenever the user looks at a cell on monitor, the classifier characterises the cell (class) that is selected by the user.

As the classifier model is created based on the data that are recorded from the user eye gaze on monitor screen, by this method the system will be compatible itself by the environment's light and user's features such as size of the eye. Therefore in the middle of the system operation if a user wants to change his or her place with another user, repetition of calibration stage is just enough to adjust the system parameters with the new user. Recalibration of the system that can be done by the user's eye gaze without any external help or using the real mouse, in fact, changes the classifier parameter and is also useful for solving the problem of unwanted head movements during the use.

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