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A SURVEY OF EYE TRACKING METHODS AND APPLICATIONS

BY

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Abstract. In the last decade, the development of eye tracking (ET) systems represented a challenge for researchers and different companies in the area of IT, medical equipment or multimedia commercial devices. An eye tracking system is based on a device to track the movement of the eyes to know exactly where the person is looking and for how long. It also involves software algorithms for pupil detection, image processing, data filtering and recording eye movement by means of fixation point, fixation duration and saccade as well. A large variety of hardware and software approaches were implemented by research groups or companies according to technological progress. The suitable devices for eye movement acquiring and software algorithms are chosen in concordance with the application requirements. Some vendors (*e.g.* SensoMotoric Instruments, Tobii or MyGaze) have invested in eye tracking technology, but their solutions are focused on commercial remote camera-based eye-tracker systems for which the light source and camera are permanently affixed to a monitor. Because these commercial systems including software and support are expensive some mobile and low cost devices for eye tracking were developed by some research groups. The eye tracking applications covers human computer interaction, brain computer interaction, assistive technology, e-learning, psychology investigation, pilot training assistance, virtual and augmented reality and so on.

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1. Introduction

Eye tracking is a technique whereby the position of the eye is used to determine gaze direction of a person at a given time and also the sequence in which there are moved (Poole & Ball, 2006). That is useful for scientists who try to understand movements of the eye while a person is involved in different activities. Different techniques where developed over the years according to technology available at that time.

Emile Java (French ophthalmologist, 1839 - 1907) was among the first who describe in 1879 the movements of the eye during text reading. He observes with a the help of a mirror, that the eye movements are not continuously along the phrase but composed from rapid movements named *saccades* combined with short stops named *fixation*.

Later, Edmund Huey (the author of The Psychology and Pedagogy of Reading published in 1908) built an eye tracker device using small contact lens provided with a hole for pupil. An aluminium pointer was connected to lens in order to observe the gaze direction during reading (Edmund Huey, 1908).

Dodge and Cline investigated the velocity of eye movements and developed the first precise and non-invasive eye tracking device based on corneal reflection (Dodge 1901), named photocronograph. The system recorded only horizontal movements of the eye using a photographic plate (Jacob and Karn, 2003). Four years later (1905), Charles H. Judd (an American psychologist and education reformer) developed a photo device that allowed to record the eye movements in both direction, horizontally and vertically (Shahzad & Mehmood, 2010).

In 1930, Miles Tinker concerned about how typography influenced reading, made a series of studies using eye tracking technology about eye movement in reading (Tinker, 1963).

Paul Fitts, well known for improving aviation safety, established in 1947 some relation between person's eye movement and his cognitive activity. He used video camera to capture and study ocular activity of airplanes pilots during flights. He concluded that the fixations were related to the importance of the control while the duration of fixation were related on how easy the information is interpreted (Russell, 2005). Next year, Hartridge and Thompson invented the first head mounted eye tracker (Hartridge, 1948). Thus constrains of head movement were eliminated (Eachus, 2009).

Alfred Yarbus developed eight small suction devices attached to eye. Some of them are covering completely corneal area leaving only a tiny rectangle window for subject. Some of them are attached only to sclera leaving the visual field unobstructed (Yarbus, 1967). Both types reflect light onto photosensitive surface. Using these devices, Yarbus defines five type of eye movement: fixation, saccades, tremor, drift, pursuit (Kassner & Patera, 2012).

In the ’70s efforts were focused on research about human eye operation and what can be revealing from perceptual and cognitive processes (Jacob and Karn, 2003). Also the number of scientific publications decrease compare with previous periods because of the methods used and effort involved in processind data.

The occurrence of personal computer in the ’80s was compared with a breath of air for eye tracking researches. Now, scientists have an important instrument for high speed data processing. They also start to investigate how eye tracking can be used for interaction between human and computer. At first this was done to help disabled people to have access to the new technology (Levine, 1981; Hutchinson, 1989). Then marketing groups saw an opportunity in using eye tracking to improve their announcement in magazines by observing what pages are actually read and afferent times. In the same context, in the early ‘90s, eye tracking was used by NFL (National Football Ligue) analyst Joe Theismann and a series of football fans to determine what parts of the screen was most viewed and what parts less (Leggett, 2010). Because of success of this approach, eye tracking technology was used by EURO RSCG, the largest advertising and marketing agency, to evaluate and measure the reactions to information on websites (Leggett, 2010).

2. Eye Tracking Approaches

Generally, the eye tracker devices measure/determine the eye ball position in several ways that can be classified in three categories: contact lens based, electrooculogram based and video based. The first category includes invasive eye trackers that use contact lens with mirrors (Yarbus, 1967) or magnetic search coil (Kenyon, 1985). The eye trackers that uses contact lens with mirrors implies an entire process of attaching the lens to eye ball and the experiment can last only a short period of time (measured in minutes), Fig. 1. The eye trackers with magnetic search coil requires two soft contact lens and between a coil of wire with 13 mm diameter. The twisted pair of wires from search coil was connected to a magnetic coil system (Kenyon, 1985) for measuring the intensity of magnetic field variation, as it is presented in Fig. 2. These eye trackers were used specially used by the scientists for research of physiology and dynamic of eye movements. Despite the vast improvements and the accuracy obtained, the systems were not widespread because of invasive process of attaching the lens and because the head had to be kept still in order not to affect the measurements.

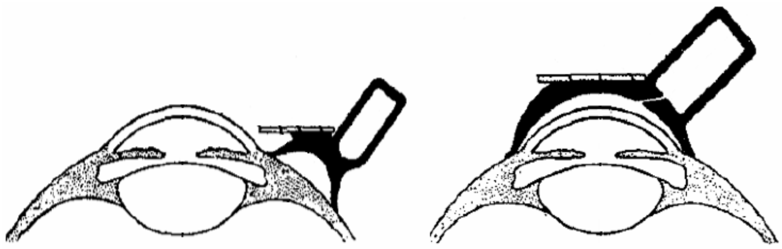
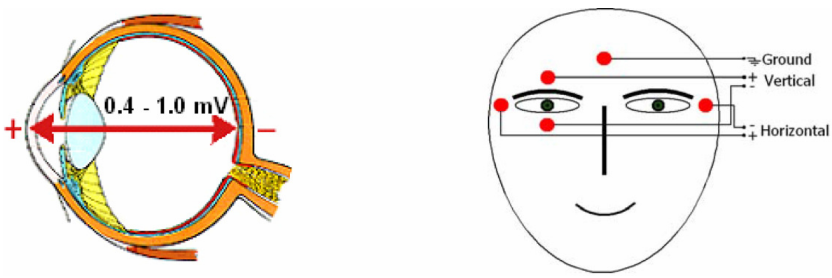


Fig. 1 – Contact lens with mirrors (Yarbus, 1967).

Fig. 2 – Contact lens with magnetic search coil (Photo courtesy of Chronos Vision).

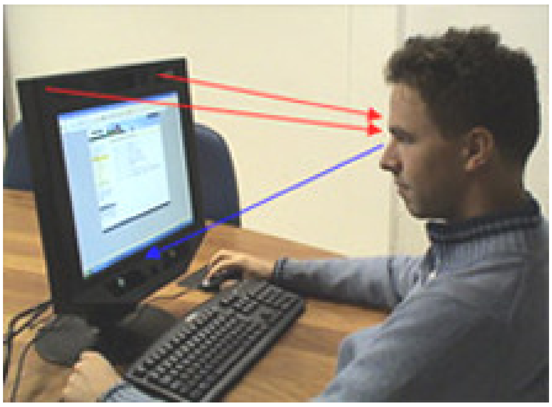
The eye trackers from second category measure the eye balls bio-potentials using electrodes placed near the eye. Because of very high nerves density of retina, the eye ball is polarised (Fig. 3 *a*). The movement of the eye cause the surrounding electric fields to move as well. These voltages can be measured by placing electrodes near the eye (Fig. 3 *b*). The amplitudes of acquired signals depend on position of the eye. Thus is possible to determine the eye positions and used in human computer interaction. The disadvantages are the costs of signals amplifiers and the presence of electrodes on subject face.



a *b*

Fig. 3 – *a*) Eye ball polarization (EOG 2010); *b*) Electrode placement (Lupu 2011).

The trackers from the third category use a video camera to track the position of the eye. This can be done remote, which means the video camera is placed some ware in front of the subject, (Fig. 4 *a*) or head mounted, which means the camera is placed below to visual axis of the eye, usually on eyeglasses frame (Fig. 4 *b*).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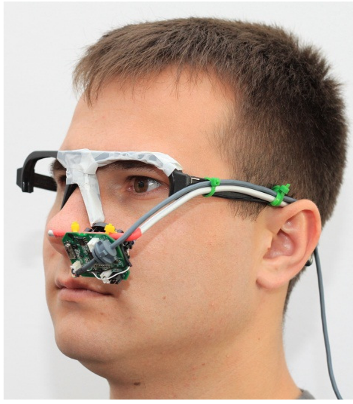
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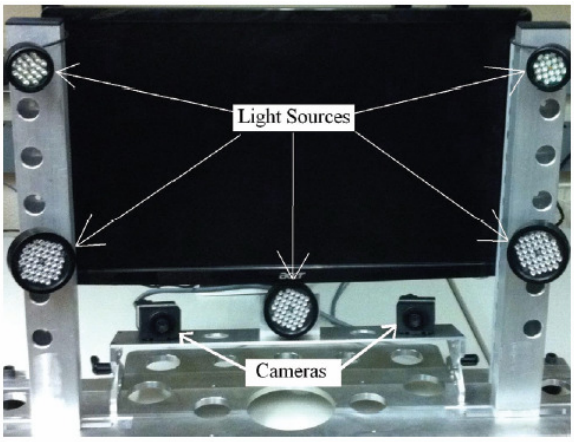
Fig. 4 – *a*) Remote eye tracker (Pentzo, 2005); *b*) head mounted eye tracker (ASISTSYS 2008).

Two types of images are used in video eye tracking: images in visible spectrum and images in infrared spectrum (Hansen, 2005). Processing images in visible spectrum is a passive approach and relies on ambient light reflected by the eyes. The traced feature is the iris contour. The results of this method are dependent to ambient light. For poor light conditions it is very hard to detect the feature of the eye for tracking. Using an infrared light source eliminate this problem. The eye is illuminated consistently and uniformly, imperceptible to user (Parkhurst, 2005). Another advantage of infrared light is that it enhances a feature of the eye which is easy to detect and track: the pupil. Thus, if the light source is collinear with the eye visual axis, the pupil looks white because of light reflection on retina (so called cat eye) otherwise black. In both situations corneal reflection can be observed as the most brighten spot in the image.

Both types of eye trackers, remote or head mounted have a major drawback if are to be used in HCI systems: the continuously head position change. This can be resolved for remote trackers using two stereo cameras (Fig. 5 *a*) or one wide angle camera (Fig. 5 *b*) to search for the person in front of it and another one to point the person face and zoom (Model, 2012; Hennessey, 2012). Features like face 3D orientation of subject face and distance are needed in order to compensate the head movement. Generally, in the case of remote eye-tracker systems, the light source and camera are permanently affixed to a monitor and the patient's presence in front of the monitor and calibration procedure for any new dialog session are required.



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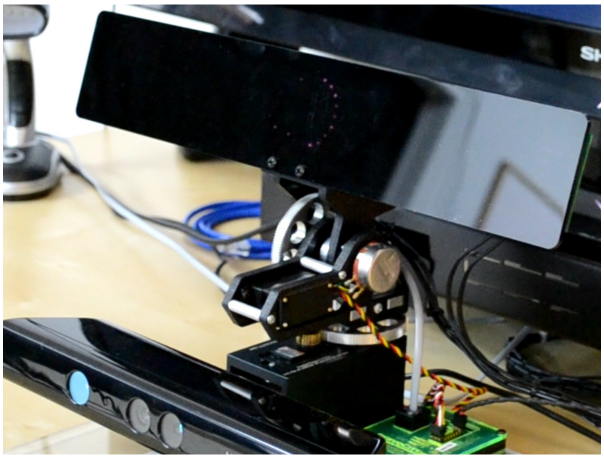

b

Fig. 5 – Remote eye trackers: *a* − stereo cameras (Model, 2012); *b* − wide angle camera and zoom camera (Hennessey, 2012).

For head mounted eye trackers is not useful to use cameras to detect the 3D face orientation. These systems offer a higher mobility to the subject, are based on embedded systems, are low cost, they do not imply the use of sophisticated algorithms for image processing thereby good performances in real-time operation are obtained. A practical solution is the use of video glasses (Lupu, 2013). Thus, the person can move his head freely without affecting the eye tracker results in HCI systems after it was calibrated, as it is presented in Fig. 6.

Fig. 6 – Head mounted eye tracker using video glasses (Lupu, 2013).

3. Detection Algorithms

In the last years several algorithms for eye pupil/iris detection have been developed. From the source light point of view there are two approaches: based on ambient or infrared light. All of them search for characteristics of the eye. There are some algorithms that search for features like blackest pixels in the image, pixels that correspond to pupil or iris and are know as feature based algorithms. Other algorithms are trying to best fit a model (ellipse) to the pupil/iris contour and are known as model based algorithms.

The feature based algorithms need to isolate the searched feature in the whole image or region of interest thru optimal image segmentation and centre of mass of obtained image. The detection is affected by the corneal reflection and/or eyelashes or eyelid but have in important advantage: low computing resources. The model based algorithms search for best candidate pixels to pupil/iris contour in the whole image or region of interest and then applies an algorithm the best fit some of the pixels found. The centre of the model is considered to be the centre of the pupil/iris. The detection of candidate pixels is affected by the noise in the image, requires high computational resources but have in important advantage: it can approximate the pupil even if the corneal reflection, eyelid or eyelashes are covering partially the pupil.

The Starburst algorithm (Parkhurst, 2005) relies on black or white pupil detection but can also be used for iris detection if eye receives enough ambient light. It is a hybrid algorithm that search for eye feature but in the end try to best fit an ellipse for the iris/pupil contour. The images are taken from a video camera placed right underneath the eye at a distance of six centimetres and an angle of 30º. The algorithm starts by removing the corneal reflection. It continues by finding points on pupil contour, applies the RANSAC (Fischler, 1981) algorithm for the founded points and best fit an ellipse that contains those points. Because of noisy images, for every frame that is processed different ellipses with different centres are fitted to pupil contour. This implies oscillations of determined gaze direction in HCI systems. Improvements can be made by preprocessing the acquired images and filtering the pupil detection output (coordinates of pupil centre in time).

The preprocessing of acquired images consists in applying filters like Scale Invariant Feature Transform (SIFT) or Speed-Up Robust Features (SURF) (Luo, 2009) that have a high degree of stability when Gaussian blur radius is smaller than 1.5 (Carata & Manta, 2010). Yet, this preprocessing does not eliminate all the noise from the image. Filtering the output coordinates improves the stability of gaze direction by denoising the eye movement signals (Spakov, 2012).

The ETAR algorithm has a feature based approaches (Lupu, 2013). It starts by searching the region where the eye is located, using HaarCascadeFilter. The region is set as region so interest (ROI) and a mask image is constructed in order to eliminate the unwanted noise from the four corners of ROI. The algorithm continues with determination of an optimal binary segmentation threshold. The pupil centre is determined by applying the centre of mass to the group of pixels that correspond to the pupil from the segmented ROI image. The analysis of determined gaze direction reveals that the algorithm is not sensitive to the noise from the image.

4. Eye Tracking Applications

The interest for applying ET methods grows with technological progress and the increasing of ET performance and accessibility. Eye trackers have existed for some years, but their use did not exceed the laboratory experiments. The devices are becoming sufficiently reliable and affordable to consider their use in real HCI. Actually, many studies are focused on appropriate interaction techniques that incorporate eye movements into the HCI in a convenient and natural way.

In 2002, Duchowski identified in his survey some viable directions for ET use in some areas: psychology and neuroscience - autism, Alzheimer's disease, schizophrenia or dyslexia; industrial engineering and human factors – driving, aviation or visual inspection; computer science - selective systems, collaborative systems, gaze-contingent displays (Duchowski, 2002). Some of these forecasts have become reality and some others like Brain Computer Interaction (BCI) or e-learning earn interest from researchers.

The usability of ET systems is assessed by metrics that are relevant to the tasks and their inherent cognitive activities. The most important specific metrics are:

Fixation − the time taken for processing image by fovea;

Saccade – the time taken by fovea to focus its attention from one image to another (time interval between two fixations);

Gaze Duration: cumulative duration and average spatial location of a series of consecutive fixations within an area of interest. Gaze duration typically includes several fixations and may include the relatively small amount of time for the short saccades between these fixations;

Area of interest − area of a display or visual environment that is of interest to the research or design team and thus defined by them (not by the participant);

Scan Path − spatial arrangement of a sequence of fixations.

Depending on the application in which ET system is involved, some researchers also use additional metrics: number of fixations on each area of interest, fixation duration mean on each area of interest, fixation duration total on each area of interest, number of areas of interest fixated, scan path length, scan path direction or transition probability between areas of interest.

The use of eye tracking in HCI have been highly promising for many years, but progress in making good use of eye movements in HCI has been slow to date. We see promising research work, but we have not yet seen wide use of these approaches in practice or in the marketplace.

Eye tracking in assistive technology

Assistive technology (AT) promotes greater independence for people with disabilities by enabling them to perform tasks that they were formerly unable to accomplish (Balan *et al*., 2013). Taking into account that most of the neuro-disabled patients can move their eyes, this can be useful for communication. Eye tracking can be used together with a computer to select a word from a menu. This device should be used by patient for a face to face conversation or a remote message sent via communication network. Such a system was proposed by ASYSTYS project team and it is presented in Fig. 7.

The keywords are selected by patient using eye tracking technique. A camera mouse can be used to move a cursor on a computer screen and to browse a menu for suggestive pictogram selection (Lupu *et al*., 2012). The keywords collection is organized as a tree structure having wide and short topology. The breadth first traversal method is suitable for keyword searching and for an easy and fast comeback to the upper level "*Go back*" images are placed at the right and left limits (Fig. 8).

An updated version of the above communication system uses an eye tracking mouse (ETM) system using video glasses and a robust eye tracking algorithm (Lupu *et al*., 2013). The validation of the usability and reliability of the proposed system was done by experimental procedure involving voluntaries and patients in a neurologic emergency clinic.

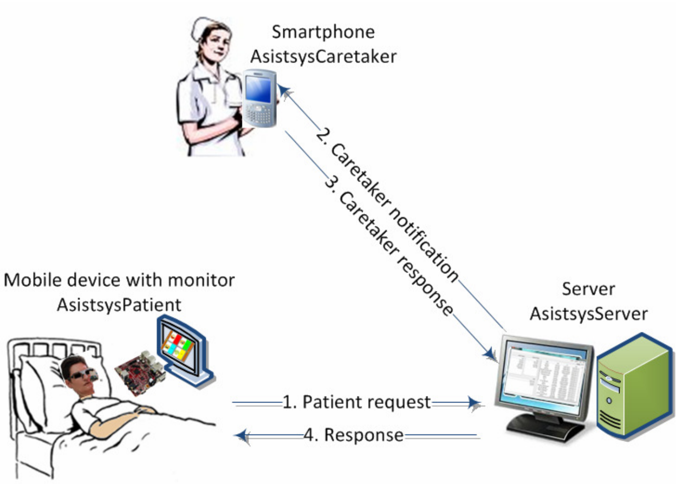

Fig. 7 – System communication for people with disabilities (Asistsys).

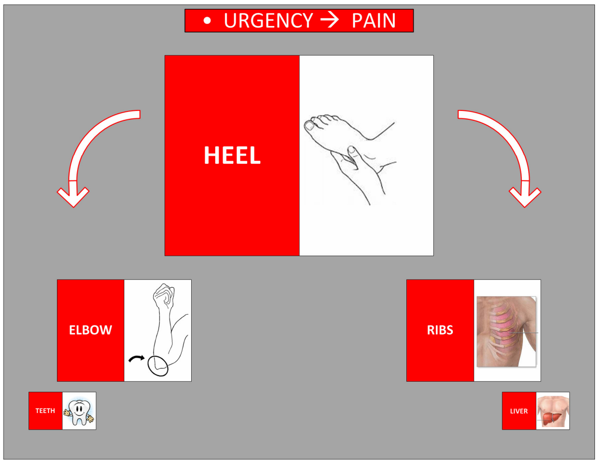

Fig. 8 – Browsing keyword collection (Lupu, 2012).

The social impact of the proposed ETM system may be significant allowing the social reinsertion of the disabled persons and increasing their self-respect. For many disabled people, such a communication system could help them to continue their intellectual and social life or to pass easier the difficult period of medical recuperation. In addition, taking into account that many people with disabilities do not afford a suitable communication system, this low-cost system could successfully replace the more expensive ones. The proposed mobile device should be also useful for people with limited hand functions or should be integrated in different virtual and augmented reality systems for recovering and rehabilitation process targeting persons suffering from neuromotor paralysis in the spirit of the new paradigm of Cyber-Physical Systems (Moldoveanu *et al*., 2012).

BCI with eye tracking

Brain computer interface (BCI) is a direct communication pathway between the brain and an external electronic device, more often a computer. BCIs are often directed at assisting, augmenting, or repairing human cognitive or sensory-motor functions. Research on BCI began in the 1970s at the University of California Los Angeles (UCLA) and was focused primarily on neuroprosthetics applications that aim at restoring damaged hearing, sight and movement.

Lee proposed a BCI method in which the BCI and eye tracking are combined to analyze depth navigation, including selection and two-dimensional (2D) gaze direction, respectively (Lee *et al*., 2010) a device to measure both the gaze direction and an electroencephalogram (EEG) pattern is proposed with the sensors needed to measure the EEG attached to a head-mounted eye tracking device (Fig. 9).

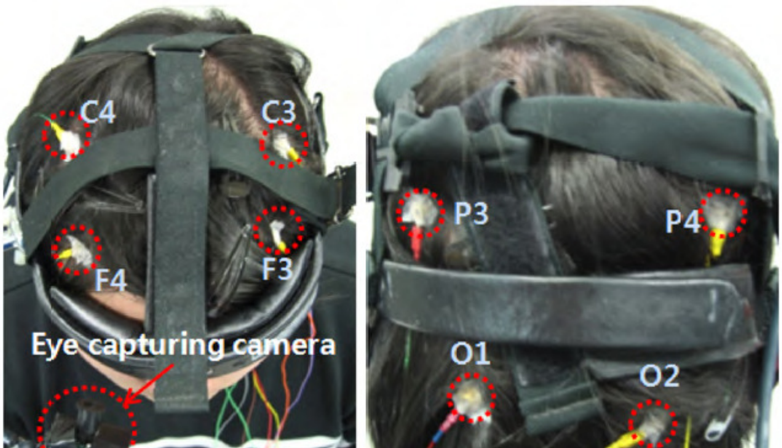

Fig. 9 − The configurations of the EEG measurement electrodes and camera for eye tracking (Lee *et al*., 2010).

The depth control for the 3D interaction interface is implemented by an imaginary arm reaching movement and the selection method is done by the imaginary hand grabbing movement (Fig. 10). For the independent operation of gazing and the BCI, a mode selection method was implemented by measuring user’s concentration and analyzing the pupil accommodation speed, which is not affected by the operation of gazing and the BCI. The proposed method offers the possibility for a hand-disabled person to perform a 3D interaction procedure by navigating surroundings through eye tracking and also it can be adapted to the control of an artificial arm or hand (Lee *et al*., 2010).

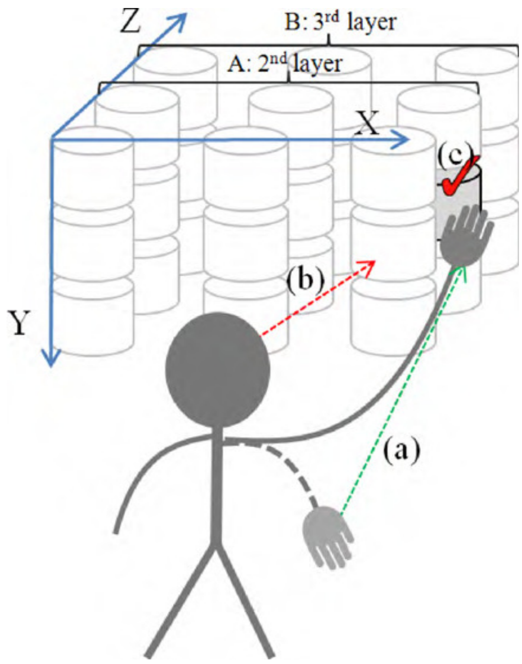

Fig. 10 − The conceptual diagram for BCI and eye tracking method (a) depth navigation based on the imaginary arm reaching movement, (b) 2D navigation using eye tracking, (c) object selection based on the imaginary grabbing movement (Lee *et al*., 2010).

Eye tracking use in psychology and neuroscience

Eye motricity is a fragile function that is linked to the central nervous system. Therefore disorders and diseases that affect the cerebral cortex, the brainstem, or the cerebellum have a strong influence on eye movements. The analysis of the resulting eye movements dysfunction can give information regarding which part of the brain is damaged and is a reliable marker for dementia and a number of other brain related diseases (Vidal *et al*., 2012).

In some projects, wearable eye tracking equipment was used in experimental psychology and clinical neuroscience on the link between eye movement and mental disorders. The viability of wearable eye tracking for longterm recordings in mobile settings and the distinct potential of eye movement analysis for mental health monitoring were demonstrated. Eye movement holds distinct information that can contribute to health monitoring and assessment, among which one can mention: autism, Alzheimer’s disease, the Acquired Immunodeficiency Syndrome Dementia Complex (AIDS Dementia Complex), multiple sclerosis, schizophrenia and dyslexia.

Eye tracking and e-learning

In the last years, various technologies (like collaborative software, cloud computing, screencasting, ePortofolios, virtual classroom) and different devices (*e.g.* mobile devices, webcams, audio/video systems or smartboards) were used to facilitate e-learning development and to increase the effectiveness and accessibility of e-learning platforms. Some previous studies revealed that eye tracking methods can improve the functionality and usability of e-learning systems: Eye Tracking Analysis in the Evaluation of E-Learning Systems, project, AdeLE project or ACM studies (Hend & Remya, 2010).

By the use of ET methods in e-learning it is possible to capture learner behavior in real-time. The data collected via eye-tracking devices indicates the person's interest level and focus of attention. From eye position tracking and indirect measures, such as fixation numbers and duration, gaze position, and blink rate, it is possible to draw information about the user's level of attention, stress, relaxation, problem solving, successfulness in learning, tiredness or emotions. It was revealed that when using eye tracking in e-learning, the learner pays more attention to the learning system and also tends to have a higher level of motivation (Hend & Remya, 2010).

5. Conclusions

In this paper we roughly describe some representative studies in the field of eye tracking, covering some aspects regarding different types of devices, algorithms for pupil detections, image processing or data filtering and also some well known applications in assistive technology, human computer interaction, virtual reality, psychology or e-learning.

As a general tendency we can conclude that in the future eye tracking approaches will be a hot subject for researchers. It is argued by some traditional conferences, international projects, books and scientific papers and technical reports. For example, held once every two years, Eye Tracking Research & Application (ETRA) Conferences join together companies and researchers involved in eye tracking technologies and highlight new hardware and software solutions. Among many others research groups, Eye-Com Corporation is an advanced center for eye tracking research and development dedicated to the creation of innovative eye tracking technology to improve and save lives, support the advancement of research, and revolutionize human-technology interaction.

Special attention should be paid for performing experimental procedures in order to evaluate the usability, accuracy and reliability of the eye tracking systems.

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STUDIU ASUPRA METODELOR ŞI APLICAŢIILOR EYE TRACKING

(Rezumat)

În ultimii ani, dezvoltarea sistemelor eye tracking a fost o provocare pentru cercetători şi diferite companii din domeniile IT, echipamente medicale sau multimedia. La modul general, un sistem eye tracking constă într-un echipament capabil să urmărească mişcările ochiului şi să poată specifica cu suficientă acurateţe punctul în care priveşte subiectul şi pentru cât timp. Dezvoltarea sistemelor eye tracking presupun în egală măsură implementarea unor algoritmi pentru detecţia pupilei, prelucrarea imaginilor, filtrarea datelor şi înregistrarea mişcării ochilor prin intermediul timpului necesar formării imaginii pe pata galbenă a ochiului, a duratei privirii unei anumite imagini şi a intervalului de timp necesar formării a două imagini consecutive. În pas cu progresul tehnologic, o varietate largă de abordări hardware şi software au fost dezvoltate de diferite companii sau grupuri de cercetare. Funcţie de aplicaţia ce utilizează un sistem eye tracking, se alege atât echipamentul potrivit pentru achiziţia mişcării ochilor cât şi aplicaţia software aferentă. Unii furnizori (ca de pildă SensoMotoric Instruments, Tobii sau MyGaze) au investit în dezvoltarea tehnologiei eye tracking, dar soluţiile oferite sunt bazate pe camere şi surse de lumină plasate la distanţă, în general ataşate la monitor. Deoarece aceste sisteme comerciale, incluzând aplicaţiile software şi suportul tehnic, sunt destul de scumpe, unele grupuri de cercetători au adus în prim plan soluţii mobile şi ieftine. Aplicaţiile eye tracking acoperă o arie largă de domenii: interacţiunea om calculator, tehnologie asistivă, e-learning, investigaţii psihologice, asistenţa antrenării piloţilor, realitate virtuală, realitate augmentată, etc.