A history of eye gaze tracking

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Abstract

Applications that use eye and gaze have recently become increasingly popular in the domain of human-computer interfaces. In this paper, we provide a historical review of eye tracker systems and applications. We address the use of gaze tracking in order to adapt entertainment and edutainment applications according to user behaviour.

Chapter 1

Introduction

In humans, gaze direction and ocular behaviour is probably one of the first *distant means of communication* developed. Parents often try to understand what their baby looks at, and they deduce that the object observed attracts his/her interest. This ability to interact with someone by a transitional object is named *joint attention*.

Kaplan says that among the fundamental prerequisites for the development of complex linguistic skills, the development of joint attention is probably one of the hardest problems to be solved [20]. The biological significance of ocular behaviour and gaze direction in humans could be illustrated by two main facts. The first one is that in primates and more precisely in humans the visual cortex is more developed than in other mammals.[1]The second one, is that humans (and not primates), have clearly visible white area (sclera) around the pigment part of the eye (iris) (cf. Figure 1.1).

It is well established that eye contact is one of the first behaviours developed

[1]The visual cortex is located in the posterior pole of the occipital cortex (the occipital cortex is responsible for processing visual stimuli). It has been proved that the visual cortex is highly specialized in the processing information about static and moving objects and is excellent in pattern recognition.

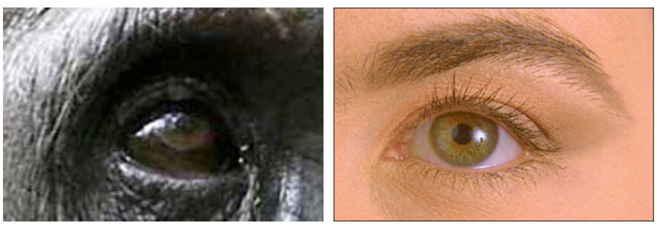

Figure 1.1: The visible white area of human eye (sclera) makes it easier to interpret the gaze direction.

by young babies. Within the first few days of life, they are able to focus their attention on their mothers' eyes (especially when baby is held at the breast level). Eye contact and gaze direction continue to play a crucial role in social communication throughout life. Amoung the communication tasks in which eye direction is important we can mention:

- emotions;
- dominance or submissiveness;
- attention or disinterest;
- ...

In this work, we provide a historical approach of eye and gaze trackers and present some of the more common applications.

Chapter 2

Eye and gaze tracking state of the art

This section introduces the latest uses of eye gaze tracking in applications, with a special focus on interactive applications and/or video games, but in order to understand the present let's have a look at the past.
After the second world war, one of the first measures of gaze direction was done in 1947 by the group of Fitts, Jones and Milton [9]. They published technical reports in the late 1940s that are considered to be the seminal research on visual sampling and represent the largest collection of eye movement data collected in a visual monitoring task. The data encompass over 500,000 frames of movie film of over 40 pilots taken under various flight conditions. The general conclusions was that:

> It is reasonable to assume that frequency of eye fixations is an indication of the relative importance of that instrument. The length of fixations, on the contrary, may more properly be considered as an indication of the relative difficulty of checking and interpreting particular instruments. [...] **If we know where a pilot is looking, we do not necessarily know what he is thinking, but we know something of what he is thinking about.**

Following this work, authors were able to propose a more efficient arrangement of instruments and identified those which were difficult to read, for a possible redesign of the actual instrument. This was the first time a survey allowed interaction between an application (an airplane cockpit) and a manual gaze tracking system. It was also the first time video was used to perform measures. Actually, they were mainly performed using a medical technique that allowed registration of eyeball movements using a number of electrodes

Figure 2.1: Typical eye tracking system using head mount. Model presented SR Research Eyelink II

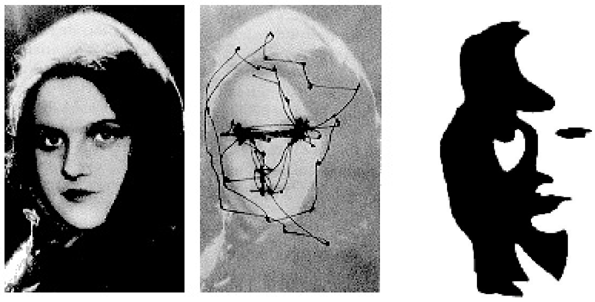

Figure 2.2: Left : The gaze tends to come and go between the eyes and mouth in the picture of a face. Right : Think where you are looking at to see either a musician or a woman face.

positioned around the eye. Most of the described techniques required the viewer's head to be motionless during eye tracking and used a variety of invasive devices.

The major innovation in eye tracking was the invention of a head-mounted eye tracker ([13], [23], [24], [30]), this technique is still widely used (cf. Figure 2.1). Another reference work in the gaze tracking world is the one done by Yarbus. Yarbus was a Russian psychologist who studied eye movements and saccadic exploration of complex images in the 1950s and 1960s. He recorded the eye movements performed by observers while viewing natural objects and scenes [33]. Here again, this work tends to show that the gaze direction is crucial in interactivity, actually Yarbus showed that the gaze trajectories followed depends on the task that the observer has to perform (cf. classical Figure and experience 2.2). Eyes would concentrate on areas of the images of relevance to the questions. Much of the relevant work in the 1970s focused on technical improvements to increase accuracy and precision and reduce the impact of the trackers [34]. In [14], Jacob proposes a brief history of the eye tracking system during these years. Since this period, works are deeply correlated with the performance of computers. The more it progresses, the more it provides the necessary resources for real time and/or complex applications. For instance, it is nowadays possible to develop a human computer interface using gaze tracking. During the 80's, interest for gaze tracking have persisted, the incredible boom of personal computers allowed to design new interfaces and ways of thinking our relation with the computer [5], [4] and [31]. Another pioneer was Dr. Levine who was one of the first to see the potential of eye tracking in interactive applications [21]. For 15 years, eye and gaze tracking have become an industrial stake, many manufacturers have developed products in this field of research. The dramatically increasing number of publications around this topic prevents from doing an exhaustive state of the art, actually many journals, conferences and publications have been created around this topic (conferences : ECEM - the European Conference on Eye Movements, SWAET - the Scandinavian Workshop on Applied Eye-tracking, ETRA - Eyetracking Research and Applications...). At least seven sponsors are represented in the last ETRA conference. Nowadays, many systems, invasive or not, allow to measure, follow, analyse, and log in real time numerous data coming from cameras. Applications are various, from military to advertisement analysis via medical applications. A complete vision of theories and applications is presented in [8].

With the advances in eye gaze sensing technologies these systems are now much more precise and far less intrusive. As a consequence, researches using eye gaze as input stream have grown increasingly. This reality leads to the existence of several ways of tracking the direction of eye-gaze. [3], [27] and [10] provide the following list of requirements of an ideal tracking device, which are still not fully satisfied by current techniques.

1. Offer an unobstructed field of view with good access to the face and head

2. Make no contact with the subject

3. Meet the practical challenge of being capable of artificially stabilising the retinal image if necessary

4. Possess an accuracy of at least one percent or a few minutes of arc. Accuracy is limited by the cumulative effects of non-linearity, distortion, noise, lag and other sources of error

5. Offer a resolution of 1 minute of arc sec^{-1}, and thus be capable of detecting the smallest changes in eye position; resolution is limited only by instrumental noise

6. Offer a wide dynamic range of one minute to 45° for eye position and one minute arc sec^{-1} to 800 sec^{-1} for eye velocity

7. Offer good temporal dynamics and speed of response (e.g. good gain and small phase shift to 100Hz, or a good step response).

8. Possess a real-time response (to allow physiological manoeuvres).

9. Measure all three degrees of angular rotation and be insensitive to ocular translation

10. Be easily extended to binocular recording

11. Be compatible with head and body recordings

12. Be easy to use on a variety of subjects

To summarize this brief history, even if eye gaze tracking systems exist since a long time, the tracking and measure of eye behaviour and gaze direction was until recently a very complex and expensive task reserved for research or military labs. The eye tracking devices were uncomfortable head mounted systems, thus they were mainly used as pointing devices for a very narrow range of applications (mainly military). However, rapid technological advancements (increased processor speed, advanced digital video processing) have both lowered the cost and dramatically increased the efficiency of eye and gaze tracking equipment.

In the next two sections, we present a review of eye movement tracking systems and applications.

2.1 A review of eye and gaze tracking systems

The most widely used current designs are video-based eye trackers. Even if these techniques are predominant, we have to mention in order to be complete, the electro-oculography tracking technique. It is based on the fact that an electrostatic field exists when eyes rotate. By recording small differences in the skin potential around the eye, the position of the eye can be estimated. Also, since this is done with electrodes placed on the skin around the eye, this technique does not require a clear view of the eye. This technique is rather troublesome though, and is not well-suited for every day use, since it requires the close contact of electrodes to the user, yet a recent application can be found in [1].

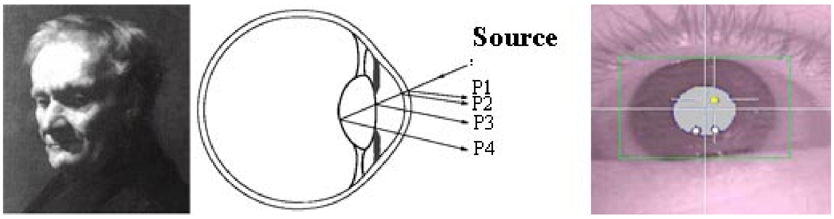

Figure 2.3: Left : the Czech anatomist Jan Evangelista Purkyne (1787-1869) and his four images. Right : representation of a bright corneal reflection of near infrared diodes light

Concerning video based eye trackers, one or two cameras focus on one or both eyes and record and/or analyse their movements. In this section, we present the very simple and known taxonomy in which we separate systems into two main categories:

- Head-mounted systems;
- non intrusive systems.

Each one splits into two others categories depending on the kind of light they use:

- ambient light;
- infrared or near infrared light.

Head-mounted systems are commonly composed of cameras (1, 2 or 3) and diode which provide light. These systems have followed the same path as computers; smaller and faster (Figure 2.4).

Nowadays, it is quite easy to follow and analyse the four Purkinje images. Purkinje images are reflections of objects from structure of the eye. There are at least four Purkinje images that are visible when looking at an eye. The first Purkinje image (P1) is the reflection from the outer surface of the cornea. The second one (P2) is the reflection from the inner surface of the cornea. The third one (P3) is the reflection from the anterior surface of the lens and the last one (P4) is the reflection from the posterior surface of the lens [10] (Figure 2.3).

Using light emitting diodes on head mounted system, it is possible to record several images which represent the reflects of emitted light in the eyes. Figure 2.3 represents such a reflect effect. The principle of almost all head mounted systems is to measure and compare P1 corneal or pupil images (or P2) with P3 retinal images (P4 images is quite difficult to follow [3] but

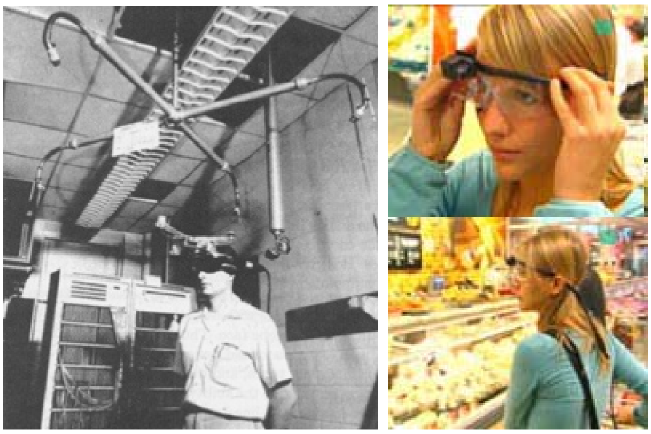

Figure 2.4: Left : Early head-mounted display device developed by Ivan Sutherland at Harvard University, 1967. Right : Example of a wearable head-mounted eye tracking system (from www.eye-square.com))

used in the *Dual Purkinje Image* method). If the illumination is coaxial with the optical path then it produces a bright pupil effect similar to red eye (Figure 2.3). If the illumination source is offset from the optical path, then the pupil appears dark. Bright Pupil tracking creates greater iris/pupil contrast allowing more robust eye tracking and more reliable tracking in lighting conditions ranging from total darkness to very bright. However, bright pupil techniques are not effective for tracking outdoors as extraneous infrared sources interfere with monitoring.

Regarding technology, some eye tracking systems require the head to be stable (for example, with a chin rest), and some function remotely and automatically track the head during motion. Concerning frame rate acquisition, most use a sampling rate of at least 30Hz until 50/60 Hz. In the field of neurobiology or in order to capture the detail of the very rapid eye movements during reading some of them can run at 240, 350 or even 1000/1250 Hz.

The other main category of eye and gaze tracking system is the non intrusive one. It provides some advantages compared to the head-mounted systems, some of the most obvious are:

- it should allow natural head movements;
- it should be able to perform with a wide variety of eye shapes, contact lenses or glasses;
- it should be portable;

- it should be real time.

With the increasing processing speed of computers, it is now possible to analyse digital videos of face and eye movements in order to provide reliable measures. We can mention three main approaches to detect and measure in a non invasive way eye and gaze, depending on the king og features they use:

- the glint;
- a 3D-model;
- a local linear map network.

The first one and the most commonly used approach is to calculate the angle of the visual axis and the location of the fixation point on the display surface by tracking the relative position of the pupil and a point of light reflected from the cornea, i.e. the glint. Infrared light enhanced measures take advantage of the bright pupil effect (Figure 2.5) (a recent study of such a system may be found in [11]). The second one consists in the use of serialized image processing methods to detect face, pupils, mouth and nostrils, once these treatments are done, a 3D model [7] is used to evaluate face orientation and finally gaze direction is estimated using eyes images (see Figure 2.6) (a very recent work can be found in [6]). The last one is more marginal [26], it consists in the use of a neural networks of the local linear map type which enables a computer to identify the head orientation of a user by learning from examples. In each case two comments can be made: firstly infrared light may facilitate results and secondly calibration is a real problem, either a model is adapted in real time or is build before the tracking and adapted for a single person.

The price range of most commercially available eye-trackers is between \$5000 and \$60.000. In the next section, we present the most popular applications using eye and gaze tracking systems.

2.2 A review of eye and gaze tracking applications

This section presents in a concise way different applications that use eye and gaze tracking systems, and how they take advantage of the data collected. Historically, the first application using eye tracking systems was, as we already saw, the user interface design. Actually, knowing where people are looking at is really important to design devices, cockpits, cars ... Many

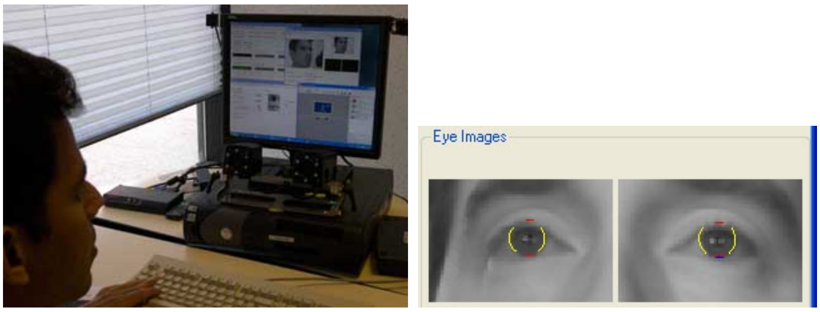

Figure 2.5: A non intrusive eye tracking system.

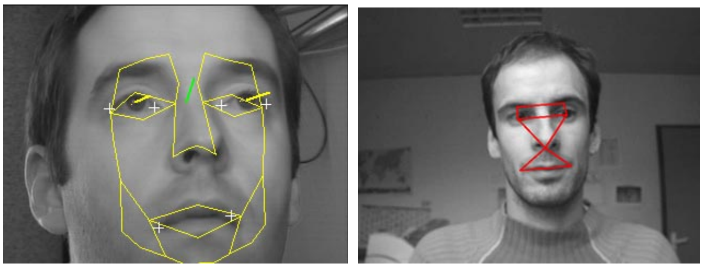

Figure 2.6: Using of a head model to detect eye and gaze orientation.

publications can be found relating to this field from [13] to [28] or [16]. All these studies are based on the *eye-mind hypothesis* [19] that what a person is looking at is assumed to indicate the thought on top of the stack of cognitive processes. In this way, the visibility, meaningfulness and placement of specific interface elements can be objectively evaluated and the resulting findings can be used to improve the design of the interface. A huge range of works that inherits directly from the previous is the human-computer interaction (HCI), but currently very few applications have been implemented for consumer products. The main reason for the slow emergence of attentive interfaces utilizing eye gaze is what Jacob [17] dubbed the *Midas touch problem* : the application should *not* react every time the target of the gaze changes, only in *appropriate* situations, and at the *right* moment, very complex notions for a computer.

Even if commercial applications are quite uncommon, a key application for eyetracking systems is to enable people with severe physical disabilities to communicate and/or interact with computer devices. Simply by looking at control keys displayed on a computer monitor screen, the user can perform a broad variety of functions including speech synthesis, control, playing games, typing... A network of excellence, supported by the European Commission's IST 6th framework program, was created around this topic: the

COGAIN network (COmmunication by GAze INteraction www.cogain.org). On this website, interested readers could found many related publications. Eyetracking systems can enhance the quality of life of a disabled person, his family and his community by broadening his communication, entertainment, learning and productive capacities. Additionally, eyetracking systems have been demonstrated to be invaluable diagnostic tools in the administration of intelligence and psychological tests

Another aspect of eye tracking usefulness could be found in the cognitive and behavioural therapy, a branch of psychotherapy specialized in the treatment of anxiety disorders like phobias [12]. Technology offers a tool for quantitatively measuring and recording what a person does with his eyes as he reads. At the opposite of helping people with disabilities, other applications include military weapon control and remote robotics. As we saw, militaries sponsored much of the early research and development on eyetracking systems, and one of their primary objectives was to aid pilots, busy flying the plane, in their weapons control. Eyetracking systems allow the pilots to observe and select targets with their eyes while flying the plane and firing the weapons with their hands. Another aspect of eye control is reached through vehicle simulation. Among all the eyetracking studies those concerning vehicle simulation is probably the most numerous, attention, tiredness, dangerous behaviour... for a complete view of simulation aspect, readers may found information via the ITS Institute's primary human factors research laboratory web site (http://www.humanfirst.umn.edu/).

This ability to know what people look at and don't look at have also been widely used in a commercial way. Market researchers want to know what attracts people's attention and whether it is good attention or annoyance (Figure 2.4). Advertisers want to know whether people are looking at the right things in their advertisement.

Finally, we want to emphasize the current and prospective aspect of eye and gaze tracking in game environment, either in rehabilitation, an entertainment or an edutainment context; actually, it is mentioned in a very interesting report done in 2005 [18] that : *...no information about eye tracking and computer games was found*. Nevertheless, some previous work was interesting to mention relating to eye behaviour in a game environment, to make possible to lay out the foundations of players eye behaviours [29]. The research suggests that action game playing might be a useful tool to rehabilitate visually impaired people or improve visual attention [2]. Recently, a Queens University study confirms that video-gamers feel more immersed and have more fun in virtual environments when they play with commercial eye tracking technology. Moreover, the growing of video game enthusiasts to leave the real world in favour of a virtual one is driving a market trend toward developing

Figure 2.7: Up : In the Legend of Zelda: the player's avatar points to interesting objects in the environment by looking at them. Down : Multimedia game screen with eye-tracking device. The gaze point if represented by a circle.

easier-to-use controls, including eye control. And when we know that game industry today is bigger than film industry and that the large user groups consuming games are spread all over the world, we realize the potential of such works. Since this study, many recent commercial games already include a concept of gaze based interaction, for example, in *The Legend of Zelda: The Wind Waker*, the players avatar indicates that a nearby object might be interesting by looking at it (Figure 2.7), but currently eye or gaze is not yet an input of commercial game.

One of the first works to tackle this problem was done by [22] in which they developed an eye-tracking system for eye motion disability rehabilitation. They used it as a joystick to play a game with an application program in a multimedia environment (see example of results Figure 2.7). Other works was done in the Laurent Itti Lab, a leading team relating to attention, concerning realistic avatar eye and head animation using a neurobiological model of visual attention [15]. The same team have already worked in the field of computational mechanisms for gaze direction in interactive visual environments [25] and works have been reinforced by [32] which presents results showing the existence of both bottom-up and top-down visual attention patterns within 3D games.

In spite of these previous studies, to our knowledge there is no existing works concerning real interactivity between game and eye and gaze tracking. All works around the eye and gaze tracking was done to control avatar or shoot, but none was used to adapt the game execution.

Chapter 3

Conclusion

To conclude, gaze tracking is used in many different applications, including video games and interactive applications. But to our knowledge, there is no existing approach that adapts the game evolution to the players behaviour, captured *via* a gaze tracking system.

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