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EYE-TRACKING AS A TOOL FOR RESEARCHING USER BEHAVIOR

Reshetniak V., Faure E. Eye-tracking as a tool for researching user behavior. This article discusses eye-tracking technology, one of the critical technologies in analyzing user behavior when interacting with computer systems, and has a wide range of practical applications. The current capabilities and limitations of existing methods and equipment for eye tracking were reviewed and analyzed, and problems and promising areas for further research were identified. The central hardware systems were studied, such as desktop trackers, mobile glasses for eye-tracking, systems for immersive environments, and systems based on embedded cameras. This research also includes analyzing and classifying eye localization methods: eye shape-based, feature-based, and appearance-based. Also were investigated modern gaze-tracking methods, which are crucial to analyzing eye movement and determining the user's point of view. Feature-based methods provide accuracy but have limitations in strong lighting conditions. Model-based methods require high image resolution and calibration to measure gaze direction using facial characteristics. Cross-ratio-based methods do not require calibration but require additional lighting. Appearance-based methods are effective with low-quality images but have limitations concerning head position. The study indicates significant potential for improving gaze-tracking technologies to enhance user interfaces and increase accessibility. It emphasizes the need to develop adaptive methods that function in different environmental conditions and hardware limitations.
Keywords: human oculomotor system, eye-tracking, eye-tracker, user experience, eye gaze estimation, pattern recognition.

Решетняк В.В., Фауре Е.В. Відслідковування погляду як інструмент дослідження поведінки користувача. В цій статі розглядається технологія відслідковування погляду, яка є однією з ключових в аналізі користувацької поведінки при взаємодії з комп'ютерними системами й має широке практичне застосування. Було розглянуто і проаналізовано сучасні можливості та обмеженя існуючих методів і обладнання для айтрекінгу, а також на визначено проблеми та перспективні напрямки для подальших досліджень. Були розглянуті основні апаратні комплекси, такі як настільні трекери, мобільні окуляри для айтрекінгу, системи для імерсивних середовищ, а також системи засновані на вбудованих камерах. Це дослідження також включає аналіз та класифікацію методів локалізації очей: на основі форми очей, на основі особливостей форми та на основі оточення області очей. Також було досліджено сучасні методи гейз-трекінгу, які є ключовими для аналізу переміщення очей і визначення точки погляду користувача. Методи на основі особливостей форми забезпечують точність, але мають обмеження при сильному освітленні. Методи на основі моделей вимагають високої роздільної здатності зображень і калібрування, але дозволяють визначати напрямок погляду за допомогою простих характеристик обличчя. Методи на основі перехресного співвідношення не потребують калібрування, але потребують додаткового освітлення. Методи на основі оточення області очей ефективні з низькоякісними зображеннями, але мають обмеження щодо положення голови. Дослідження вказує на значний потенціал вдосконалення технологій відслідковування погляду для покращення користувацьких інтерфейсів та підвищення доступності. Підкреслюється необхідність розробки адаптивних методів, які можуть функціонувати в різних умовах середовища та обмеженнях обладнання.
Ключові слова: окуло-моторна система людини, відслідковування погляду, айтрекінг, айтрекер, досвід користувача, розпізнавання образів.

Introduction.

Relevance of the study.

Eye tracking technology allows the discovery of user behavior when interacting with computer systems. According to [1], information is perceived during the moments of eye fixation between rapid eye movements (saccades). Thus, the duration of the fixation time on a stimulus can indicate the efficiency of the information-reading process. In this study, we observed the hardware and software complexes (eye trackers) to explore this efficiency. These complexes collect temporal and spatial information about gaze movement and fixation.

Since eye tracking technology allows the analysis of human behavior, it has been widely used in research in many areas. In [2], it provides an analysis of the use of eye tracking in medical research. For example, it is used to identify and research autism spectrum disorders [3], schizophrenia, depression, anxiety, Parkinson's disease, and Alzheimer's disease. [4] and [5] describes the use of eye tracking in design research. It is used to analyze the design of websites, mobile applications, and games. It is also widely used in marketing research [6]. [12] provides an overview of the application of eye tracking technology in virtual reality, [13] and [14] describe the application of this technology for augmented reality. In [15], the use of eye tracking is suggested to access mediation. It has also been proposed that this technology be used in the military to analyze soldier fatigue [16]. There are studies of the application of eye trackers in the automotive industry, where this technology can be used to track a driver's concentration and field of view [17]. Also, recent studies have used eye tracking not only to analyze human behavior but also that of animals, for example, during their training [18].

Despite a long history of development and widespread use of the technology, there are still challenges in implementing it in some areas. An example is the design research of mobile applications using eye tracking, which requires either expensive equipment or the fixation of the smartphone's position.

The purpose of the study

This study aims to explore the current capabilities of eye tracking technology and analyze the limitations of existing methods and equipment. We observed existing hardware systems and video processing methods for localizing eyes and matching eye movements with the gaze direction. Particular emphasis is placed on identifying problematic aspects of using these technologies and identifying promising research areas. This article seeks to identify the reasons for the limitations of existing systems and propose research objectives for further improvement of eye tracking technology.

Existing hardware systems for eye tracking

General overview of hardware systems

The study of eye movement began in the mid-twentieth century, but as can be seen in the graph of mentions of the term "eye tracking" in printed sources (Fig.1), eye tracking technology has been most developed since 1990 when personal computers became widespread. In recent years, the need arose to study the users' interaction in human-computer systems in different conditions and for various tasks. As is shown on the graph, eye tracking technology has been developing rapidly in recent years due to the increased use of computer systems, including smartphones and tablets, as well as the expansion of the scope of this technology.

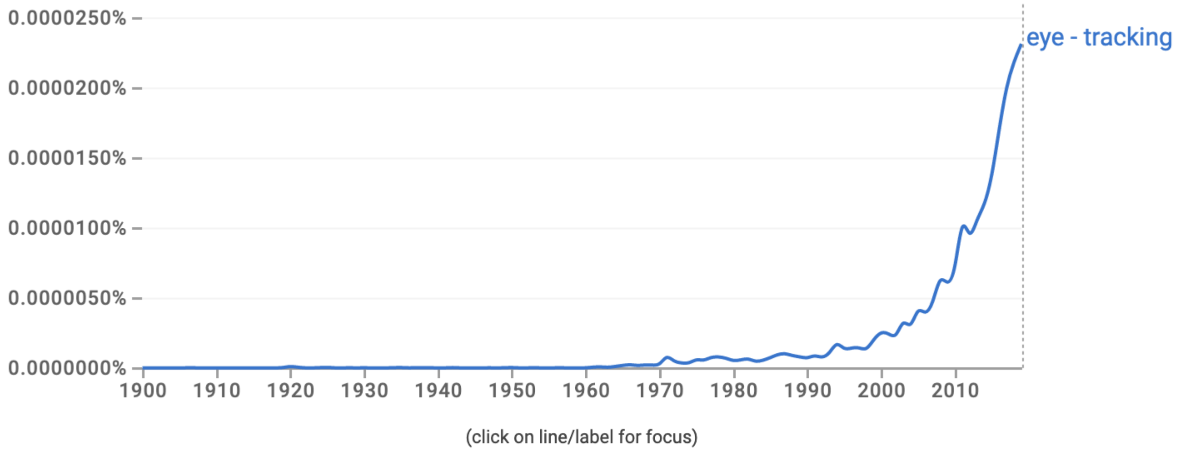

Fig. 1. Mention of the term "eye tracking" in printed publications from 1900 to 2019. Data from Google Books Ngram Viewer [19]

Software and hardware systems are used to study eye movements, which are classified according to various parameters, such as mobility, type of equipment used, areas of use, and others. In this section, the following main types of software and hardware systems will be considered, and their features, advantages, and disadvantages will be analyzed:

– Desktop eye tracking complexes;
– Mobile eye tracking glasses;
– Virtual reality eye tracking complexes.

It should also be noted that eye tracking can be performed without third-party devices, using computers and smartphones' built-in cameras (or external webcams). In this case, eye tracking is based on visible light, without using infrared light, which is used in external devices.

Desktop eye tracking complexes

Systems used with a stationary computer screen are called Desktop Eye Trackers. Such devices are the most common because they have an extended development history. [20] They consist of an infrared light emitter (or several) and one or more digital cameras that capture images in the near-infrared spectrum directed at the user's eyes. These complexes are mounted under or above the monitor, which allows real-time reading of gaze movement and transmitting the coordinates of the focus point movement on the screen. These devices include Tobii Pro Spectrum, Tobii Pro Spark, TOBII PRO NANO, iMotions Gazepoint GP3 HD, and iMotions Smart Eye AI-X.

This type of devices also includes stationary eye tracking devices on mobile devices (smartphones and tablets). Such devices have the same principle of operation as those used with computer screens. An example of such a device is the Tobii Pro Nano, which can be used with both computers and mobile devices (Fig. 2).

Fig. 2. Using Tobii Pro Nano with a smartphone [21]

Such devices provide accurate gaze tracking results, but they limit the user's head movements, require calibration every time they are used and are not mobile in their movement, which imposes restrictions on interaction with smartphones and tablets.

Mobile eye tracking glasses

Glasses equipped with sensors for tracking eye movements have replaced massive and uncomfortable head-mounted devices, such as the ASL Headmounted Eye Tracker. [20] Such glasses use the same technology as screen-based systems, but the key feature is an additional camera directed in the direction of gaze. This feature, combined with the high mobility of such devices, allows researchers to study not only human interaction with computer screens but also interaction with the environment in real-world settings such as shops, workplaces, public transportation, and so on, which is relevant, for example, in advertising. Such devices include Pupil Invisible, Tobii Pro Glasses 3 (Fig. 3), and Viewpointsystem VPS 19.

Fig. 3. Structure of Tobii Pro Glasses 3 [22]

Devices of this type have the advantage of mobility, do not require additional calibration, and do not restrict head movement. Such devices have a more comprehensive range of practical applications, as they do not need a monitor to be looked at.

Virtual reality eye tracking complexes

With the growing popularity of immersive environments, the need for eye tracking has arisen. Such devices are usually integrated into virtual reality helmets and augmented reality glasses. Still, add-on devices are also made separately and can be connected to helmets and glasses. An example of an add-on device is the Binocular Add-on from Pupil Labs for HTC virtual reality helmets. Such systems also use the technology of reading the infrared reflection of light from the eye, which allows for calculating the direction of gaze.

Compared to other devices used primarily for user behavior research, the devices used in virtual reality helmets and augmented reality glasses have more practical applications. For example, augmented reality glasses, such as Microsoft HoloLens 2, use gaze tracking to achieve a hologram effect - the image on the glasses' screen changes according to the angle of the gaze on the screen. Another application of eye-tracking technology is Foveated Rendering, which is used in virtual reality helmets:

The foveated rendering system presents the foveal vision with full-resolution rendering and the peripheral vision with low-resolution rendering. [23]

In immersive environments, gaze tracking improves user interaction. It makes it more natural, but due to the peculiarities of such environments, additional challenges arise, such as a limited workspace or constant shifting of the user's head position.

Mobile and webcam eye tracking

The previously mentioned systems require complex and expensive equipment, which significantly limits the use of the technology. At the same time, there are developing areas of eye tracking that use built-in cameras of laptops, tablets, smartphones, and regular webcams. These areas significantly reduce the entry threshold for using the technology, although they are somewhat less accurate compared to professional eye trackers.

Several software products are currently available for tracking eyes using a computer's built-in or external webcam. For example, GazeRecorder has several software products based on webcam tracking for creating heat maps of observing websites, controlling the mouse cursor, typing, and scrolling through pages [24]. A similar example is the free myEye program, which allows users to control the cursor with their eyes. It was developed to improve usability for people with amyotrophic lateral sclerosis, who can only interact with their eyes [25]. The open-source JavaScript library WebGazer.js also uses webcam data to determine where the user is looking on the page. This library can be integrated into websites to analyze user behavior [26]. One of the leaders in the tracking market, Tobii, also has a software product that supports webcam eye tracking. The Tobii Sticky software allows the researcher to conduct eye tracking research on advertising, video, and packaging using a standard webcam [27]. The company iMotions also offers its software for webcam tracking - iMotions Online [28].

Compared to professional equipment, webcam-based eye tracking has advantages primarily due to its affordability and ease of installation. This approach significantly reduces the cost of implementing the technology, as it does not require additional equipment: most laptops are already equipped with built-in cameras, and desktop computers can easily be supplemented with a regular webcam. Software solutions for webcam tracking, such as the WebGazer.js library, can be easily integrated with existing websites. Moreover, some of these software products can be used simultaneously with other programs, which allows for the research of these programs.

Despite the advantages of webcam tracking, there are also disadvantages to this approach. Using standard built-in or regular webcams can reduce the accuracy of measurements, especially in low-light conditions, compared to specialized eye tracking equipment. There is also a fairly wide variation in the quality of cameras, which makes it impossible to predict the result of the study. This method highly depends on the distance between the camera and the user. As this distance increases, the tracking quality is getting worse, similar to changes in the position of the user's head.

As for mobile eye-tracking, several test programs are available in the Google Play and Apple AppStore that allow eye tracking but do not have any practical applications. However, the Hawkeye [29] and SeeSo [30] apps can make eye-tracking research on websites.

Like webcam eye tracking, the main advantage of mobile eye tracking is its accessibility: almost all smartphones and tablets are equipped with a front-facing camera used for research. Another significant advantage is mobility: since there is no need for stationarity, it is possible to capture the natural interaction of users with mobile interfaces, which provides more accurate behavioral data.

Mobile eye tracking has the same disadvantages as webcam eye tracking: a wide variety of cameras and lower accuracy than professional equipment. However, this approach also has disadvantages related to its use on mobile devices. The small size of smartphone screens limits the amplitude of gaze movements, which makes it difficult to track the gaze accurately. The head position during usage of mobile devices can be changed more frequently and extensively than when interacting with a laptop or monitor screen. Lighting conditions may change regularly and abruptly while using a mobile device. There are also technical limitations: not all smartphone models can provide efficient real-time video processing due to high computational loads, and active use of the camera and data processing can quickly drain a mobile device's battery. Another problem is the use of mobile tracking technology for mobile application research. Unlike websites, for which it is possible to embed the tracking function in the browser, mobile applications must embed it for each application.

Webcam and mobile eye tracking are actively developing, but several challenges must be resolved. First of all, there is a need to improve tracking accuracy, especially in low-light conditions and when using low-quality cameras. This can be achieved by further improving calibration. It is necessary to find ways to minimize the impact of external factors, such as lighting and changes in head position, which can distort the tracking data. Another challenge for mobile tracking is to develop accurate algorithms that require less computing power. This will ensure high performance even on devices with limited resources. Thus, both areas need further research and development to overcome the existing limitations.

Parameters that affect tracking quality

Most devices use infrared light reflection analysis captured by one or more cameras. Therefore, the main parameters that can affect the quality of tracking are:

– Camera resolution. Higher resolution provides more accurate eye movement data.

– Number of cameras. Since the cameras are placed at different angles to the eye, it gives the ability to recognize the direction of gaze more accurately.

– Frame rate. Higher frame rates allow for smoother tracking of gaze movements and shorter changes in gaze direction.

– Accuracy. It is the offset between the actual gaze position and what the eye tracker recorded as the gaze position [31].

– Precision. It is a measure of variation in the recorded data. It is defined as the ability of an eye tracker to reliably reproduce the same gaze point measurement from one sample to the next. Precision is calculated via the Root Mean Square (RMS) of the sampled points [32].

– Synchronization latency. It is defined as the time between the time the eye image is captured and the time the data is available in the program on the host computer. This time includes image exposure time, image acquisition and transmission time, processing time, and data transfer time to the main computer [33]. Low latency is essential for virtual and augmented reality systems devices to improve the user experience.

– Gaze recovery time. This is the time it takes for gaze tracking to resume after a temporary loss of gaze (e.g. when the participant turns their back on the eye tracker). If the device cannot detect the eyes at the last location within a few hundred milliseconds, it will start searching for eyes across the entire tracking area [34].

– Battery capacity. For autonomous devices, battery capacity is an important indicator, which can impose restrictions on the tracking process.

– Ergonomic features. Systems that restrict user movement and uncomfortable devices can lead to user discomfort, which can affect data accuracy.

Researching and improving these parameters is essential for developing more efficient and accurate eye tracking systems. Equally important is a comprehensive assessment of these parameters and their impact on each other. Attention to these factors can increase tracking accuracy, improve the user's experience with the system, and increase user comfort.

Summary of the review of existing eye tracking devices

There are three main types of eye tracking devices: desktop eye tracking complexes, mobile eye tracking glasses, and virtual reality eye tracking complexes. Web-camera and mobile eye tracking stand apart because they use built-in standard webcams.

Each of these types has its advantages and disadvantages, and the choice of a complex for a particular study depends on the goals set and many requirements such as accuracy, synchronization latency, mobility, etc. Currently, hardware systems are more focused on scientific research and, accordingly, less accurate and cheaper systems for commercial, more massive use.

In general, to successfully conduct eye tracking research, it is essential to carefully analyze all aspects related to the use of different hardware systems, environmental conditions, and the goals of this research.

In the further development of eye tracking technologies, we can expect to see improvements in the characteristics of hardware systems to obtain more accurate and informative research results, the use of built-in cameras in laptops and smartphones for eye tracking, and the expansion of the technology to even more scientific and applied areas.

Methods of eye tracking

An overview of eye tracking methods

Since gaze tracking technology began, several areas have been invented: electro-oculography, electromagnetic oculography, and video oculography (eye tracking). In electro-oculography methods, sensors are placed around the eyes to measure the electric field that changes when the eyes turn, and the eye's position is determined by changes in slight potential differences around the eye [35, 36]. In electromagnetic oculography, special contact lenses with an integrated inductor are used, and the eye's position is determined by the orientation of the coil in the magnetic field. Commercial devices commonly use video oculography or eye tracking, which allows for detecting gaze direction by analyzing a video stream with a face [37].

Modern eye tracking solves two tasks: eye localization and matching the movement of the gaze with the corresponding objects of observation (gaze tracking). There are 3 main approaches to eye localization:

- Shape-based Methods;
- Feature-based Shape Methods;
- Appearance-based Methods.

Gaze tracking makes it possible to correlate eye movements with objects and areas to which the gaze is directed and thus track the movement of the gaze. Depending on the equipment, gaze-tracking methods can be characterized by the number of cameras (one or more), the presence of infrared lighting (active and passive), and the number of additional infrared lighting sources (one or more). Like eye localization methods, gaze tracking methods have the following main approaches:

- Feature-based Methods;
- Model-based Methods;
- Cross Ratio based Methods;
- Appearance-based Methods.

It should be noted that most eye localization and gaze tracking methods use additional infrared lighting and cameras capable of perceiving it. It imposes some limitations on the use of such methods. For example, using an eye tracker in bright sunlight makes it difficult. Also, since most modern smartphones do not have a front-facing infrared camera (or do not allow third-party developers to use it), it is impossible to use the following methods in mobile eye tracking.

Methods of eye localization

The primary task in image tracking when analyzing a video is to detect the eyes in it. The main advantage is that the appearance of the eyes has many similar features among people, regardless of their age, gender, or ethnicity. However, some challenges complicate such analysis: wearing glasses, adapting to different head positions, blink rate, eye closure, individual differences in eye size, and other factors. In computer vision, eye localization is often performed parallel to face detection. To effectively solve this problem, it is possible to use methods that first detect the face, which significantly simplifies the localization of eyes in the area.

Shape-based methods propose the construction of a geometric model of the eye. Among them, there are methods that use a simple elliptical eye model, where the eye model is based on the elliptical shape of the iris contour, and methods where the eye is represented by a more complex shape, such as two parabolas for the eyelids and an ellipse for the iris [39]. An essential feature of these methods is their general ability to handle shape, scale, and rotation changes [40].

In Feature-based Shape methods, the characteristics of the eye are examined to identify a set of characteristics around the eyes. The limbus, pupil, and corneal reflectance are standard features used for eye localization [40].

Appearance-based Methods detect and track eyes directly based on the photometric appearance, which is characterized by the eye's color distribution or filter response and surroundings. One of the main benefits of detection is to reduce the impact of light changes by preserving sub-bands that are less sensitive to light and removing sub-bands that are sensitive to light changes. Appearance-based methods can be based on image templates, where spatial and intensity information of each pixel is stored, or on a holistic approach, where the intensity distribution is characterized by ignoring spatial information. Appearance-based methods typically require collecting a large amount of training data representing the eyes of different subjects under different face orientations and lighting conditions. Still, the models underlying them are essentially independent of the object class [37].

Gaze-tracking methods

The main task of gaze tracking or gaze prediction is to compare eye movements with the Point of Regard (PoR), the position in the displayed content the user is supposed to view. By analyzing the movement of the PoR, it is possible to detect gaze fixations and saccades (fast gaze movements) and to detect, according to [1], the level of information absorption.

Near-infrared eye illumination is widely used in gaze-tracking methods, which allows cameras to identify eye movements. There are two methods of such lighting: the "light pupil" method and the "dark pupil" method.

The "light pupil" method (Fig. 4) utilizes the contrast between the pupil and iris created by infrared rays parallel to the camera's optical axis. It effectively reduces noise caused by eyelashes or glare and is suitable for various lighting conditions. The pupil in the image appears bright due to the reflection of light from the retina [33].

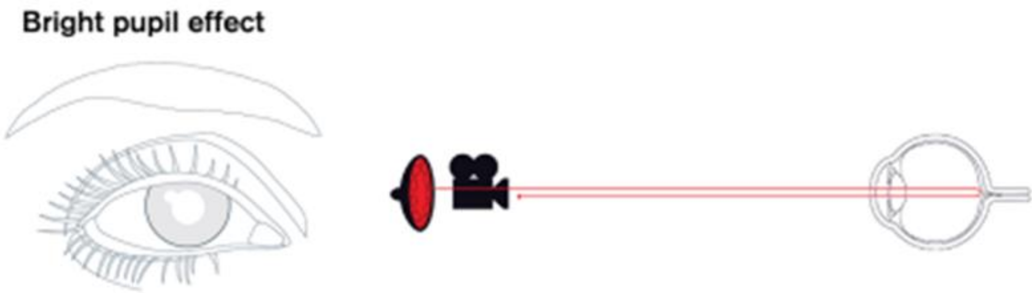

Fig. 4. The "light and light" method [38]

The "dark pupil" method (Fig. 5) also uses infrared light, but the illumination is placed at an angle to the camera's optical axis. It makes it possible to create stationary systems independent of the camera. However, the pupil becomes more sensitive to ambient light, which limits the use of the method in very bright environments [38].

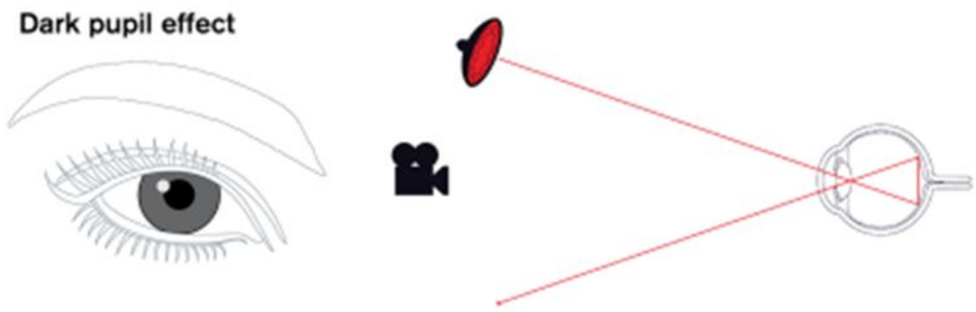

Fig. 5. Dark Pupil Method [38]

In general, the gaze focus point is determined by comparing the position of the near-infrared light (reflected by the eye) to the position of the pupil. By combining this information with head position data, the point of focus can be determined.

Using gaze tracking methods based on the visible light spectrum poses a significant challenge due to the low contrast between the iris and pupil. Compared to methods that use infrared light, this makes it difficult to determine the exact position of the pupil, which is why the position of the center of the iris is often used as an alternative in the analysis. This approach can lead to some inaccuracy in measurements, as it does not provide effective mechanisms for filtering out noise. It is necessary to implement video processing algorithms that can better distinguish between the pupil and iris to improve accuracy, as well as the use of machine learning methods to improve the accuracy of gaze detection based on data analysis. However, the use of visible light spectrum methods is unavoidable in cases where it is not possible to provide infrared light and when the camera does not support infrared perception. Thus, such methods are advisable in mobile eye tracking and webcam eye tracking.

Let's look at the main approaches of gaze tracking.

Feature-based Methods use eye features (pupil border and contrast, illumination distribution, etc.) to determine geometric vectors that reflect the shape of the eyes and head position to estimate the direction of gaze. The advantage of such methods is that the pupil and glare are easy to find and that these features can be formally related to gaze. These methods have performance issues in high light [41]. [40] provides a broad overview of feature-based methods.

Model-based Methods determine the gaze direction by fitting face and eye models to the image. These methods first build the eye's optical axis, then the gaze axis, and as a result, the point of view is determined by intersecting the gaze axis with the scene's geometry. The gaze axis is constructed by finding the pupil's cornea and center. The disadvantage of this approach is the need to use high-resolution images of the eyes and manually calibrate the system for each user to determine the eyes' location on the face accurately. The advantage of model-based methods is that they allow gaze direction to be determined using simple facial characteristics, minimizing the need for volumetric data for training for a particular person [41].

Cross Ratio based methods can determine the gaze using several sources of IR illumination and detect their glare on the cornea. [42] describes a method based on four infrared illuminators and [43] - based on five illuminants, which makes it possible to avoid additional calibration. The advantage of these methods is that there is no need for pre-calibration. Still, using additional illuminants may impose limitations due to the inability to use them with some devices.

Appearance-based methods use eye images as input to find the point of view using machine learning. These methods can work effectively with low-quality images but require significant data to train the models. Although they offer a direct image-to-gaze point conversion, they face limitations related to head pose, as changes in pose and gaze direction are not always reflected in changes in the appearance of the eye region [40].

Summary of eye tracking algorithms review

Thanks to decades of research into eye tracking methods, this technology has significantly progressed in developing various approaches and their features. The first task of eye tracking, eye localization, includes methods based on the eye area's shape, shape features, and appearance. Each approach has advantages, including accuracy in different lighting conditions and head positions. Gaze tracking methods, particularly those that use infrared light, provide high accuracy in determining the position of the pupil and the direction of gaze, although they also have limitations. Using machine learning in appearance-based methods expands eye tracking possibilities, allowing it to work effectively with low-quality images. Modern eye tracking methods have significantly improved accuracy and user-friendliness, opening up various applications, from medical research to interface design. However, existing challenges, such as wearing glasses, lighting variability, and the need for calibration, point to further study and improvement of these methods.

Conclusions.

The study discusses in detail the use of eye tracking technologies, their types, features, and the algorithms on which their operation is based. It is noted that such systems can accurately determine the user's point of view both when interacting with computer systems and with objects in real and immersive environments.

The first part discusses various hardware systems for gaze tracking: systems based on screen interaction, systems using glasses, and systems for virtual and augmented reality. Attention was also paid to mobile and webcam eye tracking, which uses built-in cameras of devices and household webcams to track eyes.

The second part of the article examines the algorithmic side of eye tracking. The main tasks solved by the eye tracking algorithms are outlined: localization of eyes in a video series and comparison of eye movement with the point of view. The main approaches to solving these problems are reviewed, and the challenges and limitations of these technologies are discussed, including the need to overcome gaze point errors and improve measurement accuracy.

Potential directions for future research are outlined, including creating more affordable gaze tracking systems that do not depend on expensive equipment, which could be widely used in various fields of research.

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