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Development of Adaptive Eye Tracking System Using Auto-Focusing Technology of Camera

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Abstract

Eye tracking technology tracks human eyes movements to understand user's intention. This technology has been improving slowly and should be used for a variety of occasions now. For example, it enables persons with disabilities to operate a computer with their eyes. This article will show a typical implementation of an eye tracking system for persons with disabilities, after introducing the design principles and specific implementation details of an eye tracking system. The article discussed the realization of self-adapting regulation algorithm in detail. The self-adapting algorithm is based on feedback signal controlling the lens movements to realize automatic focus, and to get a clear eyes image. This CCD camera automatic focusing method has self-adapting capacity for changes of light intensity on the external environment. It also avoids the trouble of manual adjustment and improves the accuracy of the adjustment.

Keywords : Eye Tracking Technology, Automatic Focusing Technology, Self-Adapting Regulating Strategy

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요 약

눈동자 추적 기술은 사용자의 의도를 이해하기 위해 눈 움직임을 탐지한다. 이 기술은 최근 점차적으로 발전하였으며 현재에는 여러 경우에 사용될 수 있다. 예를 들어, 장애인이 눈으로 컴퓨터를 사용하게 할 수 있다. 이 논문은 장애인을 위한 눈 추적 시스템 설계 원리, 구체적 적용 사항, 일반적으로 어떻게 적용되고 있는지에 대해 설명한다. 그리고 이를 구현하기 위한 눈동자 자동 추적 알고리즘을 제시한다. 자동 적용 알고리즘은 자동 초점으로 명확한 눈의 이미지를 잡기 위해 렌즈의 움직임을 조정하는 신호 피드백에 기반을 둔다. 이 CCD 카메라 자동 초점 기법은 외부 환경 빛의 강도 변화에 자동 적응하는 기능을 가진다. 이것은 수동 조절의 문제점을 피하고 조절의 정확성에 향상을 가져온다.

1. Eye Tracking and Auto-Focusing Technology

1.1 Eye tracking technology

Information process depends on our vision to a large extent. Studies have shown that about 80~90% of information is acquired through human eyes. People are interested in eye tracking technology because their eyes have the characteristics of directness and naturalness[1]. Early studies on eye tracking technology can be traced back to ancient Greece, but actual use of ocular instruments and equipment for observation and experiments started from the middle ages.

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Dodge and Cline has developed the first accurate, and practical eye tracking equipment in 1901.

Eye tracking technology is used more and more as it has been gradually developed over the years. The main application areas of the eye tracking system include pictures / advertising research (Web page assessment), dynamic analysis (aerospace-related fields, sports, cars, airplanes, typing analysis), product tests (ad. testing, Web testing, usability testing, and so on), scene study[2] (shopping, shop decoration, home, etc.) and human-computer interaction.

Eye trackers are used to measure eye movements. In general, there are two types of eye tracking technology: First type is to measure the eyes positions relative to the head. The second type is to measure a visual focus in the space[3]. Human-computer interaction system focuses on the object to which the user concerns in the scene and thus the second one is usually used. There are four major methods to measure eye movements including a method of electrooculogram, contact lenses or solenoid coil, a method of POG/VOG and a pupil-corneal reflection vector method. Now the most widely used one is the last method, a pupil-corneal reflection vector method.

1.2 Auto-focusing technology

A traditionally used manual adjustment depending on person's eyes and hands control is not only cumbersome, lengthy but also inaccurate influenced by subjective and difficult operation. Auto-focusing technique has been developed from the late 1970s. As a basic principle, auto-focusing can be divided into two categories: One is based on measuring the distance between the lens and the object, adjusting optical system of the distance, which is an active method. The other is based on the clarity of an image on the screen, adjusting optical system by an image, which is a passive method. The key issue to realize auto-focusing by the way of image processing is to select an evaluation function of image clarity.

Image acquisition from a CCD (Charge-Coupled Device) camera and image processing technology has been improved in recent years. Domestic and international scholars came up with multiple focusing criterions, and auto-focusing method based on image analysis has been applied[4]. However, most of the system still targets on a small area near the focal plane for automatic focusing, difficult to automatically adjust the focal length of real-time tracking of moving object and target location. This makes the system unable to automatically adjust the aperture to adapt to changing environmental light intensity. Autofocus algorithm for a real-time system is not strong in many cases. Therefore, looking for an accurate auto-focusing technique used for an eye tracking system is still a challenging piece of work. For eye-gaze tracking system features in this article, we propose a method of eye tracking and an automatic regulation method of CCD camera lens, capturing real-time images with dimming, zooming and focusing.

2. Realization of the Self-Adapting Eye Tracking System

In the eye tracking system based on the corneal reflection principle, CCD image sensors capture eyes images, transfer to a computer, and get the center of pupil and light spot position information in an image processing center, in order to estimate the direction of eye-gaze. The system requires a high quality of captured eye-images, and the clarity of which has a direct influence on the accuracy of the measurement. The system should allow users' head movements within a certain range in order to reduce restrictions on the user's head. In order to improve the resolution and accuracy of the system, The CCD (Charge-Coupled Device) camera only captures eye-images within a near-range. So, users' eyes might go out of sight, their heads would move back and forth, and eye size, intensity and clarity of the catching image would change, all of which affect the stability of subsequent algorithms. This put forward higher requirements for optical imaging system. CCD camera should be able to track head movements in real-time, to aim at the eyes, to adjust a zoom lens while accommodating the light intensity changes of external environment, and finally to auto-focus for a clear eye image.

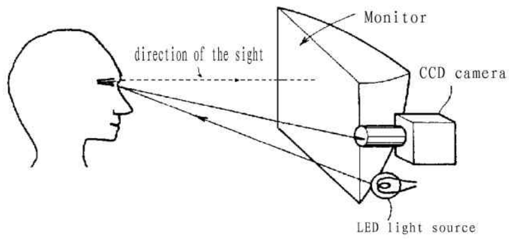
2.1 Application scenes and principles of the system

2.1.1 Research environment

Users face on a computer screen in an indoor office for less interfering, stable, reliable and useful real-time eye tracking technology. The user could move his/her head naturally sitting in front of the computer. His/her head is positioned apart 50 to 100 cm distance from the screen and can move horizontally in the range of 40 cm. His/her eyes could move horizontally and vertically in the range of 30 degrees.

2.1.2 Principles of the eye tracking system

Eye tracking system based on a corneal reflection principle uses near-infrared light source. Light emitted by near-infrared light source on the user's eyes forms high brightness reflex point (we call this point puerqin Fleck) as a reference point. When our eyeballs gaze at different places on the screen, the pupil will make divagation relative to the light spot because our eyeballs are sphere-shaped objects and the light spot will not move about. Eye gaze direction is detected by cornea reflection light spot (glints) in the eyes and pupil's location. The system principle diagram is shown in (Figure 1).



(Figure 1) Principles of the eye tracking system

2.2 Hardware design of the system

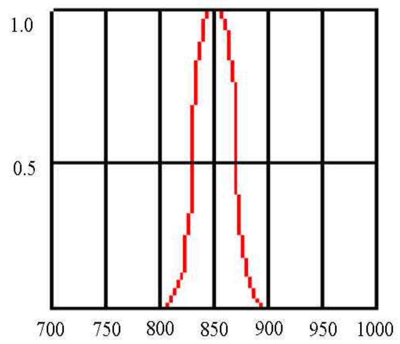
We now have to focus on the hardware design of the system including a selection of LED near-infrared light source, a camera, a lens and a filter after setting the basic structure and principles of the system.

2.2.1 A selection of LED near-infrared light source

Lighting plays an important role to detect user's vision. A well-designed lighting system can reduce the complexity of image processing, make image processing algorithm simple, increase efficiency, and improve signal noise ratio of CCD camera. Each part of the human eyes absorbs and reflects the infrared rays differently, therefore, infrared light sources have been playing a very important role in the field of capturing eye-image.

At the same time, in order to overcome the interference of the visible light, reduce the reliance on light resource in the night. The system adopts near-infrared light source. We use infrared sensitive CCD camera and an infrared filter getting the image to eliminate measurement effects. We use two infrared LED emission light sources for a stable image, respectively, placed on either side of the front in order to reduce the effect from head movements. So, the system can be used either day or night times.

We should choose the kind of the near-infrared light source minimizing a damage of eyes which are a sensitive organ. In summary, the selected system is the near-infrared LED light source with wavelengths of 850 nm. The spectral curve is shown in (Figure 2). Its detailed parameters were shown in <Table 1>.



(Figure 2) Spectral curves of the light source

<Table 1> Detailed parameters of the light source

Parts	Parameters
Model number	TL-30-350 IR-850
Wavelength	850nm
Radiant intensity	350mW/sr
Spectrum width	50nm
Shine angle	30°
Shine area	5.0mmX5.0mm

2.2.2 A selection of a camera

At present, there have been CCD image sensor and CMOS image sensor. CCD is characterized as high resolution and wide range of illumination while CMOS has a certain light intensity, low-power, low prices and high integration. CMOS technology or other sensing technology should be chosen for saccades analysis because sampling rate should be 150-200 Hz. Eye tracking studies can use CCD technology with 50/60 Hz sampling rate and frame sampling frequency of 25/30 Hz. We choose CCD image sensor because 25/30 Hz of ordinary commercial CCD camera can meet the requirements for real-time eye image analysis. According to the research objectives and design requirements, we choose the WAT-902H 1/2″ high sensitivity CCD mini video camera produced by Japan WATEC company.

2.2.3 A selection of a lens

There have been five factors to decide the lens, which include the size of monitored field, the size of objects in photos, object distance, focus distance, and the size of CCD target surface. The main foundation of choosing lens includes:

- the size of an image,
- the resolution of a lens,
- lens focus distance and angle of view, and
- an aperture or the amount of light.

In summary, we choose the H10Z1218M type of camera lens. Detailed parameters were shown in <Table 2>.

<Table 2> Detailed parameters of H10Z1218M lens

Characteristics	Parameters
Standard	1/2 ″
Interface	C
Focus distance (mm)	12-120
Aperture	1.8-22C
Angle (horizontal)	29.4-3.1
Size (mm)	70*79.5*123.5
Weight (g)	635
Characteristic	Automatic Regulation

2.2.4 A selection of a filter

The filter is one of optical accessories on the lens. Different wavelengths of light could be absorbed or through it. For example, ray 87 C″ filter can almost stop all visible light to achieve the purpose of adjusting the light. In order to reduce the external light interference, the near-infrared LED light source and the near-infrared band-pass filter (10 nm) are appropriate. However, we use unexposed and treated film which has good filtration and can replace the near-infrared band-pass filter in order to reduce costs and to achieve reliable results as well[5].

3. Self-Adapting Regulation of CCD Camera in the Eye Tracking System

3.1 Strategy of self-adapting adjustment and algorithm description

The camera on the cloud platform in the system can make two dimensional scanning, adapting to the head position changes. CCD lenses with variable focal length of a camera rely on variable power groups and compensation groups. Both groups move along the optical axis to change the focal length by lens size. So, changing the lens magnification and the field of camera angle to the target allow a continuously adjustable range of observation, adapting to a wide range of head movements.

The computer through the lens and CCD collects a series of digital images in the system operation, each frame image for real-time processing. First of all, the aperture is adjusted based on image gray scale information. Then, it is determined based on a spot in the image information if the focal length is appropriate. A zoom lens motor makes the zoom lens correspond to adjust the focal length, and control on cloud platform targeting and tracking the target. Finally, a focus operator is used to judge whether or not the focus is accurate and the image is clear, and to give the feedback signals.

3.1.1 Aperture control

Image brightness depends on the size of the CCD exposure controlled by an aperture. The image may be too bright if the aperture is too wide and the image may be too dark if the aperture is too narrow. Both cases cannot reliably adjust the focal length and focus. We should first determine the aperture size. The brightness of the image determines the appropriateness of the CCD exposure. (Figure 3) shows the same scenes as we gradually increased the size of the aperture.

(Figure 3) The same scenes with different levels of an aperture

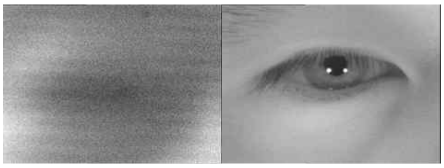
The gray scale values of each point in the image are I(x, y). The average gray scale values are:

$$V = \frac{\sum I(x,y)}{h \times w} \quad \text{(Formula 1)}$$

h and w represent the height and width of an image. The aperture size is represented by f. Experiments show that the function F=f (v) is monotonous within the aperture adjustment range. In an eye tracking system using a near-infrared light source and a band-pass filter, ideal eyes image gray scale values should be in a narrow range tested within a bounded area so that it can achieve aperture control by setting a range of gray-level threshold. For capturing image sequences, we calculate the average gray scale values of the current frame if the value is smaller than the gray-level threshold. Otherwise, we return to the control signal of the aperture and increase exposure. You control the aperture to reduce exposure. We stop the aperture adjustment when the average gray value falls within the scope of the threshold. So, the CCD camera can automatically adjust the aperture based on the gray information of captured images to achieve adaptive adjustment of light intensity changes.

3.1.2 Zoom lens adjustment and eye tracking

Focus reflects the clarity of the image. The image will be fuzzy if the focus is not appropriate. The defocused and focused images of an eye are shown in (Figure 4).



(Figure 4) The defocused and focused images of an eye

Adjust the focus roughly at first to ensure extracting spot information in the image. Then we use the adjacent pixels of gray scale variance method which has faster calculation. The formula of the operation is :

$$SMD = \frac{1}{n}[\sum|I(x,y) - I(x,y-1)| + \sum|I(x,y) - I(x+1,y)|]$$

(Formula 2)

I(x, y) corresponds to gray values in (x, y) position. n is the total number of pixels of the image. We use HCS (Hill-Climbing Search) algorithm to adjust focus roughly and quickly. We can extract spot information after processing the focused image.

The Center coordination of the two spots respectively are : (x_1, y_1), (x_2, y_2). The Center coordination c is : $(x_1+x_2/2,\ y_1+y_2/2)$. Distance between two spots :

$$d = \left((x_2 - x_1)^2 + (y_2 - y_1)^2\right)^{1/2}$$

(Formula 3)

We finish adjustment according to the distance d between the spots to control the zoom direction and amplitude. In the eye tracking system, we could establish a standard range of values for d such as D. If d<D, eyes are small in the image, system accuracy is low, and we need to increase the focal length. If d>D, we may not be able to get the complete eyes image and need to reduce the focal length. In the zoom process, we don’t need to focus on the current location to improve the CCD lens adjustment speed in the image processing if we can extract the spot information. On the other hand, we need to focus on its current location once again if we are unable to extract spot information.

3.1.3 Precise focusing

Typically, image focus is measured by the focusing evaluation function (that is, focusing operators). At present, the domestic and overseas scholars have proposed many focusing operators such as Tenengrad operator, SML operator, modulus deviation and SMD operator, and brightness changes VAR operator. Different operators have different properties and thus, the applications are different.

An ideal focusing operator should have unbiased and unimodal nature, high sensitivity, high signal to noise ratio and small amount of computing space. In practice, however, due to effects such as noise, spotlight operators not only have a global maximum value, but also have a lot of local extreme points. The up and down curve is not monotonous or smooth. To eliminate the effects of impulse noise in an image, Gaussian smoothing filter for image can effectively eliminate the sharp noise in images.

Most focused operator is now based on gradient. Deviation operator is actually a high-pass filter to calculate the image's high frequency vectors, gradient. Median filter can effectively retain the boundaries of the image, and effectively suppress pulsed noise. FSWM filtering operator can achieve the correct focus better.

FSWM filter operator calculation formula is shown as the follows:

$$FSWM = \sum_x \sum_y F_x^2 + \sum_x \sum_y F_y^2 \quad \text{(Formula 4)}$$

And,

$$F_x = med\{I(x-1,y), I(x,y), I(x+1,y)\} - \frac{1}{2} med\{I(x-3,y-2), I(x-2,y-2), I(x-1,y-2)\} - \frac{1}{2} med\{I(x+1,y+2), I(x+2,y+2), I(x+3,y+2)\}$$

(Formula 5)

$$F_y = med\{I(x,y-1), I(x,y), I(x,y+1)\} - \frac{1}{2} med\{I(x-2,y-3), I(x-2,y-2), I(x-2,y-1)\} - \frac{1}{2} med\{I(x+2,y+1), I(x+2,y+2), I(x+2,y+3)\}$$

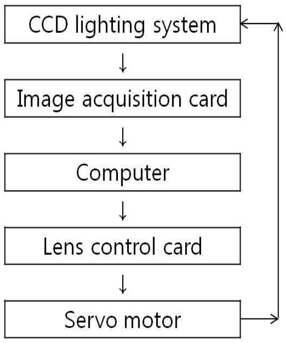
(Formula 6)

In the above formula, I(x, y) is Windows image pixel gray scale values, and MED is average values. The FSWM filter operator for criterion with climbing algorithm, realizes automatic precise focusing. In tracking eyes later, if you could extract the pupil edges in the image, then directly use the pupil edge points gradient average values to achieve focusing. The specific algorithm makes a reference to literature[6].

3.2 The result of the experiment

System hardware included camera systems, lighting, image acquisition card, computers, control card, and servo motors. CCD camera in the camera system is placed on the cloud platform, driven by a servo motor. The system used LED lighting near infrared light source for sensitive CCD camera (25 frame/s), effective pixel (K) of C440K, CCD lens with zoom lens, the focal length (FMM) of 12-120, the aperture (f) of 1.8-22C, the band-pass filter in the front, and twice times optical amplifier in the back. The system used a computer equipped with Windows XP operation system, and Pentium 4 CPU. Algorithms were implemented by Visual C++. Physical map of the experimental system is shown in (Figure 5). The system structure is shown in (Figure 6).

(Figure 5) The physical picture of the system

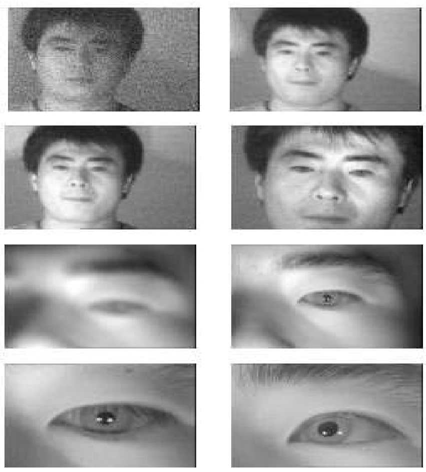


(Figure 6) The structure of the system

We conducted the experiment for 36 times in different locations during day and night times, two environments for the normal working area (facing the screen, screen distance of 40 cm-80 cm) of head movements. Aperture value is uncertain for the wide field of view with CCD lens initially. Experiments show that CCD camera can be adjusted through adaptive, successful aim at the eyes in a few seconds, capturing the clear eyes images. <Table 3> is partial results. In the 36 times of experiment, the average time of CCD lens automatic orientation to the eyes is 4.35s. Evening experiment of CCD camera self-adaptive average time is short. This is because the smaller external ambient light interference, the easier to extract spot information.

<Table 3> The results of the experiment

N.	Head locations	Environment	Adjust time (second)
1	Left front	day	4.3
2	Left front	night	3.2
3	Left back	day	4.7
4	Right back	night	3.9
5	Right back	day	5.8
:	:	:	:



(Figure 7) Captured images in the experiment

Experiment results show that the CCD camera automatically adjusting method based on image processing is quick and accurate. It has adaptive capacity for the light intensity changes of external environment and user's head position changes. The system still has problems and fails to track when the users move their heads too quickly and their eyes blink. The efficiency of the current treatment methods is not high because it waits for several frames when trace fails, and the view of CCD is increased and readjusted if it still fails to track. Future work is intended to introduce head movement prediction algorithm to overcome the lack of tracking quick head and eye movements.

4. Conclusion

This study first investigated and discussed the eye tracking technology, traditional auto-focusing technology, and a self-adapting eye tracking system. Then, we made the hardware design according to the research objectives and system requirements. In order to track eyes and to capture clear eyes images in real-time, we put forward the eye tracking technology in an automatic focusing method of CCD camera with lighting, zooming, and focusing. The automatic focusing method of CCD camera for the eye tracking system has self-adapting capacity for changes of light intensity on the external environment and user's head position. This study resulted in avoiding the trouble of manual adjustment and improving the accuracy of the adjustment for finding and meeting the requirements of the eye tracking system. The advantages of the system comparing to the most of the current focusing systems are:

- aiming, tracking and automatic focusing moving targets;
- adapting to different lighting conditions; and
- applying in real-time systems.

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