Research on Bionic Eye Anisotropic Movement Based on the Mechanism of Eye Movement

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Abstract: Building upon the fundamental neural mechanisms governing smooth pursuit eye movement control in humans, this research systematically simplifies and abstracts the intricate neural circuitry involved in this biological process. Through careful analysis and computational modeling, we have successfully established a novel bionic eye vergence movement control framework that faithfully emulates the core principles of natural ocular motility. Extensive simulation experiments were meticulously designed and implemented to rigorously validate the performance and reliability of the proposed biomimetic control model. The comprehensive experimental results conclusively demonstrate that our advanced vergence movement control system can not only accurately but also efficiently track dynamic visual targets in real-time scenarios, while simultaneously maintaining robust stability. Importantly, the system exhibits both excellent functional validity and distinctive behavioral characteristics that are remarkably consistent with those observed in natural human eye vergence movements.

Keywords: *Eye Movement Control; Anisotropic Movement; Bionic Eye; Pid.*

I. INTRODUCTION

The human eye serves as a crucial organ for human perception of external objects and environments, capable of acquiring over 90% of sensory information and enabling rapid, accurate environmental cognition[1][2]. While machine vision has seen widespread applications across various fields in recent years, it still exhibits significant functional gaps compared to the advanced capabilities of human vision. Bionic eyes (human eye simulators), designed to emulate human ocular functions, demonstrate superior adaptability compared to conventional machine vision systems. These systems find extensive applications not only in aerospace and medical fields but also across diverse sectors of the national economy including agriculture, pharmaceuticals, military defense, space exploration, meteorology, and transportation. However, the effective implementation of bionic eye functions such as positioning and tracking requires integration with ocular motion control mechanisms - an area where domestic research remains in its preliminary stages. Consequently, in-depth investigation into the fundamental mechanisms of eye movement control is imperative to facilitate the refinement and enhancement of bionic eye functionalitie[s[3][4]]。

Human eye movements are mainly divided into conjugate movements, non-conjugate movements and reflexive eye movements[5]. The anisotropic movements studied in this paper are one of the research hotspots of scholars in various countries[6], and its purpose is to achieve real-time and precise tracking of the target. Reference [7] analyzed the role of neurons related to anisotropic movement from the perspective of neural mechanisms. Zhang Xiaolin from Tokyo Institute of Technology in Japan established a relatively complete model of eye movement control based on the neural structure of eye movement[8]. This model provides new ideas for the later research on anisotropy. Wang Xin and others from Delft University of Technology have established a binocular control model that can achieve smooth tracking movement of the human eye[9]. However, this model has certain limitations and needs to be further improved. Reference [10] established a binocular control model that can achieve multiple functions of the human eye, such as smooth tracking motion, anisotropic motion, etc. In the anisotropic movement of the eyeball[11], to maintain a stable image of the target on the retina, when the retina receives external image information, it acquires the movement information of the target through image processing, thereby enabling the eyeball to perform the corresponding movement.

II. ANALYSIS OF ANISOTROPIC MOTOR NEURAL MECHANISMS

From the perception of external visual information to the corresponding movement of the eyeball is an extremely complex process[12][13]. The movement of the eyeball is involved in many areas of the brain, including not only the advanced visual cortex areas but also the primary visual cortex areas[14]. Anisotropic movement enables the retina to obtain clear images. During the anisotropic movement, both the speed and amplitude of the target's movement need to be appropriately controlled to ensure that the target remains in the center of the retina all the time. Based on the neural mechanism of eye movement control, the eye movement flowchart as shown in Figure 1 can be obtained. This figure clearly shows the process of motor information transmission among various neurons. The movement of the eyeball is a behavior of interacting with external information. During this process, neurons on the relevant neural pathways play an important role. Figure 2 illustrates the neural mechanism of smooth pursuit eye movements, demonstrating the complete motor signal transmission process across multiple neuronal layers[15]. This diagram reveals how visual motion information flows through cortical and subcortical pathways to coordinate precise eye movements. The eyeball's motion represents a complex sensorimotor behavior involving continuous interaction with external visual stimuli. During this process, specialized neurons - including those in visual cortex, brainstem and oculomotor pathways - work collectively to enable accurate target tracking through precisely timed neural computations and signal integration. The schematic particularly emphasizes key connections between visual motion processing areas and ocular motor control centers that govern this essential visual function.

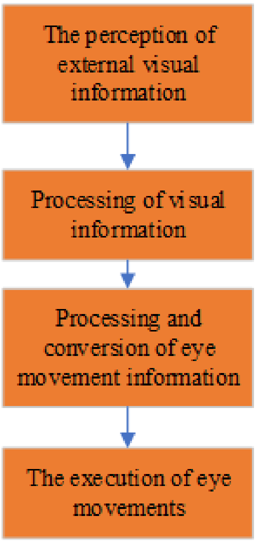

Figure.1 Smooth tracking flowchart

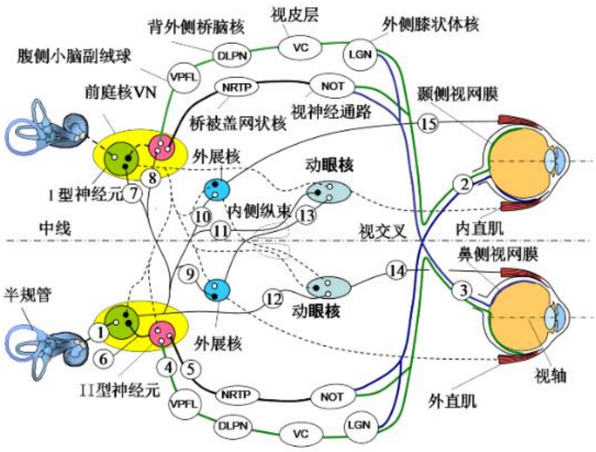

Figure.2 Diagram of the ocular motor neural circuit

The serial numbers in Figure 2 represent each neural pathway. The meanings of the English abbreviations in Figure 2 and Figure 3 are as follows: RTL:Retinal；LGN: Lateral geniculate nucleus; NOT: Nucleus of theoptic tract；VI: Visual cortex; MT: Middle temporal; MST: Medial spurior temporal; FPA: Frontal pursuit area; FEF:Frontal eye fields; SEF: Supplementary eye field; NRTP: Nucleus reticularis tegmenti pontis; DLPN: Dorsolateral pontine nucleus; CBLM: Cerebellum; VN: Vestibular nucleus; ONCL: Oculomotor nuclei; LIP: Lateral dorsal endothelial area

Anisotropic movement of the eyeball refers to a form of movement where the movement directions of both eyes are opposite, in order to track in real time the target that is constantly changing at a distance from the eyeball. The binocular motor neural circuit of the human eye is a complex system involving the synergistic effect of multiple neural structures. Figure 2 shows the structure of this neural circuit, where the black solid small circular connection lines represent inhibitory nerve fibers, while the white circular connection lines represent excitatory nerve fibers. Take the right eye as an example and describe this neural circuit in detail: The excited nerve fibers from the semicircular canals are directly connected to the type I neurons in the vestibular nucleus after transmission. The neural signals from the temporal retina of the left eye fuse with path 3 at the optic crossover through path 2. The fused signal is then divided into two branches and transmitted respectively to the type II neurons in the vestibular nucleus of the right eye. The first pathway passes through the lateral geniculate nucleus (LGN), and after transmission, it eventually reaches the type II neurons in the vestibular nucleus. The second pathway first passes through the optic fasciculus (NOT), then reaches the reticular nucleus of the pons (NRTP), and eventually also reaches the type II neurons in the vestibular nucleus. Type I neurons in the vestibular nucleus are connected to type II neurons through inhibitory nerve fiber 6, forming a regulatory mechanism.。

After the signal reaches the vestibular nerve nucleus, it will reach the extraocular muscles through both excitatory and inhibitory neural circuits[14][15], ultimately controlling eye movement. The excitation neural circuit is transmitted from the axon of type I neurons through the medial rectus muscle of the right eye to the lateral rectus muscle of the left eye. The abductor nucleus of the left eye is connected to the oculomotor nucleus of the right eye through the medial longitudinal tract. The inhibitory neural pathway is transmitted from the axon of type I neurons through the lateral rectus muscle of the right eye to the medial rectus muscle of the left eye[16]. The nerve nucleus of the right eye is connected to the oculomotor nucleus of the left eye through the medial longitudinal tract[17]。

2Establishment of the anisotropic motion model

Based on the visual pathway of eye movement and the neural control mechanism of smooth tracking movement, the block diagram of the anisotropic movement structure as shown in Figure 3 can be obtained.。

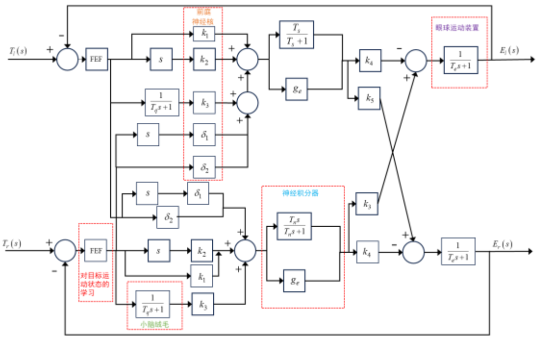

Figure.3 Block diagram of the anisotropic motion structure

In Figure 3, $T_l(s)$ and $T_r(s)$ respectively represent the angles of the moving target relative to the left eye and the right eye; k_1, k_2, δ_1, δ_2 are the gains of the synapses of the related neurons; Let $F(s)$ represent the transfer function of the cerebellar villi, $N(s)$ represent the transfer function of the neural integrator, and $Q(s)$ represent the transfer function of the eye movement device; k_3 and k_4 represent the emission weights of the otolith organs; $E_l(s)$ and $E_r(s)$ respectively represent the outputs of the left and right eyeballs.

From the above figure, it can be known that the expressions of $F(s)$, $N(s)$, and $Q(s)$ in the anisotropic motion system are respectively:

$$F(s) = \frac{e^{-\Delta_1 s}}{T_q s + 1} \quad (1)$$

$$N(s) = \frac{1}{T_n s + 1} + g_e \quad (2)$$

$$Q(s)=\frac{1}{T_e s+1} \tag{3}$$

T_q represents the time constant of the cerebellar villi; Δ_1 is the time interval of the overlap of errors between eyeball physiology and the hardware characteristics of the system; T_n represents the time constant of the neural integrator; g_e represents the gain of the information path; T_e represents the time constant of the eye movement device.

In the anisotropic movement of the eyeball, in addition to the neurons and regions shown in Figure 4, there are many neurons and brain regions that have not been described in detail involved. The mesencephalic and pons reticular structures are located near the eye motor neurons. There are neurons related to anisotropic movement in these areas, and these neurons continuously discharge electricity when the eye performs anisotropic movement. The medial superior temporal region is also involved in the prediction of the target state, but there are relatively few related studies. During the anisotropic movement of the eyeball, the eyeball has the ability to learn the movement state of the target, presenting the movement target in the center of the retina, and also endows the anisotropic movement with the ability to learn the movement state of the target.

In order to obtain an anisotropic movement model that conforms to human physiological characteristics and enable the model to simulate the anisotropic movement of the eyeball, the PID control algorithm is added to the anisotropic movement system. The PID algorithm is used to simulate the learning ability of the target movement state in the anisotropic movement, thereby completing the anisotropic movement of the eyeball.

The PID control algorithm is a classic control strategy based on error feedback. The proportional term provides a fast response capability, the integral term eliminates steady-state errors, and the differential term suppresses overmodulation and improves system stability. In digital control systems, the PID algorithm is usually implemented discretely. Its incremental variant effectively avoids the integral saturation problem and reduces the computational complexity by calculating the change of the control quantity rather than the absolute value. PID control has the characteristics of simple structure, clear physical meaning of parameters and strong adaptability, and is widely used in industrial process control, robot motion control, power electronic regulation and other fields. The PID algorithm used in this paper is the incremental PID algorithm. Compared with location-based PID, incremental PID has three significant advantages: First, the amount of calculation is smaller, and only the control increment needs to be calculated; Second, it effectively avoids the problem of integral saturation. Third, it is easier to achieve disturbance-free switching. When implementing the algorithm, it is necessary to reasonably set the three parameters of proportion, integration and differentiation. Among them, the proportion coefficient Kp determines the response speed of the system, the integration coefficient Ki affects the steady-state accuracy, and the differentiation coefficient Kd is used to suppress overshoot. In practical engineering applications, incremental PID has become an important algorithm in digital control systems due to its good real-time performance and anti-interference ability. However, it should be noted that its control accuracy depends on the rationality of the sampling period and parameter tuning.

The derivation process of the incremental PID algorithm is as follows:

The PID control law of the system within continuous time is:

$$u(t)=k_p e(t)+k_i\int_0^t e(\tau)d\tau+k_d\frac{de(t)}{dt} \tag{4}$$

The backward difference method is adopted to discretize it:

$$\int_0^t e(\tau)d\tau\approx T\sum_{i=0}^{k}e(i) \tag{5}$$

$$\frac{de(t)}{dt}\approx\frac{e(p)-e(p-1)}{T} \tag{6}$$

Discrete position PID can be obtained:

$$u(p)=k_p e(p)+k(i)T\sum_{i=0}^{p}e(i)+k_d\frac{e(p)-e(p-1)}{T} \tag{7}$$

The control quantity at time (p-1) is:

$$u(p-1)=k_p e(p-1)+k(i)T\sum_{i=0}^{p-1}e(i)+k_d\frac{e(p-1)-e(p-2)}{T} \tag{8}$$

Subtract Equation (8) from Equation (7):

$$\Delta u(p)=k_p\left[e(p)-e(p-1)\right]+k(i)Te(p)+k_d\frac{e(p)-2e(p-1)+e(p-2)}{T}$$

Therefore

$$\Delta u(p)=u(p)-u(p-1) \tag{10}$$

$$\Delta u(p)=k_P\left[e(p)-e(p-1)\right]+k_I e(p)+k_D\left[e(p)-2e(p-1)+e(p-2)\right]$$

From the above formula, the current system control quantity can be obtained as:

$$h(p)=h(p-1)+\Delta h(p) \tag{12}$$

In the above formula: $p$represents the sampling sequence; $h(p)$ represents the input value of the anisotropic motion system at sampling time p; $e(p)$ represents the retinal deviation of the anisotropic motion system at time p; $e(p-1)$ indicates the retinal deviation of the system at time (p-1). $e(p-2)$ represents the retinal deviation value at time (p-2); k_P represents the proportional parameter; k_I represents the integral parameter; k_D is the differential parameter. The structure of the anisotropic motion model based on the PID algorithm is shown in Figure 4.

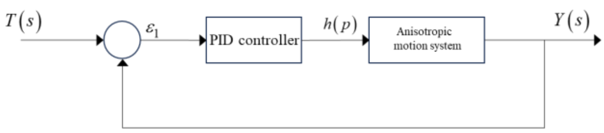

Figure.4 Structure diagram of anisotropic motion

In anisotropic movement, $h(p)$ represents the input to the anisotropic movement system at time *p*, and ε_1 represents the retinal deviation of the eyeball at time *p*.

III. SIMULATION AND ANALYSIS OF ANISOTROPIC MOTION

To verify the correctness of the anisotropic motion control model proposed in this paper, the anisotropic motion was simulated and analyzed in the Matlab2018a/ Simulink simulation environment. The performance of the anisotropic motion model in two scenarios is mainly examined: In the first case, when the target is stationary relative to the eyeball, the anisotropic motion control ability of the model under the condition of a fixed target is tested to ensure that it can still maintain an accurate anisotropic motion response when the target position remains unchanged; The second situation is when the target is in a moving state relative to the eyeball, which is used to evaluate the model's tracking ability and adaptability to dynamic targets. Through the comparative analysis of the simulation results, the performance of the anisotropic motion model under static and dynamic conditions can be comprehensively evaluated to ensure the correctness and superiority of the anisotropic motion model established in this paper. The simulation results are shown in Figures 5 and 6.。

The parameter Settings are as follows：

$$T_q = 0.2s、 T_n = 25s、$$

$$T_e = 0.24s、 g_e = 0.24$$

$$k_1 = 1\deg / spikess^{-1}、$$

$$k_2 = 1、 k_3 = 1、$$

$$k_4 = 1.5、 k_5 = 0.5、$$

$$\delta_1 = 1、 \delta_2 = 1$$

The first situation, when the target remains stationary relative to the eyeball:

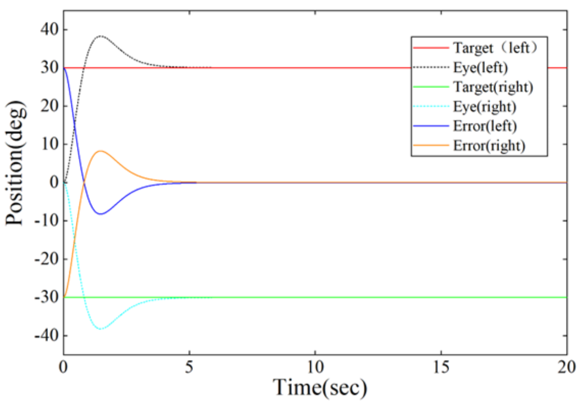

Figure 5 Simulation results of the stationary target

The second situation, when the target moves continuously relative to the eyeball:

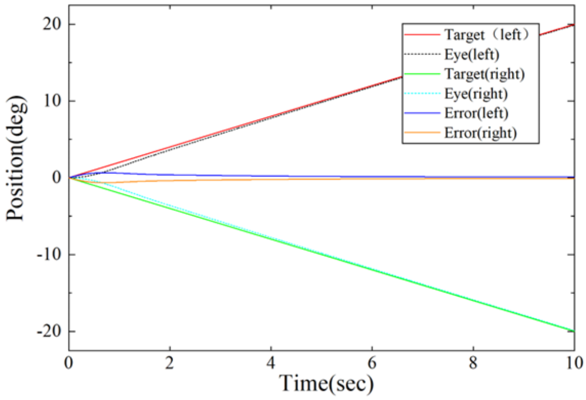

Figure 6 Simulation results of the moving target

Figures 5 and 6 show the simulation results of the anisotropic motion control model for stationary targets and moving targets. The simulation results show that whether it is a stationary target or a moving target, the anisotropic motion model based on the PID algorithm proposed in this paper can quickly enter the stable state, and the error in the stable state approaches zero. This result conforms to the characteristics of anisotropic motion. Thus, the correctness and superiority of the anisotropic motion model based on the PID algorithm established in this paper have been verified.。

CONCLUSION

Based on the neural mechanism of smooth tracking motion control of the human eye, the complex neural circuit of its movement was equivalentially simplified, and a bionic eye anisotropic motion control model based on eye movement excitation was established. Simulation experiments of this model were carried out in the Matlab/Simulink environment. The simulation results show that the anisotropic motion control model can track the target accurately and in real time. By analyzing the simulation curve and error curve of the control model, it can be seen that the anisotropic motion model can reach a stable state, thereby proving the correctness and superiority of the smooth tracking model.

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