Visual Prosthesis-Eyeball Movement Control

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Abstract: This paper focuses on the research and implementation of bionic eye motion control algorithm. First, the characteristics and forms of various eye movement patterns are summarized from the perspective of neurophysiology. Based on the neurophysiological structure of each movement mode of the eyeball, this paper analyses the relationship between various neural modules and refines the mathematical expression of each module for engineering modelling. The saccade model was established, and the effects of each module were analysed by simulation, and the results were compared with physiological results. The smooth pursuit movement model is established to constrain the retinal sliding error to some extent. Besides, the tracking accuracy is improved, the target of uniform velocity and random motion can be accurately tracked, and the problem that the existing smooth pursuit control algorithm can only track the periodic motion is solved. Besides, the control system is combined with image processing to perform the saliency processing. Based on the above control system, a model for controlling eye movement through the mouse was established. The physical model of eye movement was successfully constructed and simulated by Simulink.

***Key words*—Bionic eye; Eye movement control; Saccade; Smooth pursuit; Image processing**

1. Introduction

The analysis of visual motion plays a vital role in successful interactions with our environment. When humans perceive the objective world, more than 90% of the information is obtained through the eyes [1]-[3]. It has a variety of functions related to perception and action, such as planning and monitoring target-oriented movements or self-motion analysis for stable posture and gait. The human eye has many special natural functions, such as the two eyes can only gaze and track the same target, can compensate for the deviation of the line of sight caused by head movement, and can quickly switching on the gaze target, tracking the target smoothly, seeing objects in the background of the movement, etc. These functions are realized by different forms of movement in the eye movement. Most importantly, it is used to determine the velocity of moving objects of interest, so that they can be tracked with our gaze to keep them in foveal view.

In recent years, the rapid development of robotics and the rapid increase in the demand for robotics in industrial automation or people's daily life have made the robot's functions more perfect and more anthropomorphic [1]-[4]. In the field of robotics, although the visual system has made significant progress, it still lags behind other aspects, such as robot walking, robotic arms grabbing, and motion functions.

For the robot, “eye” is also a critical sensing device. The bionic robot eye makes the robot eye have many functions of the human eye [1]-[5]. At present, the various features and movements of the human eye have been imitated, but most of them can only implement one or several of these movements, and only one-dimensional horizontal movement.

For a long time, the saccade and smooth pursuit eye movement system were considered to be completely independent, but interactions and overlaps have recently been discovered at the anatomical and functional levels. In this paper, the modelling of the three-dimensional motion control system of the bionic robot eye is studied. The two kinds of motions of saccade and smooth pursuit are simulated on the computer. Simulation results and physiological experiment results to verify the correctness of the model. Besides, the physical model of the eyeball is built, which can generate an animation of eye movement, and the control model is also expanded, which use the mouse to control eye movement.

Among the many research methods for studying robotic bionic eyes, the research on the two-eye control algorithm combined with the physiological function of human eyes has attracted the attention of many scholars. The movement patterns of human and primate eyes are formed through long-term evolution and natural selection, so they have considerable advantages in function and performance [1]-[5]. The structure of the human eye is complex and has special functions, such as depth perception and three-dimensional scene reproduction. It can recognize and perceive the complex visual world. The eyes only focus on the same target, which can quickly shift the fixation point and the relatively slow movement. The target is precisely tracked and can coordinate with the head to compensate for each other and capture the visual target. Robots urgently need visual systems to perfect their functions, so that they can obtain information with higher performance. Bionic eyes research is an essential part. The ability to perform bionic studies from neural pathway response and motion control and apply the results to the field of intelligent robots will produce significant results.

2. Literature review

The human eye is a sphere, and each movement is done by several extraocular muscles. In addition to the eyes and cerebellum, there are also vestibular organs in the human body. The vestibular organs are composed of three pairs. Semi-regular tube, a pair of elliptical capsules and a pair of balloons [1],[2]. The semi-regular tube is the feeling of angular acceleration. The three semi-regular tubes on each side are distributed on three mutually perpendicular planes so that the acceleration in different directions can be felt. The elliptical capsule and the balloon are the receptors at the angle and position of the human body.

The natural function of the human eye is achieved by different forms of movement in the eye movement. The eye movements of the human eye are mainly divided into the following:

(1) Saccades: It is a fast jumping motion that automatically moves the eye from one fixation point to another fixation point, and is especially noticeable when people is reading. It is an erratic movement that causes the eyeball to look at the direction; that is, the line of sight suddenly changes [1],[2]. The maximum velocity of eye saccade reaches $600°/s$ for large saccades, and the total time of the movement is under 0.1 sec for a 100 jumps, the scanning angle is approximately 1 to $40°$, the duration is about 30 to 120 ms [1]-[3]. The central nervous system sends a control signal by estimating the position of the changed visual target and applies a specific acceleration and action time to the eyeball through the extraocular muscle so that the line of sight is quickly switched to the new fixation point. The eye saccade movement also has strong adaptability. After several pieces of training, it can automatically adjust the gain of eyeball beat.

In 1963, Young and Stark et al. proposed a data sampling model for saccade. The position information of the target is used as an input to output the position of the eyeball [1]. The error generated by the two is used as the input of the next moment to enter the threshold circuit. When the error exceeds the limit the pulse generator generates a signal to trigger the sampler to rotate the line of sight toward the new target position; if the error is less than the threshold, the eyeball stops moving. However, due to the lack of data on ocular neurophysiological studies at the time, the model did not consider the role of the brain. In order to solve this problem, Robinson et al.[1]-[3] made an improvement based on the Young model and proposed a parallel network composed of the medial longitudinal beam (MLF) and the neural integrator (hunger) to form an advanced link with the compensation eyeball in motion. The delay problem that arises in the process [1]-[3]. After the difference between the current target position and the eye position is generated, the sampler output signal is triggered, and then the position signal is generated through the parallel network of the neural integrator and the inner longitudinal beam and transmitted to the eye movement mechanism. The proposed model is of considerable significance because it applies the parallel pathway in the signal transmission process of neurophysiology to the control model of the eyeball for the first time.

(2) Smooth Pursuit: The continuous movement of the eye following the low speed moving target. The maximum movement speed is about $30°$ [4]. Smooth pursuit eye movements are typically made when we track an object moving smoothly in the visual environment. Their purpose is to keep the image of the object near the fovea. Significant errors are eliminated by saccadic eye movements, and the role of the pursuit system is subsequently to match eye velocity to target velocity [4]-[6].

In 1986, Robinson et al. conducted a physiological experiment on the smooth tracking movement of monkeys and humans [4]. He believed that the smooth tracking movement is an eye movement with continuous negative feedback behavior, indicating that the difference between its motion characteristics and saccade movement is large. Movement is independent of each other. In the study of the new smooth tracking control model, a transmission delay module was added, and model parameters were set based on physiological data. The establishment of this model is essential.

2.1. Problems in the research of bionic eye system

The human visual system is a sophisticated and complex system involving the brain, cerebellum, and neural circuits [1]-[6]. The physiological analysis is a multidisciplinary research direction. The study of robotic bionic eyes also involves multidisciplinary integration, such as control theory, medicine, neurophysiology, vision system and bionics. For decades, researchers in various countries have studied the bionic eye system from various angles based on different purposes and established a skilful eye system with different functional characteristics. Some progress has been made in this field of research, but there are still some difficulties to be researched and solved. The specific situation is divided into the following points:

(1) With the rapid development of modern medicine and neurophysiology [1]-[3], people have deepened their understanding of the role of different regions in the visual system. Therefore, most domestic and foreign scholars are based on neurophysiological inspiration to develop a study of the bionic eye vision system and to establish modules for different regions of the visual system to simulate the human visual system. However, most of this research has stopped at the physiological model and has not been well applied to engineering.

(2) The research and development of most bionic eye control systems are limited to the realization of one or two modes of delivery [1]-[3], and generally, only achieve one-dimensional horizontal motion. Of course, after comparing with physiological data, it is found that some models of single motion mode can better simulate the physiological response of human eyes in this movement mode, but the research on complex and intersecting multi-mode combined movement is still the same. There are big vacancies.

(3) The existing bionic eye experimental platform only considers the verification of the bionic eye movement function [4]-[6]. For the coordinated movement between the two cameras, the single mechanical structure and the acquisition of visual information during the movement of the camera are all problems. Need to be solved. Moreover, the existing bionic eye system experimental platform is too large in size to meet the micro-precision characteristics of the human visual system.

3. Research on human eye movement and visual mechanism

In this section, I will introduce the structure of eyeball, the process of visual formation, and neural mechanism of eye movement.

3.1. Eye structure and characteristics

The planar structure of the eyeball structure is shown in Fig.1. The eye is a spherical organ that has two functions [7]: one is to form an image on the fundus through the internal optical structure; the other is to transform the object into a nerve impulse through the action of the retina to transmit to the visual centre to form vision. The eye is a wonderful organ that can adjust its state in different environments so that the creature can obtain sufficient visual information in a complex environment. From an engineering point of view, we can compare it to a camera with image processing capabilities.

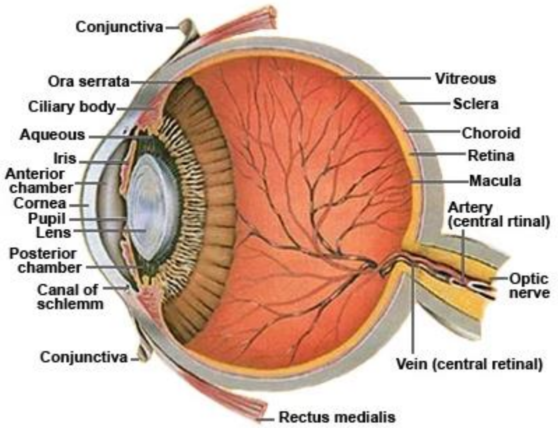


Fig. 1. *Eye structure [7]*

3.2. Visual formation

The process of forming vision can be roughly described as the light reflected by the object passes through the cornea, the pupil and the vitreous body in turn, and is projected by the lens or the like to the retina to form an image [7],[8]. The retina is a multilayered nerve structure about 200 μm thick, arranged at the back of the eye. Other cells in the retina process signals from photoreceptors. Retinal ganglion cells send processed signals from the retina to the brain through the optic nerve. At the rear end of the human eyeball retina, there is a yellow area of about 1.5 mm (about 6° viewing angle) called the macula. There is a 1.5° area in the centre of the macula that is relatively thin due to the accumulation of surrounding cells, forming a fovea area. Since there are only cones in the fovea region and no rod cells, it has a very high visual acuity [7],[8]. Light will transmit visual information through the optic nerve to the visual cortex through the two cells on the retina to produce visual information. It should be noted that only the object image is formed on the retina, and the visual information is generated by the visual centre in the cerebral cortex.

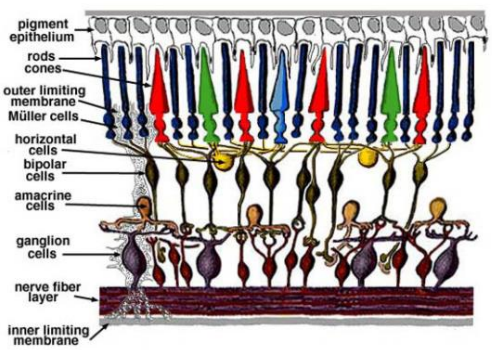


Fig. 2. *Cross-section of the retina [8]*

3.3. Neural mechanism of Saccade eye movement

One of the main functions of the central nervous system is to respond to perceptual stimuli to produce motion. Vision-guided eye movement is a typical transition from perception to motion. The visual axis is adjusted by the Saccade so that the stimulus of interest falls in the fovea of the eyeball for further processing [1]-[3].

When the target suddenly appears, after an incubation period of about 100~300ms (from the stimulus to the triggered reaction time), the eyeball's jumping motion is triggered, and the "capture" target is ended [10],[11]. The duration of the saccade motion is usually only tens of milliseconds. The maximum speed of the glance is no more than $118°/s$.

The occurrence of Saccade eye movement is the result of the interaction of many different types of neurons in the brain stem structure [9]. The structure of the brainstem neural network associated with saccade is shown in Fig.3.

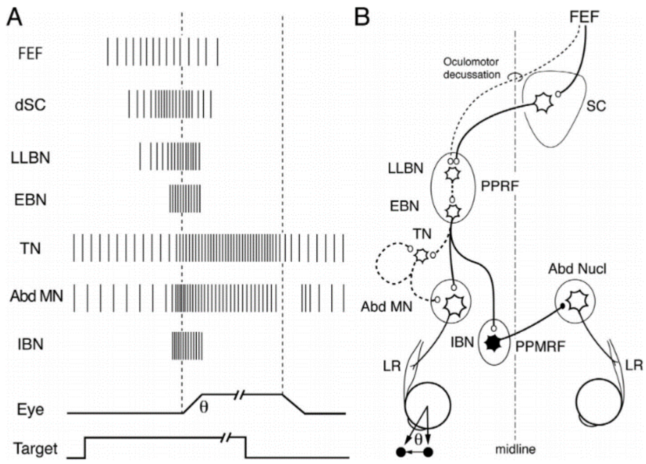


Fig. 3. *Schematic diagram of the brainstem neural mechanism of saccade eye movement [9]*

Burst Neurons: The outbreak neurons associated with the horizontal saccade are located in the PPRF, adjacent to the nucleus and the vertical saccade of the erupting neurons are located in the Rostral Interstitial Nucleus of the Medial Longitudinal Fasciculus, adjacent to the oculomotor nucleus. According to the length of the nerve pulse triggering time, it is divided into Short-Lead Burst Neurons and Long-lead burst neurons. SLBN will be released for about 8~10ms before the occurrence, and LLBN will be released for more than 100ms. PPRF is projecting the ipsilateral nucleus, NPH, MVN, and caudate cerebral corpus callosum. The input received by the PPRF comes from the superior colliculus, the cerebellar corpus callosum, via the cerebellar nucleus and FEF [9],[10].

According to the anatomical location and physiological function, it can be divided into two groups [9]-[11]. One group is Excitatory Burst Neurons located in the ipsilateral dorsal PPRF. It is connected with the ipsilateral abductor nucleus and is responsible for the expansion of the motion nucleus (MN) activation, triggering the ipsilateral lateral rectus through the abductor nucleus internuclear neurons (IN), also responsible for activation of the systolic motoneurons in the oculomotor nucleus, controlling the contralateral rectus. During the Saccade, the EBN was utterly silent. On the other hand, these neurons exhibited dramatic action potential bursts a few milliseconds before the Saccade trigger, and the number of action potentials was increased as the amplitude of the saccade, and the instantaneous eyeball velocity increased. The other group is the Inhibitory Burst Neurons (IBN) located in the Dorsomedial Medullary Reticular Formation (DMRF), with approximately 60% being transmitted to the contralateral motor abduction nucleus in reverse and inhibitory manner. IBN is involved in antagonizing the relaxation process of the muscle. Like EBN, IBN remains silent during the saccade.

Tonic Neurons: The neurons in this region are located in the same PPRF as the erupted neurons, and their function is to allow the eyeball to be fixed on the target. During the saccade process, TN does not have any triggers or activities. Until the Saccade motion process is about to end, TN will work, so that the eyeball position will eventually stay at the target position [9]-[11].

Motor Neurons: These include the oculomotor nucleus located in the midbrain, the trochlear nucleus and the abducens nucleus located in the pons. They each control their corresponding six extraocular muscles, moving the eyeball to the target position [9]-[11].

Superior Colliculus: The coding and activation of the Saccade are regulated by the subcortical region, primarily the Superior Colliculus [10],[11]. The Superior Colliculus is a multi-layered structure with a Visual Map on the dorsal layer and a Motor Map on the ventral side. The middle layer plays a crucial role in visual fixation and Saccade eye movement control and is the basis for Saccade motion time-space transformation [10],[11].

3.4. Neural mechanism of Smooth pursuit eye movement

Smooth pursuit eye movement is a voluntary eye movement that follows a slow-moving target to maintain it in the fovea and keep the target image clear [12]. The incubation period of smooth pursuit eye movement is about 100~150ms, usually shorter than the latency of Saccade. In the initial acceleration phase, the visual signal is mainly relied on, while the tracking phase is maintained, relying on the velocity memory signal.

Smooth pursuit eye movement and Saccade [12]-[14] are voluntary eye movements, which are generally considered to be two distinct systems. However, in recent years, more and more studies have shown that the two share a similar anatomical network structure. The forehead eye movement field (FEF) and the auxiliary eye movement field (SEF) of the frontal cortex participate in the generation of the smooth pursuit eye movement. FEF and SEF are also involved in the production of a saccade, but in anatomy, the FEF's smooth vision eye movement. The area is distinct from the saccade area [12].

In the cerebral cortex, the frontal cortex is mainly projected to the cerebellar corpus callosum via NRTP, and the posterior cortex mainly passes through PN to the cerebellum [12]-[14]. The pons nucleus and the pons are acted as relays by the reticular nucleus, projecting the eye movements of the cerebral cortex to the relevant areas of the cerebellum. The primary function of the cerebellum is to regulate the speed of smooth pursuit, maintain the coordinated synchronization of the eyeball and the target, and play a supporting role in smooth follow-up control. The specific roles of each part are briefly described as follows:

Middle temporal (MT): MT is the main area that produces visual motion signals. It only responds to the movement of the omentum and initiates the follow-up movement of the eyeball. The neurons in this region have the tuning characteristics of the moving direction and the moving speed, and the firing rate of the neurons is consistent with the speed of the target motion [12]. The MT extracts the motion information of the target retinal image after processing the information from the visual cortex. , convert it into a motion code belonging to the retina coordinate system [12].

4. Saccade movement control

The saccade movement can be divided into two types: reflective saccades and planned saccades. A reflective saccade is a saccade generated by a visual stimulus trigger or an auditory signal forming an auditory stimulus trigger due to a change in visual target. The planned saccade movement is a movement mode in which the eyeball rushes according to a preset trajectory without perceptual stimulation [13]. Different stimuli can cause different saccade responses. Through experiments, for the neural mechanism of the motion that can trigger saccade, the strong stimuli cause the saccade to have a higher priority than the auditory stimulation signal and the planned saccade [12]-[14].

The amplitude, duration, and speed of saccade movement are related to the number of neuron discharges, burst time, and peak discharge rate, respectively.

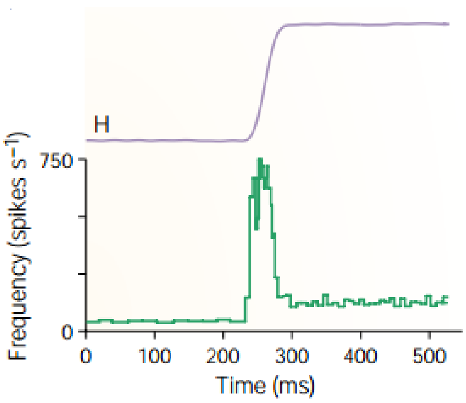


Fig. 4. *Motor neuron-instantaneous spike frequency during a rightward saccade [15]*

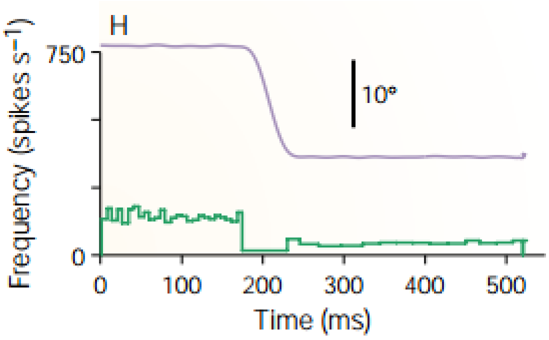


Fig. 5. *Motor neuron-instantaneous spike frequency during a leftward saccade [15]*

The upper part of the figure shows the horizontal position of the eyeball (H: the upward direction represents the movement of the eyeball to the right), while the bottom represents the discharge frequency of the abduction motor neuron in the rightward saccade (potential peak spacing) The second picture is the case when the eye moves to the left. From the figure, we can see that the discharge frequency is stable at a constant value when the eyeball position is stationary. The excitatory burst neurons produce a high discharge frequency before and during the saccade movement. When the eye position is fixed, the initial eye is maintained, a slightly higher discharge frequency [15].

There is a close relationship between the triggering of saccade and the firing frequency of excitatory burst neurons. At the same time, the excitatory burst neurons interact with the inhibitory neurons and form a negative feedback loop inside the saccade control. The role of the all-stop neuron (OPN) located in the internuclear nucleus is to prevent the system from oscillating and to stop the discharge during the initial phase of the saccade. The physiological structure model of the saccade system is shown in Fig. 6.

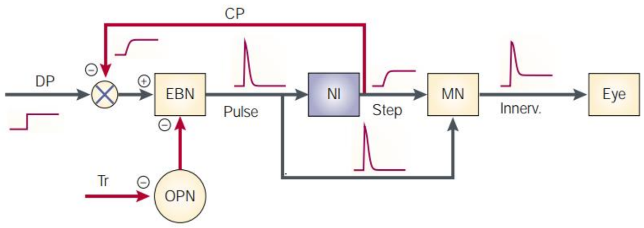


Fig. 6. *Physiological structure model of saccade movement [15]*

The input signal is the desired position (DP) of the eyeball, and the deviation generated by the current position (CP) transmitted back to the nerve pathway is transmitted to the ocular bursting neurons to generate an exciting stimulus, and the new stimulation signal is transmitted to the nerve. An integrator (NI) and a motor neuron (MN) generate motion commands to drive eye movements. In addition, omnipause neuron (OPN) also acts on the ocular outbreak neurons to prevent the eyeball from oscillating during the saccade[14], [15].

Refer to the saccade physiology model and establish the eye saccade movement control model based on the model proposed [14].

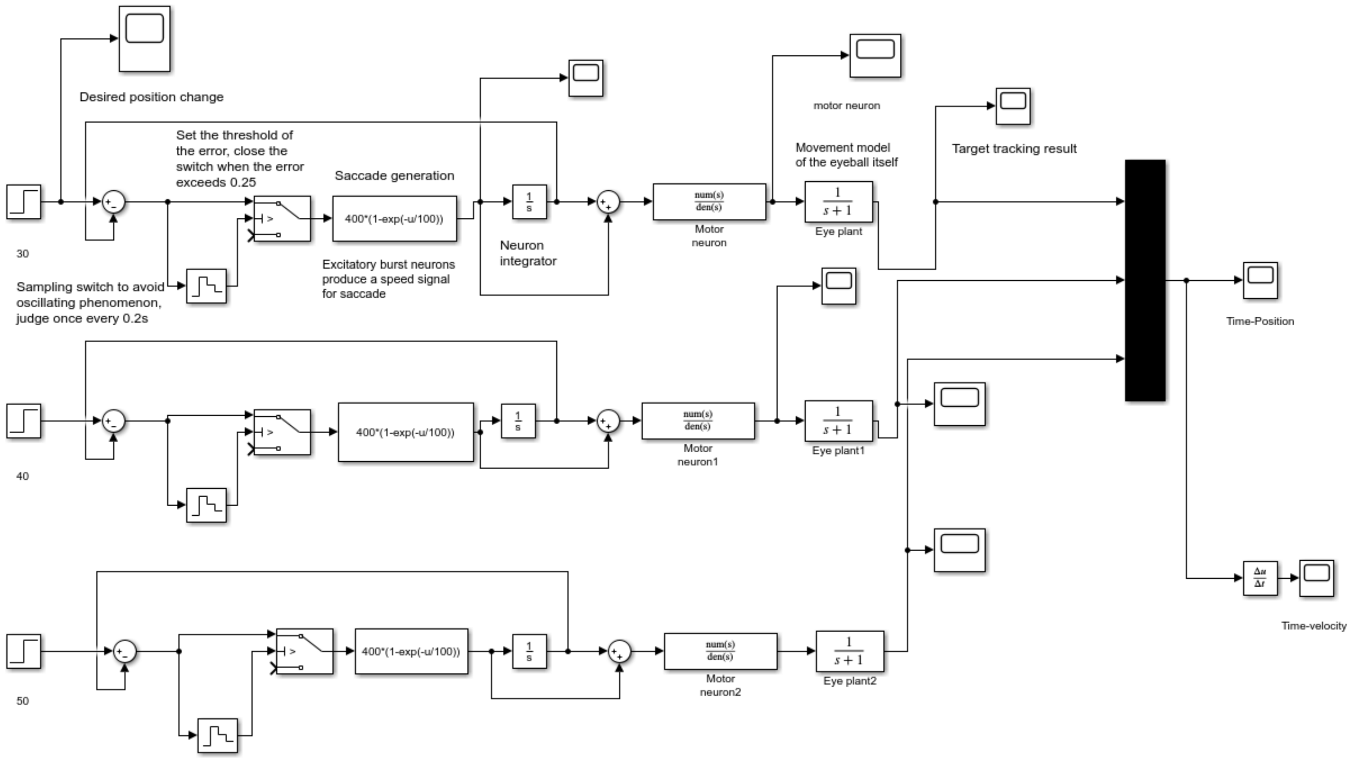


Fig. 7. *Saccade movement control model*

Introducing the concept of local feedback in the control model avoids the difficulty of obtaining the current position through visual feedback, especially the time delay generated by the saccade and neurotransmission process is sometimes longer than the duration of the glance, so if visual feedback is applied very unsuitable [15],[16]. Using the current position of the eyeball as feedback can improve its control accuracy. The input of the control model is the desired position of the eyeball, and the difference e_u of the desired eye position from the current eye position is input to the saccade generating module (excitatory burst neuron) to generate a saccade velocity signal, and an internal estimate of the saccade position signal is obtained through the neural integrator. The value acts on the eye device to control eye movement.

At the same time, in the physiological experiments on monkeys, it was found that the role of OPN is to prevent optical turbulence in the saccade, and the saccade movement can be interrupted immediately after the rapid transfer of sight. If the target continues to move, the interrupt action is concise, and the line of sight will lead to the new target position after the interruption. Therefore, we design a similar error threshold value judgment unit in the control system, set the threshold e_u=0.25, when the error exceeds, OPN acts on the suppression neurons, so that the switch is closed; when the error is smaller than e_u, the neurons are suppressed The function is to make the switch open, the saccade movement ends, and the threshold value is judged once every interval of 0.2s [15].

$$e_u = DP(t) - CP(t) \quad (1)$$

After studying the physiological data, it is found that the relationship between the excitatory burst neuron B_e and the positional deviation e_u can be expressed by a function:

$$B_e = \begin{cases} 0 & (e_u < \varepsilon) \\ G(1 - e^{-(\frac{e_u}{\tau})}) & (e_u > \varepsilon) \end{cases} \quad (2)$$

Where G is the discharge rate of excitatory burst neurons with a maximum discharge rate of 1100 spikes/s [16], e_u is the difference between the desired eye position and the current eye position, ε is the threshold for the saccade trigger, and τ is the saccade burst neuron time delay.

The motor neurons of the eyeball are the main part of the motion signal transmitted to the eyeball mechanics. The mathematical model can be represented by a second-order linear filter:

$$H_e(s) = \frac{K_m}{T_1 s^2 + T_2 s + 1} \quad (3)$$

According to experimental physiological data, we use linear filters to simulate its motion structure:

$$H_e(s) = \frac{K_e}{T_e s + 1} \quad (4)$$

4.1. Simulation results and analysis of saccade control model

Because monkey's visual system has many similar aspects to humans, Freedman [14],[17] and others obtained relevant information by detecting eye movements of monkeys, the result of physiological experiments of monkey saccade movement(see Fig.8).

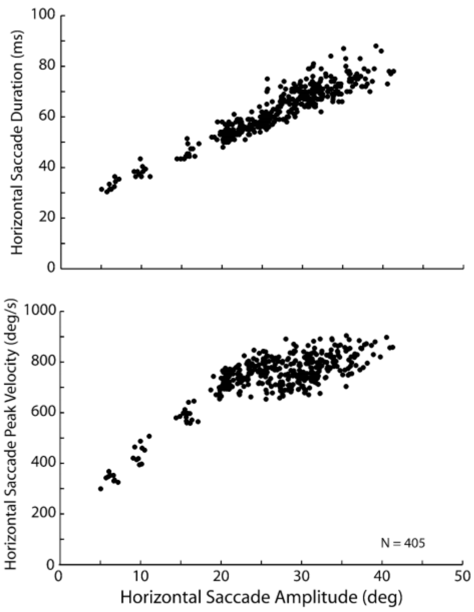


Fig. 8. *Monkey's saccade movement experimental data [14]*

In this experiment, the visual range was controlled between 5° and 45°, and the saccade movement in the horizontal direction of the monkey was detected. It can be seen that the duration of the glance increases with the increase of the amplitude of the movement, and the peak velocity monotonously increases with the increase of the amplitude. The results obtained after processing the experimental data are shown in Fig. 9.

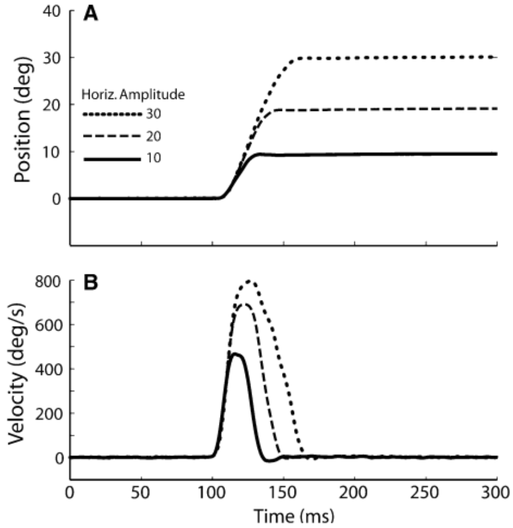


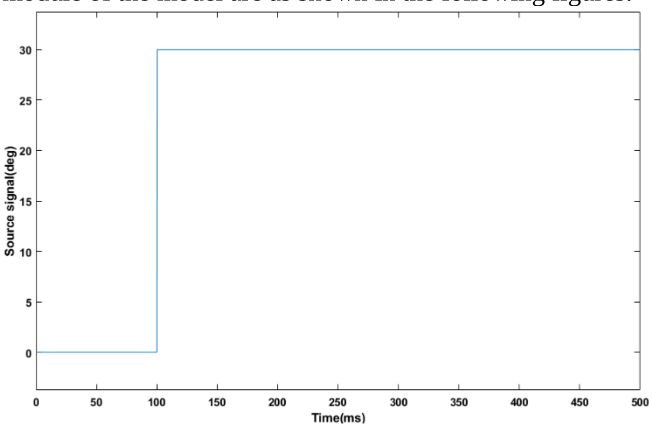
Fig. 9. *Eye position and velocity from Monkey's saccade movement experimental data [14]*

In order to verify the effect of the model, we conducted simulation experiments in the Matlab/Simulink environment. In this experiment, a set of step signals is given as an input to simulate the target motion trajectory, and the changes in the position of the eyeball and the speed of the eyeball are observed.

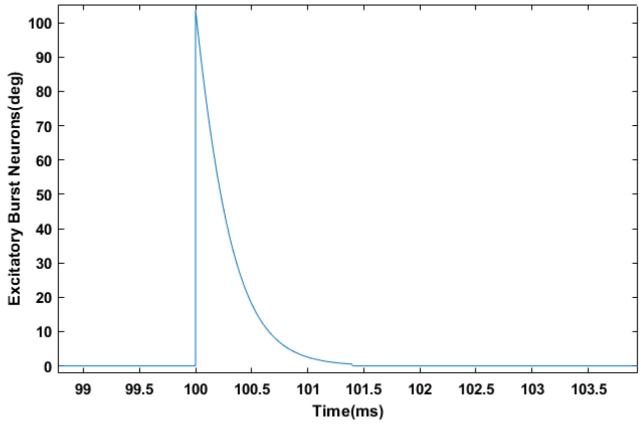
Parameter Setting:

$\tau = 100\text{ms}, K_m = 1, K_e = 1, T_1 = 0.0015, T_2 = 0.15, T_e = 1, G = 400, \varepsilon = 0.2$ (5)

In this simulation, the eyeball is rotated to the right to be positive, and the left to negative, the visual range was controlled at 30°, 40° and 50°. The simulation results of each module of the model are as shown in the following figures:



(a)



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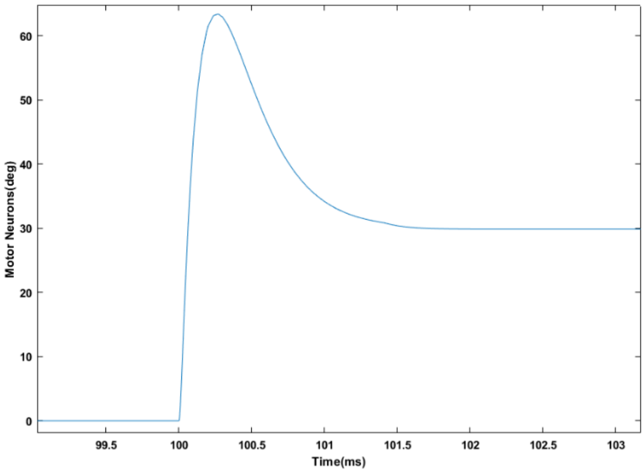

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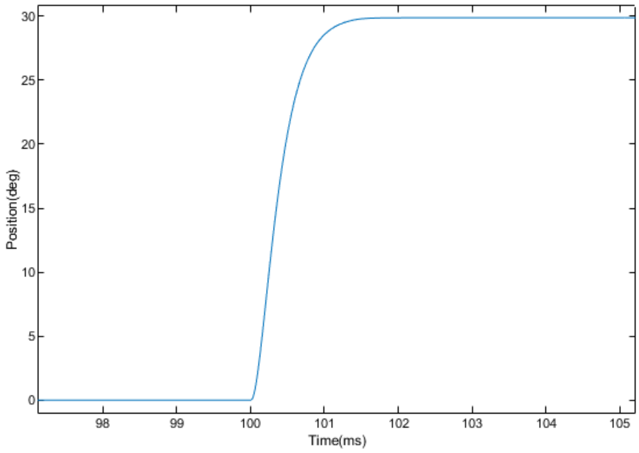
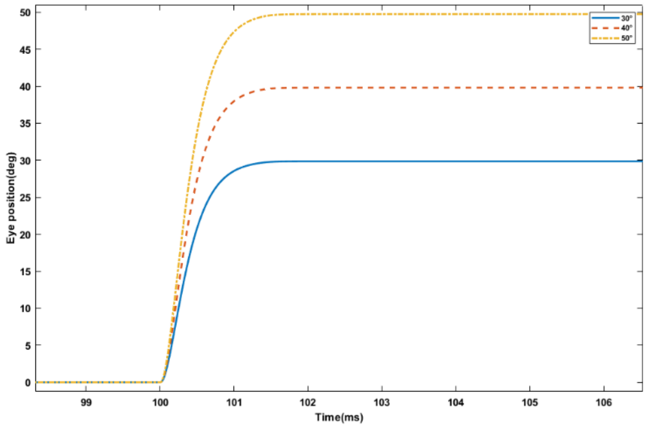


(d)

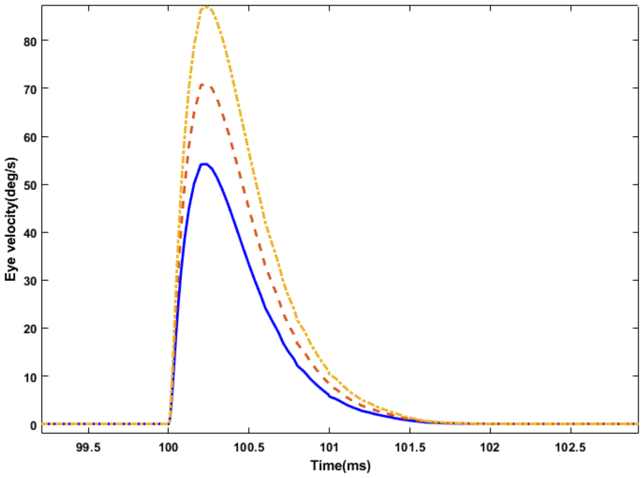
Fig. 10. *Results of saccade movement*
(a) Desired moving position. ***(b)*** The operation process of Excitatory Burst Neuron. ***(c)*** The operation process of motor neuron (Velocity of eyeball tracking object). ***(d)*** The eyeball has been positioned to the object when the curve is steady, finally reached the position of 30°

As can be seen from the above figure, the eyeball can locate the target at 102ms after the sudden movement of the target. The simulation results of the above modules are consistent with the experimental physiological data of David L. Sparks [15].

Then, simulating targets are respectively subjected to changes in the horizontal position of 30°, 40°, 50°, and their position changes and velocity changes are observed (see Fig. 11).



(a)



(b)

Fig.11. *Results of position changes and velocity changes*
(a) Variation of eyeball's position (from a visual range: 30°, 40°, 50°). ***(b)*** Variation of eyeball's velocity (from a visual range: 30°, 40°, 50°)

It can be seen from the simulation results that the motion trajectory is the same as the known physiological experiment results. Fig.11 shows the change of the position of the eye movement under the condition that the line of sight changes suddenly. As the amplitude of the saccade increases, the time of the complete shift of the line of sight will increase accordingly. As can be seen from Fig.11, no matter how the amplitude of the saccade changes, the saccade speed will change along the same trajectory at the beginning of the movement. Therefore, we can know that for a certain motion amplitude (motion direction), its motion speed changes according to a particular law. Allows us to predict the duration of the saccade and peak velocity within reasonable accuracy, and only give A graph of the change in the velocity profile of the saccade motion of the information of the magnitude and direction of motion, or only a visual target with respect to the positional information, since the vector of the saccade is related to the displacement of the target.

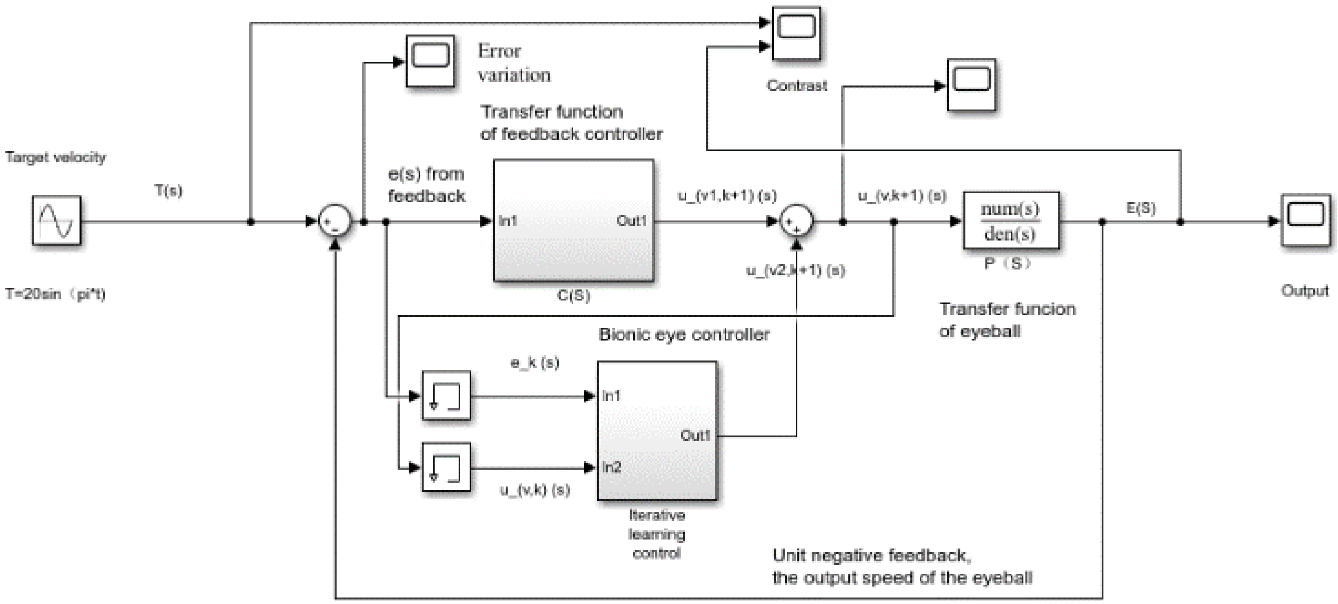
5. Smooth pursuit movement control

Smooth pursuit is one of the five primary movement mechanisms of the human eye [18]. It has the function of quickly identifying and accurately tracking targets. The purpose of smooth pursuit is to keep the moving target object in the fovea of the eyeball so that the target object is clearly and stably imaged on the retina. In the smooth pursuit process, not only the speed and amplitude of the eye movement need to be controlled, but also the target motion state needs to be predicted to ensure that the moving target object is always in the fovea of the retina.

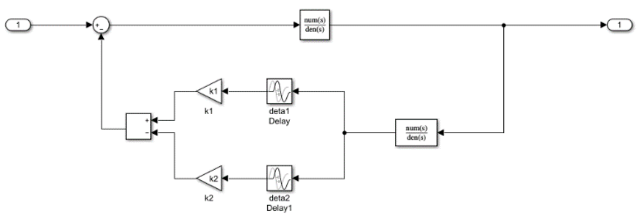
At present, according to the neural control function [18]-[20] of the brain to control eye movement, the researcher proposes a neural control loop for smooth pursuit eye movement: primary motion information perception, processing→visual information synthesis processing, motion control command→eyeball motion information conversion and handle →produce eye movements.

From the perspective of neurophysiology, after the retina receives visual information, it has a significant processing and enhancement effect on the image information. The signal also has specific initial processing. The MST has a display expression in the world coordinate system for the state of the target motion to predict the motion state of the target [18]-[20]. The cerebral cortex is also involved in the smooth pursuit movement of the eye. The FEF responds to the excitation of the target motion of different intensities by adjusting the gain of the smooth pursuit motion. In the process of eye movement, gain control is the bridge between the visual system and the motion system. Therefore, the learning of the target motion state can be achieved by changing the relationship between them. SEF-related neurons have a discharge behavior during smooth pursuit motion, and this discharge action has a predictive effect on smooth pursuit motion [21]-[23]. The back pons and NRTP receive the output of the SEF and MST regions, where the processed visual signals are converted and adjusted to convert the visual signals into corresponding motion control commands, generating neural excitation, and smooth pursuit motion after processing. The output has a promoting effect. The MST, FEF, and SEF regions receive the feedback signal of the retinal slip and the output feedback signal of the eye movement command through Thalamus. The cerebellum plays a vital role in the accuracy and adaptability of eye movements, in which at least two signal processing areas are associated with smooth pursuit motion: flocculus and Posterior vermis. The primary role of these regions is to coordinate the relationship between vestibular ocular reflexes and smooth pursuit [24]-[26] and has a particular impact on the smoothness of tracking. Oculomotor nuclei control the eyeballs to drive the eyeballs based on the transmitted nerves to achieve smooth pursuit.

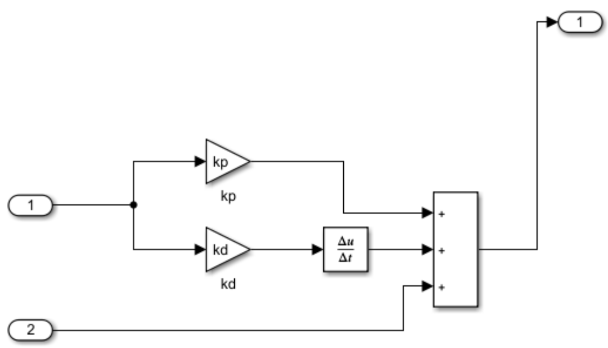
In this experiment, the iterative learning control module is used for learning and prediction (see Fig.12).



(a)



(b)



(c)

Fig. 12. *Smooth pursuit model of* $T = 20sin(\pi t)$
(a) Model of $\mathrm{T} = 20\sin(\pi t)$. ***(b)*** Subsystem of $\mathrm{C(s)}$. ***(c)*** Subsystem of iterative learning controller.

The iterative learning controller uses an internal PD controller based on historical input. Increase compensating control, PD controller can measure proportional and differential changes and compensate

$$C(s) = \frac{k_1(t_e s+1)}{(t_e s+1)(t_n s+1)+k_1 e^{-\Delta_1 s}-k_2 e^{-\Delta_2 s}} \quad (6)$$

$$P(s) = \frac{1}{t_e s+1} \quad (7)$$

Among them, $C(s)$ is the transfer function of the feedback controller, $P(s)$ represents the eyeball model, t_e, t_n, k_1, and k_2 are system parameters and are greater than zero, Δ_1, and Δ_2 are delay time.

The input of the model is the speed of movement of the target $T(s)$, and the output is the speed of the eyeball $E(s)$. The eyeball speed from Fig. 12 can be expressed as:

$$E(s) = u_{v,k}(s)P(s) \quad (8)$$

$u_{v,k}(s)$ is eyeball control, k is the number of iterations, k=1,2…

Select the iterative learning rate is:

$$u_{v,k+1}(s) = u_{v1,k+1}(s) + u_{v2,k+1}(s) \quad (9)$$

$$u_{v2,k+1}(s) = u_{v,k}(s) + (k_p + k_d s)e_k(s) \quad (10)$$

Where $u_{v,k+1}(s)$ represents the output of the feedback controller, $u_{v2,k+1}(s)$ represents the output of the iterative learning controller, k_p, k_d represents the learning gain.

We can get the feedback controller output from Fig. 12 can be expressed as:

$$u_{v1,k}(s) = e_k(s)C(s) \quad (11)$$

According to the principle of iterative learning control algorithm [27], since the target speed changes periodically, the target speed is the same at each iteration. According to the definition of retina sliding, the following results can be obtained:

$$e_{k+1}(s) = T(s) - E_{k+1}(s) \quad (12)$$

Combining the above formulas, we can get that:

$$e_{k+1}(s) = \frac{1-\mathrm{P(s)Q(s)}}{1+\mathrm{P(s)C(s)}} E_{k+1}(s) \quad (13)$$

Where $\mathrm{Q(s)} = k_p + k_d s$ (14)

In order to ensure the convergence of the retina sliding error $e_k s$, the following convergence conditions can be obtained:

$$\left\| \frac{1-P(s)Q(s)}{1+P(s)C(s)} \right\|_\infty < 1 \quad (15)$$

5.1. Iterative learning control algorithm parameter setting

In this section, a PD parameter tuning method is proposed to tune the positive parameters of the iterative learning controller k_p and k_d

Firstly, define function $\emptyset(s)$:

$$\emptyset(s) = \frac{1-P(s)Q(s)}{1+P(s)C(s)} = \frac{(t_e t_n - k_d t_n)s^2+(t_e+t_n-k_p t_n-k_d)s+1-k_p}{t_e t_n s^2+(t_e+t_n)s+k_1+1} \quad (16)$$

Set $s = j\omega$ and Substituted into above (16) can be obtained:

$$\emptyset(s) = \frac{W-U\omega^2+jV\omega}{Z-X\omega^2+jY\omega} = \frac{XU^2\omega^4-(WX+ZU^2+YV)\omega^2+WZ}{(Z-X\omega^2)^2+(Y\omega)^2} + j\frac{-(YU^2+XV)\omega^3+(WY+ZV)\omega}{(Z-X\omega^2)^2+(Y\omega)^2} \quad (17)$$

Where,

$$U = t_e t_n - k_d t_n, V = t_e + t_n - k_p t_n - k_d \quad (18)$$

Obviously, when the system parameters represented by the (18) change, the crossover frequency and phase angle of the system will also change, and the overshoot of the system response will change accordingly [28] in order to ensure that the system phase angle is not affected. The influence of system parameters changes and the adaptation of the eyeball system is guaranteed. This paper optimizes the iterative learning control parameters.

According to the (17), the amplitude-frequency characteristic of $\emptyset(j\omega)$ can be obtained:

$$|A(j\omega)| = |\emptyset(j\omega)| = \sqrt{\frac{[XU^2\omega^4-(WX+ZU^2+YV)\omega^2+WZ]^2+[-(YU^2+XV)\omega^3+(WY+ZV)\omega]^2}{[(Z-X\omega^2)^2+(Y\omega)^2]^2}} \quad (19)$$

According to the above formulas, we can get that:

$$|A(j\omega)| < 1 \quad (20)$$

According to the definition of the crossing frequency:

$$|A(\omega_{cg})| = 0 \quad (21)$$

ω_{cg} is crossing frequency

Combining (17) and (21):

$$[XU^2{\omega_{cg}}^4 - (WX + ZU^2 + YV){\omega_{cg}}^2 + WZ]^2 = 0 \quad (22)$$

$$[-(YU^2 + XV){\omega_{cg}}^3 + (WY + ZV)\omega_{cg}]^2 = 0 \quad (23)$$

After processing (20) and (21) we can get that:

$${\omega_{cg}}^2 = \frac{WX+ZU^2+YV+\sqrt{(WX+ZU^2+YV)^2-4WZXU^2}}{ZXU^2} \quad (24)$$

$${\omega_{cg}}^2 = \frac{WY + ZV}{YU^2 + XV} \; or \; {\omega_{cg}}^2 = 0 \quad (25)$$

In order to calculate, only consider the situation of ${\omega_{cg}}^2 = 0$, and put this equation into (18)

$$W = 0 \rightarrow k_p = 1 \quad (26)$$

We can get $\emptyset(j\omega)$ phase-frequency characteristics from (18):

$$\arg\emptyset(j\omega) = arctan\frac{-(YU^2 + XV)\omega^2 + (WY + ZV)}{XU^2\omega^3 - (WX + ZU^2 + YV)\omega} \quad (27)$$

In order to ensure the adaptability of the control system, the phase angle of the system will not change due to small changes in the crossing frequency, add the phase condition:

$$\frac{\mathrm{d}\arg\emptyset(j\omega)}{d\omega}|_{\omega=\omega cg} = 0 \rightarrow ZV(ZU^2 + YV) = 0 \quad (28)$$

According to (26) and (18), we can get that:

$$V = 0 \rightarrow k_d = t_e \quad (29)$$

So, we get the optimal PD parameters of the iterative learning control algorithm:

$$k_p = 1, k_d = t_e \quad (30)$$

5.2. Experiment analysis

In order to verify the effect of the proposed model, this section carried out simulation experiments in Matlab2018b / Simulink environment. In this section, three experimental sessions will be set up, two of which serve as control experiments to test the reliability of this experiment. At the same time, the superiority of the proposed iterative learning control algorithm is reflected by comparison with the Shibata model [6].

Parameter setting:

$$k_1 = 0.55, k_2 = 1, t_e = 0.015, t_n = 0.07 \quad (31)$$

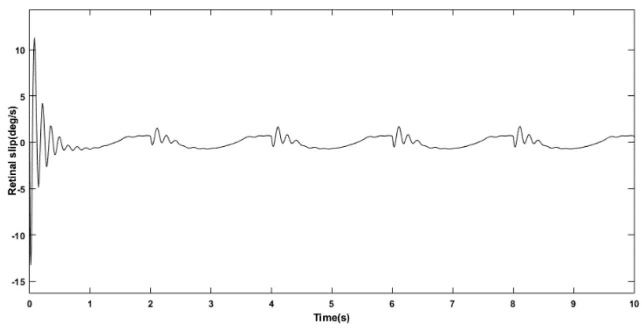
Delay time:

$$\Delta_1 = 0.16s, \Delta_2 = 0.08s \quad (32)$$

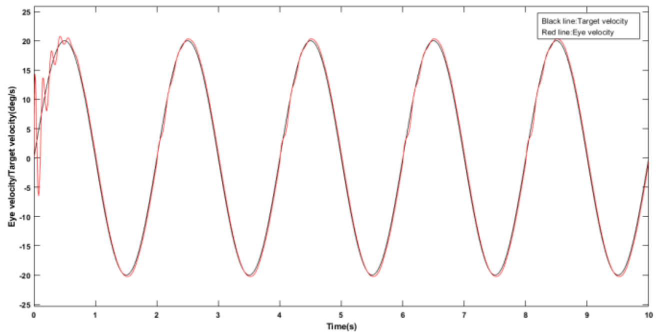
After many experiments and debugging, setting k_p, k_d :

$$k_p = 0.45, k_d = 0.015 \quad (33)$$

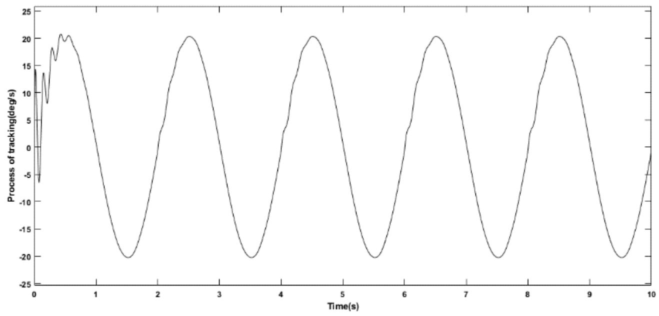
After the parameter setting is completed, run $T = 20\sin(\pi t)$ as the model of the input signal. In this case, the target speed changes sinusoidally, and the following waveform is obtained:



(a)



(b)



(c)

Fig. 13. *Experiment analysis of* $T = 20sin(\pi t)$
(a) Error variation. ***(b)*** Eye-tracking target curve (Black line: Target velocity; Red line: Eye velocity). ***(c)*** Tracking process.

It can be found from the experimental results that the model designed by this experiment and the model proposed by Shibata [6] all can reach the final stable state, that is, the eyeball speed is consistent with the target speed, and smooth pursuit is achieved. Through the error curve, it can be found that the model tracking effect of this experimental design is quite significant, and the final error can be reduced to zero. After learning, the eyeball speed can basically reach the target moving speed. Shibata's model [6] still has some error in steady-state, and the convergence time is significantly longer.

5.3. Comparative Experiments

In order to verify the feasibility of the model and avoid accidental existence, two other cases were added in this experiment: $T = 2.5t$ target uniform acceleration motion and $T = |20\sin\left(\frac{\pi t}{2}\right)|$ target velocity is parabolic.

First comparative experiment:

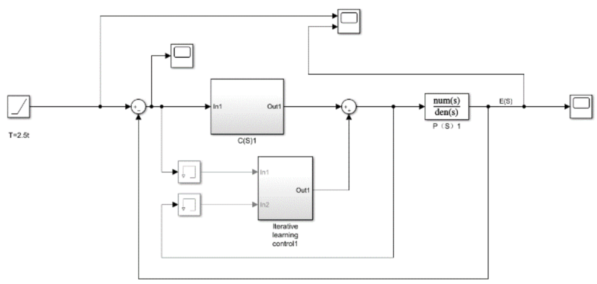
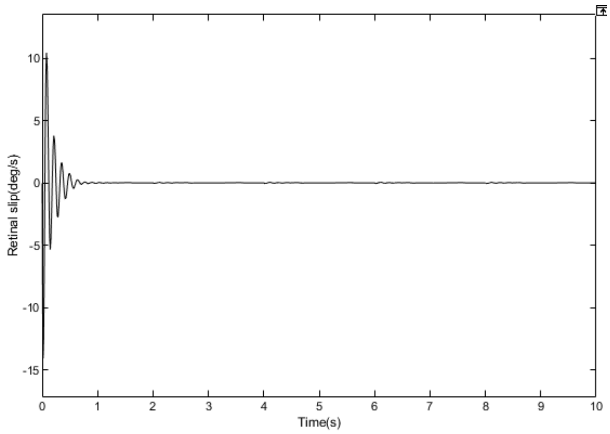
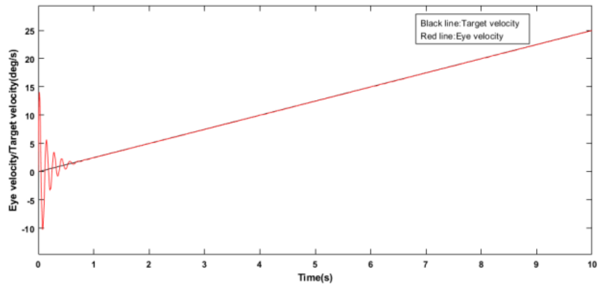


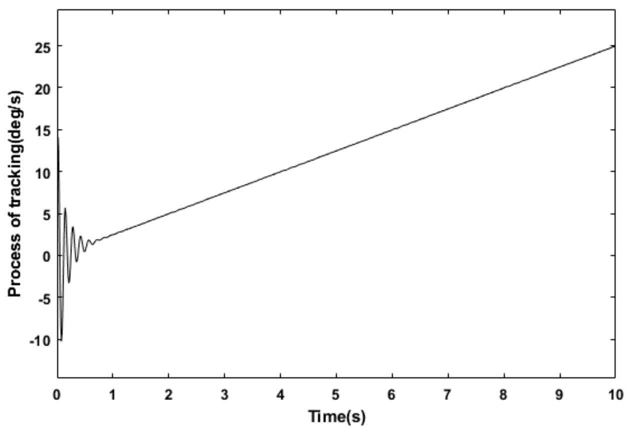
Fig. 14. *Smooth pursuit model of* $T = 2.5t$



(a)



(b)



(c)

Fig. 15. *Experiment analysis of* $T = 2.5t$
(a) Error variation. ***(b)*** Eye-tracking target curve (Black line: Target velocity; Red line: Eye velocity) ***(c)*** Tracking process.

Second comparative experiment:

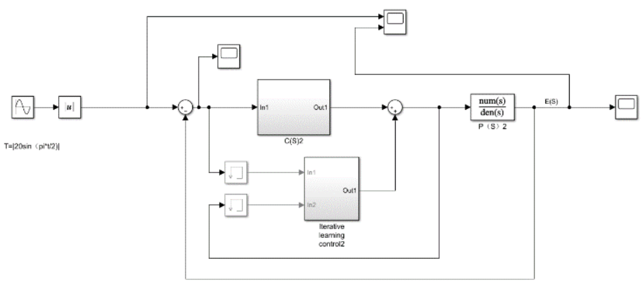
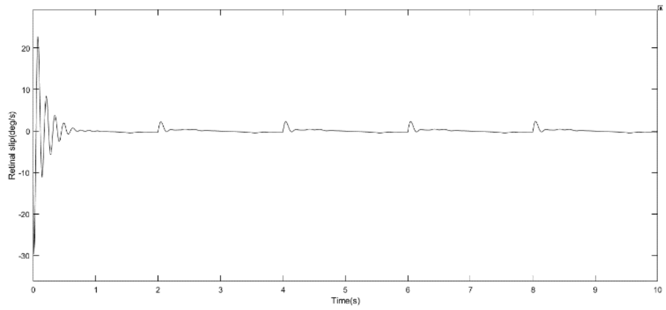
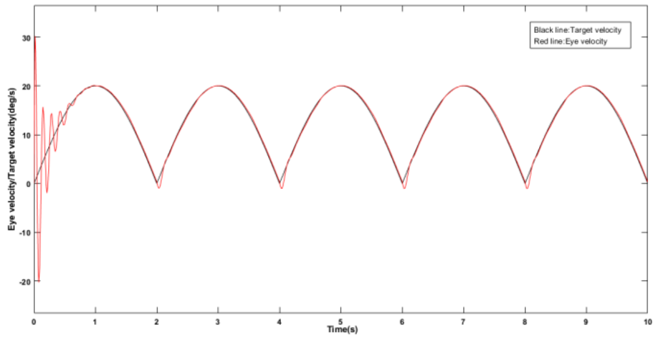


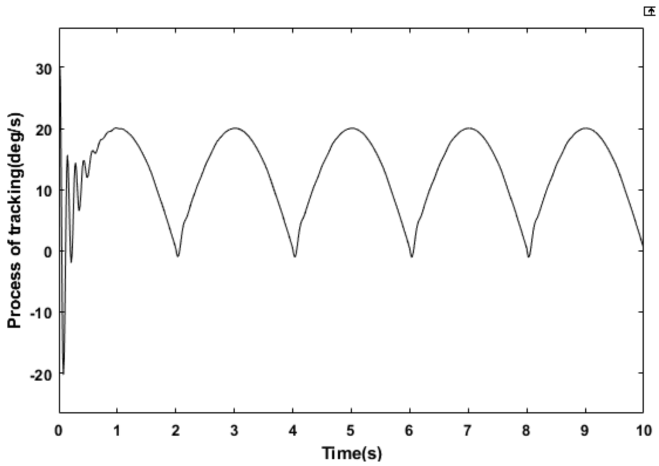
Fig. 16. *Smooth pursuit model of* $T = |20\,sin\left(\frac{\pi t}{2}\right)|$



(a)



(b)



(c)

Fig. 17. *Experiment analysis of* $T = |20\,sin\left(\frac{\pi t}{2}\right)|$
(a) Error variation. ***(b)*** Eye-tracking target curve (Black line: Target velocity; Red line: Eye velocity) ***(c)*** Tracking process.

Obtained three sets of experimental results in each set of simulation experiments, which respectively showed the tracking effect of the eyeball on the target, including the results of retinal sliding and the eye-tracking process. Through the target tracking effect in the three groups of experiments, it can be seen that in the presence of inevitable interference, the eyeball can still show a good tracking effect, indicating the success of this experiment.

6. Experiment expansion

Besides, I also construct a physical model of the eyeball, which is constructed by Simulink, and the physical animation can help us deepen our understanding of this experiment.

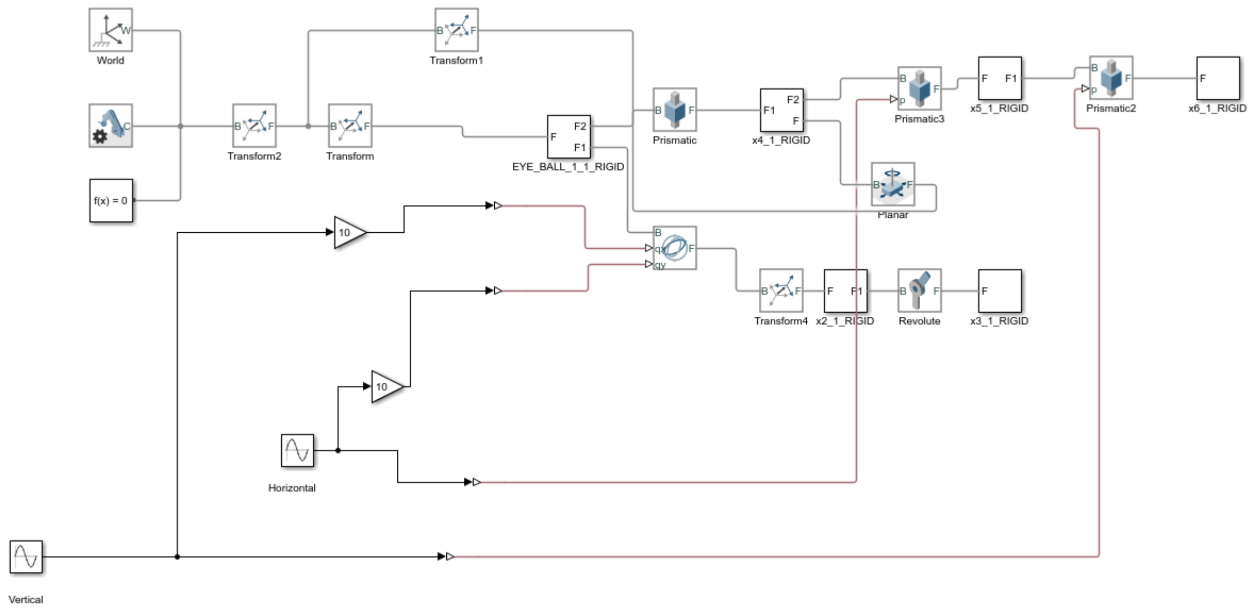


Fig. 18. Physical model of eyeball

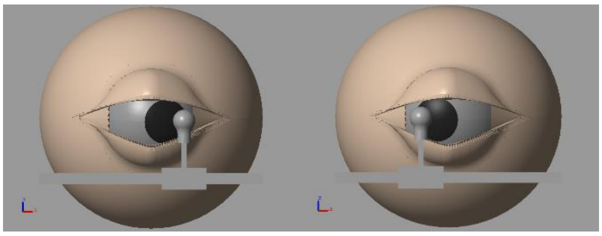


Fig. 19. Animation of the eyeball model

After running the physical model, we can see that animation is generated, and the eyeball is always following the target component. This component can maintain vertical and horizontal movements. By modifying the parameters in the physical model, the movement of the component can be modified. The tracking trajectory of eyeball also changes as the trajectory of the object changes.

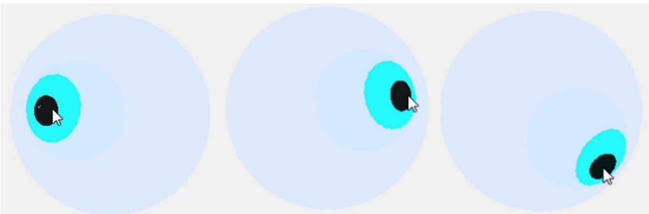


Fig. 20. Model of mouse-eyeball

Based on the characteristics of the saccade movement and the smooth pursuit movement and the analysis of the above experiments, I made another model which selected the mouse as the target. After running the Matlab code, the eyeball can follow the mouse to move and rotate. The result of the operation is shown above.

7. Image processing

Since I could not find a way to put the image as an input signal into the control system, I decided to write Matlab code to explain the principle and result of the saliency extraction.

Many processing tasks of machine vision, such as target detection and recognition, require complex calculations for each area of the picture in the form of sliding windows, which requires a large number of computing resources and time. In fact, people may only be interested in a small area in the picture [29]. If the ability to process the machine is concentrated in such an essential area of the image, the waste of computing resources can be significantly reduced. The study of visual saliency is precisely to find such a saliency region in the image by studying the human visual attention mechanism to reduce the search space for subsequent higher-level visual processing. Secondly, through the study of visual saliency, we can, in turn, give us a deeper understanding of the human visual system, and design a computational model that is more in line with the human visual system [30].

Cognitive psychology research on human visual attention has never stopped [29]-[32]. The main reason why people notice a specific area of an image while ignoring other areas is that the content of the domain (such as colour, brightness or direction) is different from other. The reason why the saliency area is highlighted is that in the field of visual saliency research, it can generally be explained by two models: bottom-up and top-down. Both models have their own cognitive psychology. Learn theoretical basis. Bottom to Up visual saliency calculation method uses the underlying information of the image such as colour, brightness and direction information as the necessary information. Through various calculation models, one or several regions are more significant than other regions, thus giving us attention is directed to these areas [30],[31]. The non-parametric clustering idea is utilized. The specific method is to super-pixel segmentation of the image. On this basis, the super-boundary of the image at different scales is obtained by clustering to calculate the significance. The Bottom to Up bottom-up saliency calculation model mainly emphasizes that the visual scene's own characteristics, that is, the underlying visual stimuli, prompt us to pay more attention to a particular area. The saliency area that attracts us under the model has different characteristics from other areas. Attributes, attention under the bottom-up model are fast, unconscious, spontaneous, and stimuli-driven, and have nothing to do with prior knowledge. Spotlight Theory [29]: It is an explanation of bottom-up based on spatial attention. The analogy of the theory is that the area that is noticed is like the area under the spotlight, which attracts and restricts people's attention within a small area. Moving the cover spotlight The human visual system focuses on different sub-areas, and areas outside this area are actively ignored[30].

For saliency area detection, the purpose is to detect a salient region in the image whose standard result is a significant region binary map manually labelled by the person, namely ground truth. In order to verify the validity of the method, the general significance experiment will calculate the precision, recall and these two calculated values with the ground truth by the threshold segmentation result [31].

The method of evaluation of the saliency area detection is generally divided into two types, one is the saliency map PO obtained on the gray value range of the whole [0, 255] (PO is a saliency image obtained by ourselves in a specific The truth value of the binary division under the threshold is obtained by binary division to obtain a Precision-Recall curve, and the value of the curve on the precision is used to determine the closeness of the significant value to ground truth. The other is to make the significant result work on the basis of image segmentation. By calculating the scalar value precision and recall between the segmentation result and the ground truth, it is judged whether the saliency is used for the image segmentation effect [32]-[34].

In this paper, we use objectwise proposals to estimate the foreground regions in the image instead of using background clues and use it to obtain a smooth and accurate saliency map. We propose a novel saliency metric called "foreground connectivity" that determines how closely a pixel or region is connected to an estimated foreground. We use the values specified by this metric as foreground weights and integrate them into the optimization framework to get the final saliency map.

Besides, The superpixel segmentation algorithm is the most critical algorithm we used in this project [32]. First, our segmentation algorithm divides the input image, and the image is represented by a super-pixel block by the similarity in the region and the dissimilarity between the regions. The algorithm uses the distance model and the distance between the regions as the judgment of whether there is a clear boundary between the two regions through the graph model [33]. (If there is no distinct boundary, it can be merged into the same region).

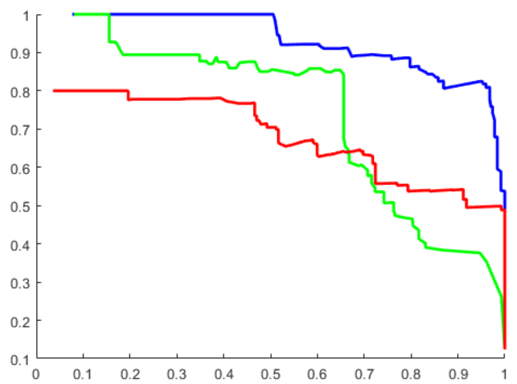


Fig. 21. *Precision-Recall curve (Blue line represents optimized saliency image; Red line represents saliency objectness image; Green line represents saliency filter image)*

Fig. 22. *Images include original maps and results after saliency processing*

8. Conclusion and future works

The eye is an indispensable part of the interaction between the biological information and the external environment. People observe the world, understand the world through their eyes. After a long period of evolution of the jungle law of "survival of the fittest", the human visual system becomes more compatible with human survival activities in terms of performance. This paper draws inspiration from the neural mechanism of the human visual system, finds the law, combines the existing science and technology and industrial conditions and establishes the bionic eye motion control system under different sports modes from the perspective of bionics to simulate human eye movement.

This paper analyzes the structural characteristics of the visual system from the perspective of neurophysiology and analyzes the formation process and imaging principle of vision. According to the eye movement mode, build saccade eye movement model, and smooth pursuit movement model elaborates the neural pathways of these exercises modes, understands the role of various parts of the neural pathway. For the saccade movement, smooth pursuit movement, an extra eyeball model was built which use mouse to control eye movement. The established smooth pursuit control model can complete the tracking of fast-moving targets well. A method with retinal sliding constraints is proposed, which can constrain the error within a given range, making tracking more accurate and obtaining visual information. The physical model of the eyeball is established, animation is generated, and the purpose of intuitionally observing eye movement is achieved.

The future work of this paper will be to reduce the movement error of the retina during smooth tracking motion, especially the random errors generated when the eyeball is in a random motion state. Besides, in the future, it is necessary to solve the problem of combining control model with image processing, which is a challenge for me.

9. Acknowledgments

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