An Active Compensation System for Robot Vision in Rough Environment Based on Bionic Eye

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***Abstract*—Motion targets tracking techniques is one of the most important aspects in the fields of mobile robot research under unknown environments. To solve the problem of unstable vision resulted from the uncertainties, a method of active compensation for robot visual was proposed based on the principle of bionic eye movements. According to oculomotor neural circuits, an adaptive oculomotor control model of eye movements was established, and the model includes that VOR, smooth purisuit and compound eye movements. In order to verify the model's performance, some simulation experiments ware conducted in different environment. Simulation results show that the model can be active compensation of visual error caused by the dynamic variation of the robot attitude and the tracking target location. Finally, physical robot experiments results also confirm the effectiveness of the control model. Compared with the conventional camera, this new one can solve the problem of unstable vision.**

***Index Terms*—bionic eye movements, oculomotor control modeling, oculomotor neural circuits, visual compensation, bionic mechanical pan-tilt camera.**

I. Introduction

In the past 20 years, moving target tracking theory and method has made great development and become one of today's research area. But it is still a challenge to use the theory and method in mobile robotics. Traditional mobile robot to track moving target are mainly focused on the image information processing. However, robot affected from outside interference, their attitude changes and dynamic changes of the tracking target in the unknown environment. Thus, there is small range of compensation, poor image stability and target miss when the servo-mechanical pan-tilt camera is adjusted only by image processing. So far mobile robot target tracking technology that is into engineering practice is mostly based on specific sites and tasks [1-3].

In robot generic technology research, bionic technology is increasingly concerned. The human eye has many special features. For example, the eye can still gaze the dynamic target when people is moving. The robot is in urgent need of the bionic eye that has the special natural functions of the human eye. As a result, modelling of oculomotor behaviour and control are recently becoming a focus of research [4]. Smooth pursuit eye movements are normally made when we track an object moving smoothly in the visual environment [5]. Their purpose is to keep the image of the object near the fovea. As an autonomy challenge and important application for robot target tracking, modelling problem for eye movement has been studied by some researchers. Young et al. proposed a smooth purist but since then there have been no further efforts to extend it or replace it [4-5]. Optician et al. established plasticity or motor learning in the pursuit system. Deon et al. put forward a dynamical neural network organization of visual system; the system model permitted a direct correspondence between internal models and system behaviour [6]. Shibata et al. studied bionic smooth pursuit control system based on fast learning of the target dynamics [7]. Simon J. B. et al. established a smooth ocular pursuit control model during the transient disappearance of an accelerating visual target [8]. Ulrich Nuding et. al. put forward a model of the dual pathways for smooth pursuit based on dynamic gain control [9]. Stephen G. Lisberger presented internal models of movement in the floccular [10].

However, these eye movement models hadn't been applied to dynamic target tracking for mobile robot. Both target location and the robot attitude change during in a dynamic target tracking process, which lead to loss of the tracking target. Thus, we propose an eye movement that included smooth pursuit and vestibule-ocular reflex (VOR). The vestibule-ocular reflex (VOR) is a reflex eye movement that stabilizes images on the retina during

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head movement by producing an eye movement in the direction opposite to head movement, thus preserving the image on the center of the visual field [11-15]. For example, when the head moves to the right, the eyes move to the left, and vice versa. This paper focuses on the modelling of oculomotor control based on neurology and anatomy of the eye movement. The model can compensate the error caused by robot’s posture change and target missed. In order to verify the model’s performance, Simulation and physical robot experiments using the control model were carried on. The simulation and test results are encouraging.

II. Model Description

A. *Oculomotor neural paths*

Figure.1 shows the oculomotor neural paths based on the previous study, which is regard as a control system, eyeball and ocular muscles are the controlled objects. The neural pathway starting from the retina via optic chiasm merges with the pathway from the retina of another eye, and then pursues two different routes. First pathway: lateral geniculate nucleus(LGN)→visual cortex (VC) → dorsolateral pontine nucleus (DLPN) → vestibular nucleus (VN). Second route: the nucleus of the tract (NOT) → nucleus reticularis tegmenti pontis (NRTP) → VN. Besides the signal from the retina, the vestibule nucleus accepts the saccadic signal from superior colliculus and the head rotational signal detected by vestibular receptors. The oculomotor control loop stating from the VN: VN→oculomotor nucleus (OMN)→Medial rectus (MR) or VN→abducens nucle(AN)→lateral rectus (LR). Figure. 1. provides a simplified diagram of some the feed-forward connections essential for eye movements. All of these cortical areas have direct projections to brainstem areas including rostral nucleus reticularis tegmenti pontis (rNRTP). These brainstem areas canters project to different regions of the cerebellum (e.g. flocculus), which play complementary roles in eye movements. The input signals are transferred through mossy fibers (mf). The signals coming from NRTP are retinal slip signals and retinal slip velocity signals [16-17].

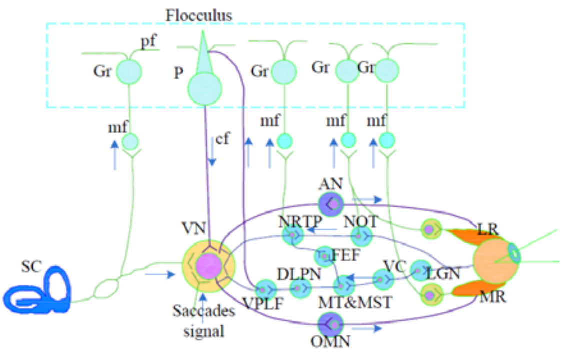

Figure 1. Oculomotor neural paths.

B. *Mathematical model of eye movement*

The VOR is ultimately driven by signals from the vestibular apparatus in the inner ear. The semicircular canals (SC) detect head rotation and drive the rotational VOR [12]. The dynamics of the semicircular canals have been the subject of many studies which have explored both nonlinear and linear aspects of canal function. Without taking into account non-linearities or adaptation effects, the majority of previous studies agree in modelling the canals as high-pass filters of angular head velocity [13]. A first-order linear approximation of canal dynamics is given by:

$$\frac{C(s)}{\ddot{H}(s)} = \frac{T_c}{sT_c + 1} \tag{1}$$

Where $C(s)$ is the Laplace transform of the firing rate modulation of canal primary fibres, $\ddot{H}(s)$ is the Laplace transform of the head’s angular acceleration, T_c is the time constant of the semicircular canals . Approximate values for T_c is 16s.

The eye plant (EP) is responsible for converting motor neural signals into eye movement [2-4]. It consists of the eyeball and the ocular muscles that control the movement of the eye. A simple first-order model was chosen to represent the dynamics of the eye plant. This model has proven to be an accurate predictor of the relation between eye angular position and motoneural firing rate for movements with spectral content up to 4Hz approximately [14]. The horizontal eye plant can be modeled as:

$$P(s) = \frac{E(s)}{F(s)} = \frac{1}{T_e s + 1} \tag{2}$$

Where $E(s)$ and $F(s)$ respectively denote the eye position and motoneuronal firing rate, and T_e denotes the eye plant time constant of approximately 0.24~0.28s [14].

There is a neural integrator between the vestibular nucleus and the oculomotor nucleus or the abducens nucleus. The neural integrator is the term used to describe the process of mathematical integration performed at the neuronal level. Such an NI is necessary in the oculomotor system to accommodate observed promoter and motor responses. The transfer function for the neural paths from VN to LR or MR is expressed as the sum of an imperfect integrator and a direct path, as shown in equation 3. Where T_n is the time constant of the integrator and its value is 25s, g_e is the gain of the direct path and its value is 0.24.

$$NI(s) = \frac{T_n}{sT_n + 1} + g_e \tag{3}$$

Cerebellar flocculus (FL) plays an import role in eye movement, but the early oculomotor models paid little attention to its function [16]. Zhang et al imitated the flocculus’s learning function by using artificial neural networks [17]. The model is applied in a complex unstructured environment, thus it required high real-time performance and robustness. We used high-precision repeat-error-compensation controller to imitate the FL, whose nature is that using control error of the past to compensate the present error. The controller can reflect the FL's function better from the control point of view. It is to be expected that the role of repetitive control gain declined in the high frequency range, a low pass filter is added in the repetitive control. The low pass filter is given by:

$$Q(s)=\frac{e^{-ls}}{sT_p+1} \tag{4}$$

Where T_p is the time constant of the low pass filter and its value is 0.2s, l is the time interval of two errors and its value is 0.012s.

According to the oculomotor neural paths, the transfer functions of semicircular canal, the neural integrator, the flocculus and the oculomotor plant, the oculomotor control system model for a single eye is developed as shown in fig.2. Because T_n =25s, g_e =0.24s, T_n is far larger than g_e, the following equation is obtained:

$$\frac{T_n}{sT_n+1}+g_e=\frac{T_n+g_e(sT_n+1)}{sT_n+1}\approx\frac{T_n(sg_e+1)}{sT_n+1} \tag{5}$$

Because of $g_e=T_e$, the pole of the controlled object sT_e+1 will be cancelled. Figure.2 is simplified as shown by Figure.3. The mathematical control model of the oculomotor movement can be obtained from the Figure.3, and can be stated in equation 6.

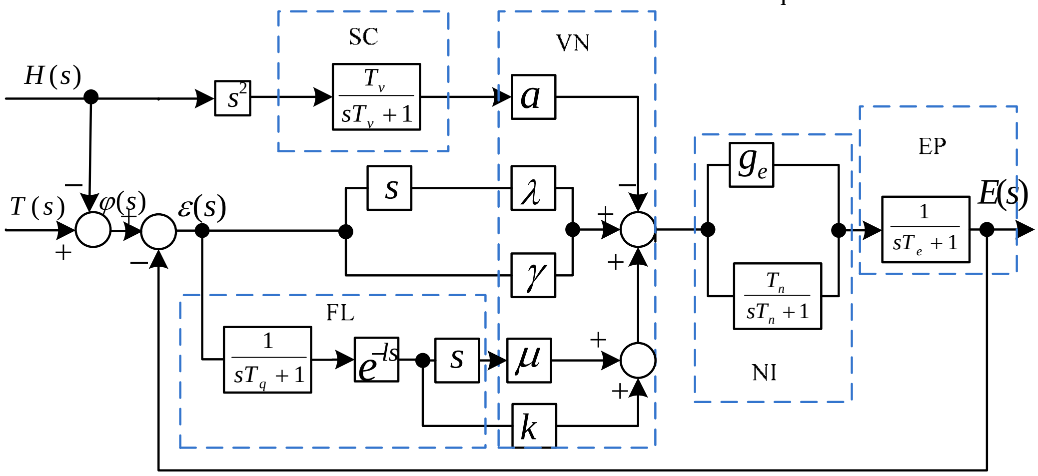

Figure 2. Diagram of the oculomotor control system.

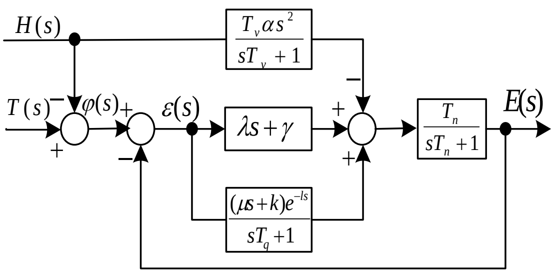

Figure 3. Simplified diagram of the oculomotor control system.

$$E(s)=H(s)\frac{-\alpha T_vT_ns^2}{(sT_v+1)(sT_n+1)}-\varepsilon(s)[(\lambda s+\gamma)+\frac{(\mu s+k)e^{-ls}}{sT_q+1}]\frac{T_n}{sT_n+1} \tag{6}$$

Where $\varphi(s)=T(s)-H(s)$, and $\varphi(s)$ represents relative angle between the dynamic tracking target and the eyeball location. $\varepsilon(s)=T(s)-[H(s)+E(s)]$, and $\varepsilon(s)$ represents the retinal error. $H(s)$ is the head attitude angle, $T(s)$ is the tracking target angle relative to eyeball. $E(s)$ is the optic axis angle. α, λ and γ separately represent the synaptic transmission gains of neural fibres that transfer the head velocity signal, the retinal slip velocity signal and the retinal slip signal, α =1, λ =1 and γ =1 are constant gains based on physiological data [17]. k and μ separately represent the weight of neural fibres that compensate retinal slip signal and retinal slip velocity signal, k =2.5, μ =1 are selected by system identification.

III. Simulation Studies

The model not only contains the VOR and smooth pursuit, but also includes complex movements of both them. In order to study the model's performance, some simulation experiments were carried on for different eye movements. Simulations were performed using SIMULINK, a graphical interface to MATLAB.

A. Simulation for VOR

The VOR's role stabilizes images on the retina during head movement by producing an eye movement in the direction opposite to head movement. Its input is head pose information, Thus, the VOR's mathematical model can be obtained by $T(s)=0$ from equation 6, which can be stated as equation 7. Figure 4 shows the simulation results when Head smooth change smoothly, HA and EB respectively represent the head (robot) attitudes' change input and the eye ball (bionic mechanical pan-tilt camera) attitudes' output; RLD represents sliding displacement of the retina, in other word, it also represents the visual error caused by robot attitudes' change. The simulation results indicate that eye movement is produced in the direction opposite to head movement. Figure5 shows simulation results under harsh environment, and the simulation results show that the model has robust and adaptive.

$$E(s)=H(s)\frac{-\alpha T_v T_n s^2}{(sT_v+1)(sT_n+1)}-[H(s)+E(s)][(\lambda s+\gamma)+\frac{(\mu s+k)e^{-ls}}{sT_q+1}]\frac{T_n}{sT_n+1} \tag{7}$$

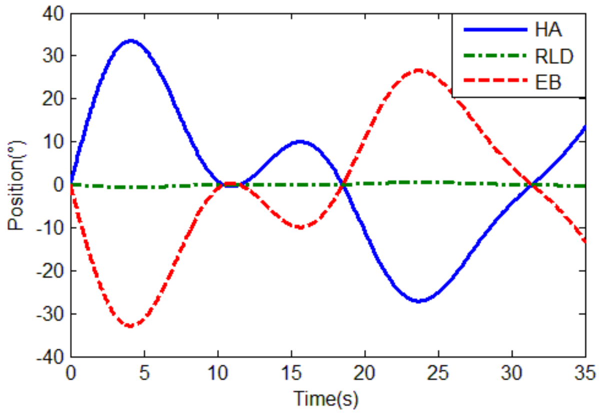

Figure 4. The simulation results of the VOR under ideal environment.

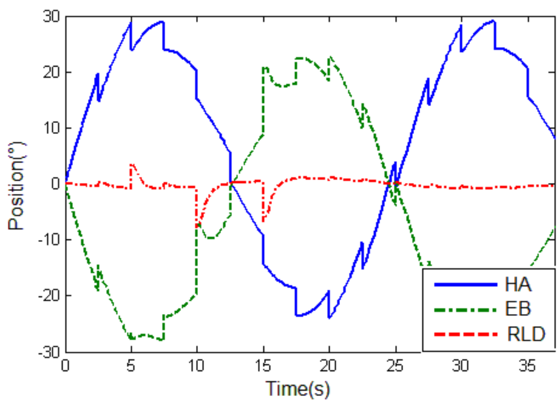

Figure 5. The simulation results of the VOR under harsh environment.

B. Simulation for smooth pursuit

Smooth pursuit eye movements allow the eyes to closely follow a moving object. Smooth pursuit differs from the vestibulo-ocular reflex, which only occurs during movements of the head and serves to stabilize gaze on a stationary object. Most people are unable to initiate pursuit without a moving visual signal. The pursuit of targets moving with velocities of greater than 30°/s tend to require catch-up saccades. According to the features of eye smooth pursuit, the mathematical model of the smooth pursuit can be obtained by $H(s)=0$ from equation 6, which can be stated as equation 8. Figure 6 show the simulation results when target motion is smooth, and TL represents the tracking target location change. The simulation shows that eyeball can track target well during target moving. Figure.7 shows the simulation results when moving target is disturbed suddenly, meanwhile, it also shows that the smooth purist controller can play excellent control performance.

$$E(s)=[T(s)-E(s)][(\lambda s+\gamma)+\frac{(\mu s+k)e^{-ls}}{sT_q+1}]\frac{T_n}{sT_n+1} \tag{8}$$

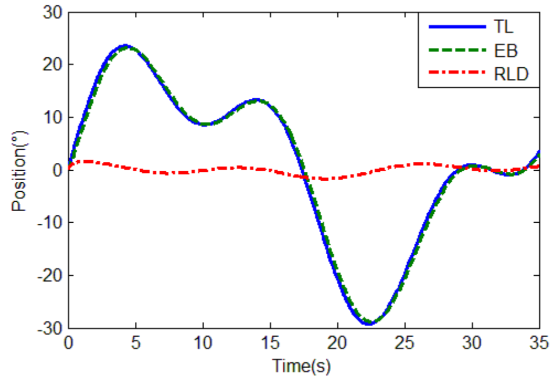

Figure 6. The simulation results of the smooth pursuit during tracking target mutation.

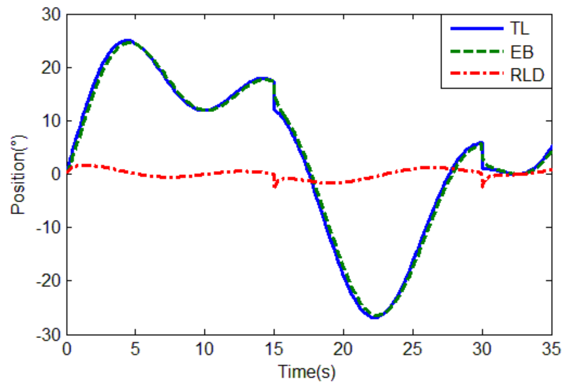

Figure 7. The simulation results of the smooth pursuit during tracking target mutation.

C. Simulation for compound eye movements

Eye movement is the voluntary or involuntary movement of the eyes, helping in acquiring, fixating and tracking visual stimuli. It may also compensate for a body movement, such as when moving the head. In fact, because head and tracking target are in motion, in most instances the human eye's movement is a complex movement that includes smooth pursuit and VOR etc. The mathematical equations of the compound eye movements can be expressed as equation 6, and the simulation results are shown as Figure. (8-11). RP represents relative potentiometer between eye ball and the tracking target location. Figure.8 is the simulation result that robot attitude and tracking target have taken place in sine rule changes, and it indicates that the model can be compensated the errors caused by changes of the robot attitude and tracking target location. Figure 9 and Figure 10 are the simulation results that respectively represent robot posture and tracking target occurring interference during robot target tracking. Figure 11 is the simulation results that represent both robot posture and tracking target occurring interference during robot target tracking. These simulation results indicate that the model has robust and high accuracy.

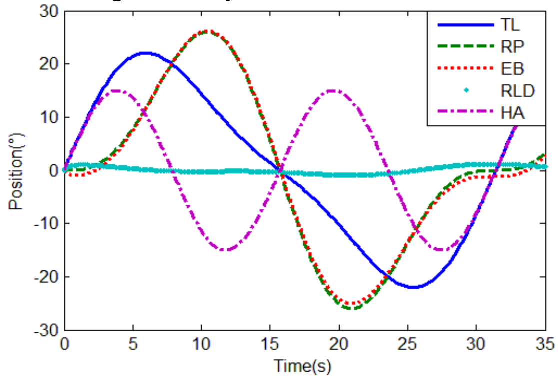

Figure 8. The simulation results of the compound eye movements under ideal environment

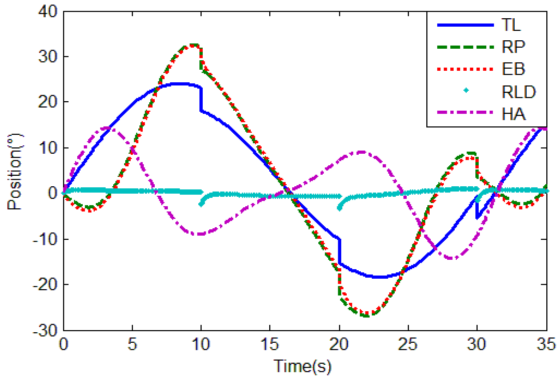

Figure 9. The simulation results of the compound eye movements during tracking target mutation

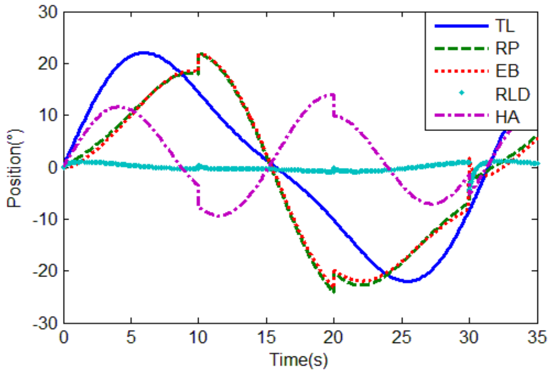

Figure 10. The simulation results of the compound eye movements during head attitude mutation

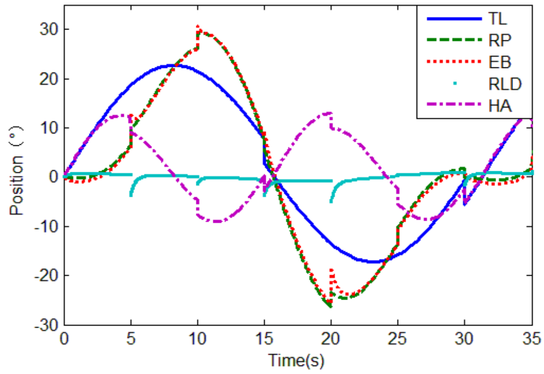

Figure 11. The simulation results of the compound eye movements during both head attitude and tracking target mutation.

VI. Experimental Validations

In order to study the bionic eye model's performance, an experimental platform based on mobile robot under harsh environment is designed. The platform is configured in a conventional layout, as shown in figure12. The mobile robot is tracked robot, and has a 100cm long, 55cm width, and 50cm height. The Bionic mechanical camera designed is installed in the mobile robot. Its structure is spherical parallel mechanism, which using the worst performance index as the optimizing target in required workspace. And ordinary camera is installed in the mobile robot to compare experimental results.

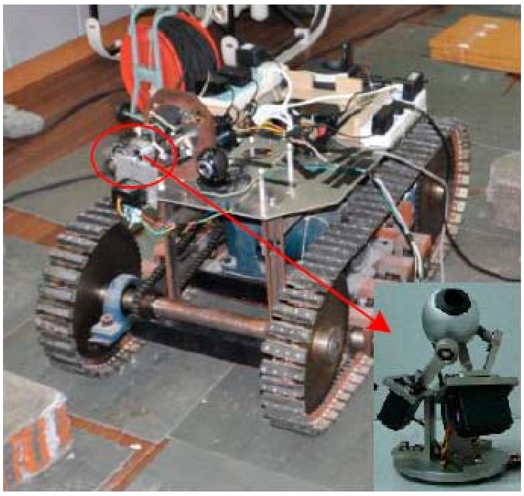

Figure 12. The experimental platform based on tracked robot.

The control system integrated with a set of sensors, and with computing and communications. The whole hardware architecture is sketched in Figure 13, where the various formats information exchanges between the instruments are shown. The mobile robot is under the operator's manual control, the measurement unit (MU) collects data and transmits them to personal computer. Aforementioned sensors, actuators and digital communication devices have different signals and interfaces. High real-time performance is required in the Pan-tilt control and image processing system. We opted for a mixed-signal system-on-a-chip MCU TMS320F2812.The chip is integrated with necessary control and communication ports. The sensors include robot attitude sensor (3DM-GX1) and eyeball attitude sensor (LandMark10 AHRS). The 3DM-GX1 and the LandMark10 AHRS provide control input and Feedback information with update frequency of 100Hz and 200Hz, respectively.

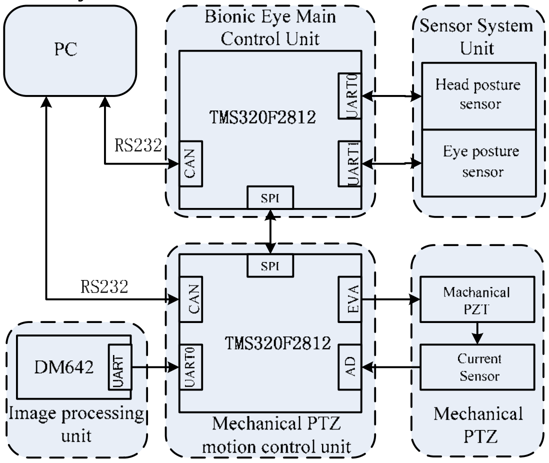

Figure 13. The hardware architecture of the control of the bionic mechanical pan-tilt camera.

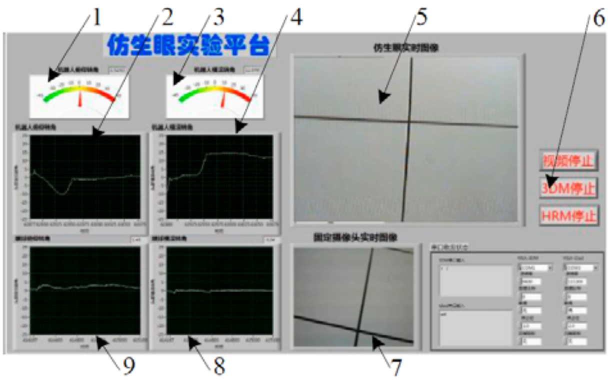

Figure 14. The human-machine interface of the bionic mechanical pan-tilt camera.

Software of the bionic mechanical camera system consists of software of the onboard system and the human-machine interface (HMI) of the personal computer. The software of the onboard system is complicated due to the complexity of the bionic mechanical camera. In this system, all codes are implemented in C language, and are compiled, linked and stored in the in-system programmable FLASH memory of the MCU. Its functions are signals processing, data filtering, fault tolerance and diagnosis, bionic eye movement algorithm (detailed in section 3), the real-time detailed experimental data recording, etc. For the communication and interaction purpose, a human-machine interface (HMI) is designed in the personal computer, as Figure14, including: 1) Real-time information of the robot attitude's pitch angle; 2) Robot pitch attitude's observer 3) Real-time information of the robot attitude's roll angle; 4) Robot roll attitude's observer; 5) Image Monitor from the bionic mechanical pan-tilt camera; 6) Command editor; 7) Image Monitor from the traditional camera; 8) and 9) are vision error observer in roll and pitch, respectively. The HMI is developed using labview object-oriented programming environment, and its main functions include data display and storage, target monitoring, etc.

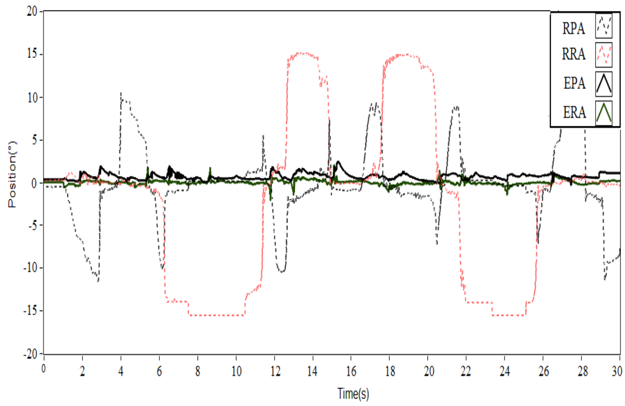

Figure 15. The experimental results of the bionic mechanical pan-tilt camera based on tracked robot

Part of the experimental results is displayed in Figure 14 and Figure 15. RPA and RRA respectively represent the robot attitude in the pitch and roll direction; EPA and ERA respectively represent the eyeball output attitude in the pitch and roll direction. The robot attitude's pitch angle is ranged from -10° to 10°, and the robot attitude's roll angle is ranged from -15° to +15°. The results from Fig.14 shows that the bionic mechanical pan-tilt camera can adjust based on the dynamic changes of the robot attitude and the tracking target location, but the traditional cameras can't. Figure15 shows that the control system has high accuracy and robustness during robot moving in the harsh environment.

V. CONCLUSION

This paper presents a unified oculomotor control system model based on human eye's anatomical structure and physiological mechanism. The model includes vestibule-ocular reflex, smooth pursuit eye movements and compound eye movements. Meanwhile, these eye movements' system is simulated according to characteristics of eye movements, and the simulation results indicate that the model is effective. In addition, a method of active compensation for robot visual was proposed based on the principle of eye movements. In order to verify the model's performance, some experiments are designed and the onboard hardware and software of the system are developed. The experimental results validate that the presented the method is valid and the eye movement's model is robust. Compared with the conventional camera, this new one can solve the problem of unstable vision that is resulted from robot's attitude and tracking target location changes.

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