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REALIZATION OF PHYSIOLOGICAL EYE MOVEMENTS BY AUTOMATIC SELECTION OF CONTROL LAWS USING ARTIFICIAL NEURAL NETWORK

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Abstract Eye movements are realized in hardware with controlling an optic axis according to the movement types of an object and a head using artificial neural network. Saccadic and smooth pursuit eye movements are realized as an autokinesis, and compensatory eye movement as a reflex by a hardware mechanism. In order to have basic optic axis movements, by which an object is caught in a central pit of retina, an oculomotor machine is developed for independent horizontal movements of a head and an eyeball. A CCD camera is used for the function of an eyeball. The image output from a camera is fed to the control of a servomotor instead of eye muscles to realize eye movements. The mechanism of a head rotation is linked through bearings to the neck of an oculomotor machine. An accelerometer is used for the function of semicircular ducts in order to predict possible displacement of a head rotation. The oculomotor machine is controlled for the above voluntary and reflex movements individually using neural network systems. The cooperative eye movements are then realized by automatic selection of control laws according to the movement types of an object and a head using a structuralized neural network information processing system.

Keywords eye movement, control system of optic axis, neural network

1. Introduction

The visual pattern recognition is supported by a regulatory mechanism of an optic axis, by which an object can be caught in a central pit of retina, even if there occur movements of an object and/or a head. This mechanism is thought to consist of various physiological eye movements such as saccadic, smooth pursuit and compensatory eye movements, optokinetic eye movement and vergence [1-3]. On the way of discovery of physiological facts about eye movements, an attention has been paid to their regulatory mechanism from the view point of control engineering. Thus, their control mechanisms have been investigated by simulation techniques using appropriate models [4-5]. An attempt is made, in this study, to realize main eye movements including saccadic, pursuit and compensatory eye movements in hardware system. For this purpose, an oculomotor machine which is capable of basic horizontal eye movement is developed. Its head part possesses a CCD camera for the function of image acquisition of an eye. The image information is used to control an optic axis of a camera by driving a servomotor instead of the regulation of an eye position by eye muscles. Then, the basic two voluntary eye movements are realized by controlling an optic axis using an experimental system consisting of a driving apparatus of an object and an oculomotor machine. In addition, a compensatory eye movement is realized so that an accelerometer is attached to the head part for the function of semicircular ducts predicting possible displacement of a head rotation. Finally, smooth cooperative eye movements are realized with combination of three eye movements by using an experimental system for an optic axis regulation [6].

2. Experimental system for optic axis regulation

2.1 Oculomotor machine and driving apparatus of object

For the realization of basic physiological eye movements, an oculomotor machine is developed which has a single eyeball with a capability of its horizontal movement. The machine consists of head and neck parts as depicted in Fig.1. A CCD camera on the head part substitutes image acquisition function of an eye. A servomotor is driven on the basis of output image data from a camera to make a control of an optic axis which is performed by eye muscles. A head rotation mechanism with bearings connecting to the neck is developed with an accelerometer for the function of semicircular ducts in order to have a compensatory eye movement. Here, a driving apparatus of an object is also developed for the control experiment of an optic axis of an oculomotor machine. A black stripe with a white background is chosen as an object to be caught in a central pit of retina. The object is designed to move in an arbitrary velocity in a circular direction. Combining a driving apparatus

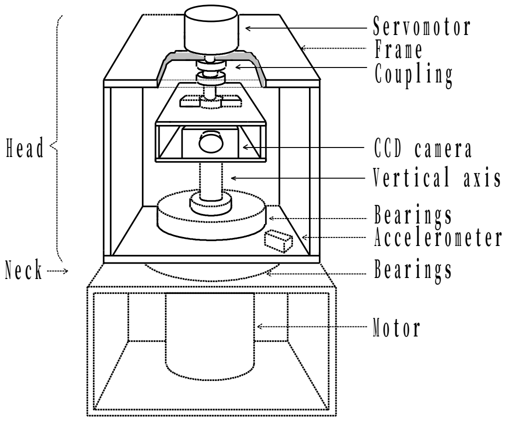

Fig.1 Outline of an oculomotor machine.

of an object with an oculomotor machine, an experimental system for an optic axis regulation is constructed as shown in Fig.2.

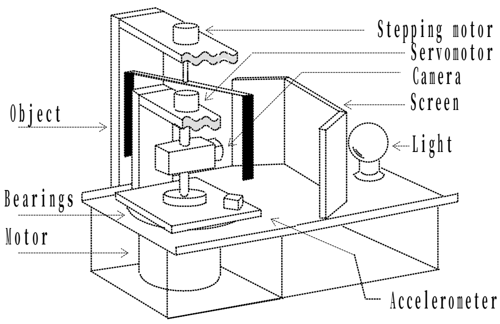

Fig.2 Experimental system for optic axis regulation.

2.2 Hardware control system of oculomotor machine and driving apparatus of object

To realize basic eye movements, an oculomotor machine and a driving apparatus of an object are controlled by a hardware control system which is outlined in Fig.3.

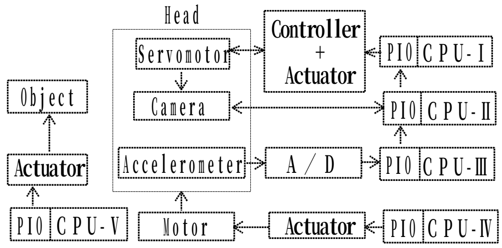

Fig.3 Block diagram of hardware control system.

The image data from a CCD camera is processed with an information about acceleration of a head movement in order to drive a camera for adjusting its optic axis according to types of an object movement and a head rotation. The head part linked to the neck through bearings and an object are driven by independent motors. The actuator on the upper right of Fig.3 includes a function of conversion of a pulse sequence into torque which drives an oculomotor machine. The controller consists of a generator of various types of pulse sequences characterized by eq.(1) according to displacement v given as an input.

$$P=f(k,a,t)''v \qquad (1)$$

where P denotes a pattern of a pulse sequence. k is a parameter for conversion of displacement v into the number of pulses, a gives an acceleration pattern of driving a servomotor and t is a parameter to determine pulse frequency which gives rotational velocity of a camera.

3. Realization of optic axis control using neural network

In order to have saccadic, pursuit and compensatory eye movements independently on the basis of previous studies [6], their movement principles are explained inclusive of control systems using neural networks.

3.1 Neural network for improvement of control performance

Three layered full connection type neural network is used for the synthesis of learning control systems. Its learning algorithm is based on a back propagation. As it is difficult to give a precise supervised signal to an oculomotor machine, a neural network is in parallel combined with control systems for the improvement of their control performance [6-8]. The image data and controlled deviation are used for learning of the neural network which gives a change to the parameters of a controller and an input component directly to the actuator.

3.2 Saccadic eye movement

Saccadic eye movement is caused by a rapid change in point of regard, by a rapid movement of an object or by a large acceleration of a moving object [1-3]. Figure 4 (a) shows a principle of basic saccadic eye movement which occurs at rapid change in point of regard with an intention of looking at an object. When an object change its position to the place indicated by a black dot, a single control attempt is given to the oculomotor machine by expecting a displacement of an object so that its optic axis may be adjusted to the object. i.e. the optic axis of a camera is rapidly changed from the place indicated by dotted line to the place by solid line. An optic axis is controlled to have no positional difference between an object and its image, i.e. practically to make its position error from an object as small as possible. The control system with a neural network is given by Fig.4 (b), if a desired value of position of a moved object is r . In order to make an optic axis reach a desired value in a single attempt, the controller generates an appropriate pulse sequence which is given by the following pattern:

$$P=f(K ,a ,t)"r \qquad (2)$$

where the number of pulses in a single control operation is characterized by constant K , but pulse frequency determined by a parameter t is dependent on a variable acceleration pattern a .

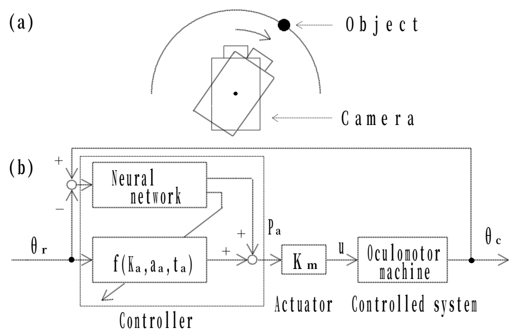

Fig.4 Principle and control system of saccade.

A control law is given by the learning function of a neural network, i.e an appropriate acceleration pattern with a suitable pulse frequency is given by varying parameters a and t so that position error of an optic axis from an object may be made smaller in every control operation.

3.3 Pursuit eye movement

This is a control of a camera to follow-up an object when it moves from the place 1 to 2 as illustrated by Figure 5 (a). In order to follow-up a velocity of an object, a rotational velocity of a camera is controlled by a PI-feedback control law using a measured velocity error between a camera and an object in the course of their movement. The control law and pulse sequence pattern are given by the following equations with a desired value r , a constant parameter K and an acceleration pattern A :

$$v = K e + K \; ? e\,dt ; \quad e = r - r \qquad (3.1)$$

$$P = f(K ,A ,t)"v \qquad (3.2)$$

It is hereby important to take a less time until the velocity error reaches a value within a certain range. In this case, a control is given to a camera to catch up with a velocity of a moving object by varying parameter t and input component into the actuator using a result from a neural network learning system as illustrated in Fig.5 (b).

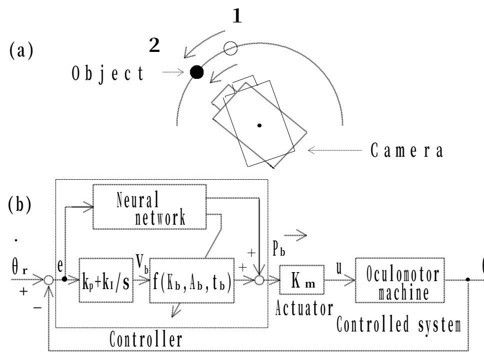

Fig.5 Principle and control system of pursuit.

3.4 Compensatory eye movement

The principle of a compensatory eye movement control is illustrated in Fig.6 (a). If a head moves from the position 1 to 2 with a certain acceleration looking at a standing object indicated by black dot, a camera is moved in an opposite direction of a head rotation by a rotational angle expected using data from an accelerometer.

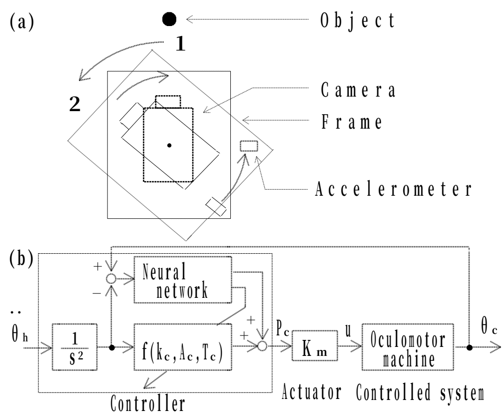

Fig.6 Principle and control system of compensatory eye movement.

On processing data from an accelerometer in every short time interval, a controller gives a camera iterative drive to catch an object expecting its rotational angle in the next time interval. It is hereby important to make an image of a moving object as steady as possible. The controller in this case is given as a driving pattern described by eq.(4).

$$P=f(k, A, T)''r \quad (4)$$

with a constant acceleration pattern A and a constant pulse frequency characterized by T.
After iterative control of a head movement, a neural network learning system determines parameter k for a pulse conversion rate and an input component to the actuator.

4. Cooperative control of optic axis using structuralized neural network

4.1 Neural network for selection of control laws

In section 3, saccadic, pursuit and compensatory eye movements have been treated independently. However, an organism has a capability of catching an object by appropriate switching and linkage of basic eye movements, even if there occur complex combinations of movements of an object and a head. An appropriate choice of control laws for saccadic and pursuit movements is difficult in a variety of movements of an object, taking into account that a saccadic eye movement is induced when an object rapidly moves at the change in a point of regard and/or when a velocity of an object cannot be followed-up by a pursuit eye movement. It becomes more difficult to select an appropriate control law, if a compensatory eye movement has to be considered at the same time. Here, it is mentioned how to select previously mentioned control systems by learning system using another neural network for a smooth control of an optic axis, i.e. how to combine three kinds of control laws in order to give an appropriate acceleration pattern for the control of an optic axis.

A structuralized neural network consisting of four neural networks is here introduced as illustrated in Fig.7 [6]. The network for reflex detects an acceleration which will contribute to the input to the actuator and/or give information about a relative movement of an object to the head.

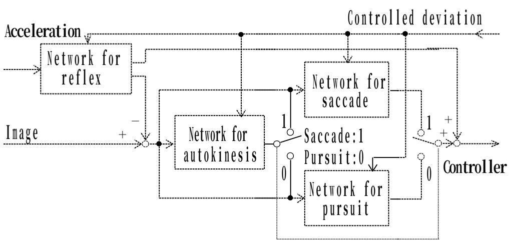

Fig.7 Structuralized neural network for selecting control laws for complex eye movements.

The network for autokinesis provides information about an appropriate selection of a control law of either saccade or pursuit according to the positional difference between an optic axis and an object. It is, thus, possible to give a continuous pattern of acceleration to the actuator according to the switching of control laws.

4.2 Automatic selection of control laws for eye movements by structuralized neural network

The control laws for the eye movements are basically selected by using information from an accelerometer attached to the head part. If it detects an acceleration of a head, a control law is switched to the one for a compensatory eye movement control, otherwise remains a voluntary eye movement control for saccade or pursuit. The selection of a control law is however difficult, if both of a voluntary and a reflex eye movements occur simultaneously. The proposing structuralized neural network is useful to deal with such a difficult case.

4.3 Experimental results

Three kinds of eye movement controls are tried under various conditions by using an experimental system with previously mentioned control systems. As for a saccadic eye movement, a feedforward control is given to make a controlled deviation as small as possible in a single control operation expecting a displacement angle of an object. The absolute position error between an optic axis and an object has been attained within 1.0[deg] by a single operation, when an object is placed in a variety of angles smaller than 15[deg]. As for a pursuit eye movement, a feedback control is given to make a camera follow-up an object by changing its rotational velocity using its velocity error from an object. A compensatory eye movement control gives also a satisfactory result as long as an acceleration varies within a narrow range of value during a head rotation. It is well known that a control is switched from pursuit to saccade, if an object in a low velocity changes its movement in a high velocity of greater than 45[deg/s], because an eye cannot follow-up an object by pursuit with a compensation of a position error induced by velocity change of an object [1-3].

Here, the optic axis control is performed using an experimental system with application of a control law selected automatically by a structuralized neural network, when the velocity of an object varies from 9[deg/s] to 27[deg/s].
Figure 8 illustrates velocities and positions of an optic axis and an object, when pursuit and saccade eye movement control laws are automatically selected with their alternations.
In the illustrations, dotted lines denote an object movement. Solid lines indicate control performance of an optic axis resulting from complex controls of saccade and pursuit eye movements. Chain lines give control performance concerning a velocity and a position of an optic axis under the control of only pursuit eye

movement which remains unchanged in the whole control process. In the present case, a control law is four times changed during an experiment according to the displacement of an optic axis from an object which is induced by velocity change of an moving object, i.e. a pursuit eye movement is switched to a saccade eye movement, when an positional difference between an optic axis and an object reaches about 9[deg] or a velocity of an object reaches about 22[deg/s]. Solid arrows indicate changes in control laws from pursuit to saccade and dotted arrows from saccade to pursuit. It is hereby remarked that the time scale in this experiment is longer than in the case of physiological eye movements because of a large mass and friction of an oculomotor machine.

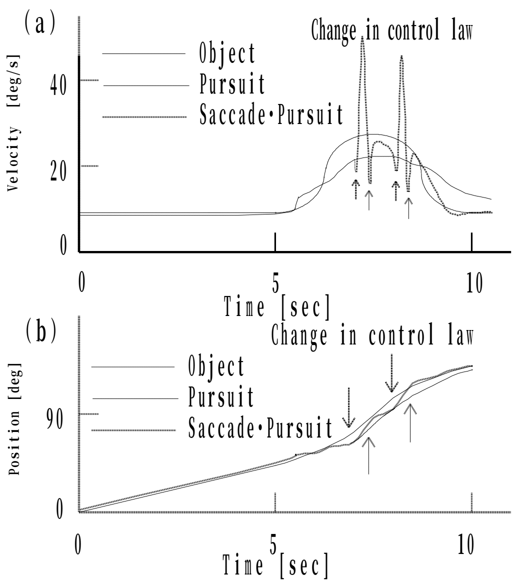

Fig.8 Control of optic axis for velocity change of object by automatic selection of control laws.

5. Summary

In this study, an experimental system for an optic axis regulation has been developed combining an oculomotor machine with a driving apparatus of an object, which has been applied to the experiment of an optic axis control depending on an type of movement of an object and a head. The control systems with a neural network have been proved good enough for independent controls of saccadic, pursuit and compensatory eye movements, although their results are not satisfactory enough comparing with physiological phenomena. Furthermore, an automatic selection of control laws has been practically achieved by using a structuralized neural network i.e. smooth switching of eye movement controls has been realized which is dependent on a relative velocity of a camera to an object. For unification of the voluntary and reflex eye movements, there still exist some problems in technology, which remain as subjects including an improvement of structure and algorithm of control systems. In the present study, an eyeball moves only in a horizontal direction, however, its vertical movement is inevitable to realize physiological eye movements actually [9], and also movements of two eyeballs are necessary for supporting their visual recognition. Those will lead us to the way to the actual realization of physiological eye movements of an organism. However, the present experimental results from the control of an oculomotor machine have provided valuable information about an actual physiological control mechanism of eye movements and also possibilities of their applications in technology.

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