BINOCULAR MOTOR SYSTEM BASED ON ITS ANATOMY AND PHYSIOLOGY (Eye robot)

Biomedical System Engineering

Tokyo Medical and Dental University

H. Wakamatsu

Motivation

- **Theoretical Biology and Medicine**
  - **Representation of oculomotor system**
  - **Eye movement pattern and neuropathology**
- **Application of Optical Control Model to Robot**
  - **Human-like eye movement**

Binocular motor system based on anatomy and physiology

Control of binocular movements by reciprocal control paths

Adaptation mechanism

Synthesized binocular motor system

- **Vestibular oculomotor reflex (VOR)**
- **Pursuit eye movement**
- **Conjugate eye movement**
- **Vergence eye movement**

Eye movement

Unification of

1 Saccade

2 Pursuit

3 Optkinetic reflex

4 Vestibloocular reflex

Conjugate

+

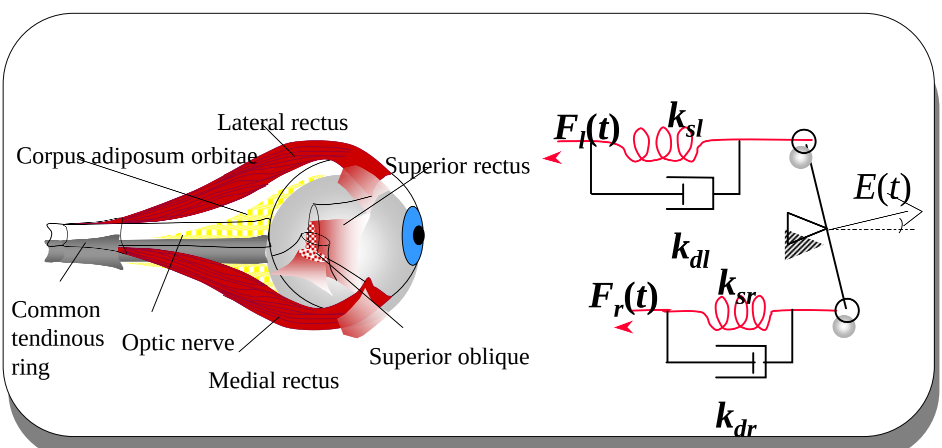
Vergence

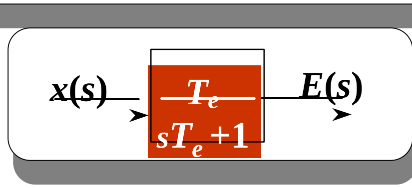
Ocular motor model of single eye

1. **Principle of cooperative control based on vestibular & optical signals**
2. **Dynamic characteristics and frequency response of the model**
3. **Adaptive systems**

Principle of cooperative control

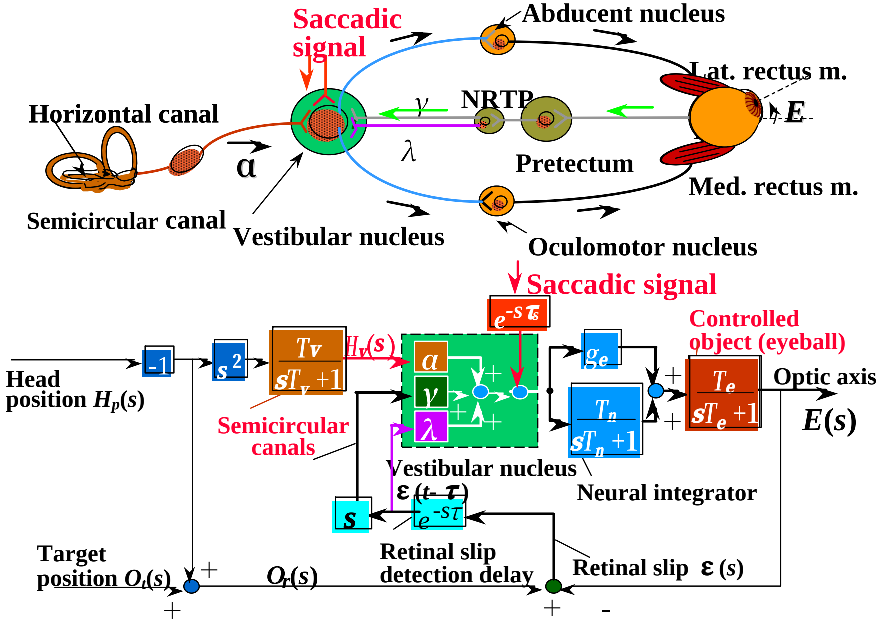
- Control by vestibular signal
- Control by retinal signals

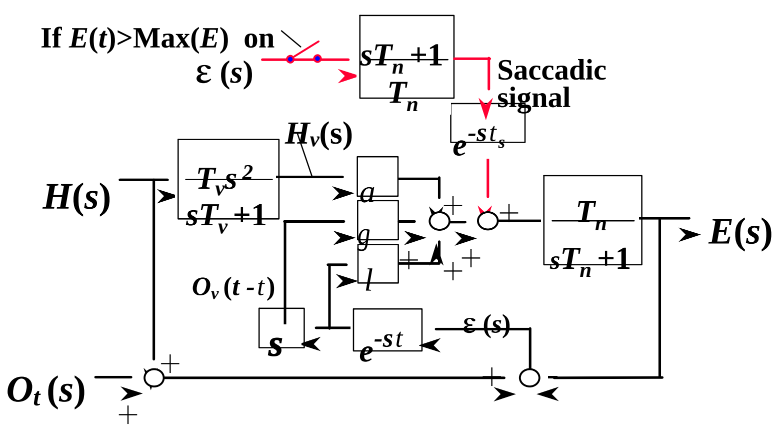




Transfer function of ocular muscles and eyeball

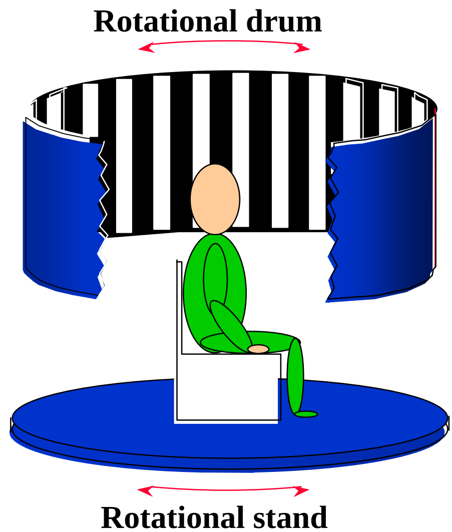
Basic neural paths for horizontal eye movements



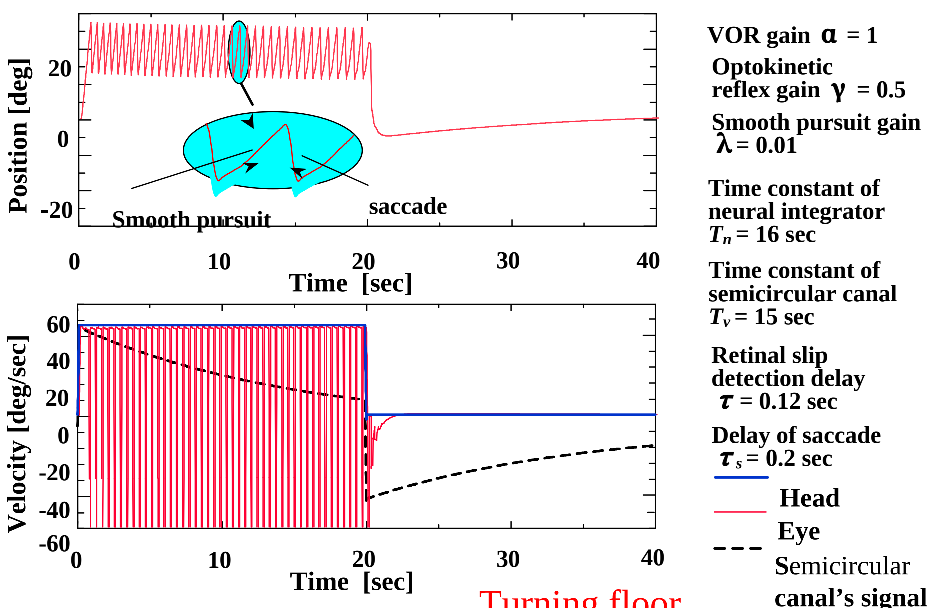


$$E(s) = \frac{T_n}{(T_n s + 1)} \left[a \frac{T_v s^2}{T_v s + 1} H(s) + (g\, s + l\,) e^{-st} e(s) \right]$$

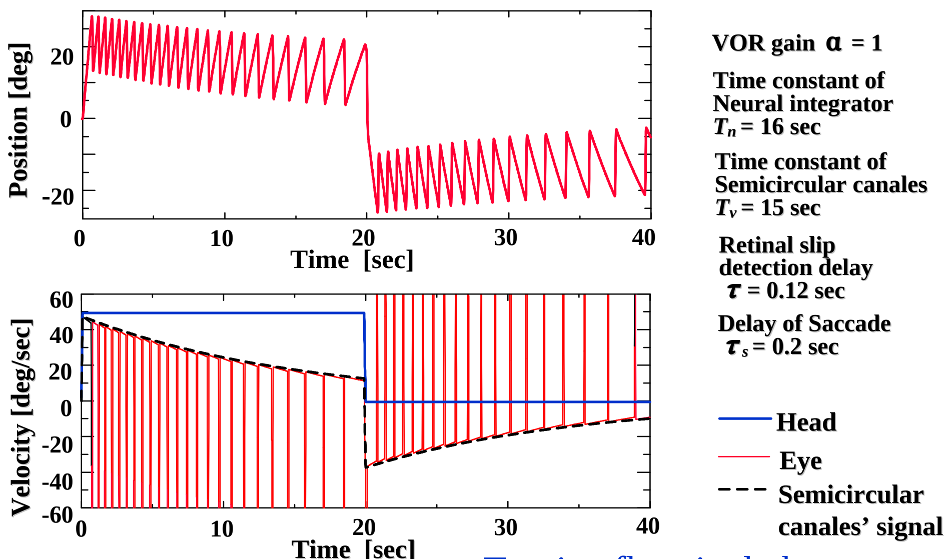
A simplified oculomotor control system without cerebellum



Simulated experimental method



Characteristics of normal eye movement



VOR gain α = 1

Time constant of Neural integrator T_n = 16 sec

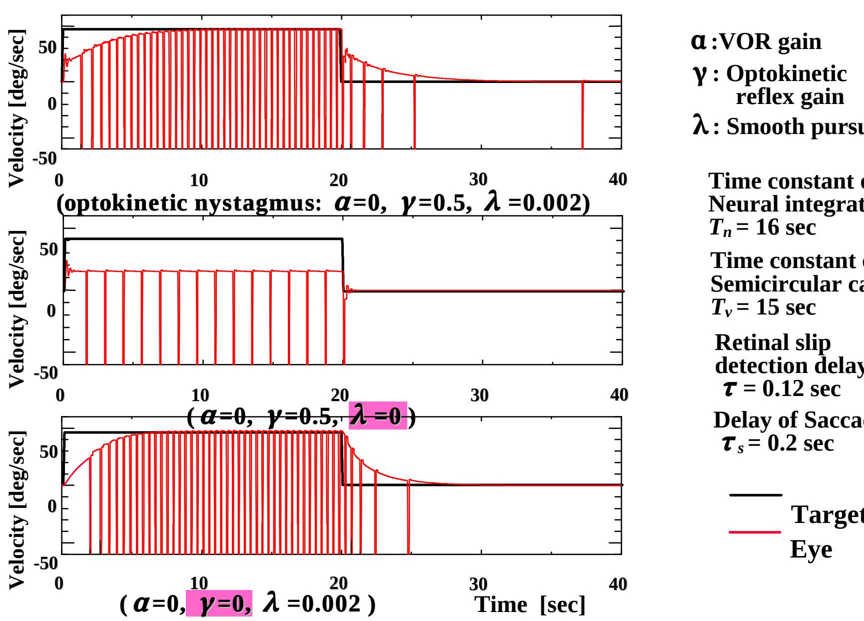
Time constant of Semicircular canales T_v = 15 sec

Retinal slip detection delay τ = 0.12 sec

Delay of Saccade τ_s = 0.2 sec

Turning floor in darkness

Characteristics of the model in VOR (vestibular nystagmus)



α : VOR gain

γ : Optokinetic reflex gain

λ : Smooth pursuit gain

Time constant of Neural integrator T_n = 16 sec

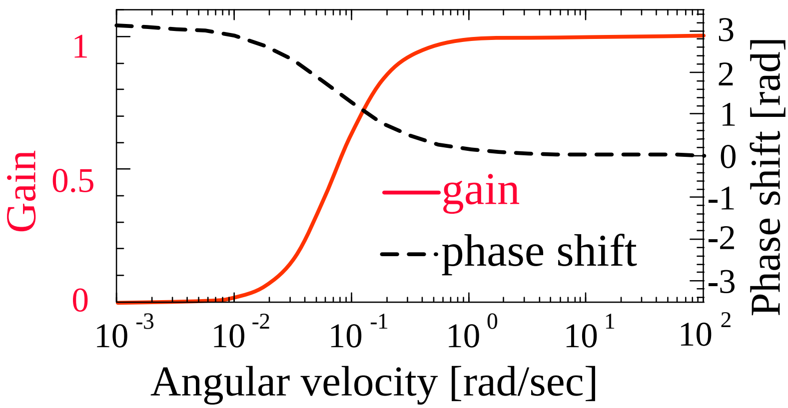
Time constant of Semicircular canales T_v = 15 sec

Retinal slip detection delay τ = 0.12 sec

Delay of Saccade τ_s = 0.2 sec

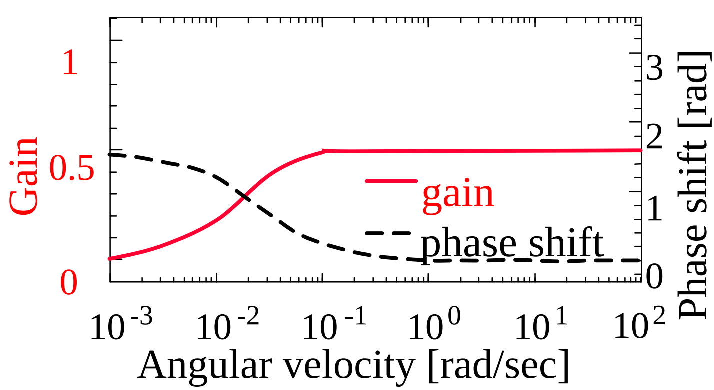
Turning object & still floor

Characteristics of the model for optokinetic eye movement



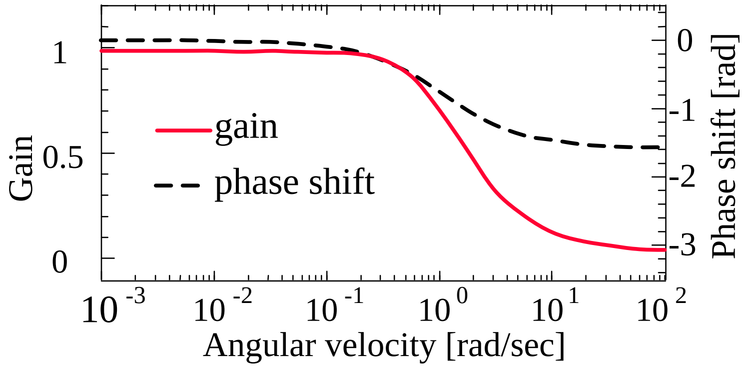
$$\frac{E(jw)}{H(jw)} = \frac{aw^2}{(1/T_v^2 + w^2)(1/T_n^2 + w^2)} \left[\left(w^2 - \frac{1}{T_v T_n} \right) + \left(\frac{1}{T_v} + \frac{1}{T_n} \right) jw \right]$$

Frequency response of VOR model



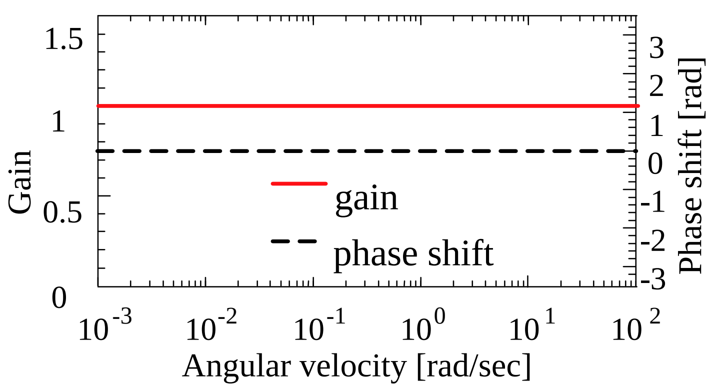
$$\frac{E(jw)}{O_t(jw)} = \frac{gw}{(1+g)^2 w^2 + 1/T_n^2} \left[(1+g)w + \frac{1}{T_n} j \right]$$

Frequency response of the optokinetic reflex model
(g = 1, a = 0, l = 0)



$$\frac{E(j\omega)}{O_t(j\omega)} = \frac{\lambda}{(\lambda + 1/T_n)^2 + \omega^2}(\lambda + 1/T_n - j\omega)$$

Frequency response of smooth pursuit (λ = 1)

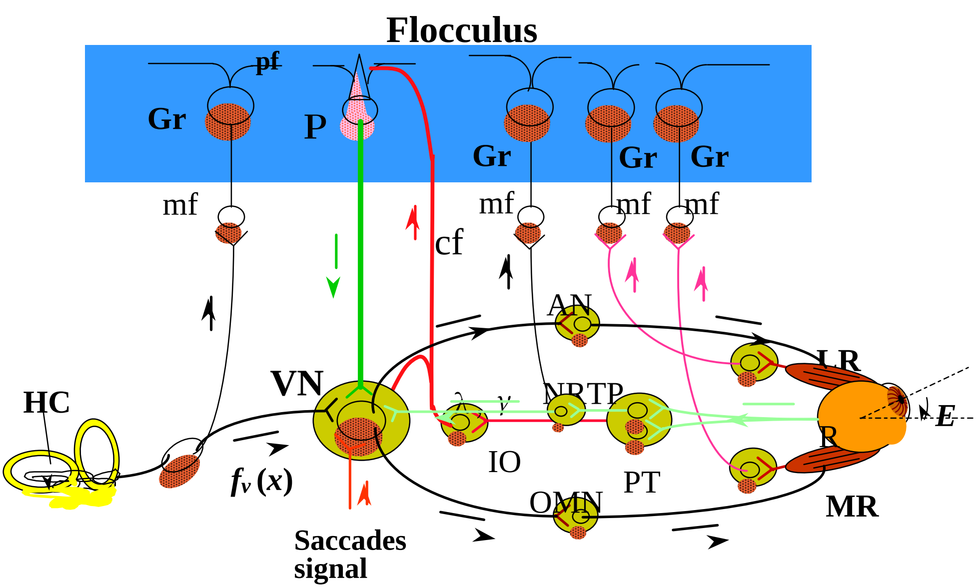


$$\frac{E(j\omega)}{H(j\omega)} = \frac{-(\alpha + \gamma)T_v T_n \omega^2 + [\lambda T_v + \gamma]T_n j\omega + \lambda T_n}{(T_v j\omega + 1)[(1 + \gamma)T_n j\omega + \lambda T_n + 1]}$$

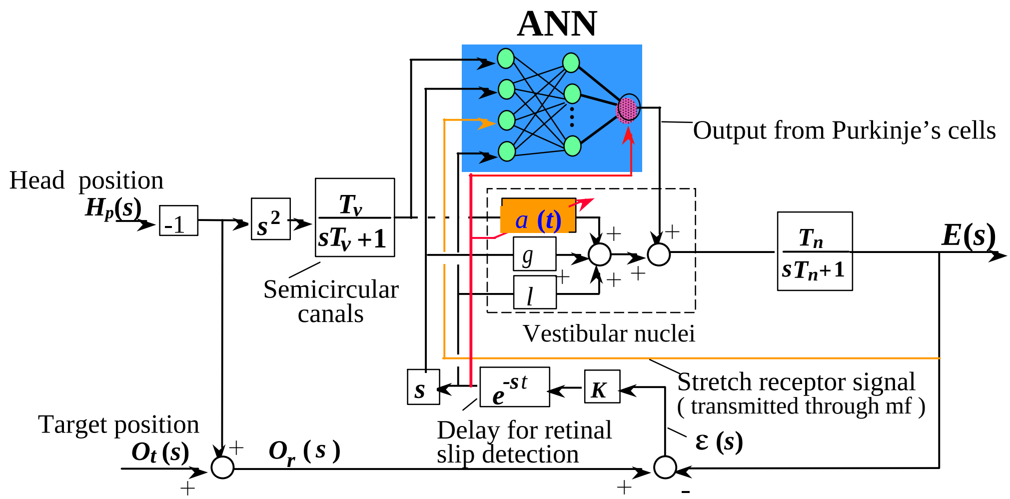
Frequency response of the whole model
($\alpha = \gamma = \lambda$ = 1)

Adaptive characteristics of ocular motor system

- Adaptation mechanism
- Role of neural paths into flocculus from stretch receptors

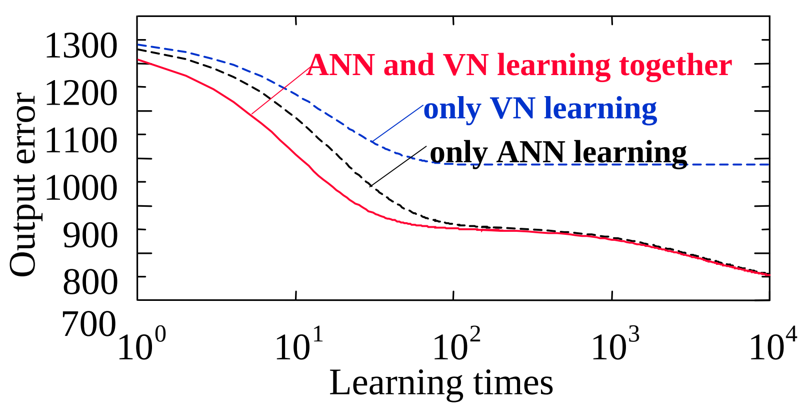


Neural paths for horizontal eye movements based on anatomical structure including cerebellum

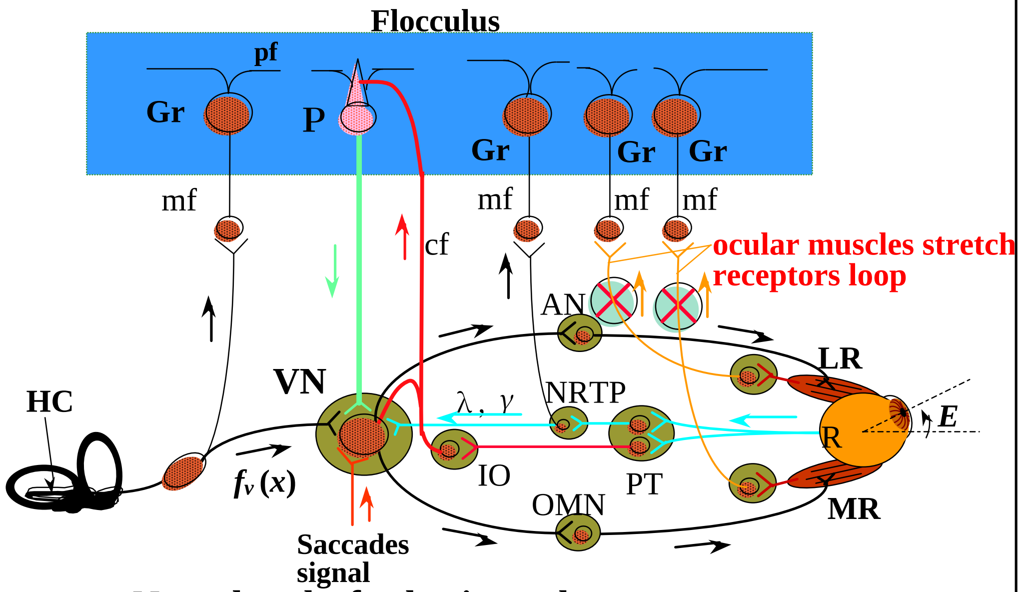


$$a(kT+T)=a(kT)+d\left(r-a(kT)\right)+xe(kT+t)H_v(kT+t)$$

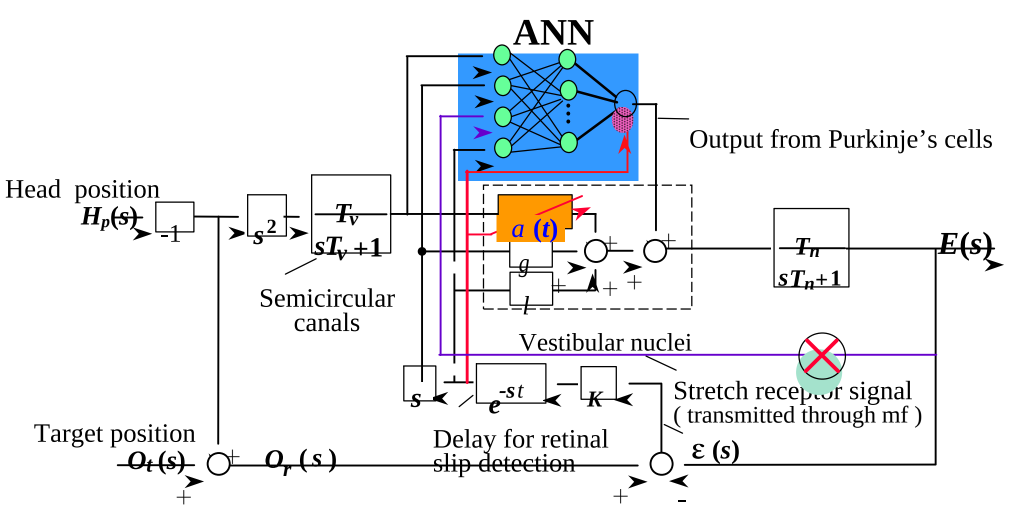
Block diagram of eye movements control system for a single eye



Learning errors Se^2(***kT***) **for ANN and VN learning models**

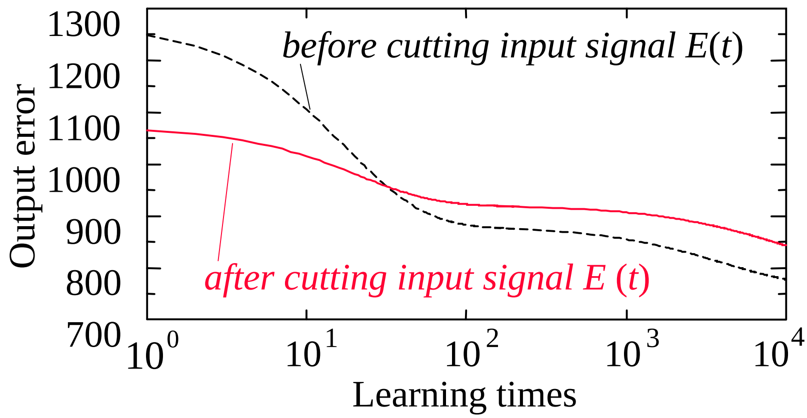


Neural paths for horizontal eye movements based on anatomical structure



$$a(kT+T) = d\big(r - a(kT)\big) + xe(kT+t)H_v(kT+t)$$

Block diagram of eye movements control system for a single eye



ANN learning errors before and after cutting off the stretch receptor signal *E*(*t*)

Concluding remarks

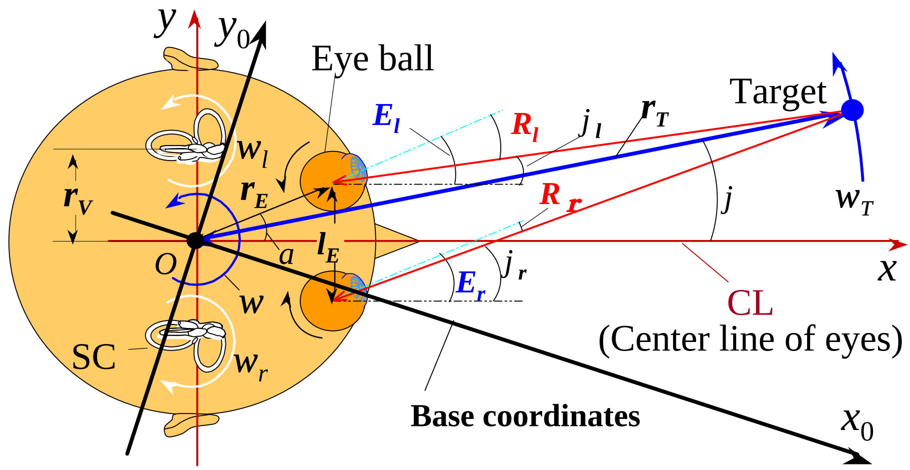
1. **Eye movement depends on**
   smooth pursuit (low frequency)
   optkinetic reflex(high frequency)
   VOR (high frequency)
2. **Learning systems**
   short term(vestibular nucleus)
   long term(cerebellum)
3. **Necessity of stretch receptor signal for the appropriate learning**

Binocular motor control system

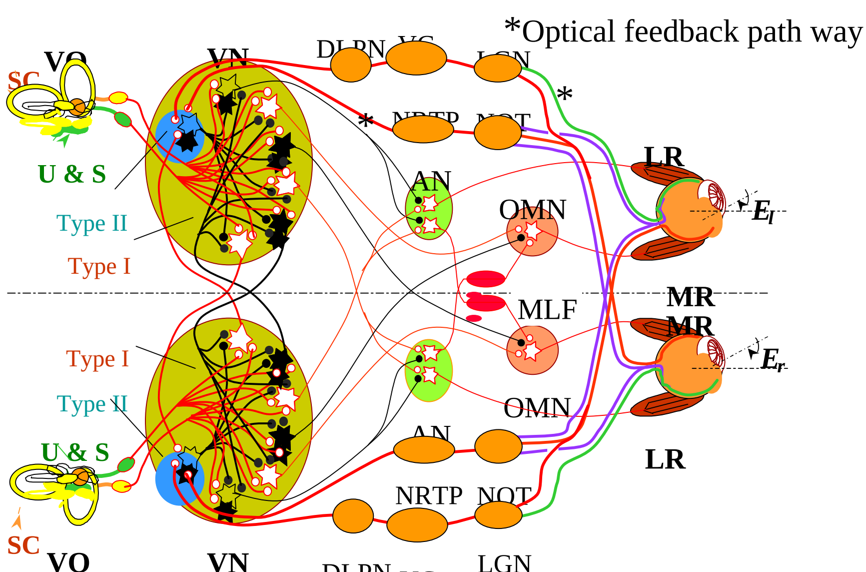
- **The basic model of binocular movement and its analysis**
- **Its application to binocular axes control system**

Binocular motor system

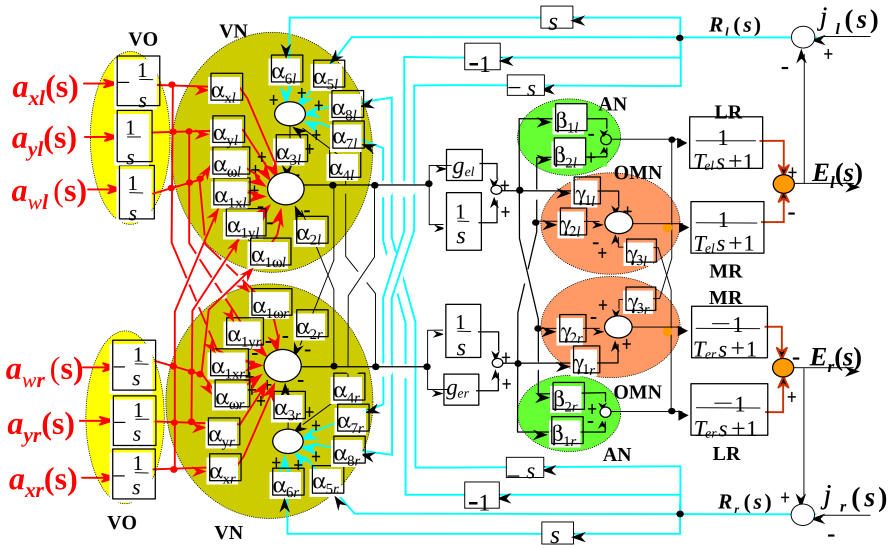
The basic model of binocular
movement and its analysis



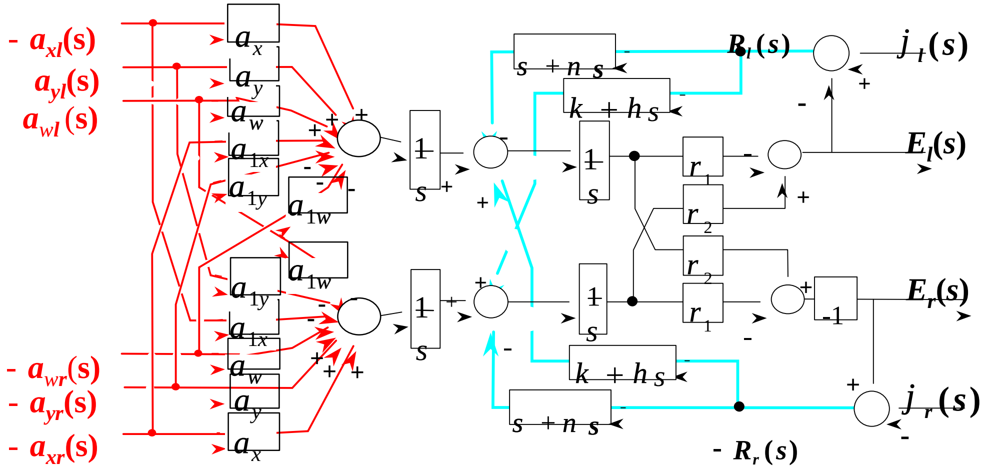
The relationship between target , head, eyeballs and vestibular organs



Neural pathways of horizontal binocular motor control system



Mathematical model of eye movement for a binocular motor system based on the physiological model



Simplified model

$$
\begin{bmatrix} E_l(s) \\ E_r(s) \end{bmatrix} = \frac{1}{\sigma - \kappa + \left(\frac{1}{\rho_1 - \rho_2} + \nu - \eta s\right)} \begin{bmatrix} \alpha_x - \alpha_{1x} & \alpha_y - \alpha_{1y} \\ \alpha_{1x} - \alpha_x & \alpha_{1y} - \alpha_y \end{bmatrix} \begin{bmatrix} v_x(s) \\ \frac{1}{s} a_c(s) \end{bmatrix}
$$

Vergence VOR

$$
- \frac{1}{\sigma + \kappa + \left(\frac{1}{\rho_1 + \rho_2} + \nu + \eta s\right)} \begin{bmatrix} 2\alpha_\omega + (\alpha_x + \alpha_{1x}) r_V & \alpha_{1y} - \alpha_y \\ 2\alpha_\omega + (\alpha_x + \alpha_{1x}) r_V & \alpha_{1y} - \alpha_y \end{bmatrix} \begin{bmatrix} \omega(s) \\ v_y(s) \end{bmatrix}
$$

Conjugate VOR

$$
+ \frac{1}{2} \frac{\sigma - \kappa + \nu s - \eta s}{\sigma - \kappa + \left(\frac{1}{\rho_1 - \rho_2} + \nu - \eta s\right)} \begin{bmatrix} \varphi_l(s) - \varphi_r(s) \\ \varphi_r(s) - \varphi_l(s) \end{bmatrix}
$$

Vergence

$$
+ \frac{1}{2} \frac{\sigma + \kappa + \nu s + \eta s}{\sigma + \kappa + \left(\frac{1}{\rho_1 + \rho_2} + \nu + \eta s\right)} \begin{bmatrix} \varphi_l(s) + \varphi_r(s) \\ \varphi_l(s) + \varphi_r(s) \end{bmatrix}
$$

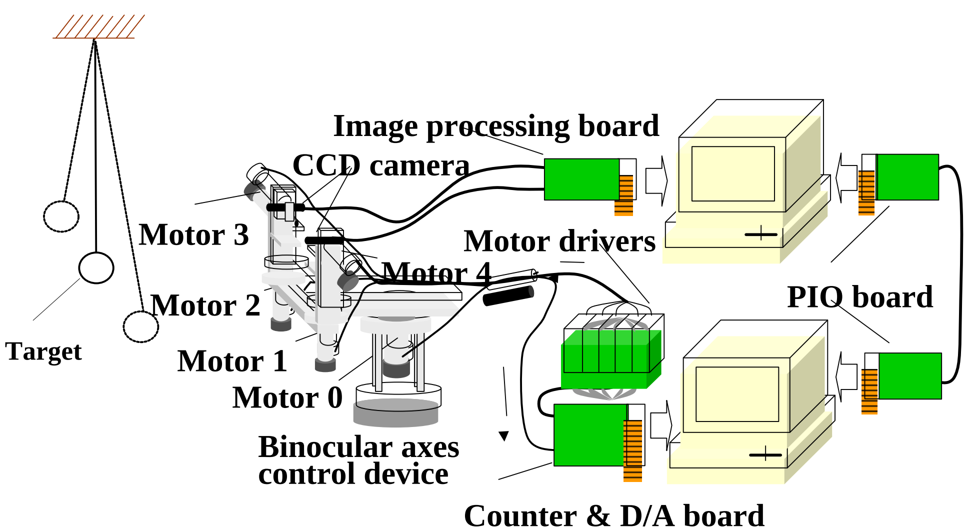
Conjugate

Concluding remarks

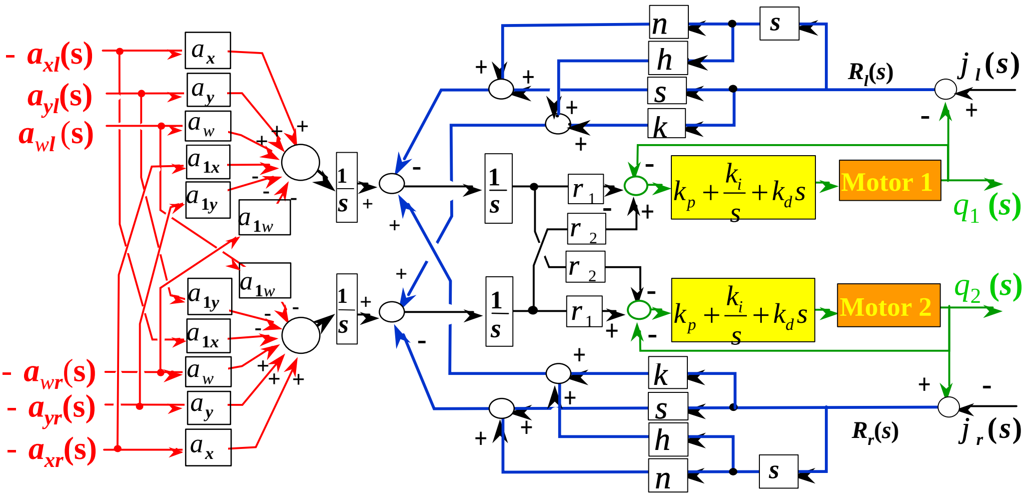
1. **Different transfer function between vergence and conjugate Eye movements.**
2. **Only a single object can be seen by both eyes.**
3. **Elimination of centrifugal force by reciprocal neural paths.**
4. **Principle of straightforward VOR was clarified.**

Application to industrial system

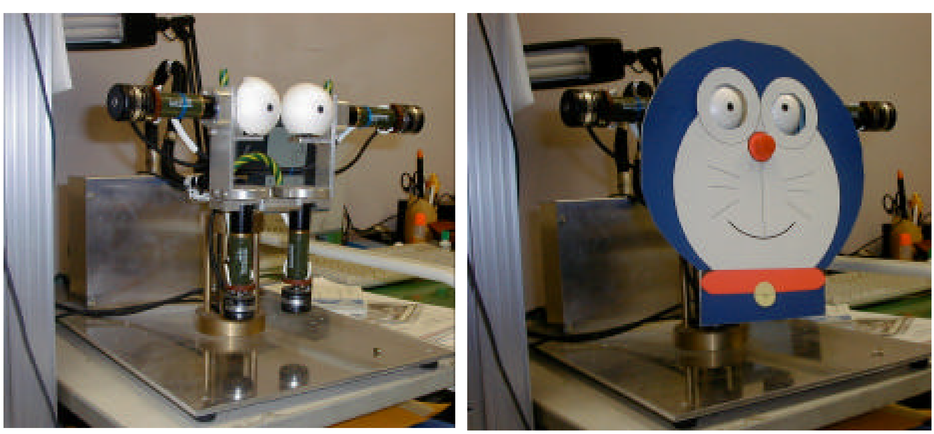
Application of biological binocular motor system to eye robot



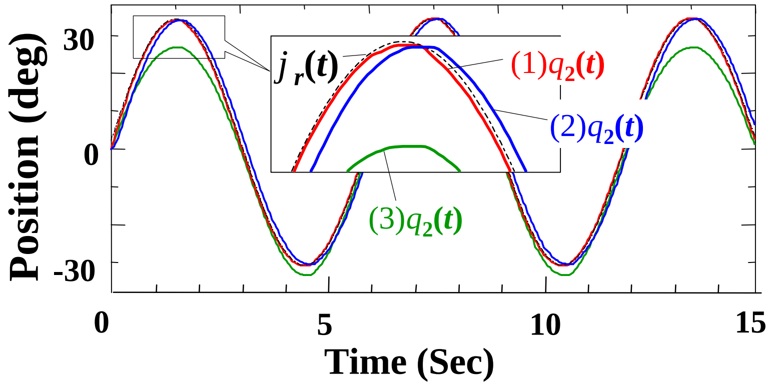
Eye robot based on binocular axes control system



Block diagram of the binocular axes control system



Binocular eye robot control system

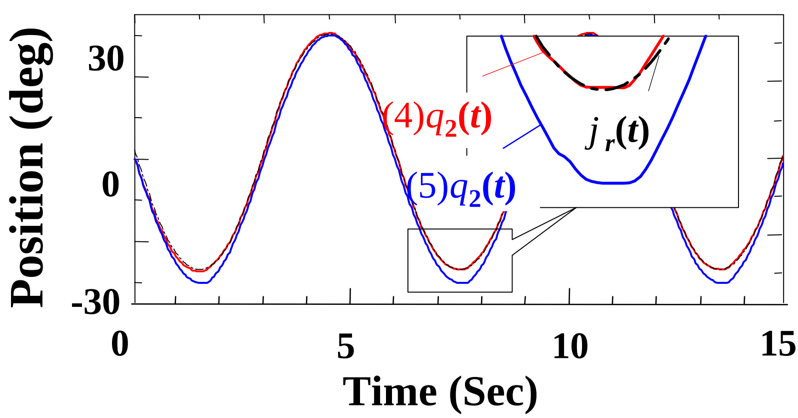


Response of the binocular eye robot control system

(1) fixed target and rotating head,

(2) fixed head and rotating target,

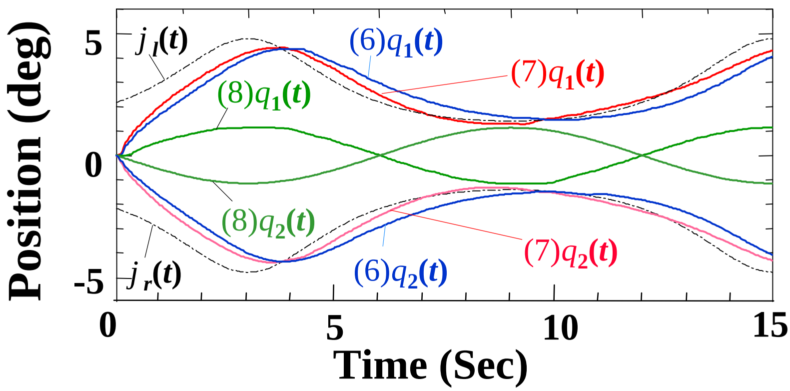
(3) rotating head in a dark environment



Response of the binocular eye robot control system

(4) fixed target and moving head in *y*-direction,

(5) moving head in *y*-direction in a dark environment.



Response of the binocular eye robot control system

(6) fixed head and moving target in *x*-direction,

(7) fixed target and moving head in *x*-direction,

(8) moving head in *x*-direction in a dark environment.

Concluding remarks

1. **Different eye movement from conventional industrial eye**

2. **Adaptive control systems coping with some defects**

3. **Accurate measurement of distance**

Future view

1. Diagnosis of eye movement

2. Pathology and Adaptation
   physiological functions caused
   by some defects and injuries

3. Virtual reality
   Accurate measurement of position
   from target