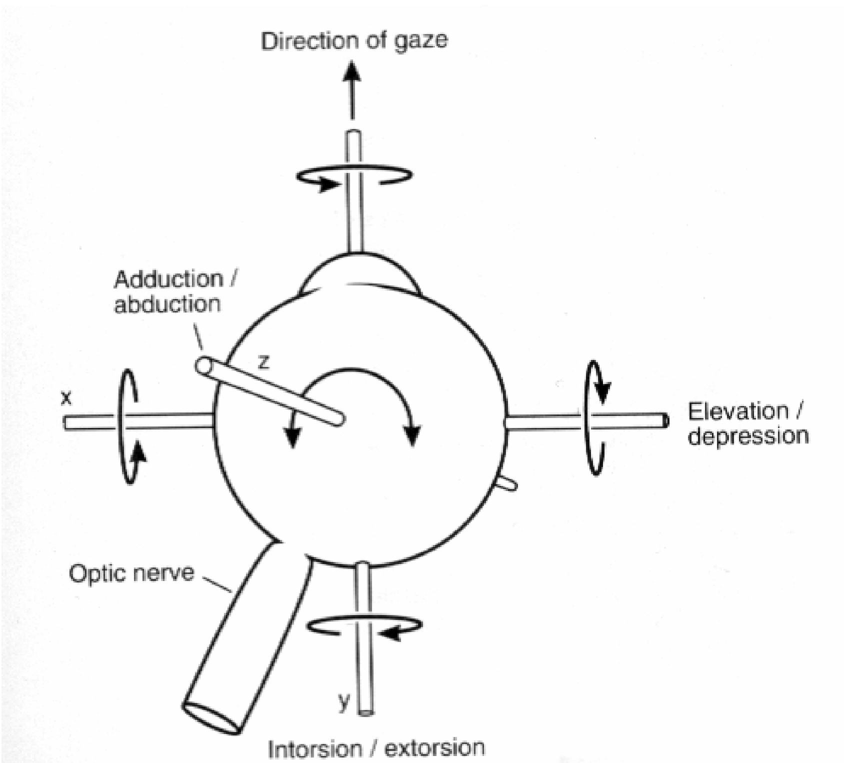
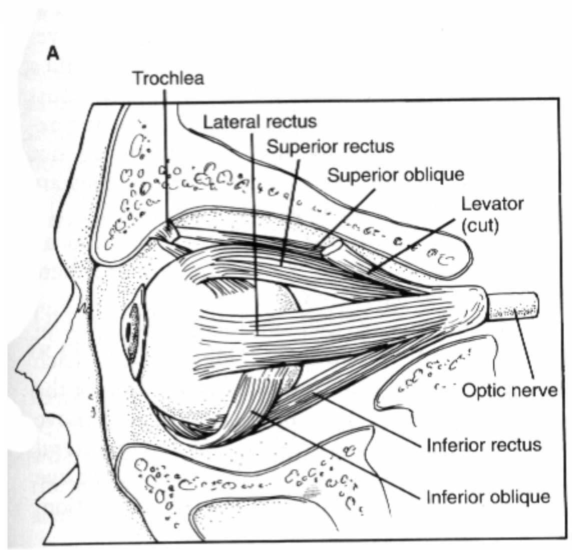
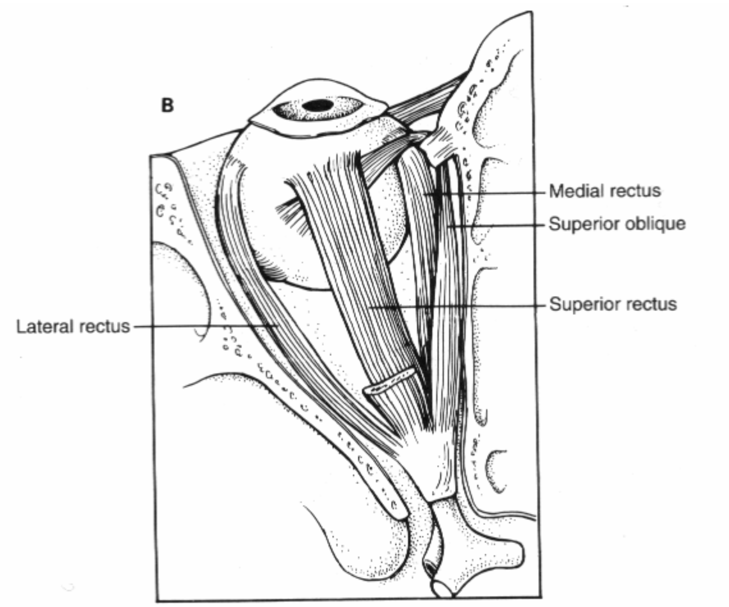
Eye movements

- We detect objects over a visual angle of 200^0, but the high resolution part of the retina (the *fovea*) is only 1^0 of the visual field
- The oculomotor system has two major functions:
  1. to bring targets onto the fovea
  2. to keep them there
- It is relatively simple (only 6 muscles for each eye, and 5 types of movement)


Direction of gaze
Adduction / abduction
z
x
Elevation / depression
Optic nerve
y
Intorsion / extorsion


A
Trochlea
Lateral rectus
Superior rectus
Superior oblique
Levator (cut)
Optic nerve
Inferior rectus
Inferior oblique


B
Medial rectus
Superior oblique
Superior rectus
Lateral rectus

Five types of eye movements

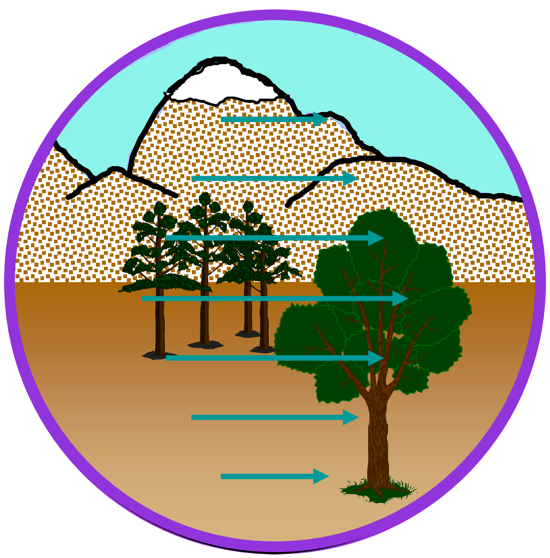
TABLE 43–1. A Functional Classification of Eye Movement

Eye movement	Function
	Movements that stabilize the eye when the head moves
Vestibulo-ocular	Uses vestibular input to hold images stable on the retina during brief or rapid head rotation
Optokinetic	Uses visual input to hold images stable on the retina during sustained or slow head rotation
	Movements that keep the fovea on a visual target
Saccade	Brings new objects of interest onto the fovea
Smooth pursuit	Holds the image of a moving target on the fovea
Vergence	Adjusts the eyes for different viewing distances in depth

Vestibulo-ocular and Optokinetic Reflexes

- Vestibular-ocular reflex (VOR). During head movements in any direction the vestibular labyrinth signals how fast the head is rotating, the oculomotor system responds by rotating the eyes at an equal and opposite velocity → this stabilizes the eyes relative to the external world and keeps visual images fixed on the retina
- The VOR is almost always active, it allows us to see clearly when we are moving (external or self motion)

- the Optokinetic Reflex (OKR) uses visual information (visual motion) to complement the VOR
- OKR has long latency (~60-100ms), respond better to slow movement
- VOR has short latency (~14ms), respond well to fast movement, but somewhat insensitive to slow motion



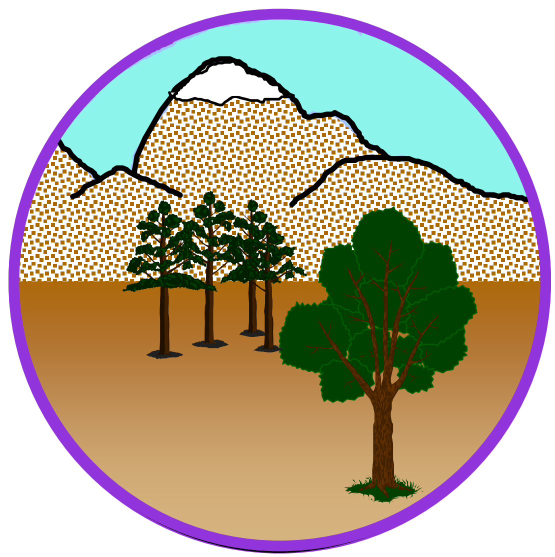
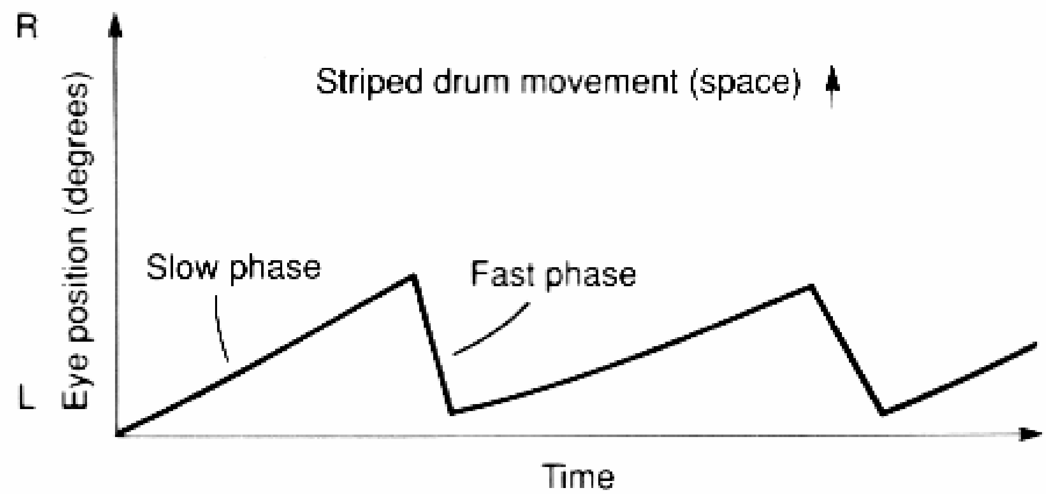


FIGURE 43–2
The optokinetic reflex. A human's horizontal eye position as he sits still inside a vertically striped drum rotating slowly to his right. Eye position is plotted against time. Note that during the slow phase the eyes move in the same direction as the striped drum so as to keep the drum still on the retina.



Smooth pursuit

- Move the eyes to keep a single target on the fovea
- Computes how fast a target is moving, moves the eyes accordingly
- Voluntary movement, but it *requires* a moving target, you cannot make a smooth pursuit movement without a real target
- Can be as fast as 100 deg/s

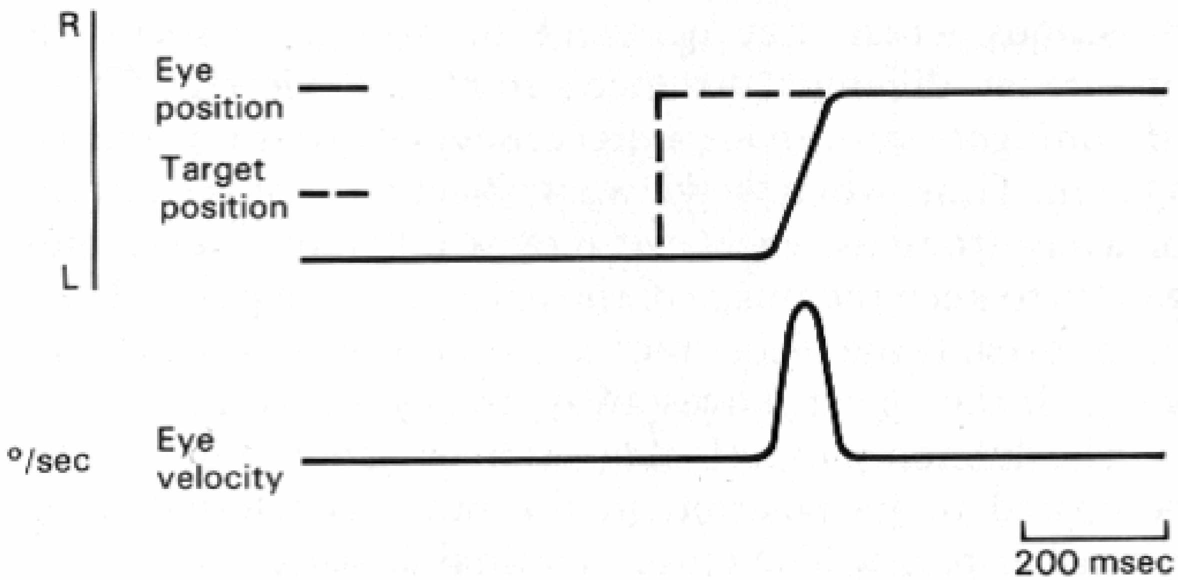
Smooth pursuit alone is not enough for tracking

Figure 4.24. Response to a target moving off at constant velocity: left, response of smooth pursuit system alone leads to a permanent positional lag because of time required for the eye to approach the target velocity; right, diagrammatic representation of how a saccade of appropriate size can eliminate positional error of this kind.

Saccadic eye movements

- Saccadic system points the fovea toward objects of interest, switch of attention or to catch up a fast moving target (when smooth pursuit is not enough)
- Saccades can be made in response to stimuli like sound, tactile or remembered locations in space
- Driven by “retinal error”
- Can be as fast as 900 deg/sec → no time for corrections, open loop

FIGURE 43–4
The saccadic system. A human's eye position as he looks at a spot of light that suddenly jumps to the right. Eye position **(solid line)** and target position **(dotted line)** plotted superimposed against time. Eye velocity is shown beneath. The eye stays still for about 200 ms and then moves rapidly to the new target position. The eye velocity rises and falls smoothly.



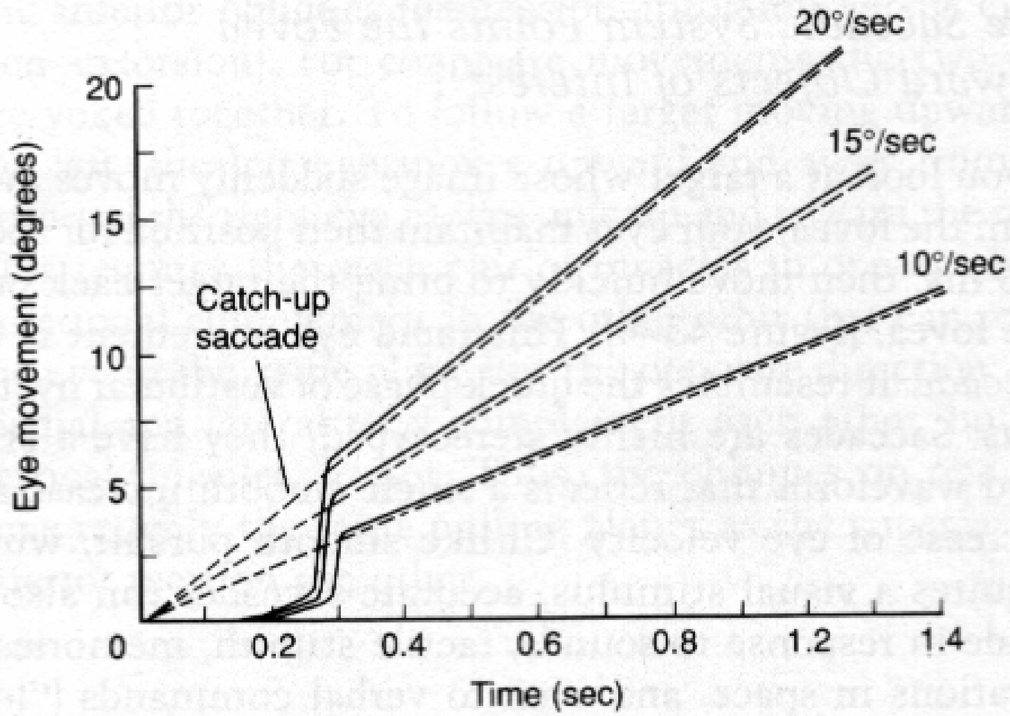


FIGURE 43–3
The smooth pursuit system. A monkey's eye position **(solid line)** plotted against time as he follows a target **(dotted line)** that begins to move at time 0. Note that the monkey makes a rapid movement (saccade) to catch up to the target and then follows it with an eye movement that has the same speed as the target. Pursuit is shown for three different target speeds. (Adapted from Fuchs, 1967.)

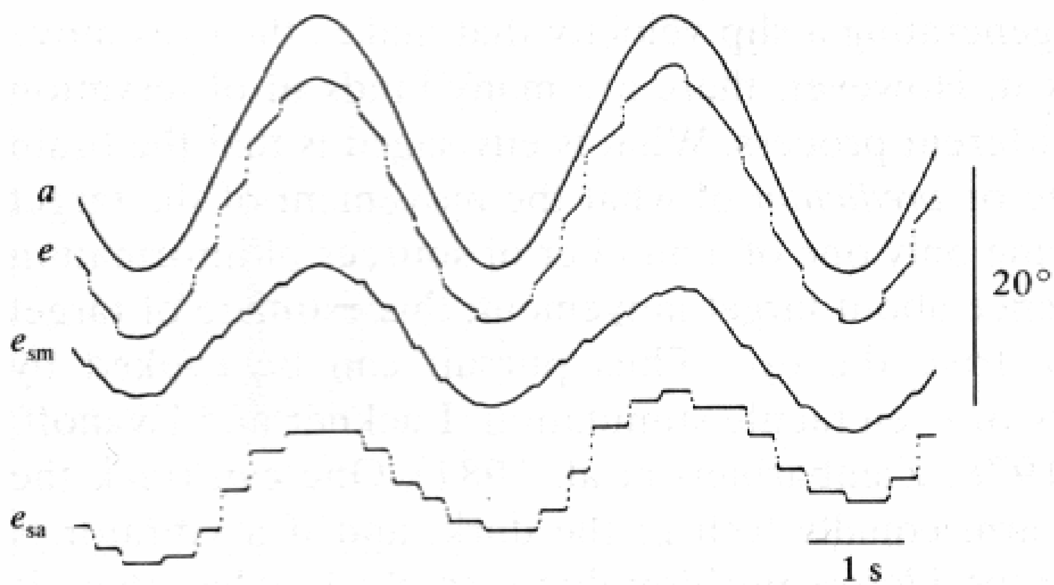
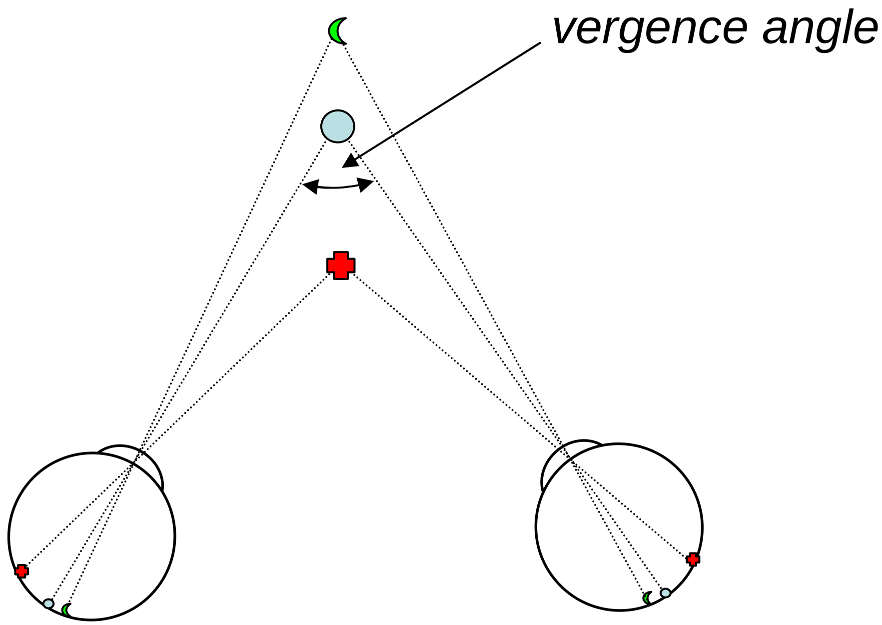
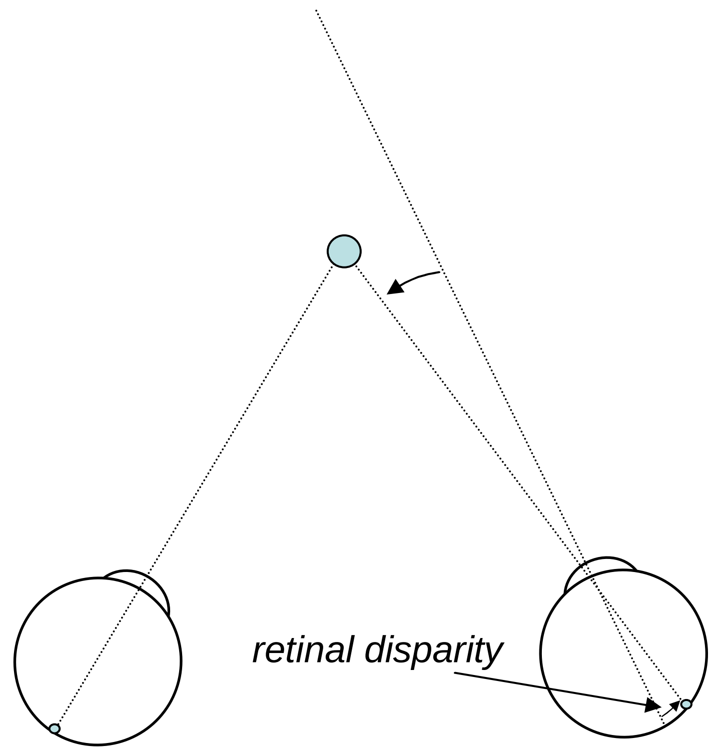


Figure 3.16. The separation of smooth and saccadic components of foveal tracking. *a*, target position; *e*, eye position; e_{sm}, cumulative eye position obtained by removal of saccades; e_{sa}, the isolated saccadic component (after Collewijn and Tamminga, 1984).

Vergence

- Aligns the eyes to look at targets with different depths
- VOR/OKR Smooth Pursuit and Saccades are *conjugate m*ovements → both eyes move in the same directions
- During vergence movements the eyes move in opposite directions to keep the image of the target aligned perfectly on each fovea (*disconjugate movement*)
- Linked to *accomodation*





Binocular disparity drives vergence

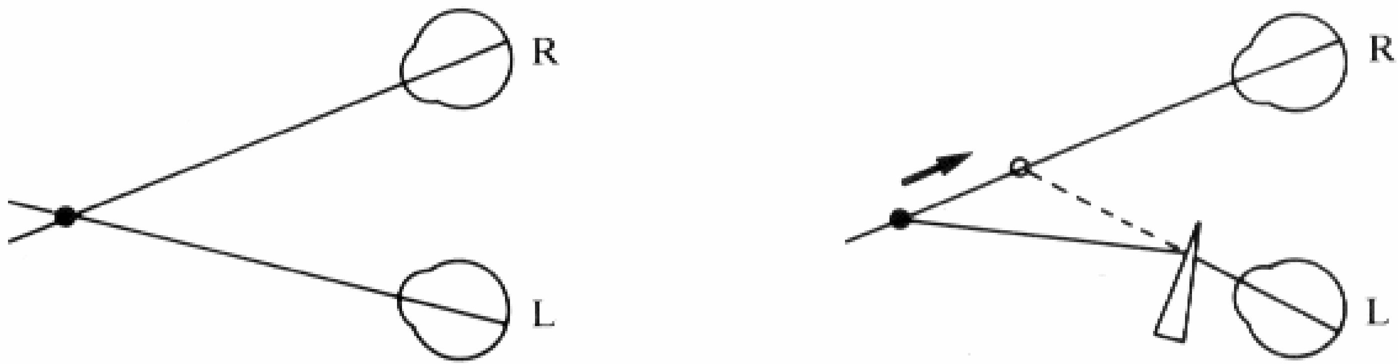


Figure 5.3. Prism vergence: introducing a weak prism in front of one eye when both are binocularly fixating necessitates unilateral vergence to bring the two retinal images back into correspondence.

Accommodation drives disparity

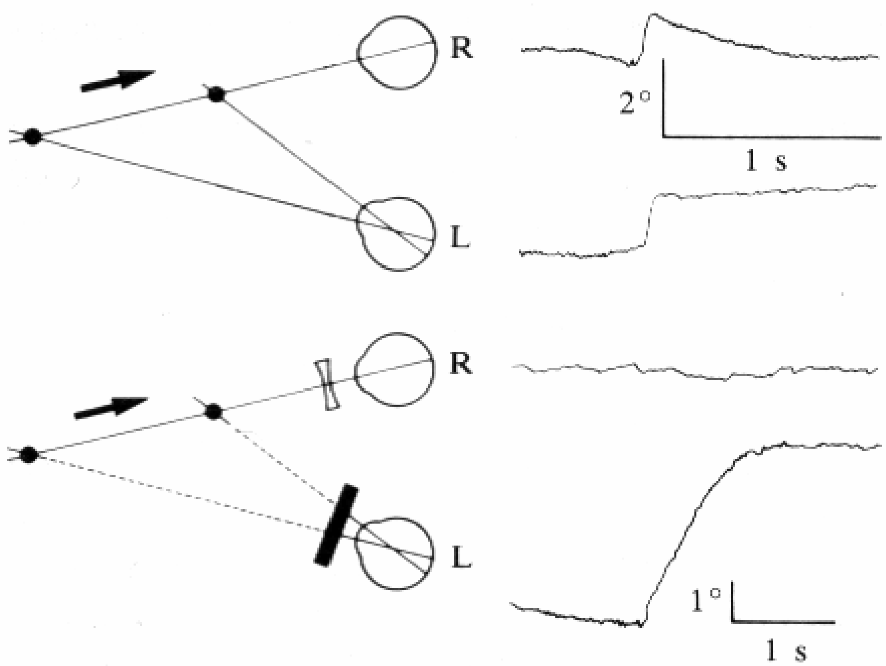


Figure 5.5. Asymmetrical convergence: above, under normal binocular viewing conditions, movement of the fixation point along the line of sight of one eye results in a mixed conjunct and disjunct movement of both. Below, if the eye which has to move is covered, then it alone moves in a simple monotonic manner: this is pure *accommodation convergence* (data from Alpern and Ellen, 1956; Alpern, 1957).

Saccades and Vergence

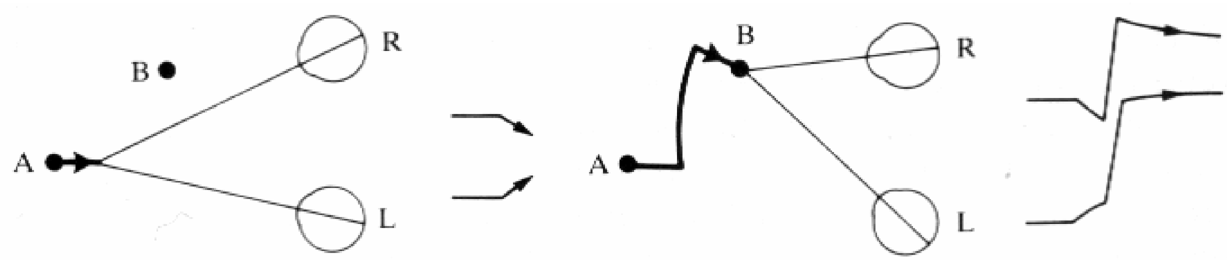


Figure 5.22. The sequence of events in a mixed vergence and version movement. The thick line on the left in each diagram shows the locus traced out by the point of fixation; on the right of each diagram, the time course of the movement of each eye is plotted separately.

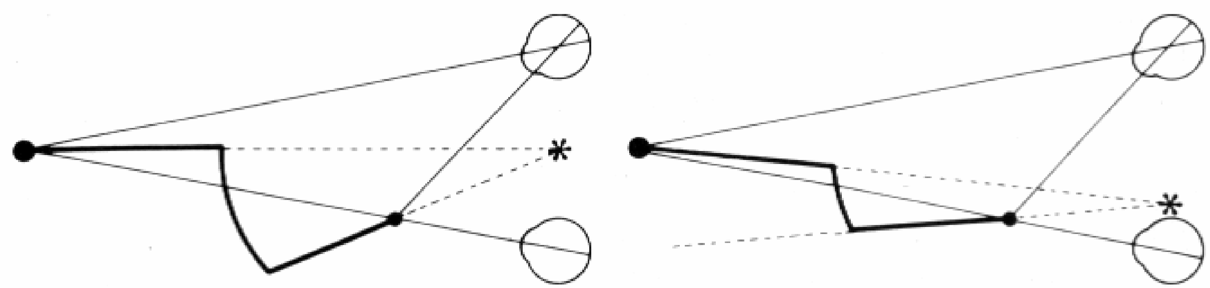
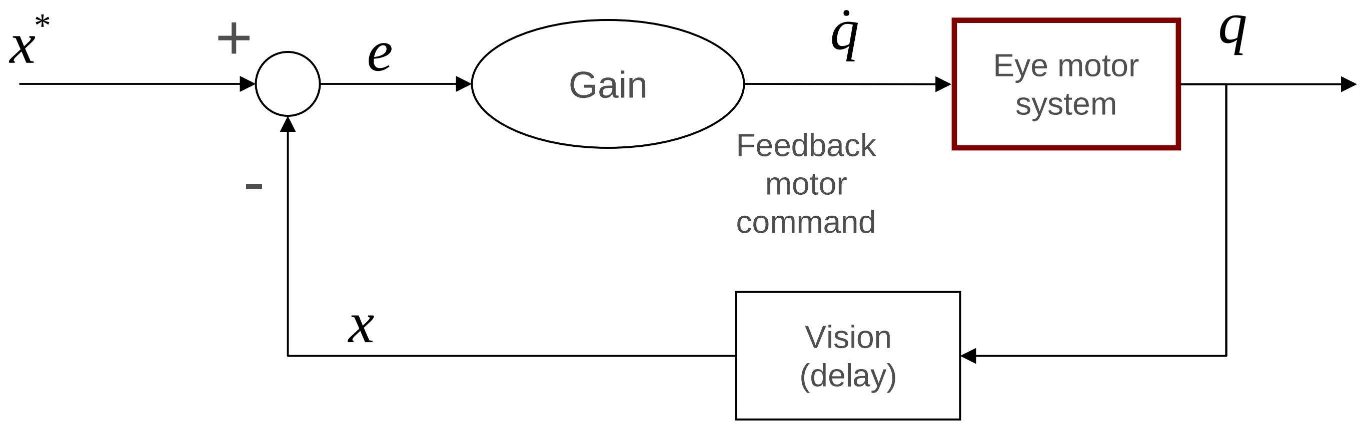
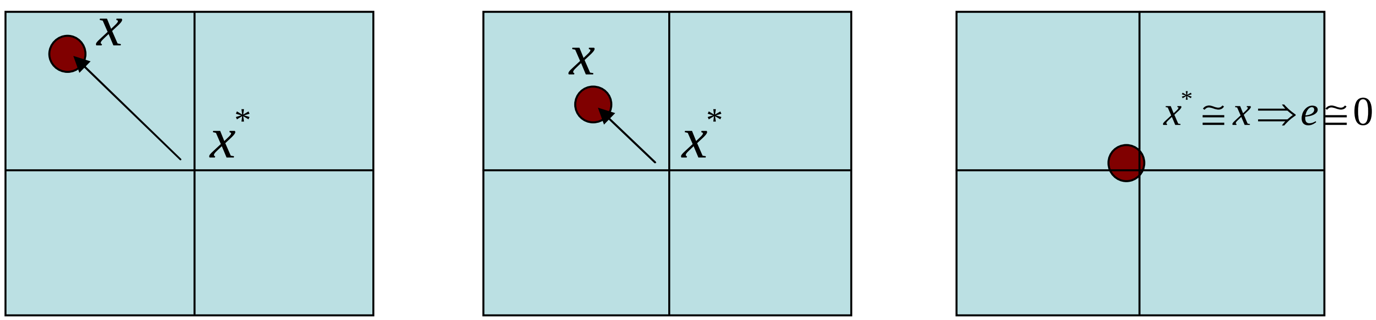


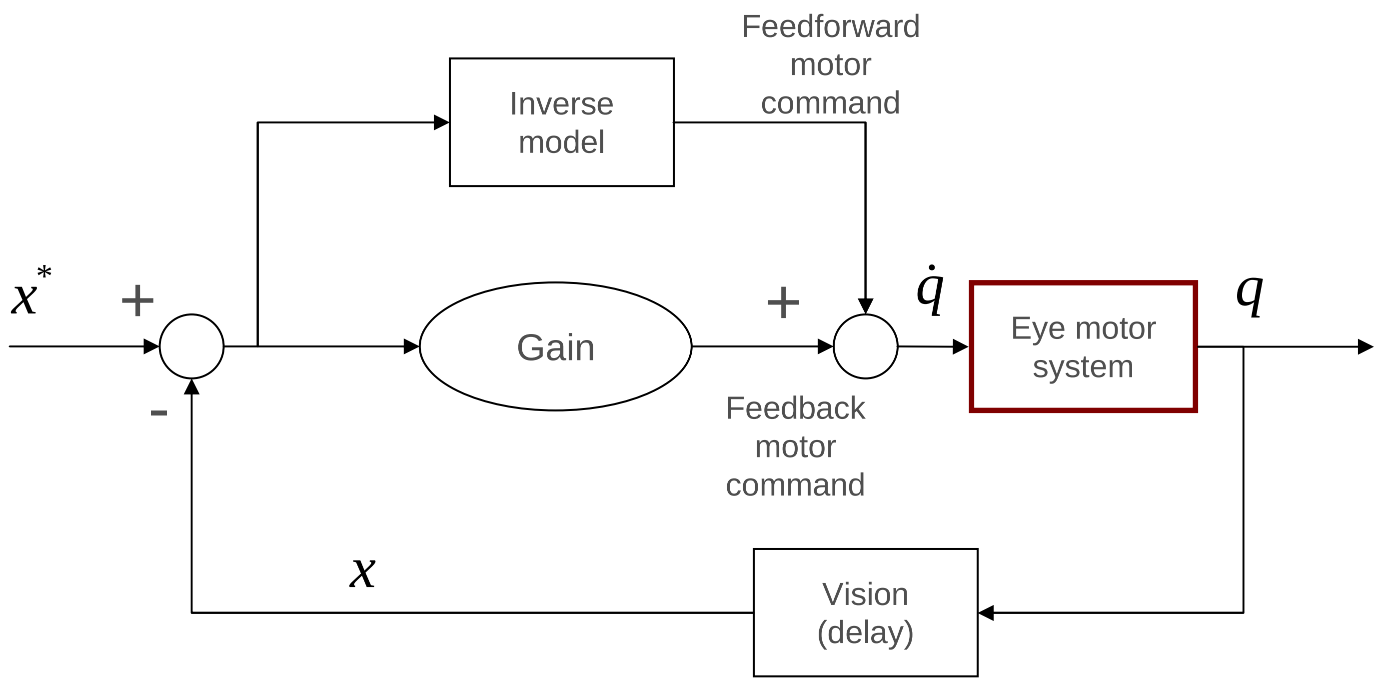
Figure 5.23. Mixed vergence and version with unequal contributions of the two eyes. On the left, the fixation locus (as in figure 5.22) when the eyes contribute equally to vergence: on the right, when the left eye is dominant and contributes less to vergence. The asterisk shows the position of the binoculus in each case.

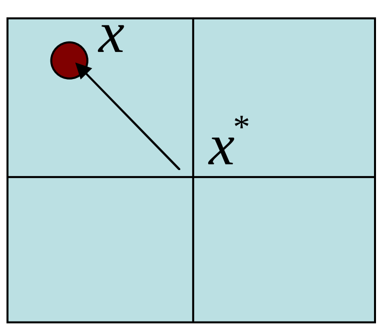
Robotic Example: eye movements



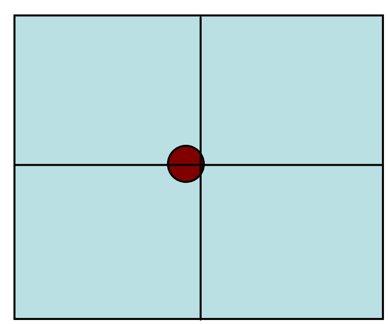


Saccadic movements



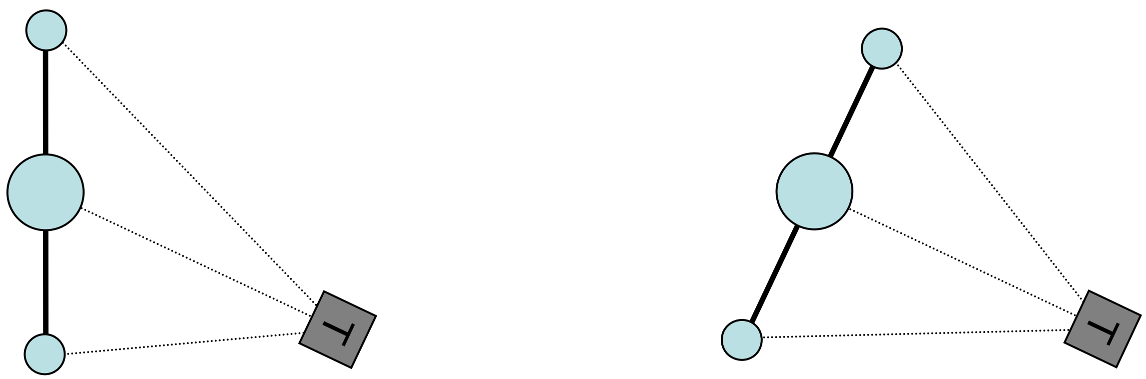


$$\Delta q = f(x^* - x)$$



The Neck?

- Redundant degrees of freedom:



- Possible solution, try to reduce (zero) the difference between the angles of the eyes:

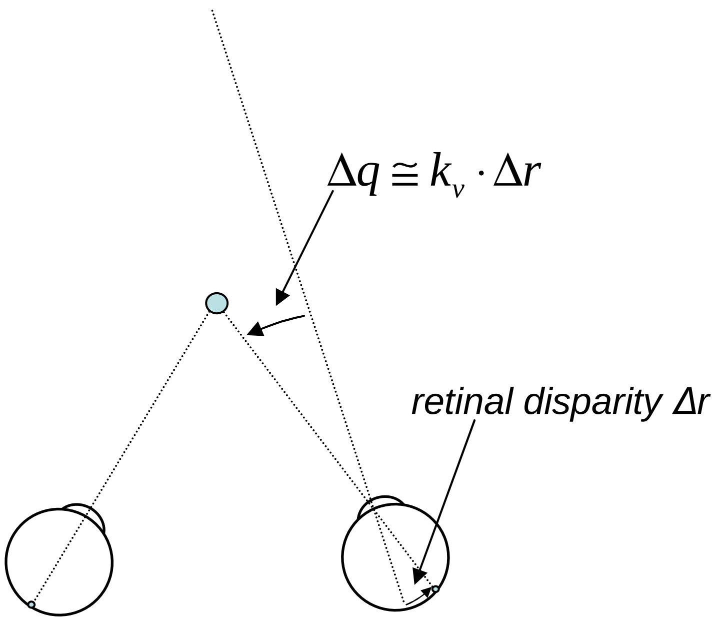
$$\dot{q}_{neck} = K_p \cdot \left(q_{left\_eye} - q_{right\_eye} \right)$$

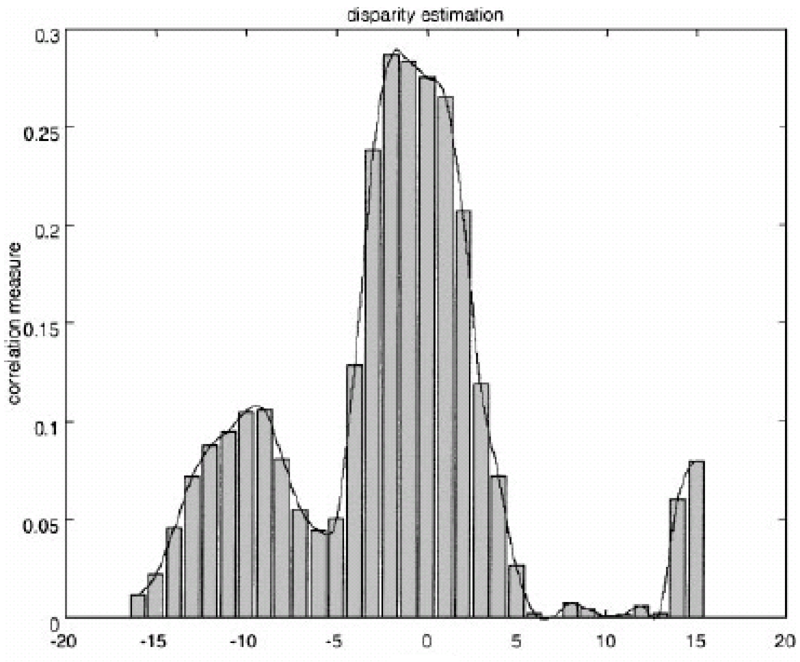
Vergence Control

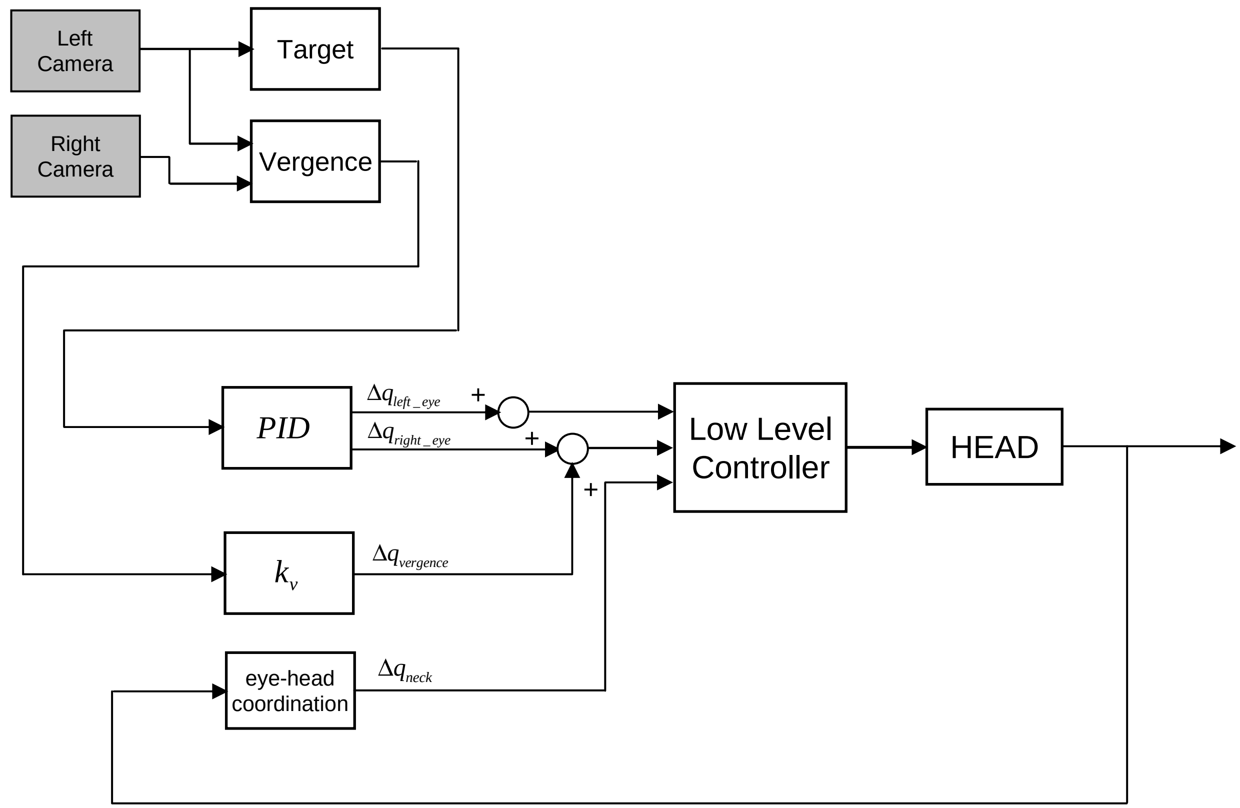
- Rotate one of the eye of an amount proportional to the retinal disparity
- Maximize the similarity between the two images:

$$s(d) = \Delta\left(I_r(x+d, y), I_l(x, y)\right)$$

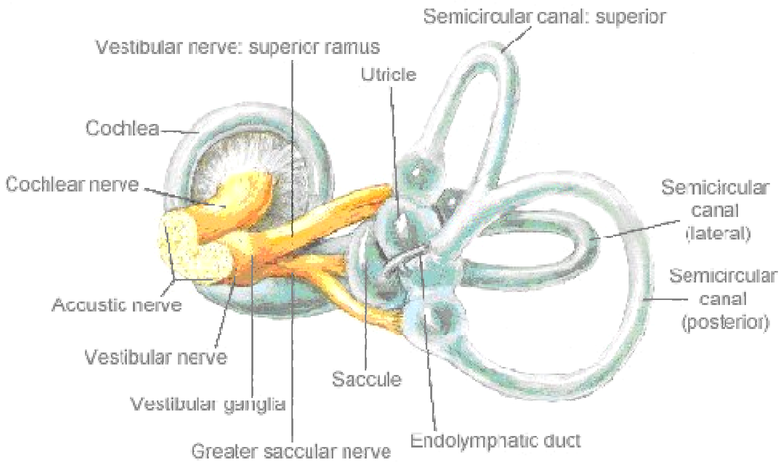
where Δ is a similarity measure like SSD or normalized correlation

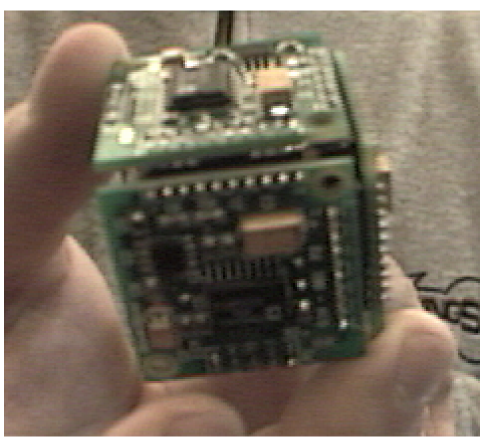


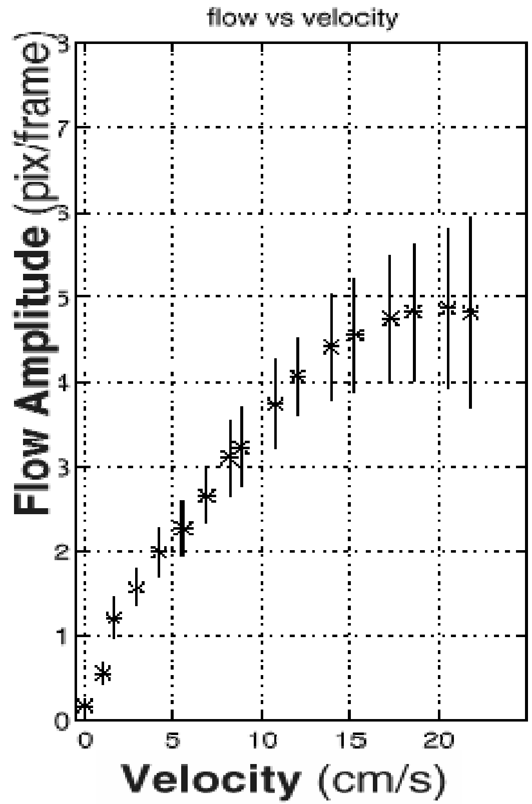



Left Camera
Right Camera
Target
Vergence
PID
Δq_{left_eye}
Δq_{right_eye}
+
+
+
k_v
$\Delta q_{vergence}$
eye-head coordination
Δq_{neck}
Low Level Controller
HEAD

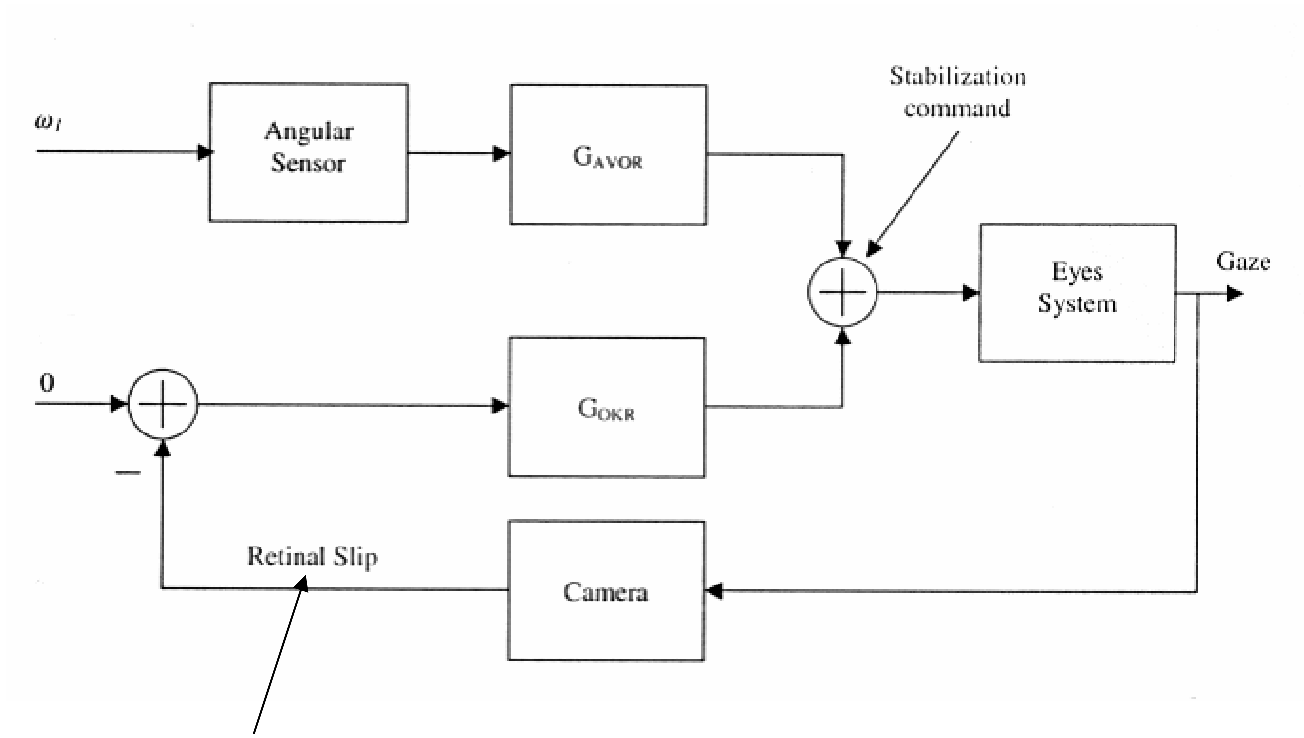
The artificial vestibular system





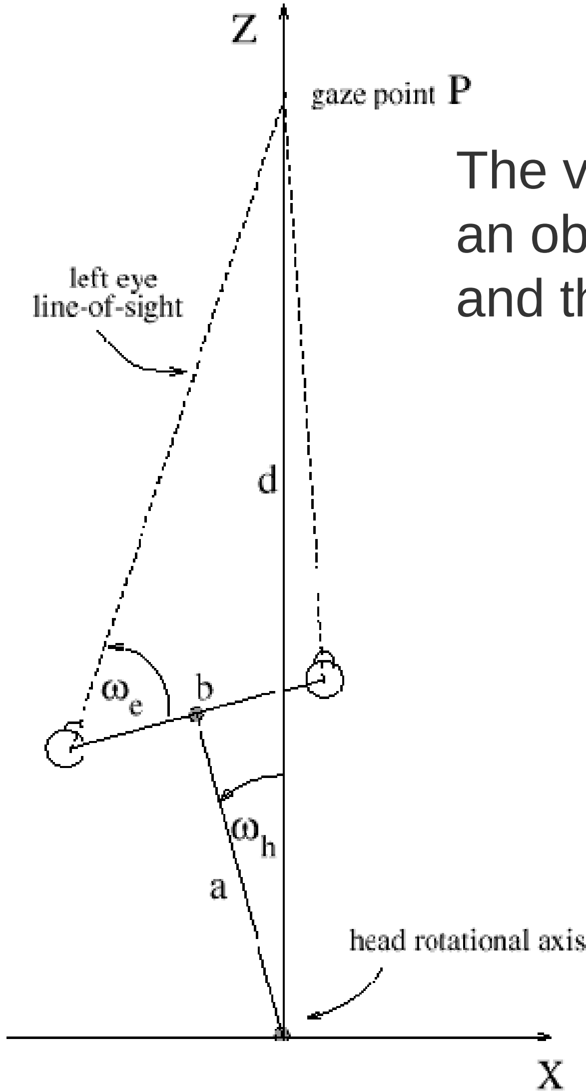


Simple method for image stabilization

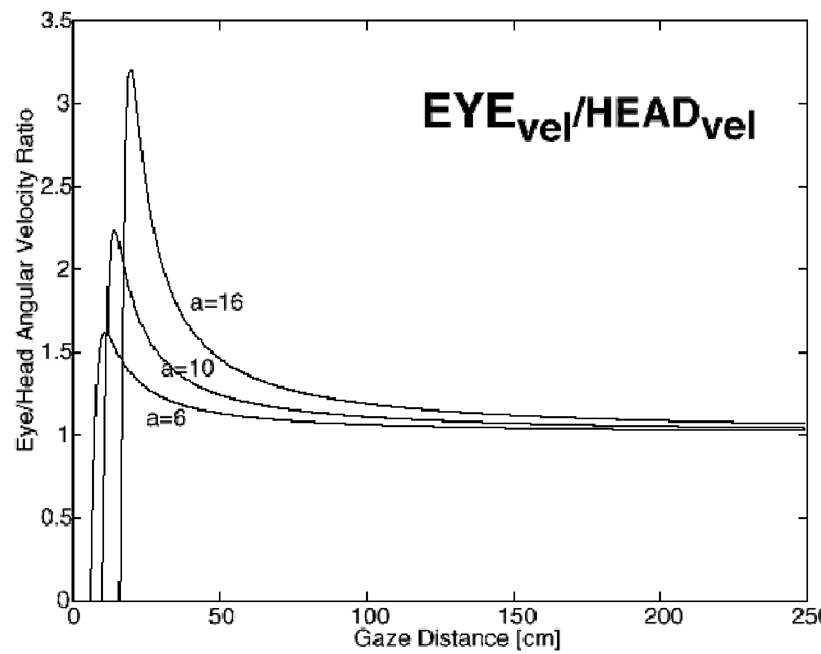


u component, optical flow

VOR kinematics



The velocity required to stabilize the image of an object depends on geometric parameters and the distance of the fixation point

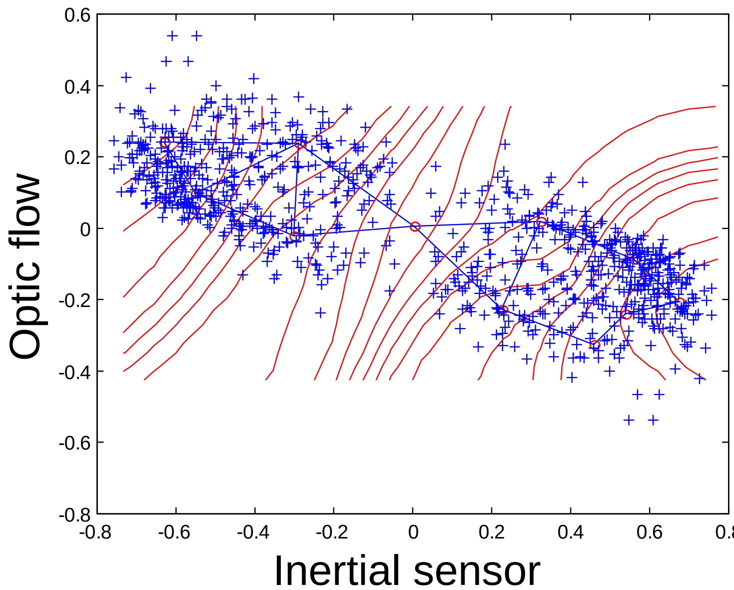


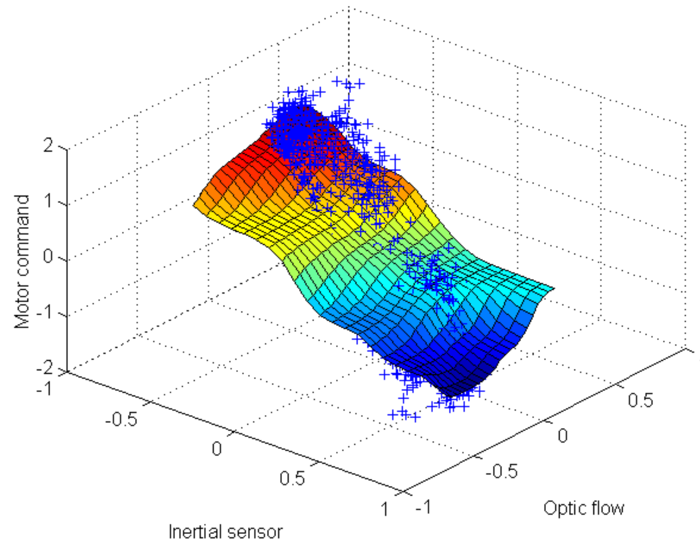
Compensatory eye movements

$$\frac{u_0}{f_x} = -\frac{T_x}{z(0,0)} - (\omega_y + \xi)$$

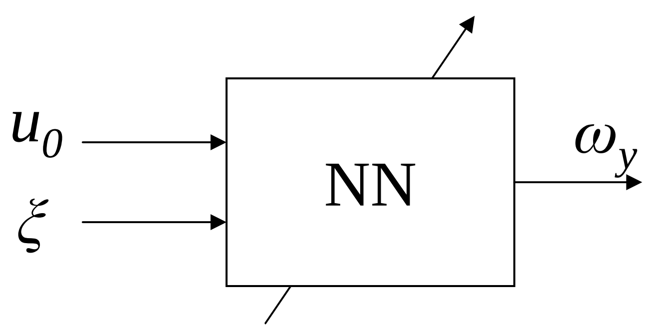
- The image is stable when the optical flow is zeroed
- Performance. Sensed by estimating the optical flow u_0
- Disturbances sensed by means of an inertial device (gyroscope) ξ
- Compensation is obtained by moving the eye: ω_y

Neural network results





RBF, Gaussian kernel



Learning…