Corso di Percezione Robotica (PRo)

C. Modulo di Percezione

Fondamenti di visione artificiale retinica

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Sommario della lezione

- Principi di base della visione retinica
- Alcune proprietà delle immagini retiniche
- Le relazioni matematiche tra immagini retiniche e cartesiane
- La foveazione
- Una testa robotica antropomorfa
- Esempi di applicazione in robotica

Riferimenti bibliografici:

G. Sandini, G. Metta, "Retina- like sensors: motivations, technology and applications". in Sensors and Sensing in Biology and Engineering. T.W. Secomb, F. Barth, and P. Humphrey, Editors. Springer-Verlag. 2002.

Principi di base della visione retinica

Standard image

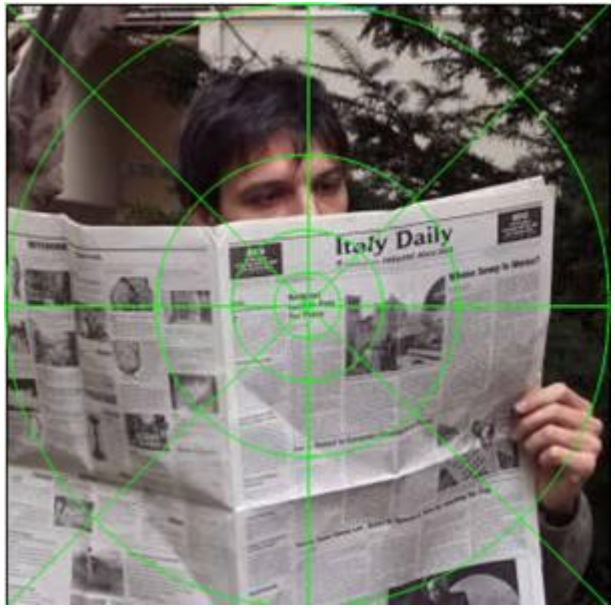
Retina-like image

Log-polar image (magnified to 200% for display)

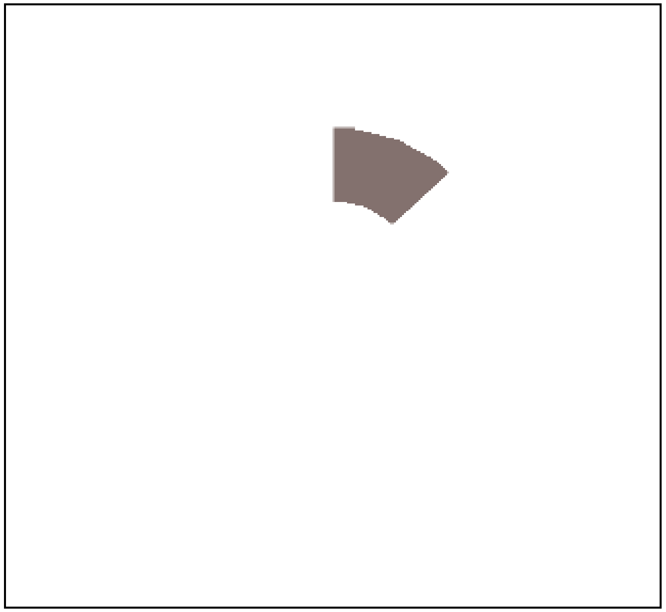
Log-polar projection

Costruzione di un'immagine retinica

Immagine cartesiana tradizionale



Divisione in circonferenze e spicchi

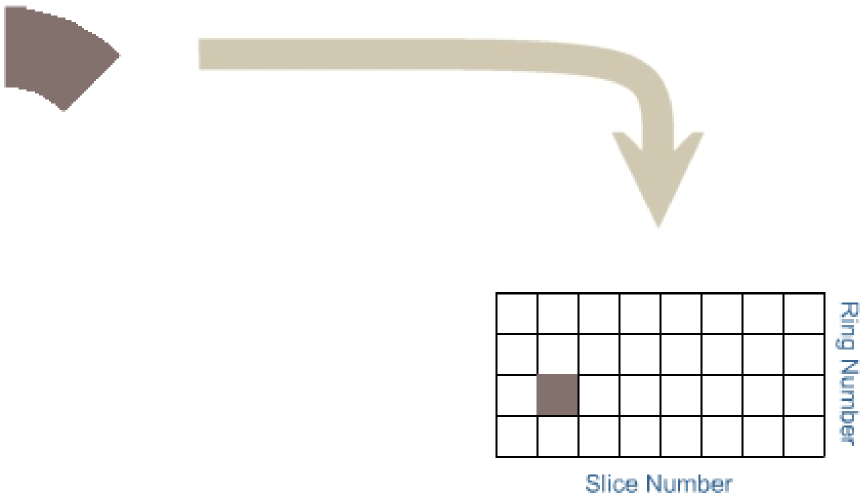


Calcolo del valore medio di un settore

http://www.retinica.com/

Costruzione di un'immagine retinica

http://www.retinica.com/

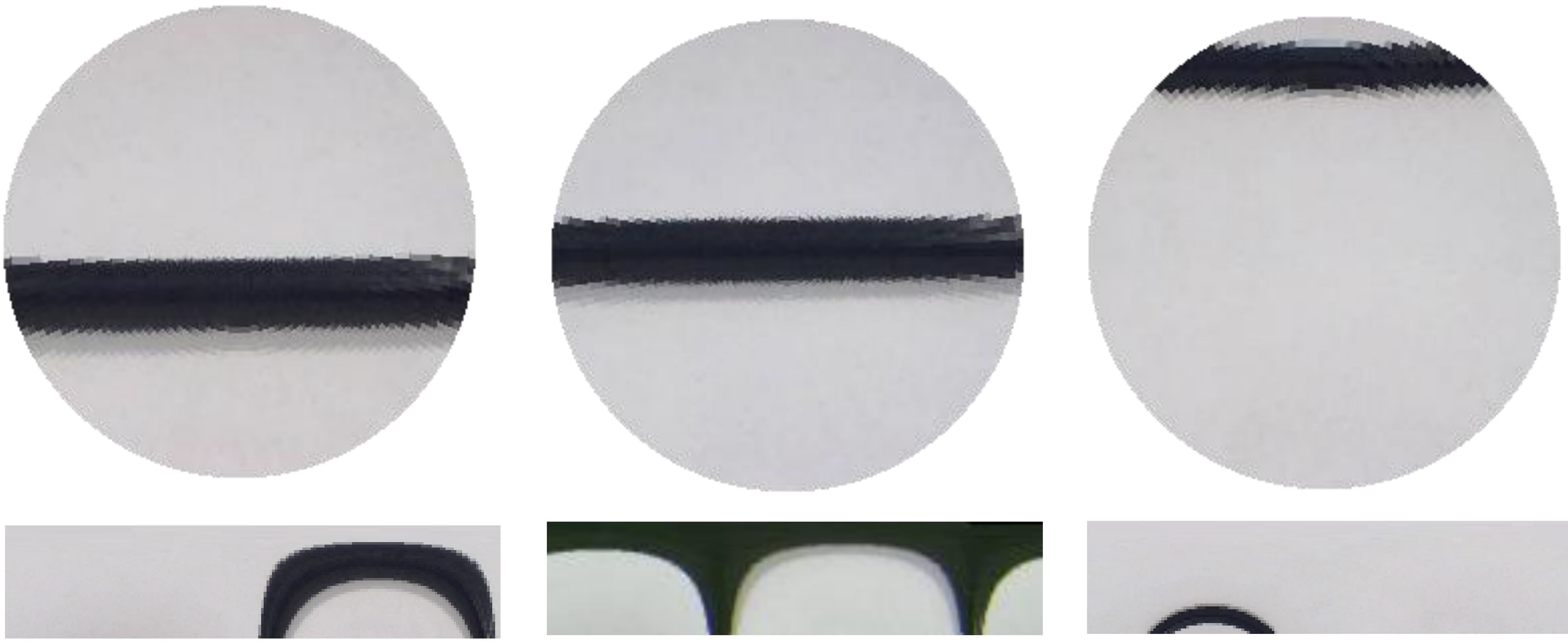


Copia del valore medio di un settore
in un pixel di un'immagine polare

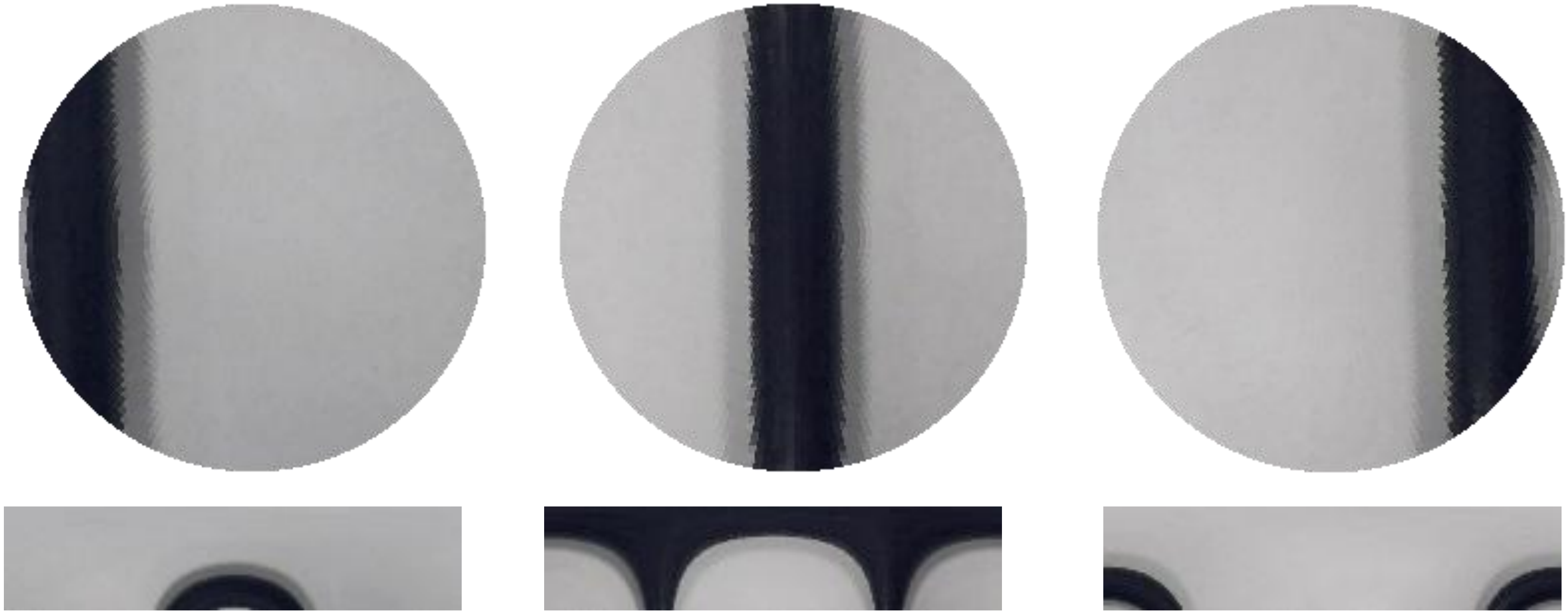
Immagine polare risultante

Immagine cartesiana
ricostruita dalla polare

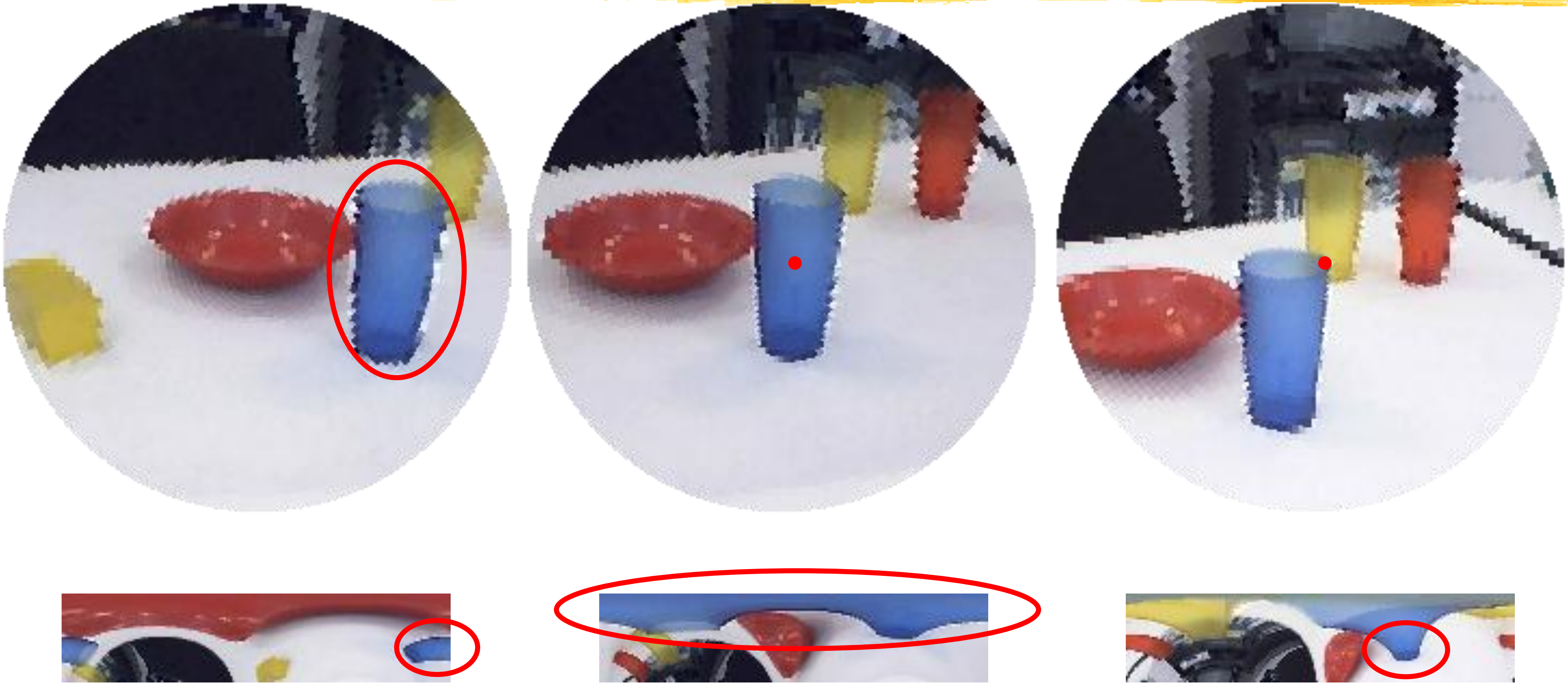
An example of pattern translation



An example of pattern translation



An example of simulated foveation

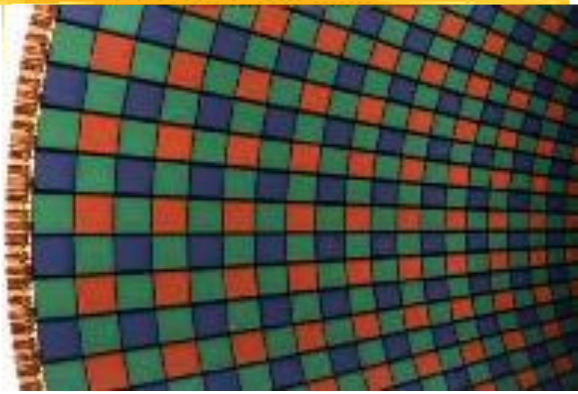


Object detection in the periphery

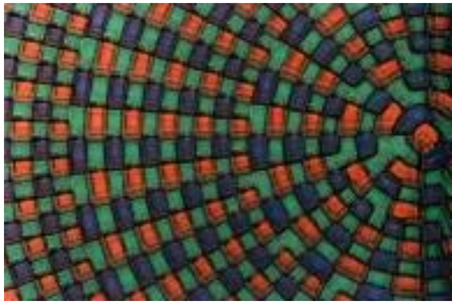
Object foveation

Foveation of a point of interest (edge)

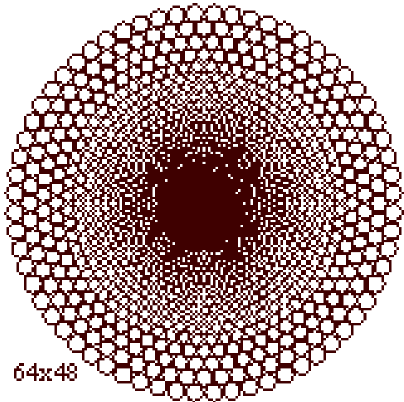
The Retina-like Giotto cameras



- Technology: 0.35 micrometer CMOS
- Total Pixels: 33193
- Geometry:
  - 110 rings with 252 pixels
  - 42 rings with a number of pixels decreasing toward the center with a "sunflower" arrangement



- Tessellation: pseudo-triangular
- Pixels: direct read-out with logarithmic response
- Size of photosensitive area: 7.1mm diameter
- Constant resolution equivalent: 1090x1090
- On-chip processing: addressing, A/D, output amplifier



Le relazioni matematiche

From standard image to log-polar image

$$\rho(x,y)=\begin{cases}(F-1)+\log_{\lambda}\left[\left(F-\tfrac{1}{2}-\sqrt{x^2+y^2}\right)(1-\lambda)+\lambda\right] & \text{if } \sqrt{x^2+y^2}>\left(F-\tfrac{1}{2}\right)\\ \left(\sqrt{x^2+y^2}+\tfrac{1}{2}\right) & \text{if } \sqrt{x^2+y^2}<\left(F-\tfrac{1}{2}\right)\end{cases}$$

$$r(\rho)=\left[\left(F-\tfrac{1}{2}\right)+\lambda\frac{1-\lambda^{\rho-F}}{1-\lambda}\right] \text{ if } \rho>F$$

$$\theta(x,y)=\frac{\Theta}{2\pi}\cdot\arctan\left(\frac{y}{x}\right)+\frac{\Theta}{2}+\text{Shift Factor}$$

$F=42$
$P=152$
$\Theta=252$
$X=545$
$Y=545$
$\lambda=1.02314422608633$

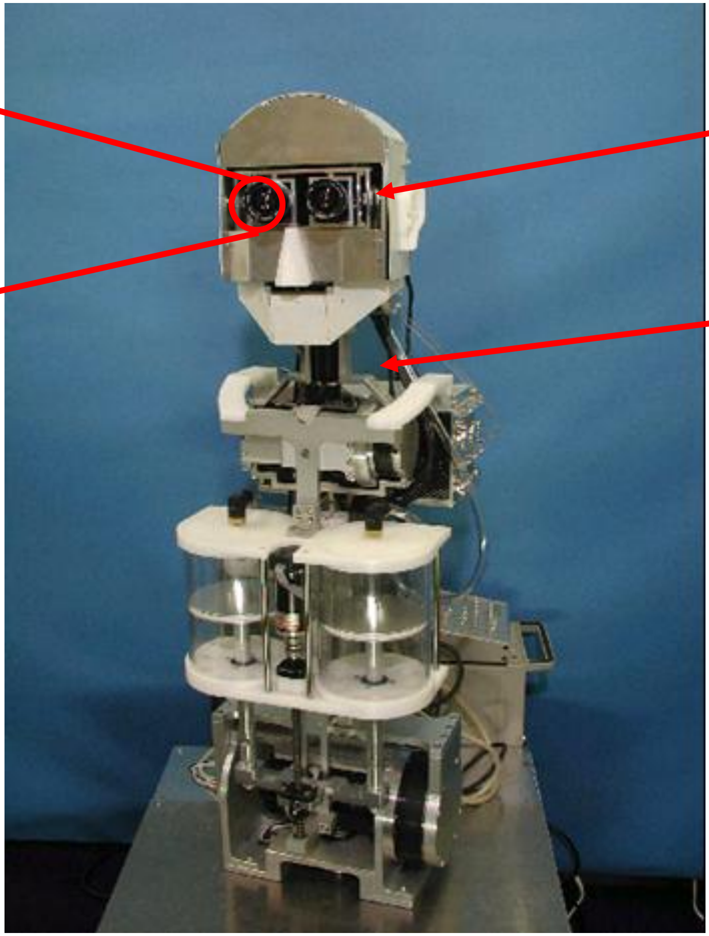
$F=$ size of the fovea in rings.
$P=$ total number of rings.
$\Theta=$ maximum # of pixels in each ring.

$2X=$ horizontal size of the cartesian image.
$2Y=$ vertical size of the cartesian image.
$\rho=$ ring number in the log polar image.
$\theta=$ angular polar coordinate.

Retina-like vision for visuo-motor co-ordination of a robot head

WE-4 robotic head with Giotto cameras

Retina-like Giotto cameras by the University of Genova, Italy



3 dof for eye movements

4 dof for neck movements

WE-4 robotic head by Takanishi Lab, Waseda University, Tokyo, Japan

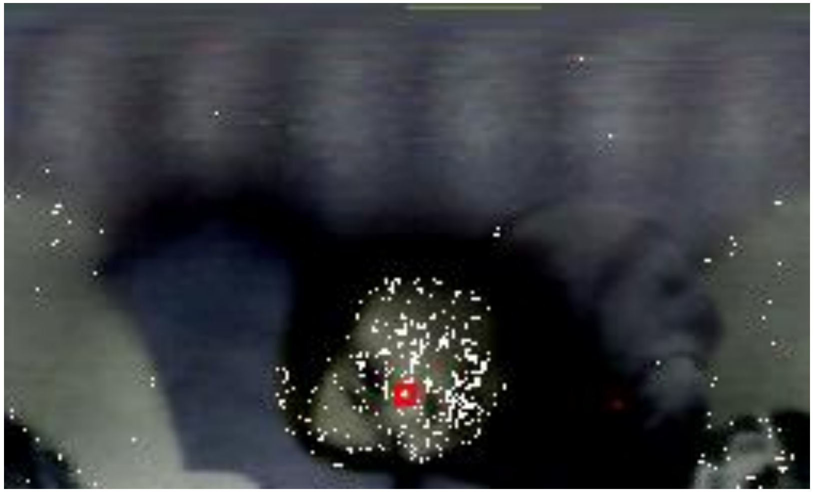
Face detection by hue

Hue = information on the color

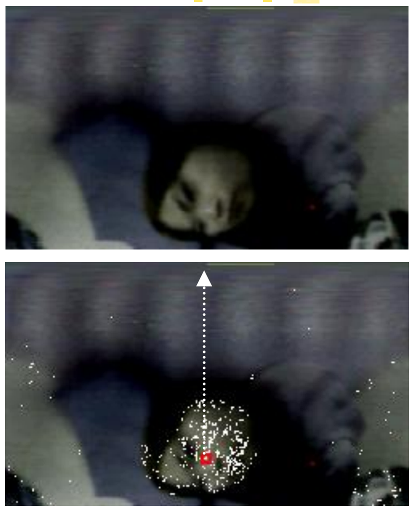
$$Hue = \cos^{-1}\left(\frac{(R-G)+(R-B)}{2\sqrt{(R-G)^2+(R-B)(G-B)}}\right)$$

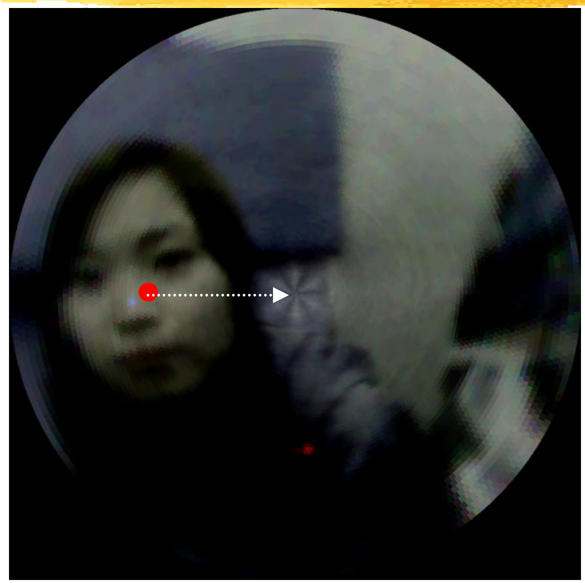
if B>G then Hue = 2π - Hue

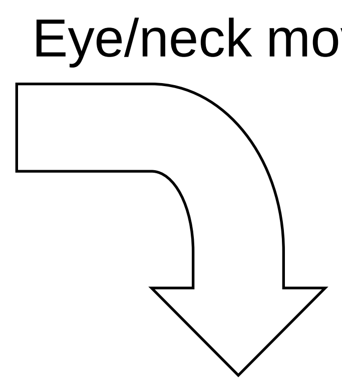
R, G, B = RED, GREEN, BLUE components, respectively



An example of foveation

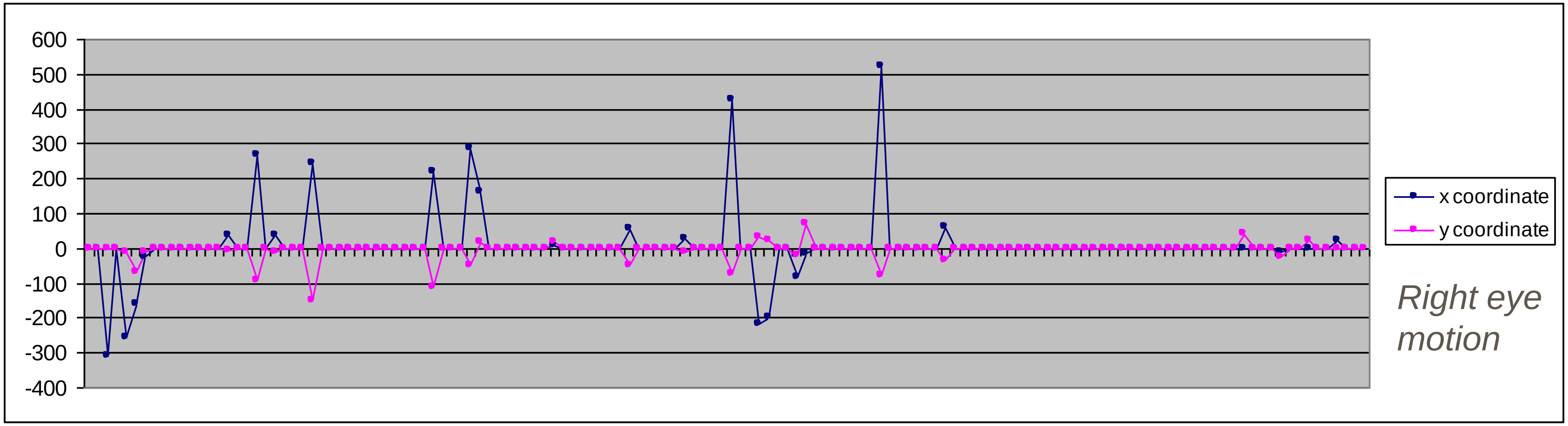






Proportions are rescaled for display purposes

Experimental trials



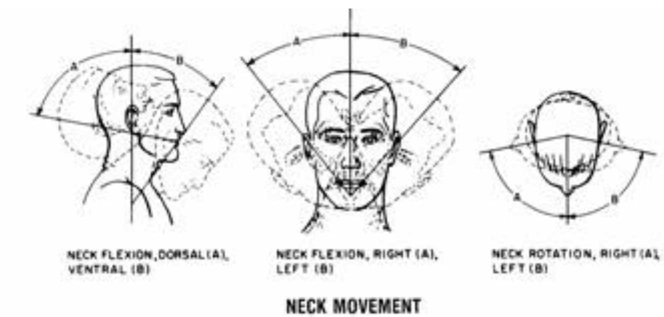
[Cecilia Laschi, Hiroyasu Miwa, Atsuo Takanishi, Eugenio Guglielmelli, Paolo Dario, 2002]

Example of design and development of a human-like robotic head

The ARTS humanoid robot head

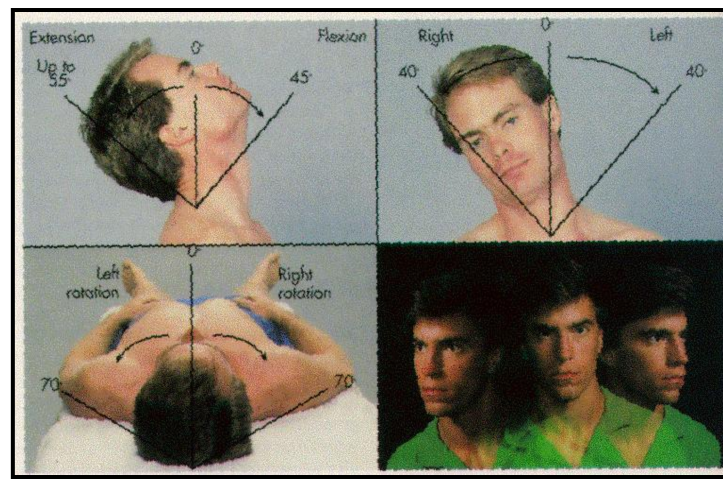
Synthesis of characteristics of the human oculo-motor system

- Eye movements:
  - Saccades
  - Vergence
  - Pursuit
- Ranges of motion:
  - 120° for the tilt eye movements
  - 60° for the pan eye movements
- Eye speed:
  - Up to 900°/sec (in saccades)
- Inter-ocular distance: between 60 and 80 mm



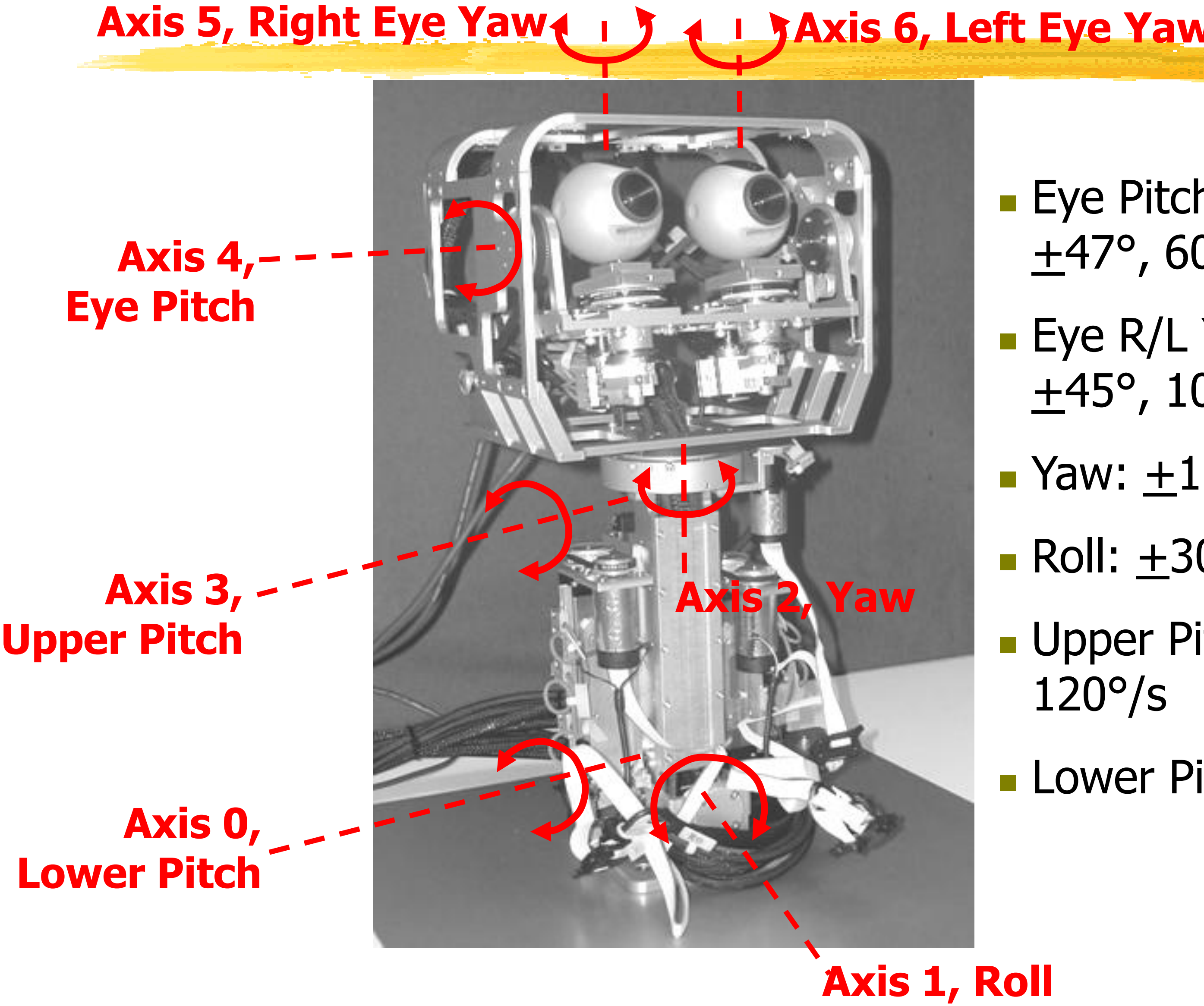
	Average	[illegible]
Ventral flexion	60°	[illegible]
Dorsal flexion	61°	[illegible]
Right-left flexion	41°	[illegible]
Right-left rotation	79°	[illegible]

RANGE OF MOVEMENT AT THE NECK JOINT*
*Male civilians.



[Thibodeau & Patton, 1996]

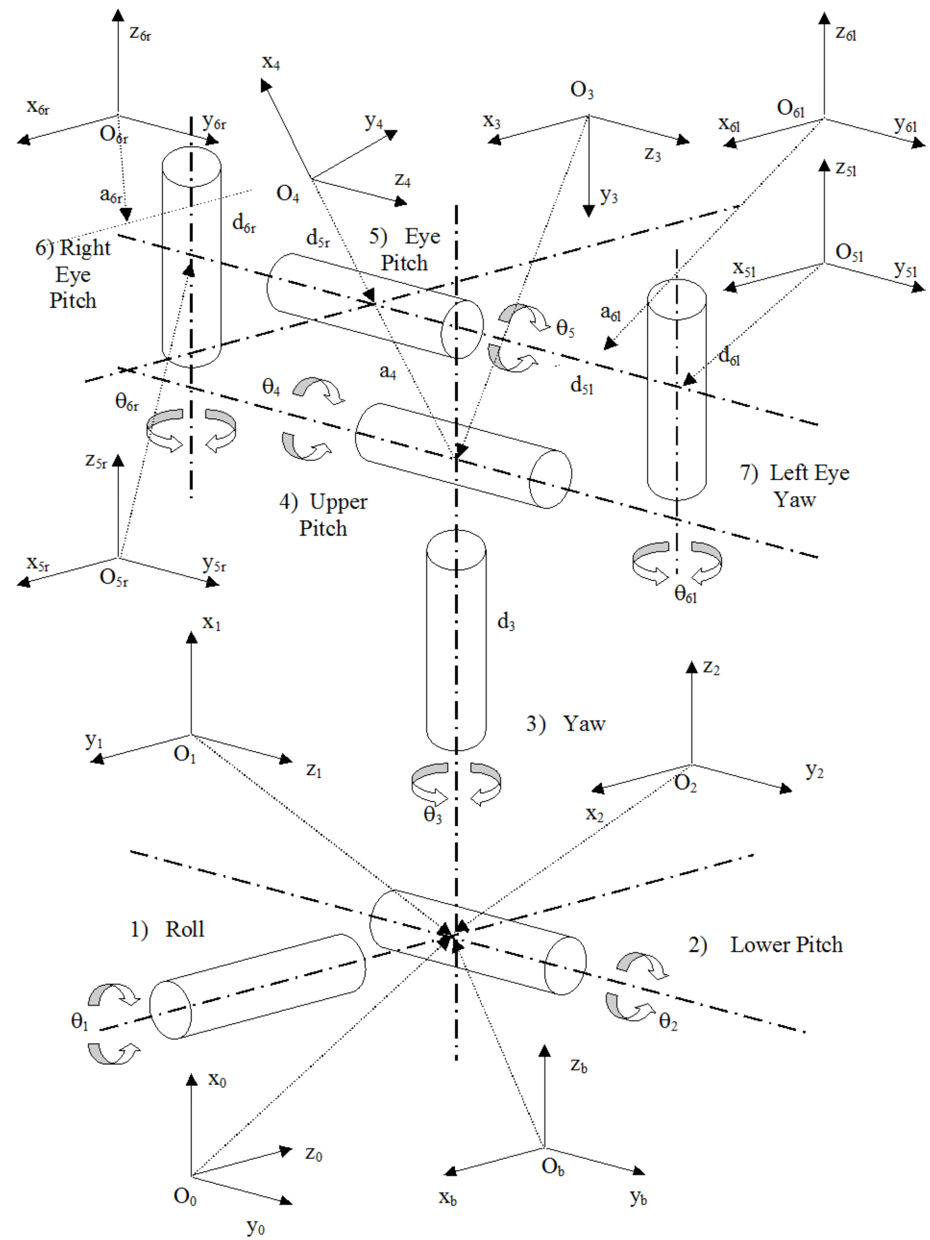
Kinematic structure of the SSSA Robot Head



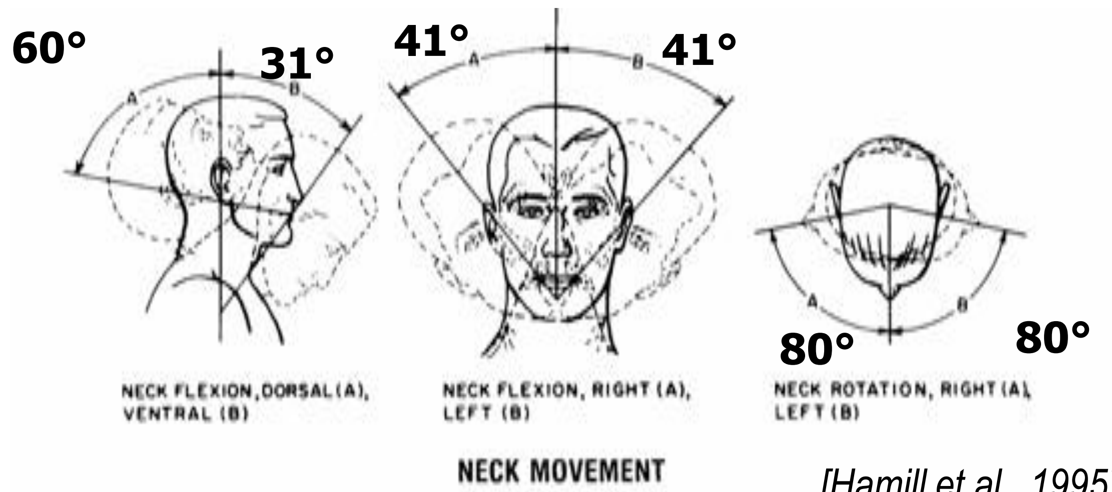
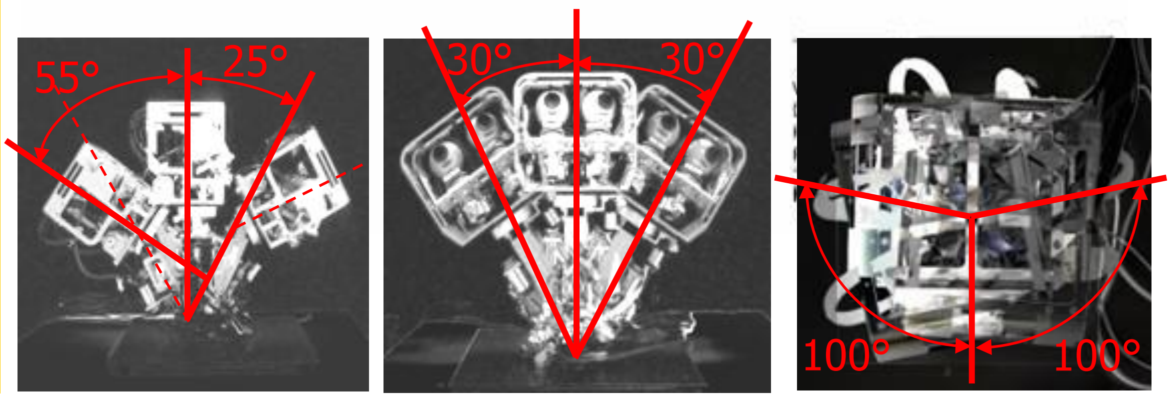
- Eye Pitch Axis: ±47°, 600°/s
- Eye R/L Yaw Axis: ±45°, 1000°/s
- Yaw: ±100°, 170°/s
- Roll: ±30°, 25°/s
- Upper Pitch: ±30°, 120°/s
- Lower Pitch: ±25°, 20°/s

Head kinematic chain and Denavit-Hartenberg parameters

Joint	a_i (mm)	d_i (mm)	α_i (rad)
J1	0	0	$-\pi/2$
J2	0	0	$\pi/2$
J3	0	195	$-\pi/2$
J4	137.5	0	0
$J5_r$	0	$-30 \div -50$	$\pi/2$
$J5_l$	0	$30 \div 50$	$\pi/2$
$J6_l$	a_{6l}	d_{6l}	0
J6r	a_{6r}	d_{6r}	0

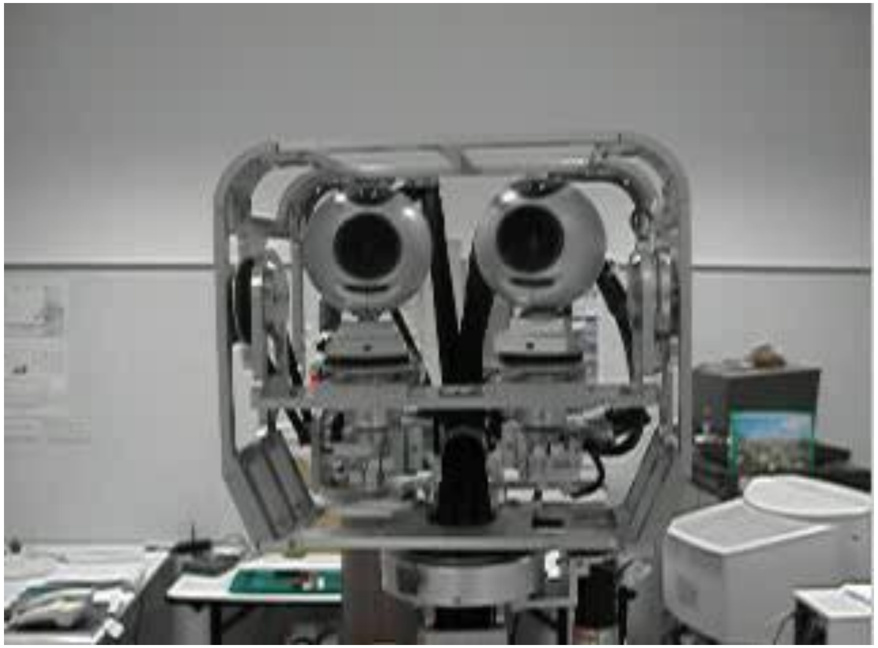


Comparison of performances between human and robotic head

	Neck:	Eye:
Human	 [Hamill et al., 1995]	Pitch: ± 60°, 600°/s Yaw: ± 30°, 600°/s
Robot		Pitch: ± 47°, 600°/s Yaw: ± 45°, 1000°/s

The movements of the 7 dofs of the robotic head

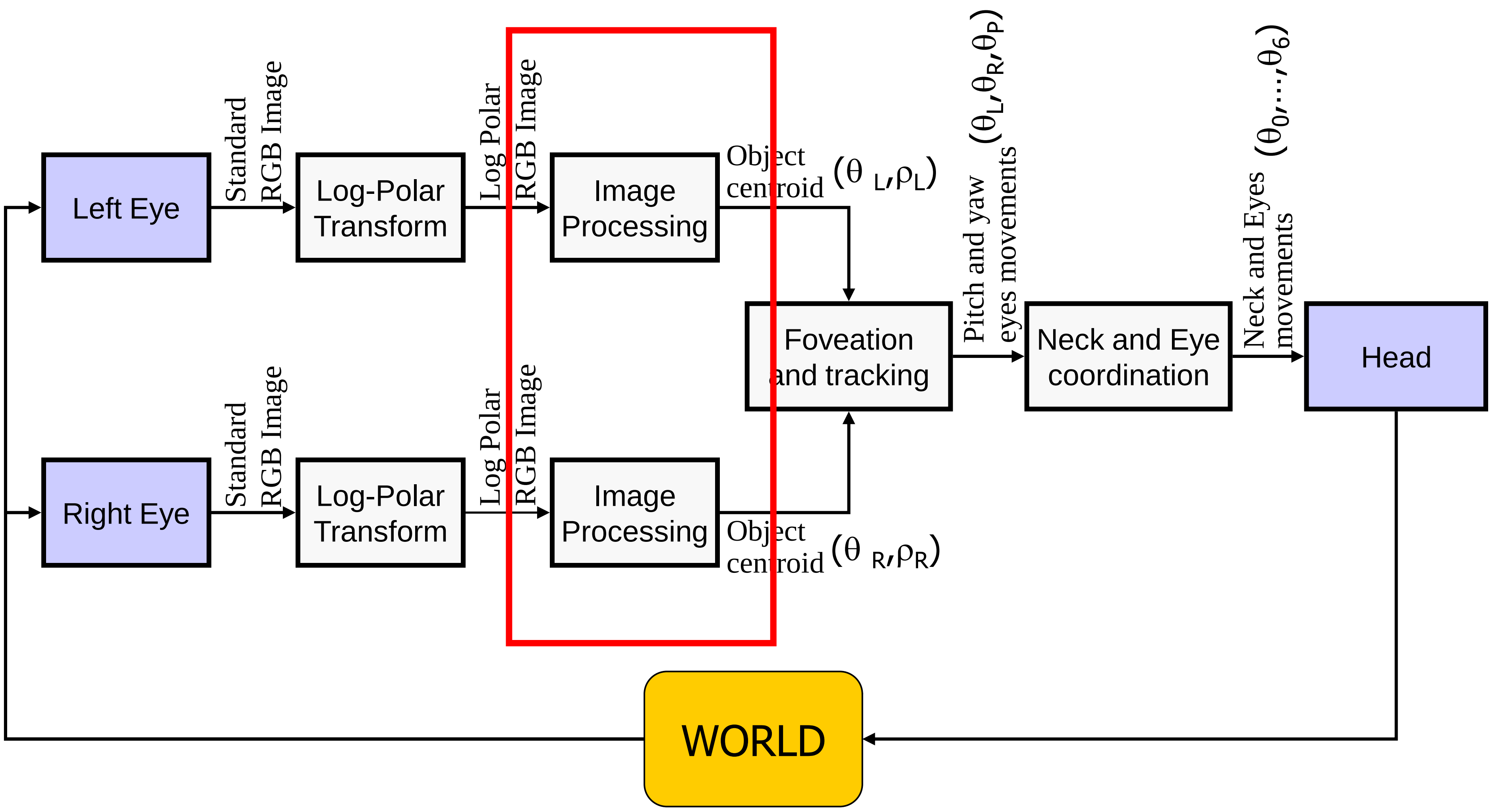
Neck Movements



Saccades, 400°/sec

saccade 300° sec.avi

Overall sensory-motor scheme of the visual apparatus

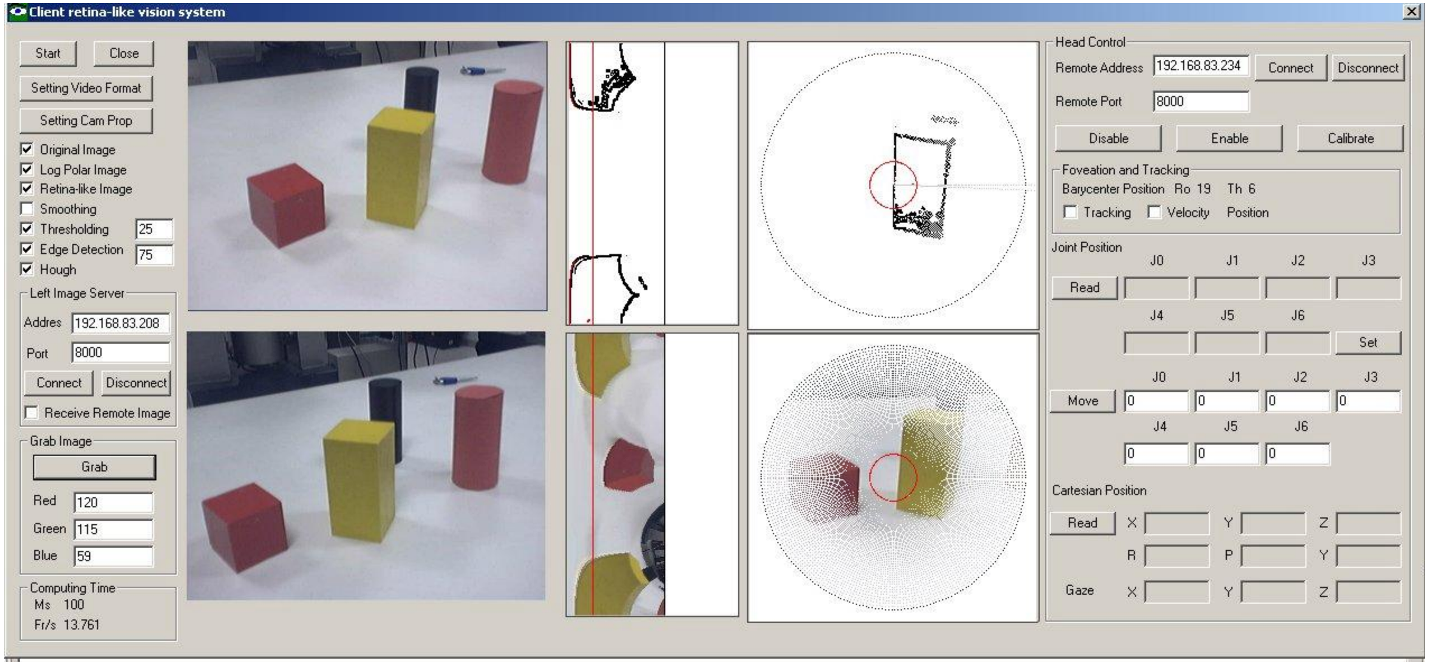


Examples of algorithms developed for retina-like image processing

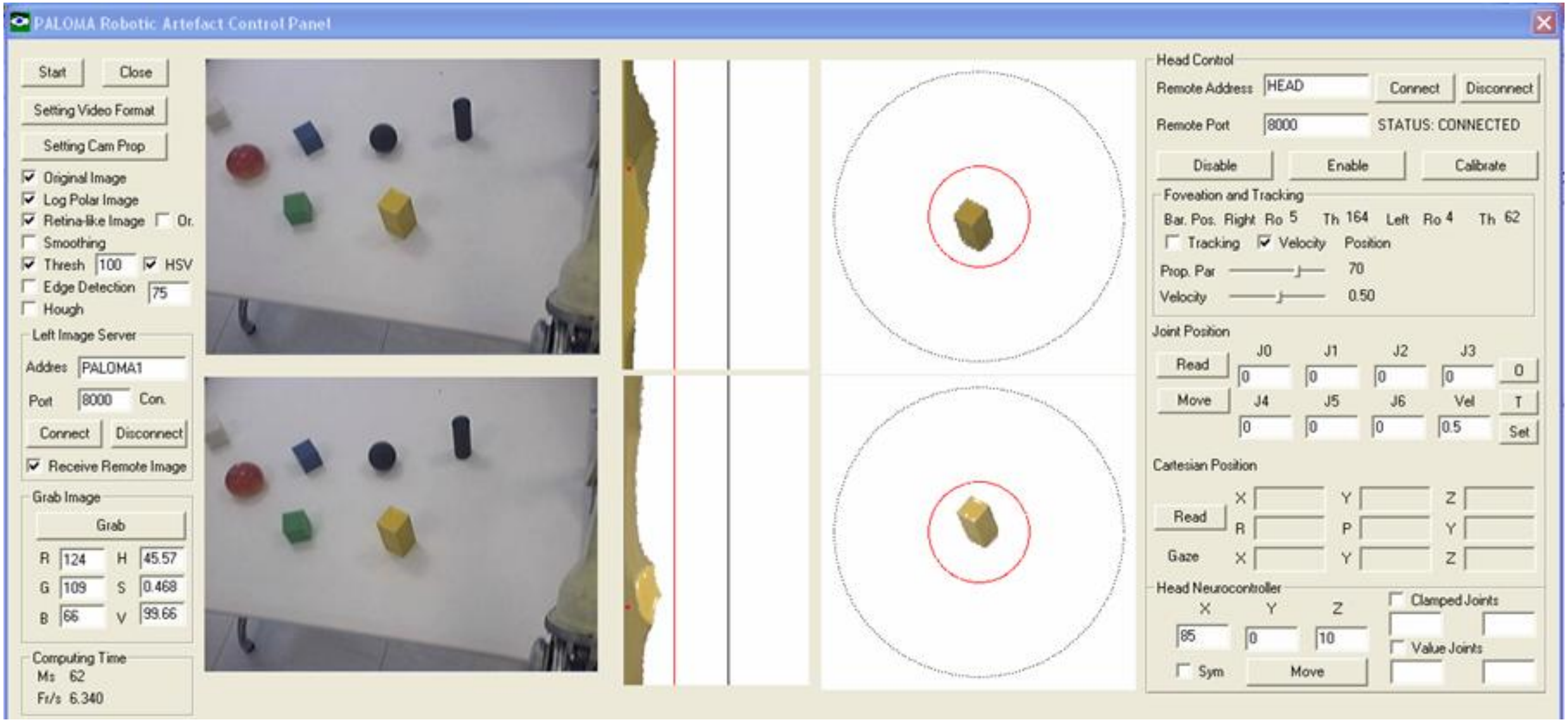
- Acquiring standard image
- Creating log-polar image from standard image
- Creating retina-like image from log-polar image
- Thresholding of image based on RGB and HUE
- Computation of the centroid of a thresholded area
- Edge detection
- Line detection

Simulation of retina-like cameras and basic image processing

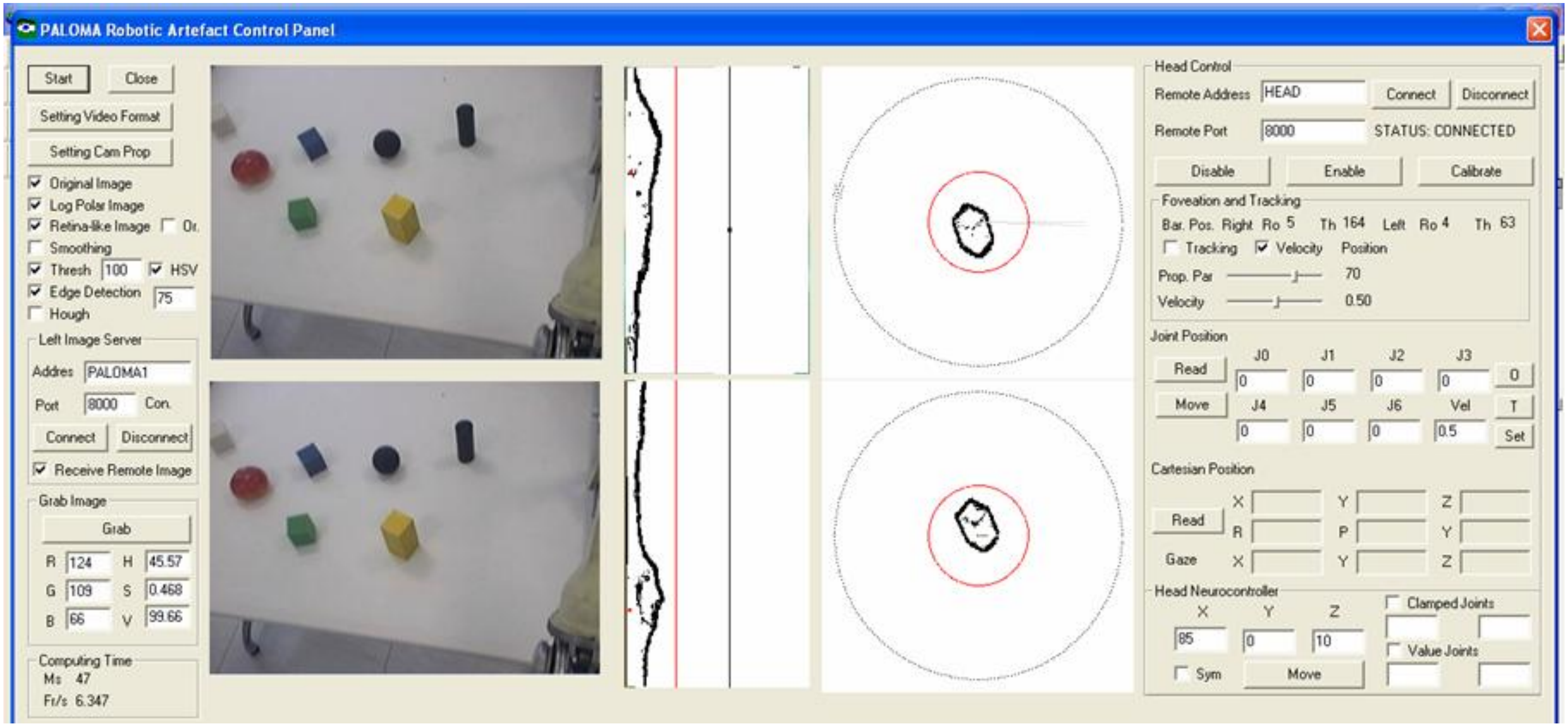
- Acquiring standard image
- Creating log-polar image from standard image
- Creating retina-like image from log-polar image



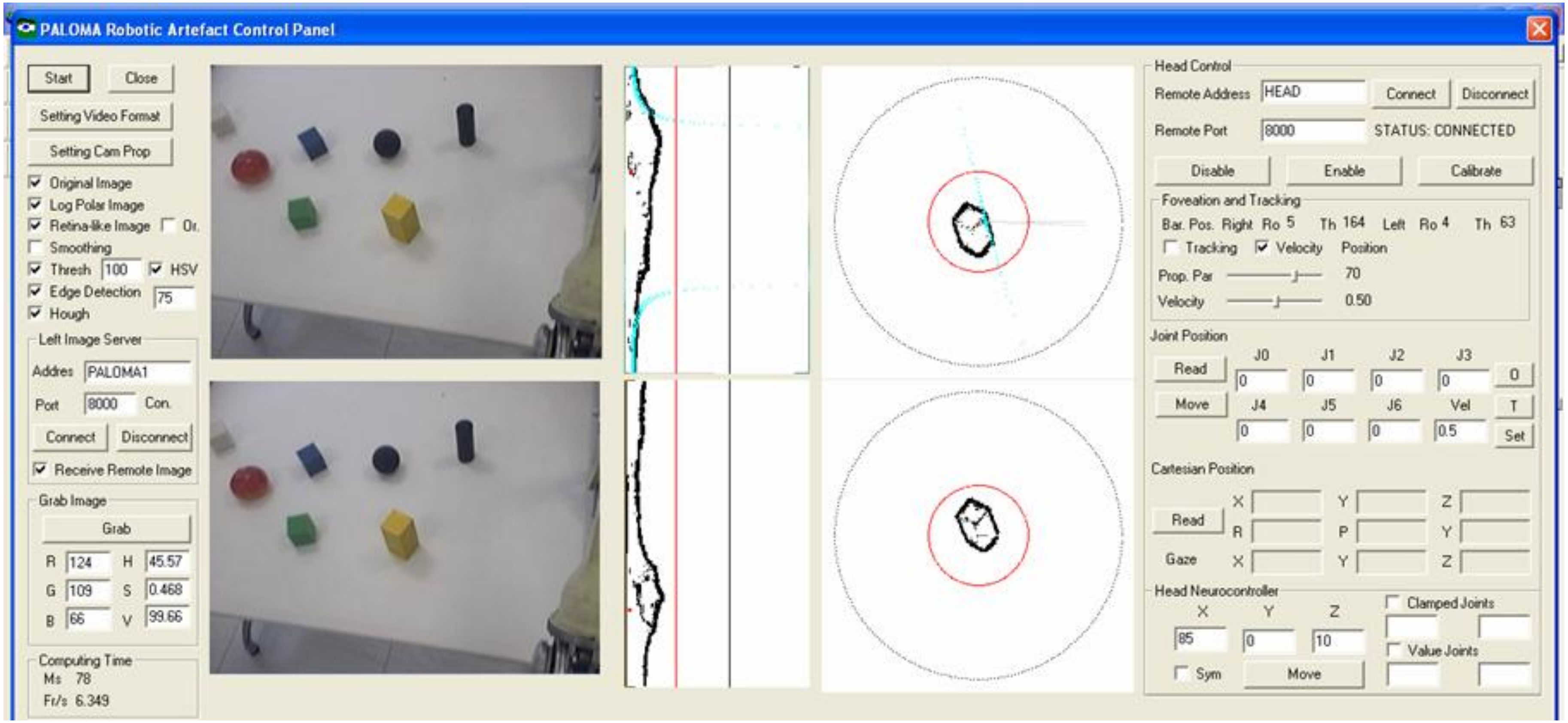
Thresholding of image based on RGB and HUE



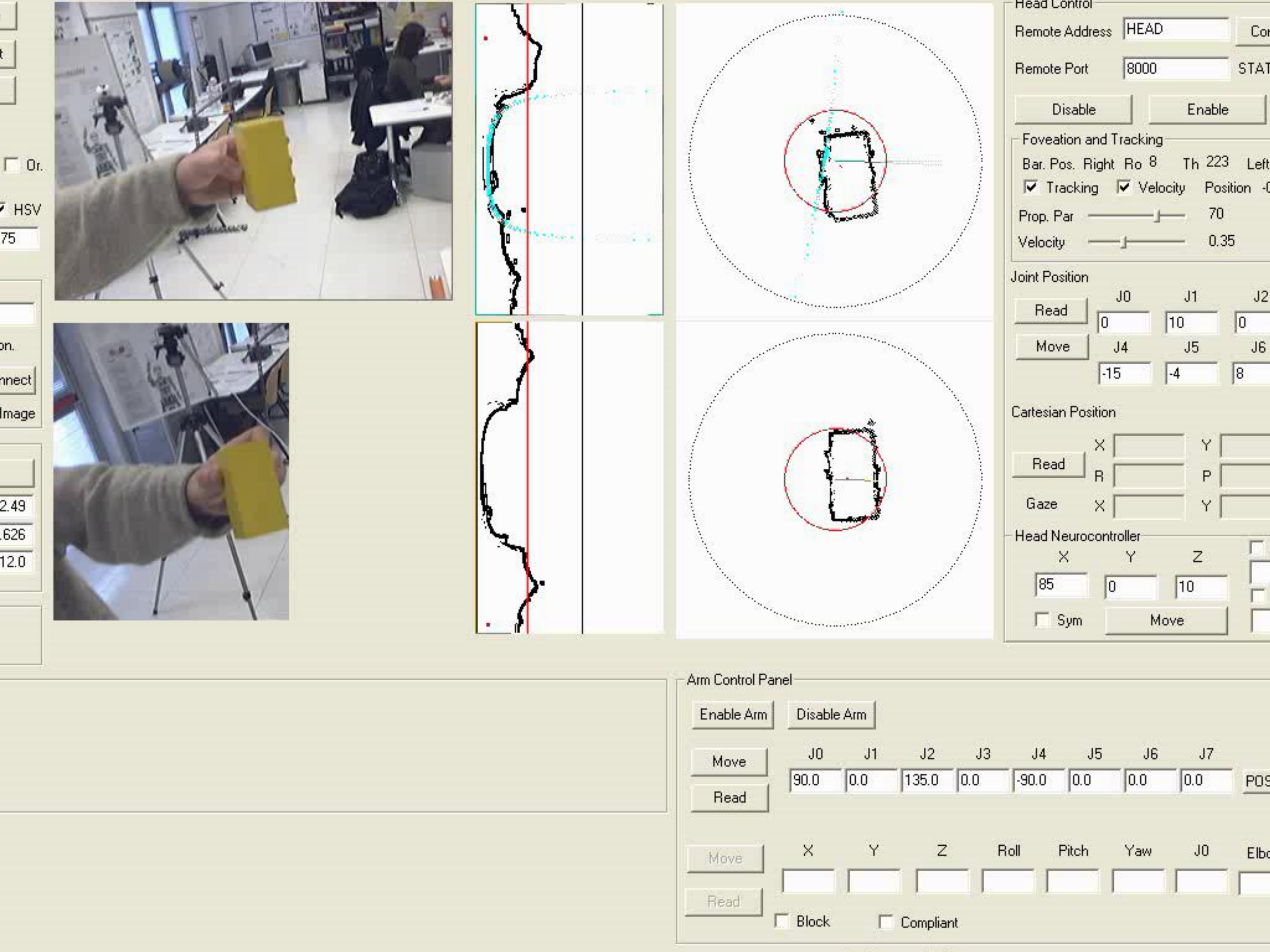
Edge Detection (gradient based method)



Line detection (Hough method)

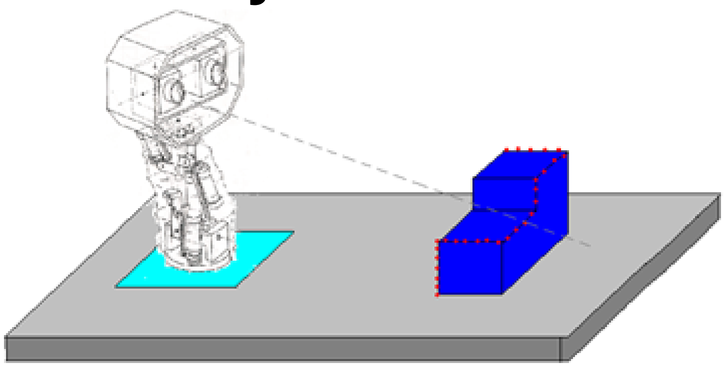


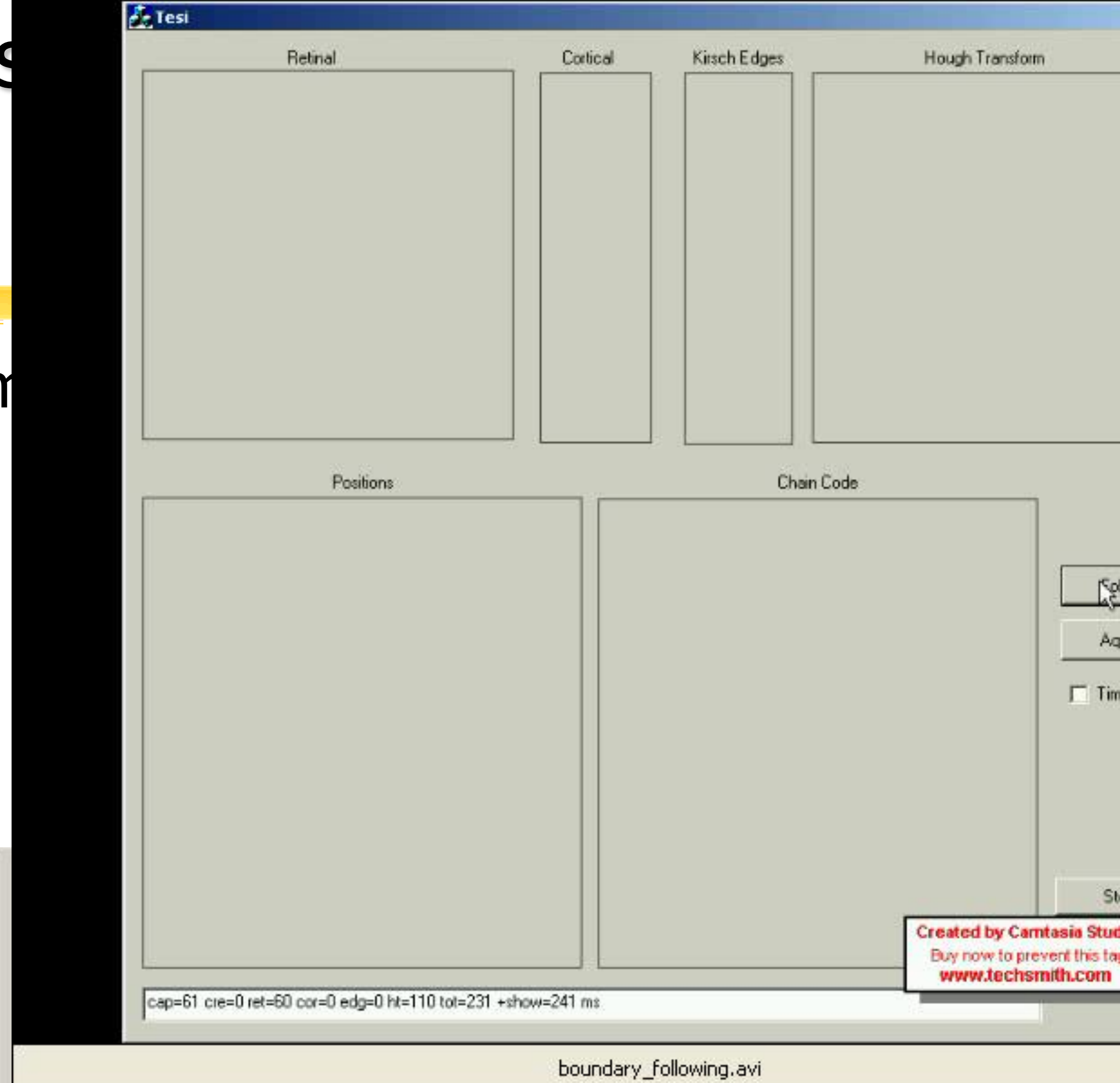
- Applied only to pixels belonging to the fovea


Head Control
Remote Address
HEAD
Remote Port
8000
Disable
Enable
Foveation and Tracking
Bar. Pos. Right Ro 8 Th 223
Tracking
Velocity
Position
Prop. Par 70
Velocity 0.35
Joint Position
Read
Move
J0 J1 J2
0 10 0
J4 J5 J6
-15 -4 8
Cartesian Position
X Y
R P
Gaze X Y
Head Neurocontroller
X Y Z
85 0 10
Sym
Move
Or.
HSV
Image
Arm Control Panel
Enable Arm
Disable Arm
Move
Read
J0 J1 J2 J3 J4 J5 J6 J7
90.0 0.0 135.0 0.0 -90.0 0.0 0.0 0.0
X Y Z Roll Pitch Yaw J0
Block
Compliant

Preliminary activities

Foveation and tracking of borders of object and reconstruction of the geom of the object



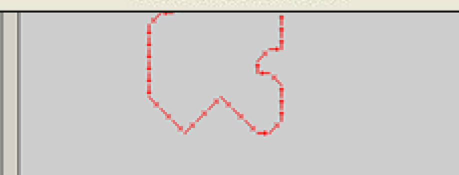


Retina Like image

Log Polar Image

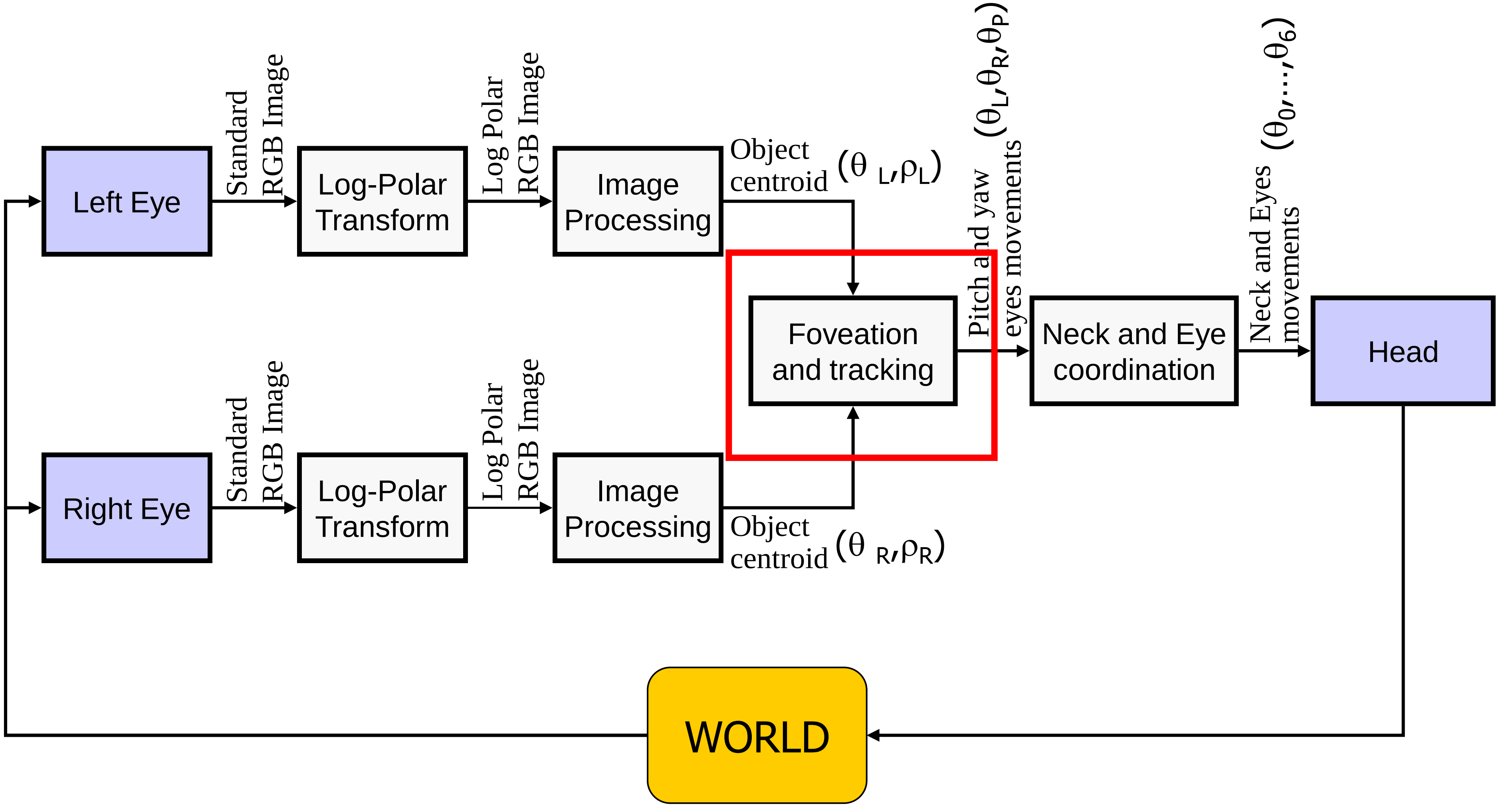
Edge of log polar image

Detected lines (Boundaries)



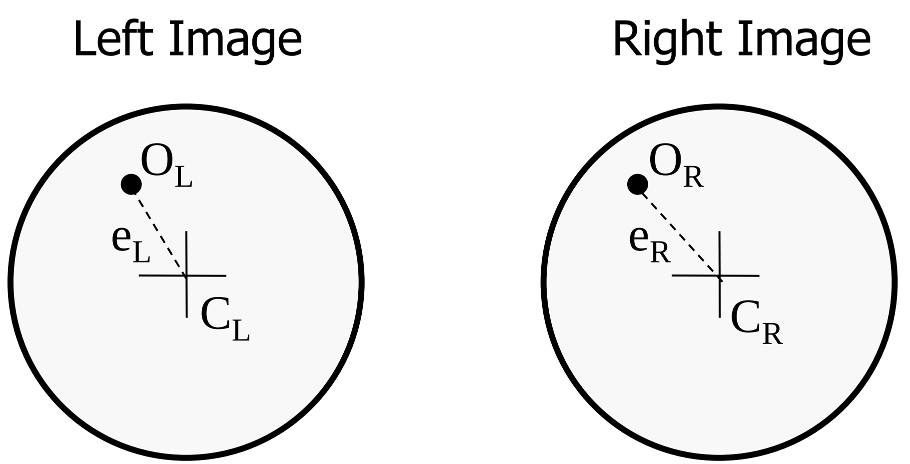
Boundary reconstruction based on eye positions

Overall sensory-motor scheme of the visual apparatus



Foveation of the object centroid

Proportional control based on the visual error

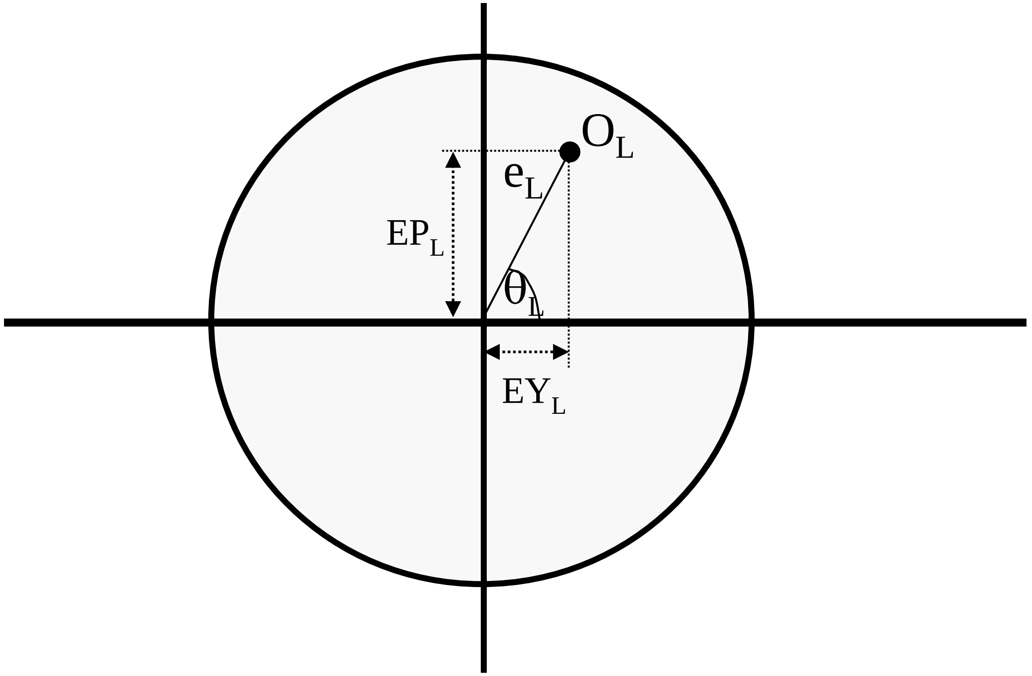


$O_L = (\rho_L, \theta_L)$ $O_R = (\rho_R, \theta_R)$

$e_L = \rho_L / M_{ro}$ $e_R = \rho_R / M_{ro}$

M_{ro} is the maximum ρ value (i.e. 152)

Computation of yaw and pitch eye movements



$EY_L = e_L * \cos(\theta_L) * P_L$

$EY_R = e_R * \cos(\theta_R) * P_R$

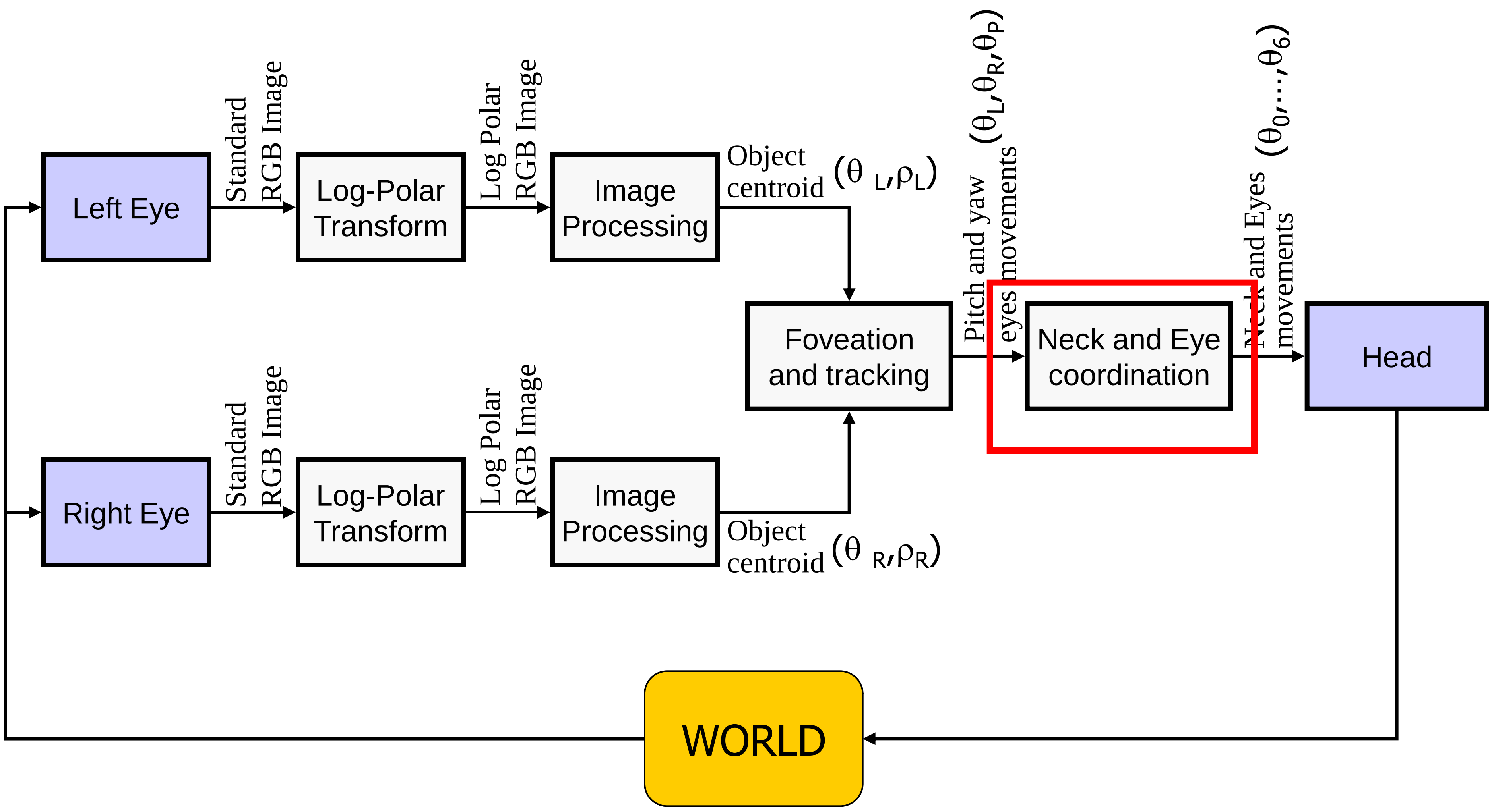
$EP_L = e_L * \sin(\theta_L) * P_L$

$EP_R = e_R * \sin(\theta_R) * P_R$

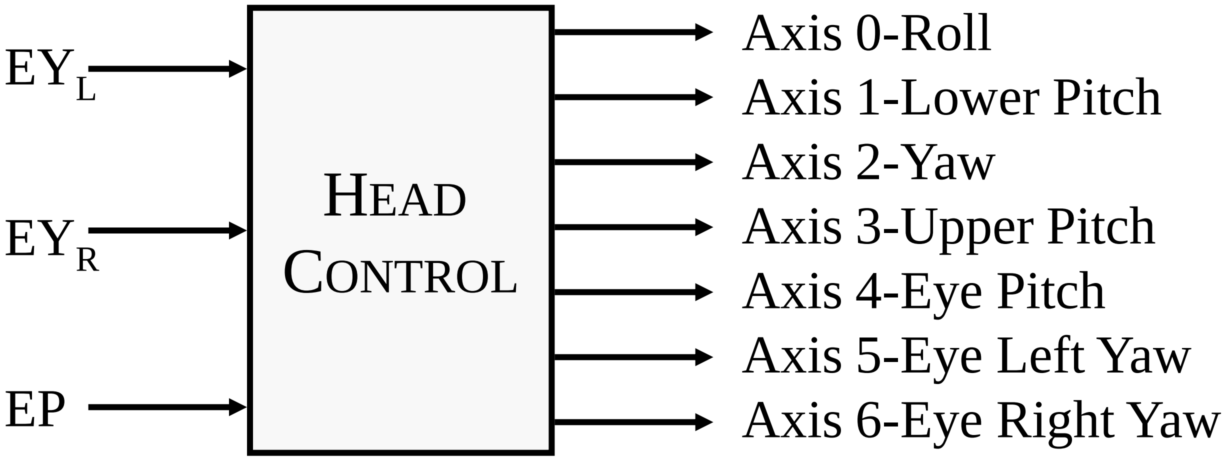
$EP = (EP_L + EP_R)/2$

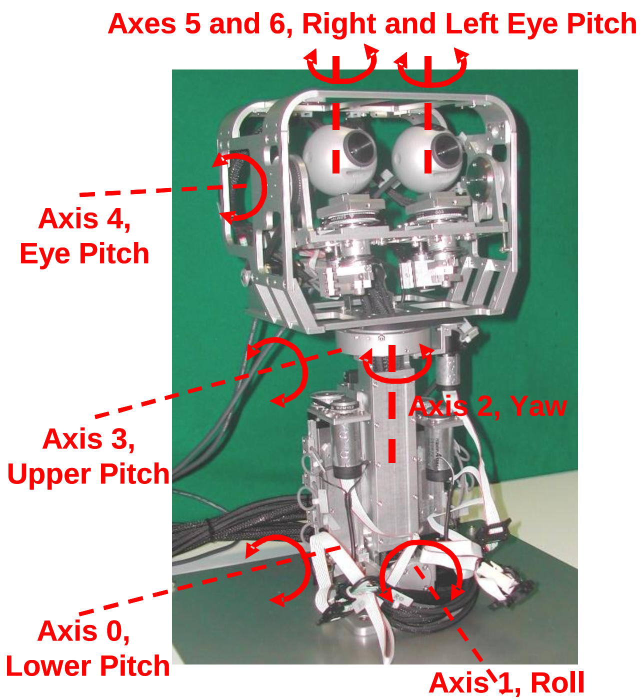
P_L and P_R are the proportional parameters for left and right eye, respectively.

Overall sensory-motor scheme of the visual apparatus



Eye-neck coordination



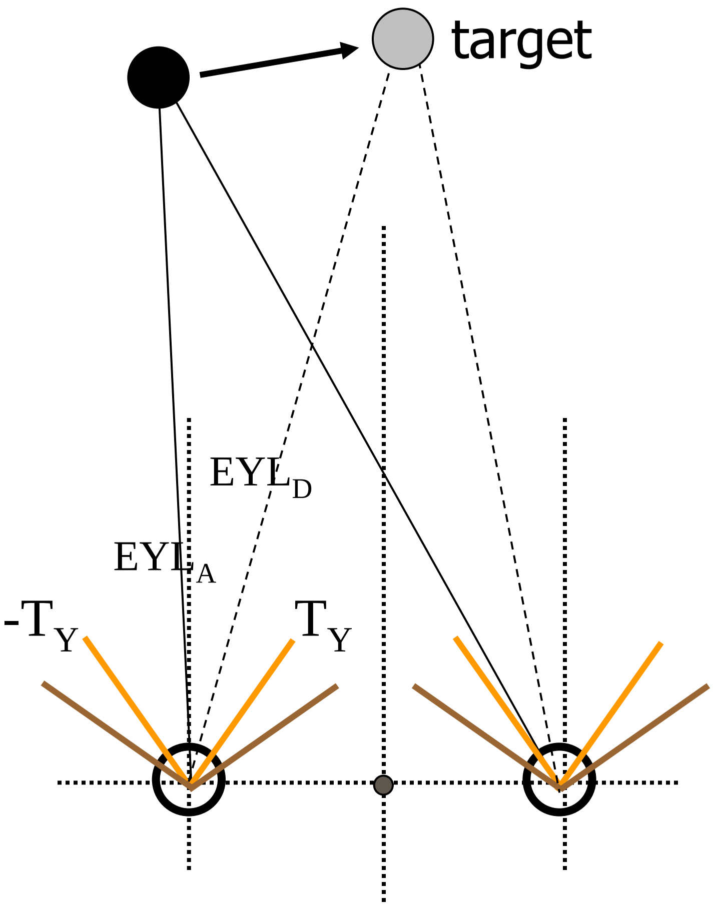


Solution 1

Distribution of the movements between the neck and eye DOF

Strategy for the coordination of neck and eye movement (yaw)

- If the movement is small, it is executed by the eyes, only



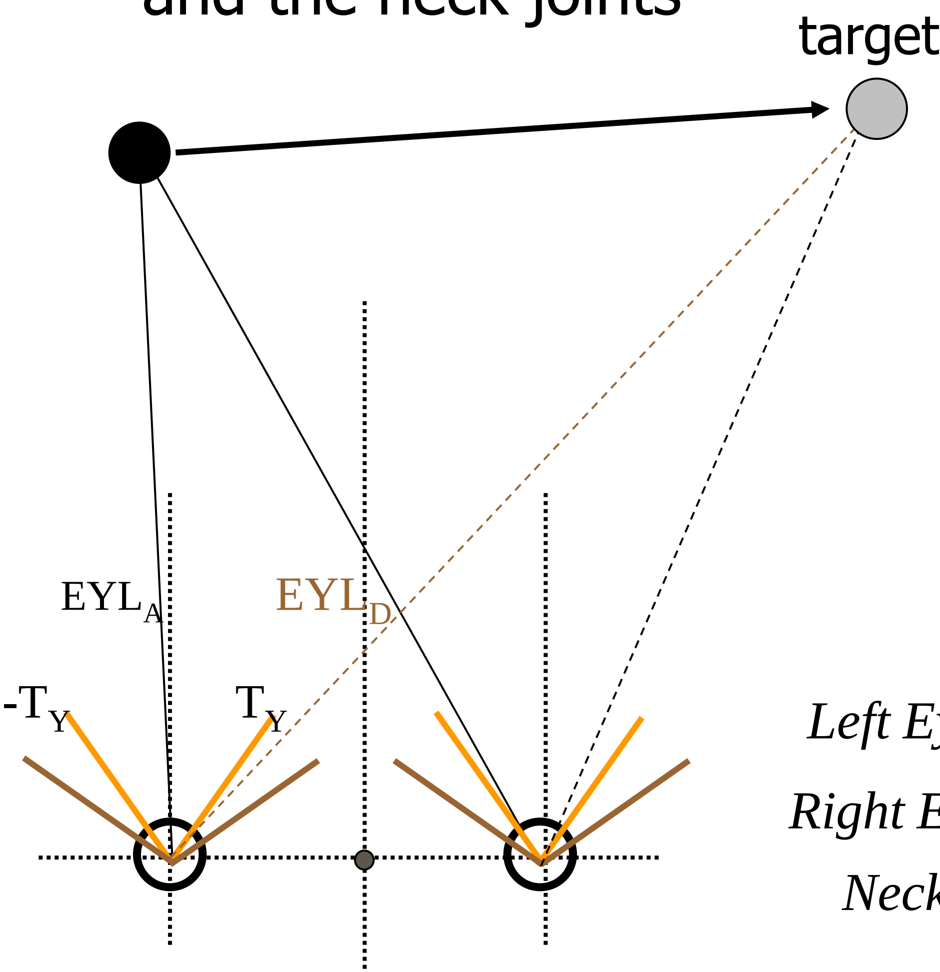
$$EYL_A + EY_L < T_Y$$
and
$$EYR_A + EY_R < T_Y$$

⇓

Left Eye Yaw	$EYL_D = EYL_A + EY_L$
Right Eye Yaw	$EYR_D = EYR_A + EY_R$
Neck Yaw	$YAW_D = YAW_A$

Strategy for the coordination of neck and eye movement (yaw)

- If the movement is larger, it is distributed among the eyes and the neck joints



$$EYL_A + EY_L > T_Y$$

or

$$EYR_A + EY_R > T_Y$$

⇩

Eyes and neck

$$\theta = \text{atan}((\tan(EY_L) + \tan(EY_R))/2)$$

Left Eye Yaw	$EYL_D = EYL_A + EY_L - \theta$
Right Eye Yaw	$EYR_D = EYR_A + EY_R - \theta$
Neck Yaw	$YAW_D = YAW_A + \theta$

Strategy for the coordination of neck and eye movement (pitch)

Eye, upper and lower pitch of the head are calculated as a percentage (proportional to the available range) of EP.

$K1 = EP * EYP_{Av} / P_{Av}$

$K2 = EP * UP_{Av} / P_{av}$

$K3 = EP * LP_{Av} / P_{av}$

$EYP_D = EYP_A + EP * K1$

$EUP_D = EUP_A + EP * K2$

$ELP_D = ELP_A + EP * K3$

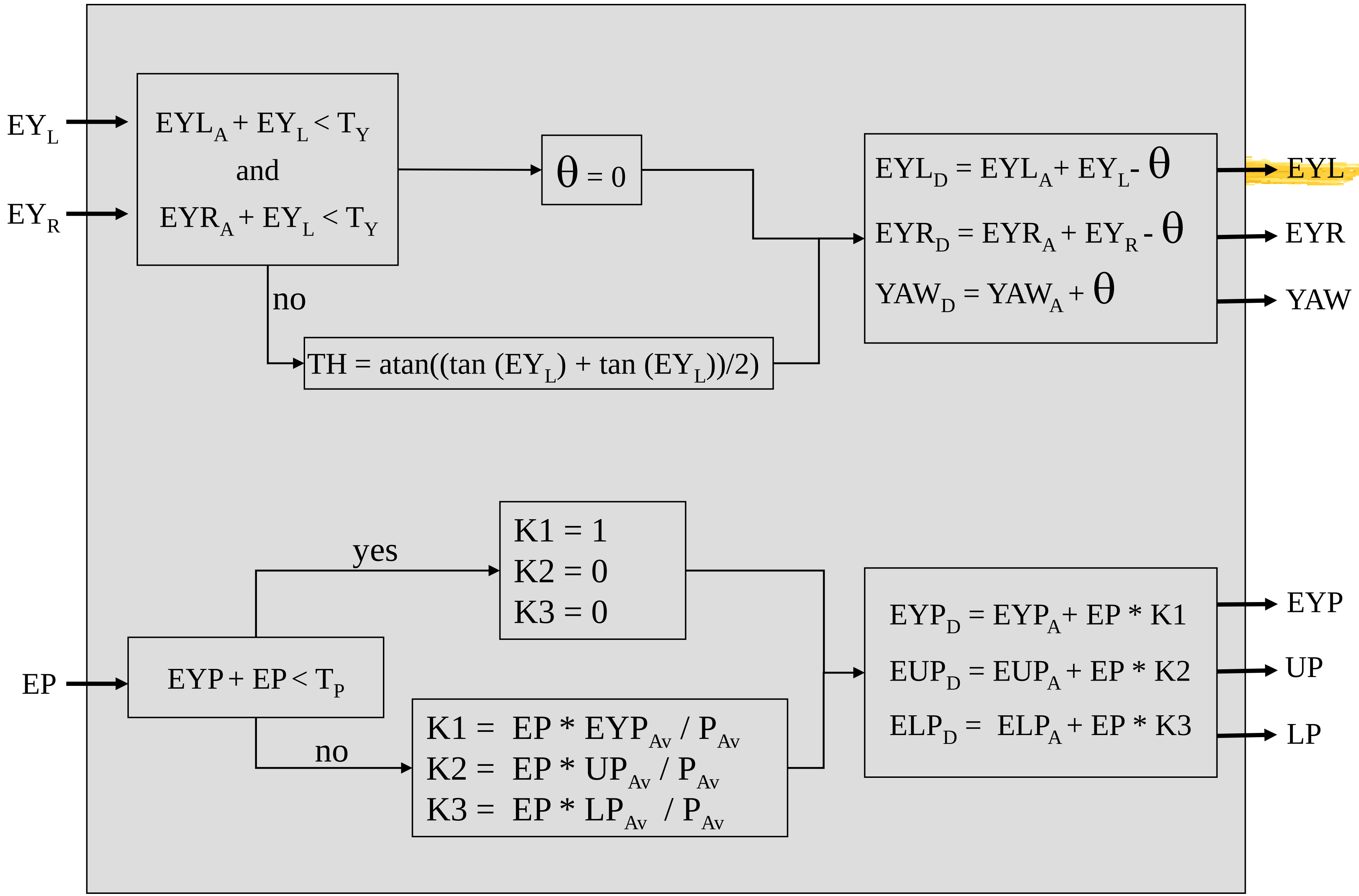
$EYP_{AV} = EYP_M - EYP_A$

$UP_{AV} = UP_M - UP_A$

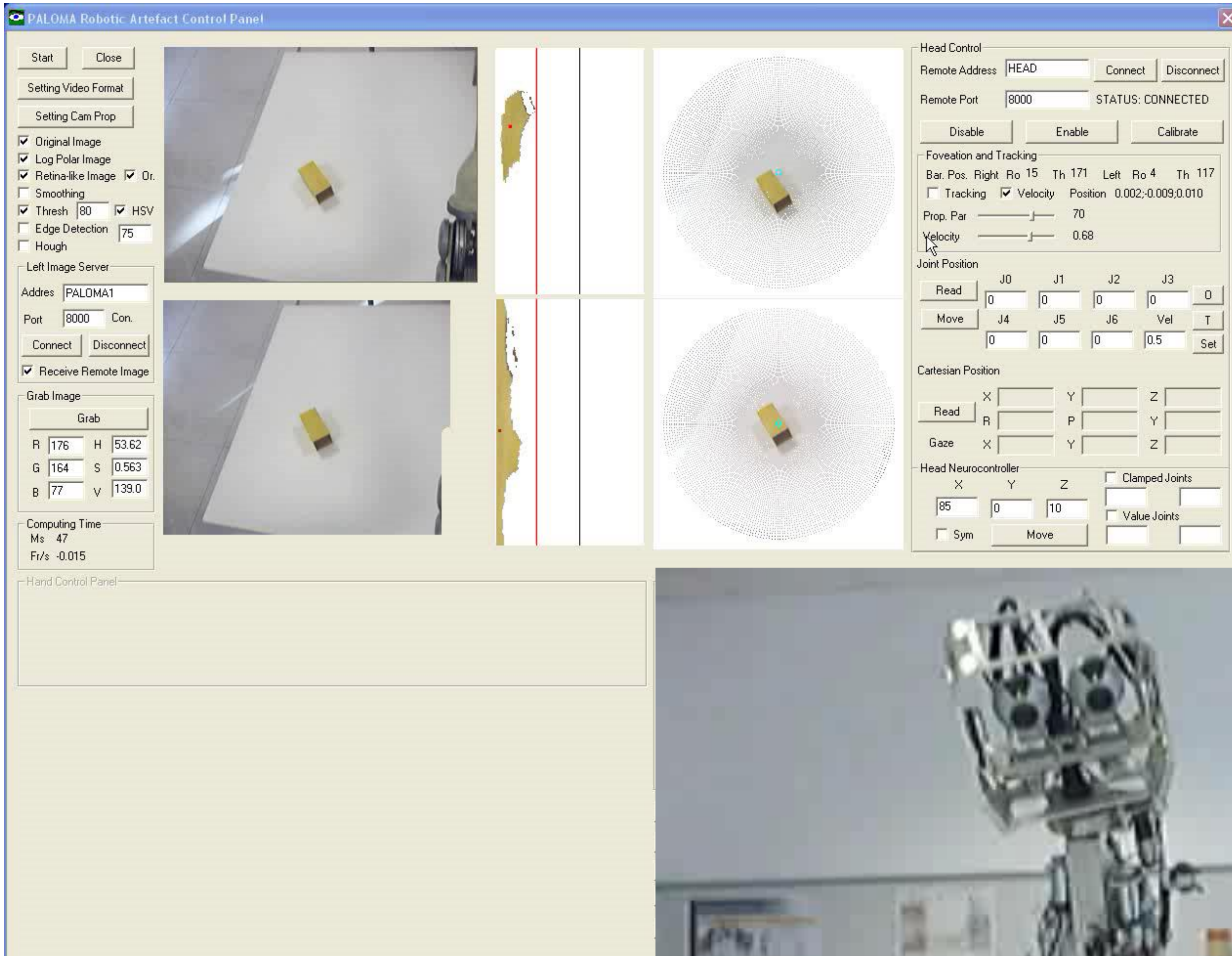
$LP_{AV} = LP_M - UP_A$

$P_{AV} = EYP_{AV} + UP_{AV} + LP_{AV}$

EYP_M, UP_M and LP_M are the range limits respectively for eye pitch, upper pitch and lower pitch axis

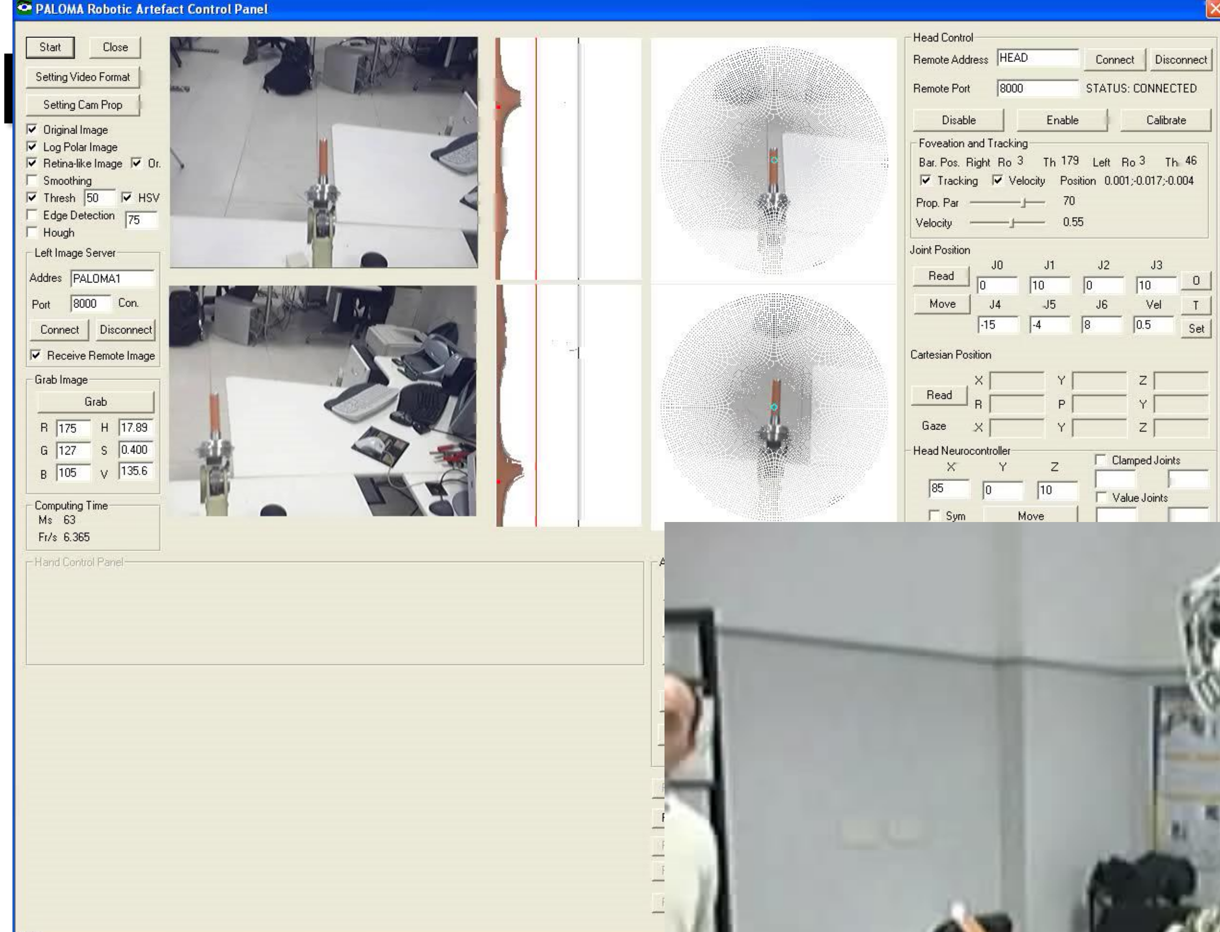

EYL
EYR
EYLA + EYL < TY
and
EYRA + EYL < TY
θ = 0
EYLD = EYLA + EYL - θ
EYRD = EYRA + EYR - θ
YAWD = YAWA + θ
EYL
EYR
YAW
no
TH = atan((tan (EYL) + tan (EYL))/2)
yes
K1 = 1
K2 = 0
K3 = 0
EP
EYP + EP < TP
EYPD = EYPA + EP * K1
EUPD = EUPA + EP * K2
ELPD = ELPA + EP * K3
EYP
UP
LP
no
K1 = EP * EYPAv / PAv
K2 = EP * UPAv / PAv
K3 = EP * LPAv / PAv

Pursuit Movement



Frame rate: 10 fps for both images
Head Control loop: 100 ms

Hand Tracking



Frame rate: 10 fps for both images
Head Control loop: 100 ms
Arm movement 0.2 m/s

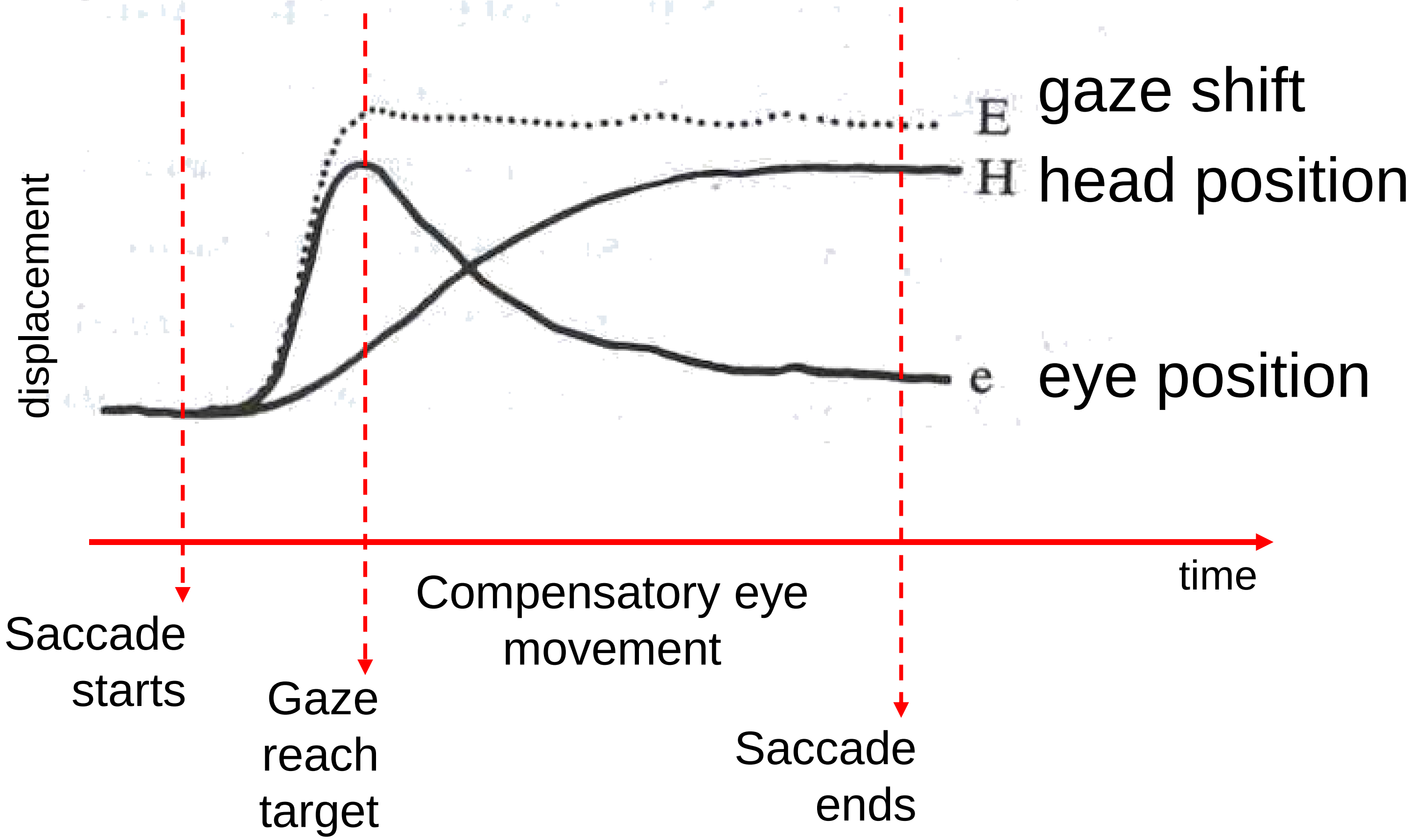
Solution 2

Implementation of a biological model of head-eye coordination

E.S. Maini, G. Teti, C. Laschi, M. Rubino, P. Dario, “Bio-inspired control of eye-head coordination in a robotic anthropomorphic head”, *IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, Pisa, Italy, February 20-22, 2006

What happens in Humans

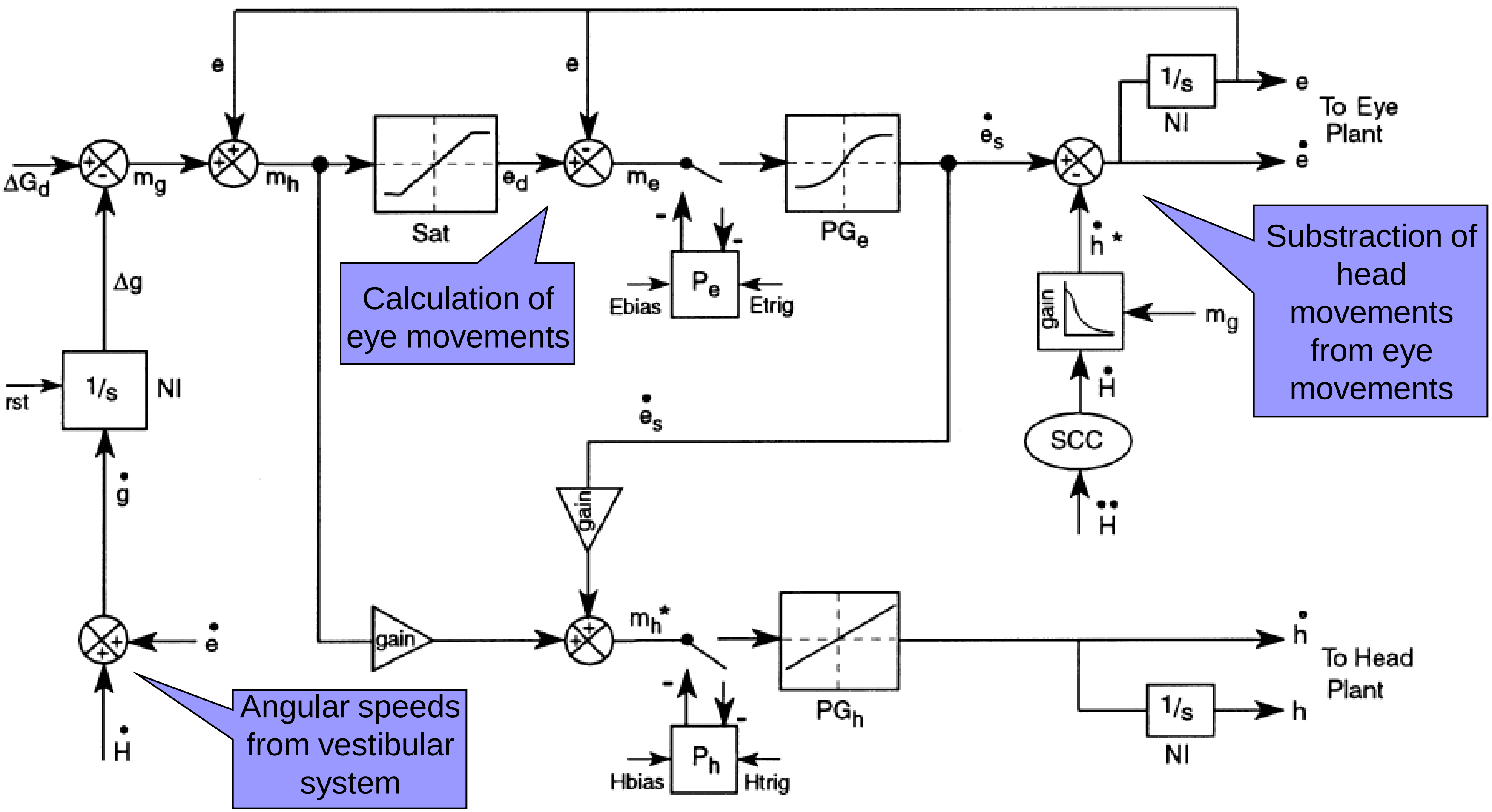
to foveate a visual target in the periphery, gaze shifts are usually made with combined eye and head movements



Biological Models

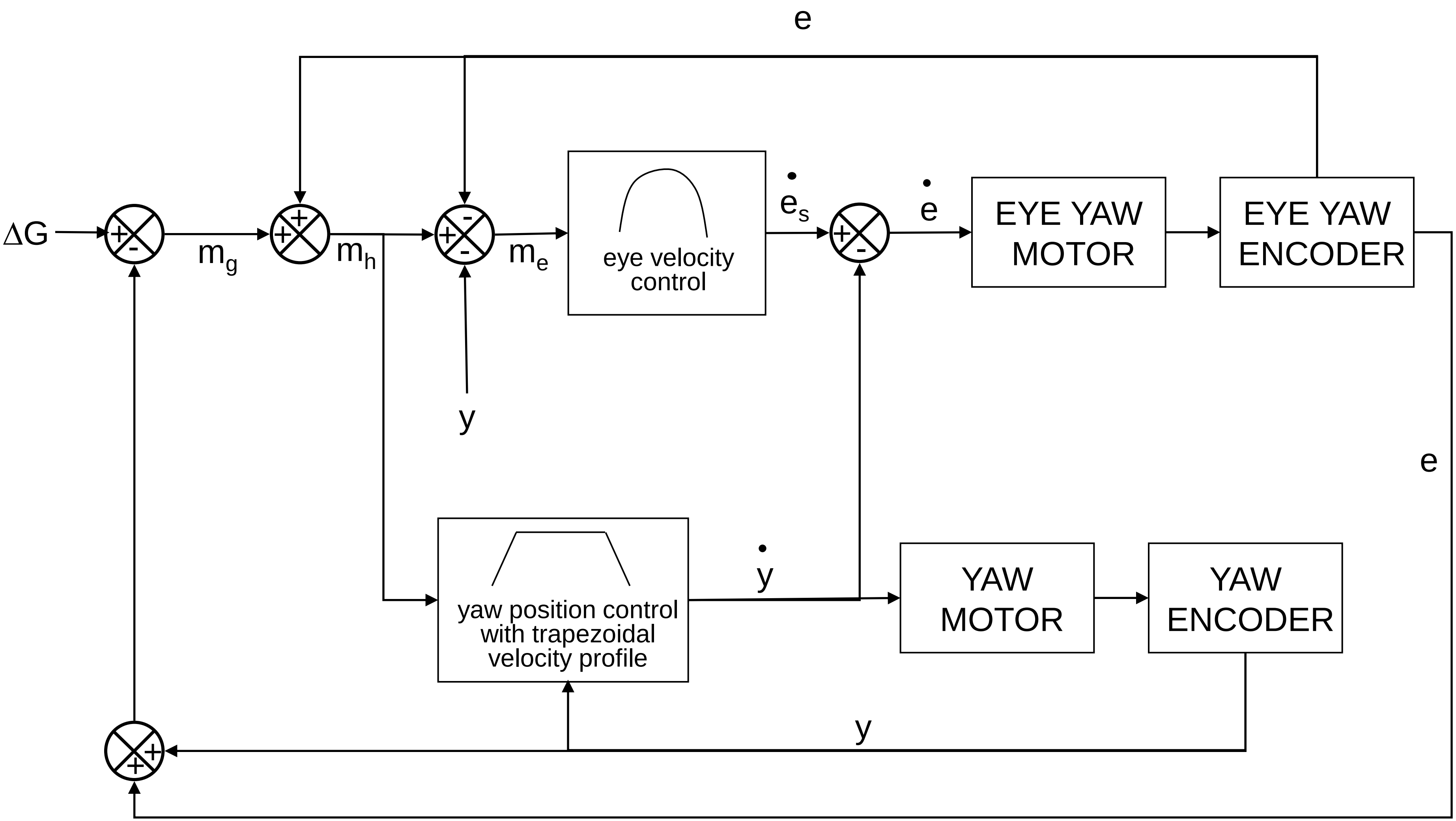
- *Laurutis V.P. and Robinson D.A.,"The vestibulo-ocular reflex during human saccadic eye movements.", J Physiol (Lond) 1986, Vol. 373, pp. 209–233*
- *Lefèvre P. et al, "Experimental study and modeling of vestibulo-ocular reflex modulation during large shifts of gaze in humans.", Exp Brain Res 1992, Vol. 91, pp. 496–508*
- *Guitton D. and Volle M., "Gaze control in humans: eye-head coordination during orienting movements to targets within and beyond the oculomotor range.", J Neurophysiol 1987, Vol. 58, pp.427–459*
- *Guitton D., "Control of eye-head coordination during orienting gaze shifts.", Trends Neurosci 1992, Vol.15, pp.174–179*
- Goossens H.H. and Van Opstal A.J., "Human eye-head coordination in two dimensions under different sensorimotor conditions", Exp. Brain Res.1997, Vol. 114, pp. 542–560
- *Suzuki T. and Hirai N., "Reaction times of head movements occurring in association with express saccades during human gaze shifts", Neuroscience Letters 1998, Vol. 254, pp. 61–64*
- *Tweed D. et al, "Eye-head coordination during large gaze shifts.", J Neurophysiol 1995, Vol. 73, pp. 766–779*

The Biological Model



Goossens H.H. and Van Opstal A.J., “Human eye-head coordination in two dimensions under different sensorimotor conditions”, *Exp. Brain Res.* 1997, Vol. 114, pp. 542–560

The Artificial Model for horizontal motion



Experimental trials

Objectives:

1. To investigate the effectiveness of the bio-inspired paradigm to achieve an appropriate control of a multi-DOF robotic head
2. To verify if the proposed control paradigm is able to produce a motor output coherent with the reported patterns of eye-head coordination in humans

Experimental Methodology

In accordance to Goossens & Van Opstal two kinds of experiments were done:

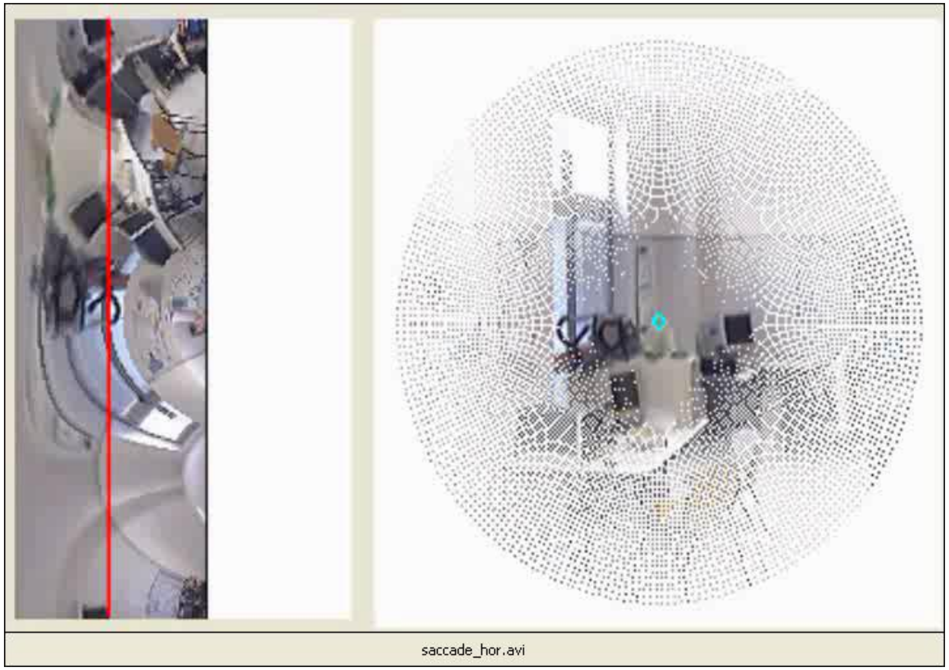
- ***aligned* experiments**: eyes and head of the robot were aligned at a straight-ahead position.
- ***not aligned* experiments**: the eyes of the robot were randomly deviated from the straight-ahead position with an initial deviation in the range 20°-55°.
- from the starting position the gaze shift was presented to the robot and the resulting displacements and timing of eye-head movements were recorded through the proprioceptive sensors of the head

Experimental Trials

- **Aligned** Experiment:
  horizontal saccadic movements of 45° on horizontal and vertical direction.
- **Not Aligned** experiment:
  saccadic movement of 45° amplitude with an initial deviation of 25° in the same direction. Required movement for the eye was 20° whereas the head moved 45°
- 10 trials for each experiment
- Maximum velocities have been set to 400 deg/s and 300 deg/s respectively for eye yaw motion and eye tilt motion

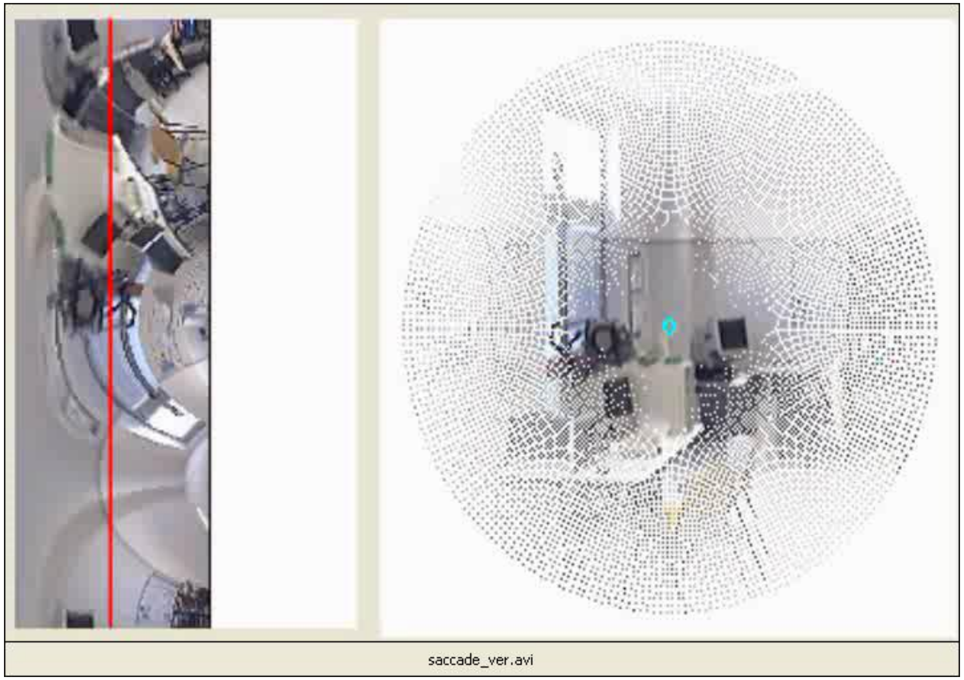
Experimental Trials: horizontal saccades

Left eye only



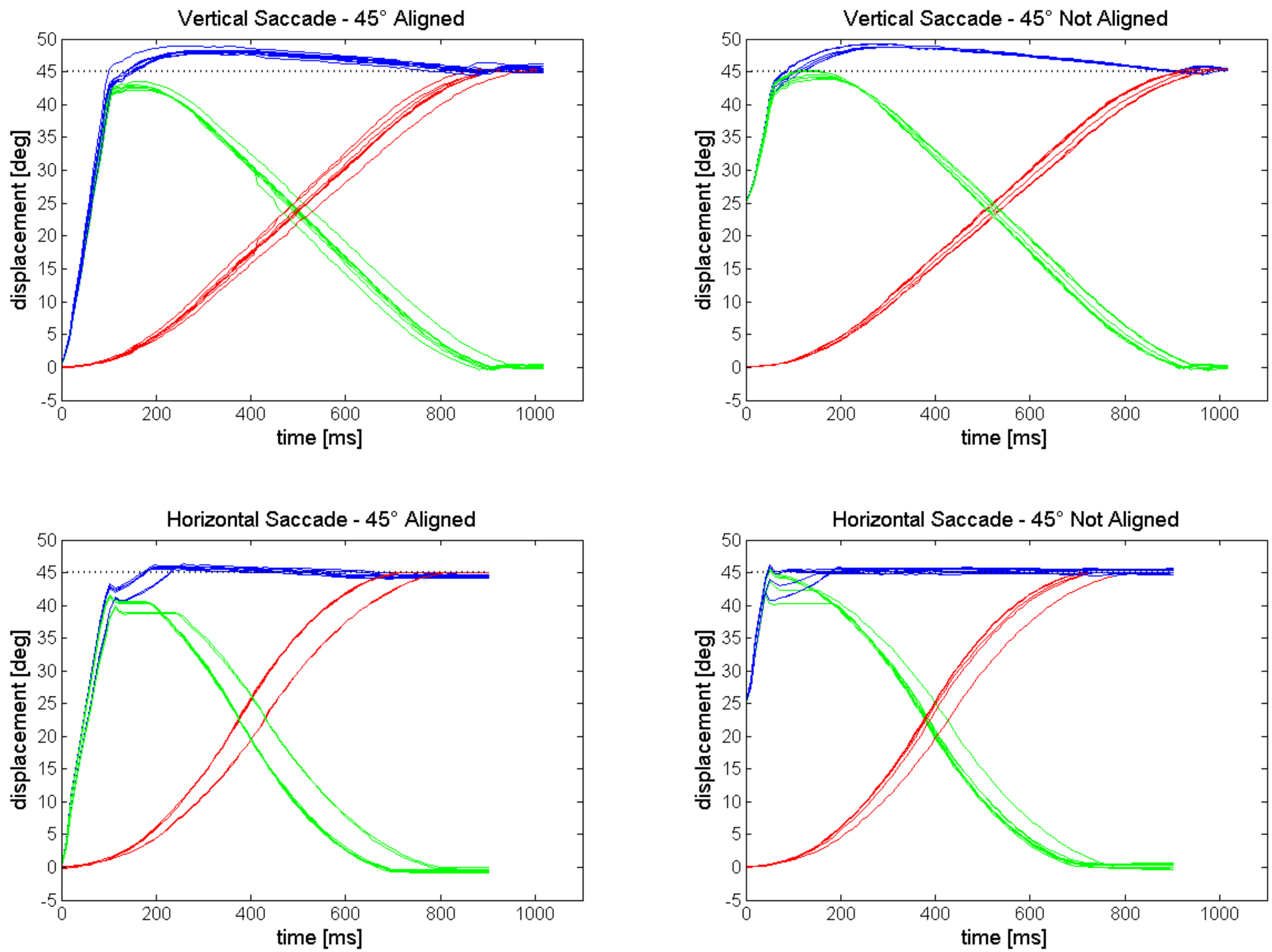
Camera View

Experimental Trials: vertical saccades



Camera View

Experimental Results

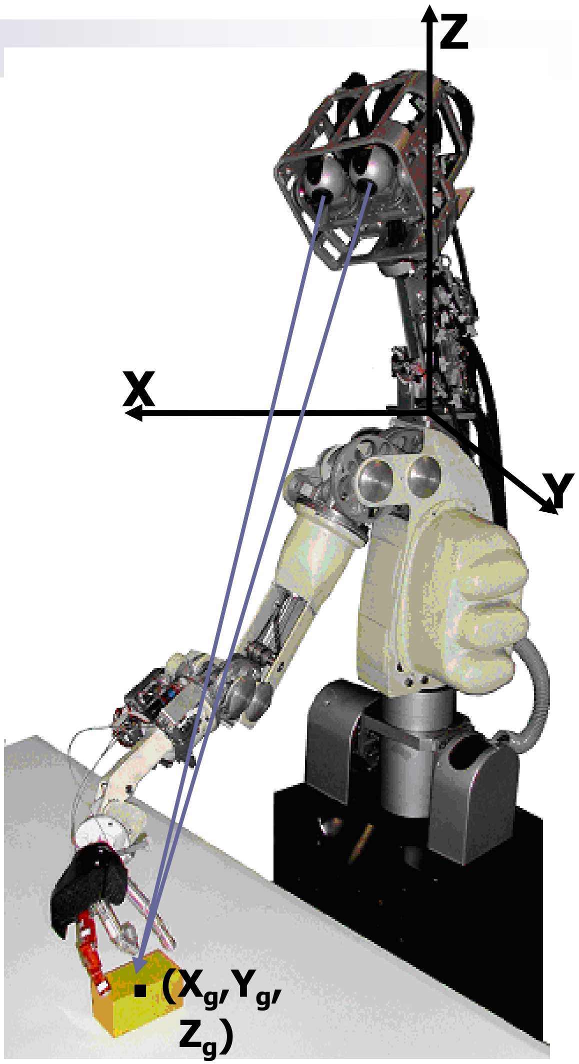


Solution 3

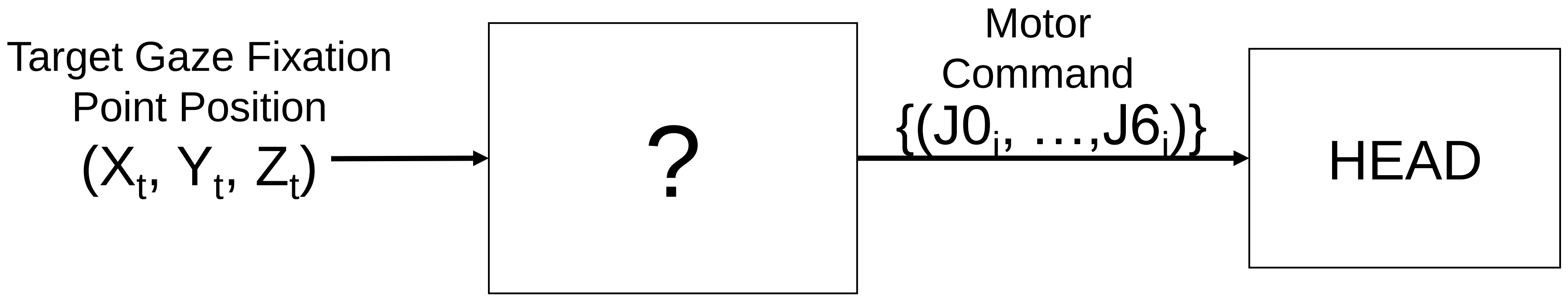
Implementation of a bioinspired model of head-eye coordination based on learning

G. Asuni, G. Teti, C. Laschi, E. Guglielmelli, P. Dario, “A Robotic Head Neuro-controller Based on Biologically-Inspired Neural Models”, *IEEE International Conference on Robotics and Automation – ICRA 2005*, Barcelona, Spain, April 18-22, 2005, pp.2373-2378.

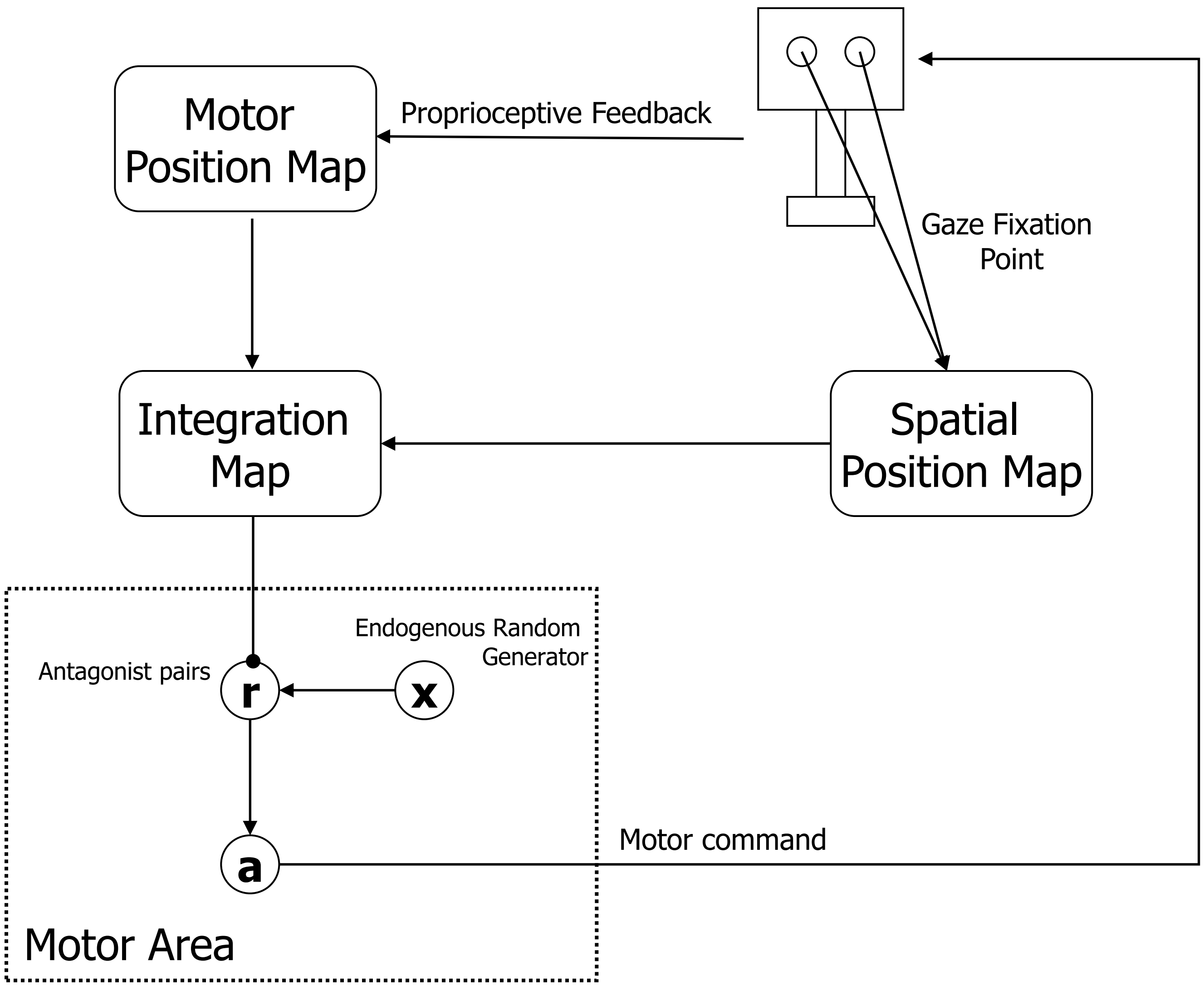
Addressed Problem



To develop a control module that receives in input a target gaze position and provides in output a command sequence able to reach it

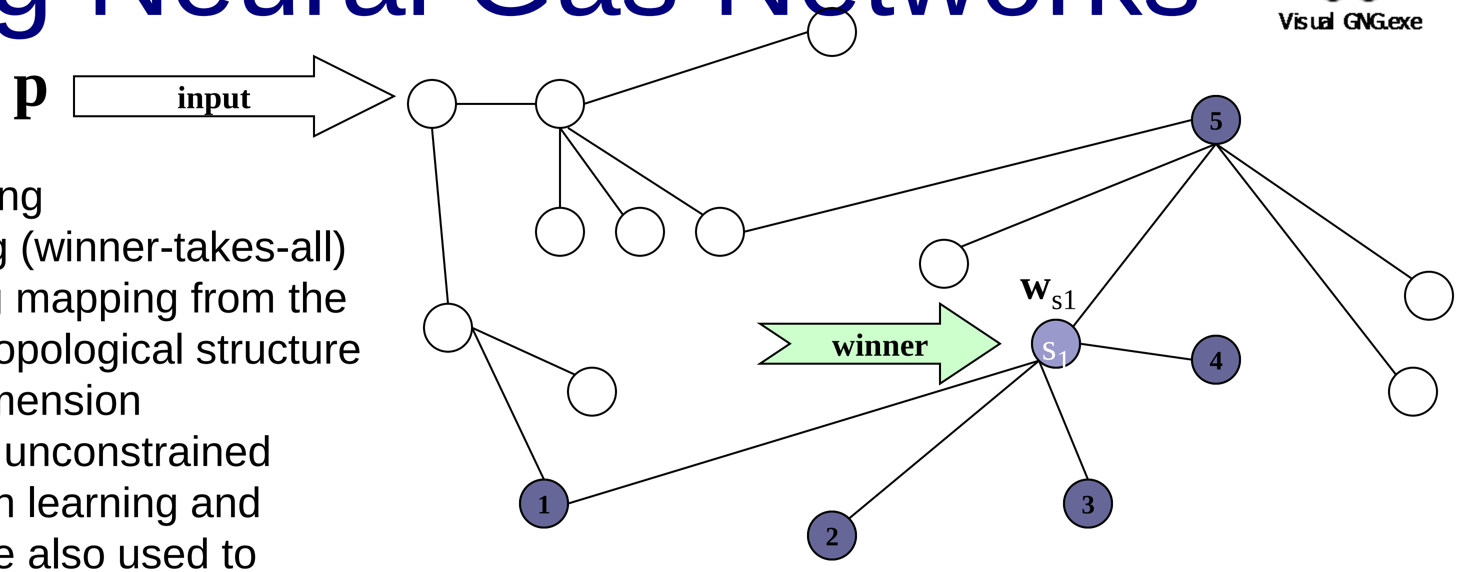


The proposed neural model



Implementation tools: Growing Neural Gas Networks

Visual GNG.exe



- Unsupervised learning
- Competitive learning (winner-takes-all)
- Topology-preserving mapping from the input space onto a topological structure of equal or lower dimension
- Network topology is unconstrained
- Competitive Hebbian learning and connection aging are also used to generate the topology
- Growth mechanism (the network size need not be predefined)
- The growth process can be interruped when a user defined performance criterion has been fulfilled

$\mathbf{w}_i$ is the weight vector associated to the unit i

Set of direct topological neighbors of the winner unit (S_1)

$$N_{s1} = \{ ① ② ③ ④ ⑤ \}$$

Updating rules:

$$\mathbf{w}_{s1} = \mathbf{w}_{s1} + \varepsilon_b (\mathbf{p} - \mathbf{w}_{s1})$$

$$\mathbf{w}_i = \mathbf{w}_i + \varepsilon_n (\mathbf{p} - \mathbf{w}_i) \; (\forall i \in N_{s_1})$$

Bernd Fritzke, “Growing Cell Structures - A Self-organizing Network for Unsupervised and Supervised Learning”. ICSI TR-93-026, 1993. *Neural Networks* 7(9):1441-1460, 1994a

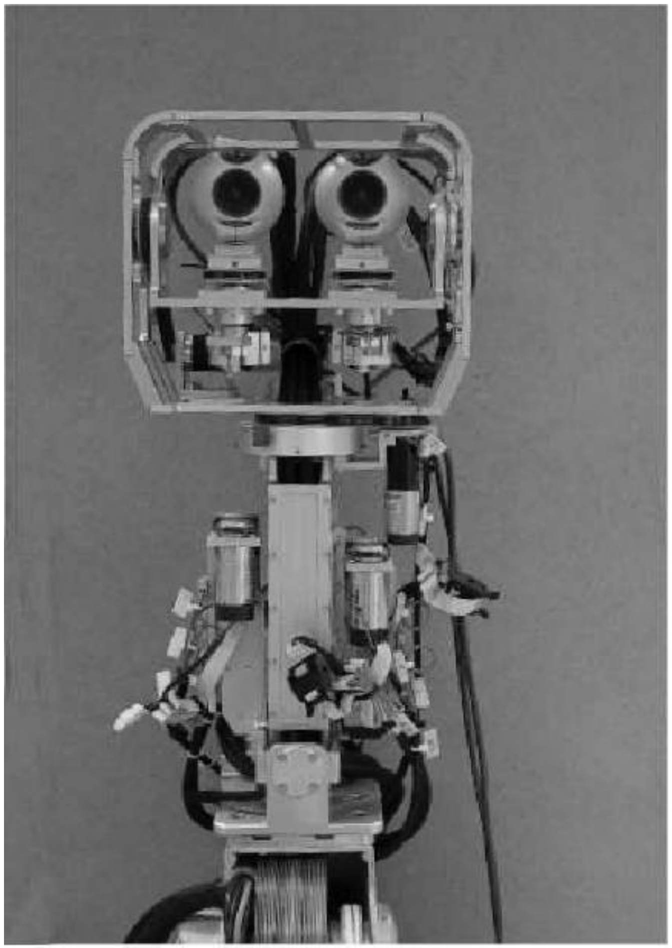
Testing phase

- After the training phase, given a target fixation point the system provides the joint rotations that drives the current gaze fixation point in the target point

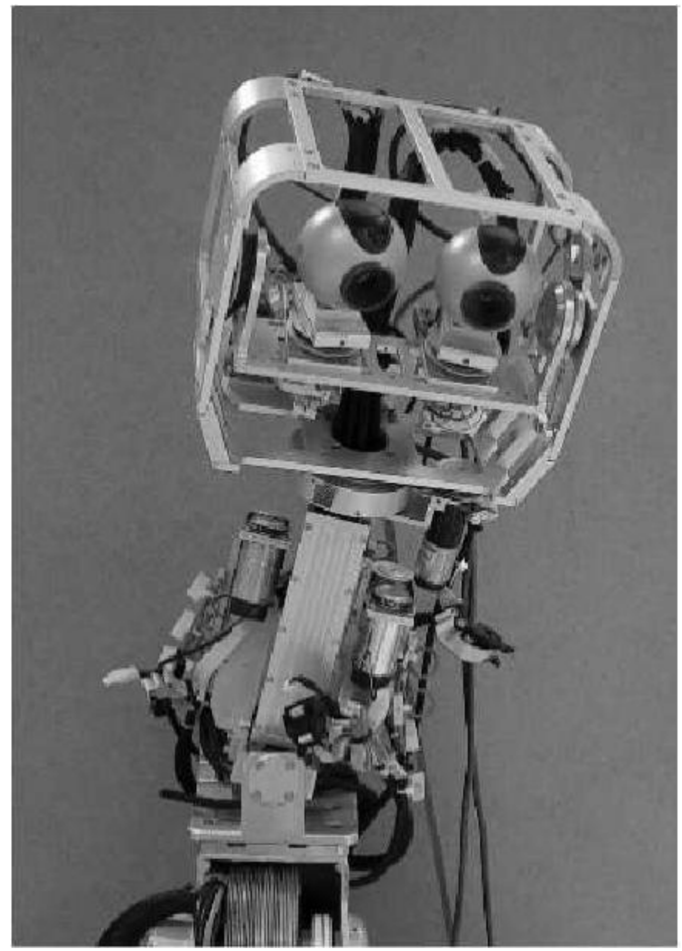
- Three different modalities:
  1. Normal (without any constraint)
  2. With a clamped joint 0
  3. With symmetric angles for eye joints

All trials have been executed without additional learning

Experimental results: normal gazing



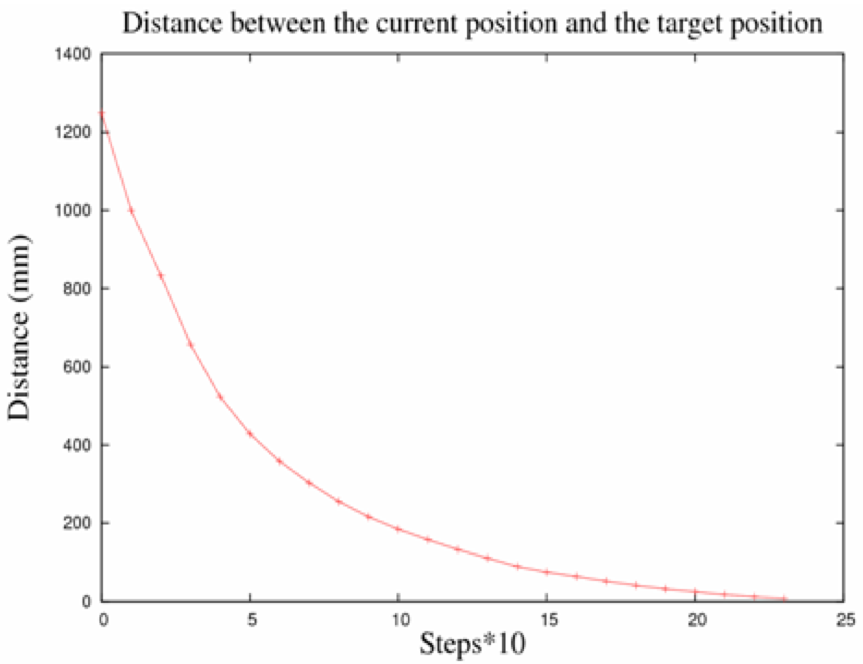
Initial posture



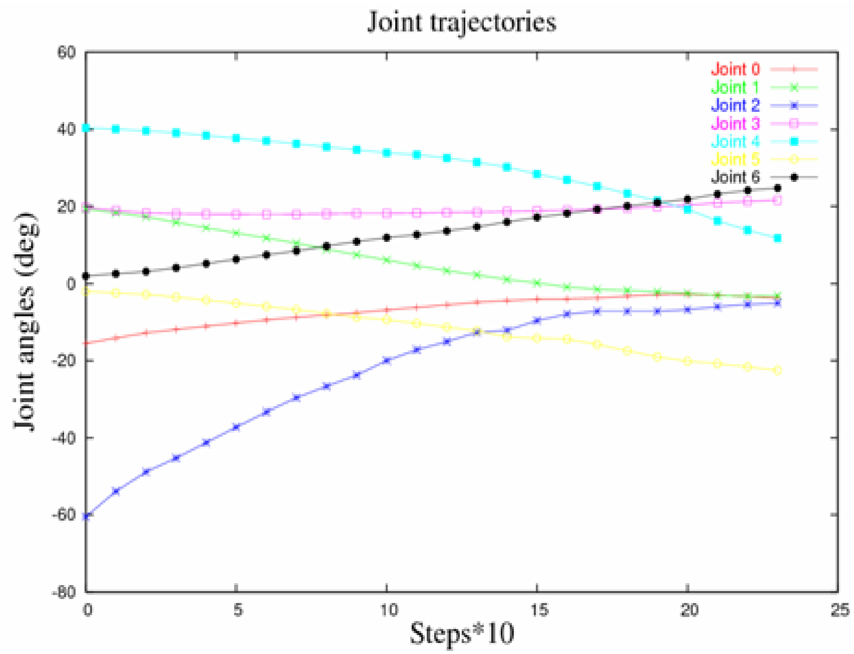
Final posture (normal)

Experimental results: robotic head (7 d.o.f)

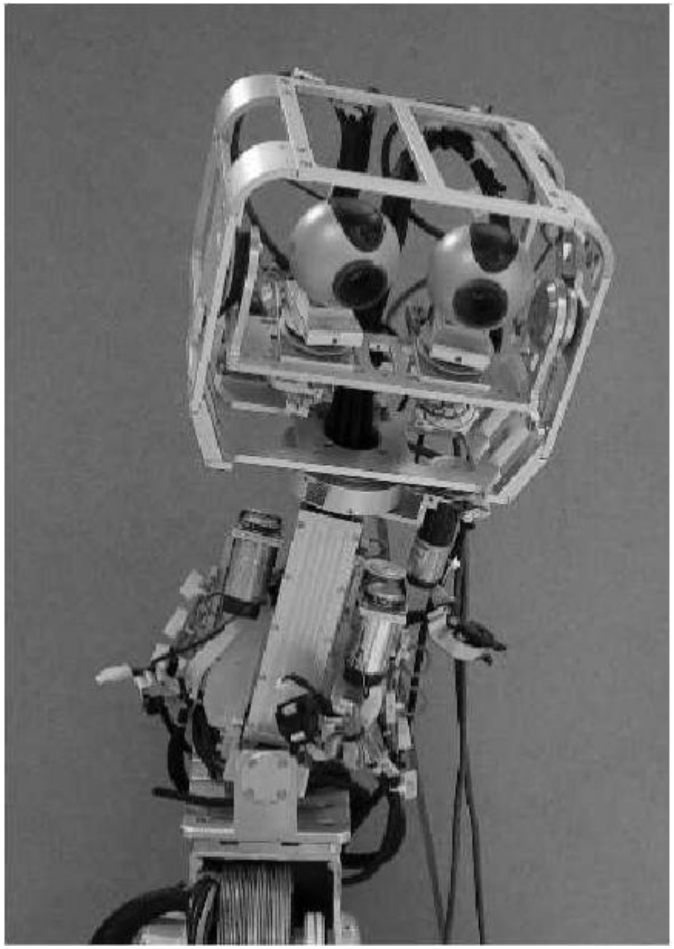
Distance between the current gaze fixation point and the target: monotonic trend



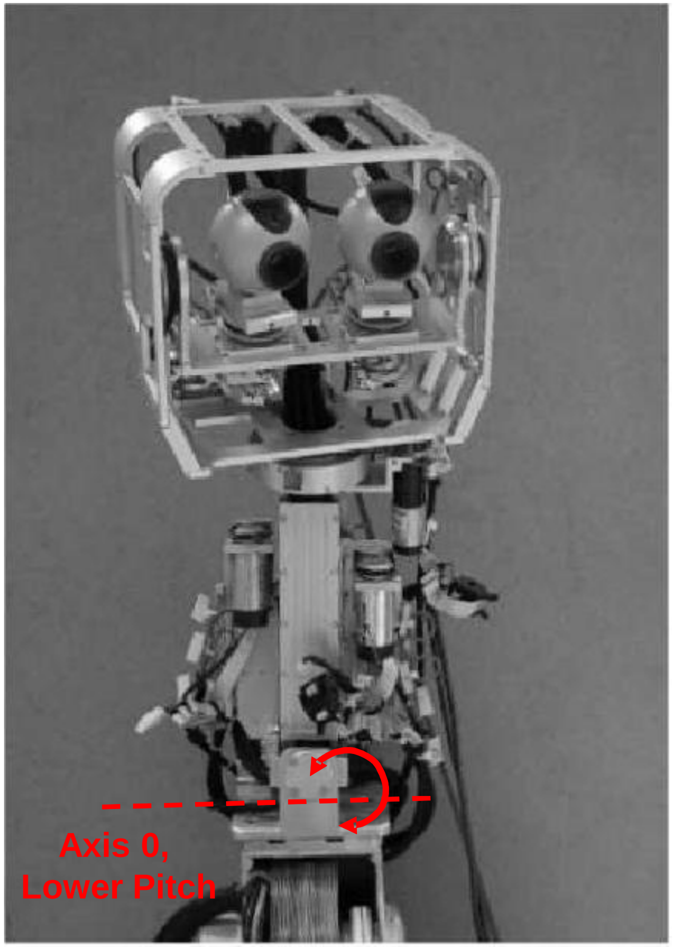
Joint trajectory



Experimental results: gazing with a clamped joint

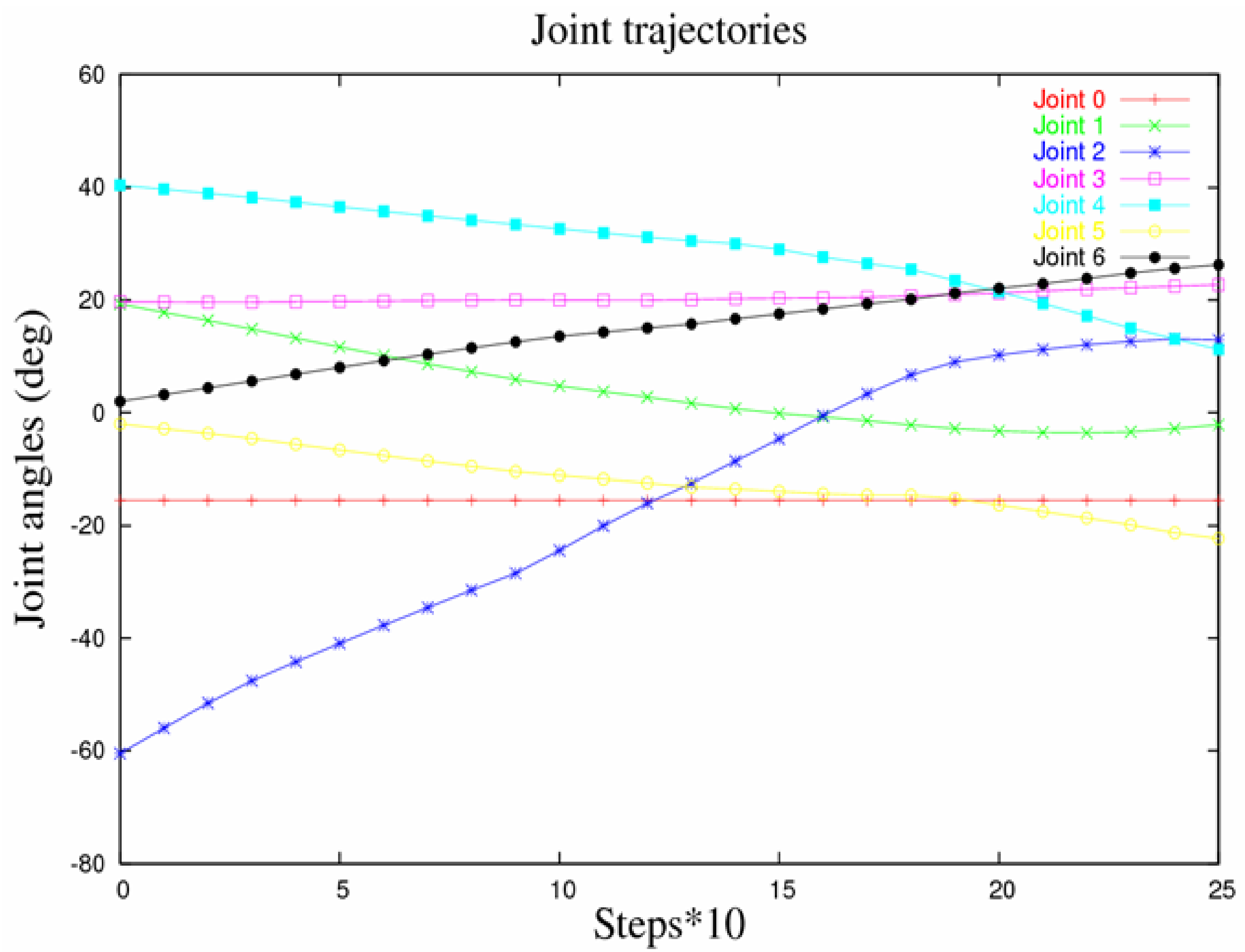


Final posture in normal mode



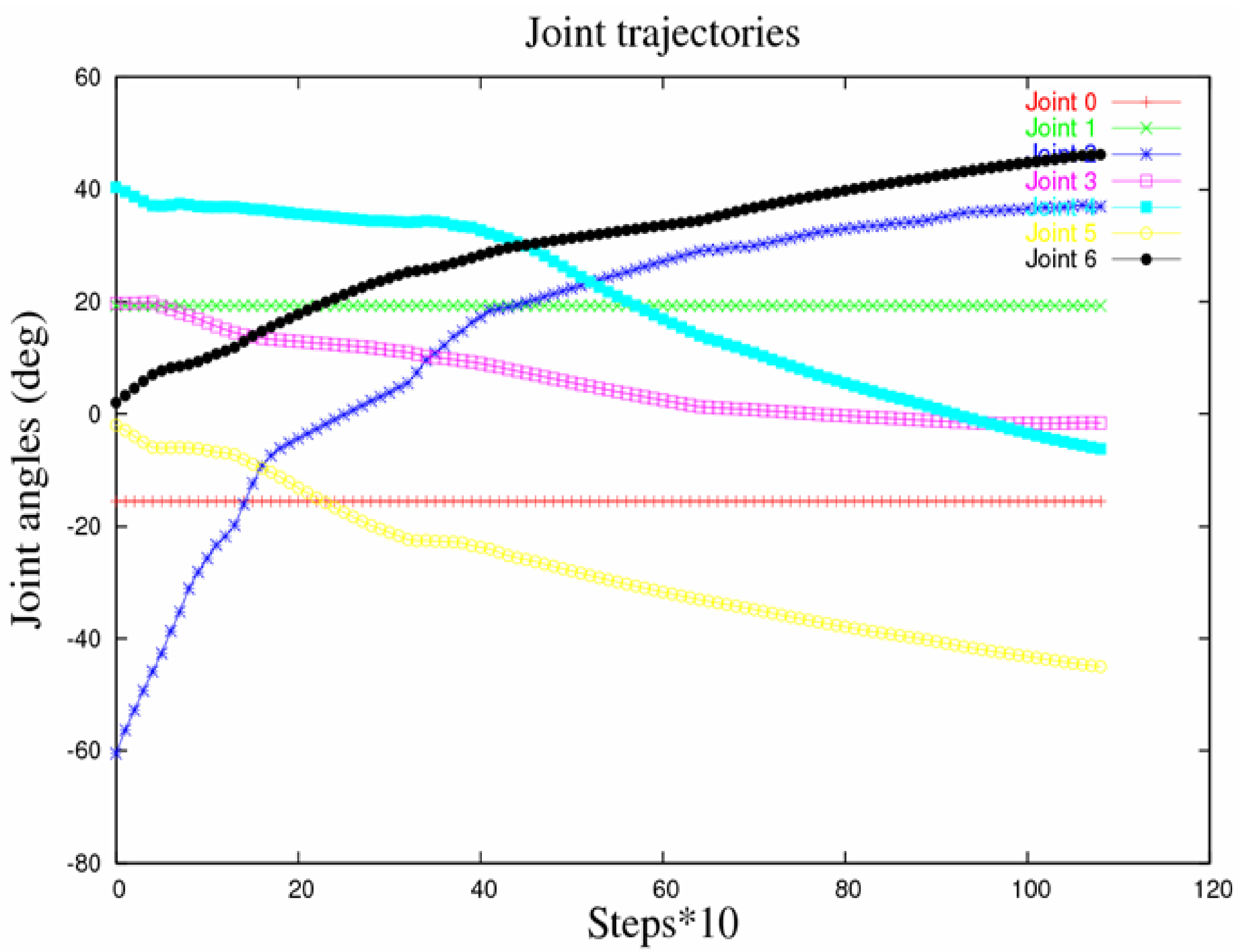
Final posture (clamped joint 0)

Experimental results: robotic head (7 d.o.f)



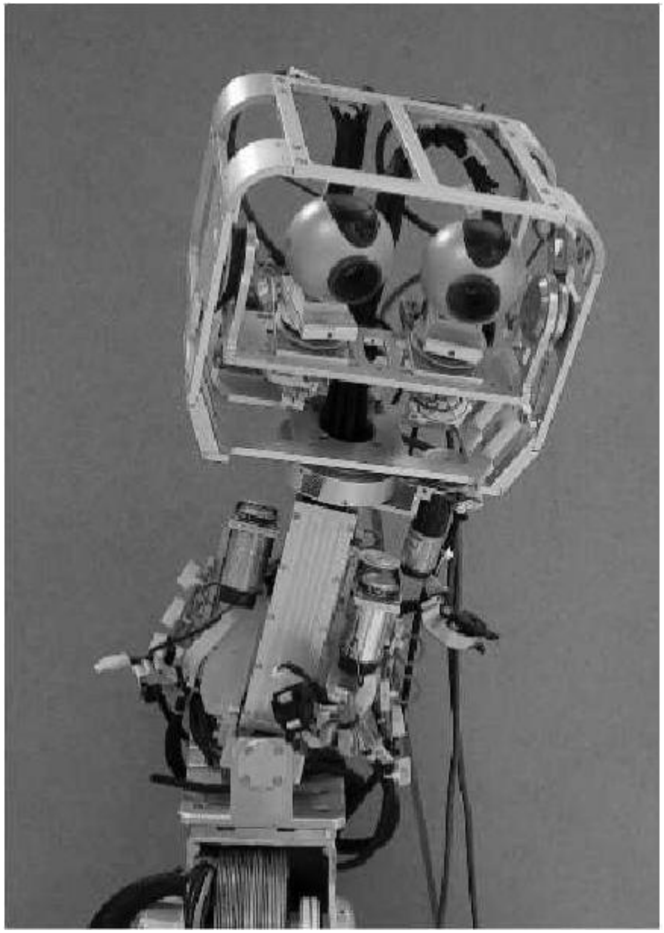
Joint trajectory: clamped joint 0

Experimental results: robotic head (7 d.o.f)

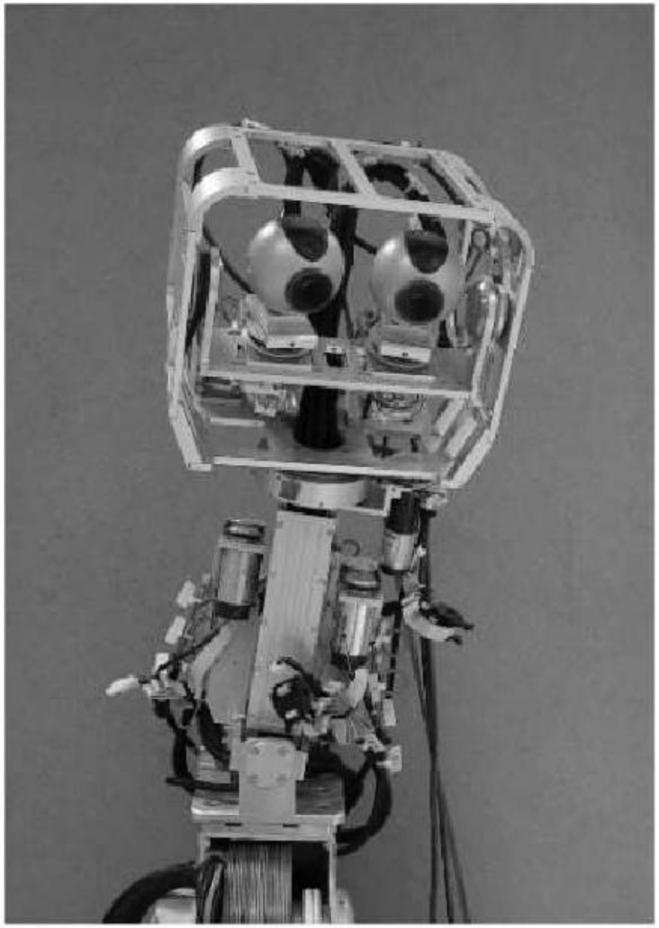


Joint trajectory: clamped joint 0 and joint 1

Experimental results: gazing with symmetric eye angles

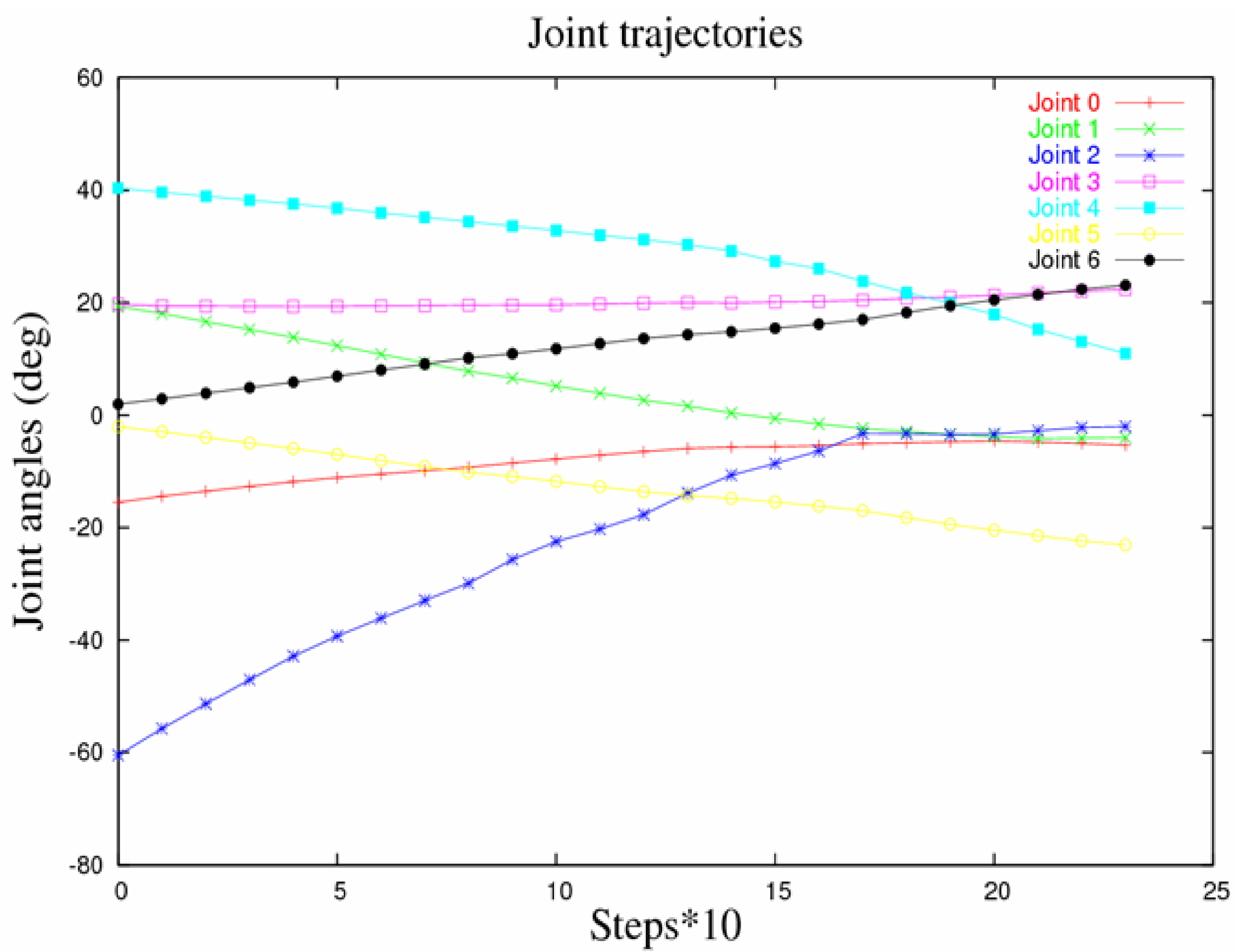


Final posture in normal mode



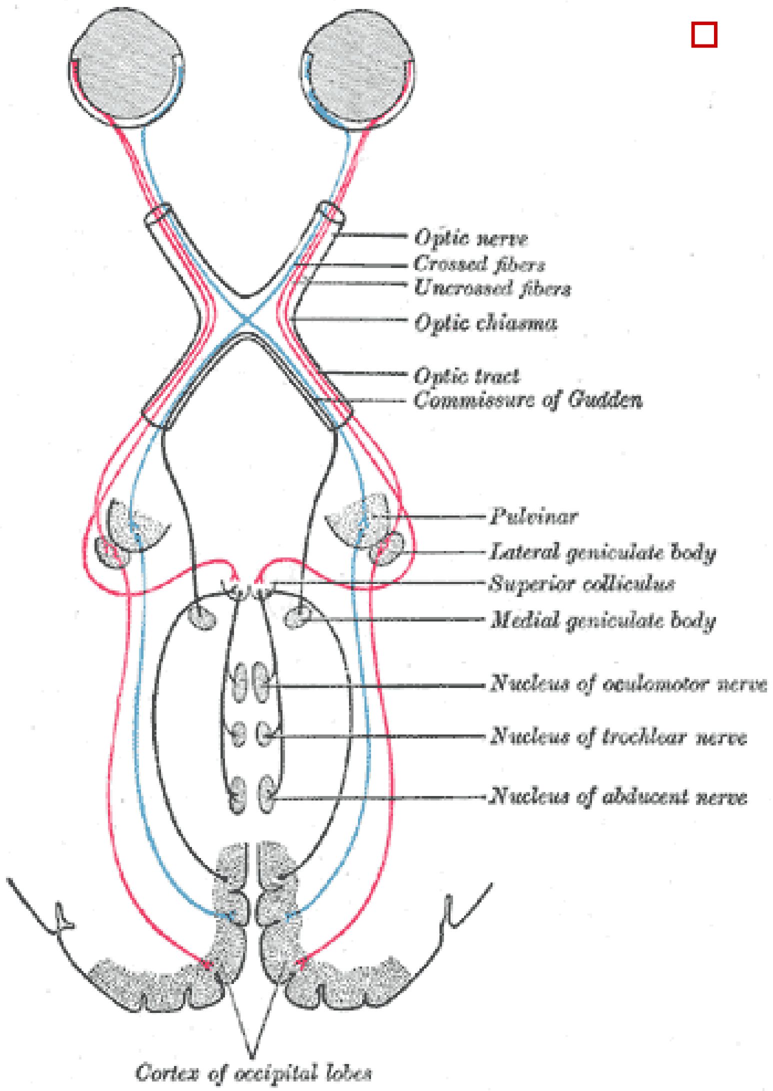
Final posture with symmetric angles for eye joints

Experimental results: robotic head (7 d.o.f)

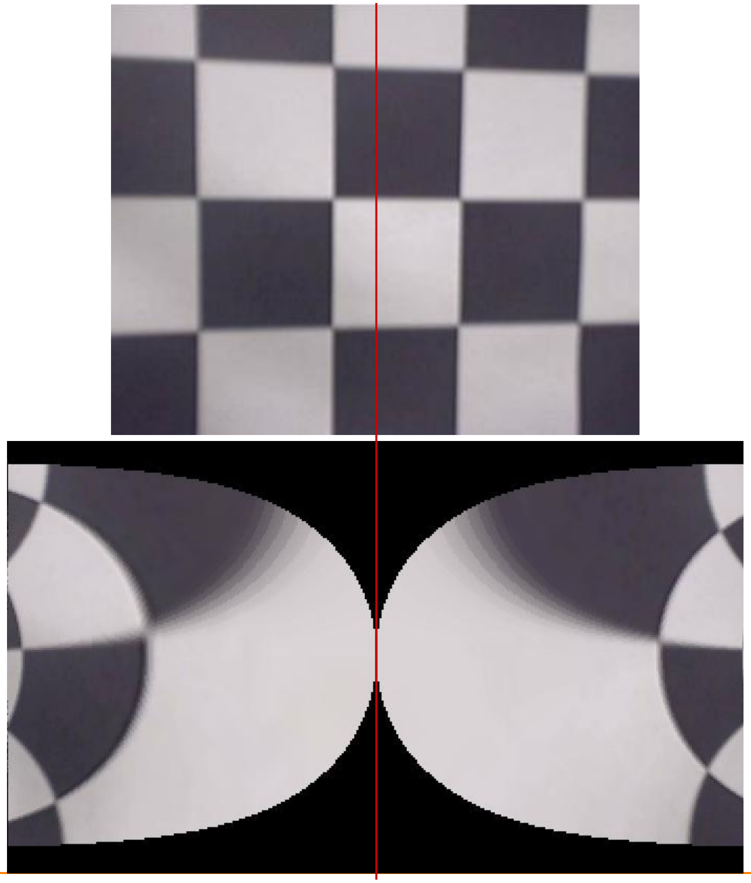


Joint trajectory: symmetric angles for eye joints (vergence)

Validation of a model of gaze control (by Prof. Alain Berthoz, College de France, Paris)



- Implementation of the mapping from the polar coordinates in visual space to the superior colliculus coordinate system, according to the model



L. Manfredi, C. Laschi, E.S. Maini, B. Girard, N. Tabereau, A. Berthoz, "Implementation of a neurophysiologic model of saccadic movements on an anthropomorphic robotic head", accepted for Humanoids 2006, Genova, Italy, Dec.4-6, 2006.

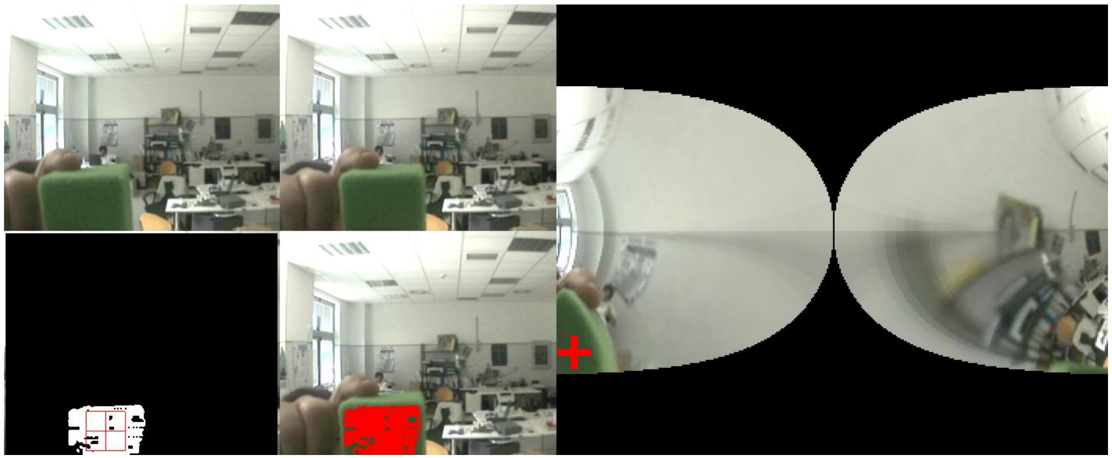
Validation of a model of gaze control (by Prof. Alain Berthoz, College de France)

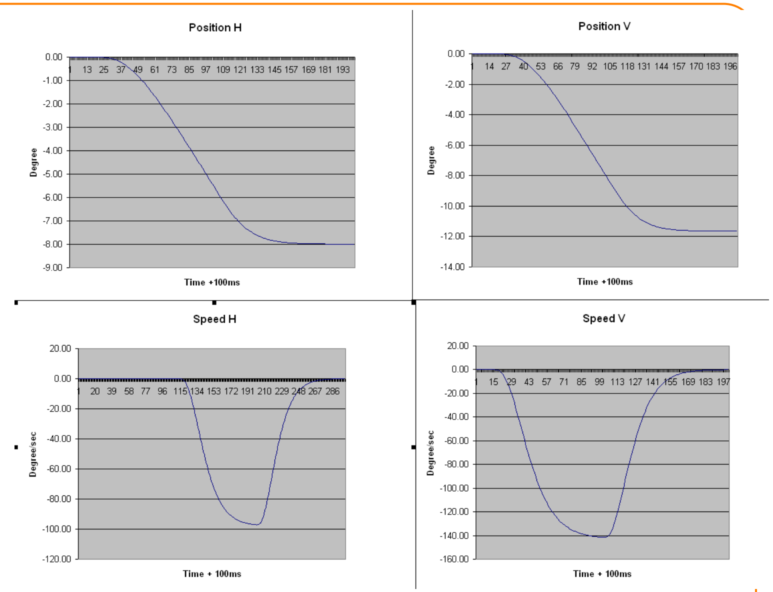
- Implementation of the mapping from the polar coordinates in visual space to the superior colliculus coordinates system, according to the model
- Generation of saccade movements:
  - A stimulus of a given colour can be detected in the map and the coordinates calculated in the superior colliculus, in real time
  - These coordinates are sent to the gaze control model to calculate the velocity profile for gaze control
  - The velocity profiles are used to control the robot head to generate the saccade movements of the eyes

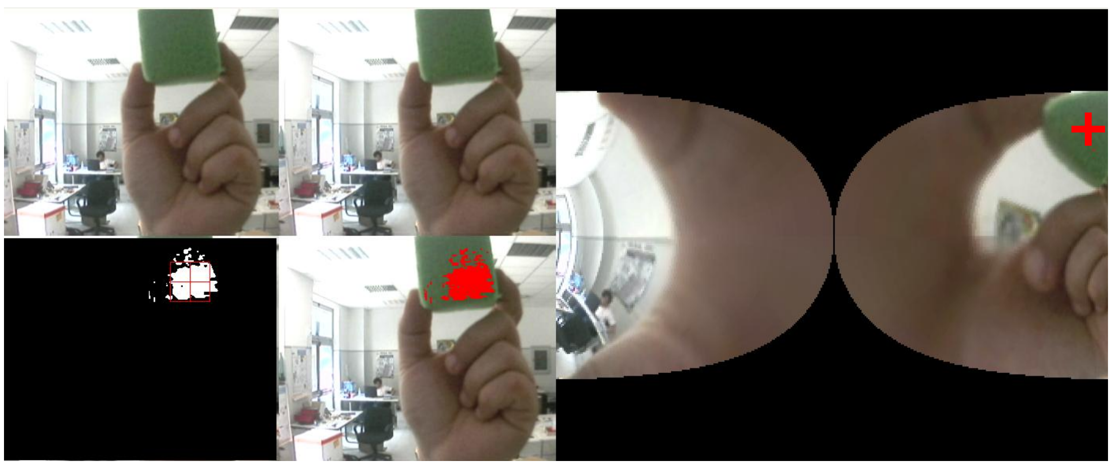
Original images

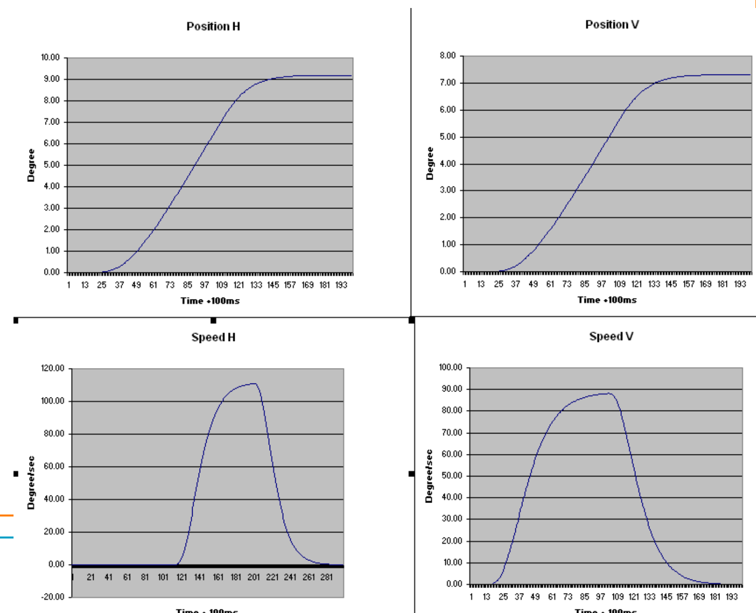
Collicular mapping (red point: stimulus coordinates)

Generation of saccade movements









Generation of saccade movements

Stimulus #1

Stimulus #2

Saccades executed by the right eye