

Corso di Percezione Robotica (PRo)



C. Modulo di Percezione

Cenni sulla visione
artificiale retinica

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Sommario della lezione

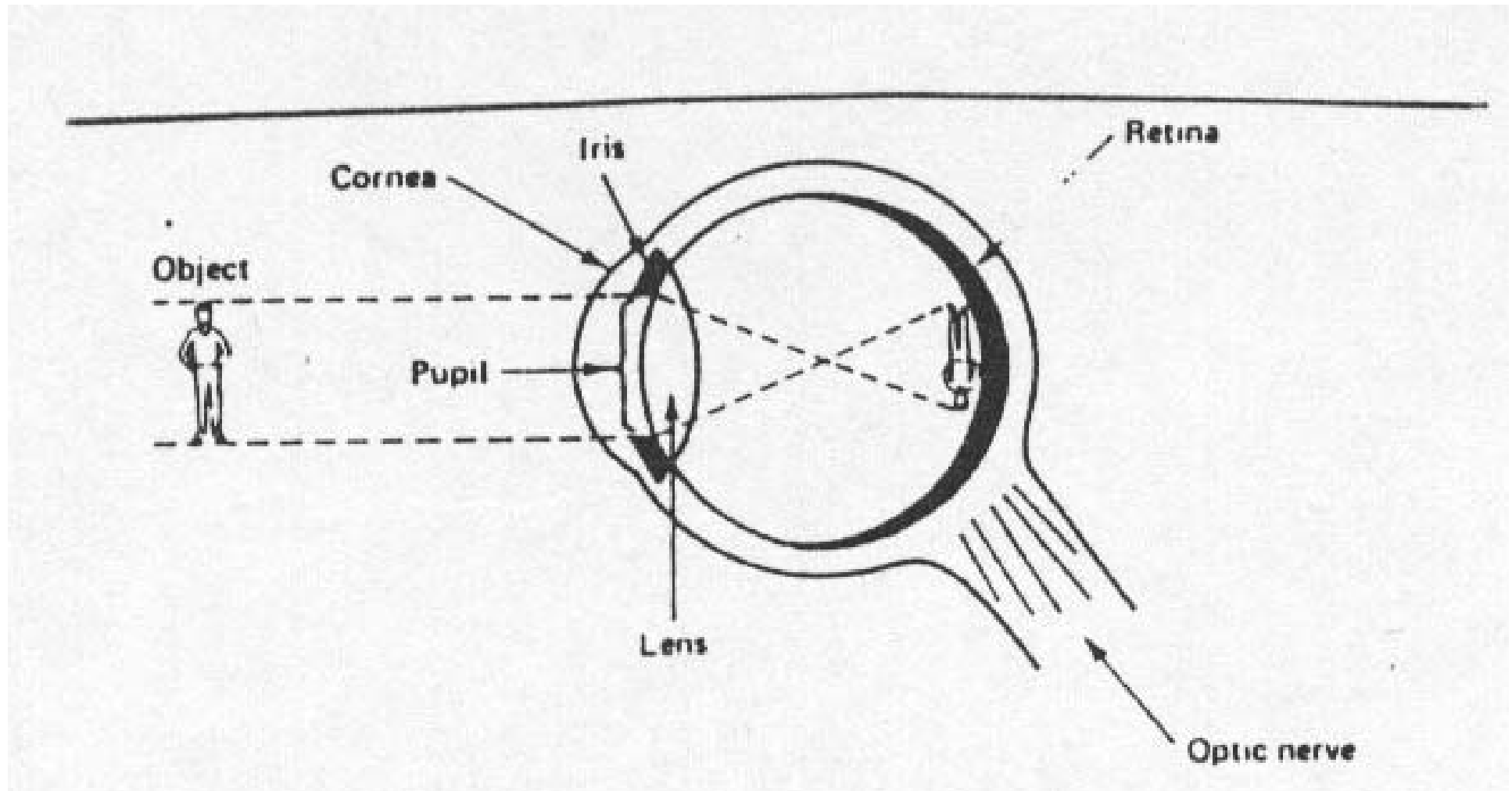


- Immagini digitali e classi di tecniche di elaborazione delle immagini
- Principi di base della visione retinica
- Alcune proprietà delle immagini retiniche
- Le relazioni matematiche tra immagini retiniche e cartesiane
- La foveazione
- Una testa robotica antropomorfa
- Esempi di applicazione in robotica

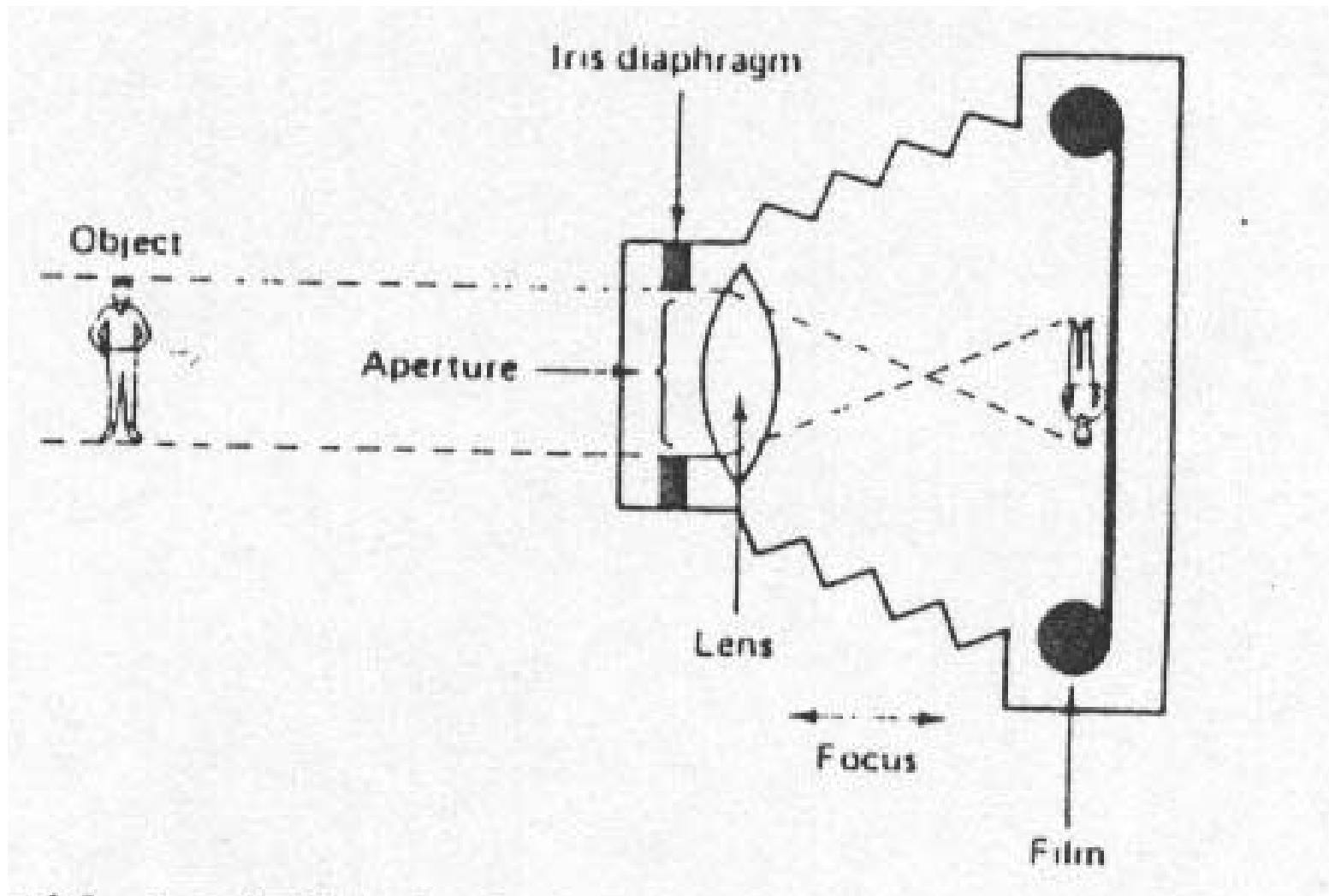
Riferimenti bibliografici:

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.

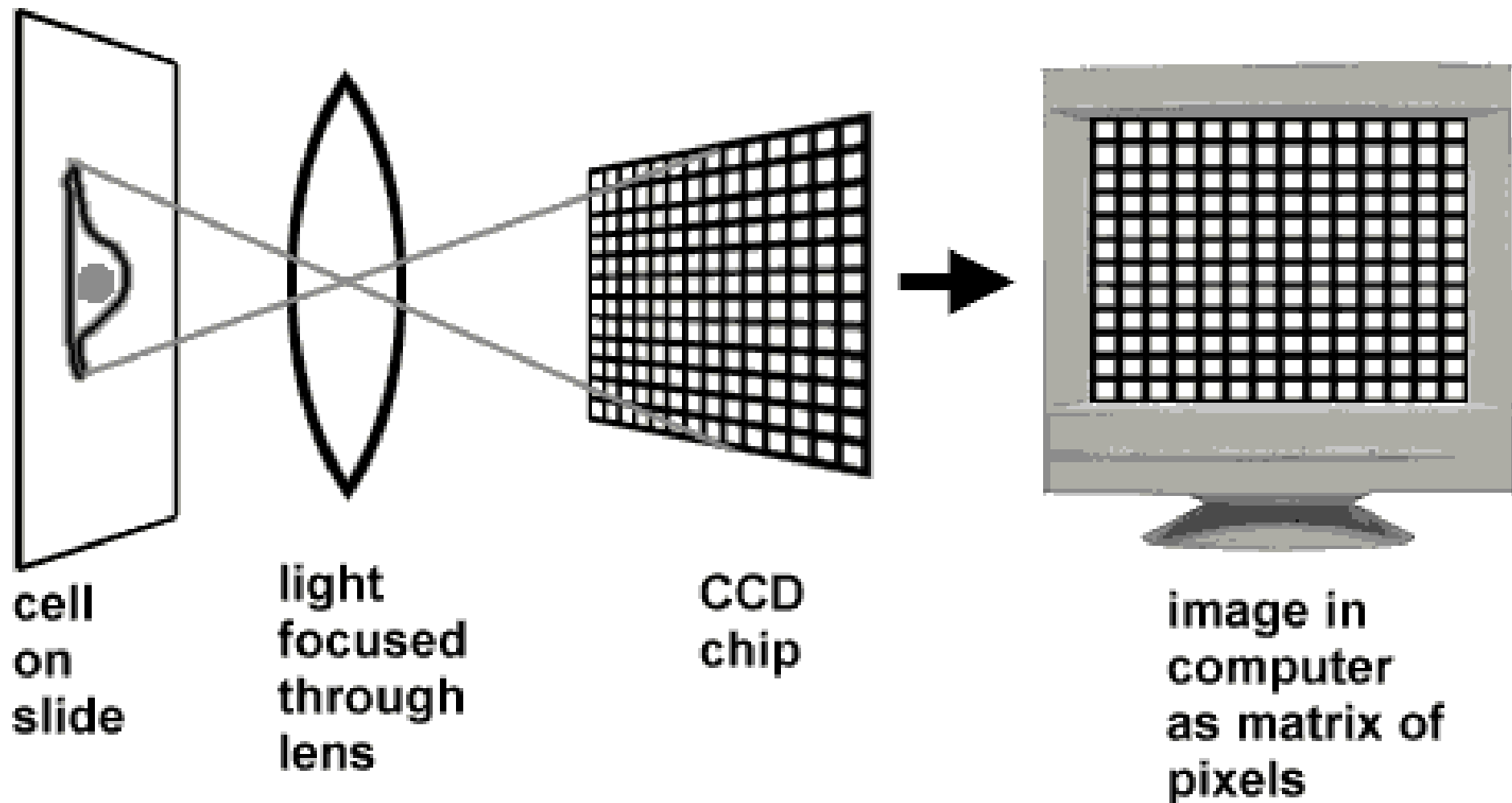
Formazione dell'immagine nell'occhio



Formazione dell'immagine nella macchina fotografica



Formazione dell'immagine nella telecamera



Funzione immagine ed immagine digitale



- $f(x,y) \in \mathbb{R}^2 \times \mathbb{R}$
- (x,y) : coordinate spaziali
- $f(x,y)$: valore dell'intensità luminosa in quel punto

Funzione immagine ed immagine digitale



- CAMPIONAMENTO DELL'IMMAGINE: digitalizzazione delle coordinate spaziali
- QUANTIZZAZIONE DELL'INTENSITA' (o DEI LIVELLI DI GRIGIO): digitalizzazione in ampiezza
- PIXEL: elemento dell'immagine digitale

Un esempio di immagine digitale

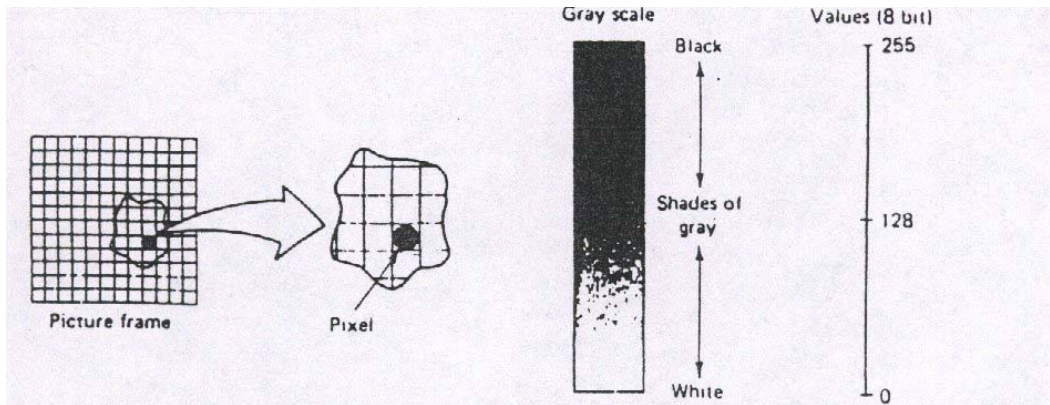
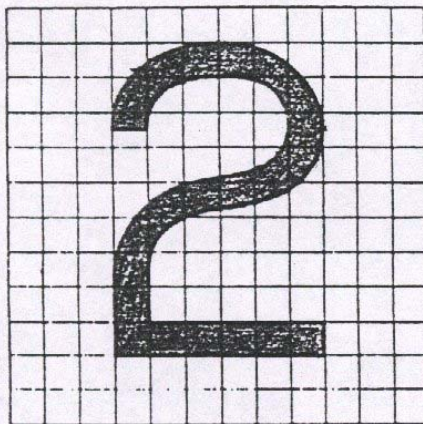


Figure 6-12 A picture frame is divided into picture elements, called pixels, for conversion to a gray-scale value.



(a)

0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	50	128	240	255	150	0	0	0	0
0	0	0	200	128	0	0	128	128	0	0	0
0	0	0	128	0	0	0	0	255	0	0	0
0	0	0	0	0	15	50	200	225	0	0	0
0	0	0	25	200	225	175	128	0	0	0	0
0	0	0	200	56	0	0	0	0	0	0	0
0	0	0	255	0	0	0	0	0	0	0	0
0	0	0	255	0	0	0	0	0	0	0	0
0	0	0	255	255	255	255	255	255	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0

(b)

Figure 6-13 (a) a 12 x 12 pixel grid and (b) matrix for the number 2 (Example 6-1).

Classi principali di tecniche di elaborazione delle immagini

EARLY PROCESSING / PRE-ELABORAZIONE

- Elaborazione dei valori dei pixel, a livello

locale

Es:

- FILTRAGGIO
- RILEVAMENTO DEI BORDI (EDGE DETECTION)

SEGMENTAZIONE

- Identificazione delle parti che costituiscono una scena

- CONTORNI (BOUNDARY): elementi di una immagine segmentata basati sulla **discontinuità**
- REGIONI: elementi di una immagine segmentata basati sulla **uniformità**

Principi di base della visione retinica

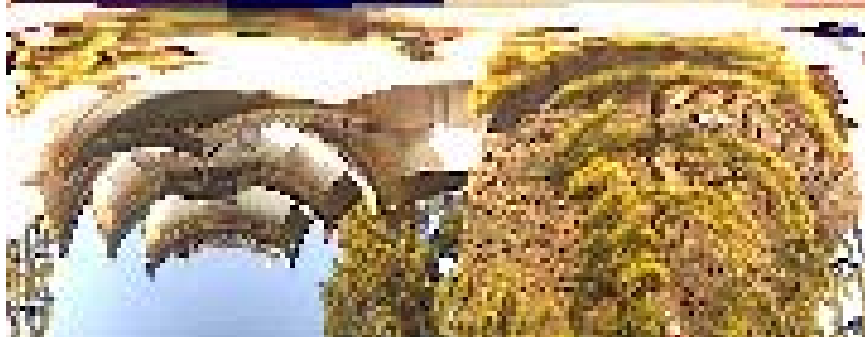
Standard image



Retina-like image



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



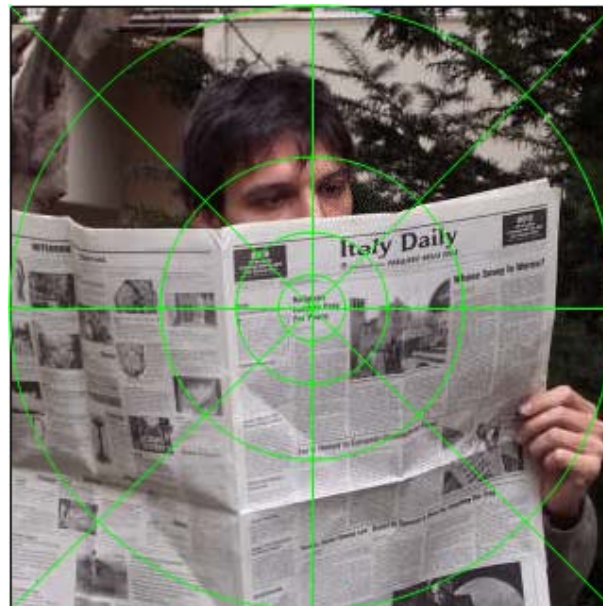
Log-polar projection



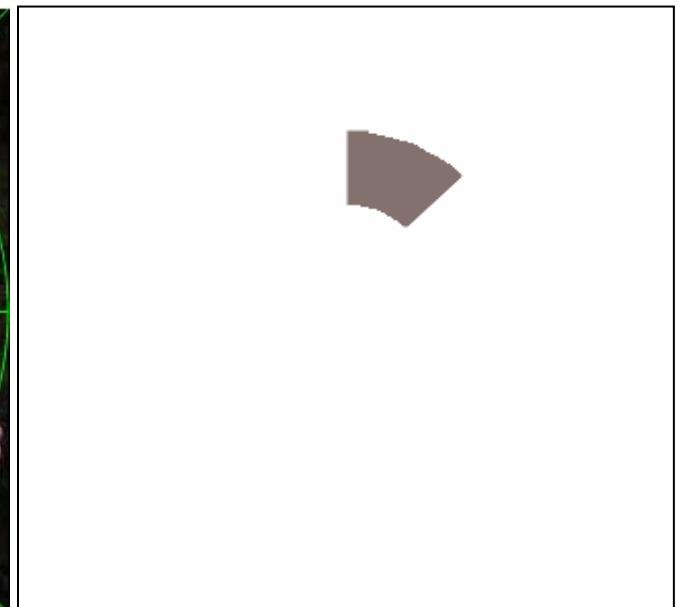
Costruzione di un'immagine retinica



Immagine cartesiana tradizionale



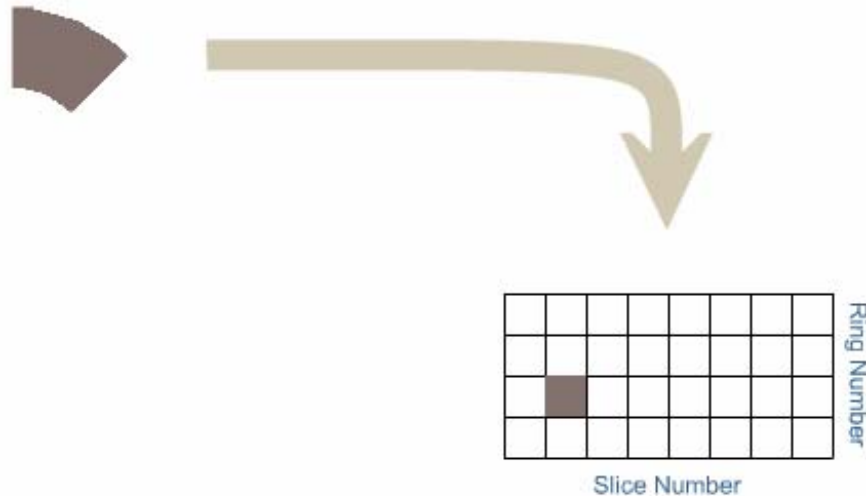
Divisione in circonferenze e spicchi



Calcolo del valore medio di un settore

Costruzione di un'immagine retinica

<http://www.retinica.com/>



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

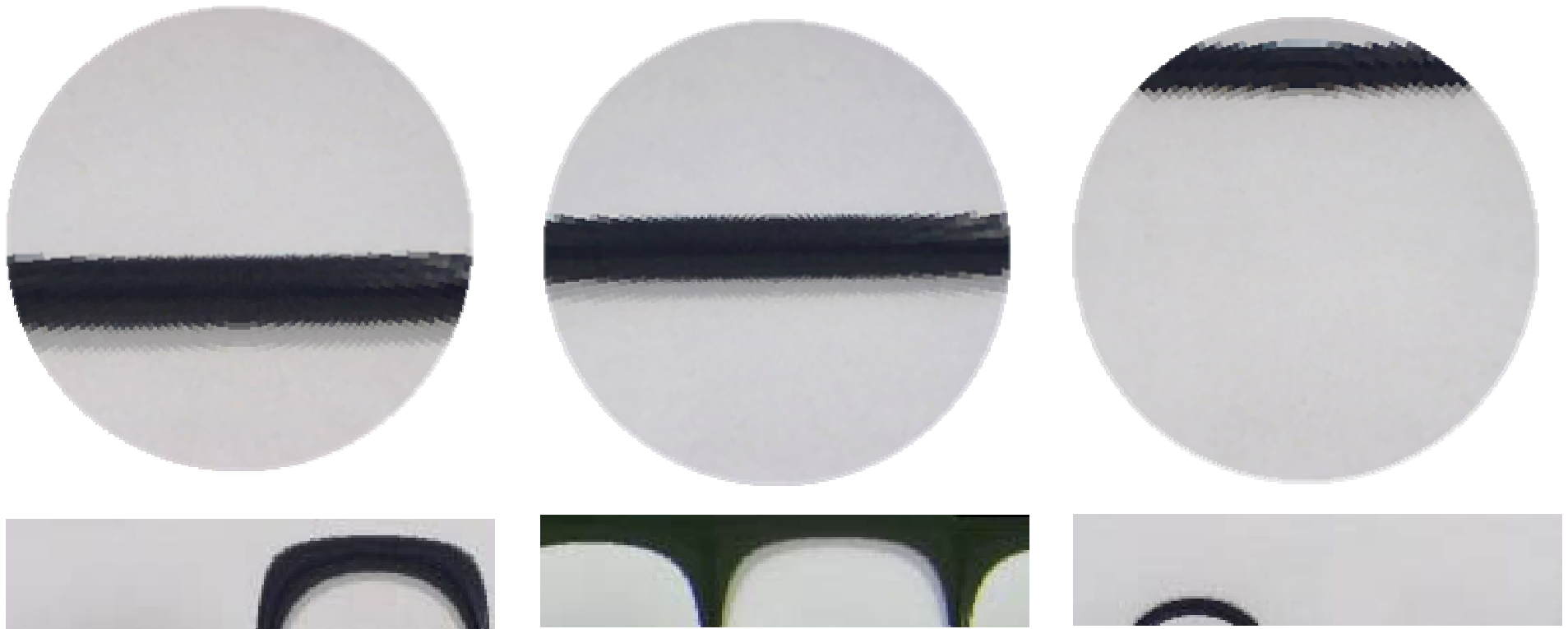


Immagine polare risultante

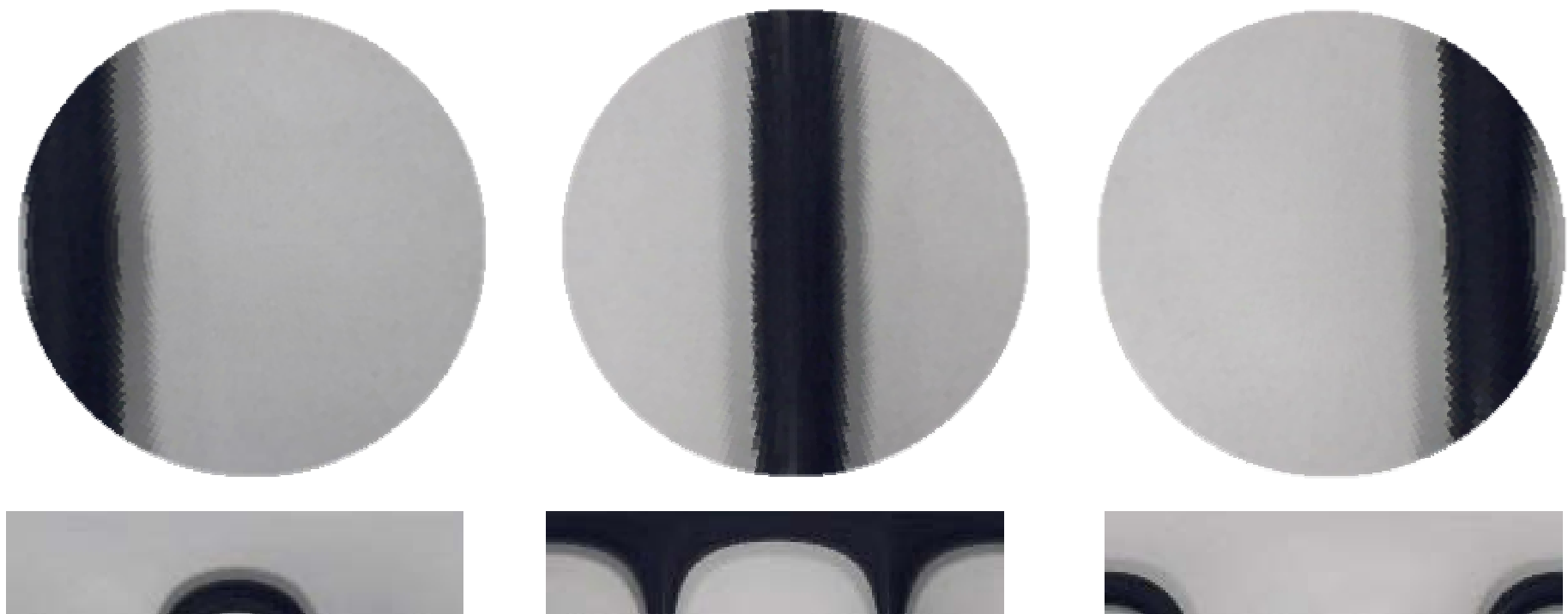


Immagine cartesiana ricostruita dalla polare

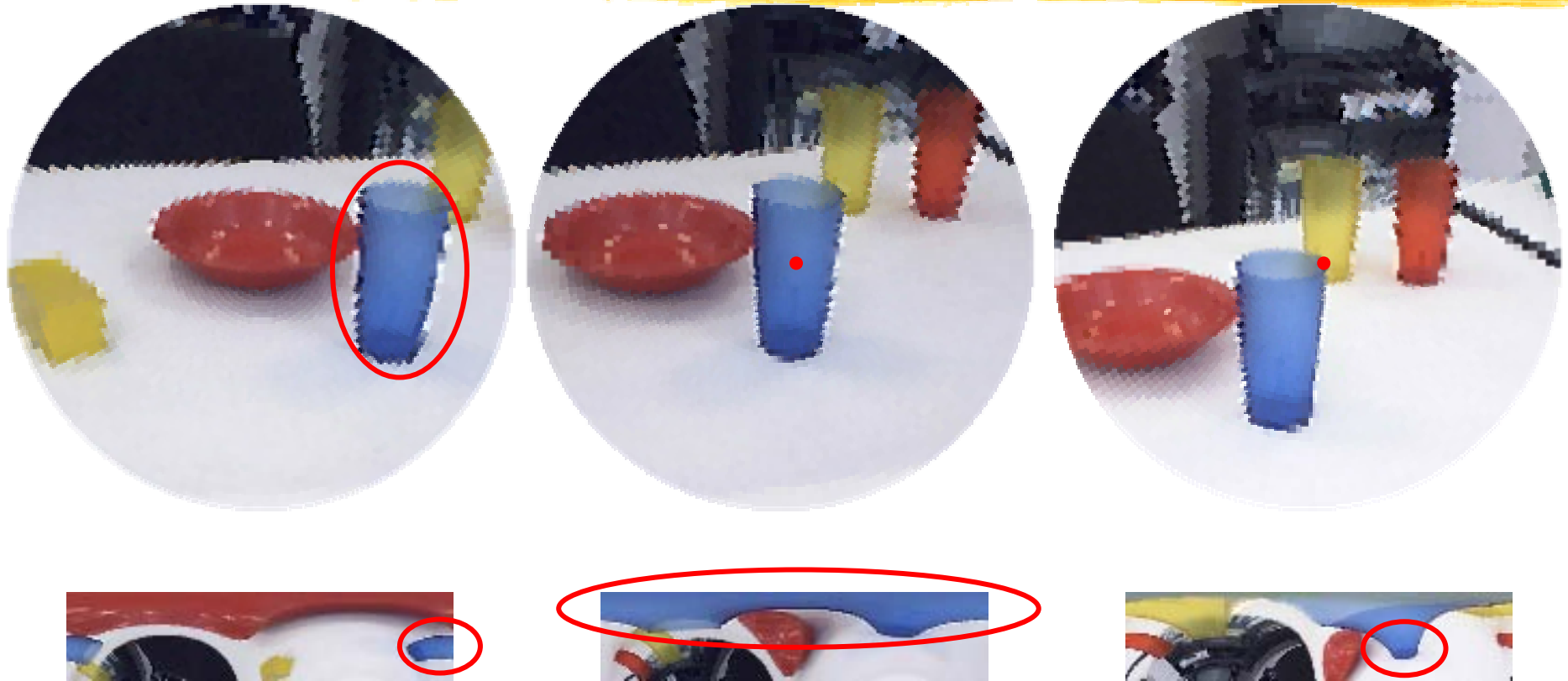
An example of pattern translation



An example of pattern translation



An example of simulated foveation



Object detection
in the periphery

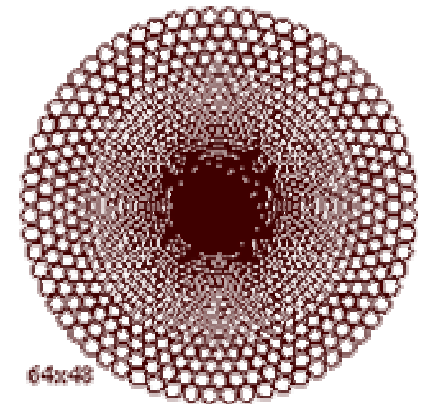
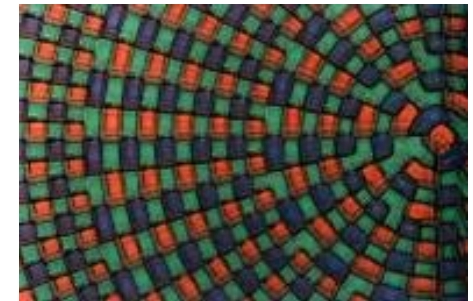
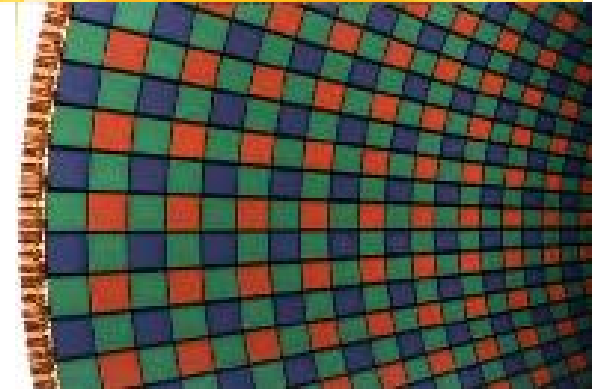
Object foveation

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

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

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

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

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

F = size of the fovea in rings.

P = total number of rings.

Θ = maximum # of pixels in each ring.

$2X$ = horizontal size of the cartesian image.

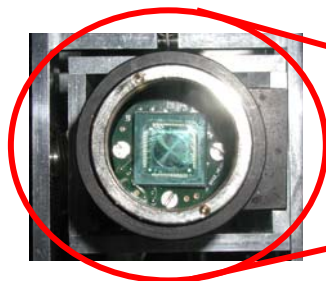
$2Y$ = vertical size of the cartesian image.

ρ = ring number in the log polar image.

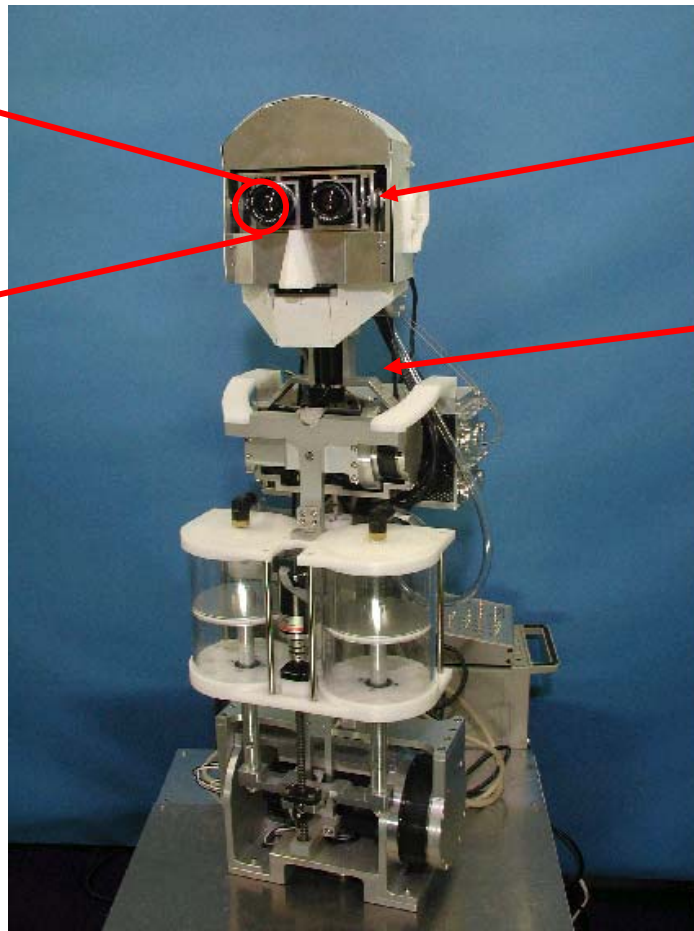
θ = angular polar coordinate.

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*

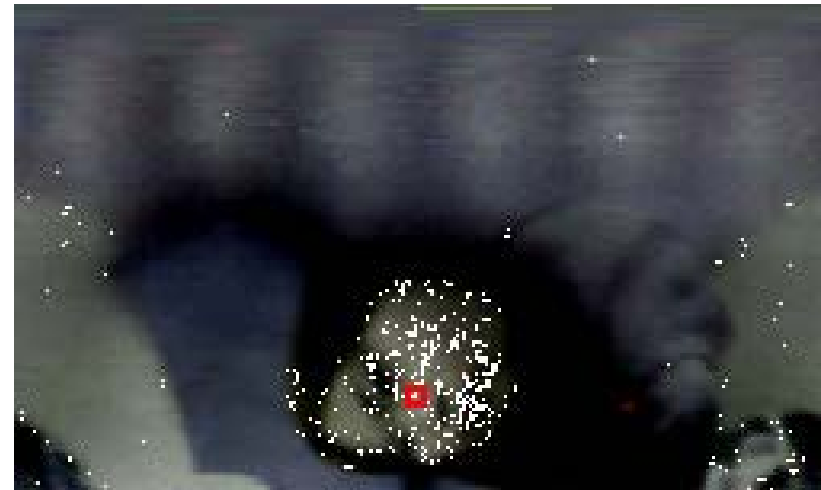
Face detection by hue

Hue = information on the color

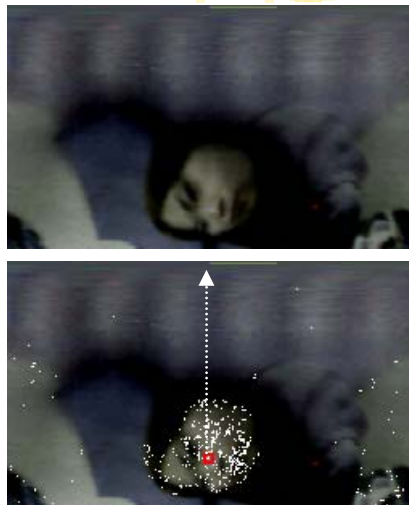
$$\text{Hue} = \cos^{-1} \left(\frac{(R - G) + (R - B)}{2\sqrt{(R - G)^2 + (R - B)(G - B)}} \right)$$

if $B > G$ then $\text{Hue} = 2\pi - \text{Hue}$

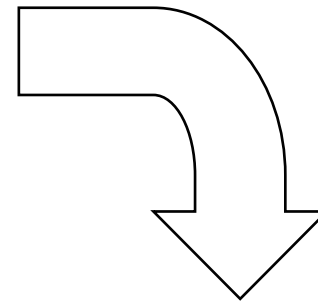
R, G, B = RED, GREEN, BLUE components, respectively



An example of foveation

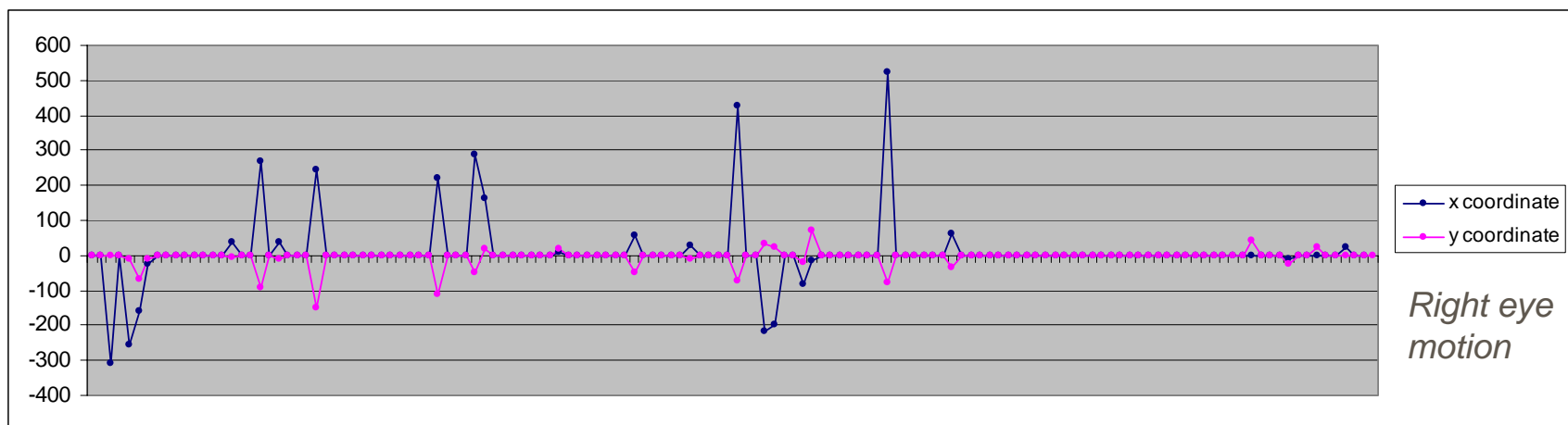


Eye/neck movements



Proportions are rescaled for display purposes

Experimental trials



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

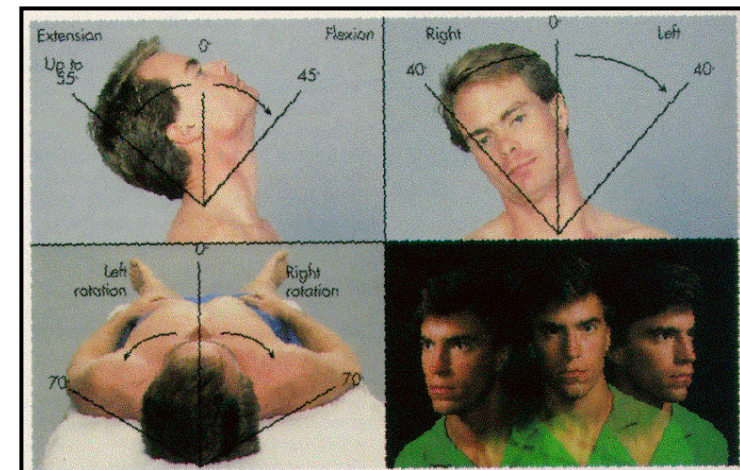
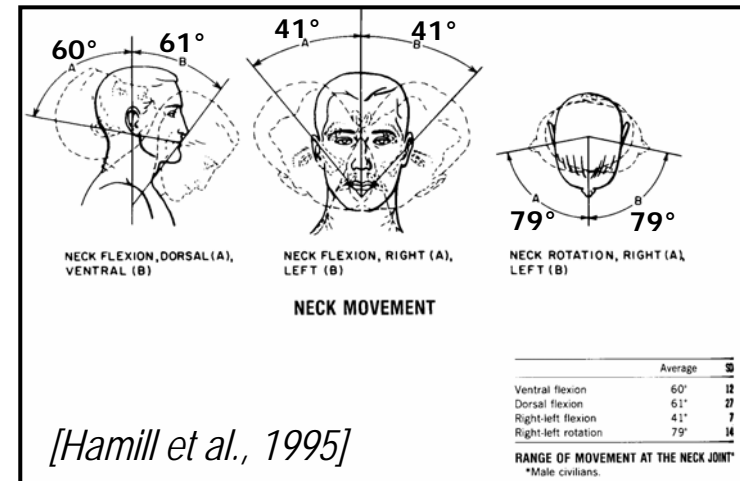
Example of design and development of a human-like robotic head



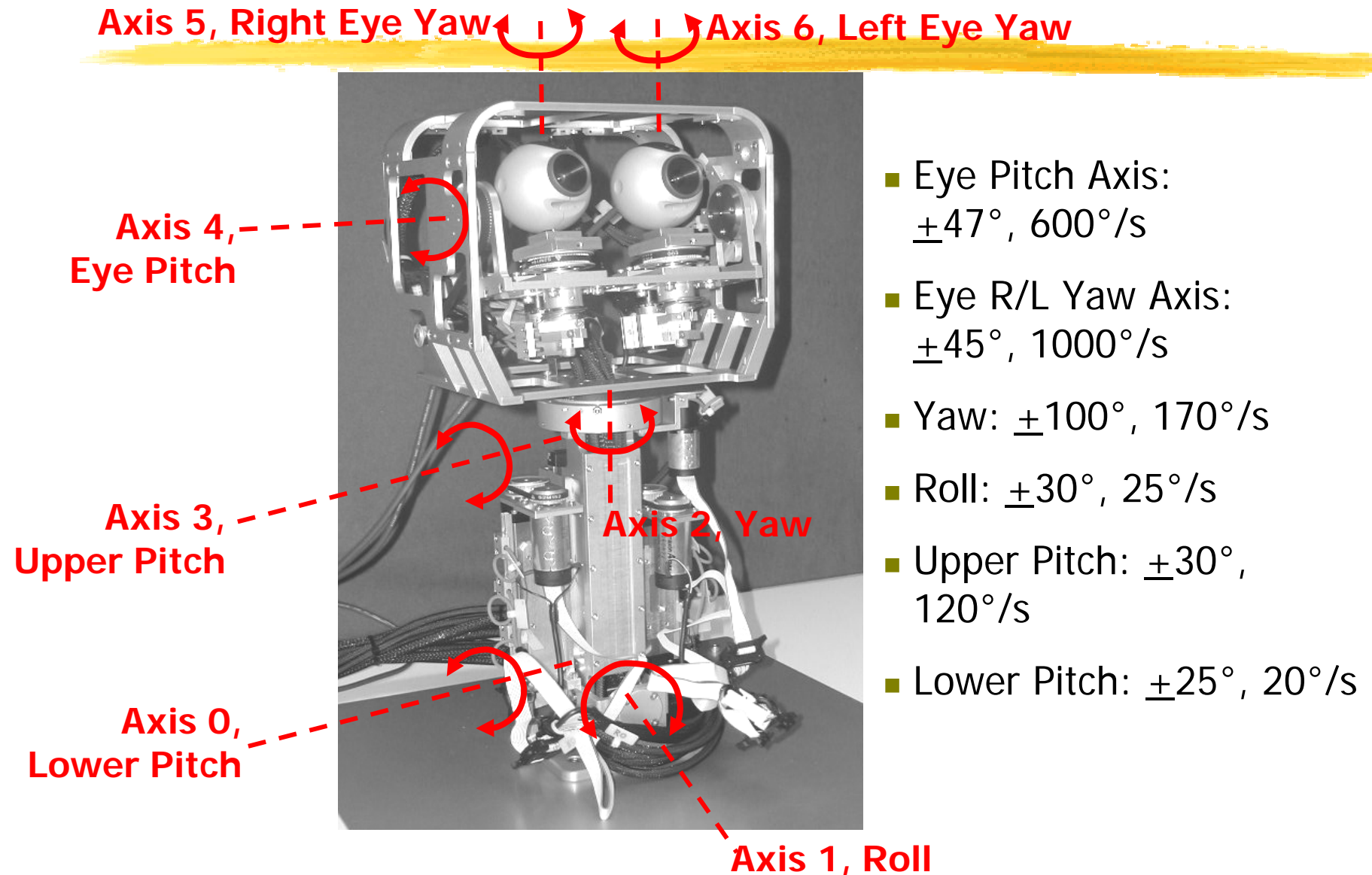
The ARTS humanoid robot head

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

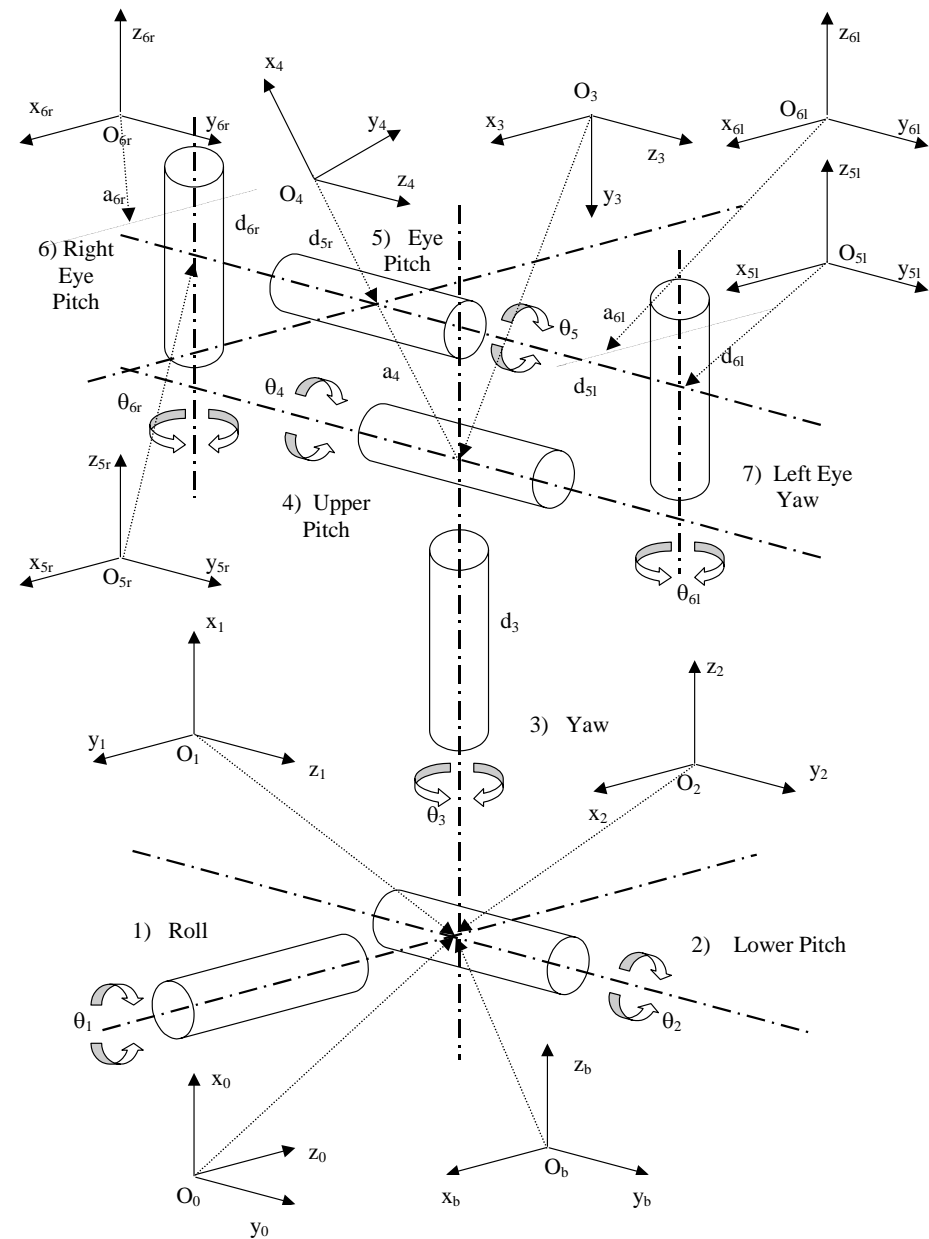


Kinematic structure of the SSSA Robot Head



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 ÷ -50	$\pi/2$
J5 _l	0	30 ÷ 50	$\pi/2$
J6 _l	a_{6l}	d_{6l}	0
J6 _r	a_{6r}	d_{6r}	0

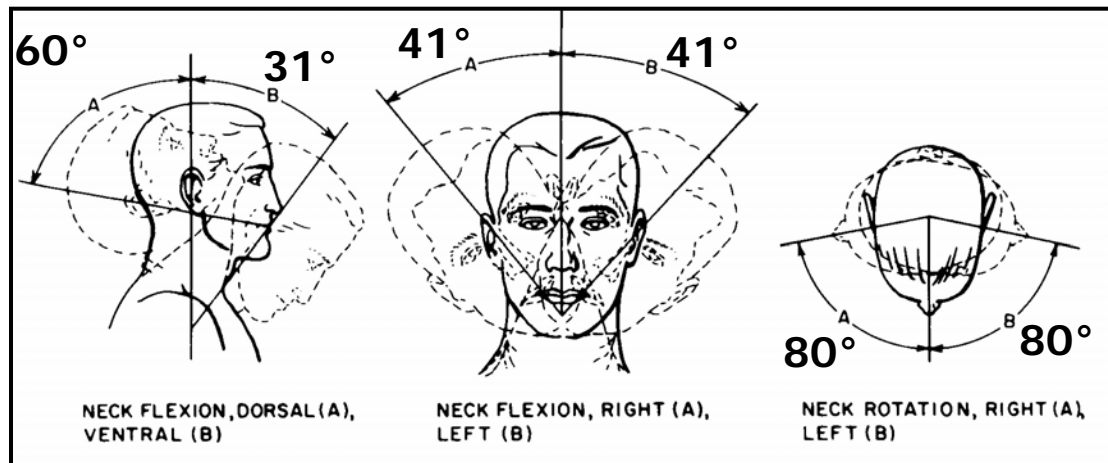


Comparison of performances between human and robotic head

Neck:

Eye:

Human

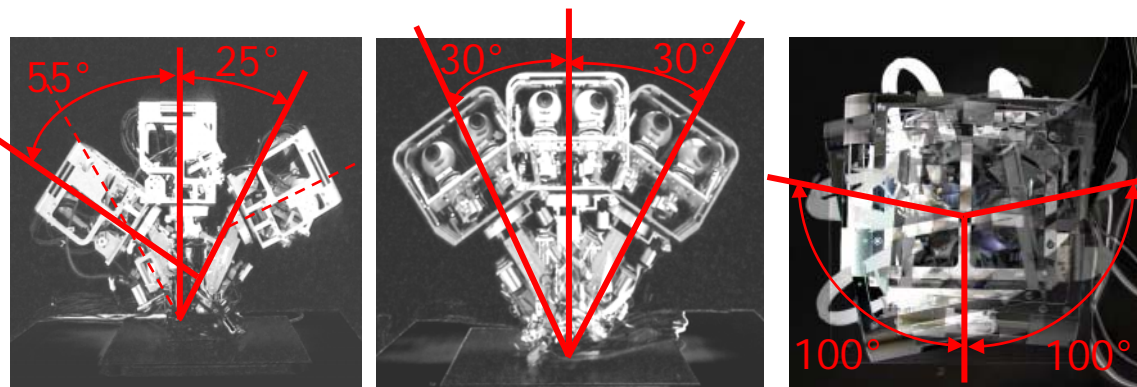


[Hamill et al., 1995]

Pitch: $\pm 60^\circ$, $600^\circ/s$

Yaw: $\pm 30^\circ$, $600^\circ/s$

Robot



Pitch: $\pm 47^\circ$, $600^\circ/s$

Yaw: $\pm 45^\circ$, $1000^\circ/s$

The movements of the 7 dofs of the robotic head

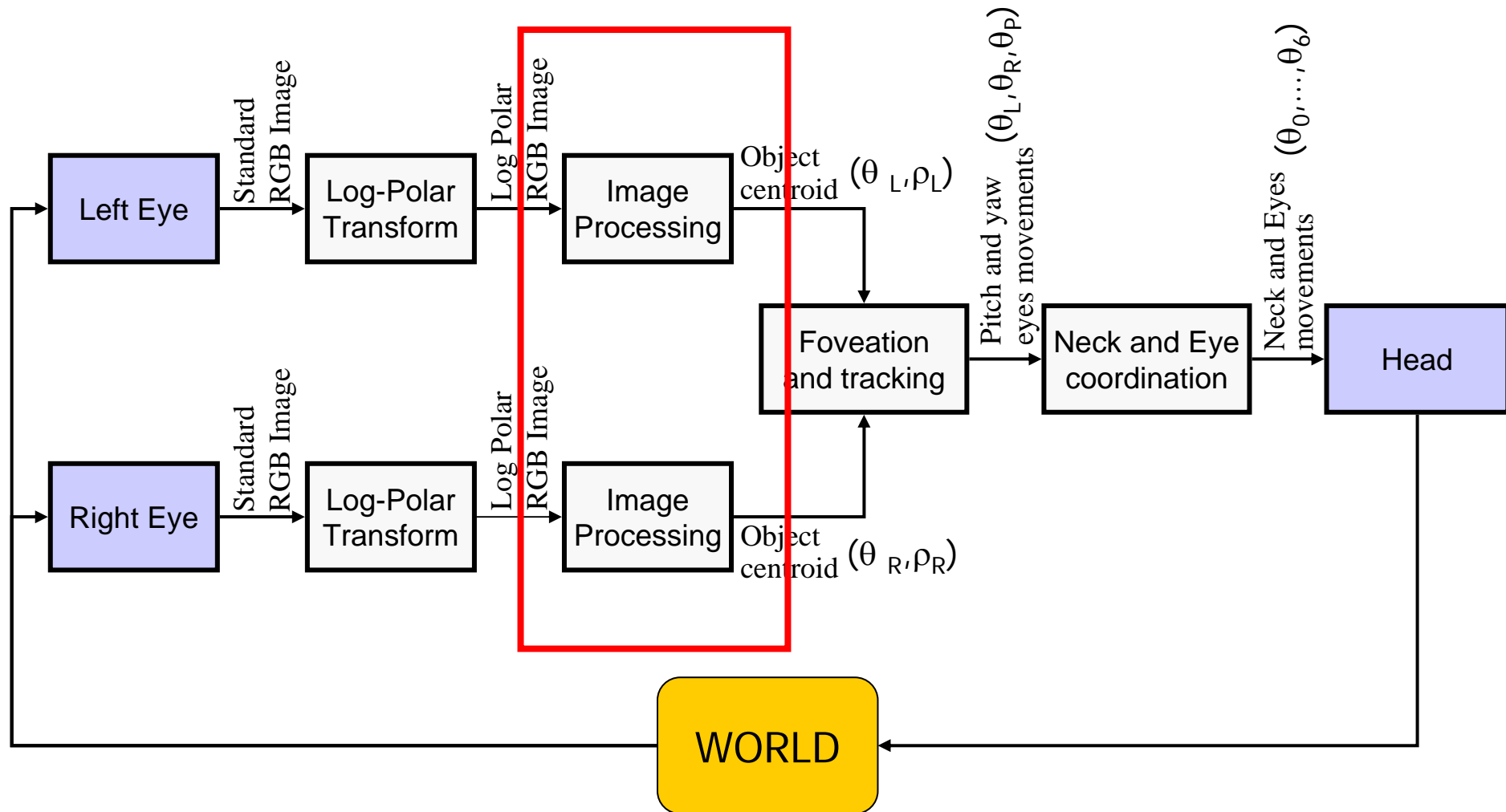


Neck Movements



Saccades, $400^\circ/\text{sec}$

Overall sensory-motor scheme of the visual apparatus



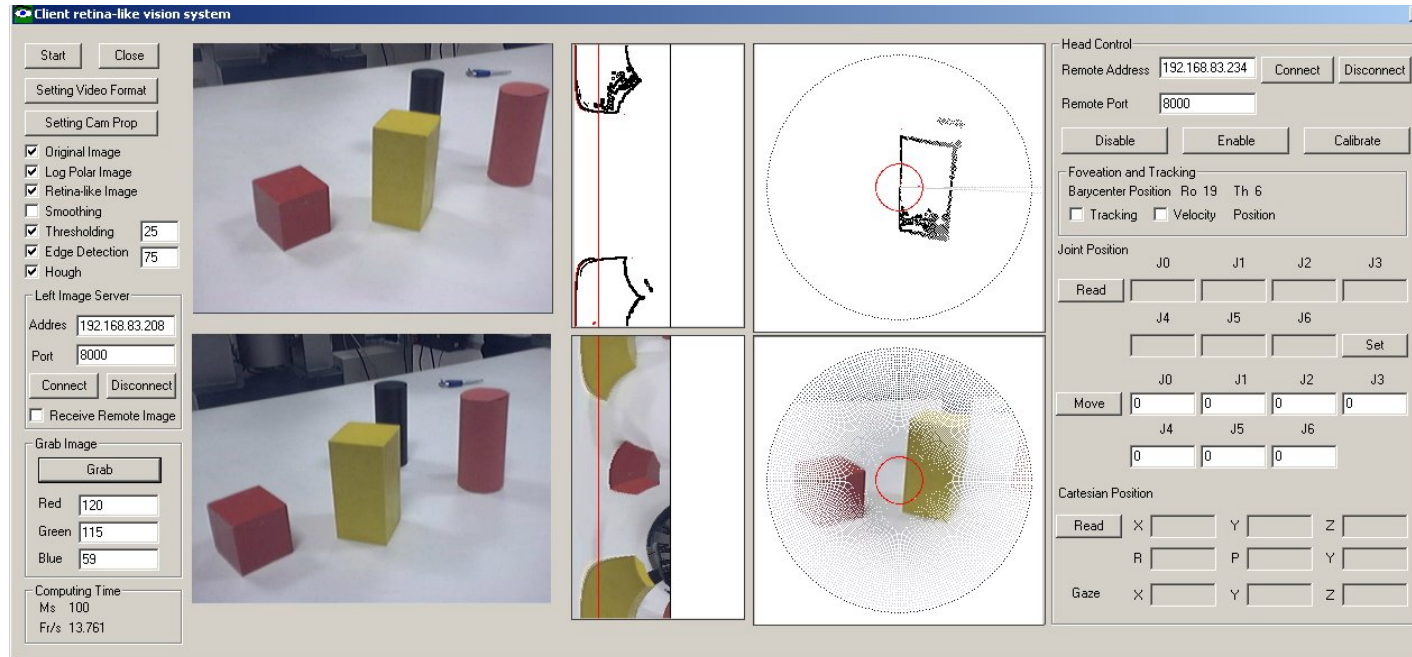
Examples of algorithms developed for retina-like image processing



- 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

The screenshot displays the PALOMA Robotic Artefact Control Panel interface. The main window is divided into several sections:

- Left Panel:** Contains control buttons (Start, Close, Setting Video Format, Setting Cam Prop) and a list of image processing options: Original Image, Log Polar Image, Retina-like Image, Smoothing, Thresh (100), Edge Detection (75), and Hough. It also includes a Left Image Server section with address (PALOMA1) and port (8000), and a Grab Image section with a Grab button and color/position data (R: 124, H: 45.57, G: 109, S: 0.468, B: 66, V: 99.66). A Computing Time section shows Ms: 62 and Fr/s: 6.340.
- Image Viewers:** Two vertical image windows on the left show the original scene (a table with colored blocks) and its processed version (a yellow block highlighted).
- Processing Results:** Two circular images on the right show the processed scene with a red circle highlighting the yellow block.
- Right Panel:** Contains control sections for Head Control (Remote Address: HEAD, Remote Port: 8000, STATUS: CONNECTED), Foveation and Tracking (Bar. Pos. Right Ro 5 Th 164 Left Ro 4 Th 62, Tracking, Velocity Position, Prop. Par 70, Velocity 0.50), Joint Position (Read/Move buttons for J0-J6, Vel, T), Cartesian Position (Read buttons for X, Y, Z, R, P, Y), Gaze (X, Y, Z), and Head Neurocontroller (X: 85, Y: 0, Z: 10, Clamped Joints, Value Joints, Sym, Move).

Edge Detection (gradient based method)

The screenshot displays the PALOMA Robotic Artefact Control Panel software interface. The main window is divided into several sections:

- Left Panel:** Contains control buttons (Start, Close, Setting Video Format, Setting Cam Prop) and a list of image processing options: Original Image, Log Polar Image, Retina-like Image (with Or. checkbox), Smoothing, Thresh (100), HSV, Edge Detection (75), and Hough. Below these are fields for Left Image Server (Address: PALDMA1, Port: 8000) and Grab Image (Grab button, R: 124, H: 45.57, G: 109, S: 0.468, B: 66, V: 99.66). A Computing Time section shows Ms: 47 and Fr/s: 6.347.
- Image Display Area:** A 2x3 grid of images. The top-left image is the original scene with colorful blocks. The top-middle image shows the edge detection result (black edges on a white background). The top-right image shows the edge detection result with a red circle and a white crosshair centered on a detected object. The bottom row contains identical images to the top row.
- Right Panel:** Contains control sections for Head Control (Remote Address: HEAD, Remote Port: 8000, STATUS: CONNECTED), Foveation and Tracking (Bar. Pos. Right Ro 5 Th 164 Left Ro 4 Th 63, Tracking checkbox, Velocity Position slider at 70, Velocity slider at 0.50), Joint Position (Read/Move buttons, J0-J6 sliders, Vel slider at 0.5, T Set button), Cartesian Position (Read buttons, X, Y, Z sliders), and Head Neurocontroller (X, Y, Z sliders, Clamped Joints checkbox, Value Joints sliders, Sym checkbox, Move button).

Line detection (Hough method)



- Applied only to pixels belonging to the fovea

PALOMA Robotic Artefact Control Panel

Original image
 Inverted image
 Retinalize image O...
 Smoothing
 Thresh: 40 HSV
 Edge Detection: 75
 Hough

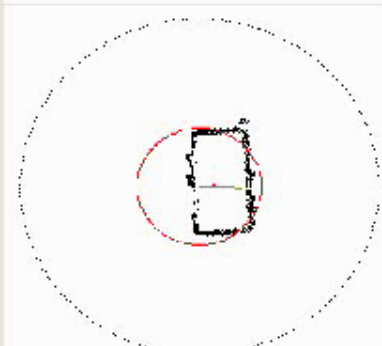
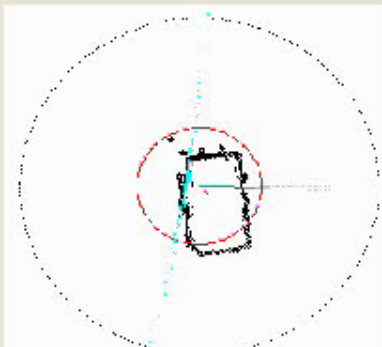
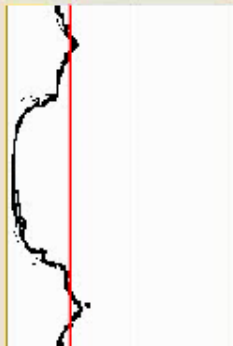
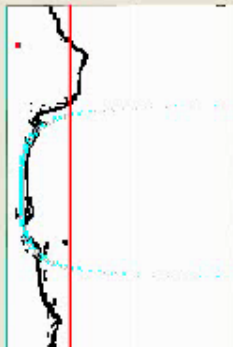
Lcf: Image Server
 Address: PALOMA1
 Port: 8000 Conn...

 Receive Remote Image

Grab image

R	147	H	52.49
G	131	S	C.626
E	55	V	112.0

Computing Time
 M: 1.75
 F: 6.372



Head Control
 Remote Address: HEAD
 Remote Port: 8000 STATUS: CONNECTED

Invertible Tracking
 Max Pos: Right: 8 H: 228 Left: 13 H: 7
 Tracking Velocity Position: -0.004;0.014;0.023
 Pos: Pos: 70
 Velocity: 11.15

Joint Position

J0	J1	J2	J3	
0	1J	0	1J	0

J4	J5	J6	Vel	
1E	4	3	C.5	Set

Cartesian Position

X	Y	Z
11	11	Y

X	Y	Z

Head Neurocontroller
 Clamped Joints
 Value Joints
 Stop

Hand Control Panel

Arm Control Panel

J0	J1	J2	J3	J4	J5	J6	J7	
90.0	0.0	135.0	0.0	-90.0	0.0	0.0	0.0	POS INIT

X	Y	Z	Roll	Wrb	Yaw	J0	E bow	Vel

Block Zmpian

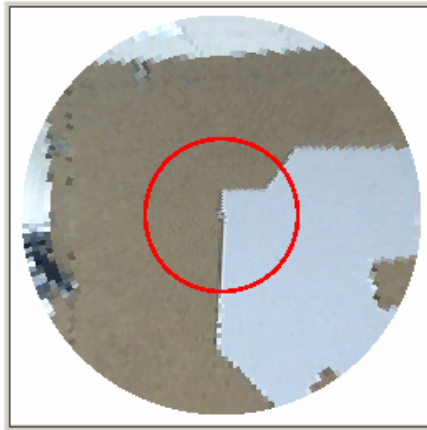
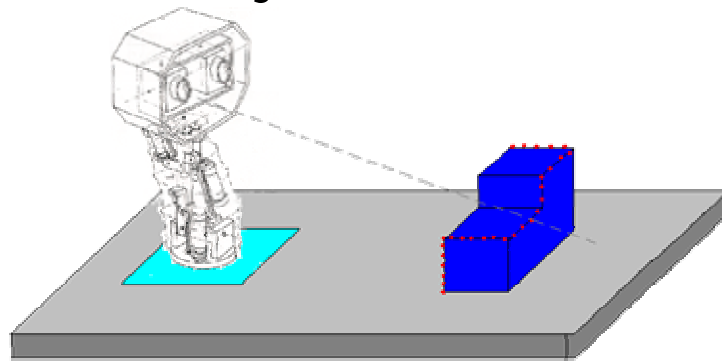
Arm Neurocontroller
 No Yaw
 Clamped
 Clamped Joint: Tool

X	Y	Z	Pos Init	Mode
85	0	10		

Length:

Preliminary activities

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



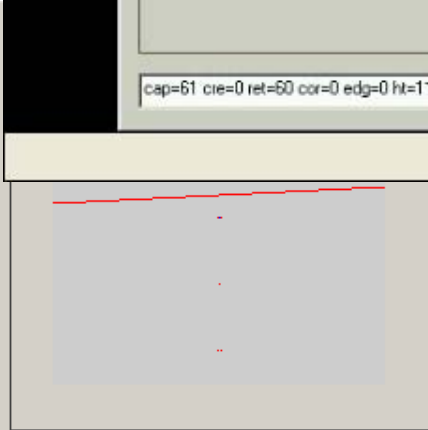
Retina Like image



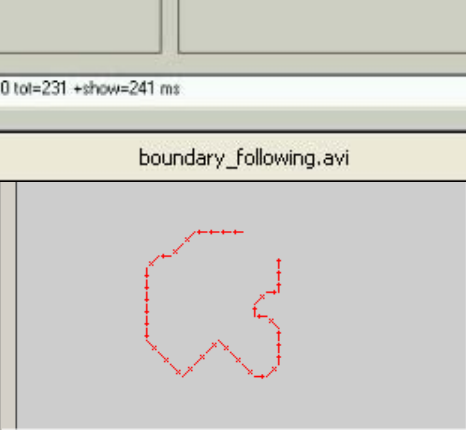
Log Polar Image



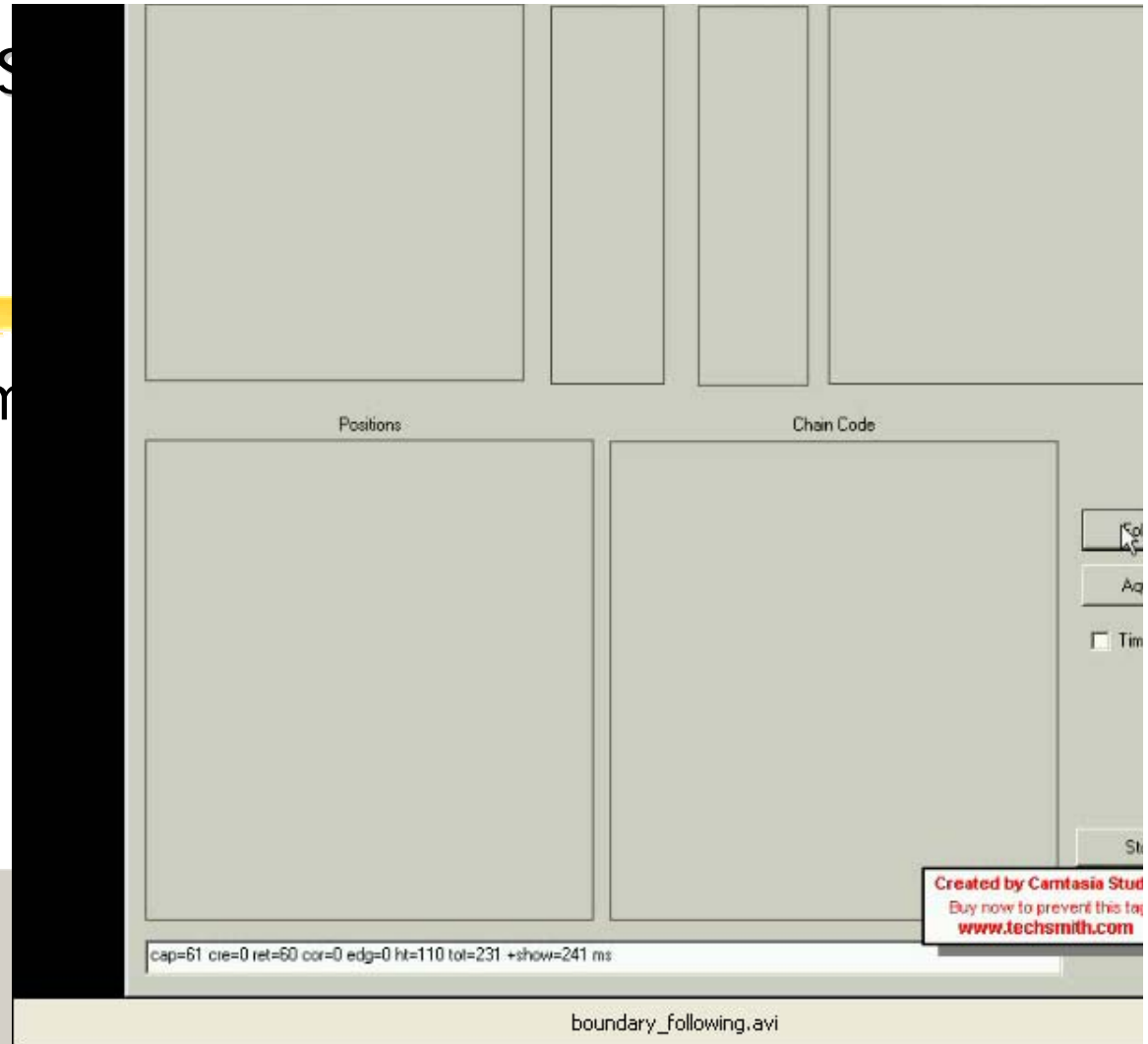
Edge of log polar image



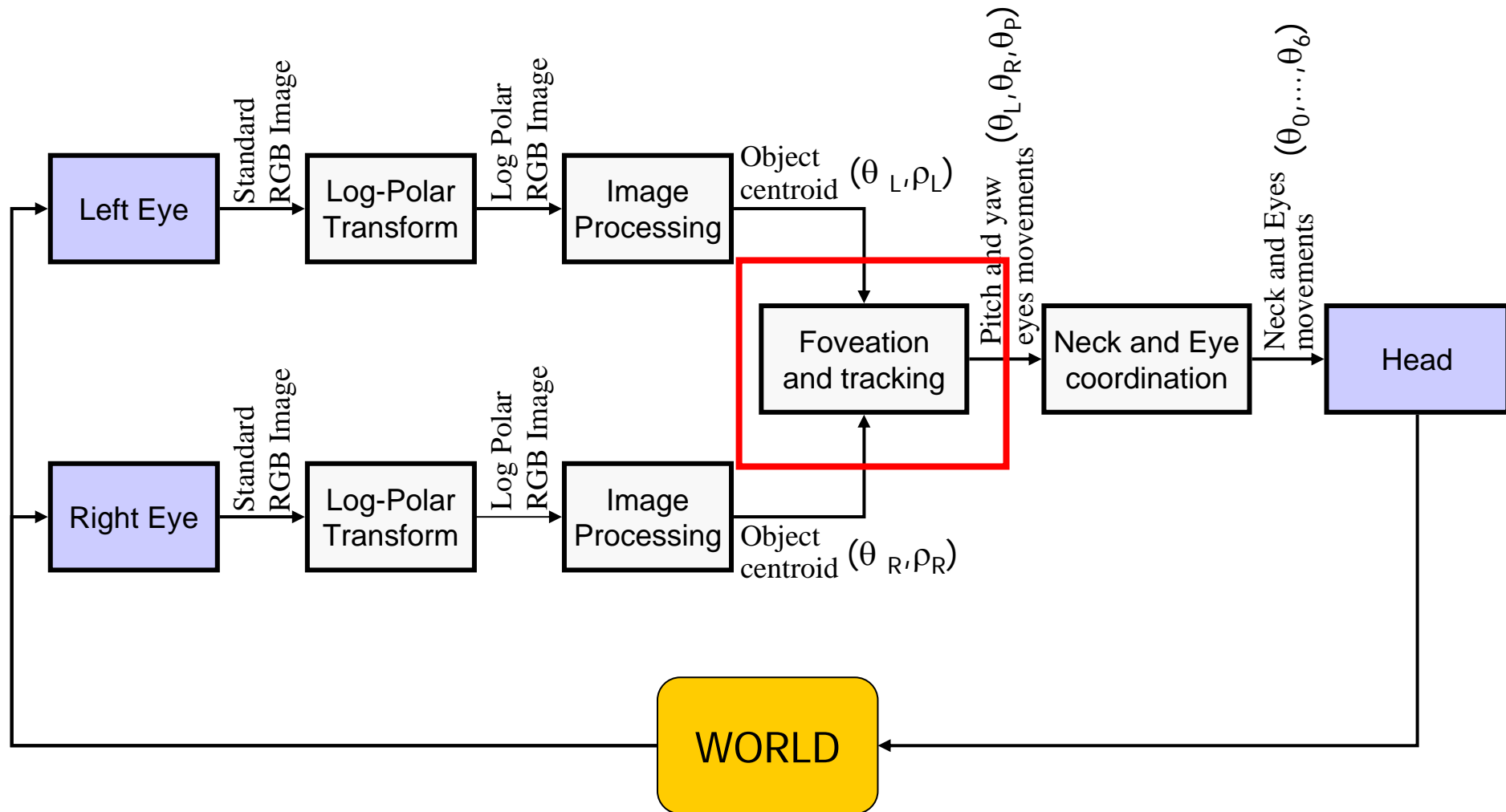
Detected lines (Boundaries)



Boundary reconstruction based on eye positions



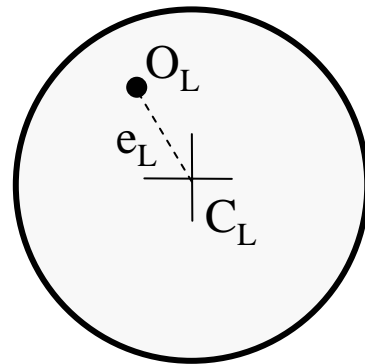
Overall sensory-motor scheme of the visual apparatus



Foveation of the object centroid

Proportional control based on the visual error

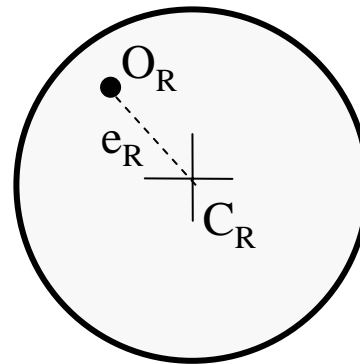
Left Image



$$O_L = (\rho_L, \theta_L)$$

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

Right Image

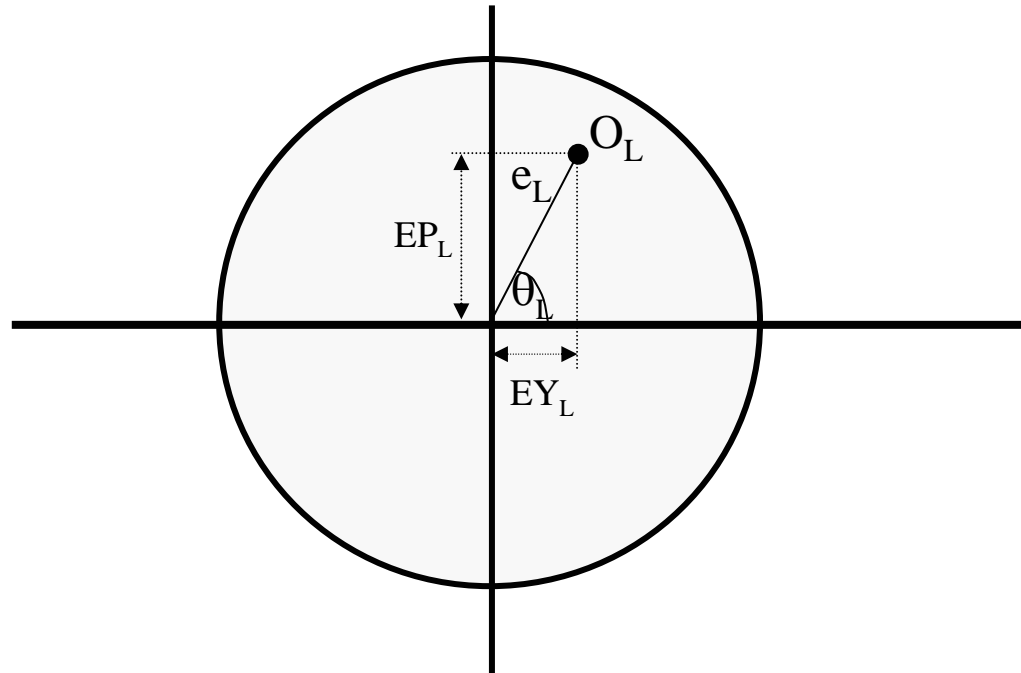


$$O_R = (\rho_R, \theta_R)$$

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

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

Computation of yaw and pitch eye movements



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

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

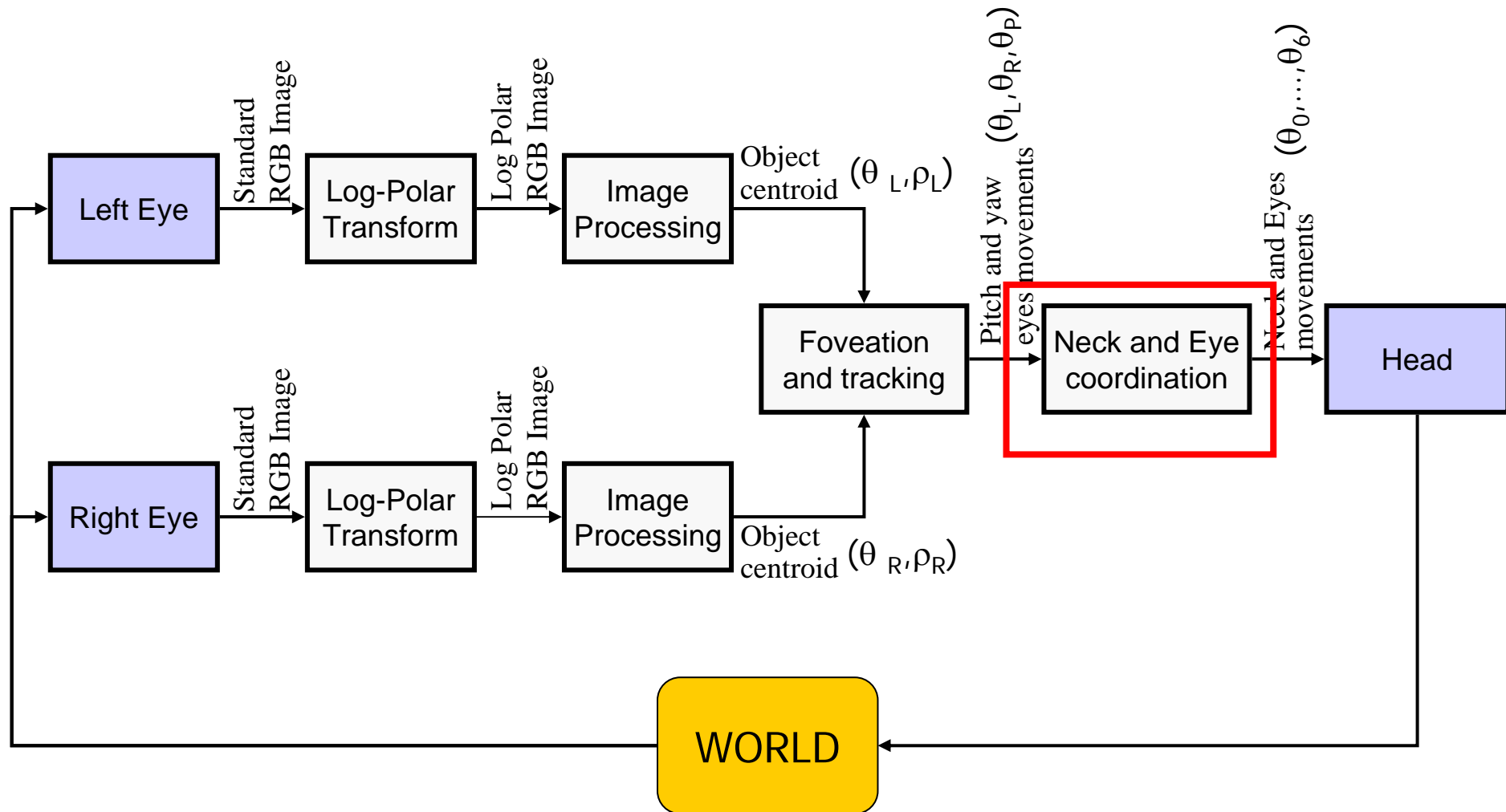
$$EY_R = e_R * \cos(\theta_R) * P_R$$

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

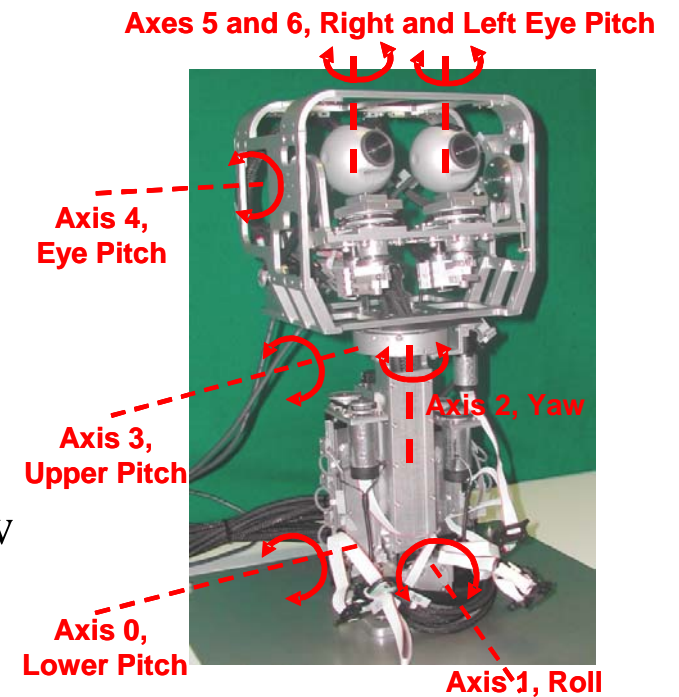
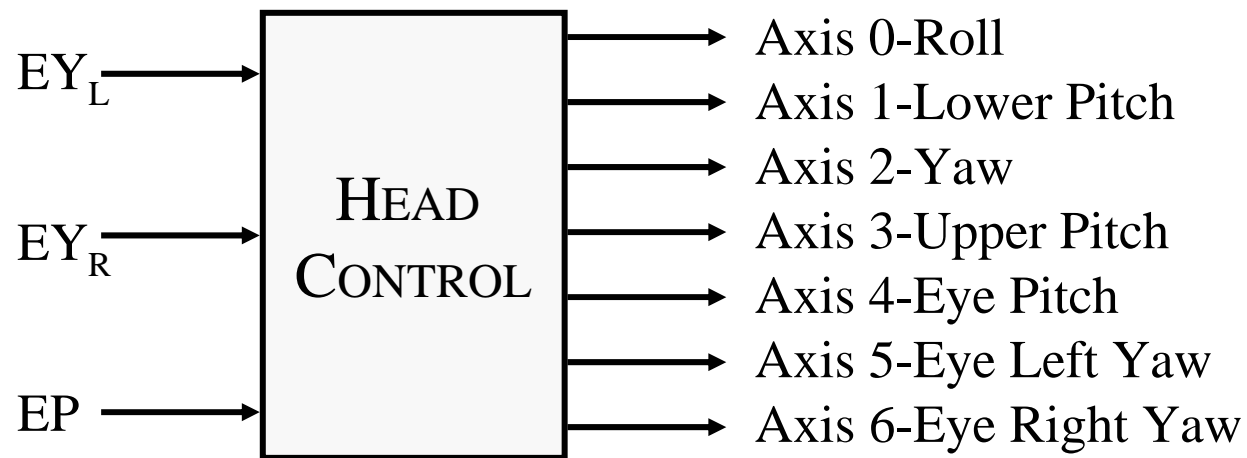
$$EP = (EP_L + EP_R) / 2$$

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



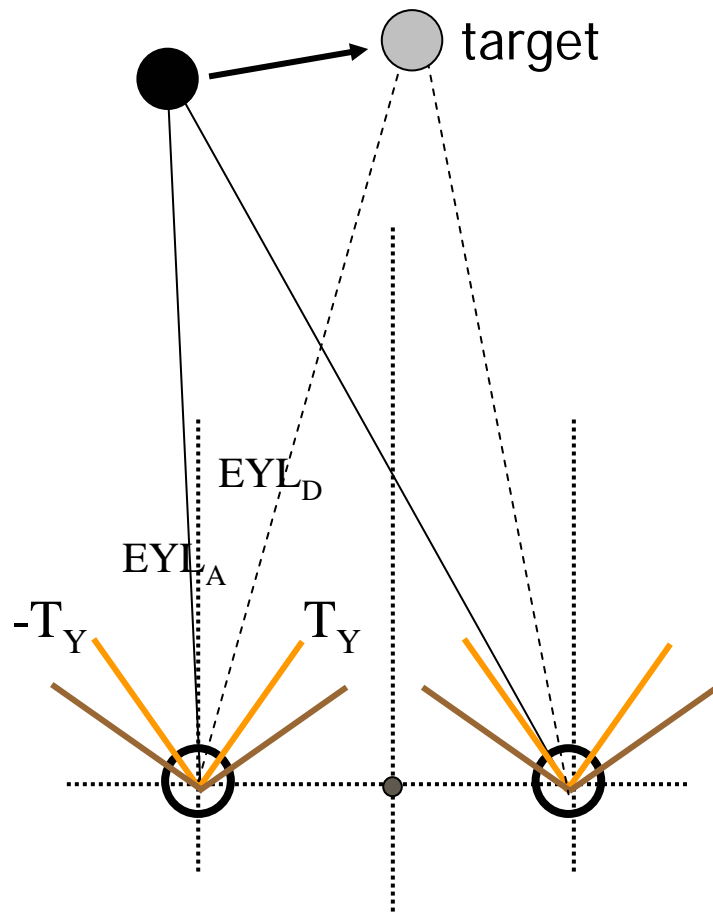
Solution 1



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

$$EYR_A + EY_R < T_Y$$



Only eyes

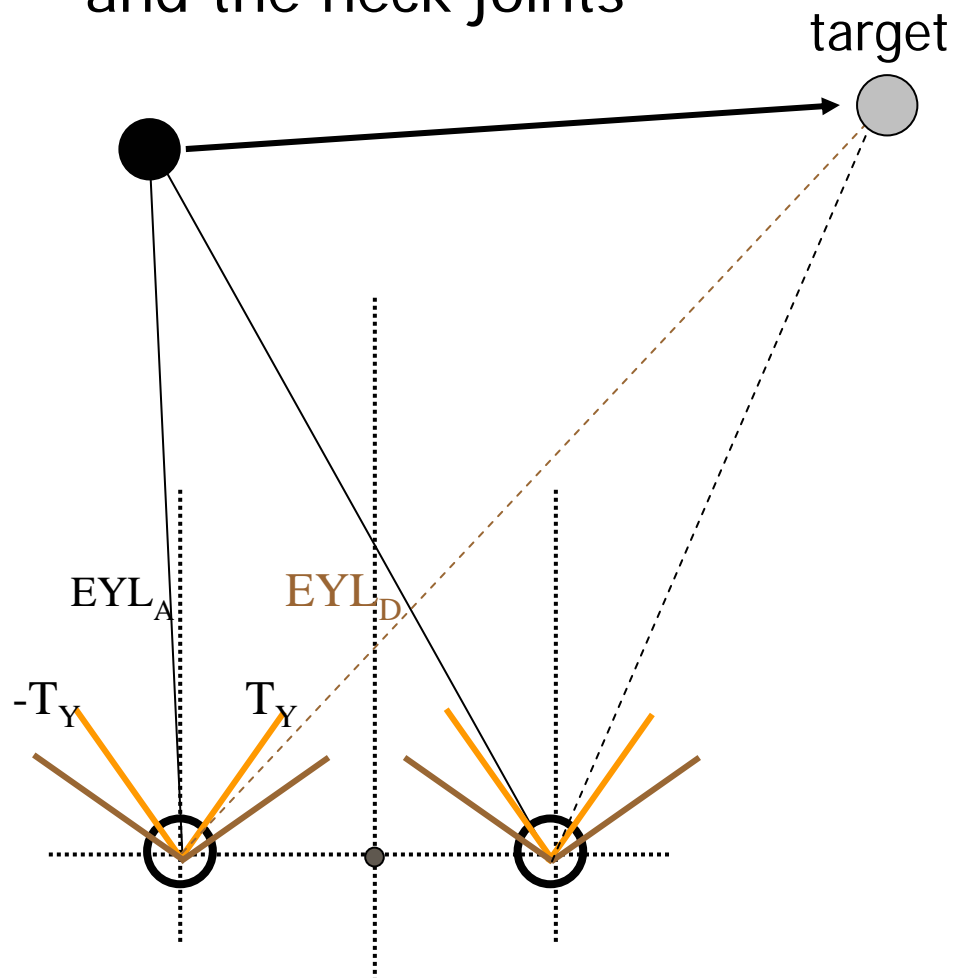
$$EYL_D = EYL_A + EY_L$$

$$EYR_D = EYR_A + EY_R$$

$$YAW_D = YAW_A$$

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

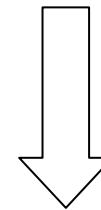
- If the movement is larger, it is distributed among the eyes and the neck joints



$$EYL_A + EYL_L > T_Y$$

or

$$EYR_A + EY_R > T_Y$$



Eyes and neck

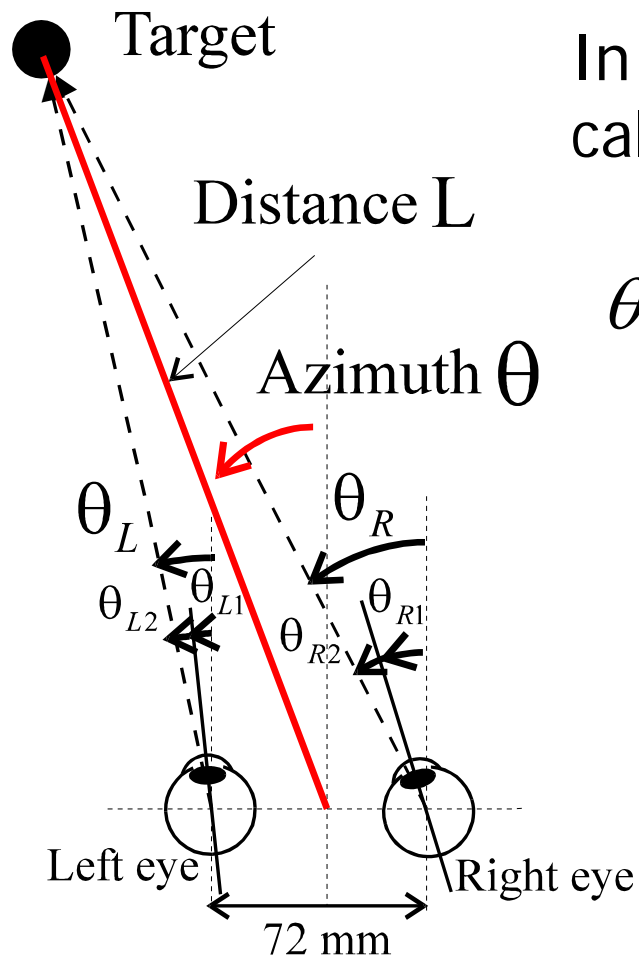
$$\theta = \text{atan}((\tan(EY_L) + \tan(EY_R))/2)$$

$$EYL_D = EYL_A + EYL_L - \theta$$

$$EYR_D = EYR_A + EY_R - \theta$$

$$YAW_D = YAW_A + \theta$$

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



In particular the neck yaw angle is calculated as follows:

$$\theta(Y) = \arctan\left(\frac{tg\theta_R + tg\theta_L}{2}\right)$$

The upper and lower pitch of the head were instead calculated as a percentage of the eye pitch.

These proportions were extrapolated from experimental measurements on human beings.

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.

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

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

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

$$EYP_D = EYP_A + EP * K1$$

$$EUP_D = EUP_A + EP * K2$$

$$ELP_D = ELP_A + EP * K3$$

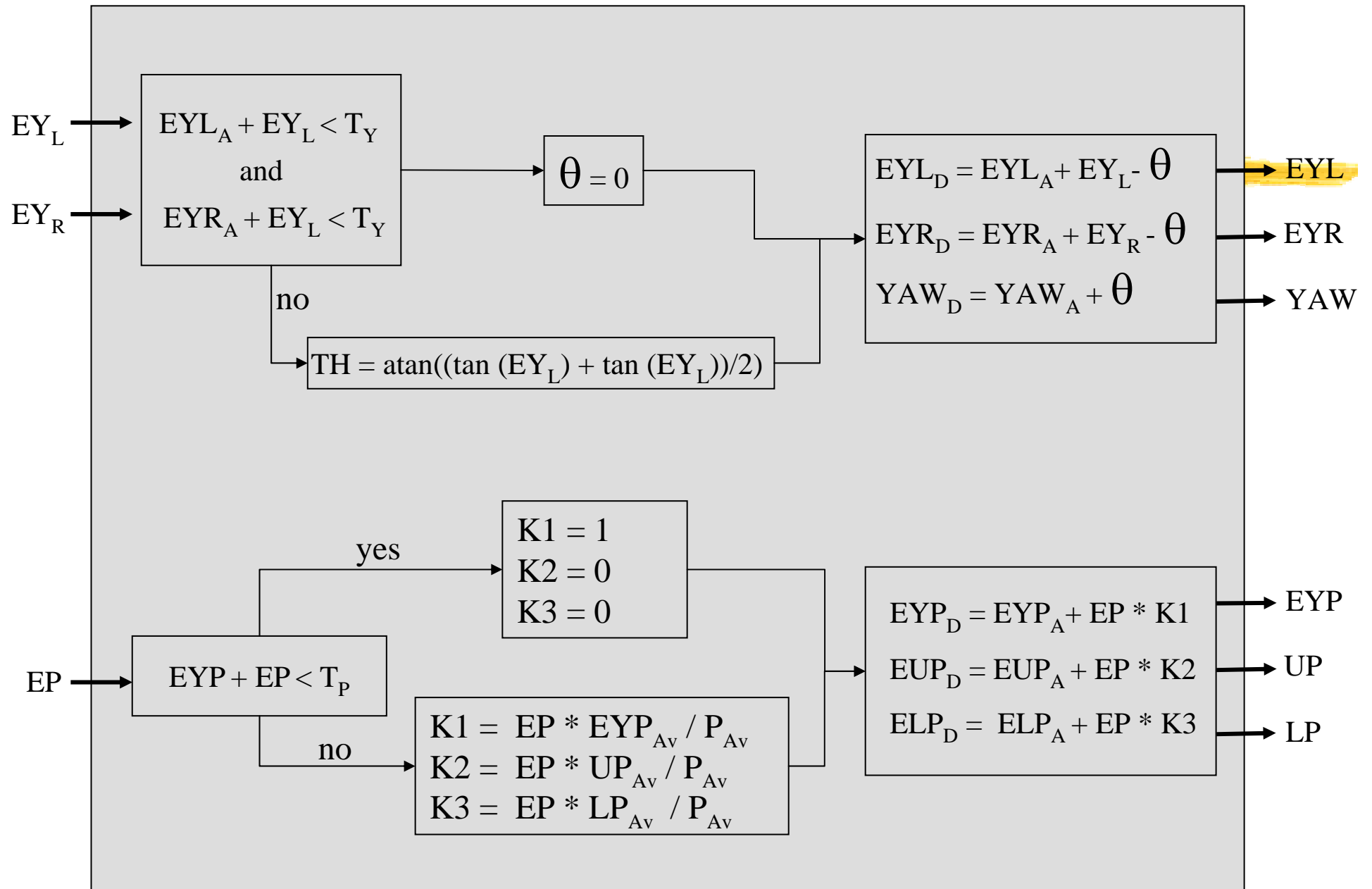
$$EYP_{AV} = EYP_M - EYP_A$$

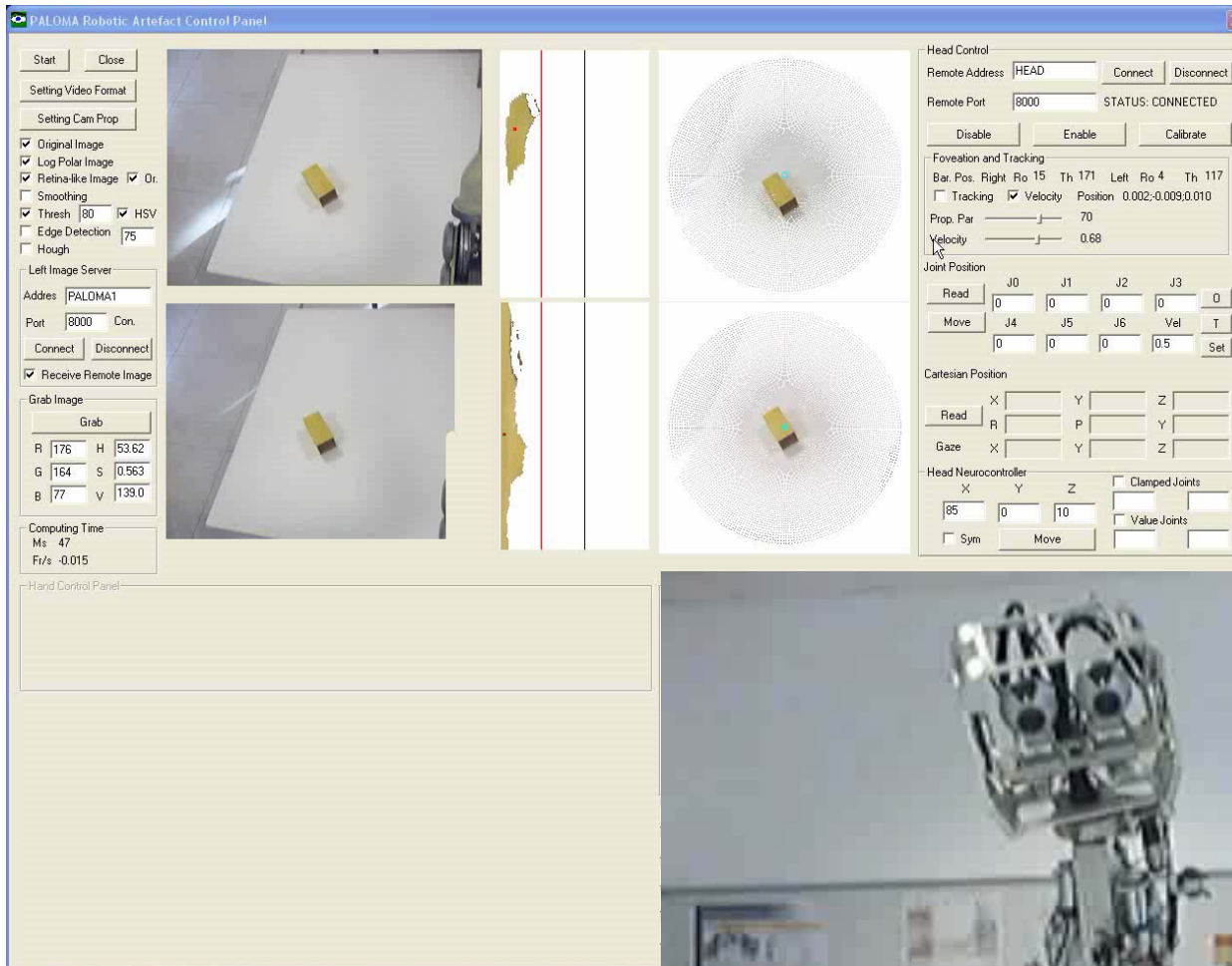
$$UP_{AV} = UP_M - UP_A$$

$$LP_{AV} = LP_M - UP_A$$

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

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

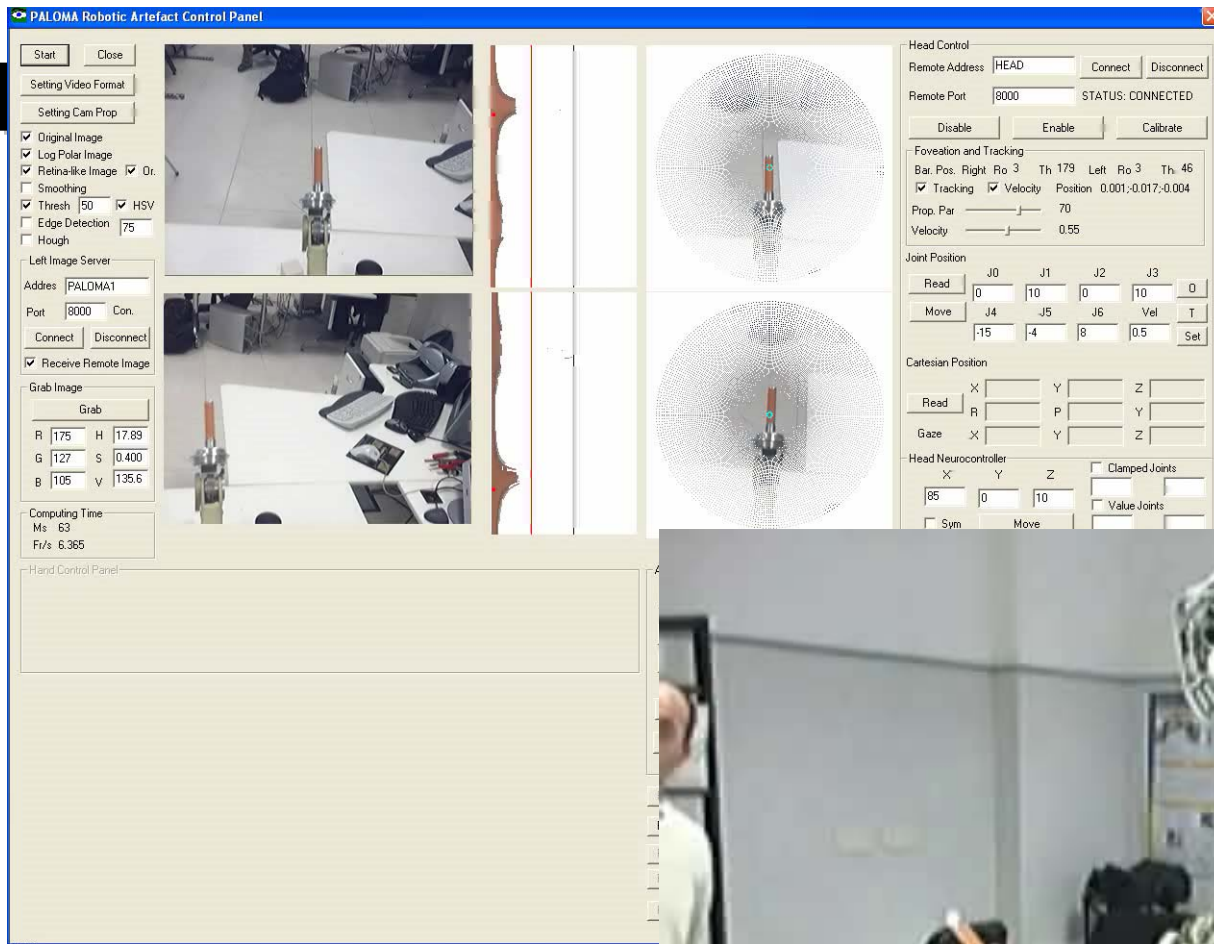




Pursuit Movement

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





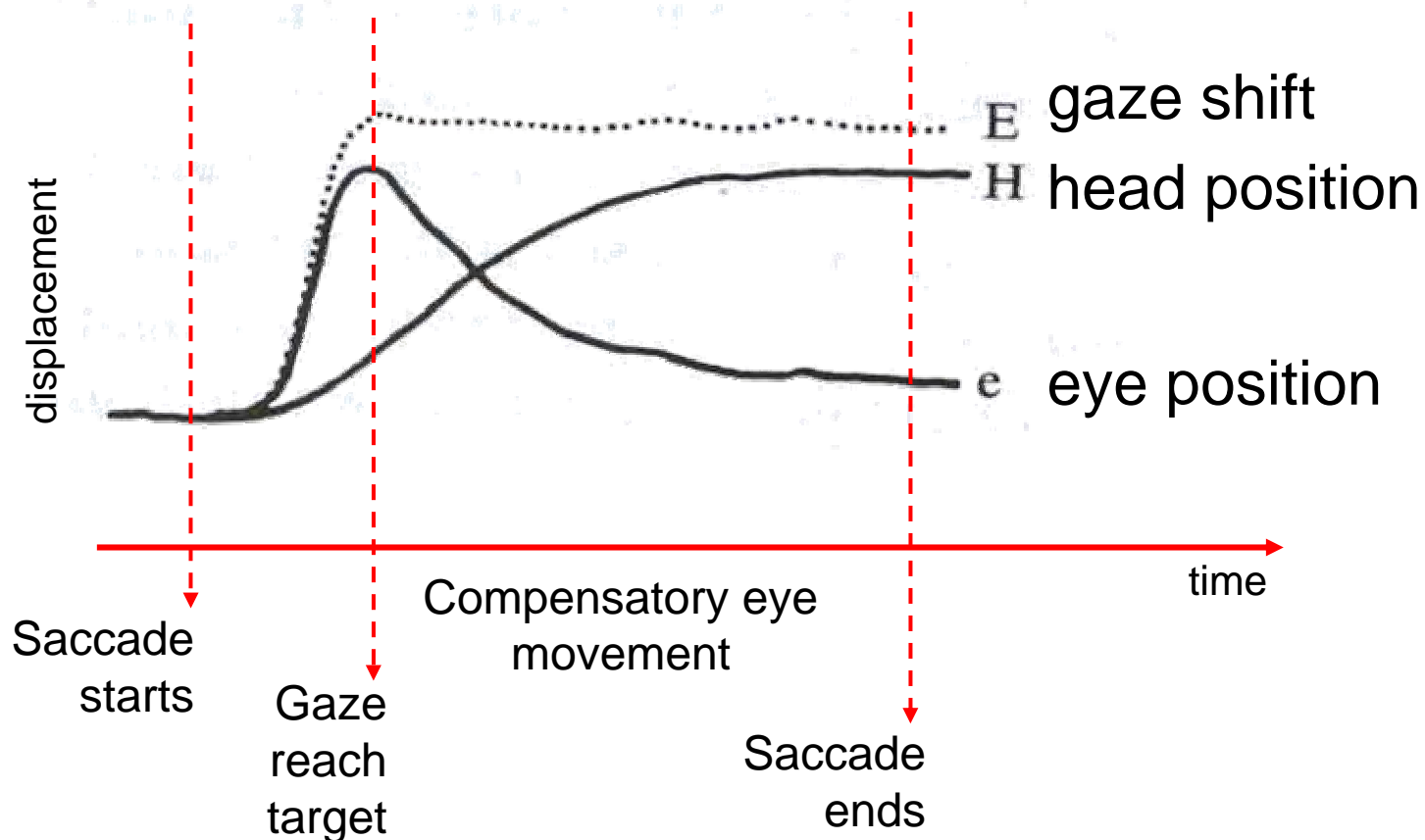
Solution 2

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

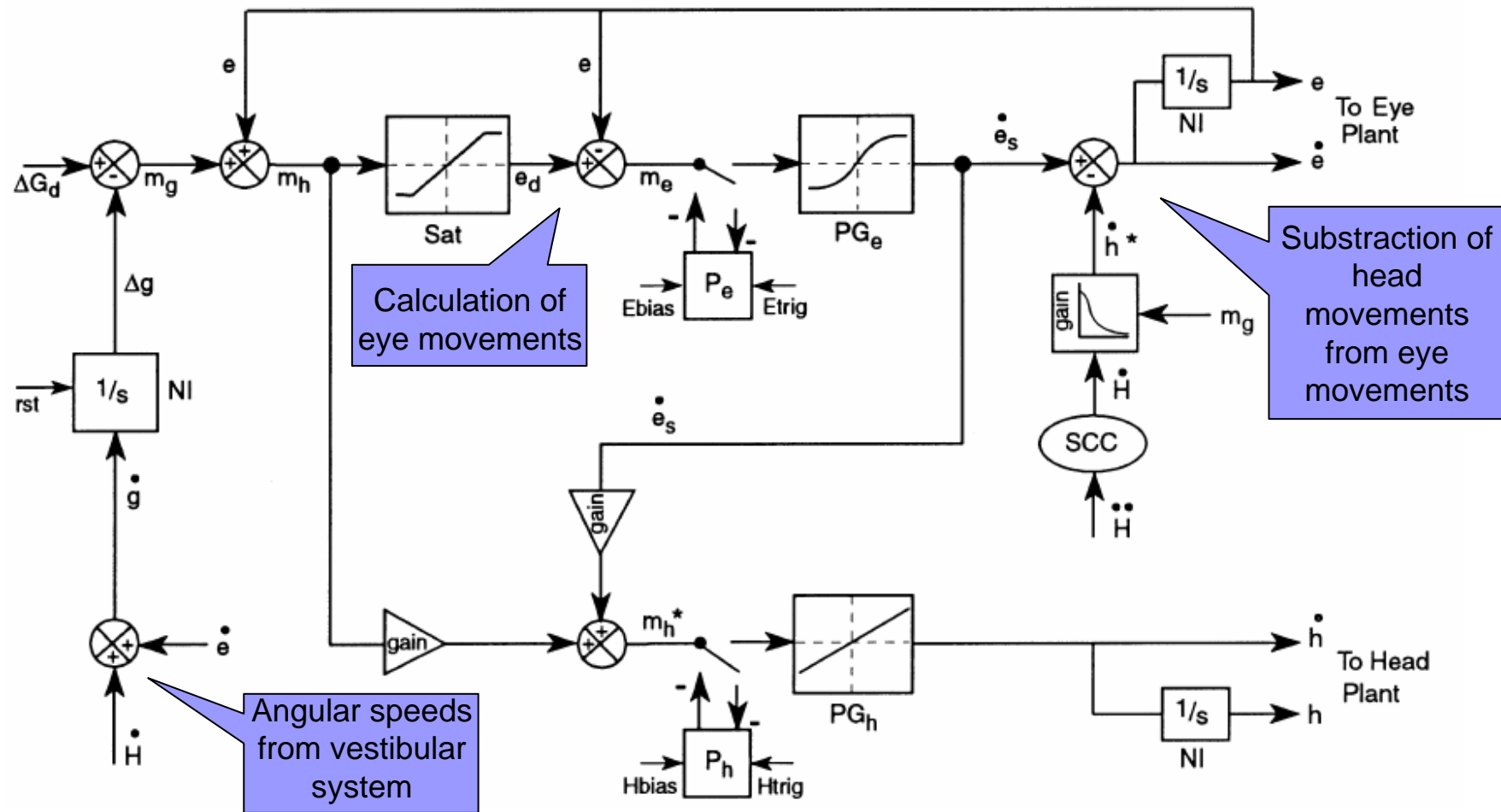




Biological Models

- *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*

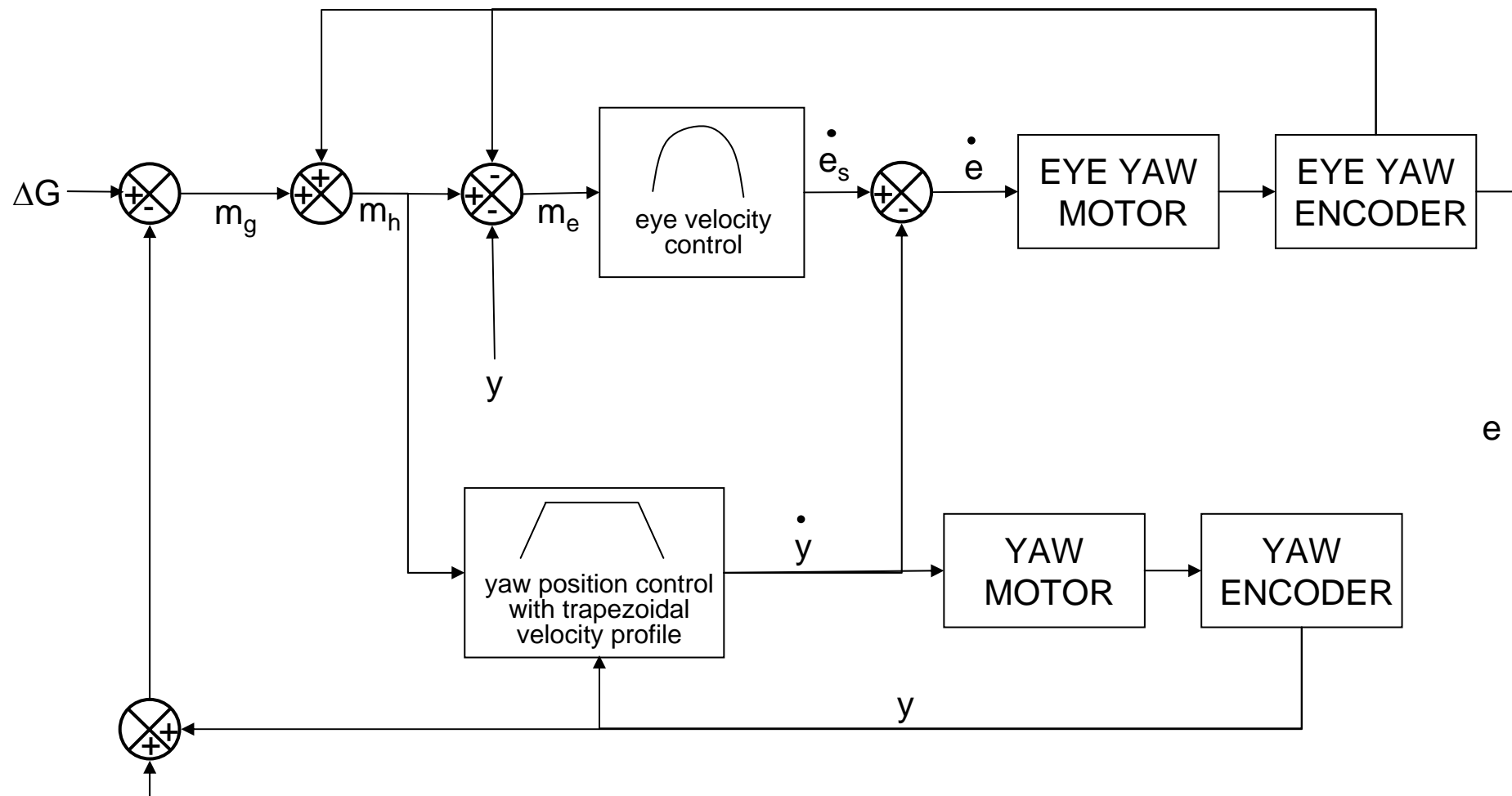
The Biological Model



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

e





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 head position.
- ***not aligned experiments***: the eyes of the robot were randomly deviated from the straight head 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



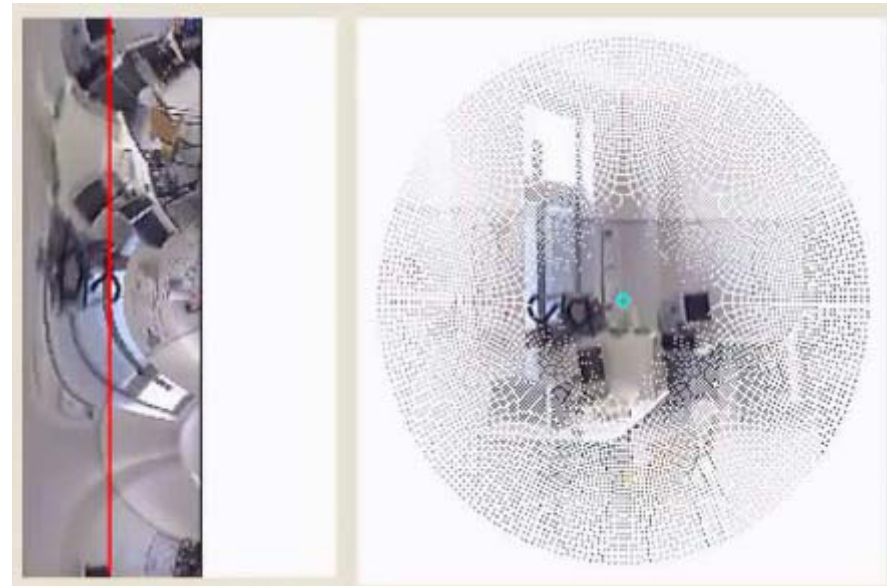
Experimental Trials

- **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

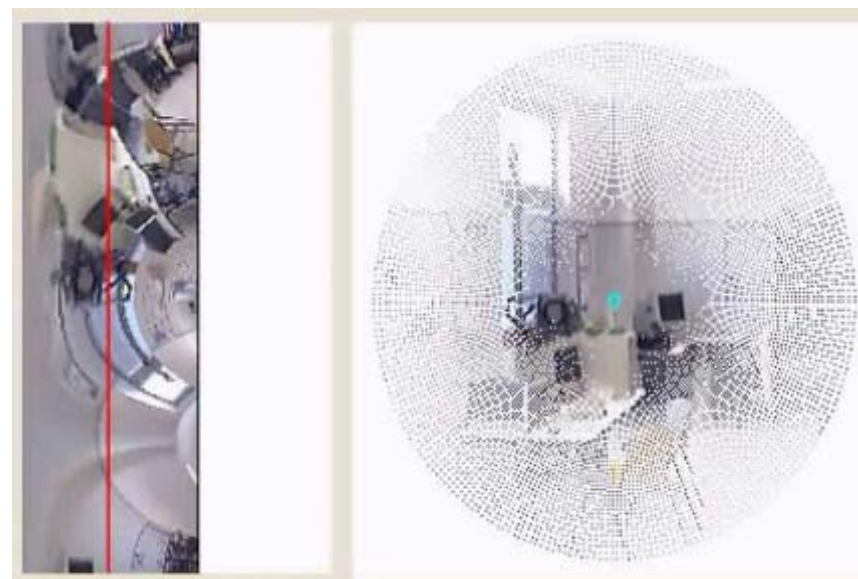


Left eye only



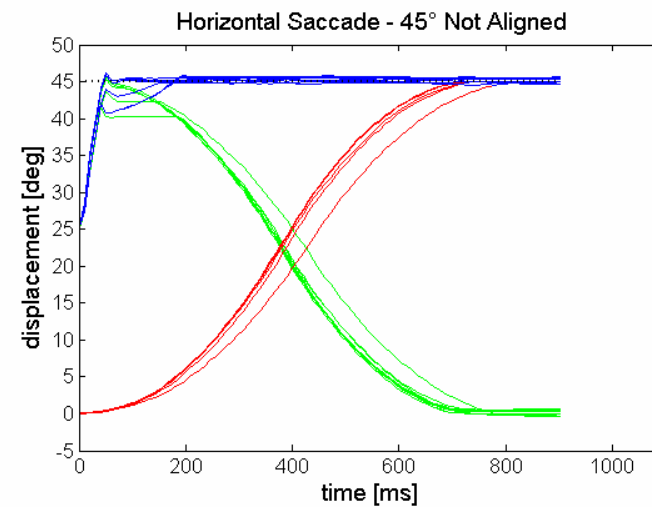
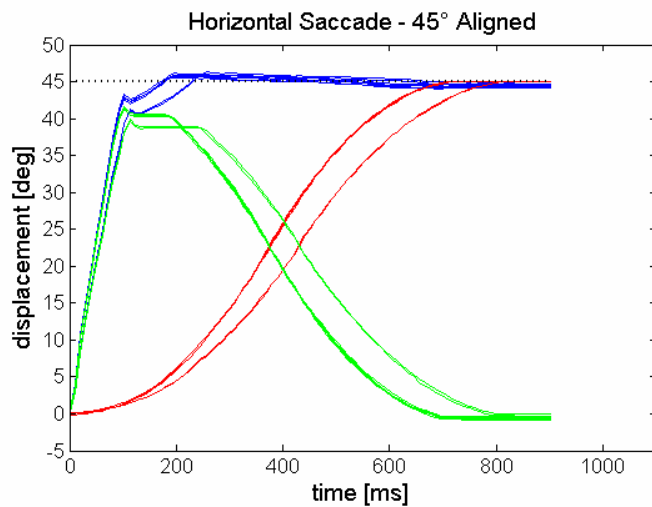
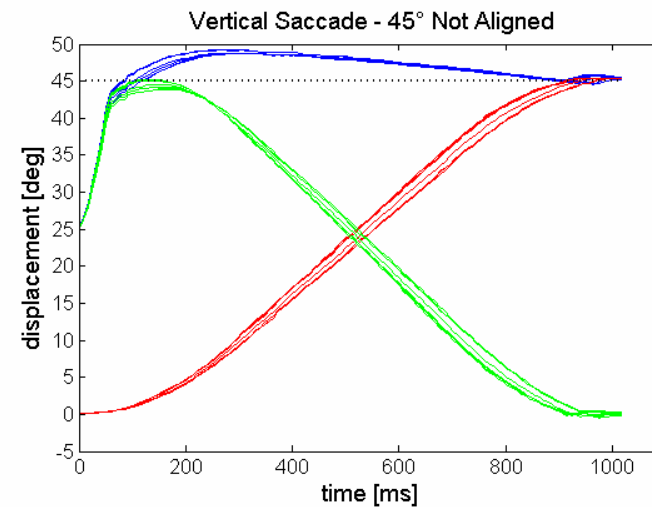
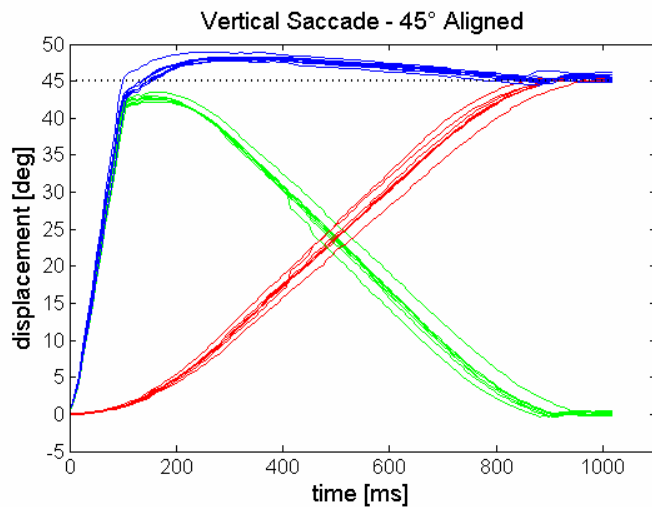
Camera View

Experimental Trials: vertical saccades



Camera View

Experimental Results



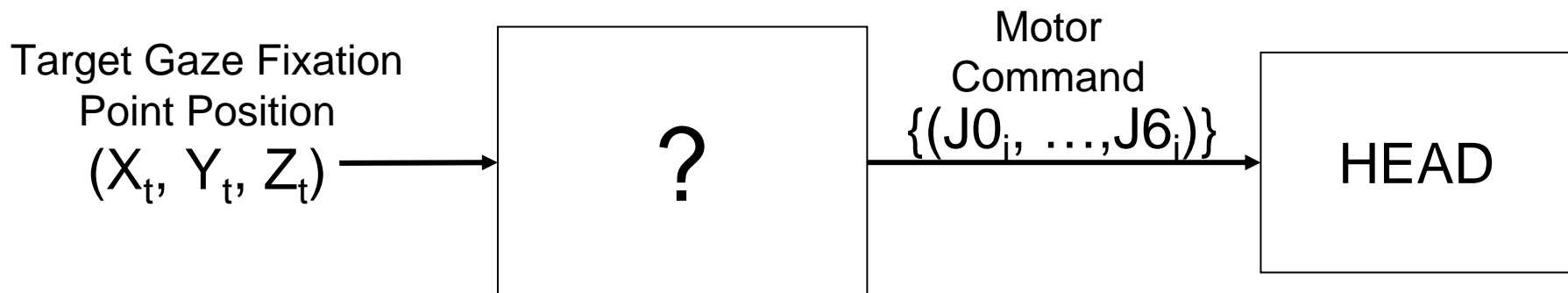
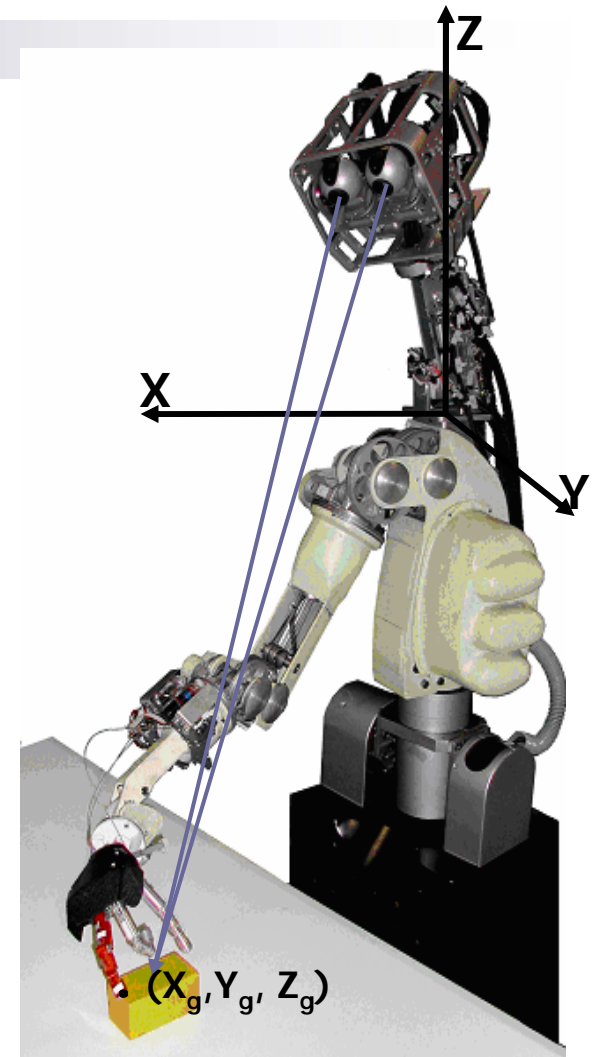
Solution 3

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

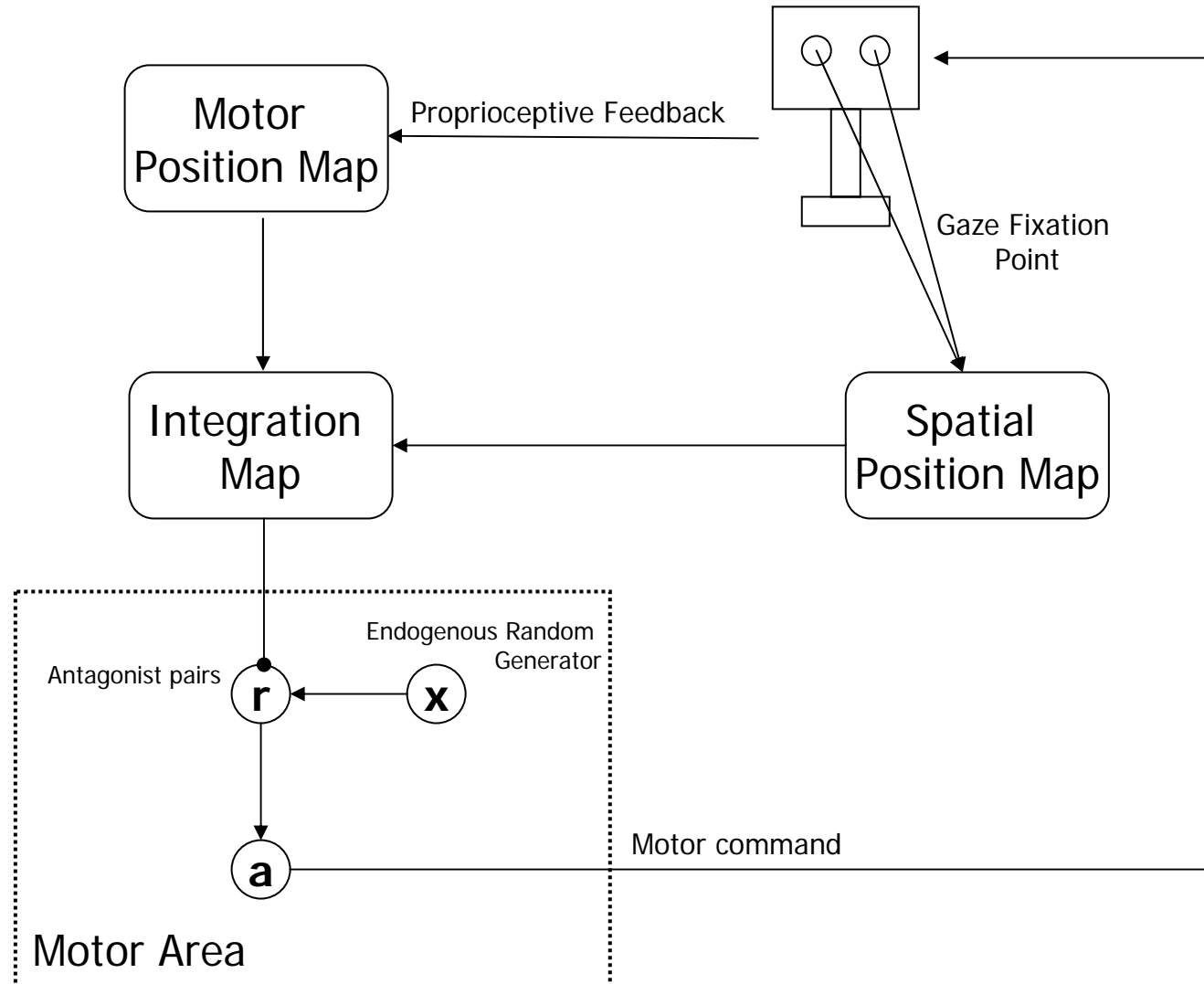
G. Asuni, G. Teti, C. Laschi, E. Guglielmelli, P. Dario, "A Robotic Head Neuro-controller Based on Biologically-Inspired Neural Models", *IEEE International Conference on Robotics and Automation – ICRA 2005*, Barcelona, Spain, April 18-22, 2005, pp.2373-2378.

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



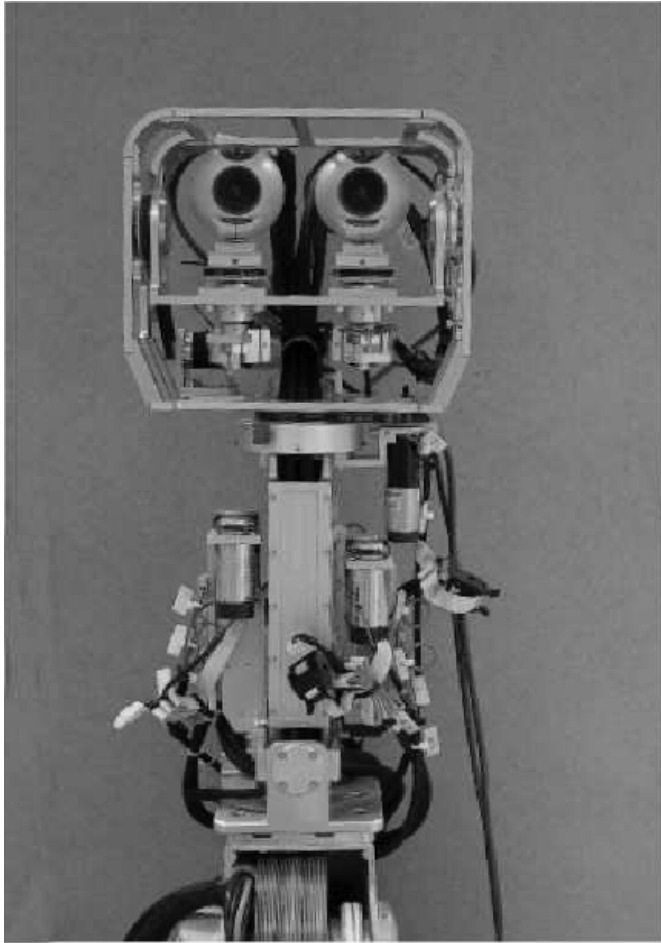


Testing phase

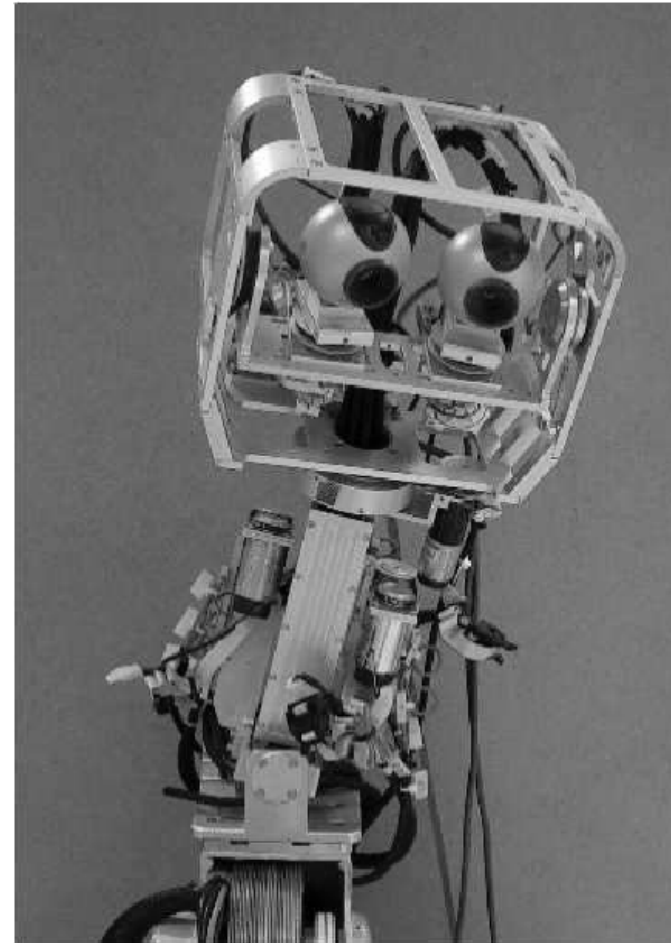
- After the training phase, given a target fixation point the system provides the joint rotations that drives the current gaze fixation point in the target point
- Three different modalities:
 1. Normal (without any constraint)
 2. With a clamped joint 0
 3. With symmetric angles for eye joints

All trials have been executed without additional learning

Experimental results: normal gazing



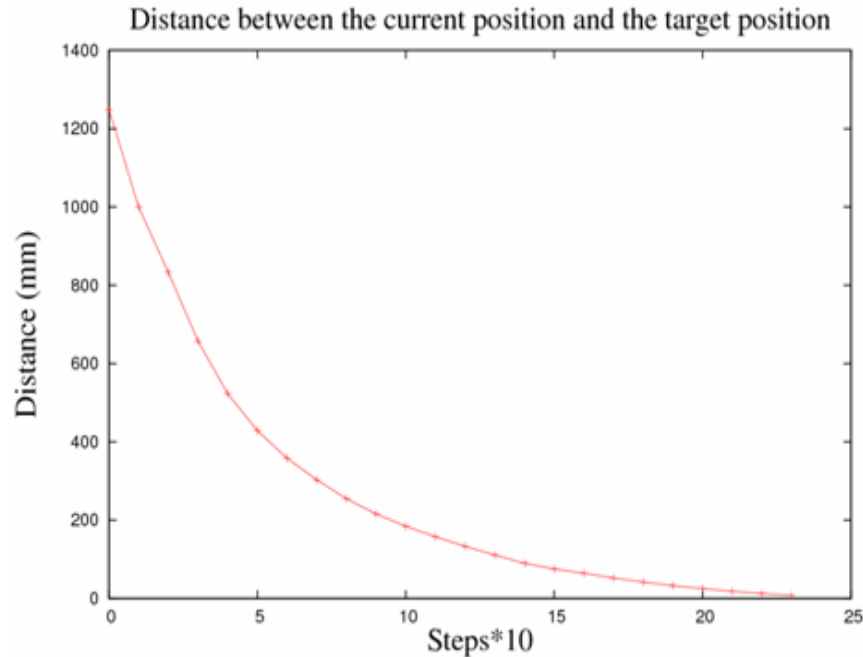
Initial posture



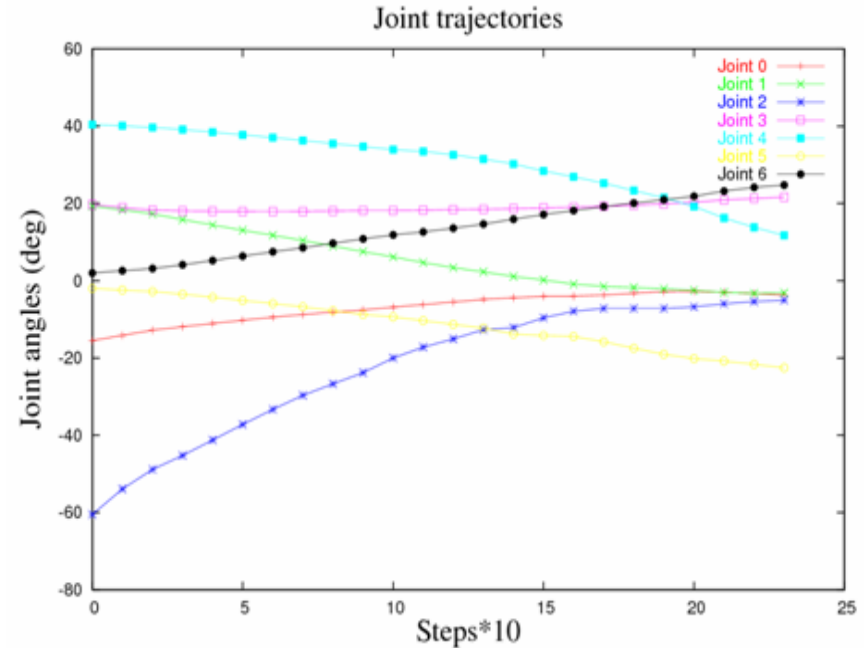
Final posture (normal)

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

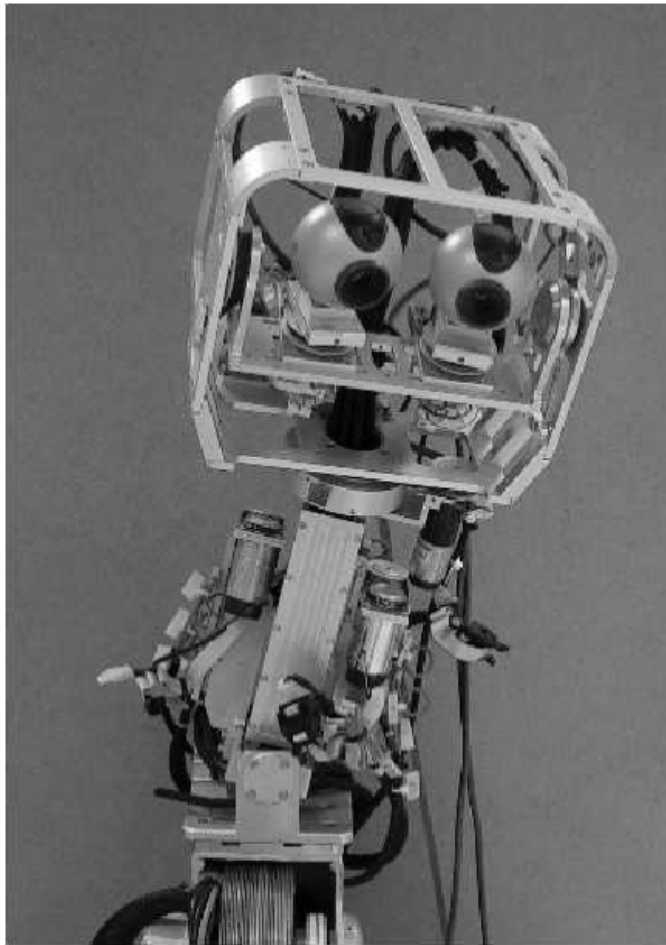
Distance between the current gaze
fixation point and the target:
monotonic trend



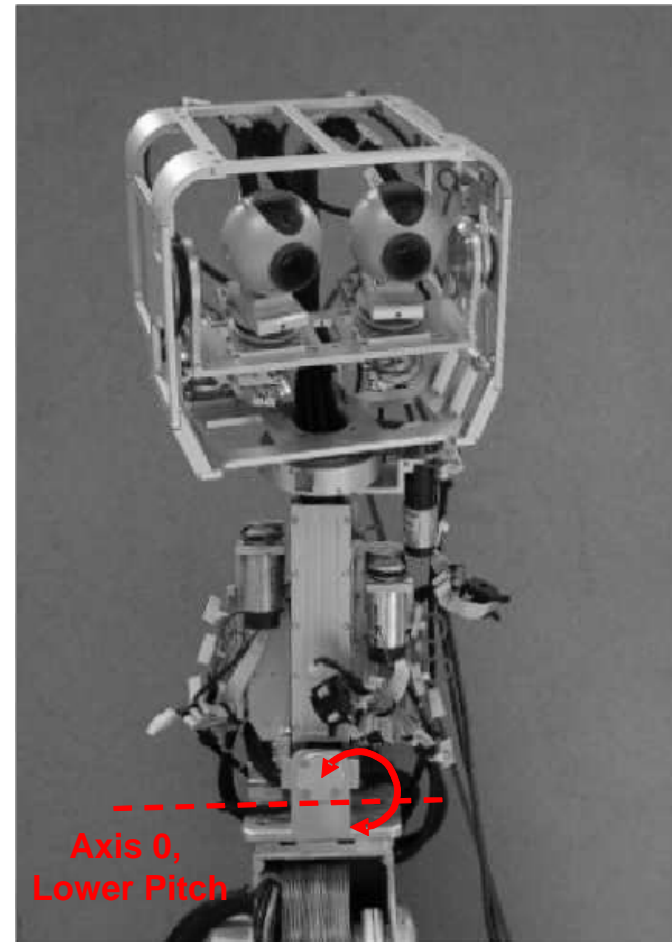
Joint trajectory



Experimental results: gazing with a clamped joint

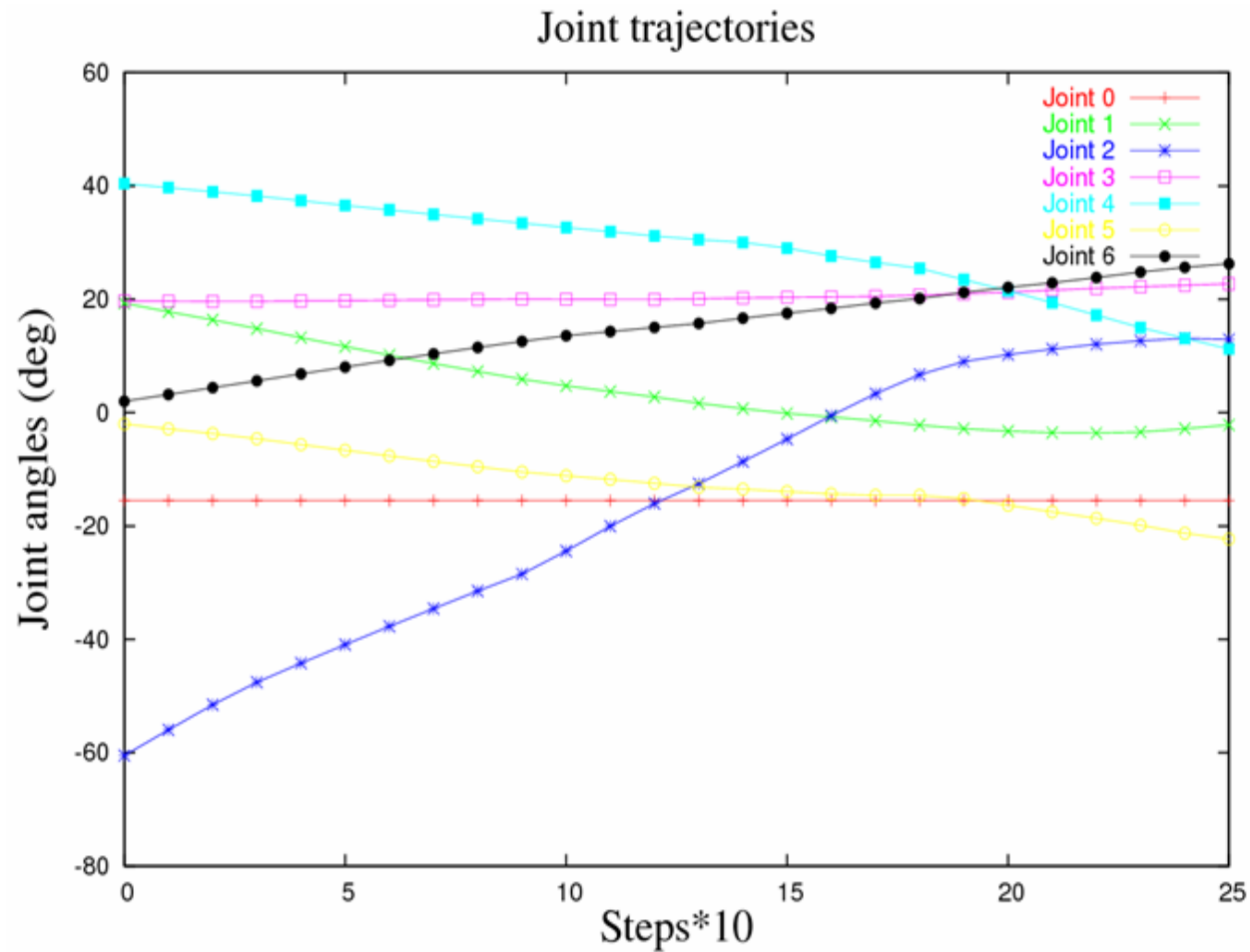


Final posture in normal mode



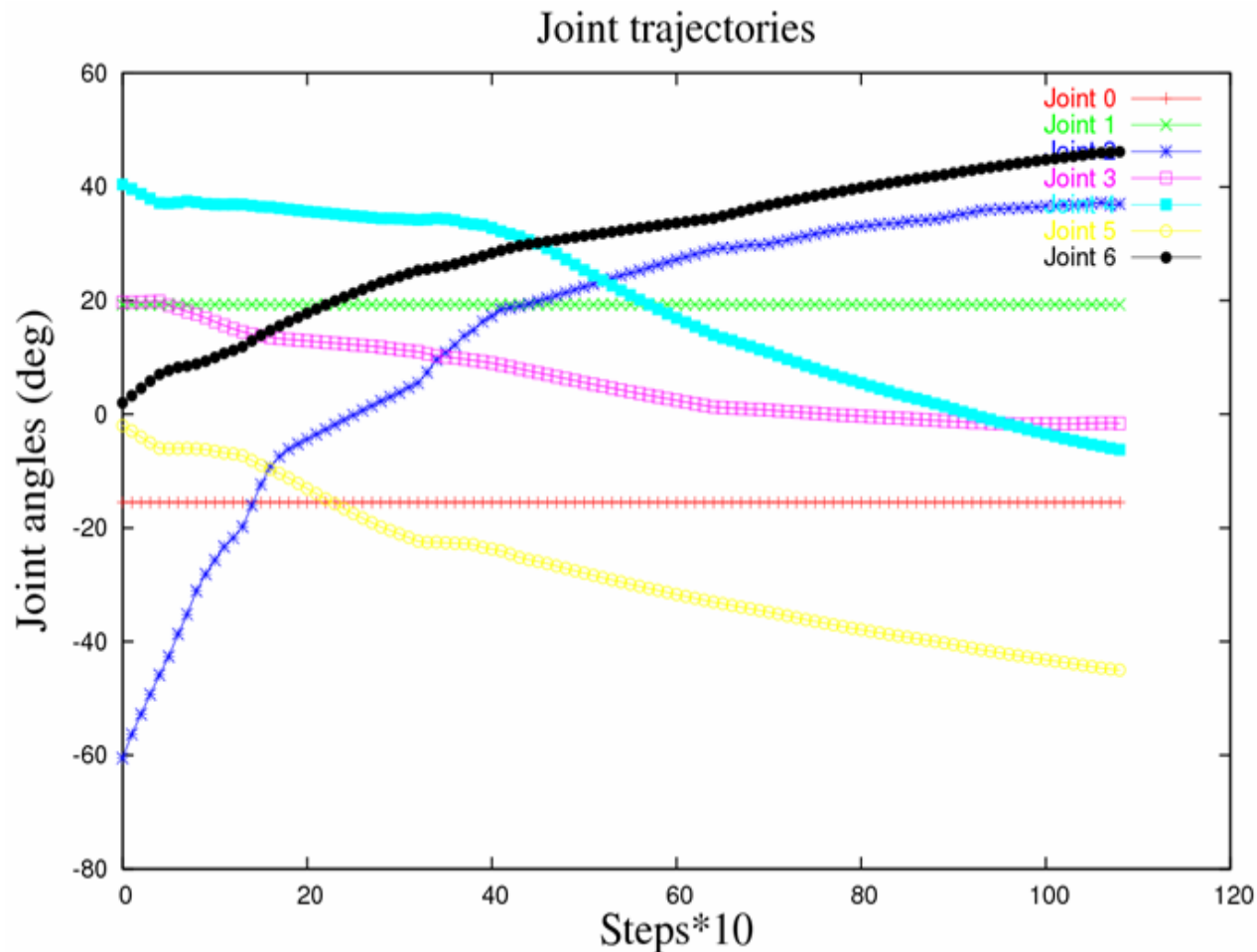
Final posture (clamped joint 0)

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



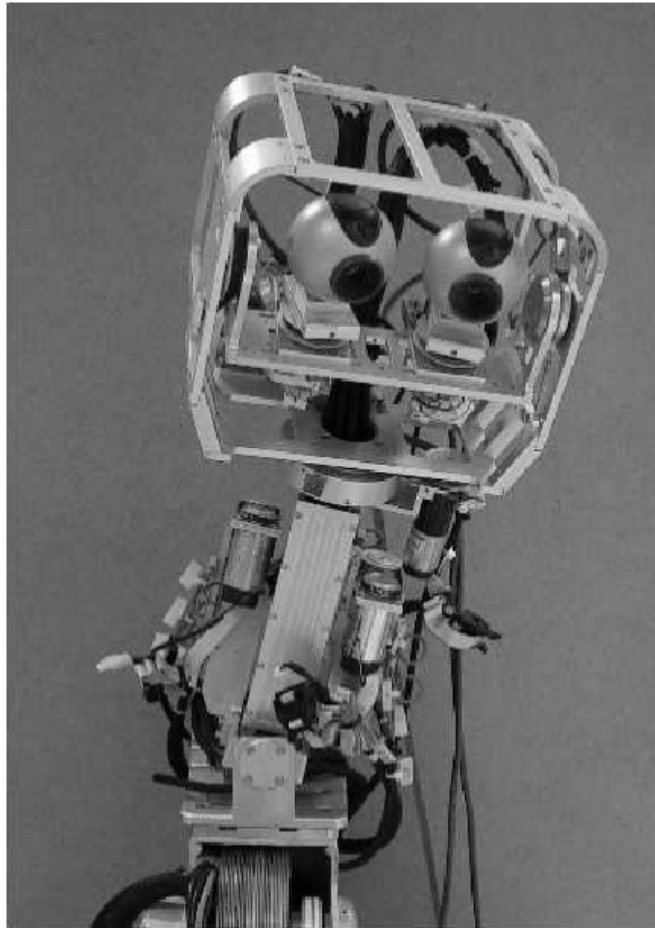
Joint trajectory: clamped joint 0

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



Joint trajectory: clamped joint 0 and joint 1

Experimental results: gazing with symmetric eye angles

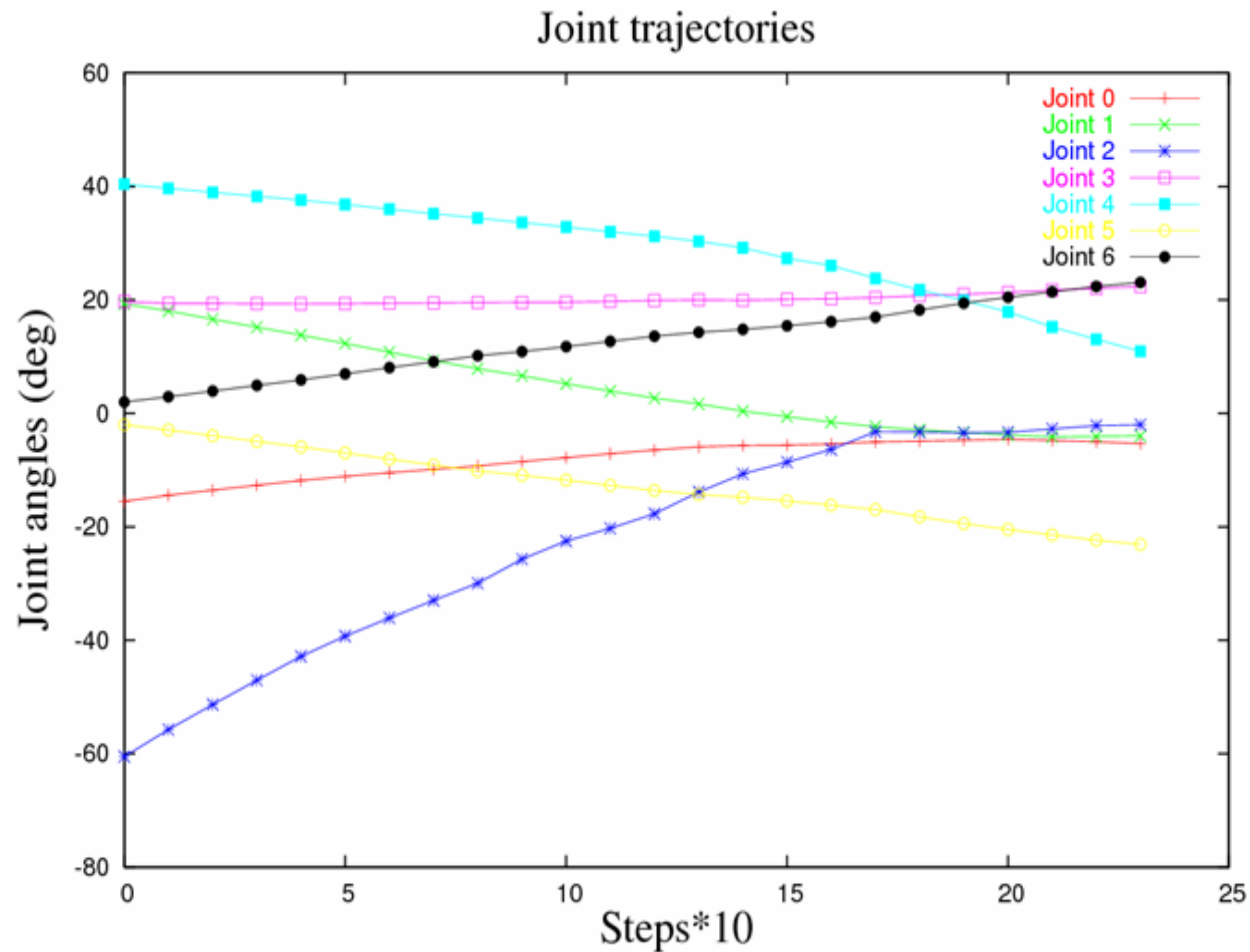


Final posture in normal mode



Final posture with symmetric
angles for eye joints

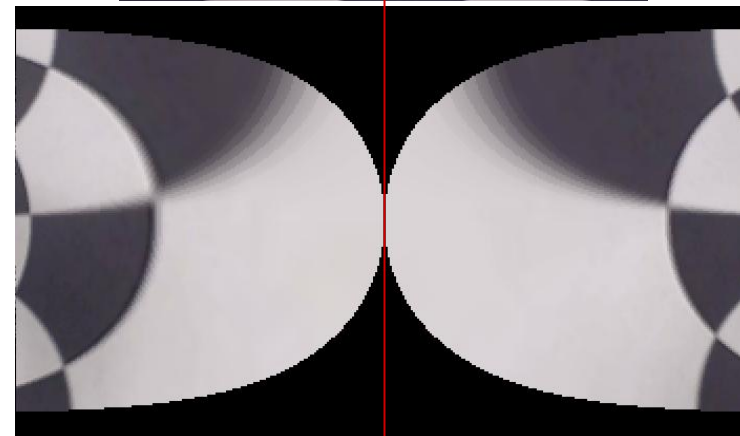
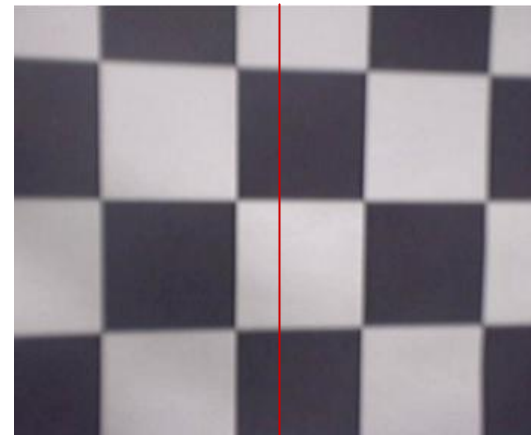
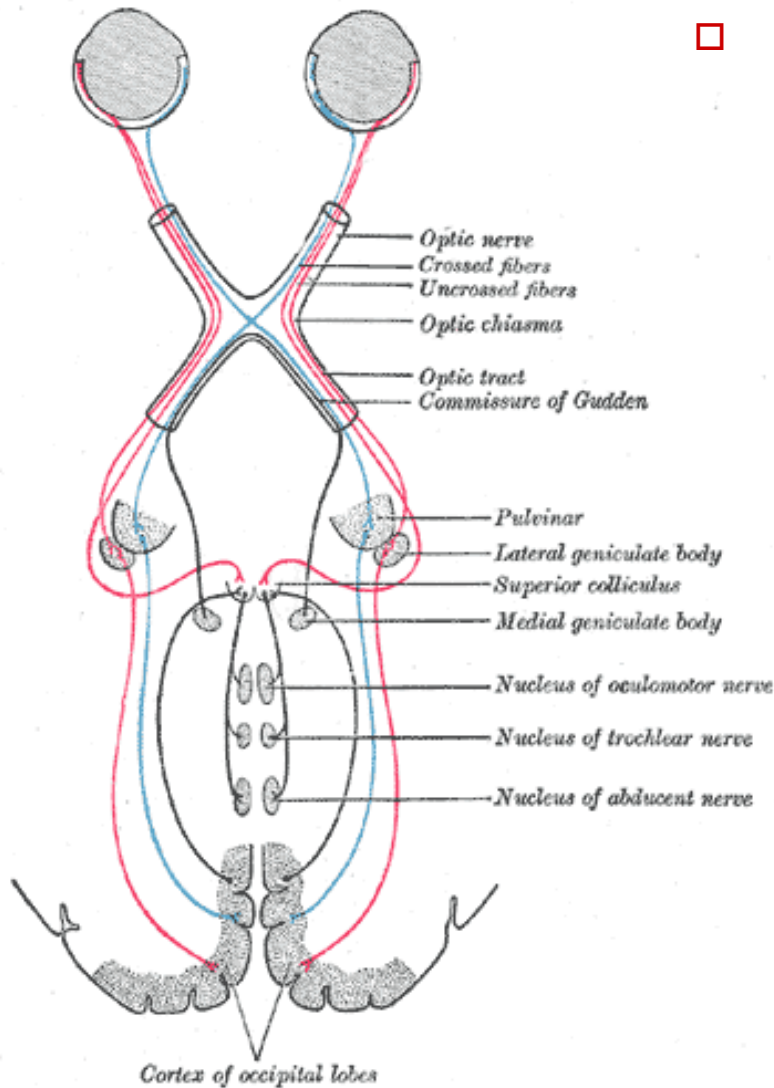
Experimental results: robotic head (7 d.o.f)



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



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

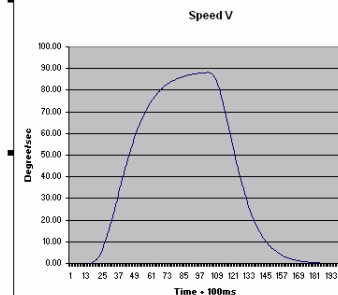
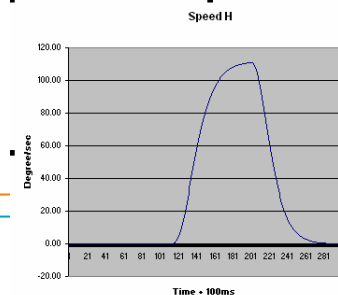
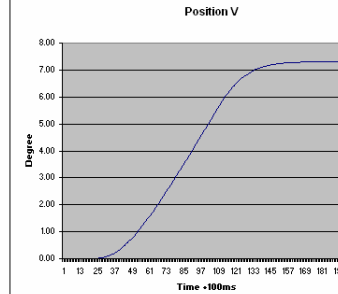
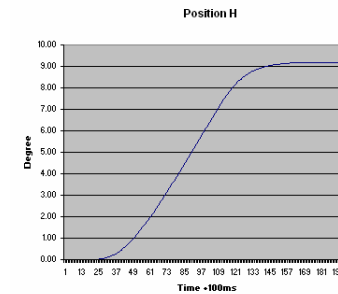
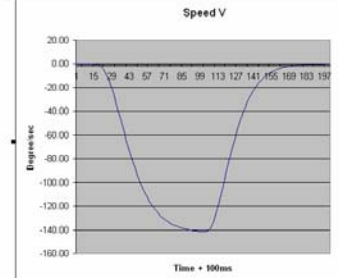
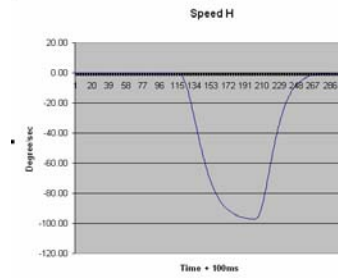
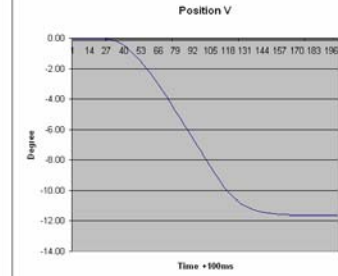
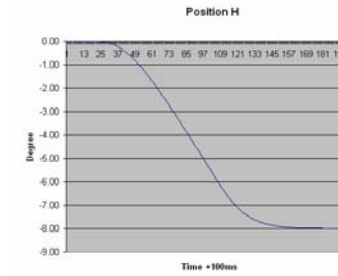
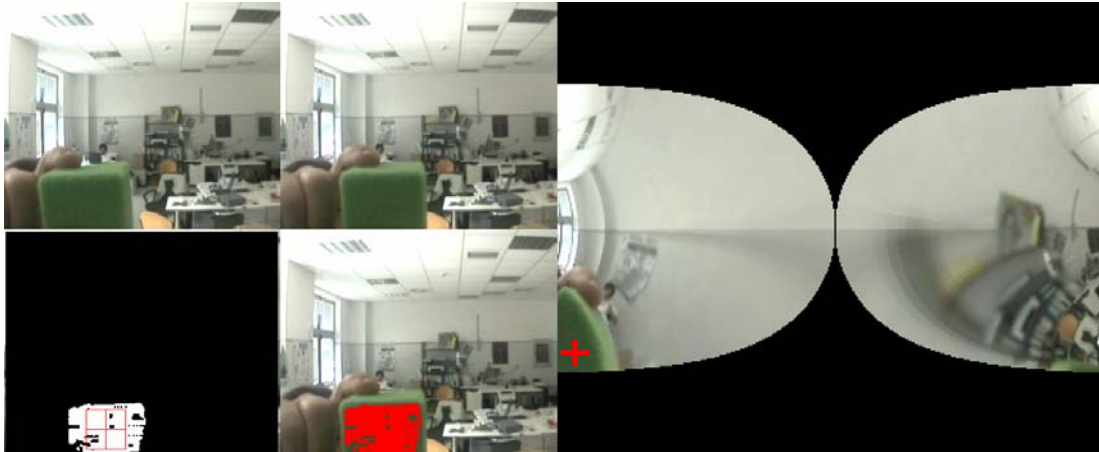
- Implementation of the mapping from the polar coordinates in visual space to the superior colliculus coordinates system, according to the model
- Generation of saccade movements:
 - A stimulus of a given colour can be detected in the map and the coordinates calculated in the superior colliculus, in 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