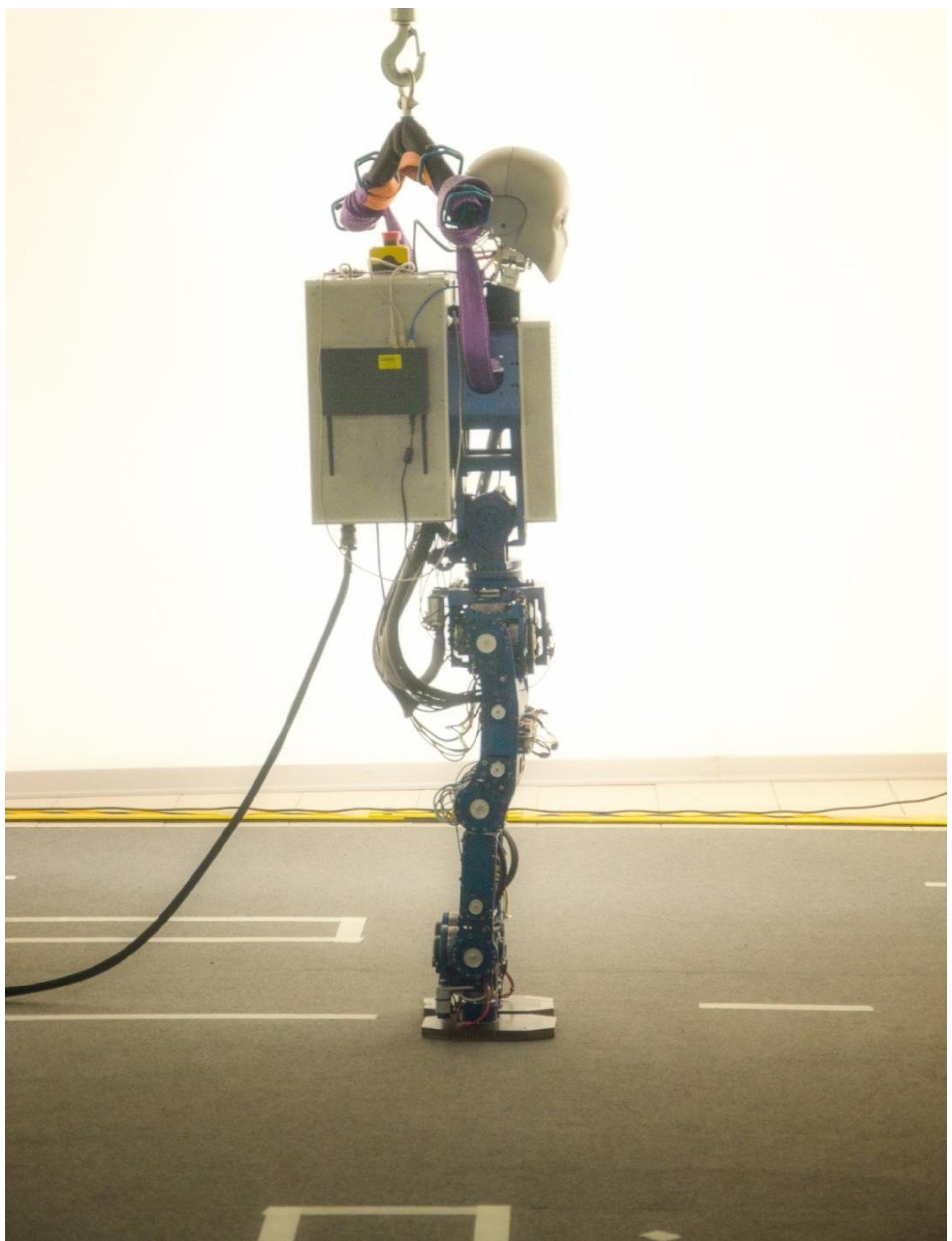
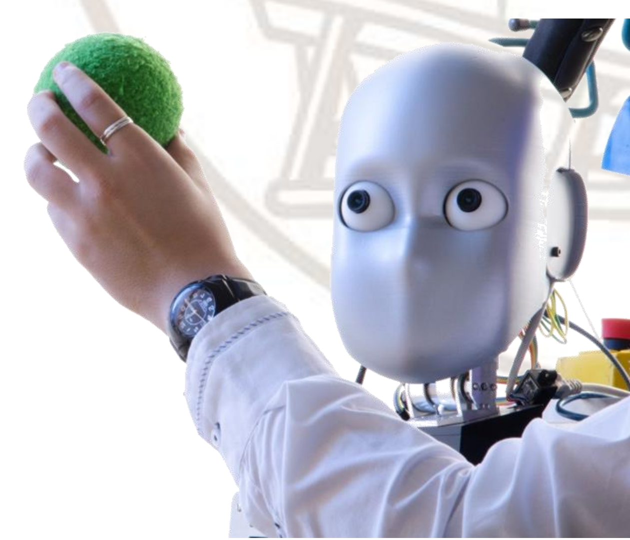
THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna



Bioinspired Models of Robot's Behaviour implemented on humanoid robots



Outline of the lecture

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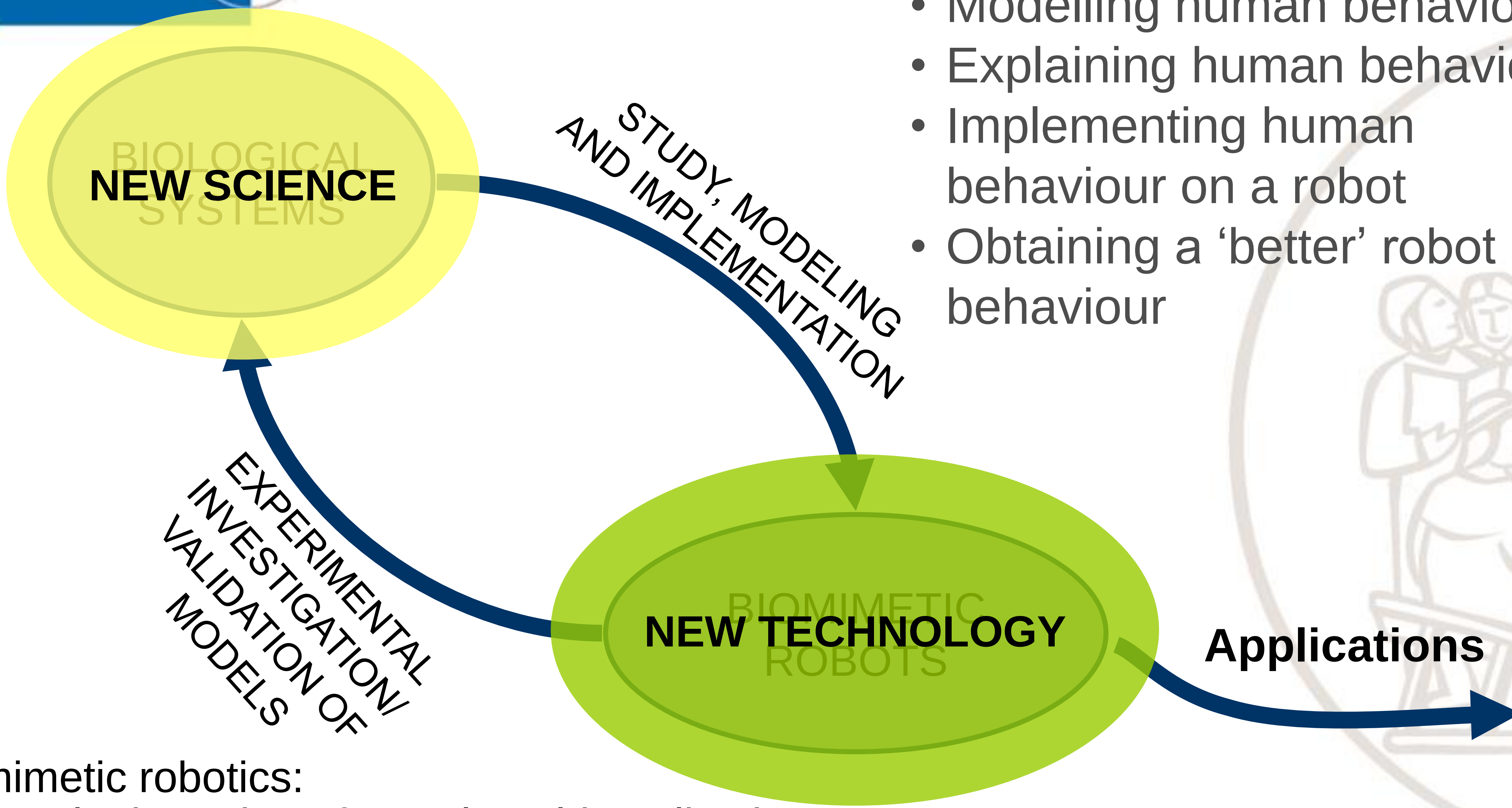
Scuola Superiore Sant'Anna

- Why bioinspired models in robotics?
- Behaviour: perception-action loops – are perception and action so different?
- The wonder of the vestibular system:
  - VOR
  - Head stabilization
- Anticipation and prediction in perception-action loops:
  - *Perception is a simulated action*: Expected Perception (EP) in the tactile space and EP in the visual space
  - Prediction of other agents' movement: smooth pursuit and punching
- Gaze control: an action selection problem
- Why is gaze control so important for movement?
  - Trajectory planning in locomotion
- Robot tasks integrating gaze control, trajectory planning, head stabilization, and EP

Why bioinspired models in robotics?

From neuroscience to robotics
- Observing human behaviour
- Modelling human behaviour
- Explaining human behaviour
- Implementing human behaviour on a robot
- Obtaining a ‘better’ robot behaviour



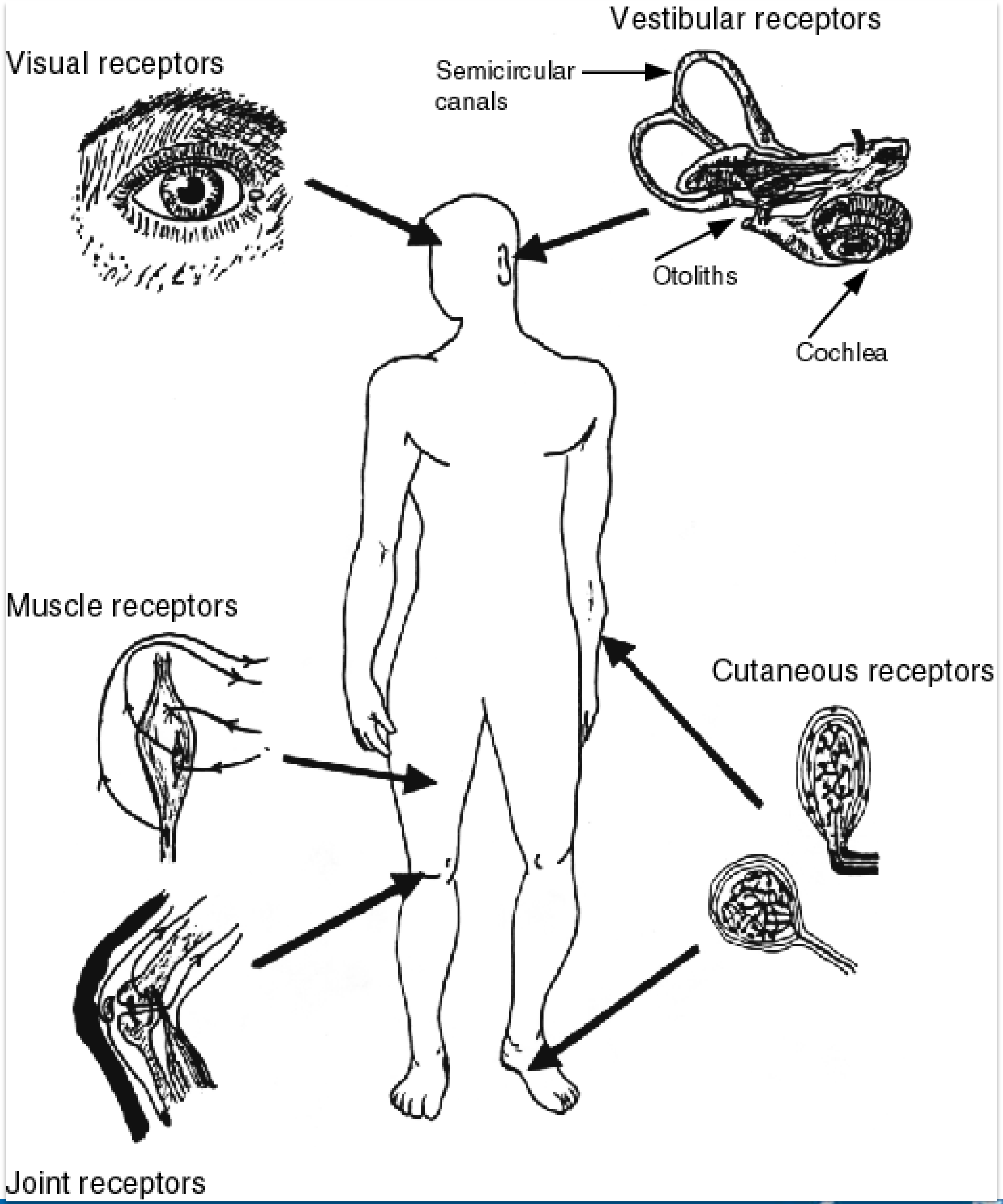
Biomimetic robotics:
- developing robots for real-world applications
- studying biological systems by robotic platforms

Unified approach to the study of living organisms and robots

The human “sense of movement”

In humans the **sense of movement** is given by the integration of a variety of sensory signals, mostly proprioceptive.

The **vestibular system** that provides perception of the head movements and postures relative to space plays a key role.



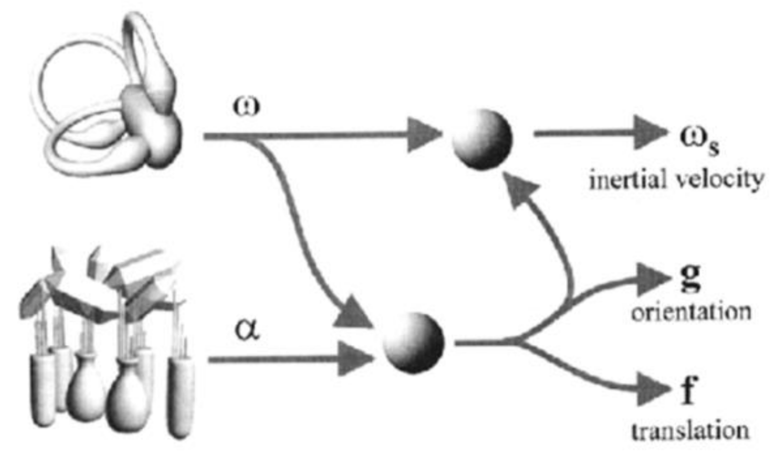
Berthoz A.(2002),*The sense of movement*. Harvard University Press

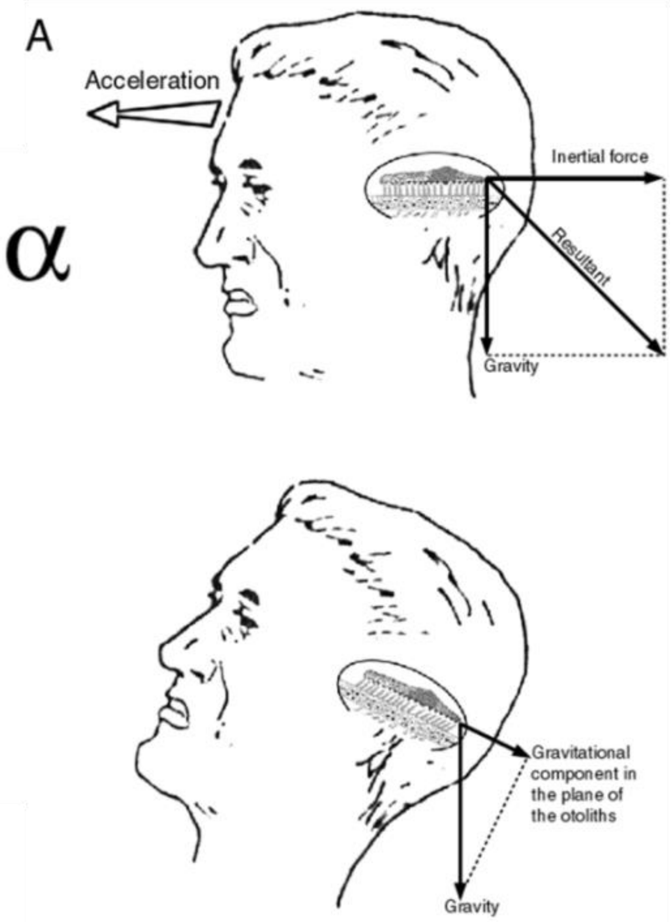
The vestibular system

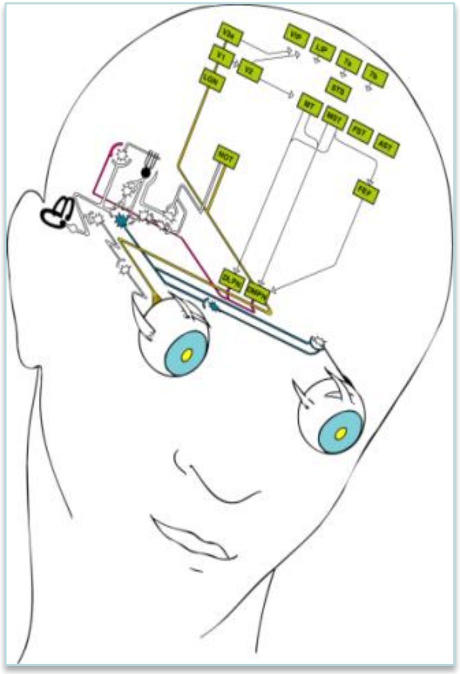
The vestibular system comprises of two components:

1. the **semicircular canal system**, which detects rotational movements (**angular velocities**);
2. **otolithic organs**, which detect **linear accelerations**.

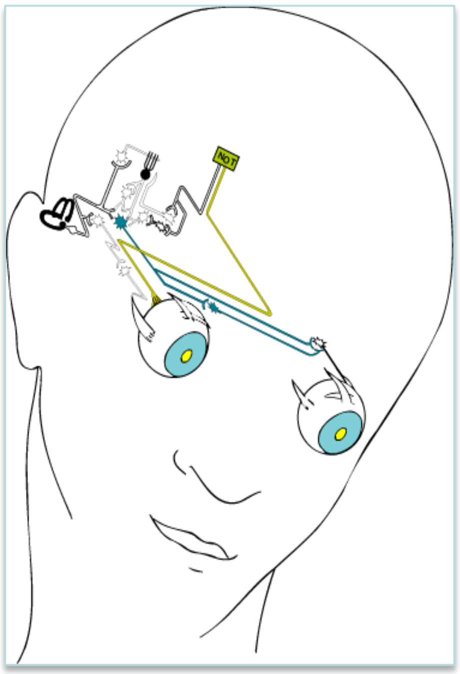
$$\dot{f} = \omega \times f + \dot{\alpha} - \omega \times \alpha$$



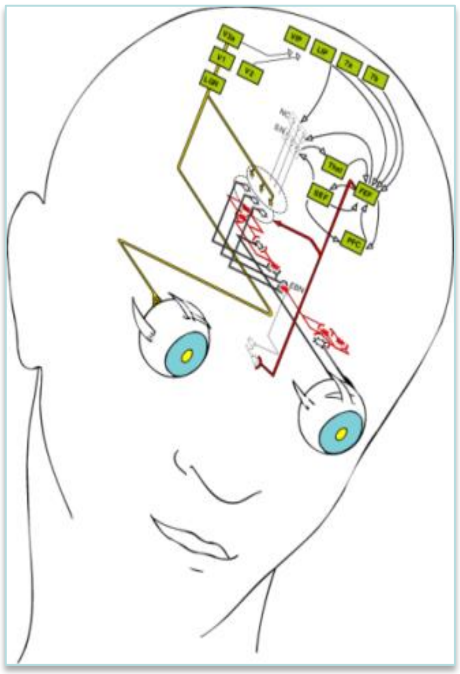




Smooth Pursuit



VOR



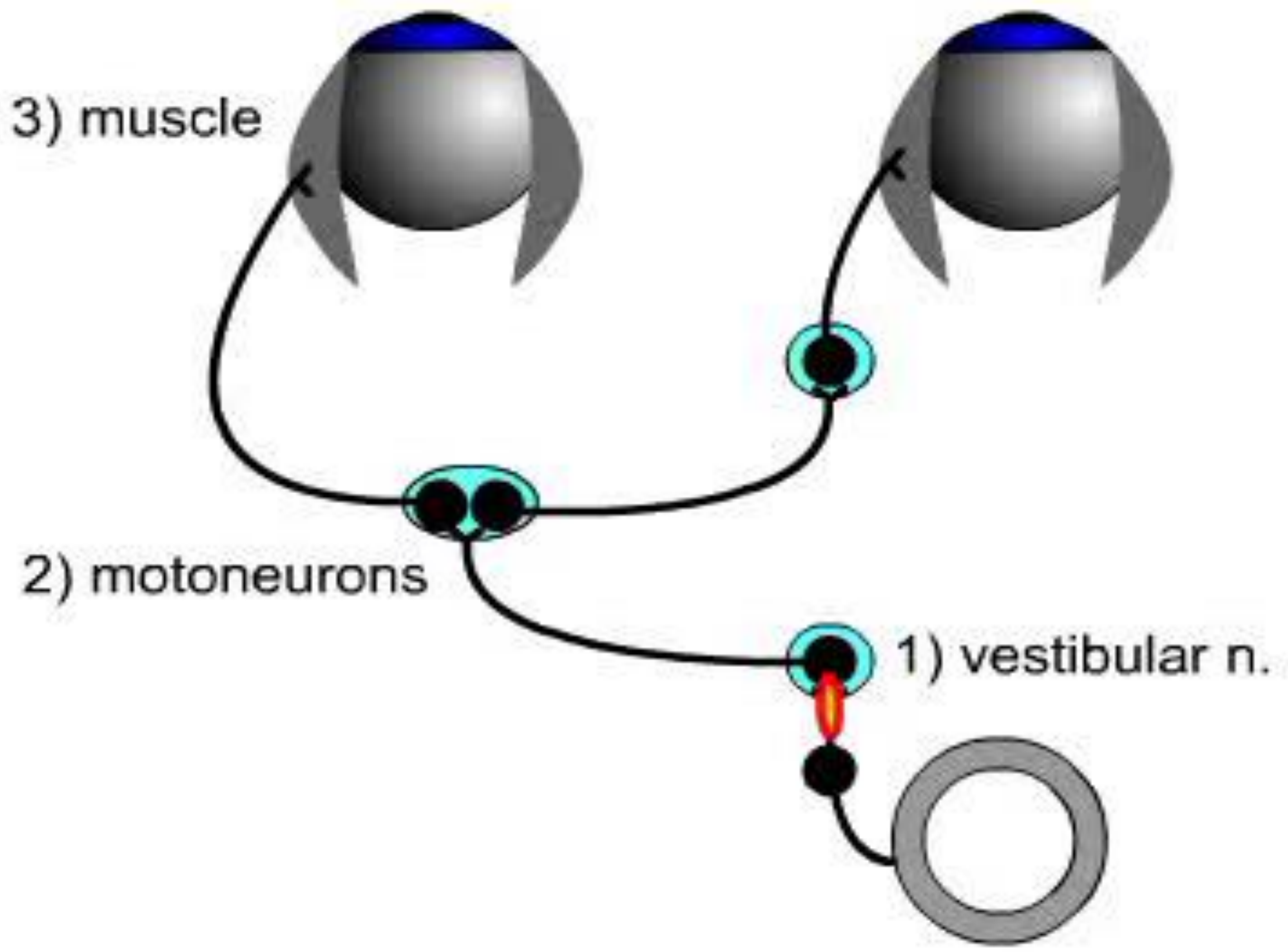
Saccades

The vestibular information is integrated with retinal motion information to allow the correct representation of head position. The vestibular system contributes to our **balance** and our sense of **spatial orientation**.

Vestibulo-Ocular Reflex (VOR)

Explain the neural mechanism for a horizontal VOR.

The direct path is a short reflex with 3 synapses.



Vestibulo-Ocular Reflex (VOR)

Explain the neural mechanism for a horizontal VOR.

When the **head rotates rightward** the following occurs.

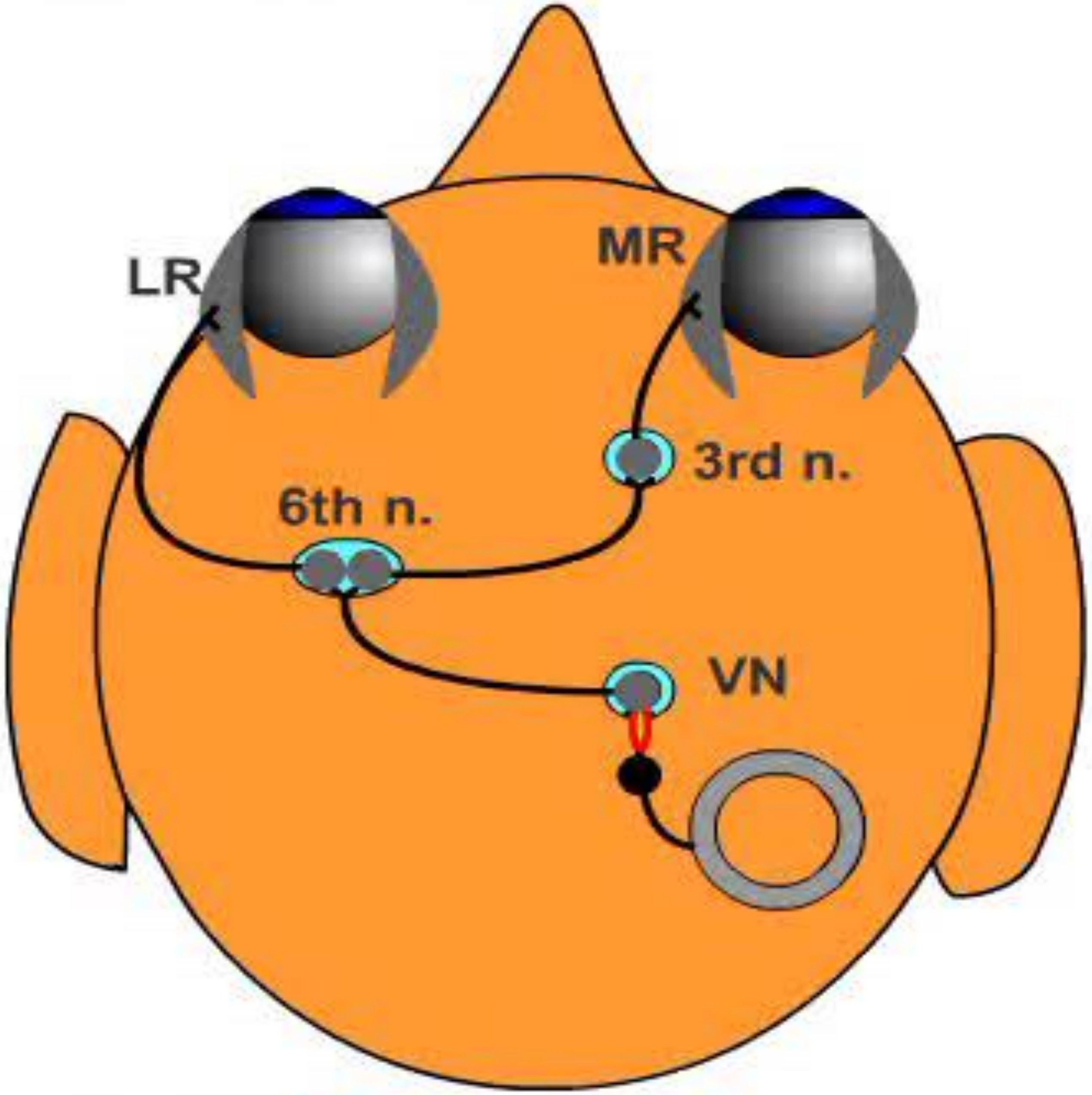
The right horizontal canal hair cells depolarize.

The right vestibular nucleus (VN) firing rate increases.

The motoneurons (in the right 3rd and left 6th nuclei) fire at a higher frequency.

The left lateral rectus (LR) extraocular muscle and the right medial rectus (MR) contract.

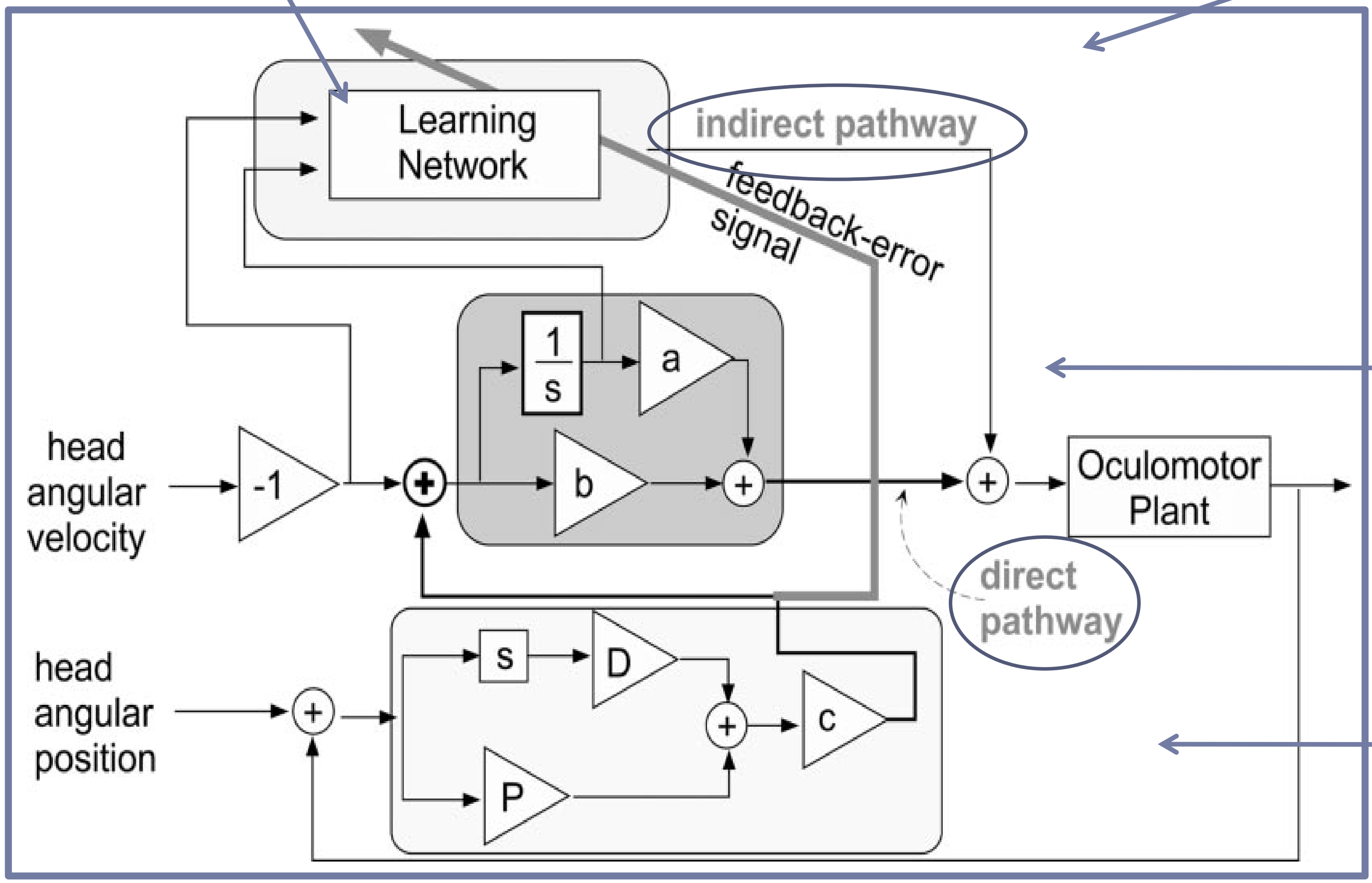
Both **eyes rotate leftward**.



VOR model

Introduction of a ***temporal eligibility*** window to obtain the time-alignment

Algorithm *feedback-error-learning* ***(FEL)***: acquires an inverse dynamics model of the oculomotor plant
⇨ **Algorithm *recursive least squares (RLS)***



VOR: *feedforward* open-loop controller using an inverse control model

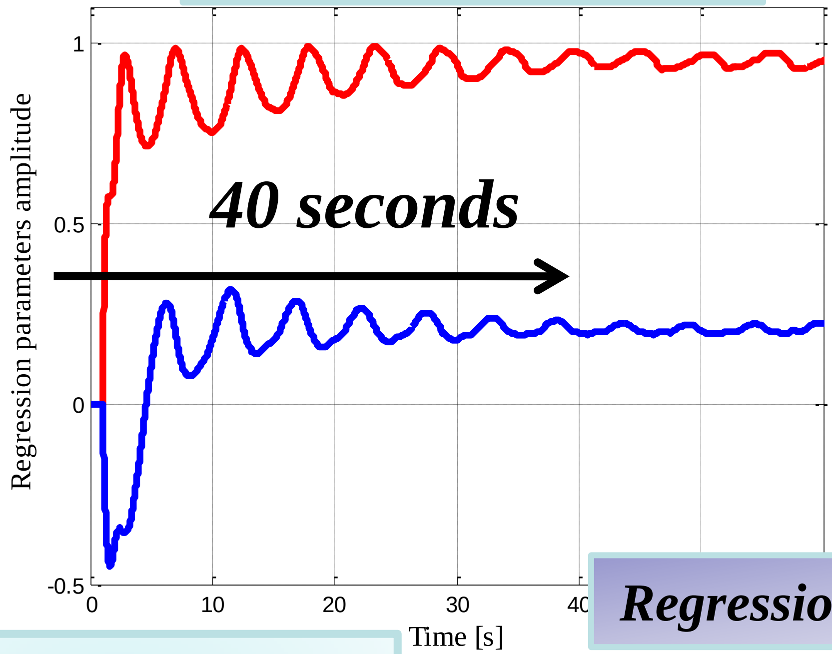
OKR: compensatory *negative feedback* controller

(T.Shibata & S.Schaal, 2001)

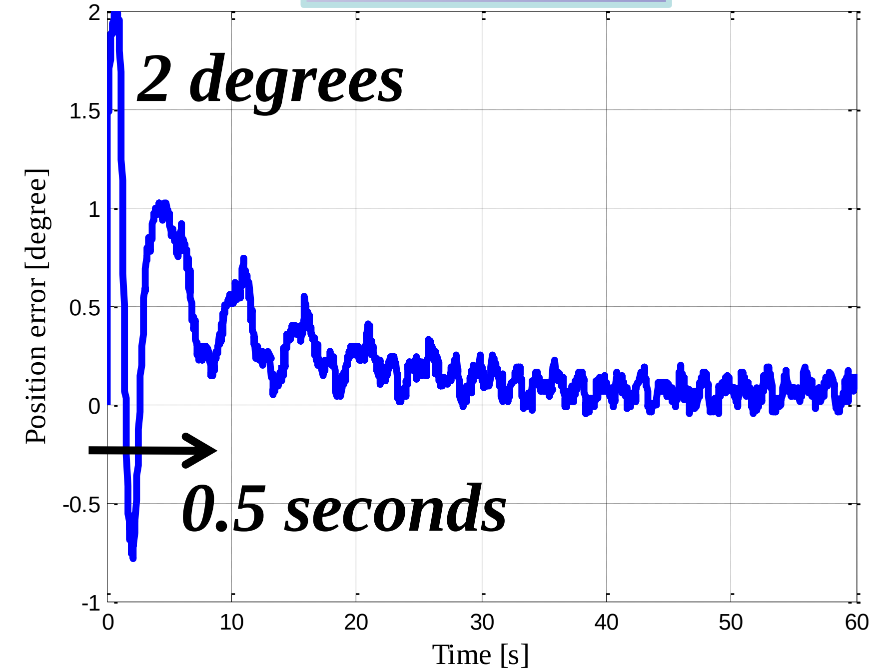
Results

TRAINING PHASE:
sinusoidal motion head (**0.2 Hz**)

Regression parameters

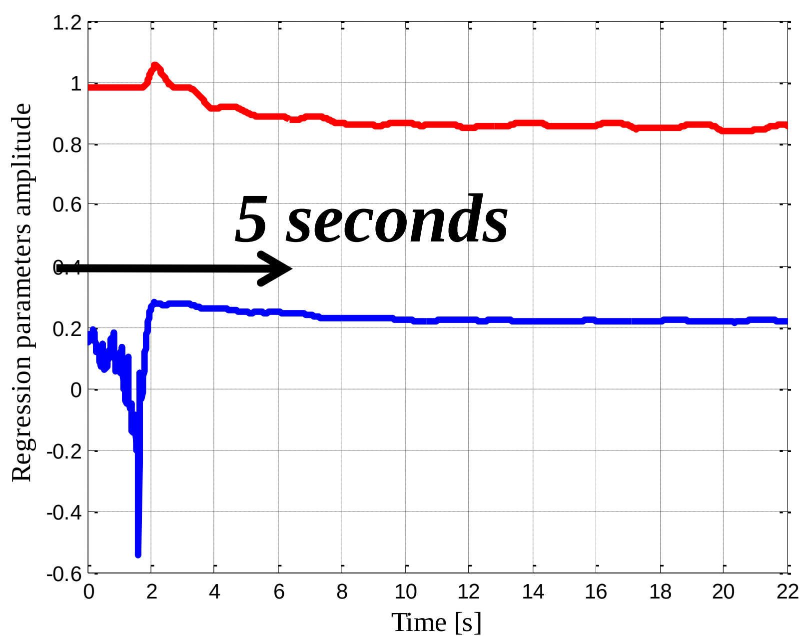


Position error

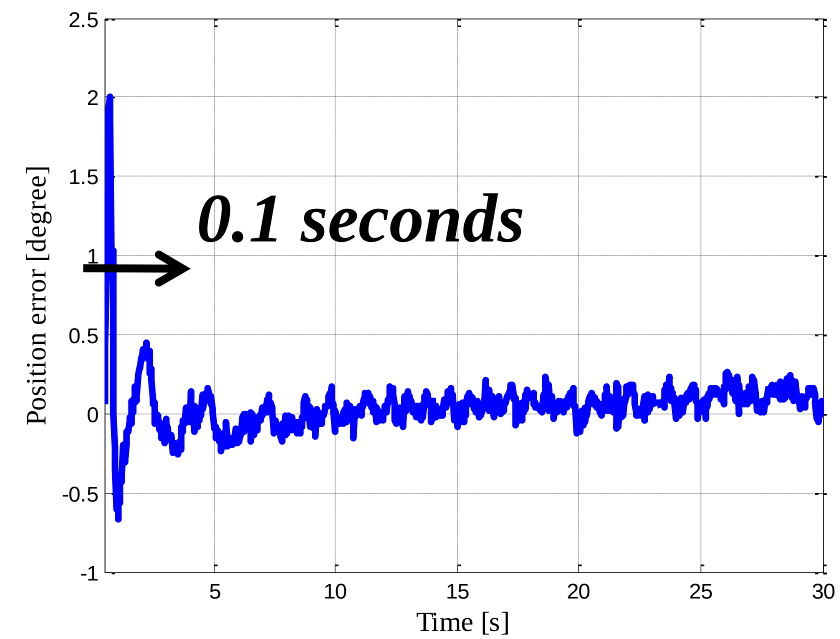


POST TRAINING PHASE:
sinusoidal motion head (**0.4 Hz**)

Regression parameters



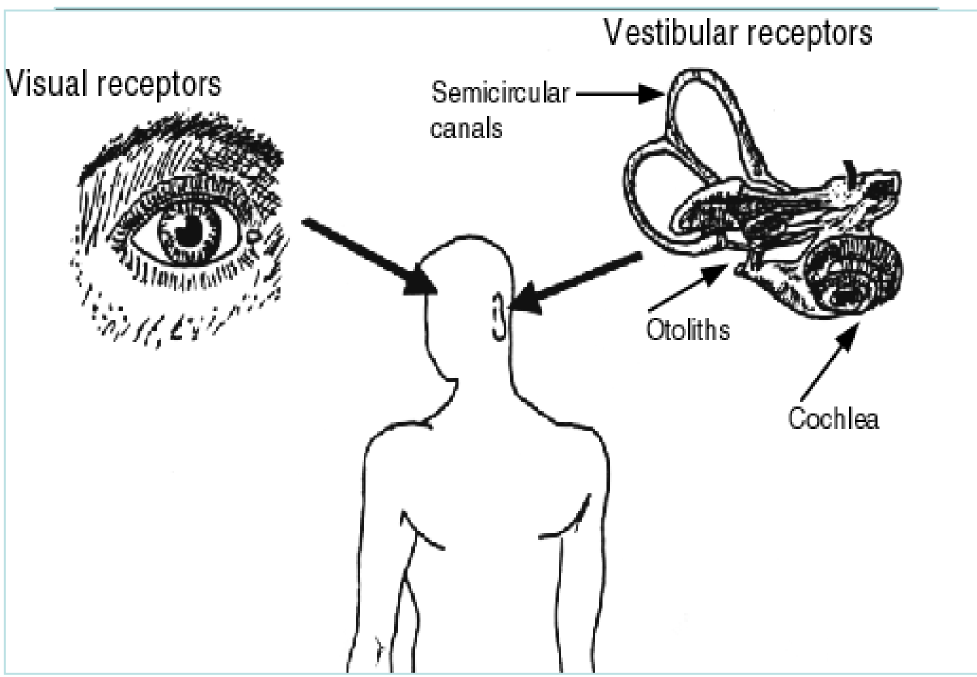
Position error

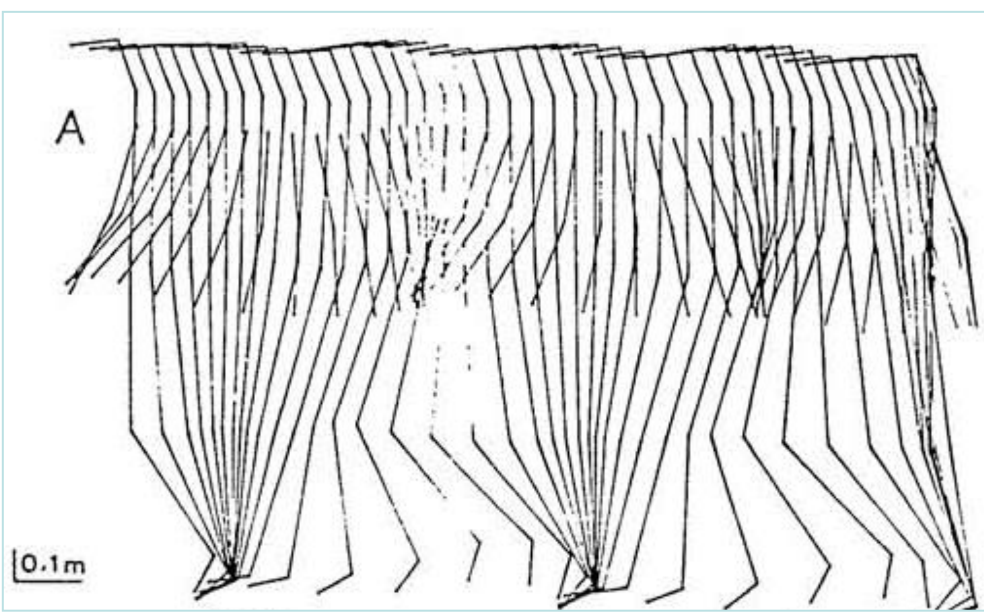


Robotic implementation of VOR

E. Franchi, E. Falotico, D. Zambrano, G. G. Muscolo, L. Marazzato, P. Dario and C. Laschi (2010) “A comparison between two bio-inspired adaptive models of Vestibular Ocular Reflex (VOR) implemented on the iCub robot”, *Proceedings of the IEEE Int. Conf. Humanoids 2010*

Head stabilization in biped locomotion



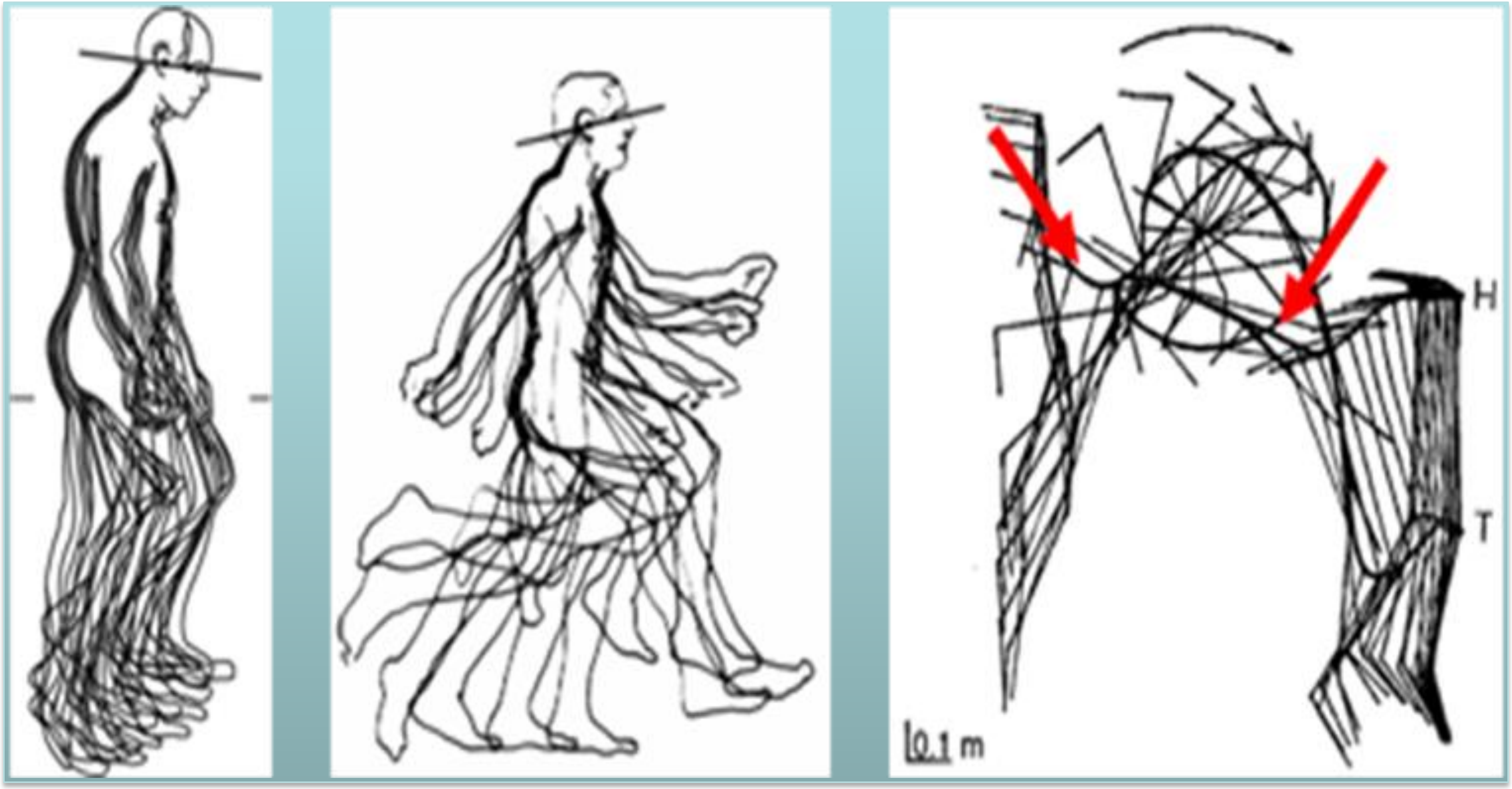


Pozzo T. et al. (1990).

Berthoz A., 2002, *The sense of movement*. Harvard University Press

Head stabilization in biped locomotion

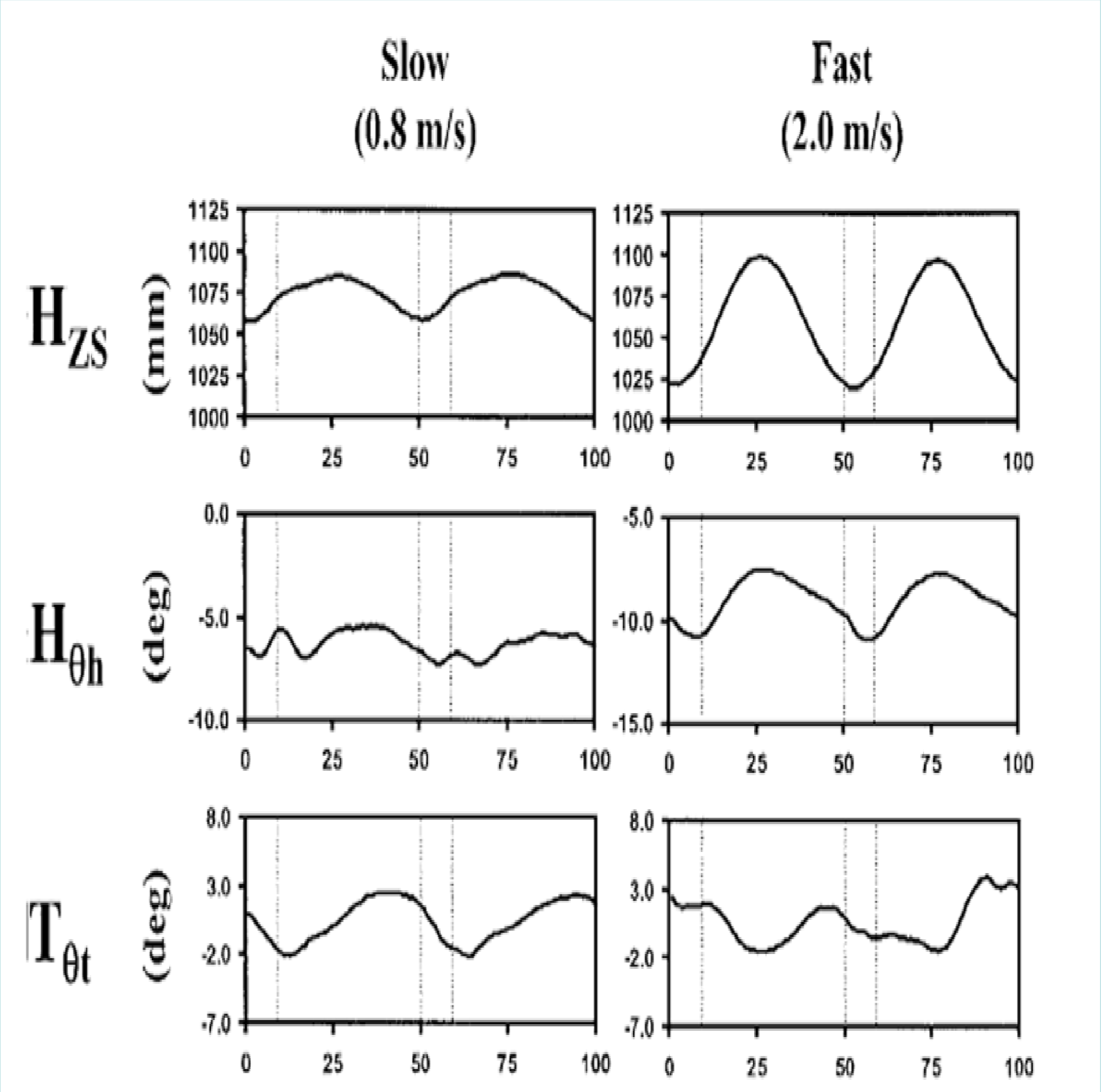
The brain uses the information coming from vestibular system to generate a ***unified inertial reference frame***, centred in the head, that allows whole-body coordinated movements and head-oriented locomotion.



It has been demonstrated that, in humans, gaze anticipates the head turns during locomotion and that gaze direction could be a reference for the stabilization of the head.

Berthoz A., 2002, *The sense of movement*. Harvard University Press

Head stabilization in humans
Head motion during straight walking



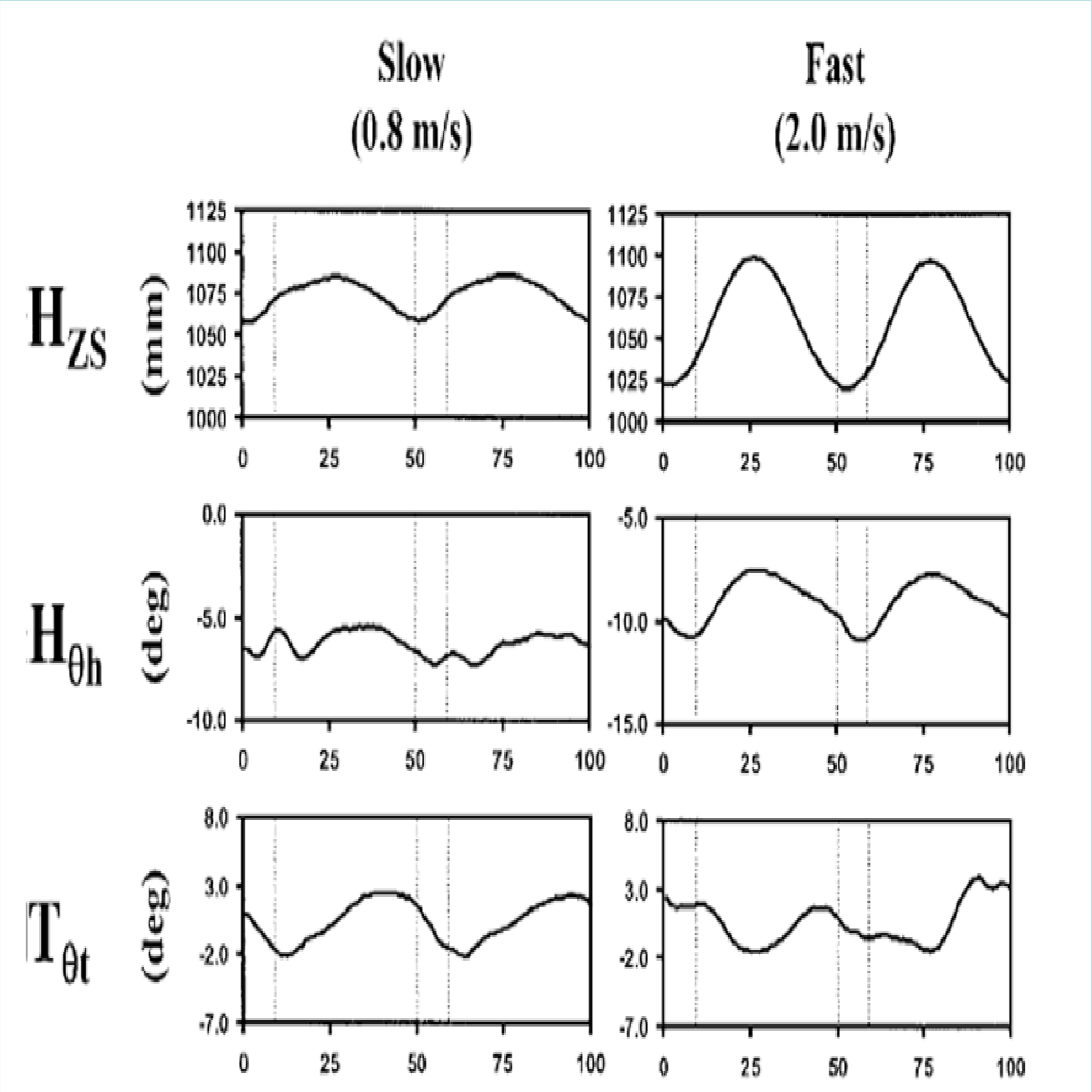
✓ **Vertical and lateral translations** of the head **are not stabilized to zero** during human walking

✓ The head **oscillates up and down**
- ✓from about 4 cm during slow walking (0.8 m/s)
- ✓to about 10 cm in fast walking (2 m/s)

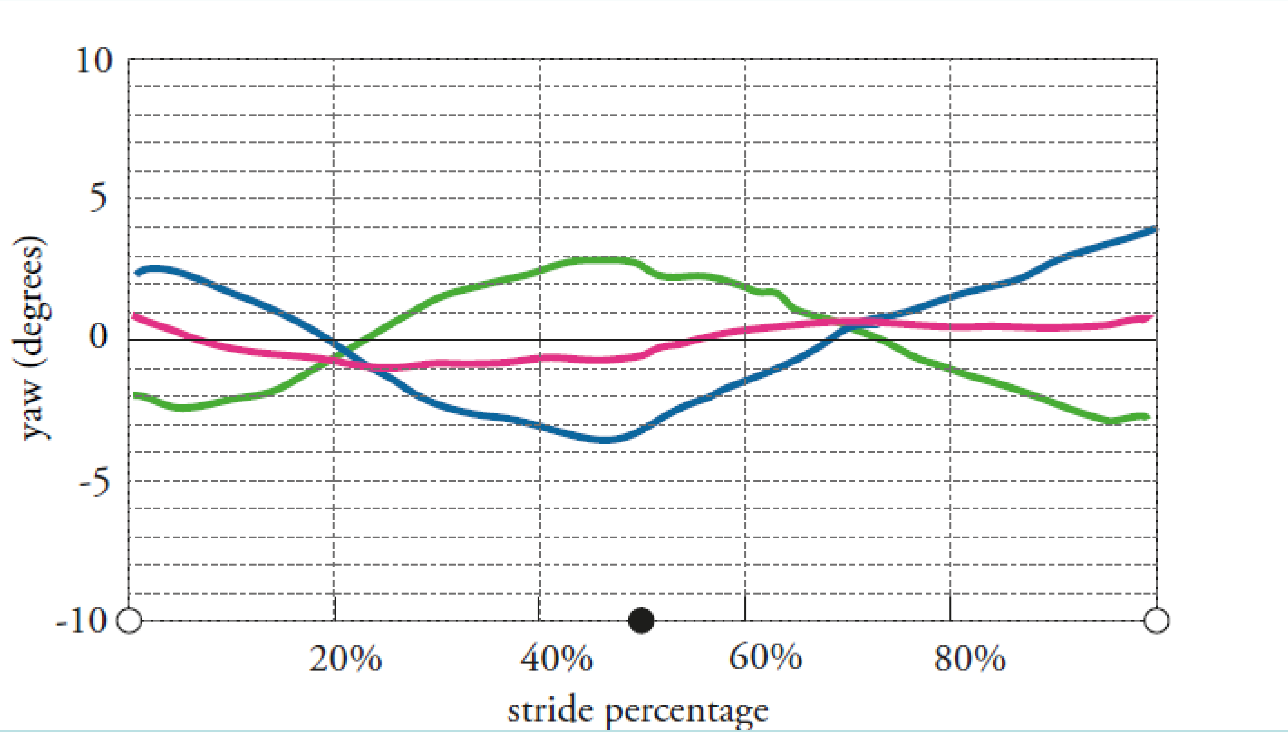
✓ The head **oscillates left to right**
- ✓about 5 cm in average in walking speeds between 1.4 and 1.8 m/s

E. Hirasaki et al. (1999)

Head stabilization in humans
Head motion during straight walking (II)



- ✓ Instead, head **orientation appears to be stabilized**
- ✓ Head yaw varies in a compensatory way to counteract body (trunk) yaw, the same for the pitch



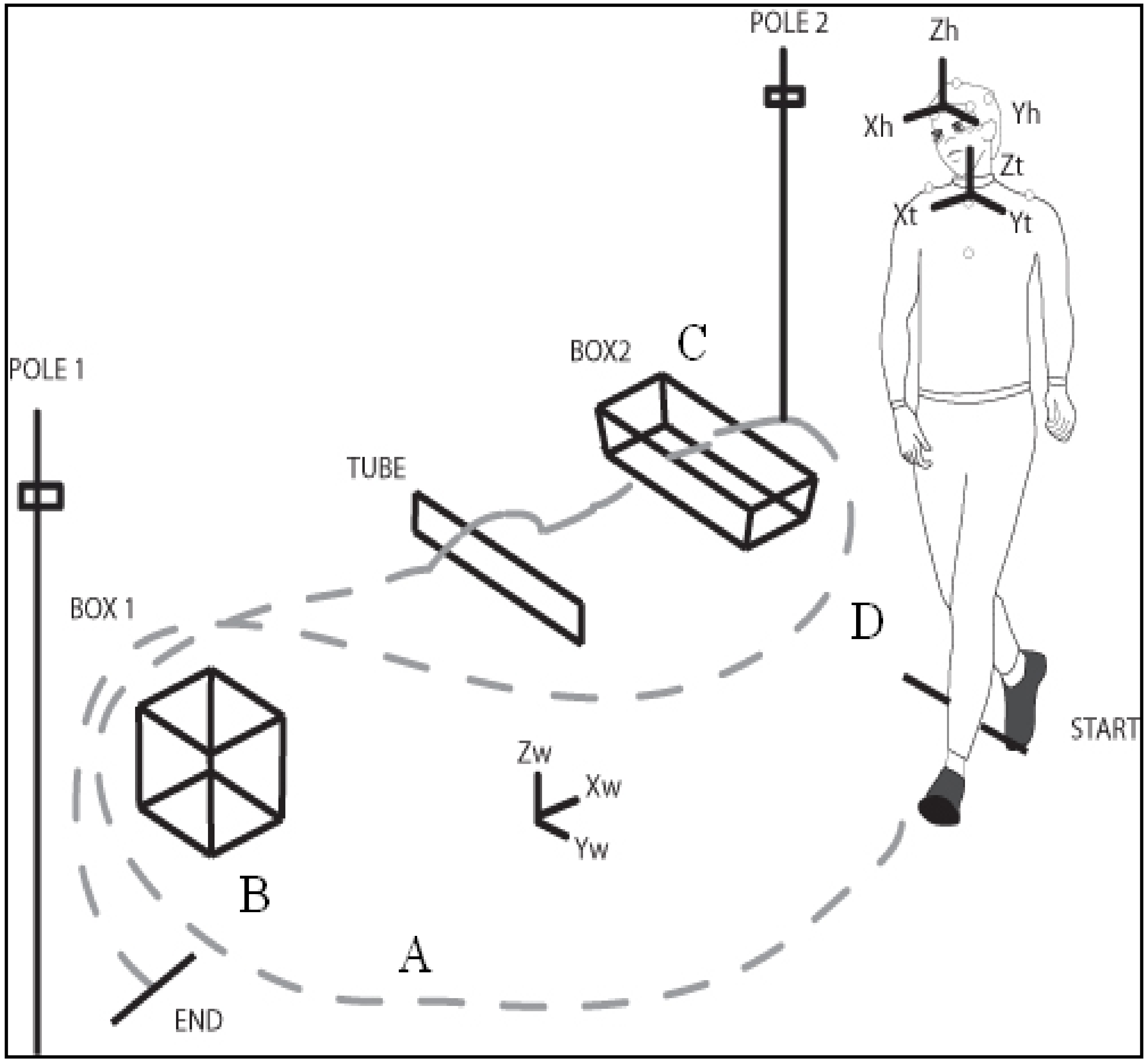
T. Imai et al. (2001)

Head stabilization experiments

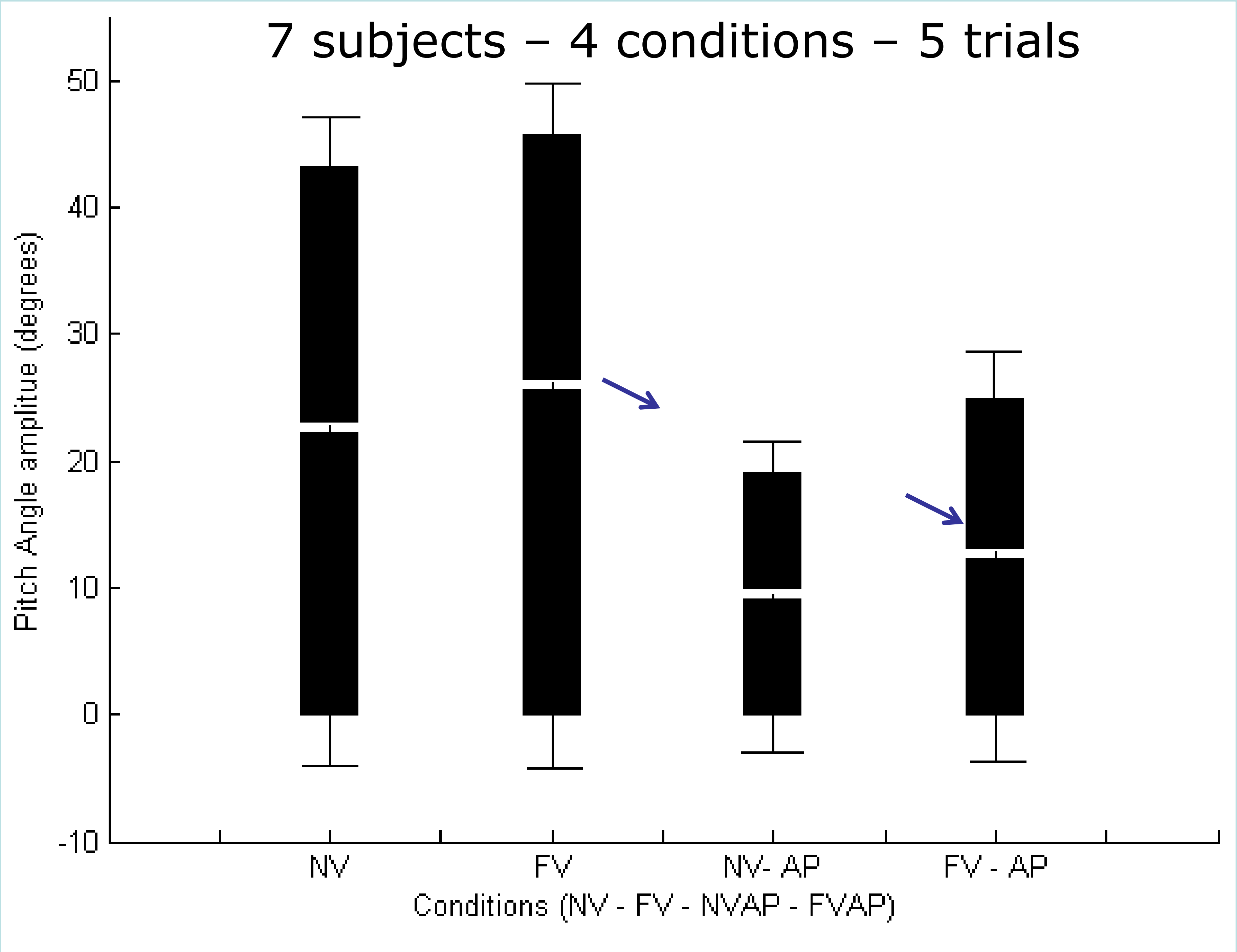
Experimental protocol:

- ✓ 2 visual conditions:
  - ✓Free Gaze (FG)
  - ✓Anchored Gaze (AG)
- ✓ 2 velocity conditions:
  - ✓Normal
  - ✓Fast
- ✓ 2 Path conditions:
  - ✓Straight walking
  - ✓Walking in the scenario

Head and trunk movements measured in ten subjects performing a complex locomotor task



Head Stabilization – Results
Peak-to-peak amplitude of the head pitch rotation



✓ Despite the linear and rotational motion of trunk, the head pitch orientation has little variation (9.2°) in AG condition respect to FG (23.4°).

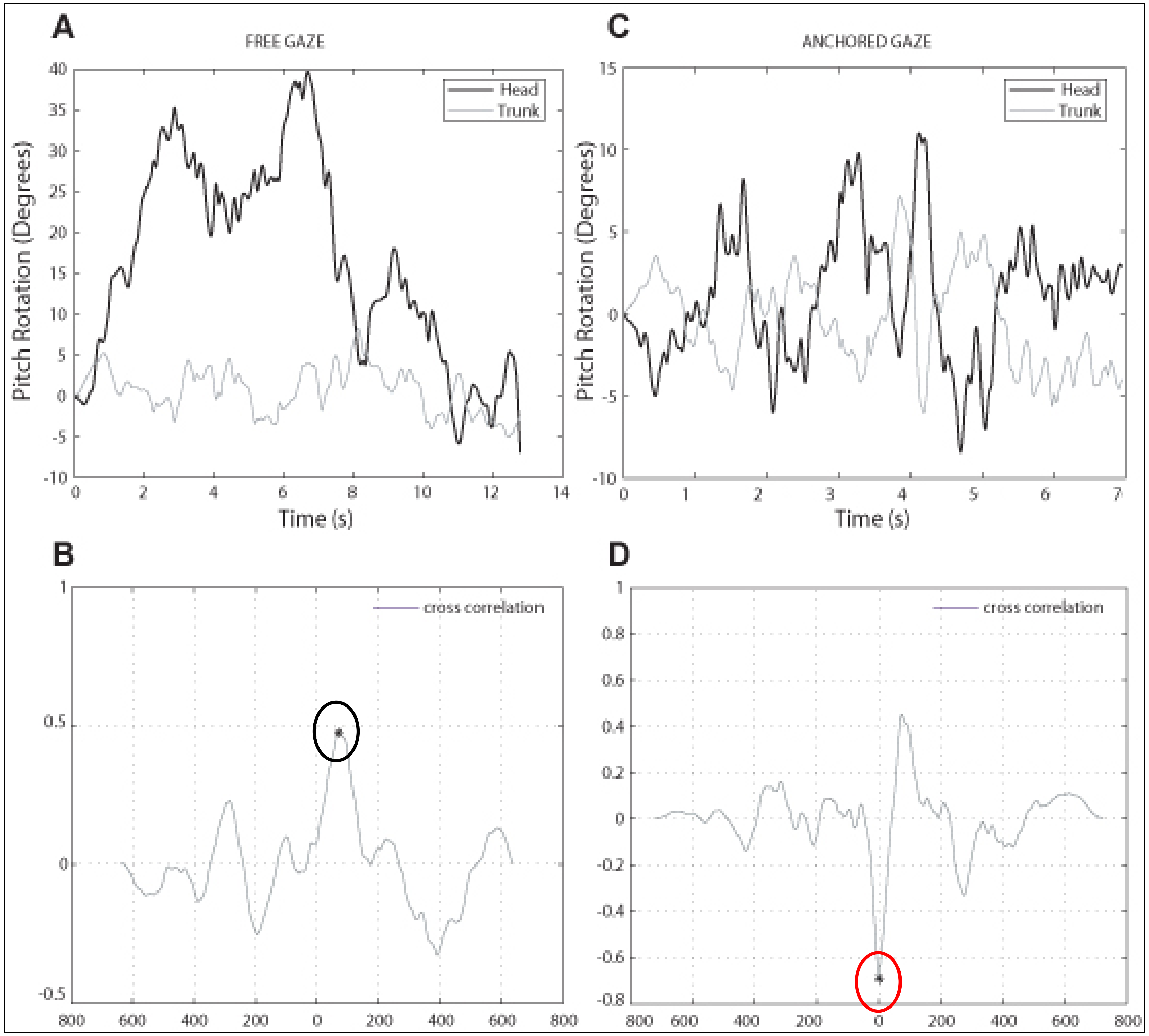
Head Stabilization – Results

Head pitch rotation compensation for trunk pitch rotation

Cross correlation between the trunk pitch and head pitch rotations related to the trunk.

✓ For the AG condition the cross-correlation between the two signals has a minimum value corresponding to zero. This result indicates that the two signals are in **anti-phase**.

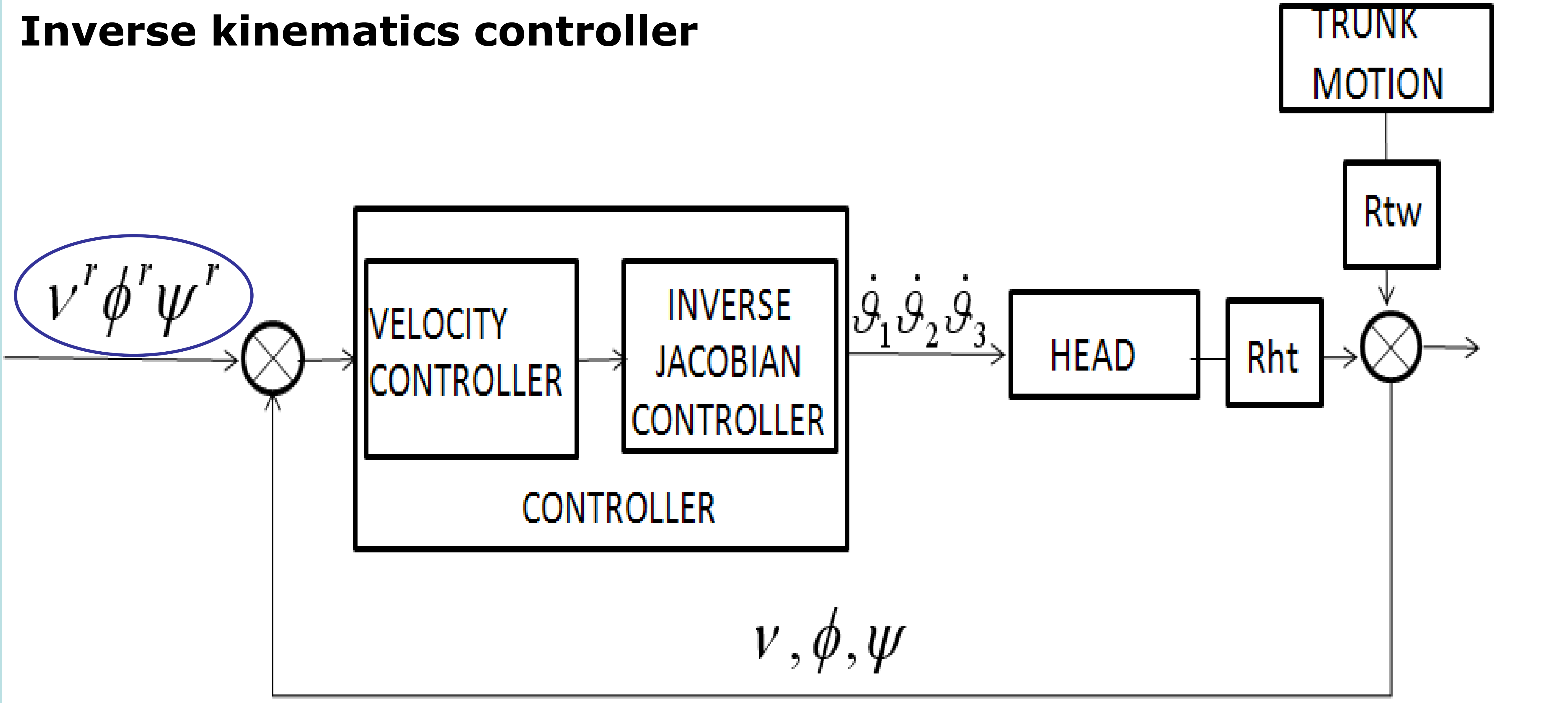
✓ The head pitch rotation relative to the trunk in AG condition appeared to **compensate for trunk pitch rotation.**



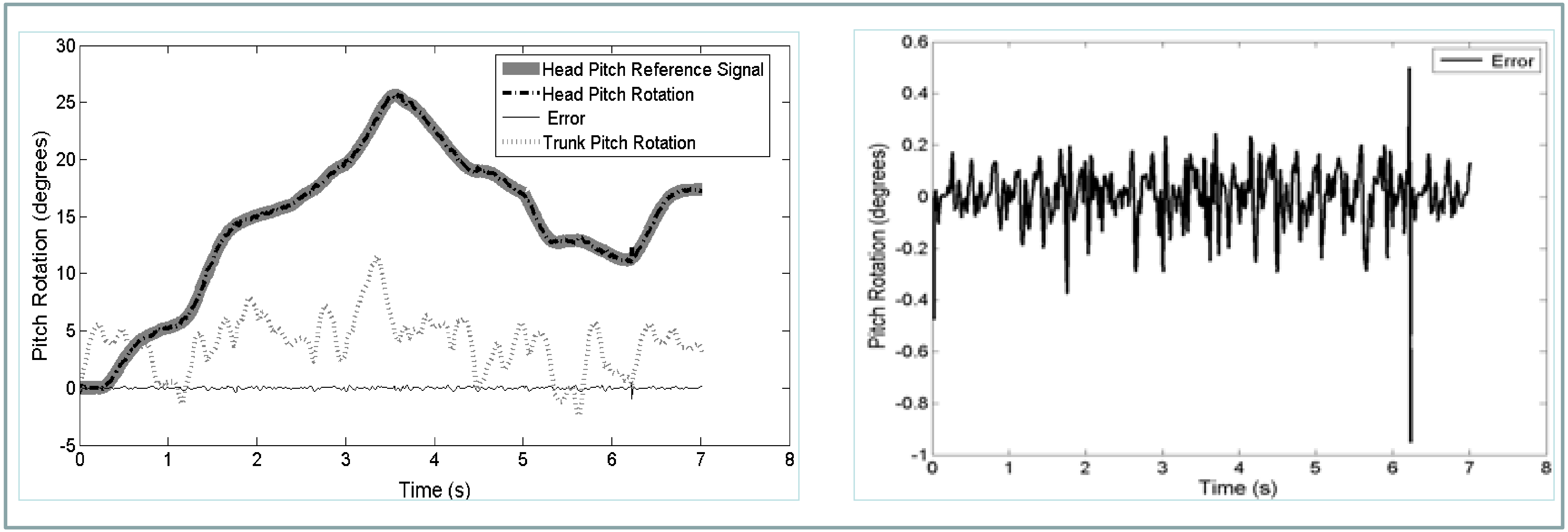
Head stabilization model

- ✓ **Experimental data** of 30 trials performed by 8 subjects.
- ✓ The head rotation in space is the reference input for the model

Inverse kinematics controller

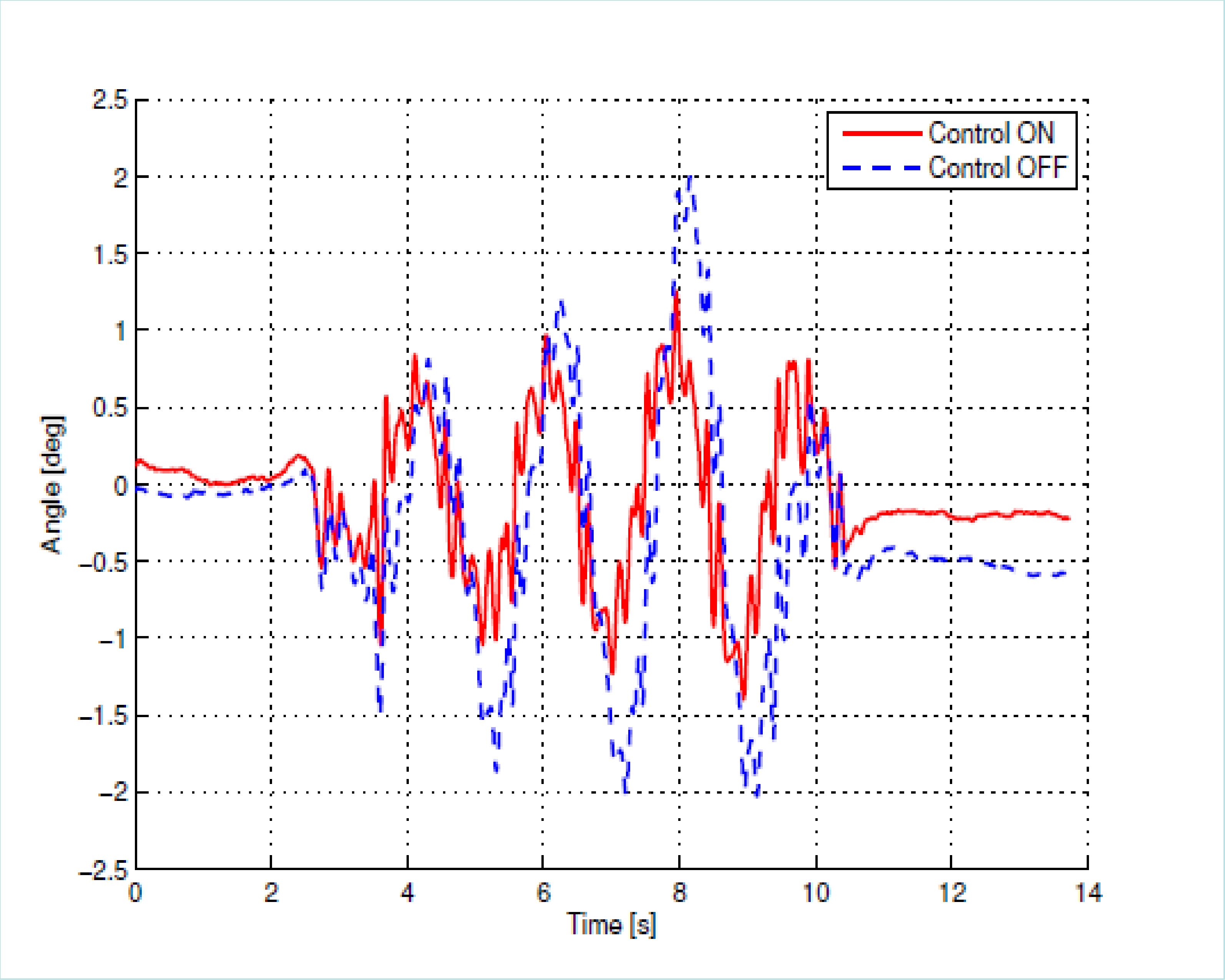


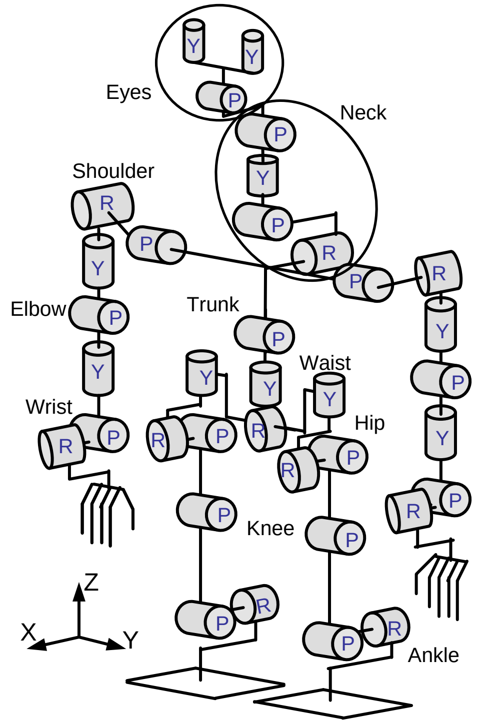
Head stabilization model - results



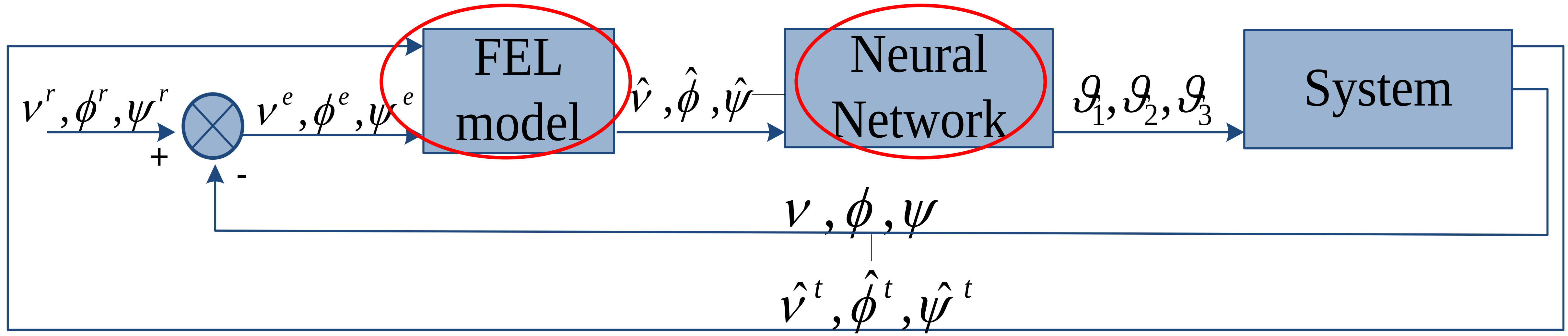
Results of the execution of the model for a trial in AG condition. The peak to peak amplitude of the error is less than 1 degree

Head stabilization model implemented on the KOBIAN robot





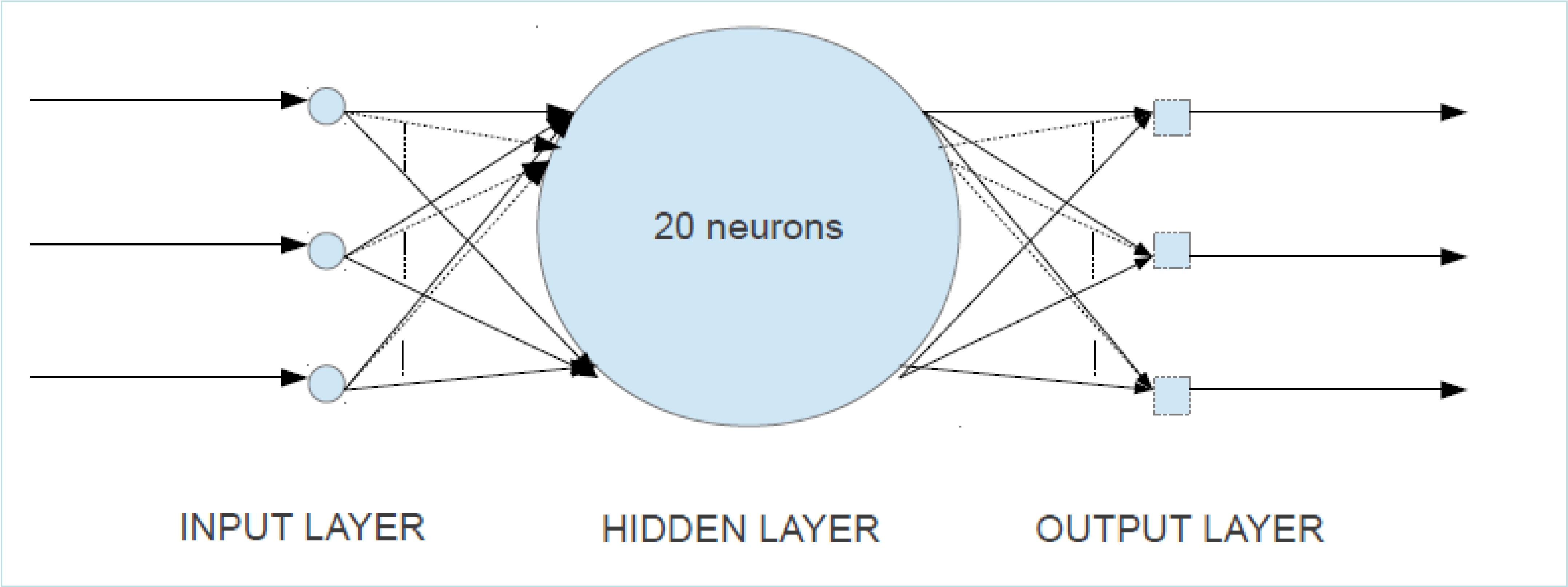
Adaptive head stabilization model



- ✓ The controller is based on a feed feedback error learning (**FEL**) model. This model estimates the orientation of the head, which allows following a reference orientation .
- ✓ The output of this model is sent as input to a **Neural Network** which computes the joint positions relative to the estimated orientation

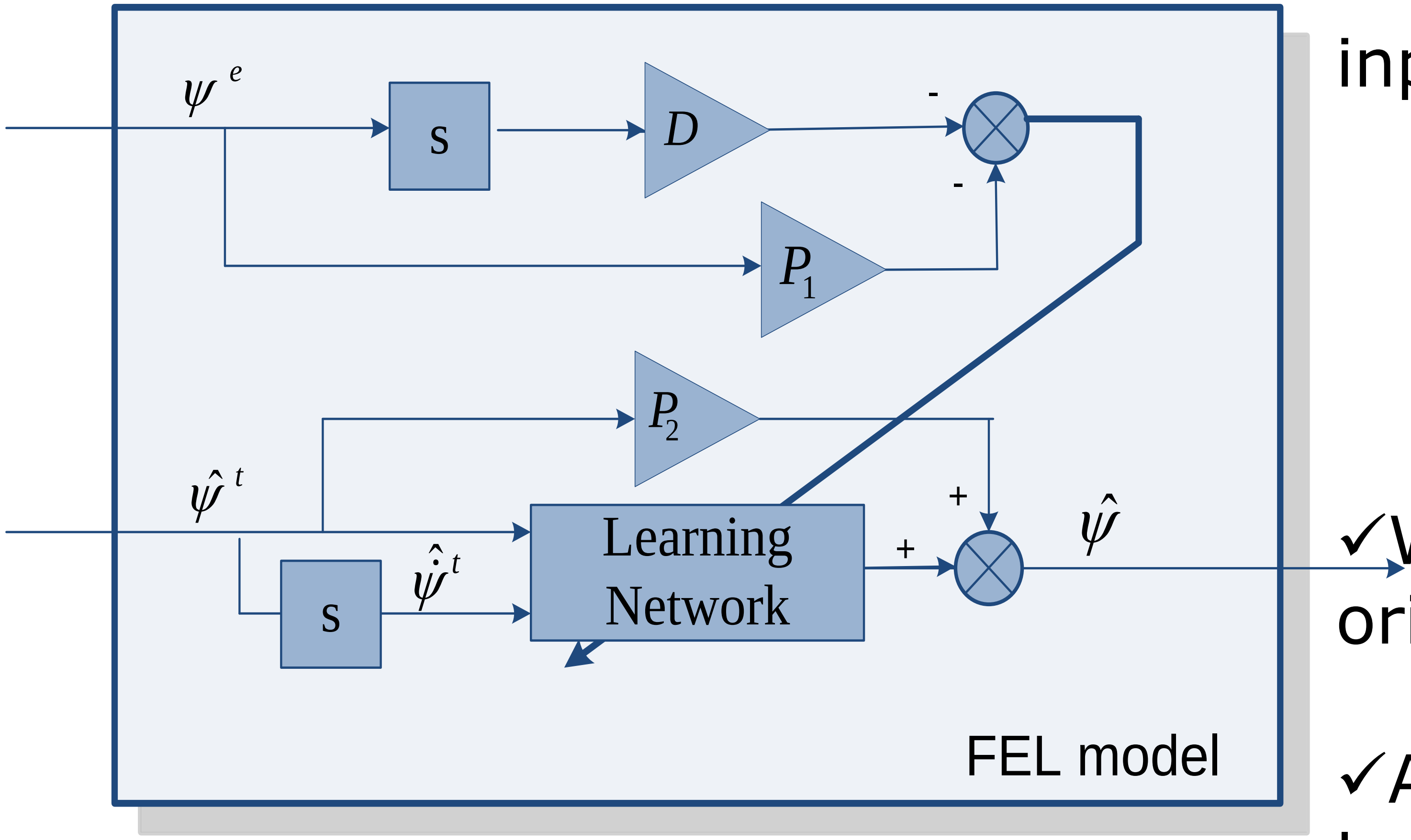
Adaptive head stabilization model
Neural Network

- ✓ Artificial Neural Network capable of solving the inverse kinematics problem without using the closed form solution.



- ✓ The network has one hidden layer of 20 units. It takes as input the head orientation (ν,ϕ,ψ) and as output the neck joints angles ($\theta 1$, $\theta 2$, $\theta 3$).

Adaptive head stabilization model
FEL Model



The recursive least squares algorithm (RLS) is employed for learning, because it is robust and it guarantees convergence.

- ✓ The learning controller takes as input
    - ✓ trunk orientation
    - ✓derivative derivative of trunk orientation
    - ✓the orientation error.
- ✓We replicate this model for each orientation (roll, pitch and yaw).
- ✓As a computationally efficient learning mechanism, we use RLS

Adaptive head stabilization model
Simulation in Matlab SIMULINK (I)

✓ The FEL model has been trained on *sinusoidal* motions with the following dynamics:

$$x(t) = A * \sin(\omega * t)$$

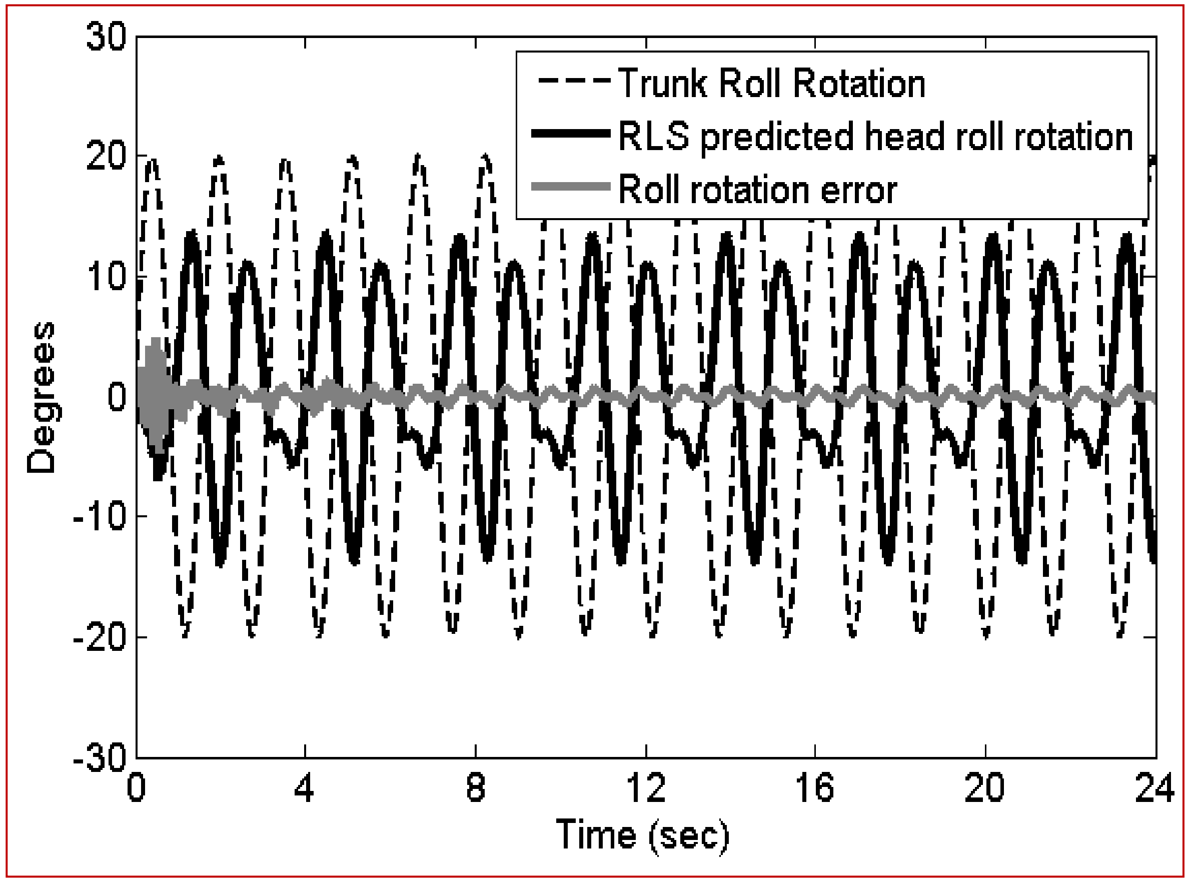
where x(t) is the trunk roll, pitch or yaw orientation (expressed in degrees) at the time t and A is the amplitude of the dynamics.
Frequency test 0.1 – 1.5 Hz
Amplitude 5-20 degrees for each orientation

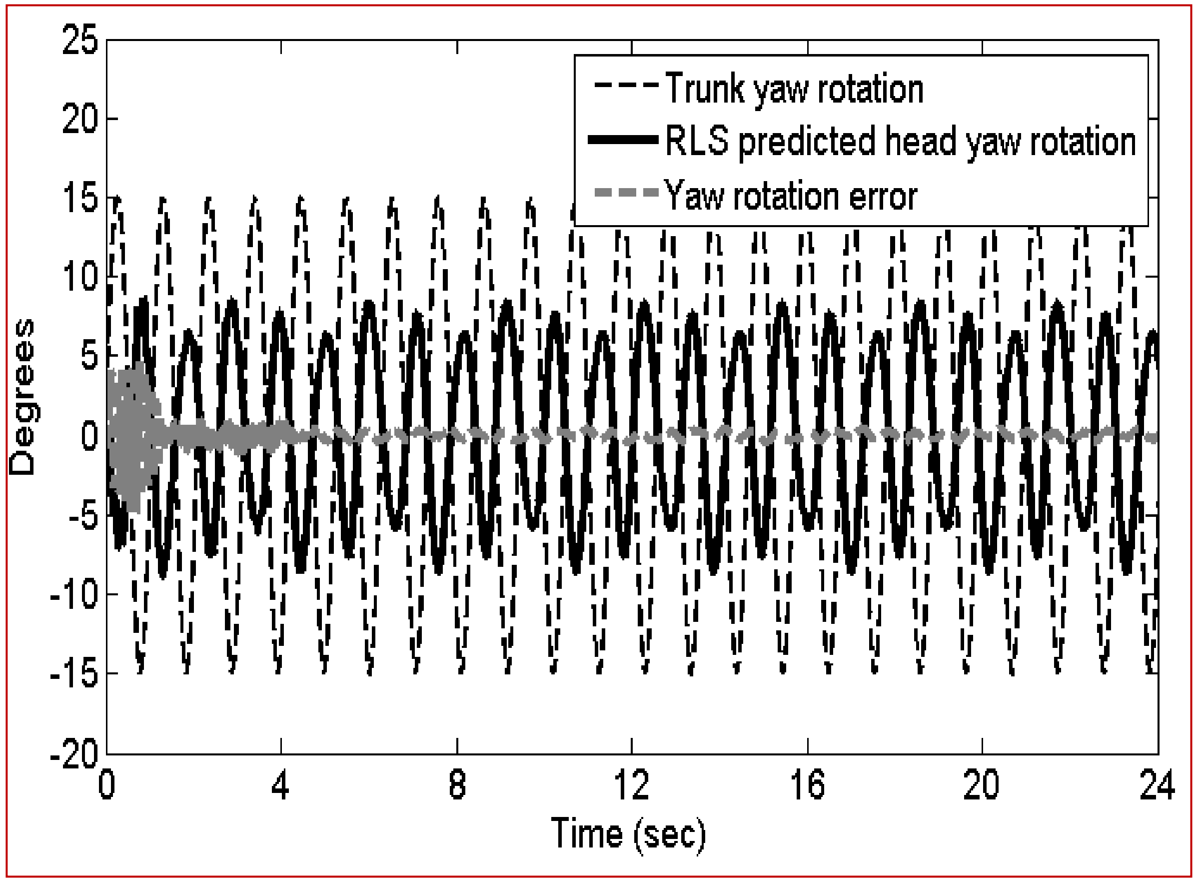
✓ Simulation of the direct kinematics of the **SABIAN robot head** (3 DoFs)

✓ The IMU has been modelled as zero-mean white noise

✓ The control loop runs at 100 Hz, the same frequency of the IMU data

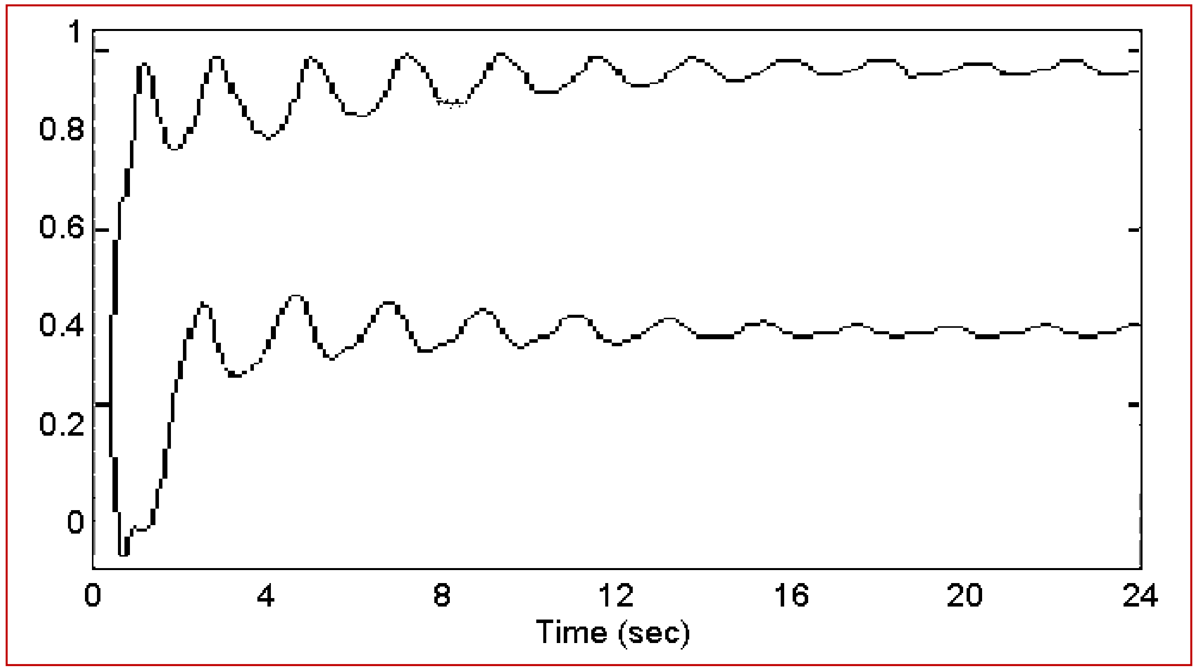
Adaptive head stabilization model – results in simulation





✓**Rotation error** = difference between the reference head rotation and the head rotation (for roll, pitch and yaw).

✓**Head orientation reference** constant and equal to zero for all three angles in all the simulations



Simulation in Matlab SIMULINK

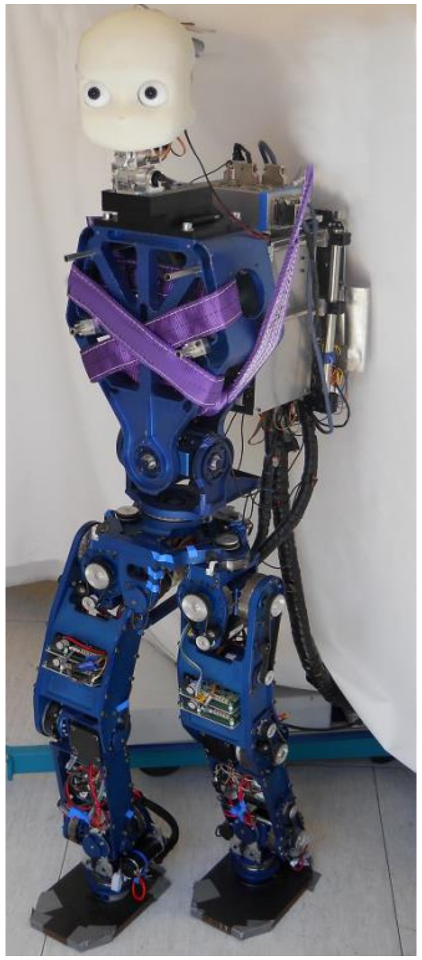
SABIAN robotic platform

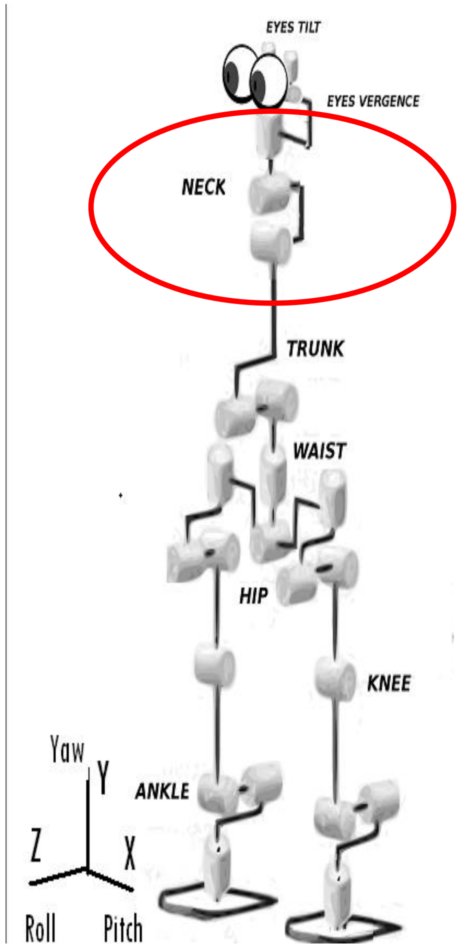
✓**SABIAN** (Sant'Anna BIped humANoid) is a copy of **WABIAN** (WAseda BIped humANoid)

✓The SABIAN robot has 7 DOF in each leg, 2 DOF in the waist, which help the robot perform stretched knee walking, 2 DOF in the trunk.

✓iCub head has been mounted on the SABIAN platform. The iCub head contains a total of 6 DOFs:

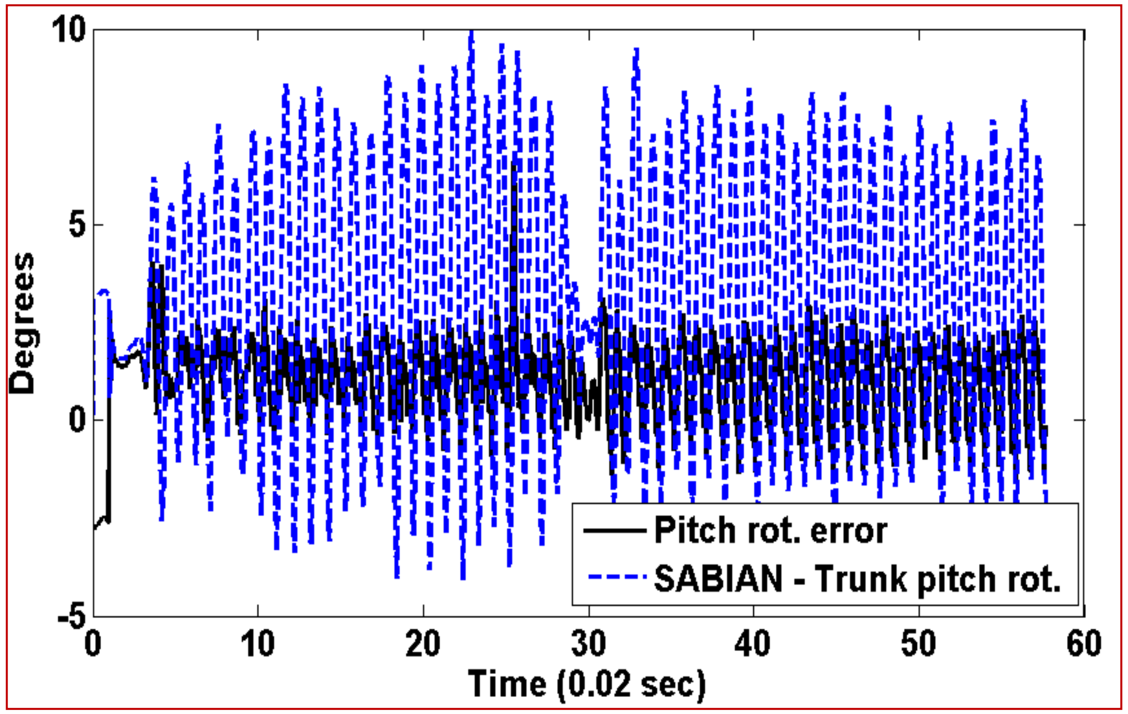
- ✓3 for the neck (pan, tilt and swing)
- ✓3 for the eyes (an independent pan for each eye and a common tilt).

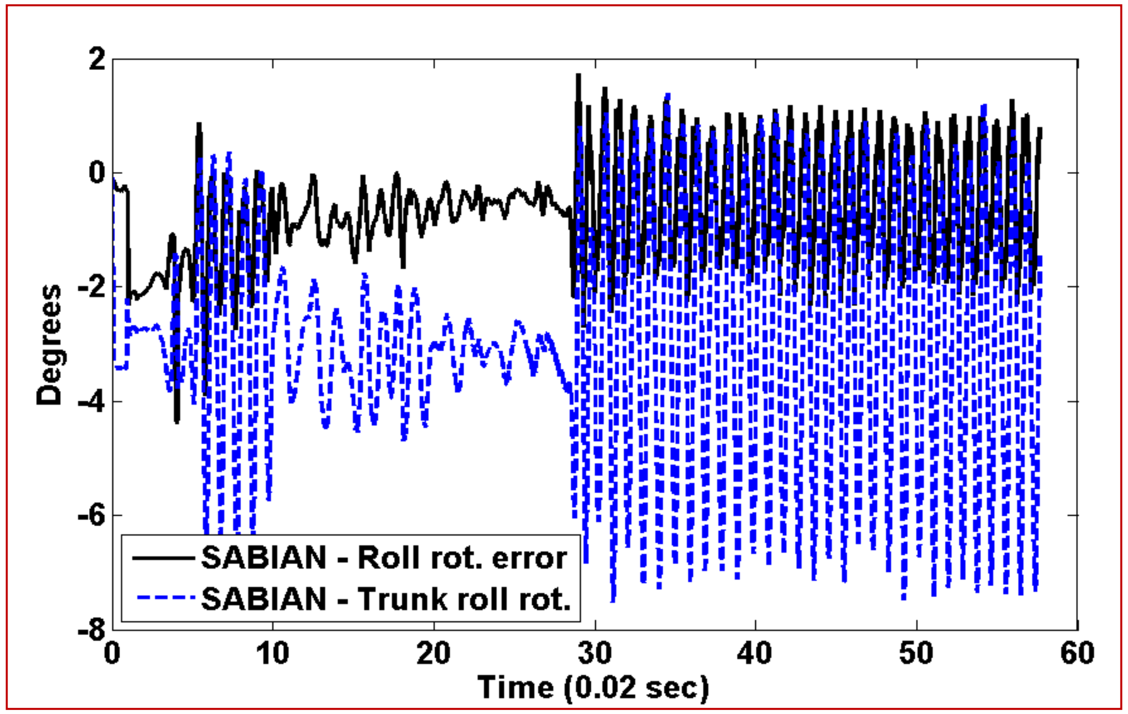


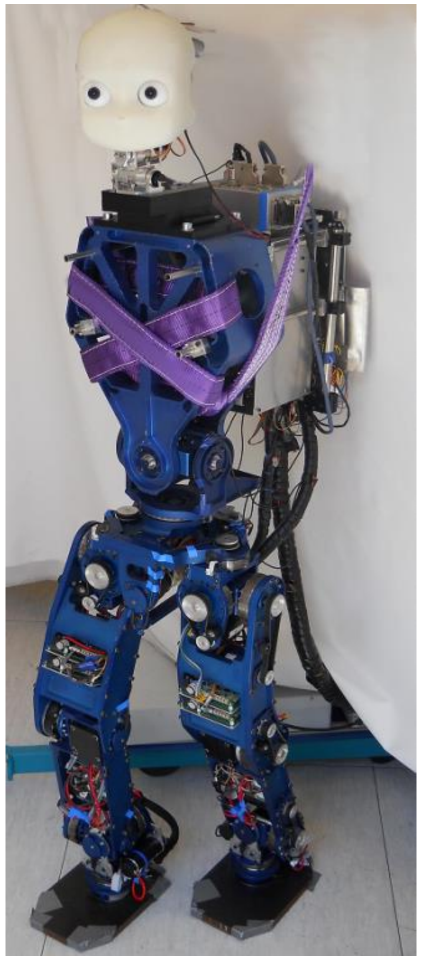


Adaptive head stabilization model – results on the Sabian robot

EXTERNAL PERTURBATION TEST



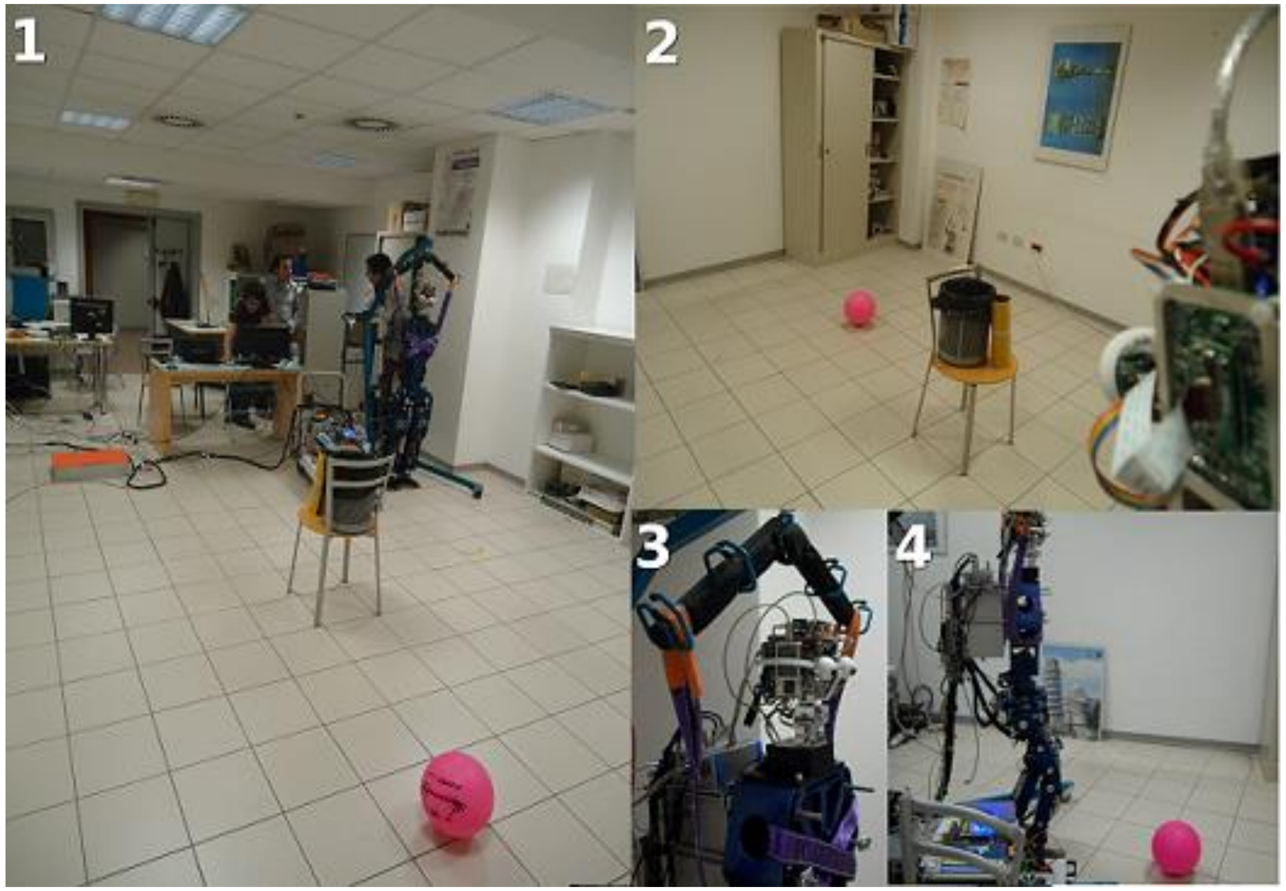




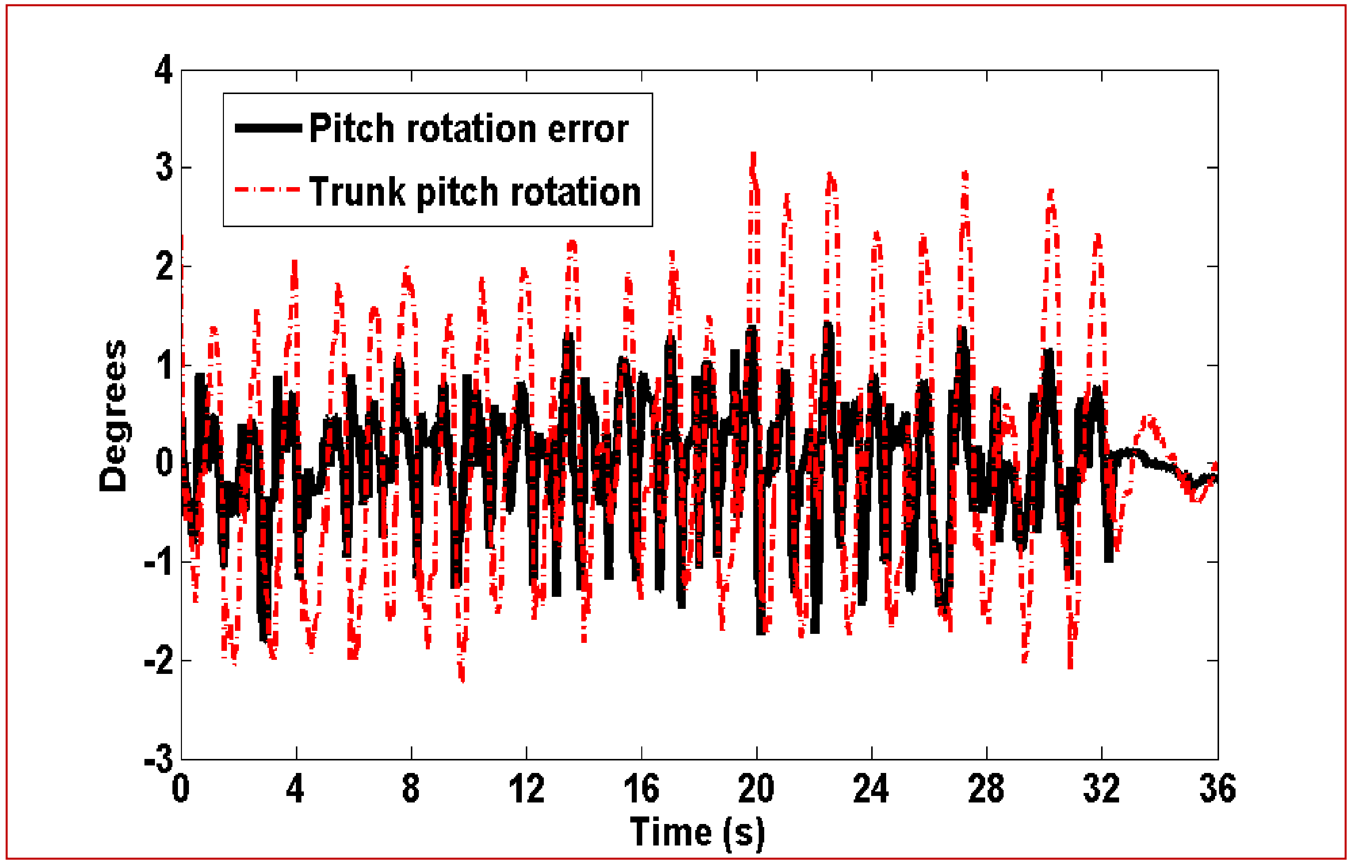
✓ The pitch and the roll rotation error are less than **2 degrees**, while the trunk peak-to-peak amplitude was almost 15 degrees for the pitch and 8 for the roll

Adaptive head stabilization model – results on the Sabian robot

WALKING TEST



1. The scenario with the robot in the starting position and the red ball indicating the end of the path.
2. The scenario from the robot viewpoint.
3 & 4. The robot performing the walking pattern with head stabilization.



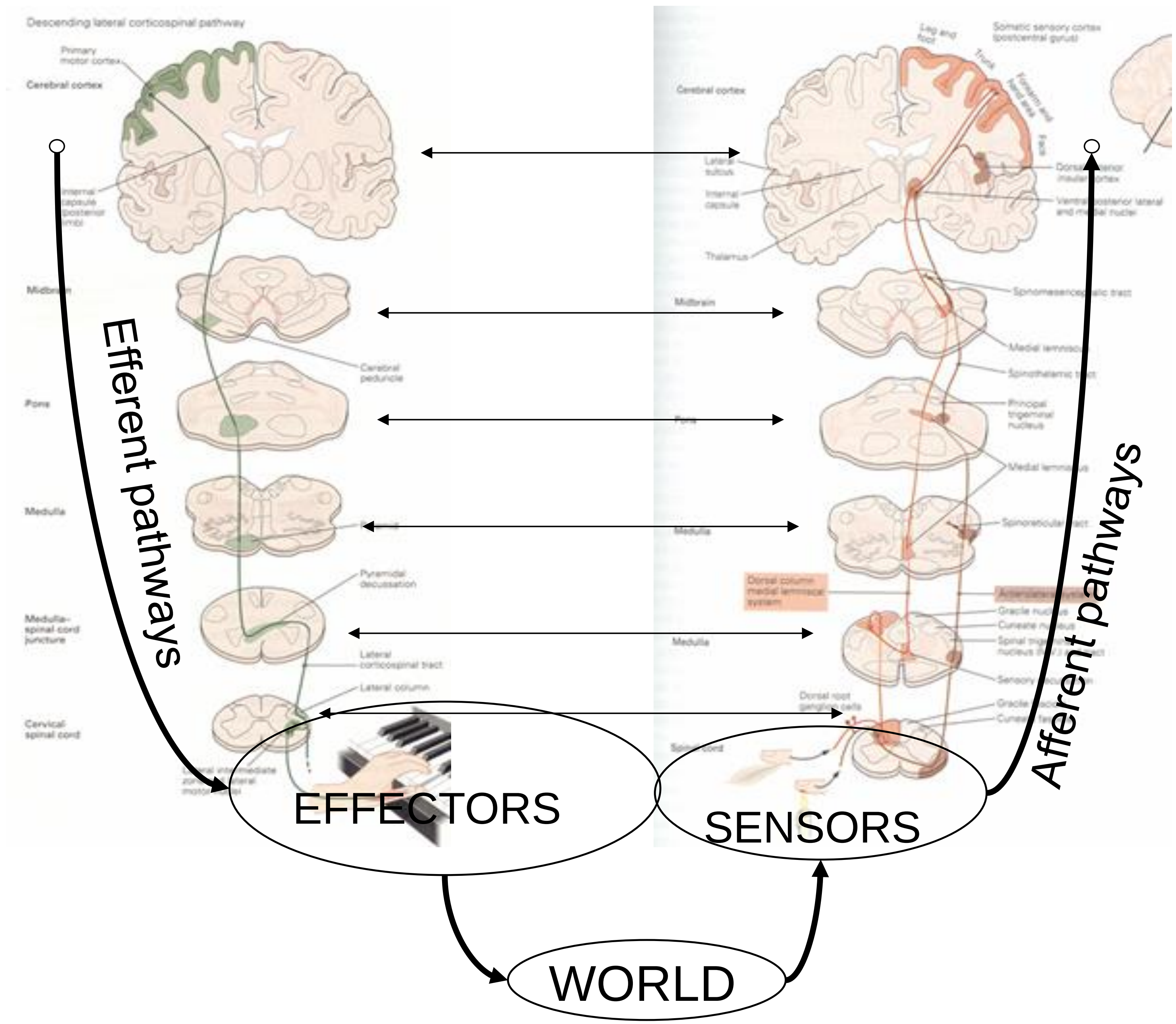
✓ This experiment started with the network weights and the regressor parameters of the FEL set to the values reached at the end of a training phase

✓The peak to peak amplitude of the head is less than **2 degrees** during the whole pattern execution.

Natural perception and action pathways

According to neurophysiological findings, human motor control is based on **sensory predictions** more than on sensory feedback (*Berthoz A.,2002,The sense of movement. Harvard University Press*)

“Perception is simulated action”

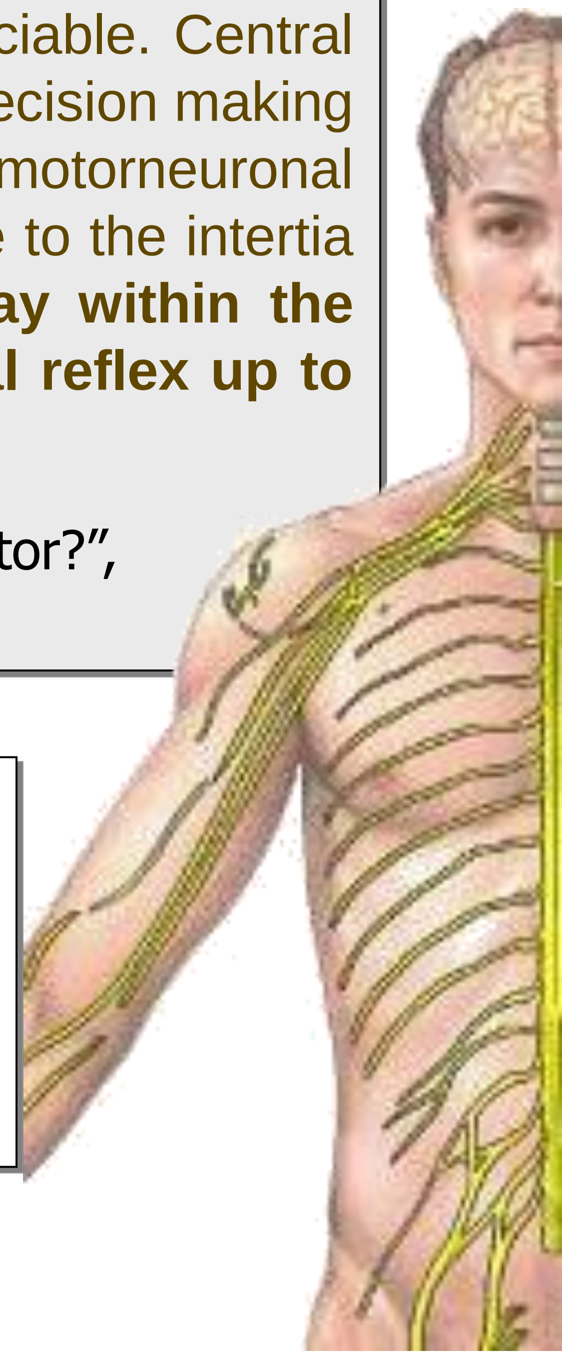


[from Kandel et al., “Principles of Neuroscience”, McGraw-Hill]

Delays in the human nervous system

"In motor control **delays** arise in **sensory transduction**, **central processing**, and in the **motor output**. Sensor transduction latencies are most noticeable in the visual system where the retina introduces a delay of 30-60 ms, but sensory conduction delays can also be appreciable. Central delays are also present due to such ill-defined events such as neural computation, decision making and the bottlenecks in processing command. Delays in the motor output result from motorneuronal axonal conduction delays, muscle exictation-contraction delays, and phase lags due to the intertia of the system. **These delays combine to give an unavoidable feedback delay within the negative feedback control loop, and can lie between about 30 ms for a spinal reflex up to 200-300 ms for a visually guided response.**"

R.C. Miall, D.J. Weir, D.M. Wolpert, J.F. Stein, "Is the cerebellum a Smith predictor?", *Journal of Motor Behavior*, vol. 25, no. 3, pp. 203-216, 1993



"Fast and coordinated arm movements **cannot be executed under pure feedback control** because biological feedback loops are both too slow and have small gains"

M. Kawato, Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, 9, 718-727(1999). Elsevier Science Ltd.

A. Berthoz, *Le sens du mouvement*. Odile Jacob, Paris, 1997

R.S. Johansson, "Sensory input and control of grip", in M. Glickstein (Ed.), *Sensory Guidance of Movements*. John Wiley, Chichester, UK, pp. 45-59,1998

Motor anticipation proposed by A. Berthoz

In humans, perception is not just the interpretation of sensory signals, but a ***prediction*** of consequences of actions

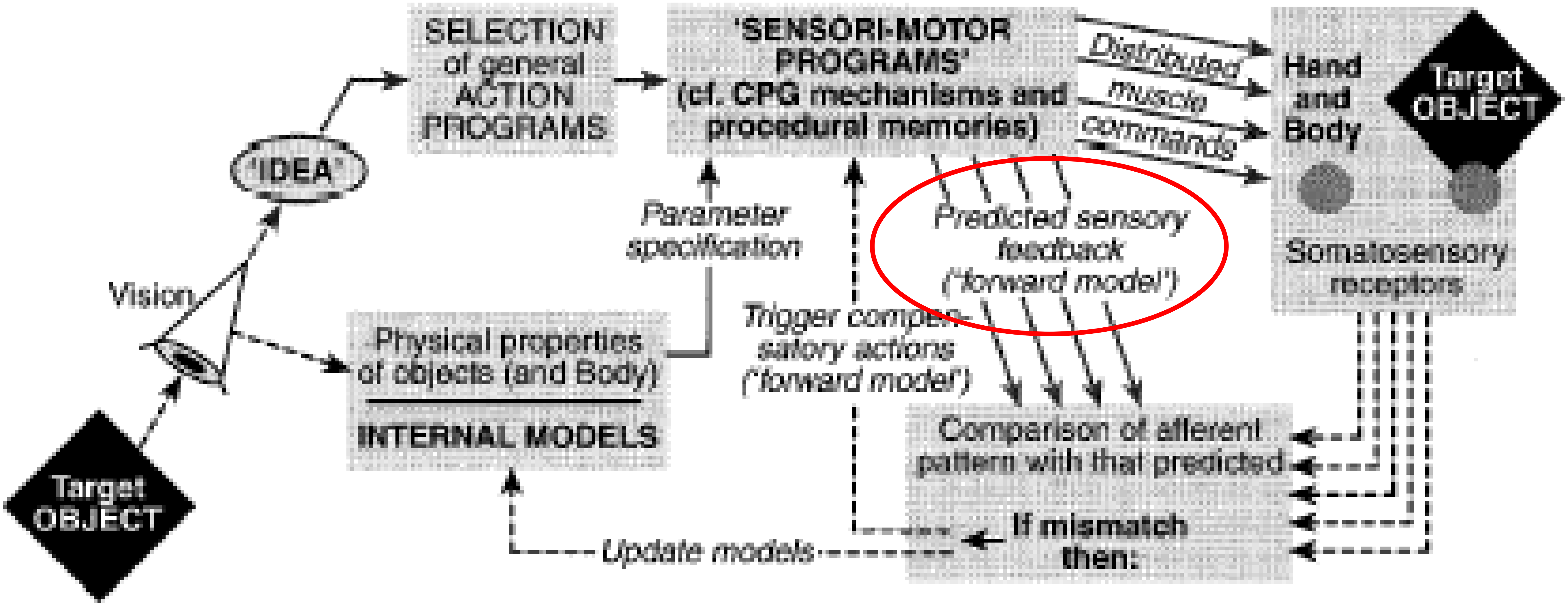
Perception can be defined as a ***simulated action*** (Berthoz, 2002): perceptual activity is not confined to the interpretation of sensory information but it anticipates the consequences of action, so it is an internal simulation of action.

Each time it is engaged in an action, the brain constructs hypotheses about the state of a variegated group of sensory parameters throughout the movement.

Berthoz A.(2002),*The sense of movement*. Harvard University Press

Sensory prediction proposed by R. Johansson

“Because of the long time delays with feedback control the swift coordination of fingertip forces during self-paced everyday manipulation of ordinary ‘passive’ objects must be explained by other mechanisms. **Indeed, the brain relies on feedforward control mechanisms and takes advantage of the stable and predictable physical properties of these objects by parametrically adapting force motor commands to the relevant physical properties of the target object**.”



Corrections are generated when expected sensory inputs do not match the actual ones

R.S. Johansson, “Sensory input and control of grip”. In *Sensory Guidance of Movements*, John Wiley, Chichester, UK, pp. 45-59, 1998

Anticipation and Internal models

- Anticipatory mechanisms guide human behavior, i.e., predictions about future states, allowing to perform accurate movements
- This is due to a nervous system that adapts to those existing limitations (feedback noisy and delayed together with a continuously changing environment) and compensates for them
- The bases of human anticipation mechanisms are the ***internal models*** of the body and the world

- Internal models can be classified in two conceptually distinct groups:
  - Forward Models: causal representations of the motor apparatus
  - Inverse models: inversion of the causal relation, they give the causal event

R.C. Miall and D.M. Wolpert, Forward Models for Physiological Motor Control. *Neural Networks*, vol. 9, no. 8, pp. 1265-1279, 1996

What happens in robotics?

Robotics perception and action: the hierarchical paradigm

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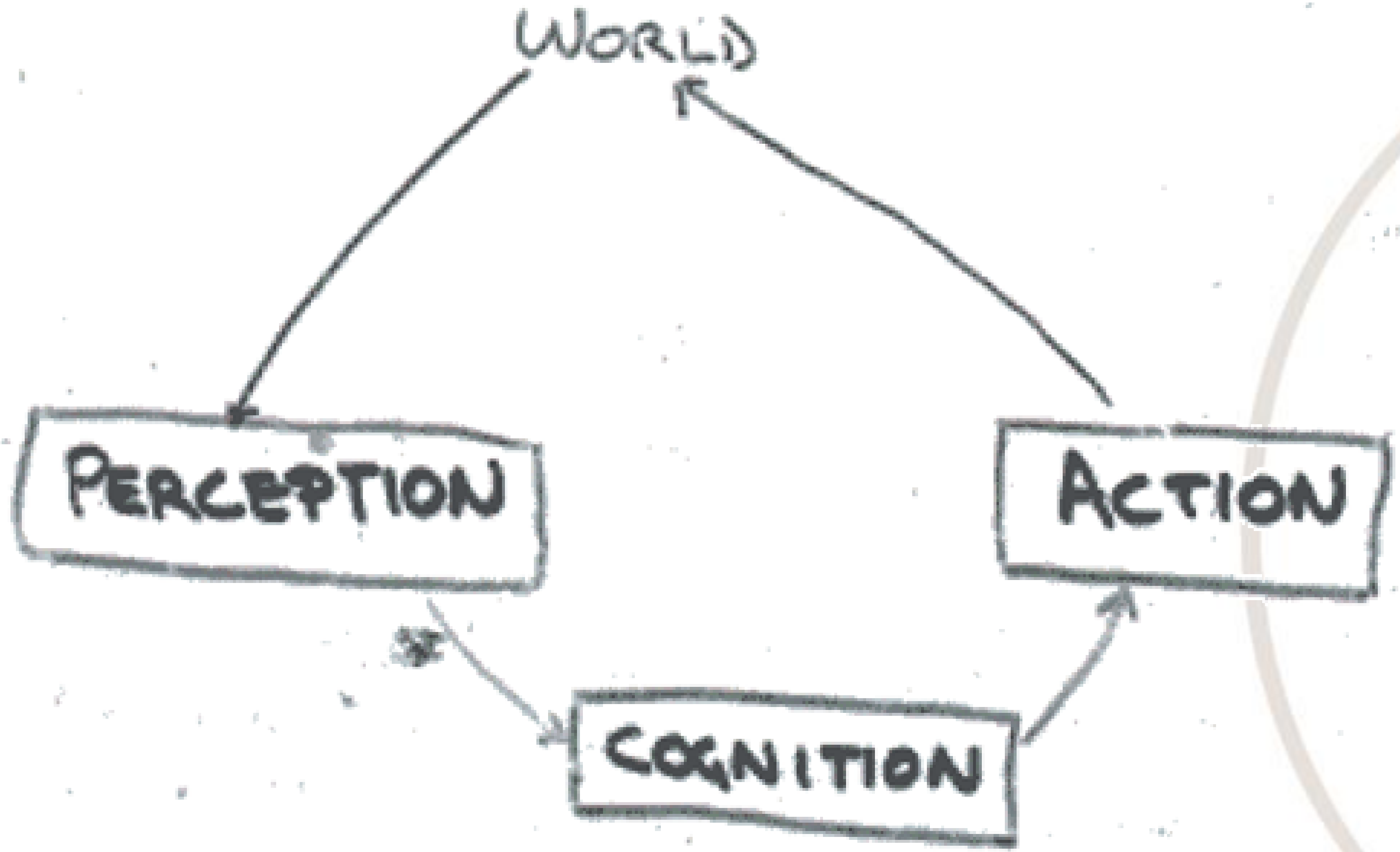

Figure 1: The traditional model where cognition mediates between perceptions and plans of actions.

R. Brooks, *Cambrian Intelligence*, MIT Press, 2000

Robotics perception and action: the reactive paradigm (S-A)

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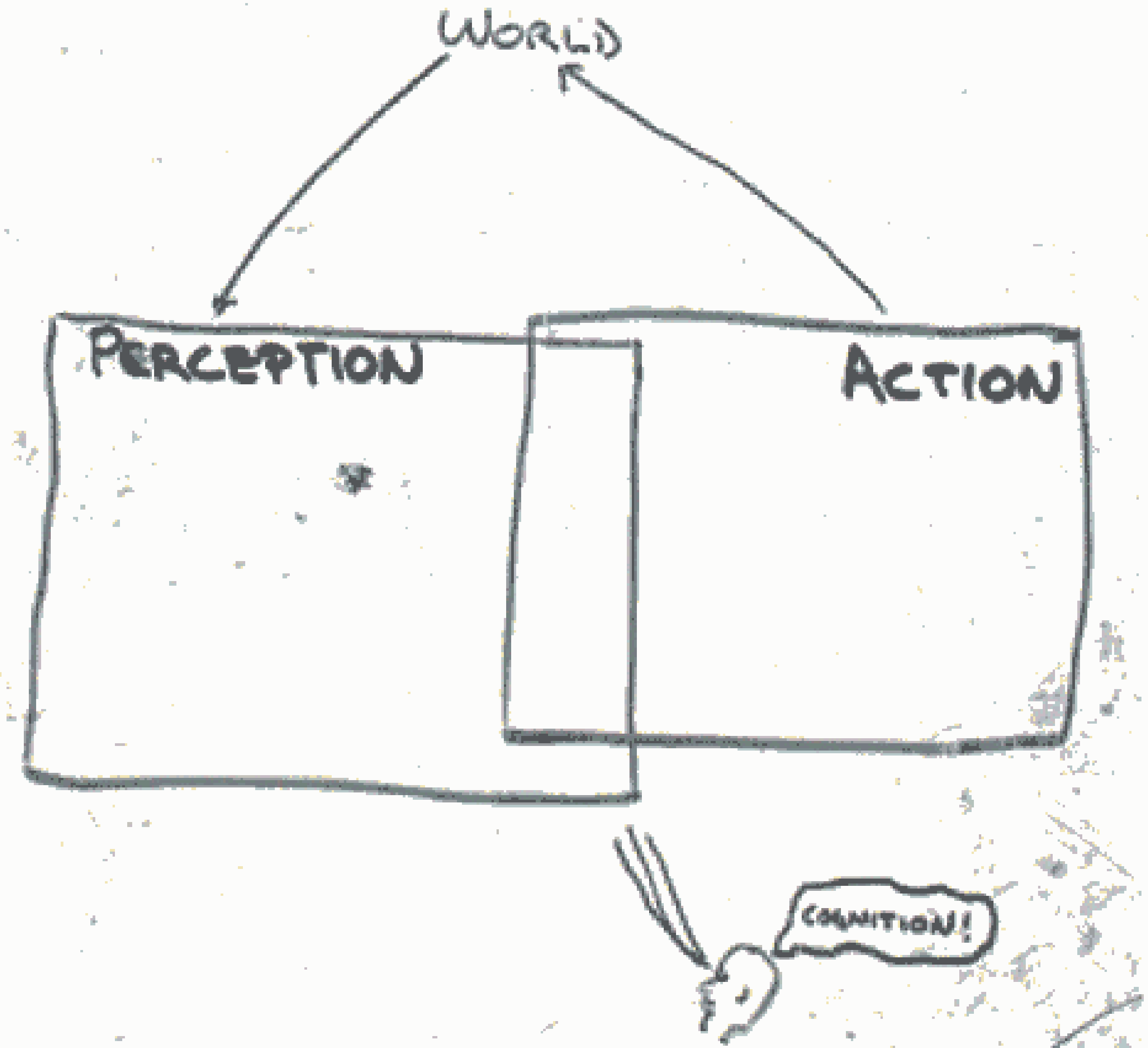
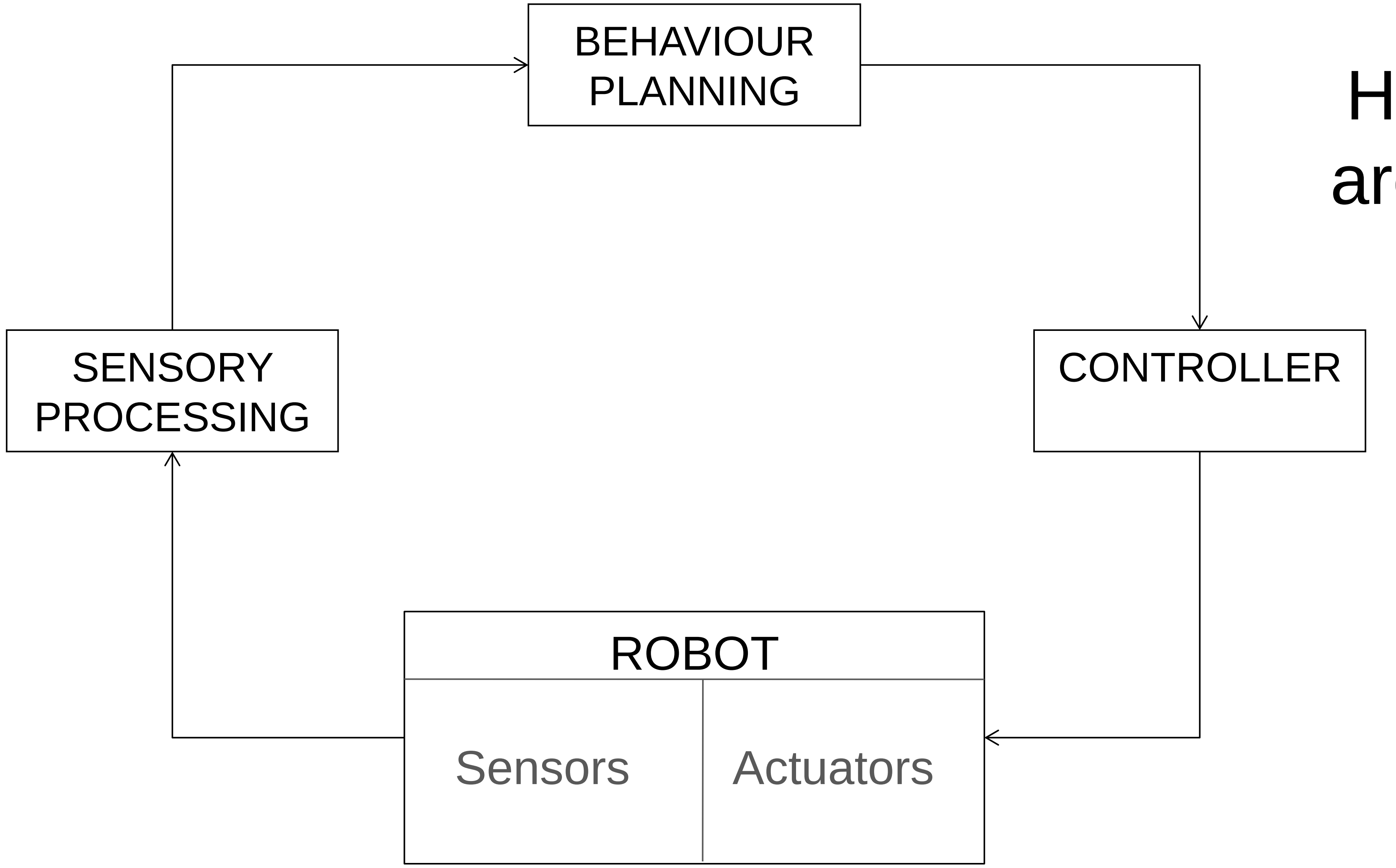


"The world is its own best model" (just need sensors)

"Cognition is in the eyes of the observer"

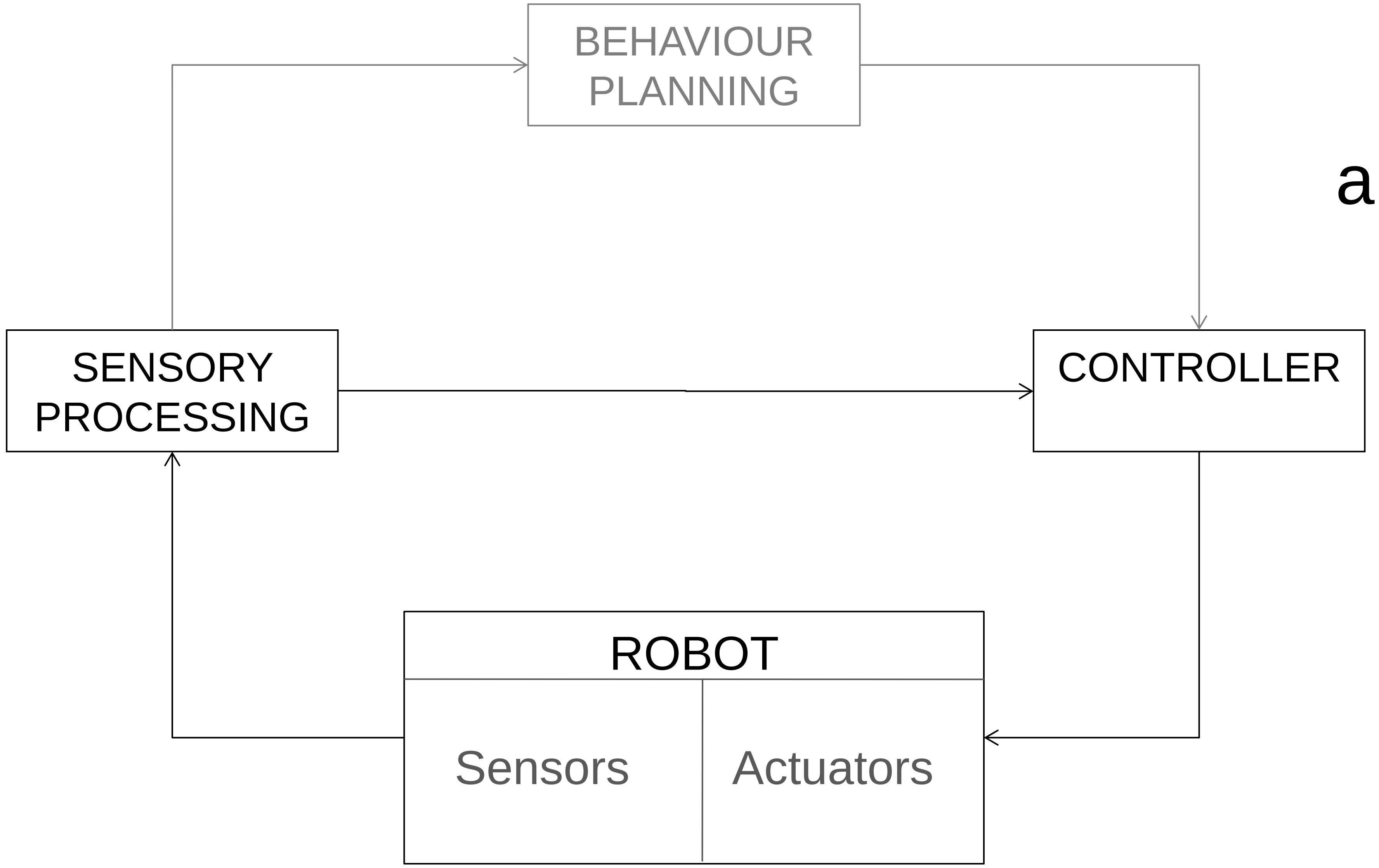
R. Brooks*, Cambrian Intelligence,* MIT Press, 2000

Basic scheme for robot behaviour control



Hierarchical architectures

Basic scheme for robot behaviour control

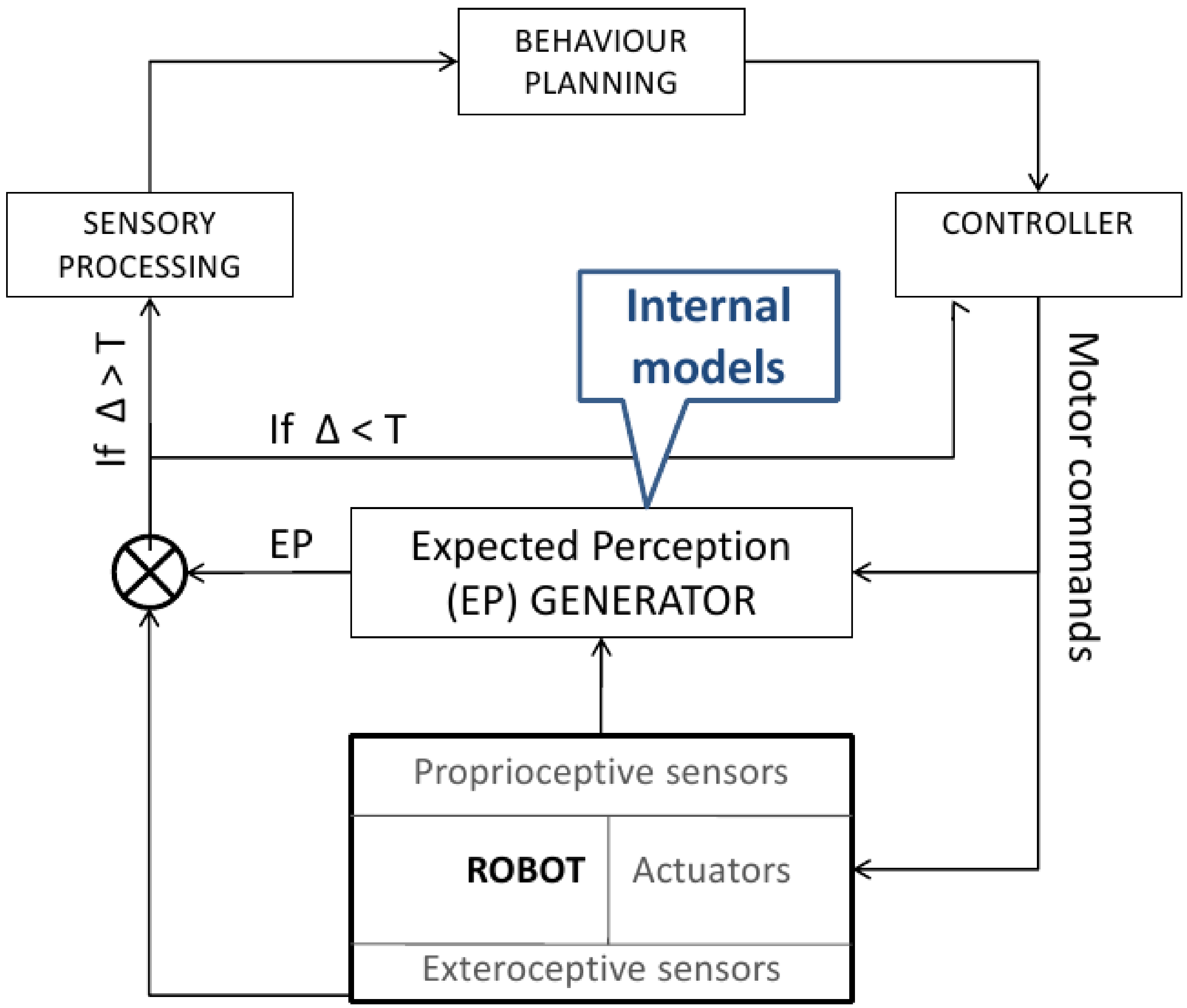


Reactive architectures

Expected Perception (EP) System

Expected Perception:

- Internal Model to predict the robot perceptions
- Comparison between actual and predicted perception
- ***Open loop*** controller if the prediction error is low
- ***Closed loop*** controller if the prediction error is high



Expected Perception in the visual space

EP architecture applied to 3D reconstruction of the environment


09ar0078cl [RF] © www.visualphotos.com

Task: free walking in an unknown room with obstacles

Classical approach:

- 3D reconstruction of the environment
- path planning for collision-free walking

-> large computational burden

In a Visual EP architecture, after a first 3D reconstruction of the environment, images can be predicted, based on internal models and on the ongoing movement.

Predicted images are compared with actual ones and in case of unexpected obstacles a mismatch occurs and the motor action is re-planned

Visual EP System (implementation)

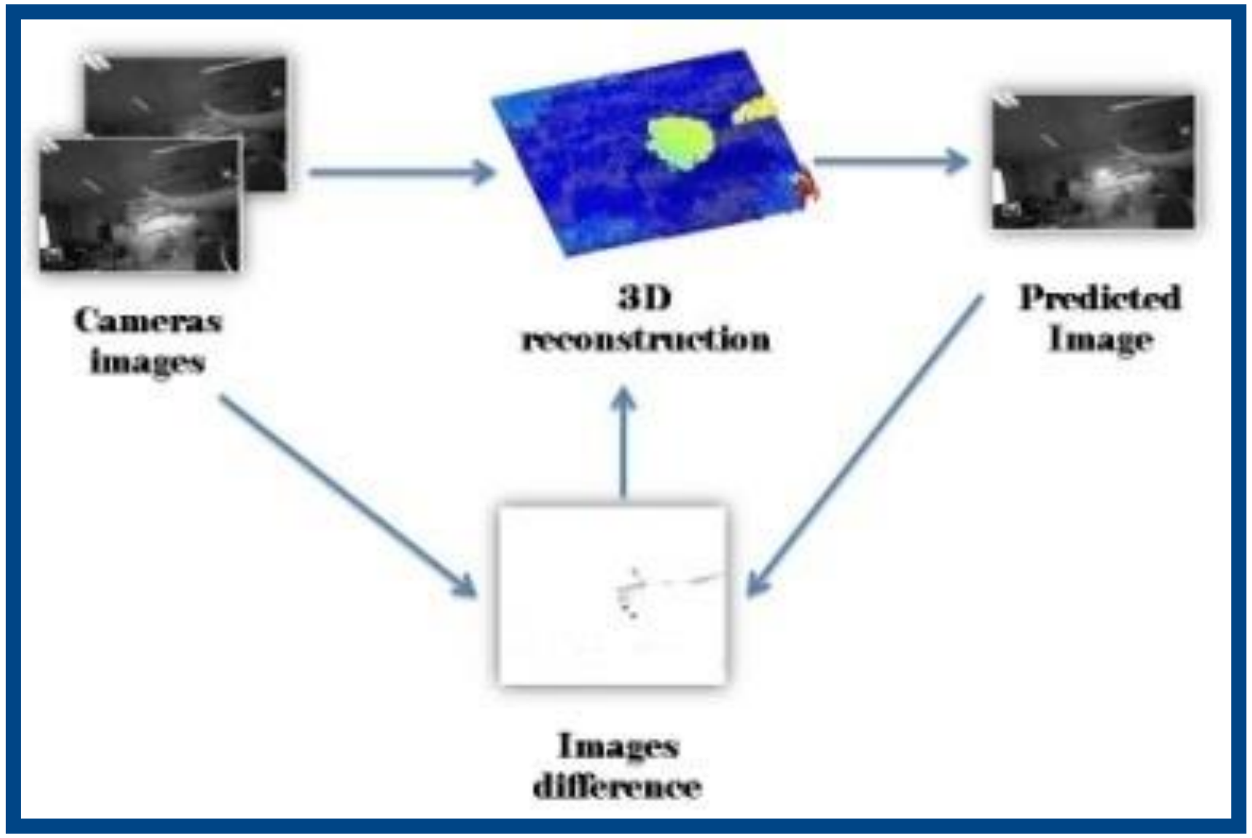
The system performs a real time 3D reconstruction of the environment (30fps) used to generate an **expected synthetic camera image**. The cloud of 3D points is updated using an image sensory-motor prediction.

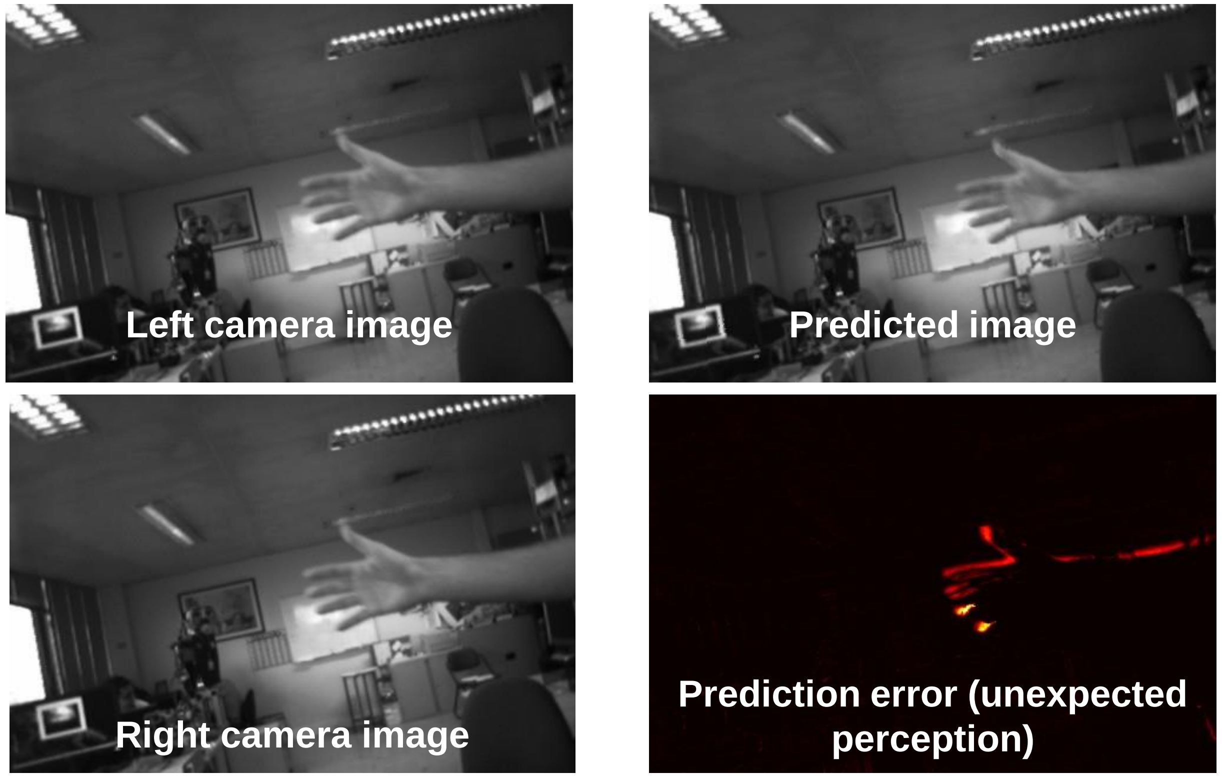
At each step:

- the next predicted image (EP) is calculated.
- the predicted and actual cameras images are compared.
- the 3D reconstruction of the visible environment is updated based on the prediction error

The system has 2 advantages:

- A faster real-time 3D reconstruction
- Recognition of the unexpected objects in the scene





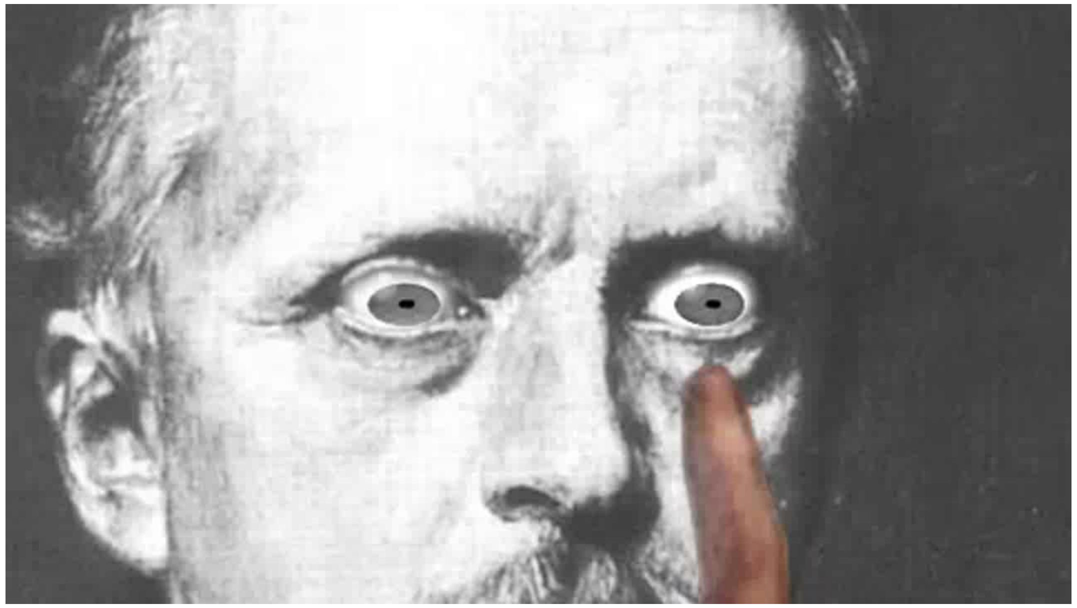
Moutinho, N.; Cauli, N.; Falotico, E.; Ferreira, R.; Gaspar, J.; Bernardino, A.; Santos-Victor, J.; Dario, P.; Laschi, C.; 2011. "An expected perception architecture using visual 3D reconstruction for a humanoid robot," *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, San Francisco, CA, USA, 25-30 Sept. 2011 , pp.4826-4831.

EP of external moving objects
Prediction of movements of other agents

Applications: avoiding, reaching, hitting or caching moving objects

- The Expected Perception is not only generated by self motion
- Movements of other agents can be predicted, when their motion dynamics follows rules that can be learnt
(e.g. laws of physics)
- In this case the planning is based on a long term prediction (more than one step ahead) of the object trajectory

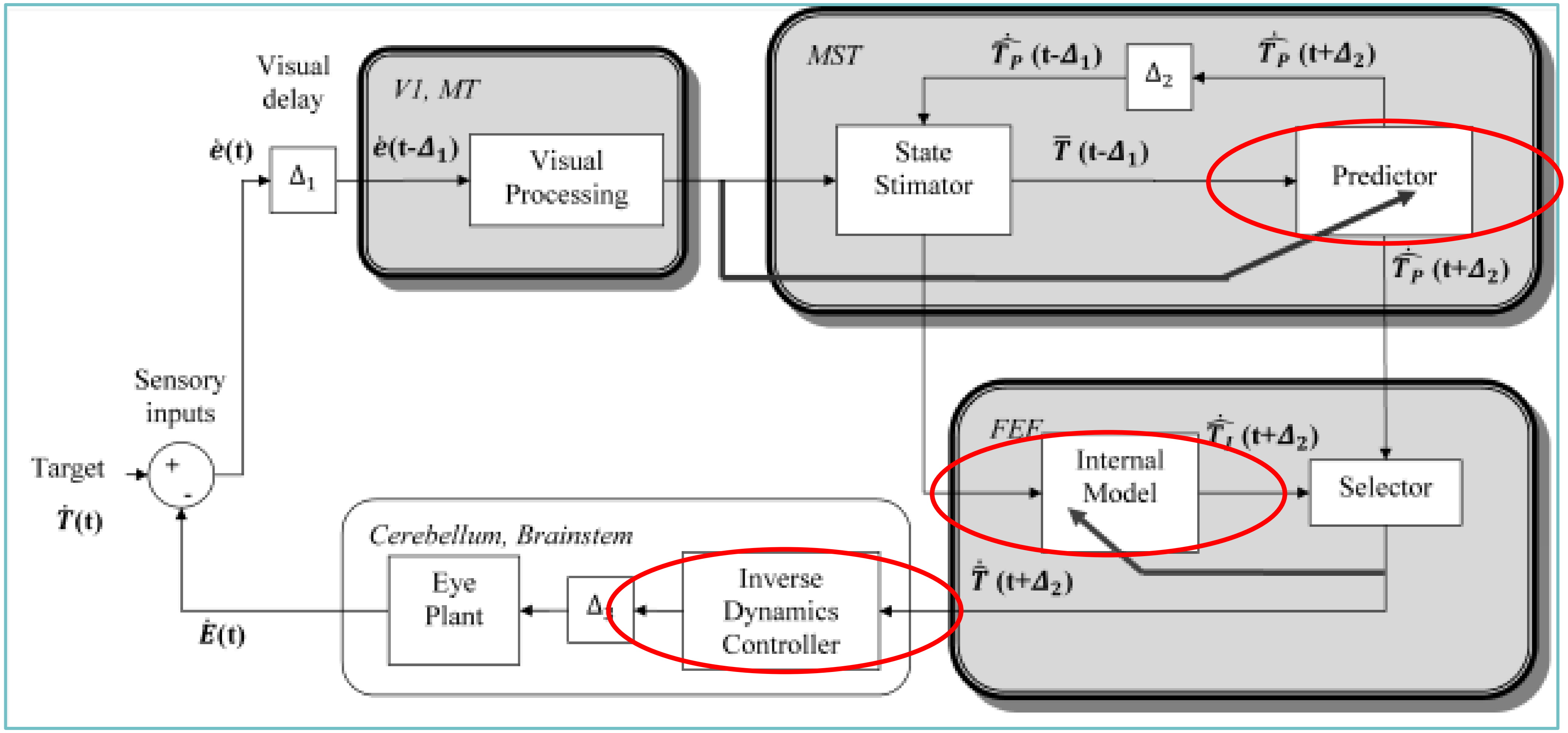
Smooth pursuit



- The purpose of the smooth pursuit eye movement is to follow a moving target minimizing the retinal slip, i.e. the target velocity projected onto the retina

- During maintained smooth pursuit, the lag in eye movement can be reduced or even cancelled if the target trajectory can be ***predicted***

A predictive model for smooth pursuit

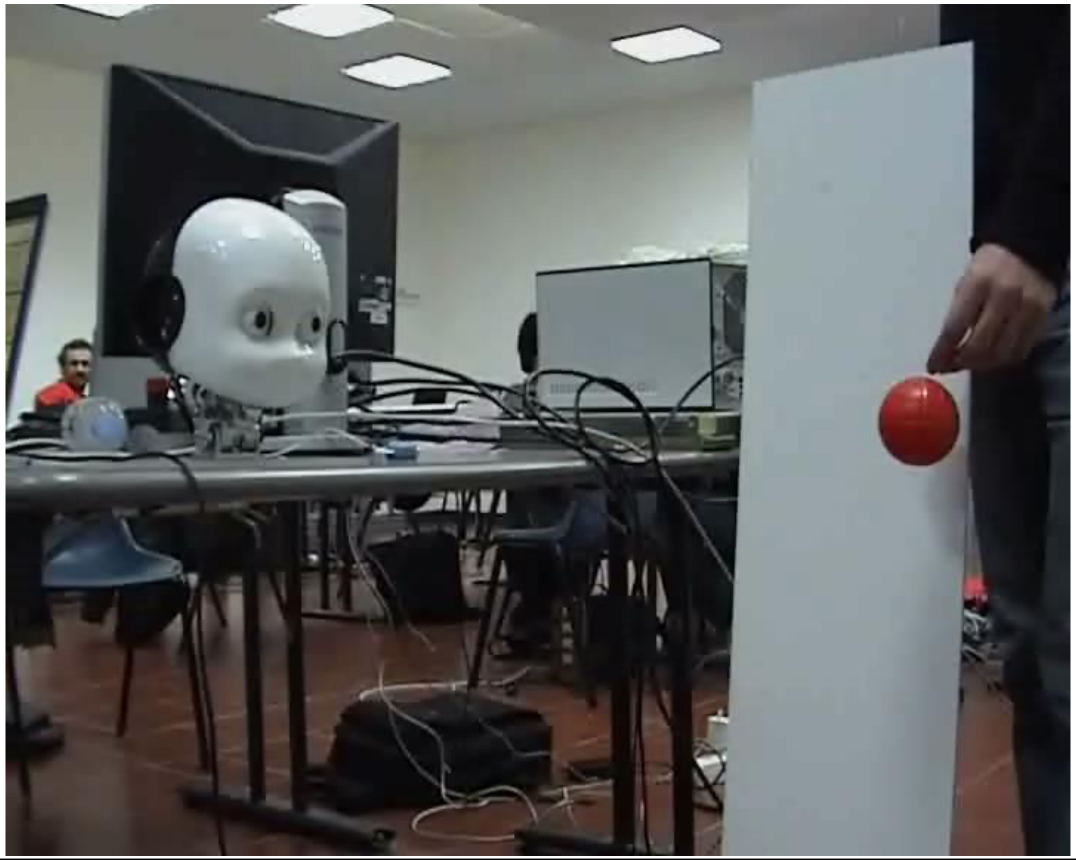


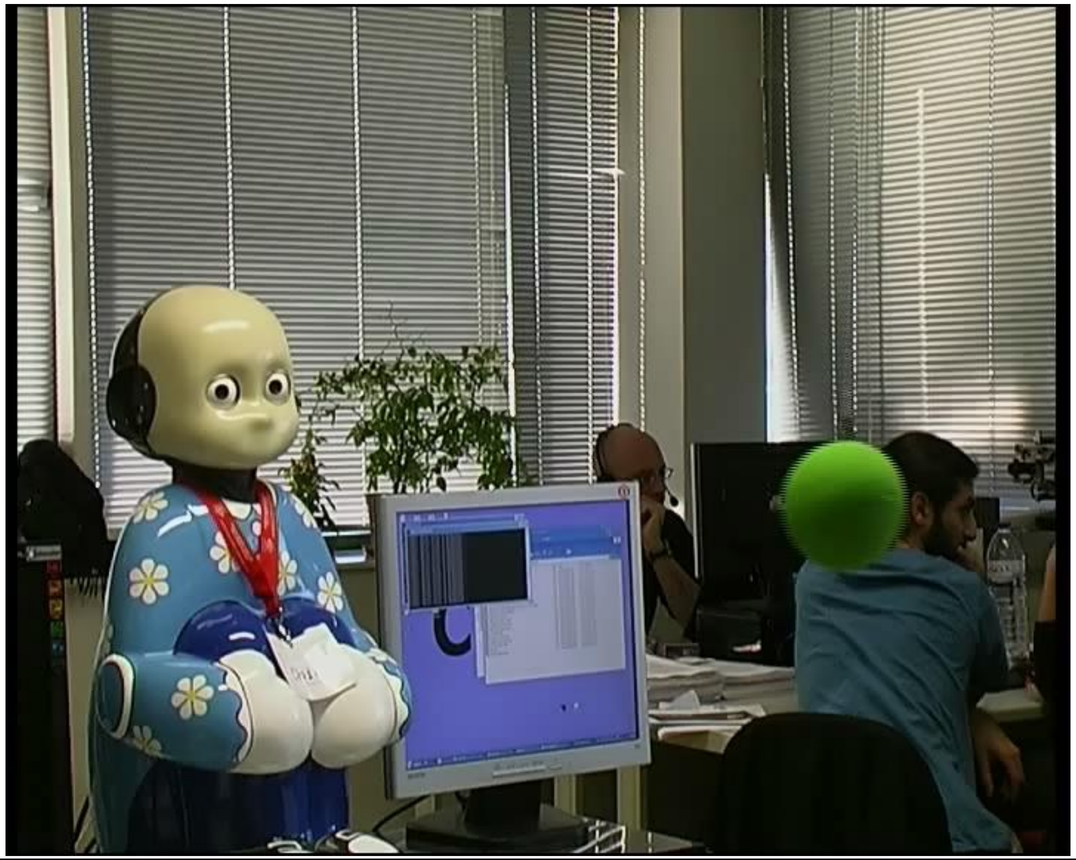
This circuit is based on Shibata and Schaal's model (*Shibata 2005*) of smooth pursuit and consists of **three subsystems**:

1. a **recurrent neural network** (RNN) mapped onto medial superior temporal area (MST), which receives the retinal slip with delays and ***predicts*** the current target motion,
2. an **inverse dynamics controller** (IDC) of the oculomotor system, mapped onto the cerebellum and the brainstem,
3. and **a memory block** that recognizes the target dynamics and provides the correct weights values before the RNN.

Zambrano D, Falotico E, Manfredi L, and Laschi C. (2010). "A model of the smooth pursuit eye movement with prediction and learning". *Applied Bionics and Biomechanics*

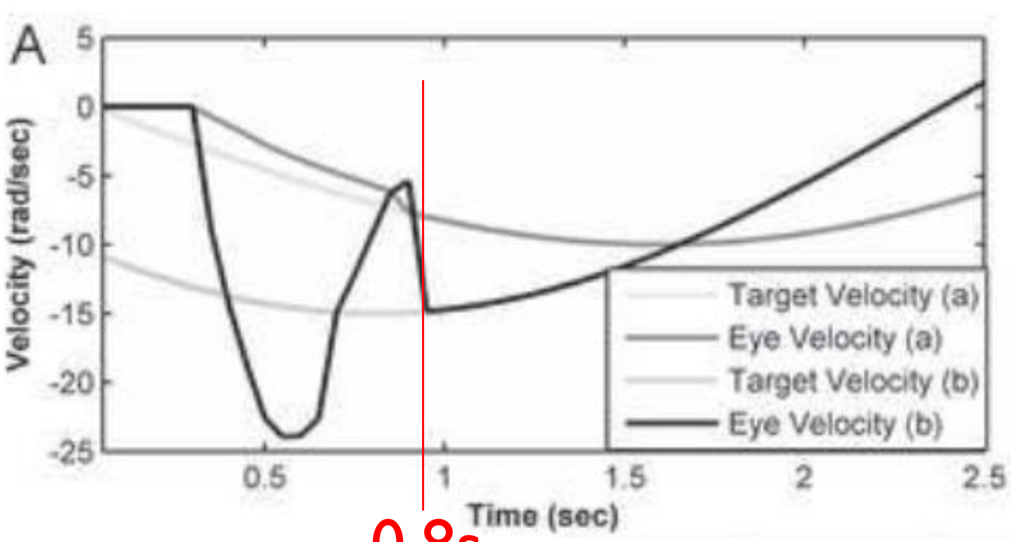
The predictive smooth pursuit on a robot head

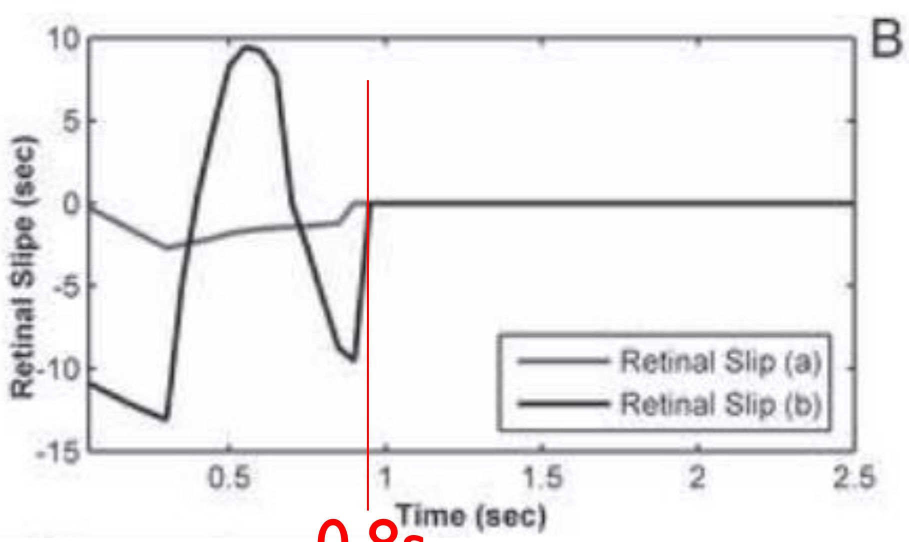




iCub platform head, 6 dof:
3 for the eyes
3 for the neck

The *retinal slip* (target velocity onto the retina) reaches zero after that the algorithm converges. When the target is unexpectedly stopped, the system goes on tracking the target for a short time.



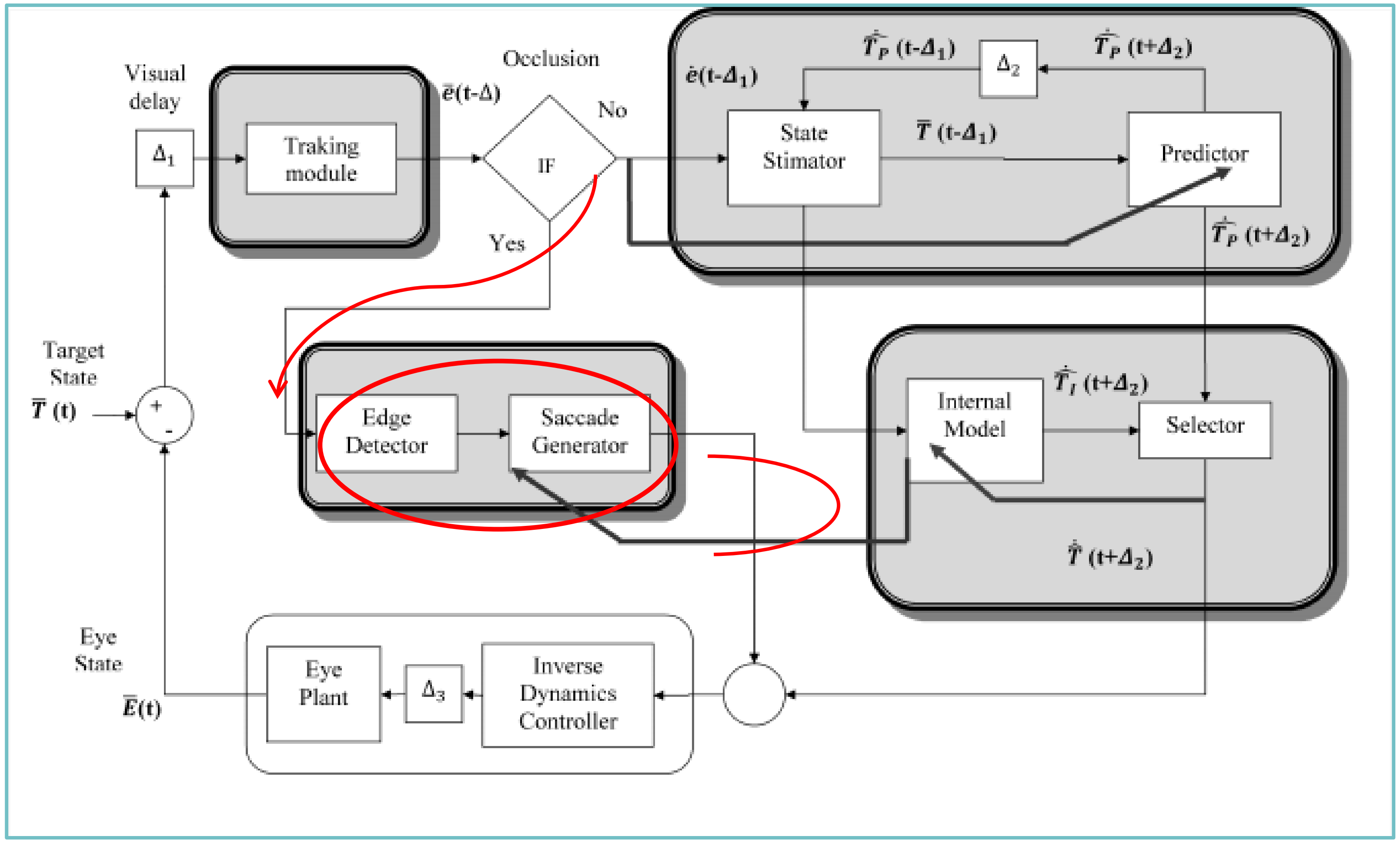


Sinusoidal dynamics:

a) angular frequency: 1 rad/s, amplitude: 10 rad, phase: π/2
b) angular frequency: 1 rad/s, amplitude: 15 rad, phase of ¾ π

In collaboration with Istituto Superior Tecnico, Lisbon, Portugal

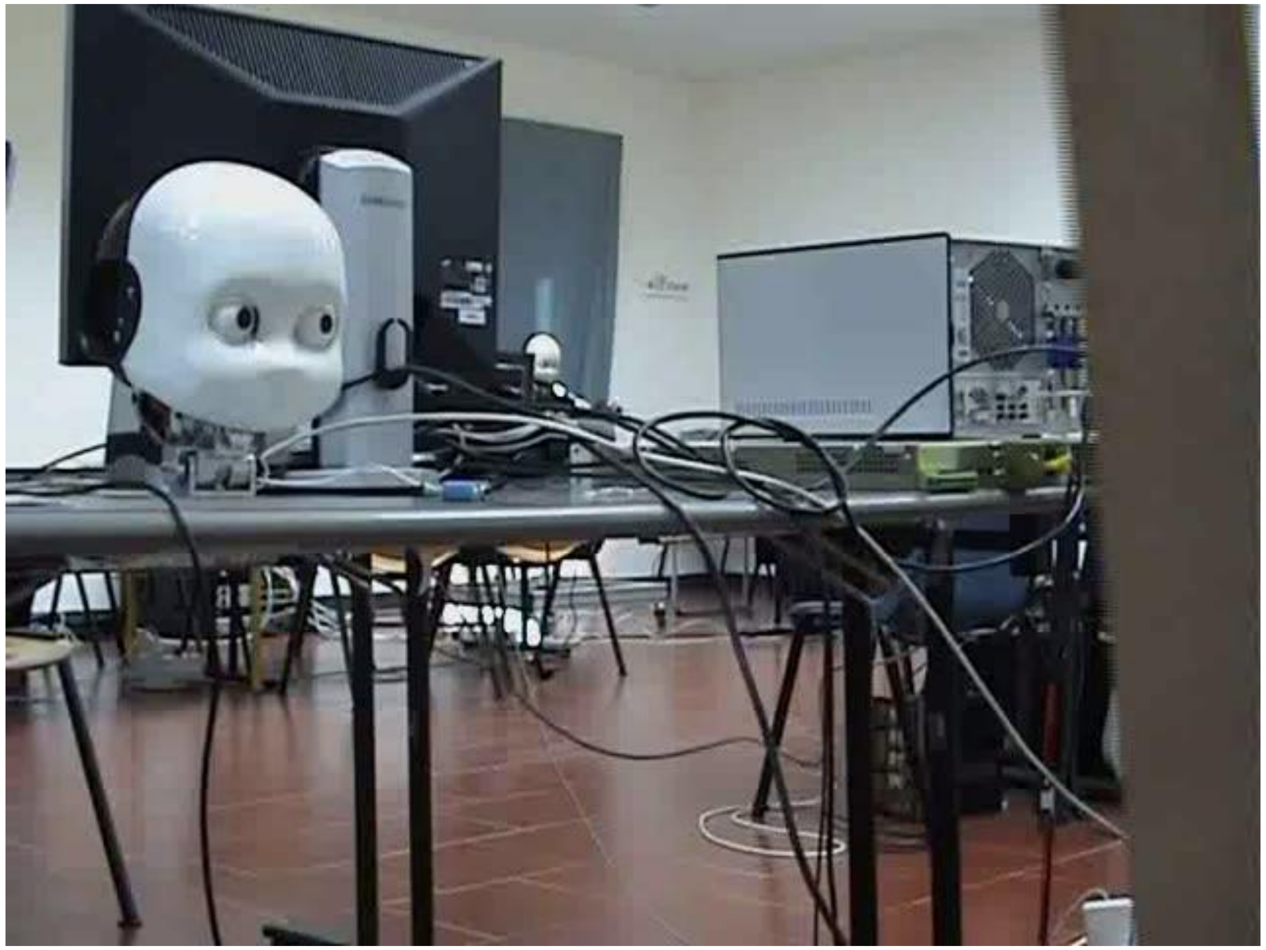
Smooth Pursuit and Saccades: Occlusions



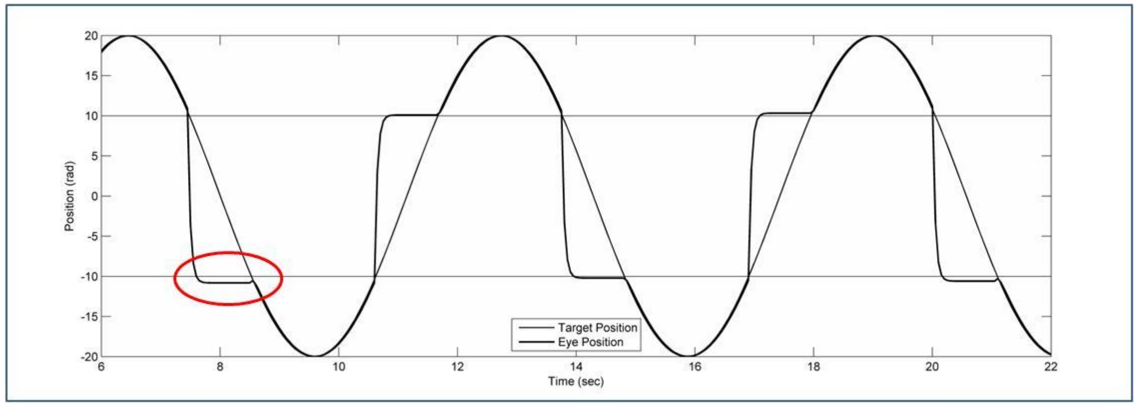
If the object disappears behind the occluder a event of occlusion is notice and another module starts to detect the edges in the image to find where the object will reappear.

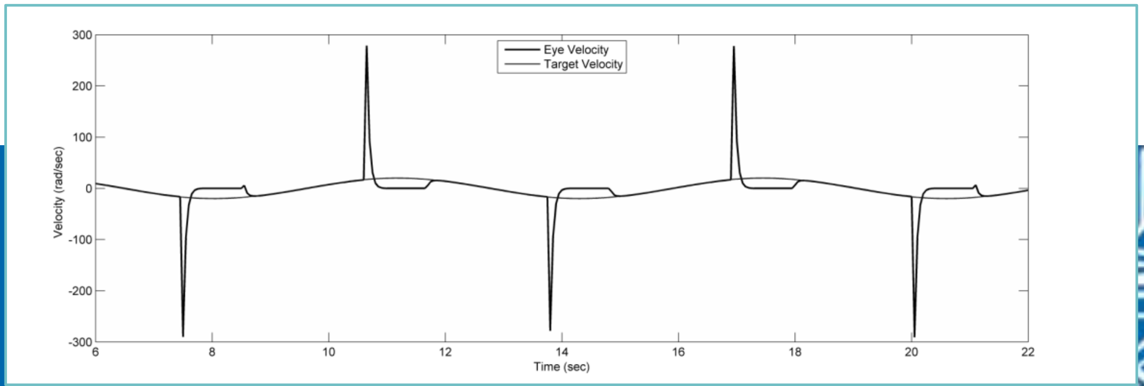
At this point the **saccade generator** module repeats the prediction of the target dynamics until the predicted position is equal to the edge detected from the previous module.

Implementation of smooth pursuit with occlusions



Saccades to the end of the occlusion



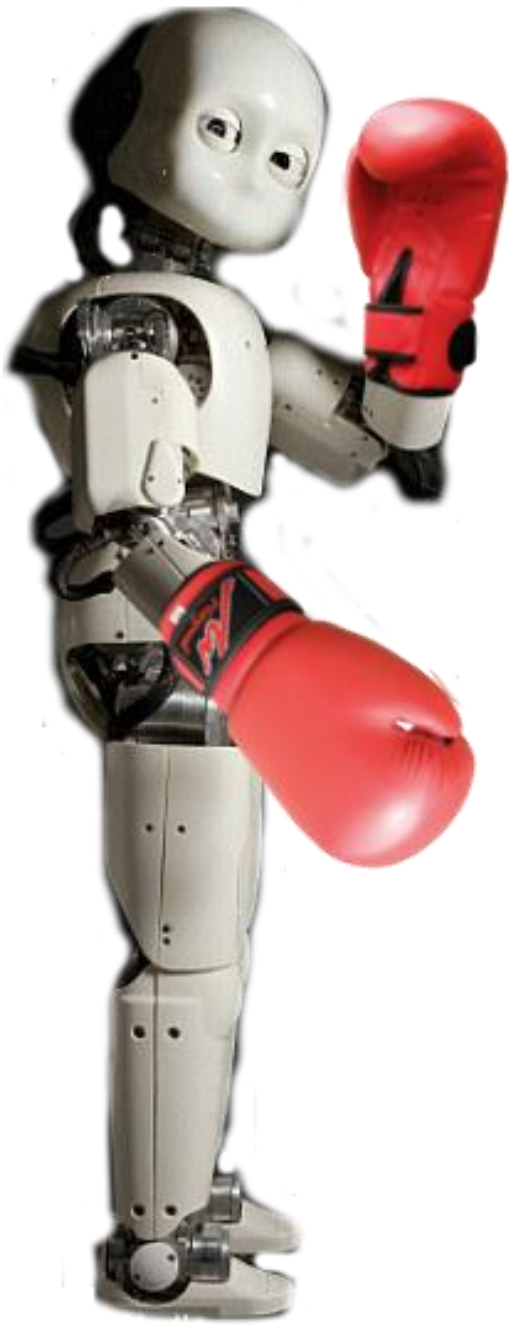


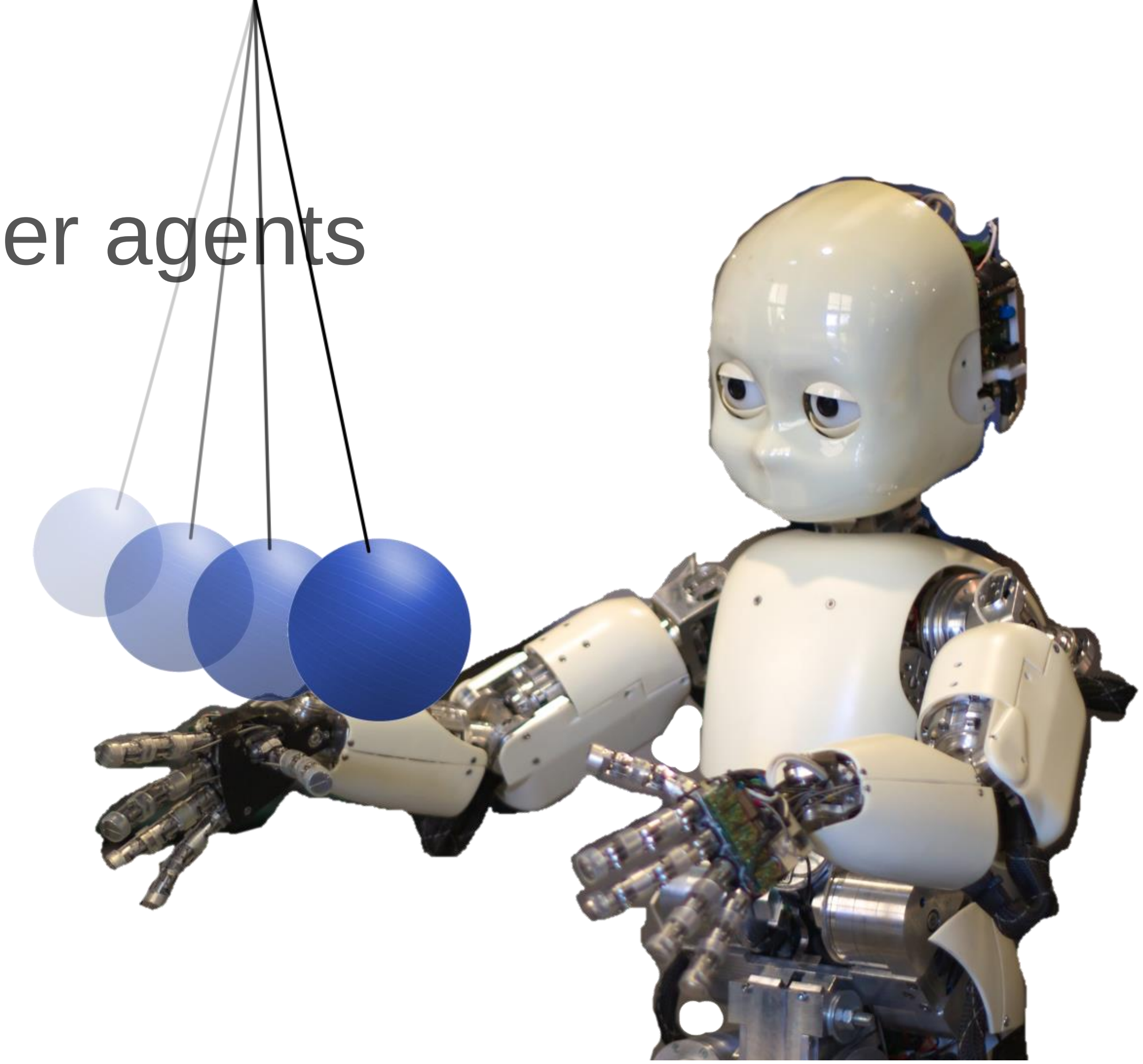
The tracking algorithm based on particle filtering detects the position of the target on the image and sends the results directly to the smooth pursuit system. When the target reappears, **the gaze points to the position of the target reappereance**, so the tracking algorithm is able to find the ball at the center of the image.

E. Falotico, M. Taiana, D. Zambrano, A. Bernardino, J. Santos Victor, P. Dario, and C. Laschi. “Predictive Tracking Across Occlusions in the iCub Robot.” *9th IEEE-RAS International Conference on Humanoid Robots*, December 7th-10th, 2009, Paris, France.

EP of external moving objects
Prediction of movements of other agents

Punching a moving target



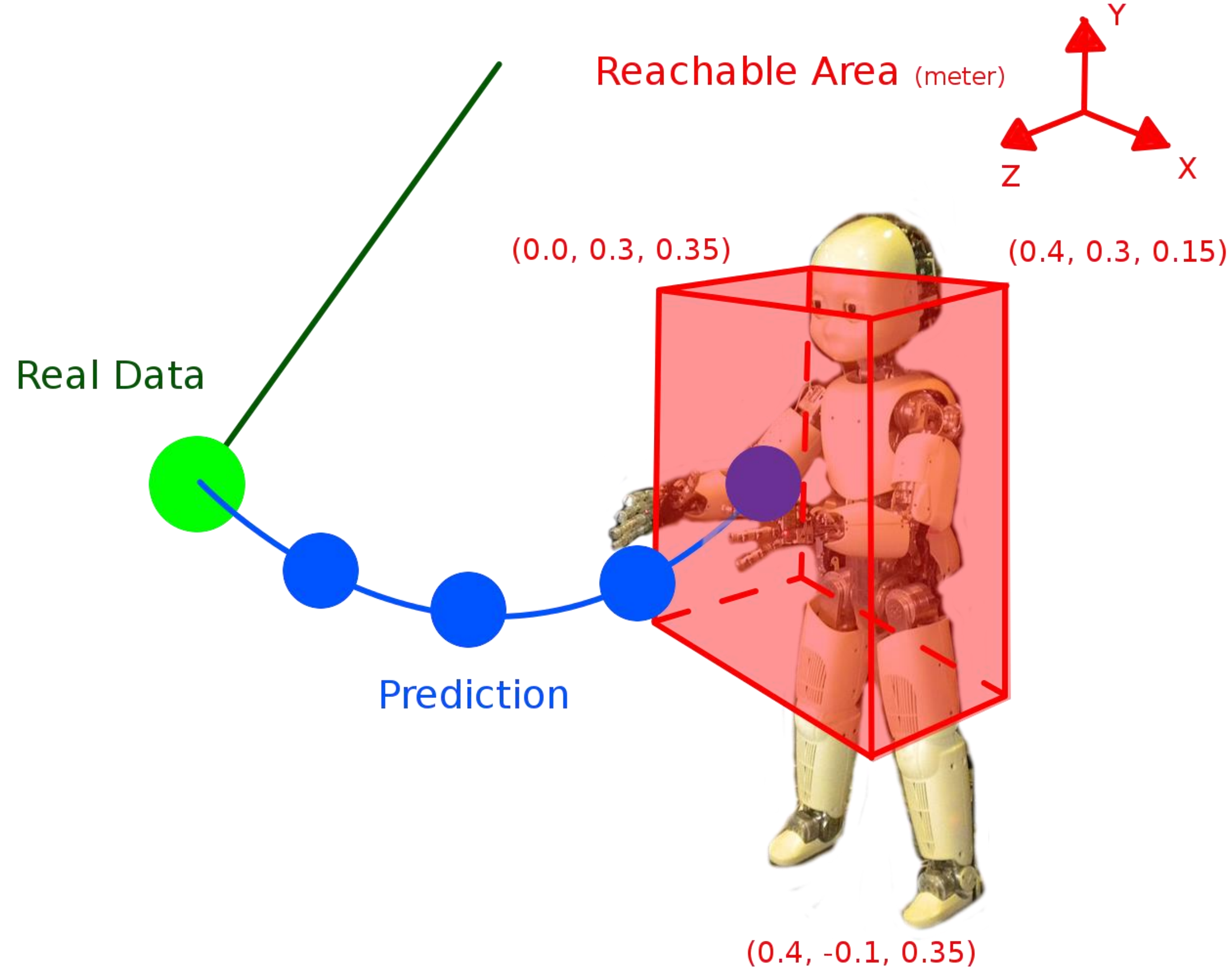


The robot punches a target oscillating in front of it with a predictable dynamics (pendulum)

An internal model is used to predict the dynamics of the moving target

The prediction allows to anticipate the movement of the arm and hit the ball

Punching a moving target
Experiment on Simulation/Robot



Experiment environment:

- A pendulum oscillates in front of the robot

Goal:

- Punching a predictable moving target when it reaches the robot arm workspace

Solution:

- *External model* used to predict the trajectory of the target (position through time) using a *Kalman Filter*
- Arm controller used to move the hand towards the desired position with a fixed time delay

Pendulum dynamics model

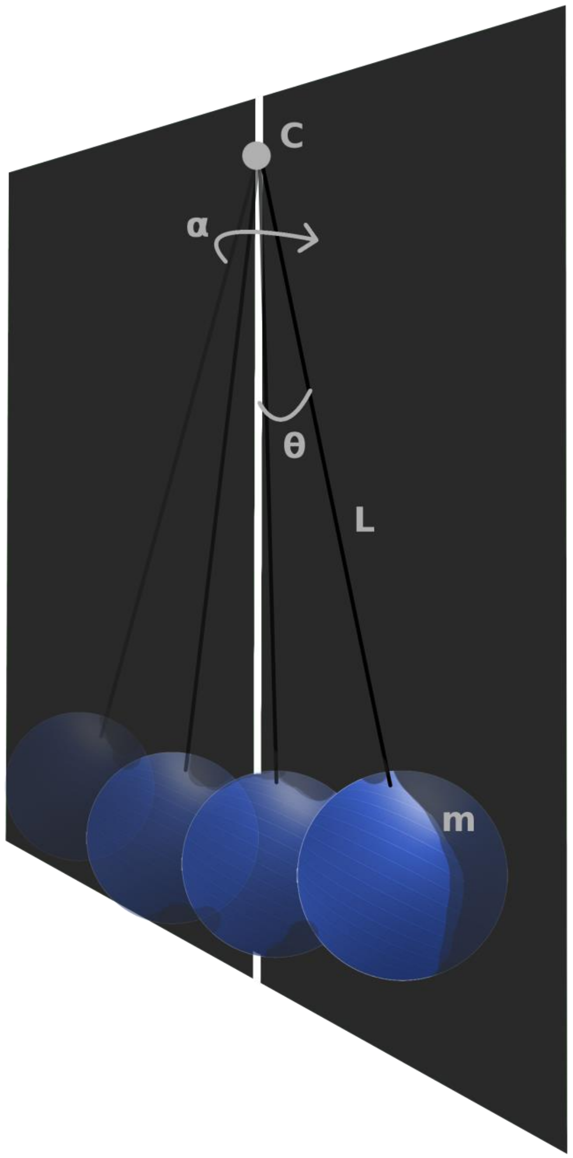
Pendulum model approximation used:

- 2D pendulum model moving on a plane
- The plane is centered on the pendulum pivot C and rotated of an angle α on the Y axis

$$\ddot{\theta}+\frac{b}{m}\dot{\theta}+\frac{g}{L}\sin(\theta)=0$$

In order to obtain the 3D position of the target the following function has been used:

$$h(\theta, L, C, \alpha)=\begin{bmatrix} C_x+L\sin(\theta)\cos(\alpha) \\ C_y-L\cos(\theta) \\ C_z-L\sin(\theta)\sin(\alpha) \end{bmatrix}$$



Punching a moving target - robot experiments

The prediction is iterated ahead 0.5 seconds
As the predicted target is inside the arm workspace, the robot executes a movement to punch the ball in the ***predicted position***

Hierarchical vs. Expected Perception

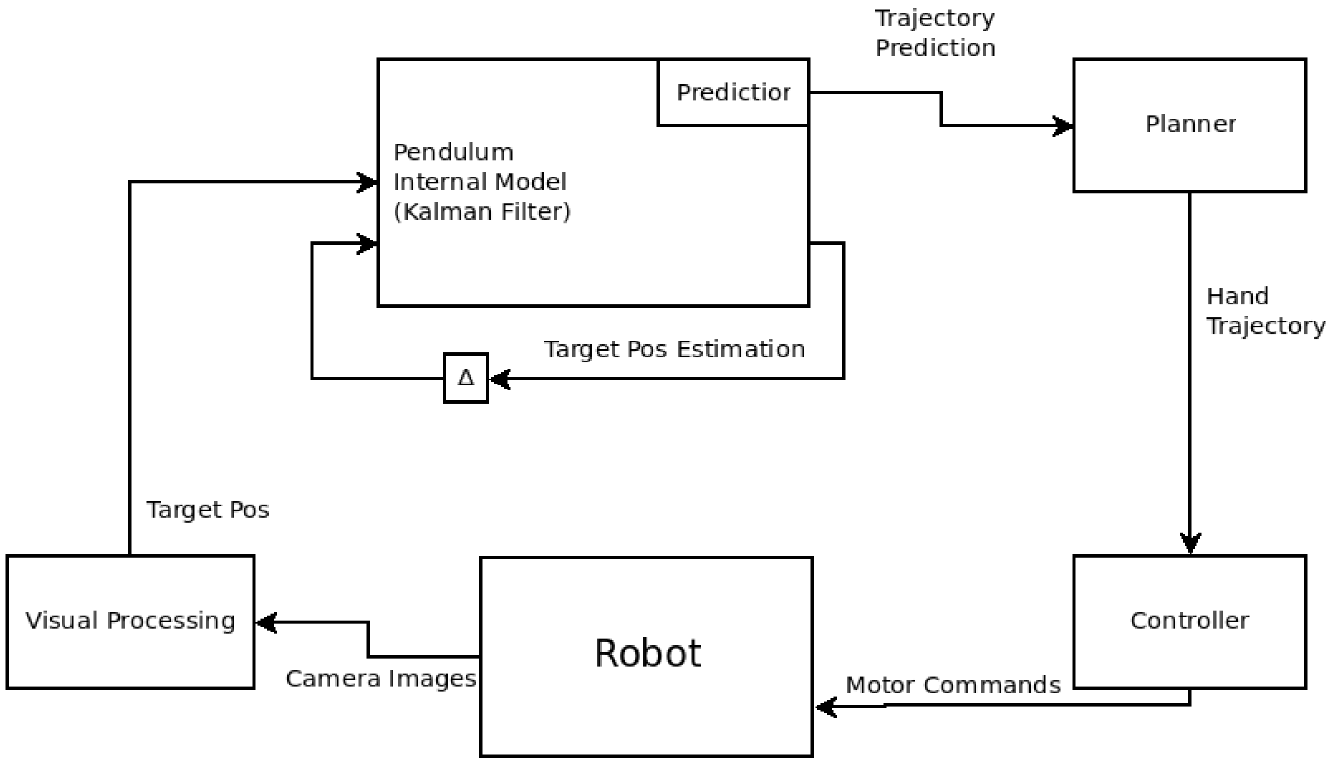
Implementation of 2 control systems:

- Hierarchical: the robot updates the prediction of the pendulum trajectory and moves the hand towards the desired position each step (0.03 seconds).

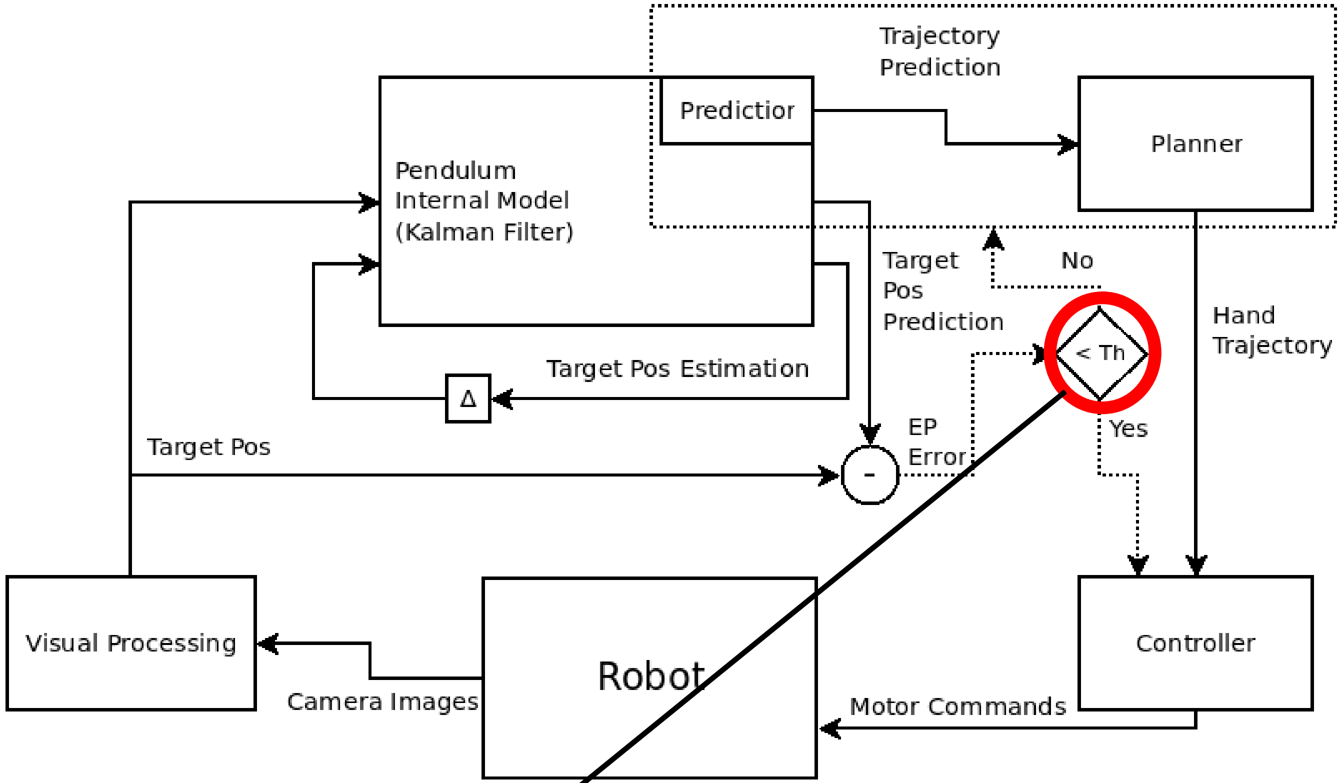
- EP: at the beginning of each cycle (oscillation) the robot predicts the pendulum trajectory and moves the hand. During the cycle, only in case of mismatch between the predicted and the actual trajectory, the robot updates the prediction and moves again the hand in the new desired position

Hierarchical vs. Expected Perception

Hierarchical



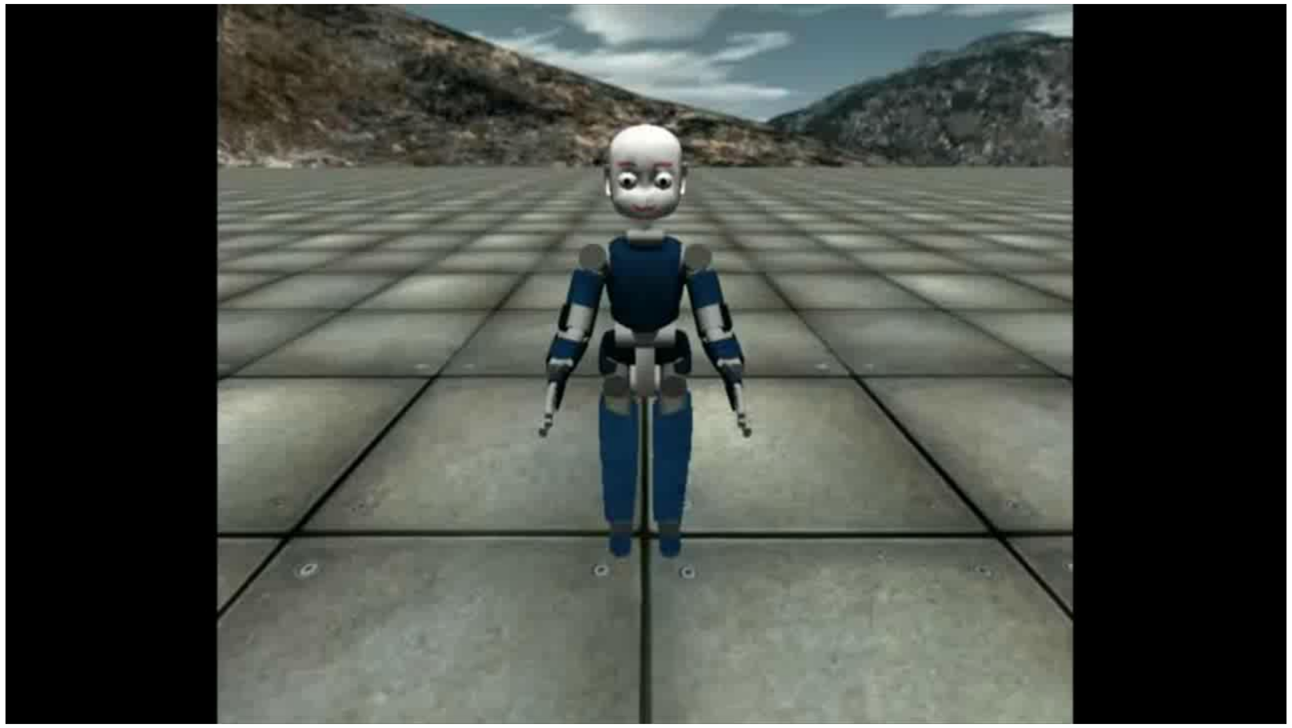
Expected Perception



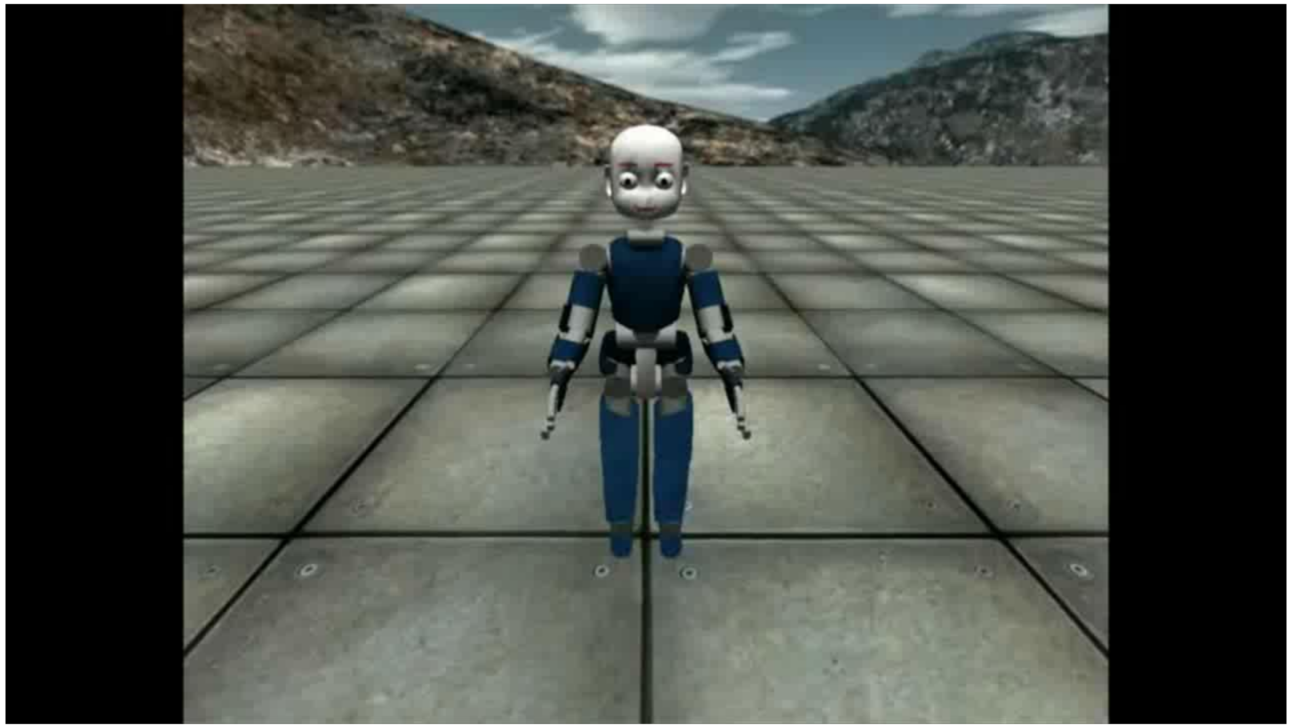
The threshold (Th) value is a key parameter
The threshold of acceptable error depends on this value which allows to avoid generating a new prediction
If Th tends to 0 this architecture corresponds to the hierarchical one

Punching a moving target

EP

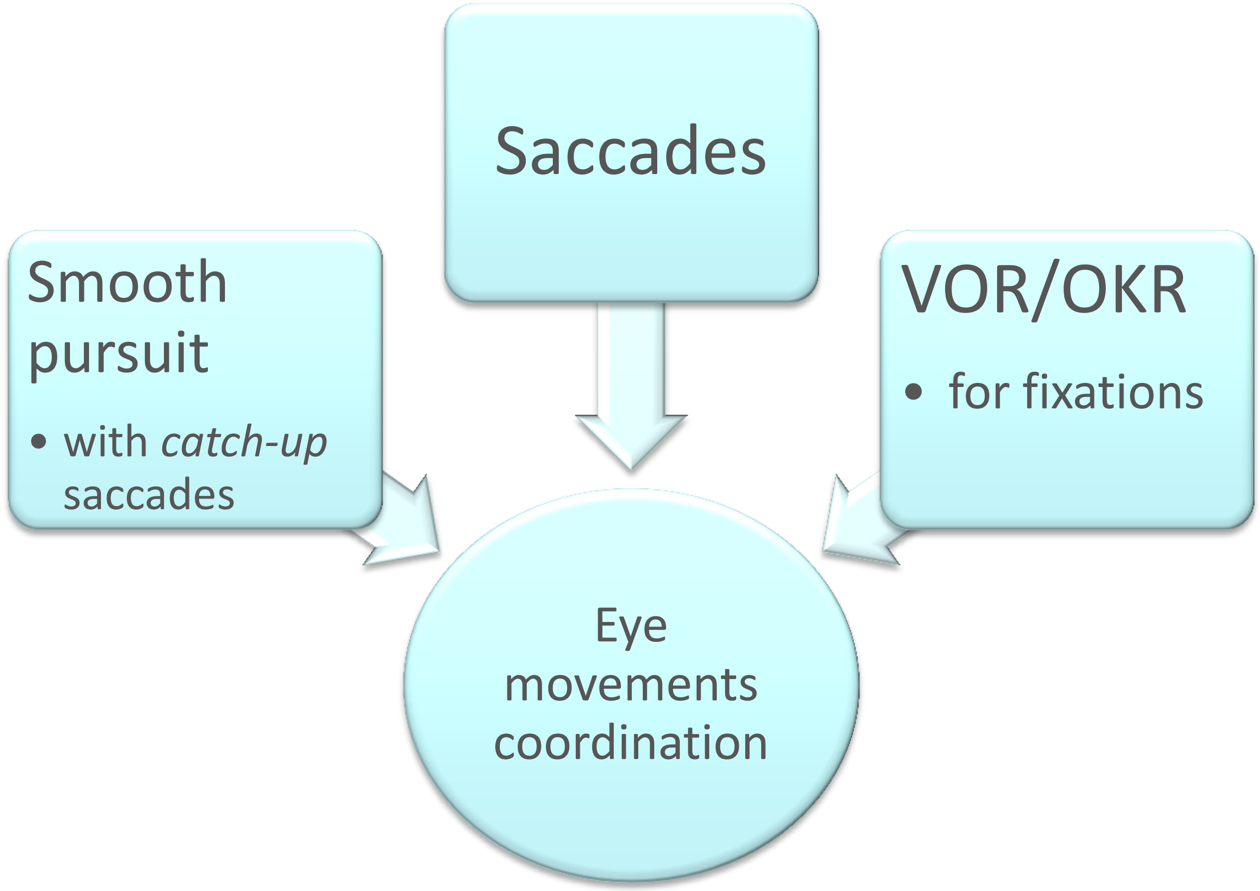


Hierarchical

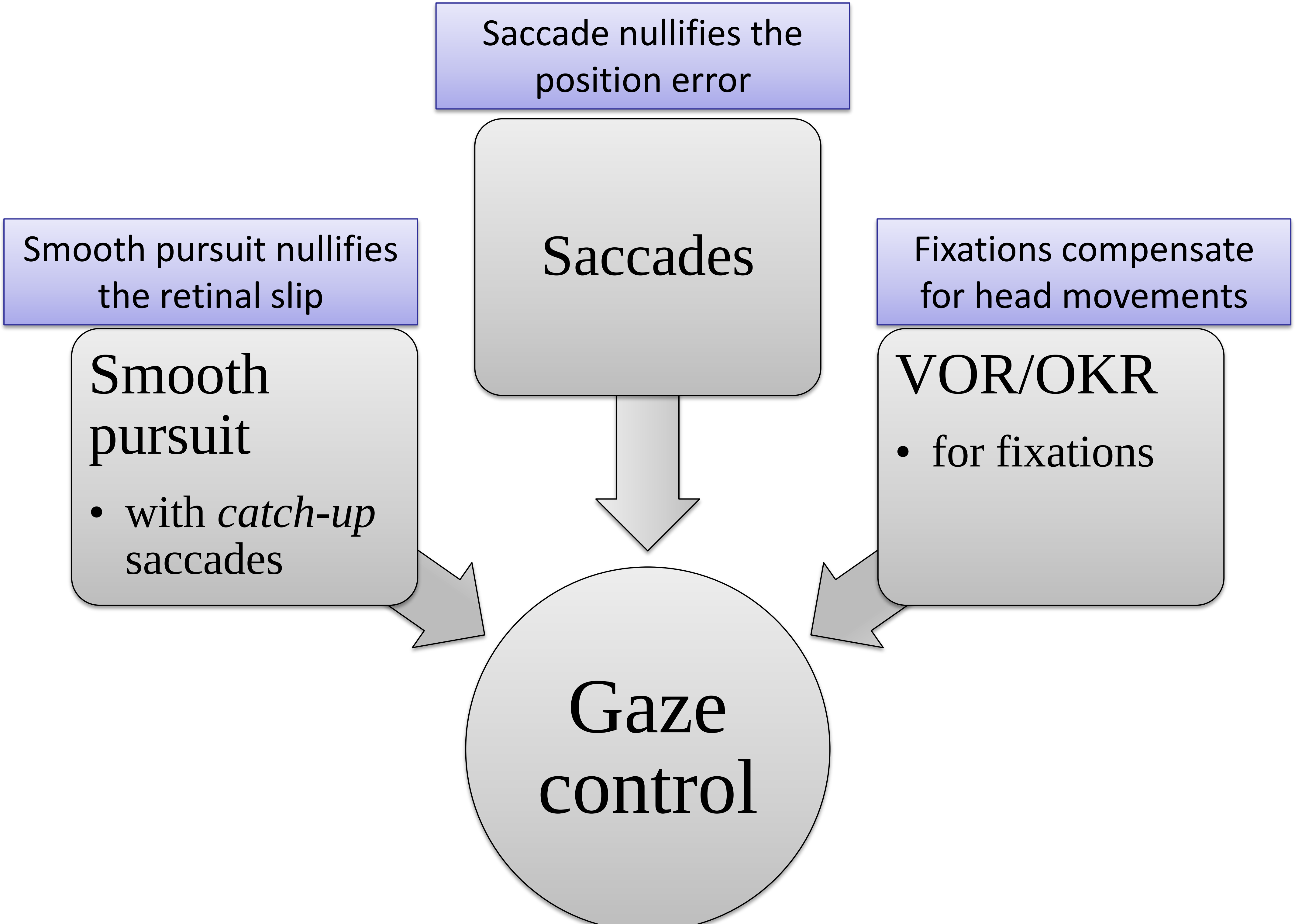


Eye movements – Action Selection

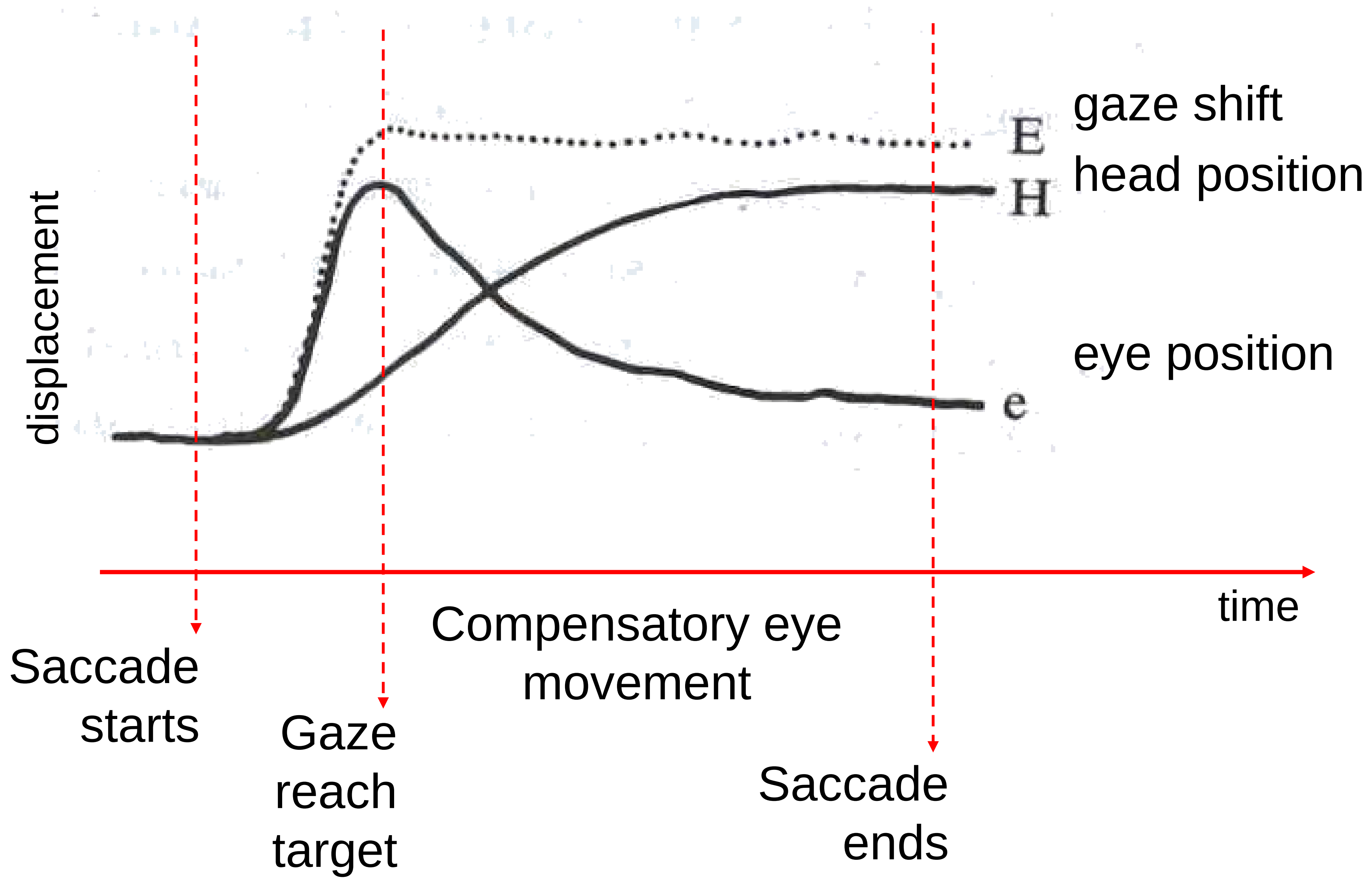
- Eye movements are driven by different sub-systems in ***competition for a common resource***, the eye muscles;
- These functional units are physically separated within the brain but are in competition for behavioral expression;
- There is a mechanism (***action selector***) that arbitrates between competing choices. The action selection is viewed in terms of signal selection, by encoding the propensity for selecting a given action as a scalar value (***the salience***).



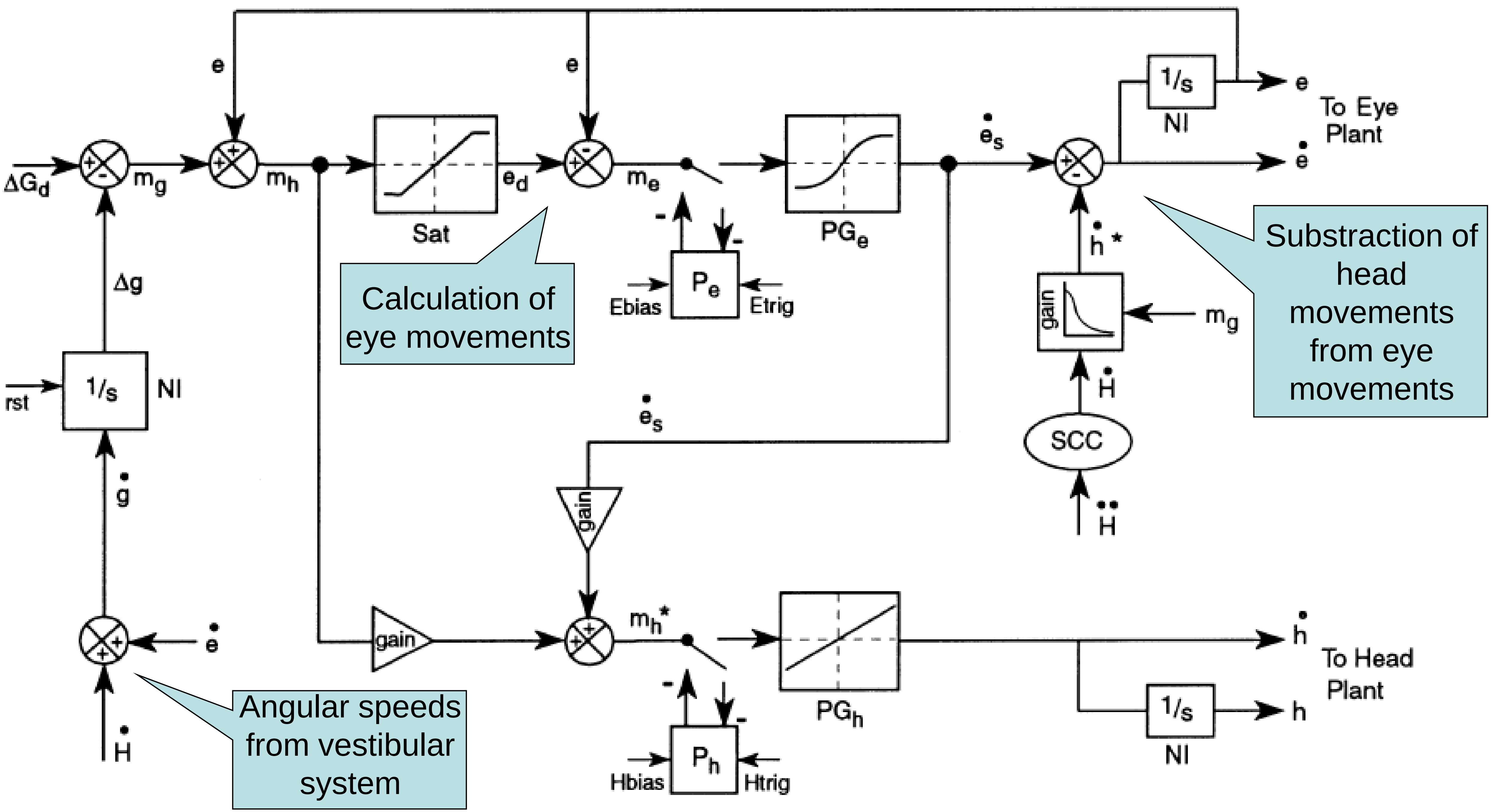
Integrated eye movements



Coordination of eye and head movements in fast gaze shifts



A model of fast gaze shift, coordinating eye and head movements



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

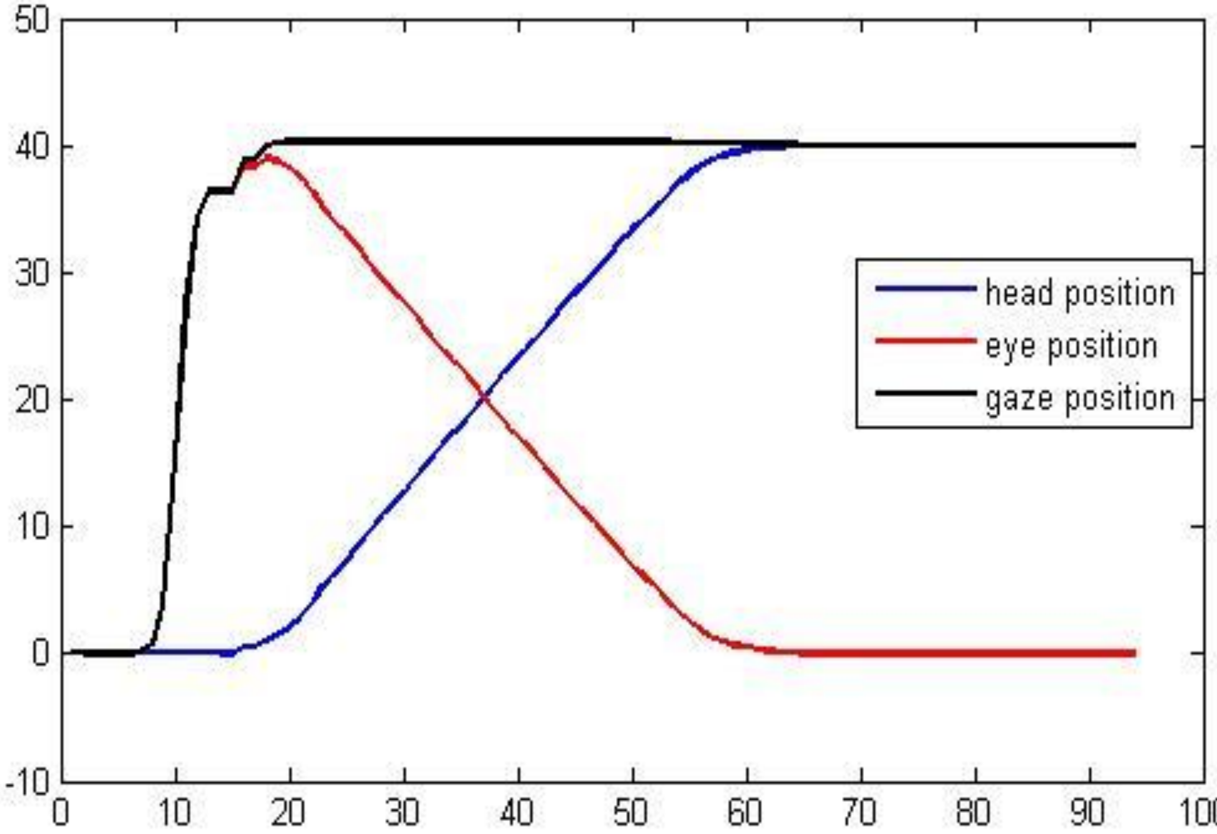
Model of fast gaze shift

The saccade starts and the eye joint moves at his **highest velocity** thus realizing the initial phase of the saccade.

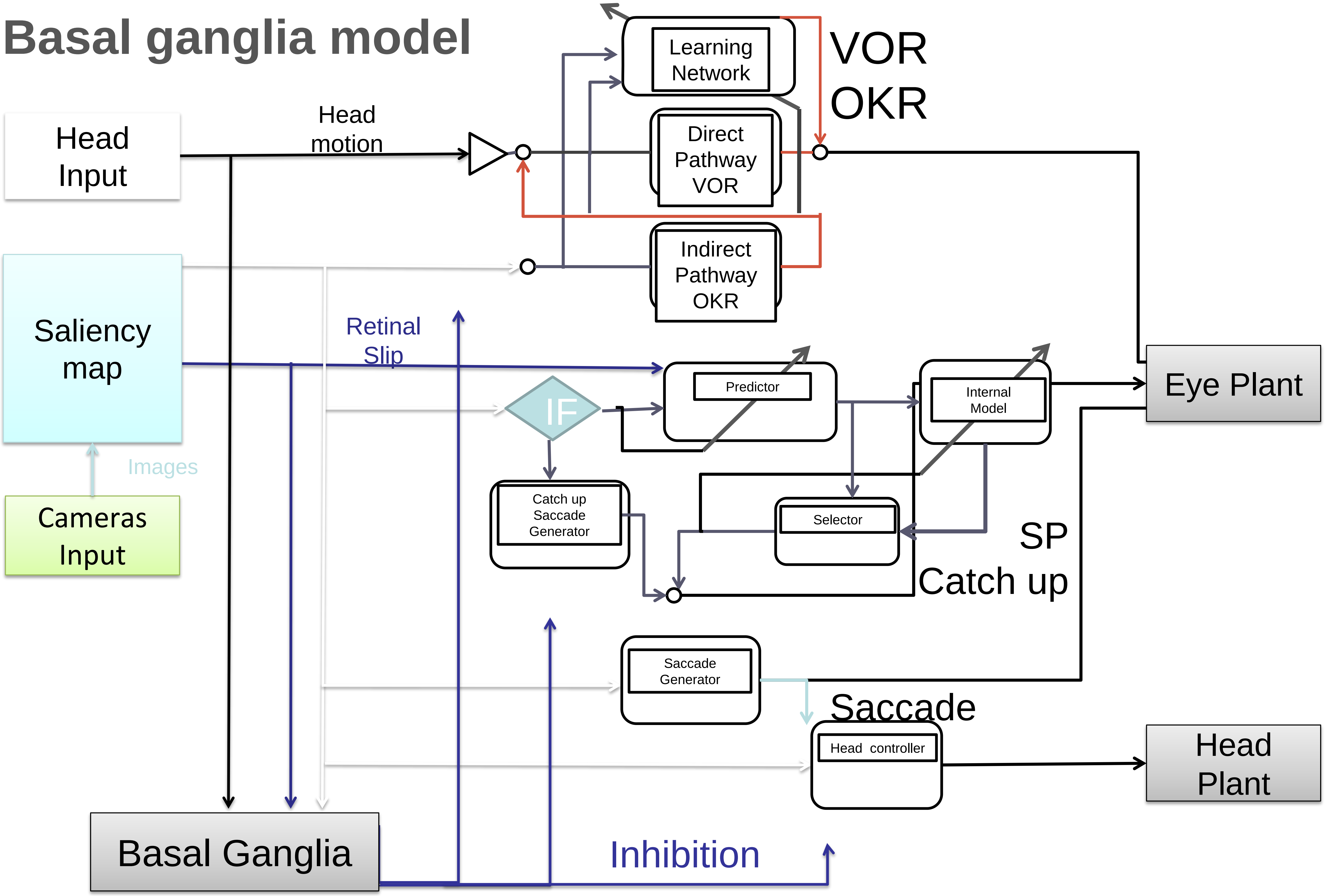
At the same time the head does not move, but it will start moving only after the head delay time is passed.

Given that the speed of the eye is much higher than the speed of the head, the *eye reaches the target position well before the head.*

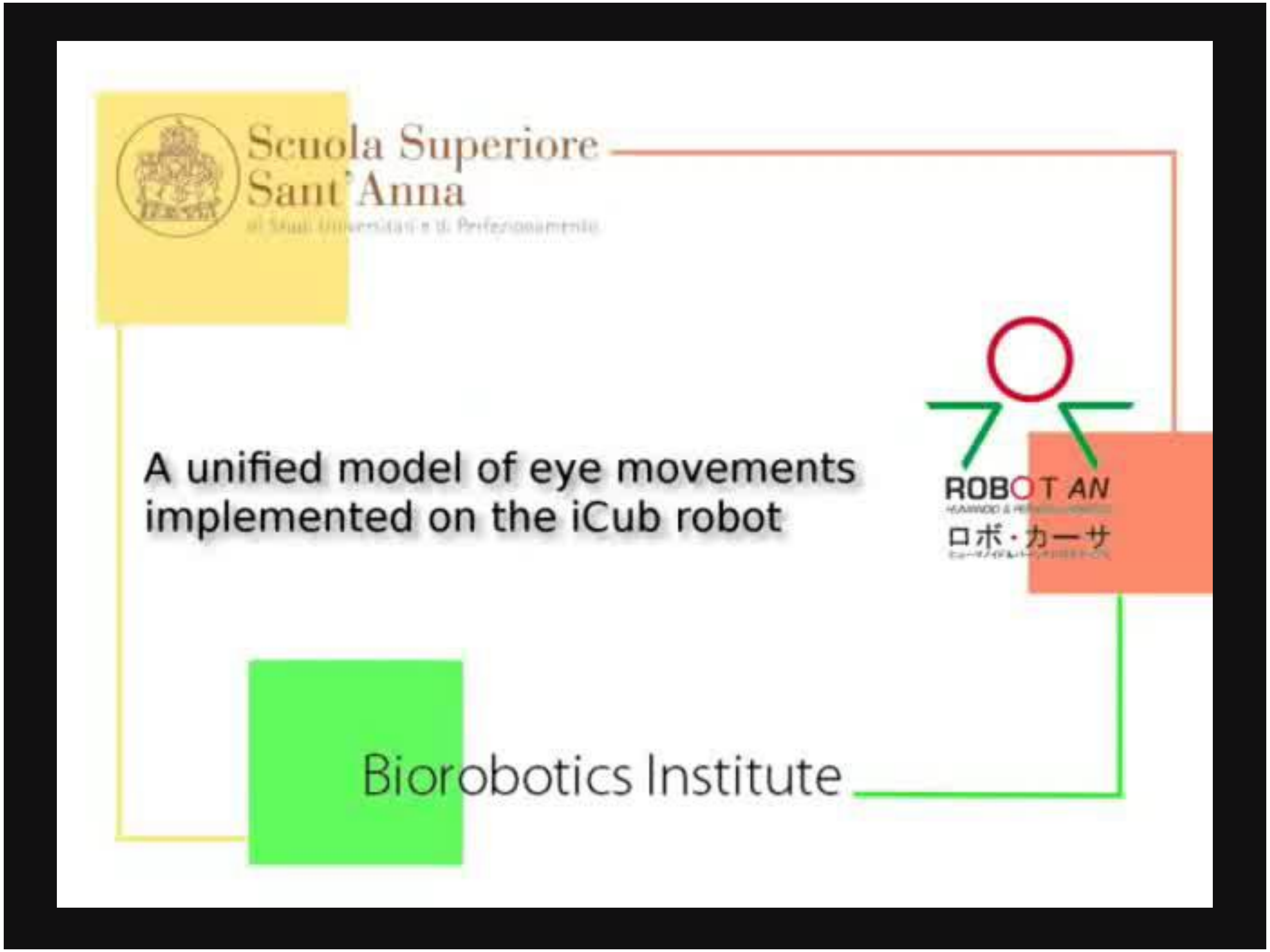
Time course of head, eye and gaze position of a saccade of 40 degrees



Basal ganglia model

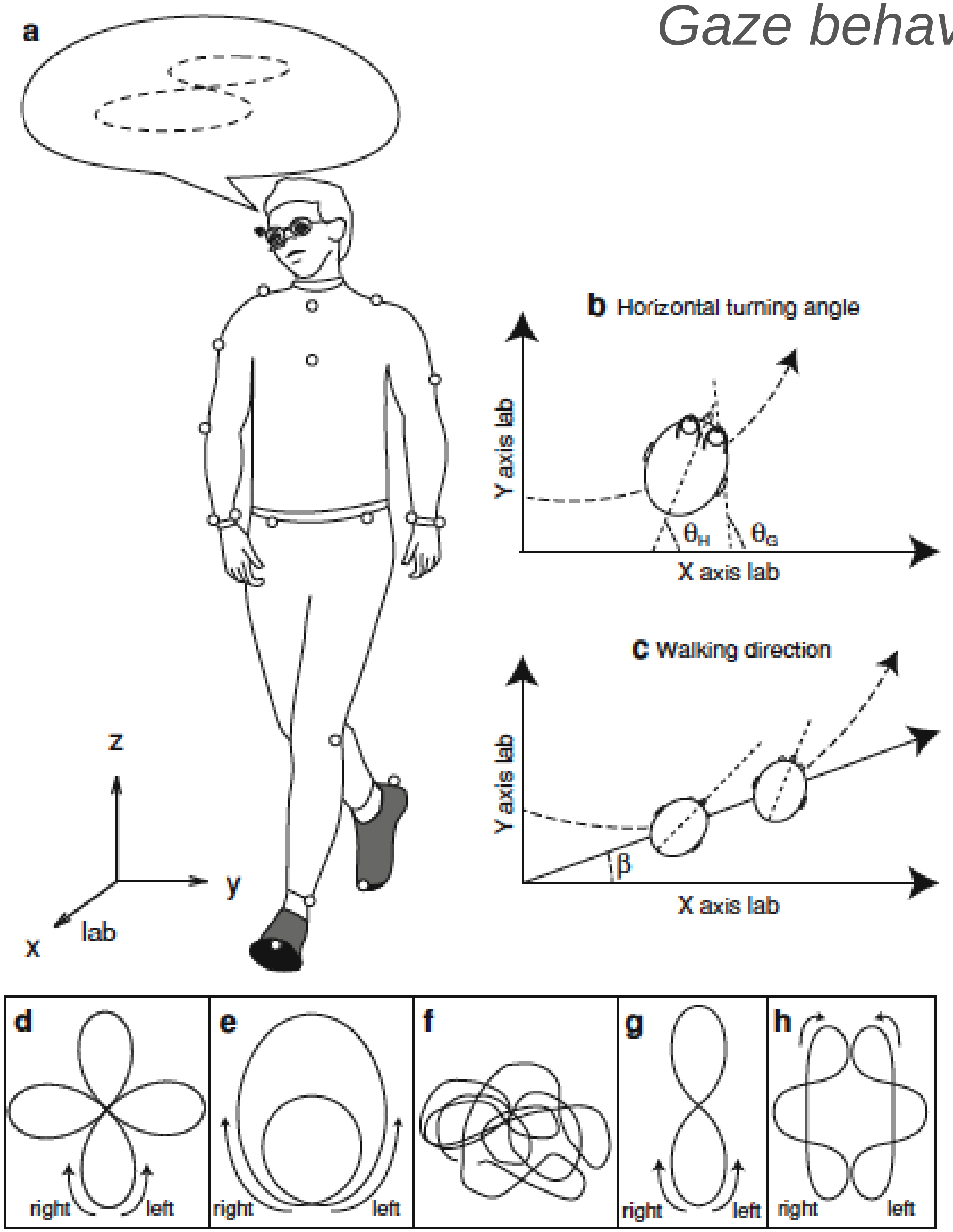


Robotic implementation of gaze control, integrating different eye movements



Gaze control and motor actions

Gaze behaviour in steering

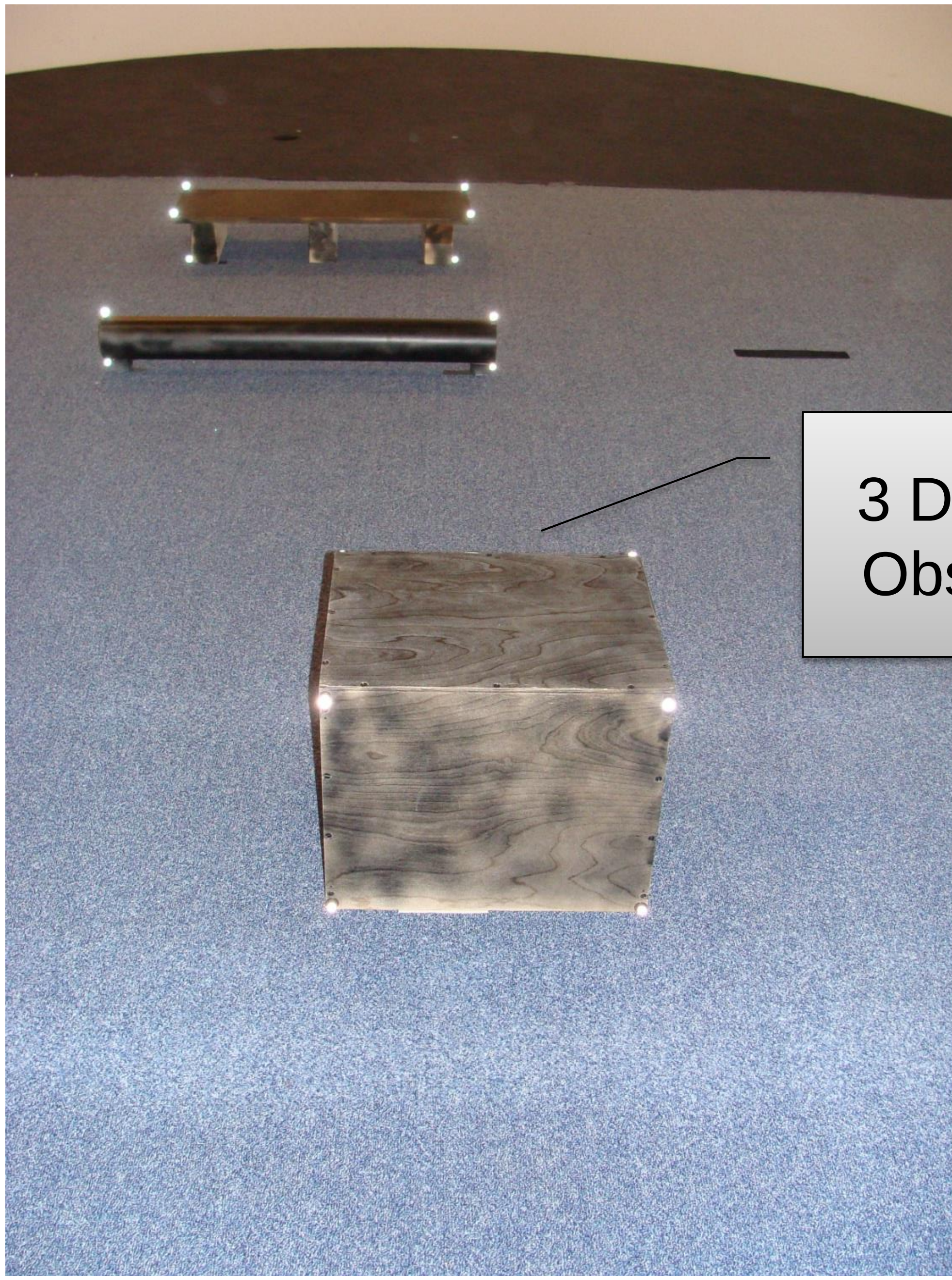


During locomotion, a top-down organization has been demonstrated with the head as a stabilized platform and **gaze anticipating the horizontal direction** of the trajectory.

Gaze direction **anticipates** the head orientation, and head orientation anticipates reorientation of the other body segments.

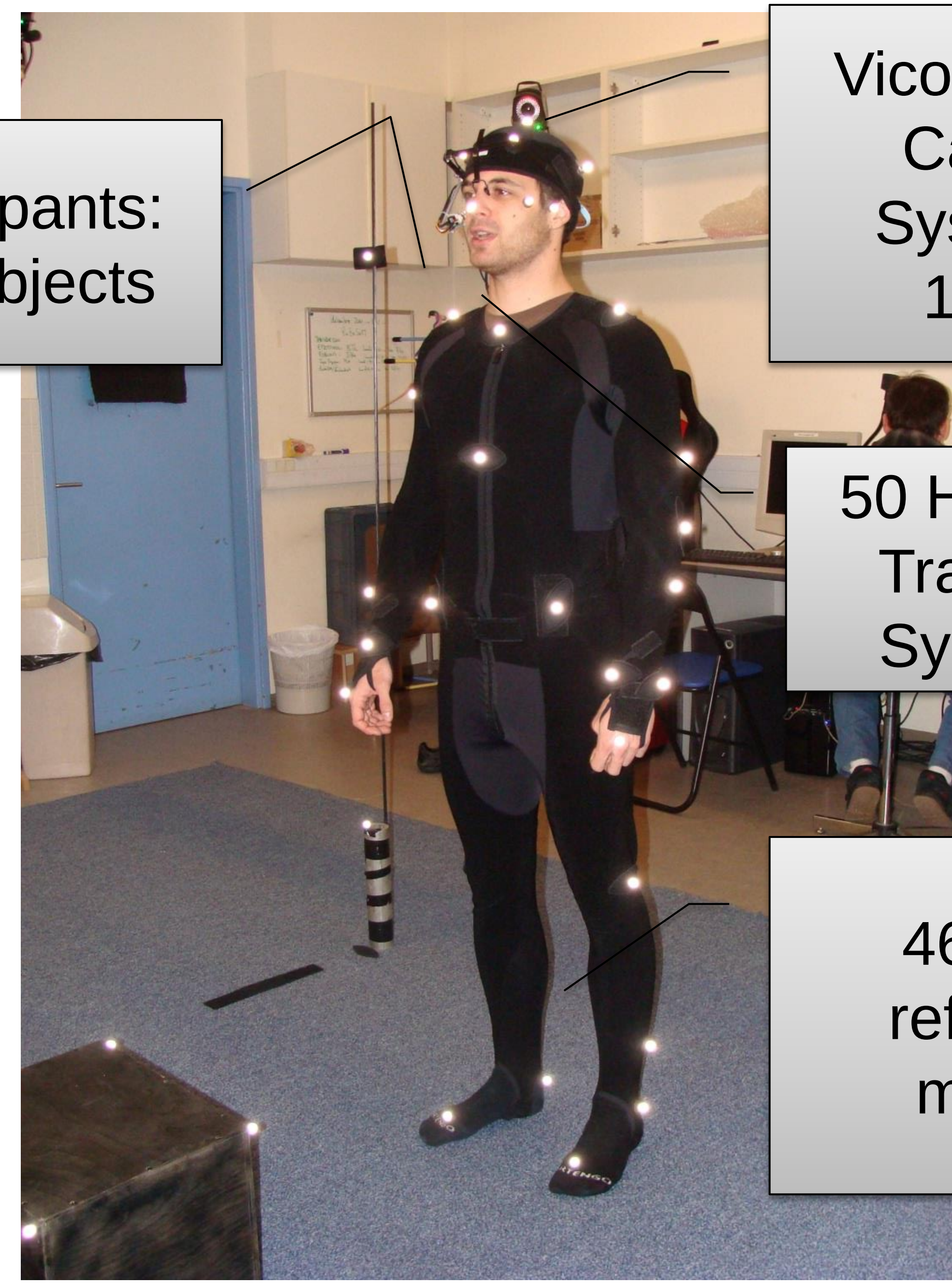
Bernardin & Berthoz 2012. Gaze anticipation during human locomotion *Exp Brain Res*

Experimental scenario



3 Different Obstacles

Participants: 10 Subjects



Vicon Motion Capture System at 120Hz

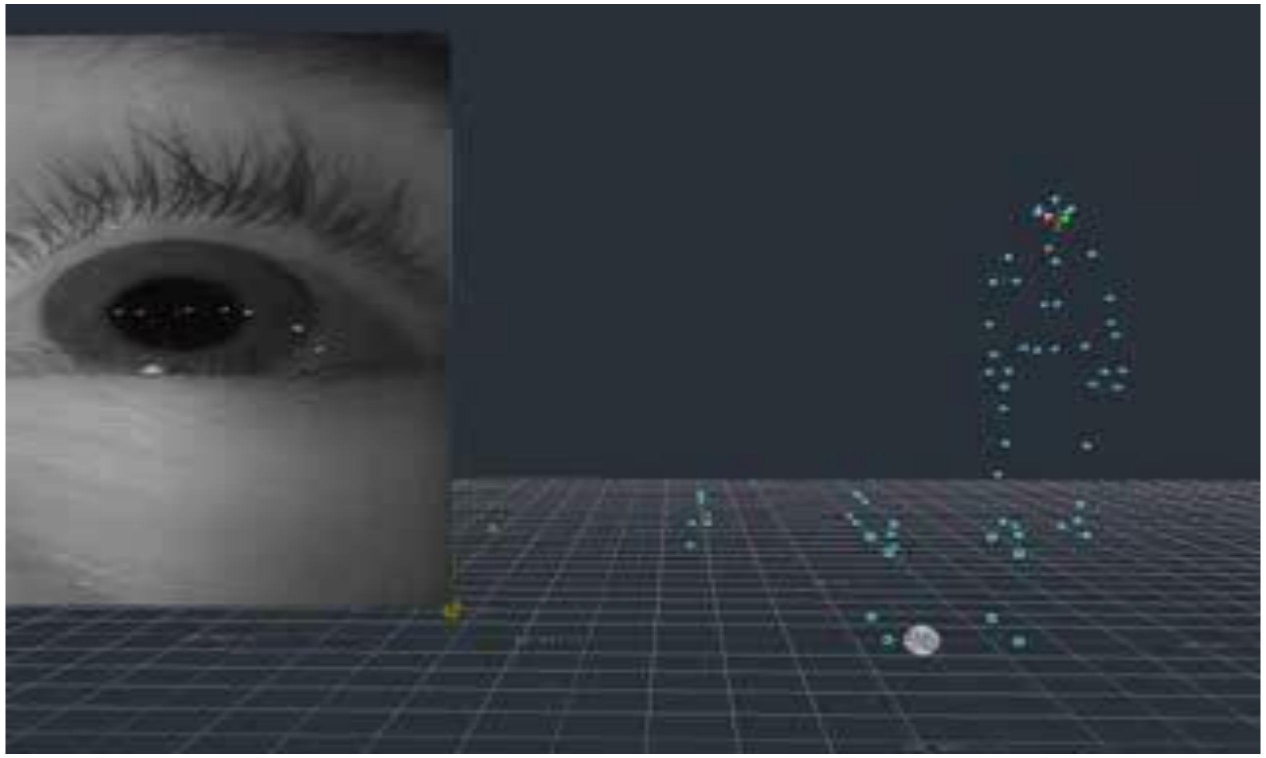
50 Hz Eye Tracker System

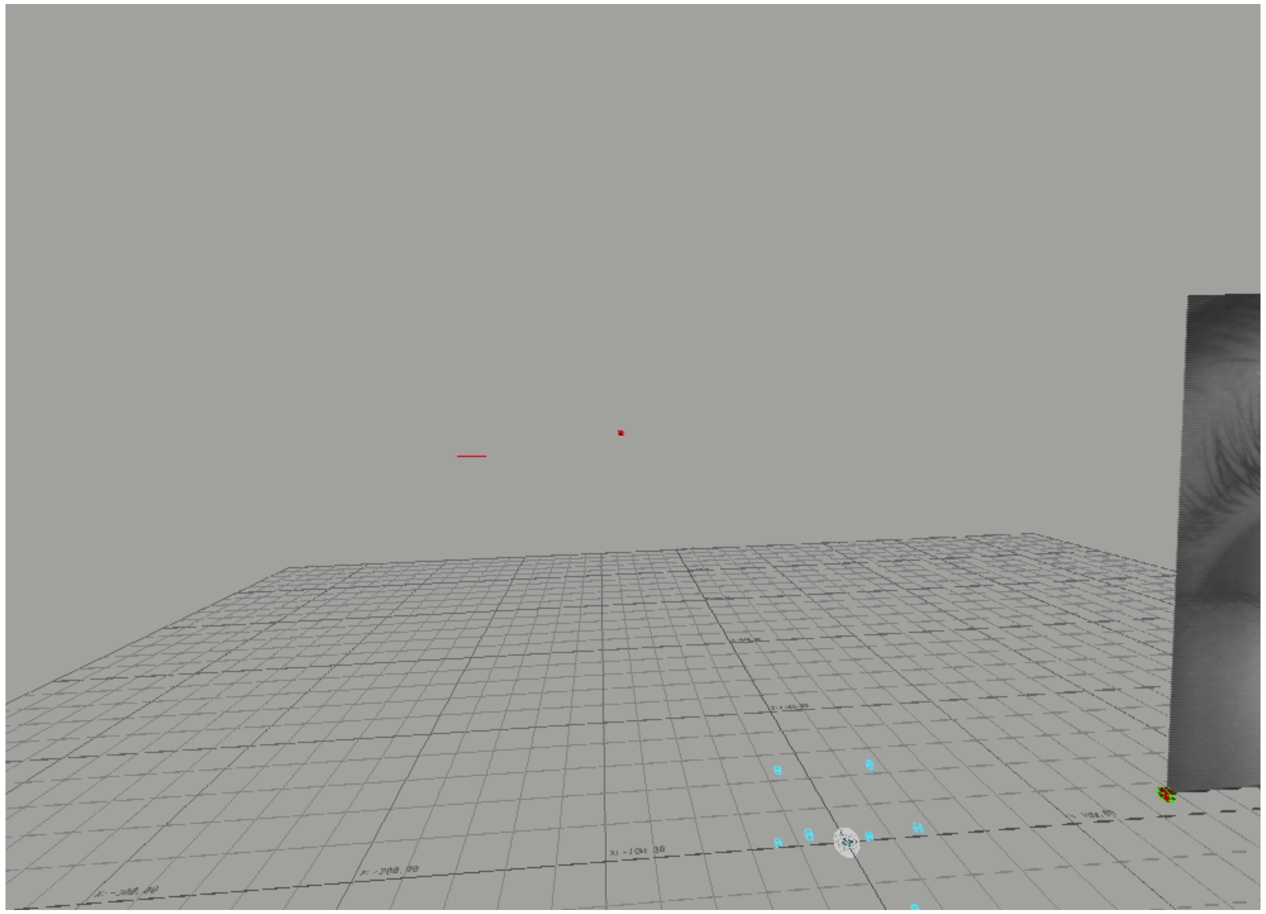
46 light-reflective marker

Experiments conducted in collaboration with College de France, Paris

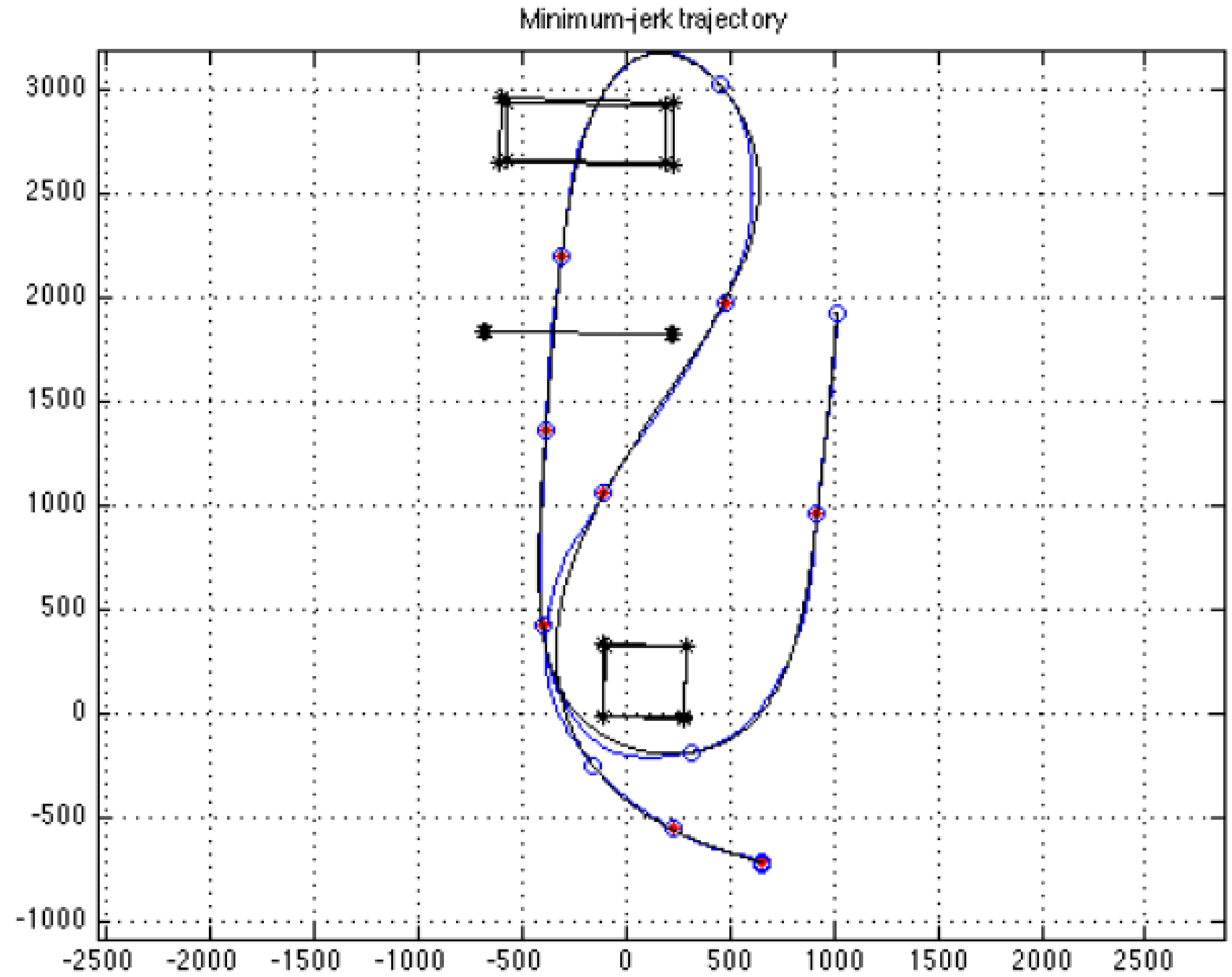
Experimental scenario

Recording of eye fization points with a wearable gaze tracker





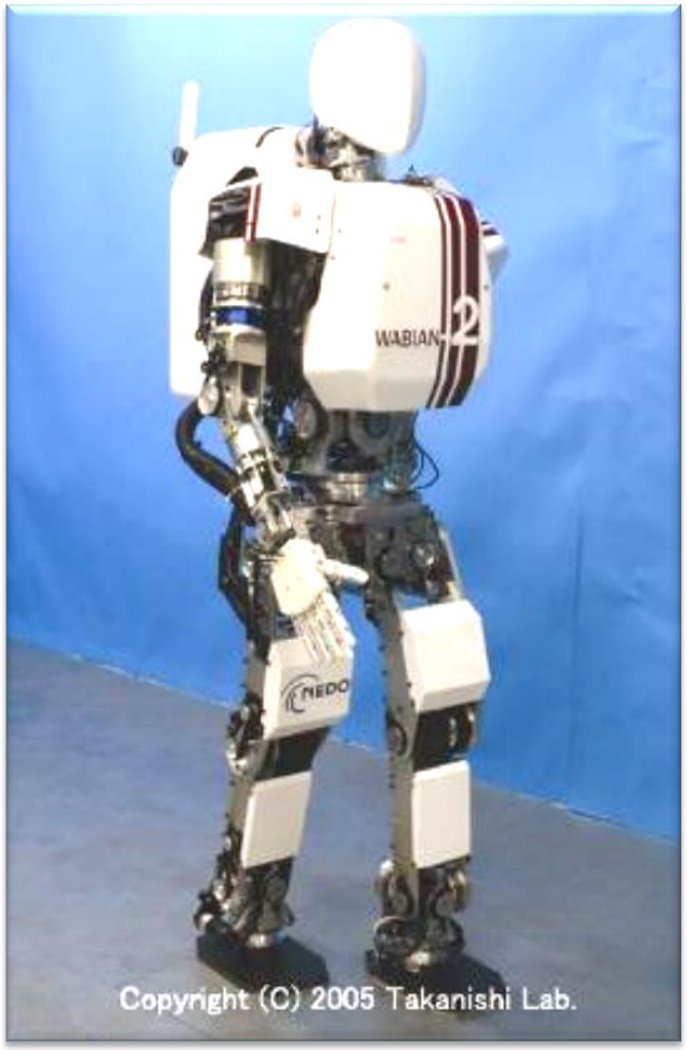
Trajectory planning in the experimental scenario: the model (blue line) predicts the subject trajectory (black line) through multiple via-points



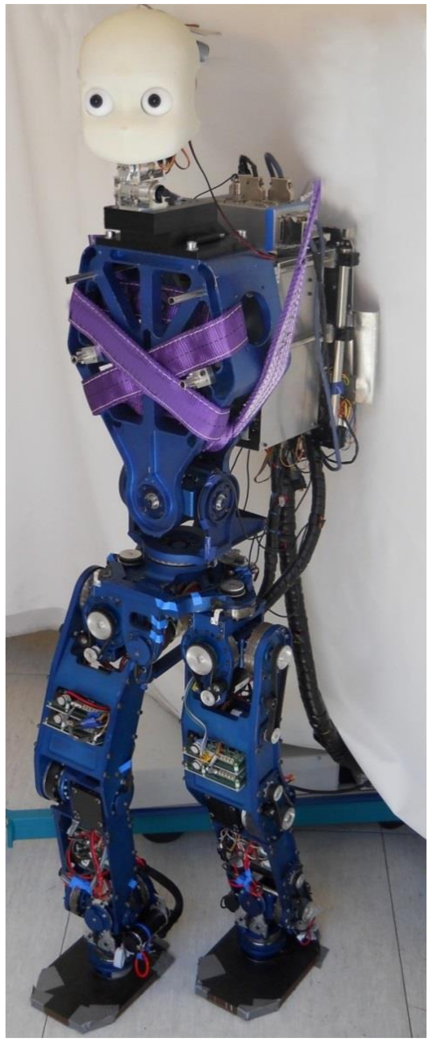
Zambrano D, Bernardin D, Bennequin D, Laschi C and Berthoz A (2012), “A Comparison of Human Trajectory Planning Models for Implementation on Humanoid Robot”. *Proceedings of the 4th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob2012)*, June 24-27,2012, Rome Italy

Robotic Implementation

The Wabian platform is the result of more than 30 years of experience on biped humanoid robots at Waseda University. The Sabian platform is a copy of the legs and trunk developed at the joint lab 'Robot-An' at the BioRobotics Institute



Wabian



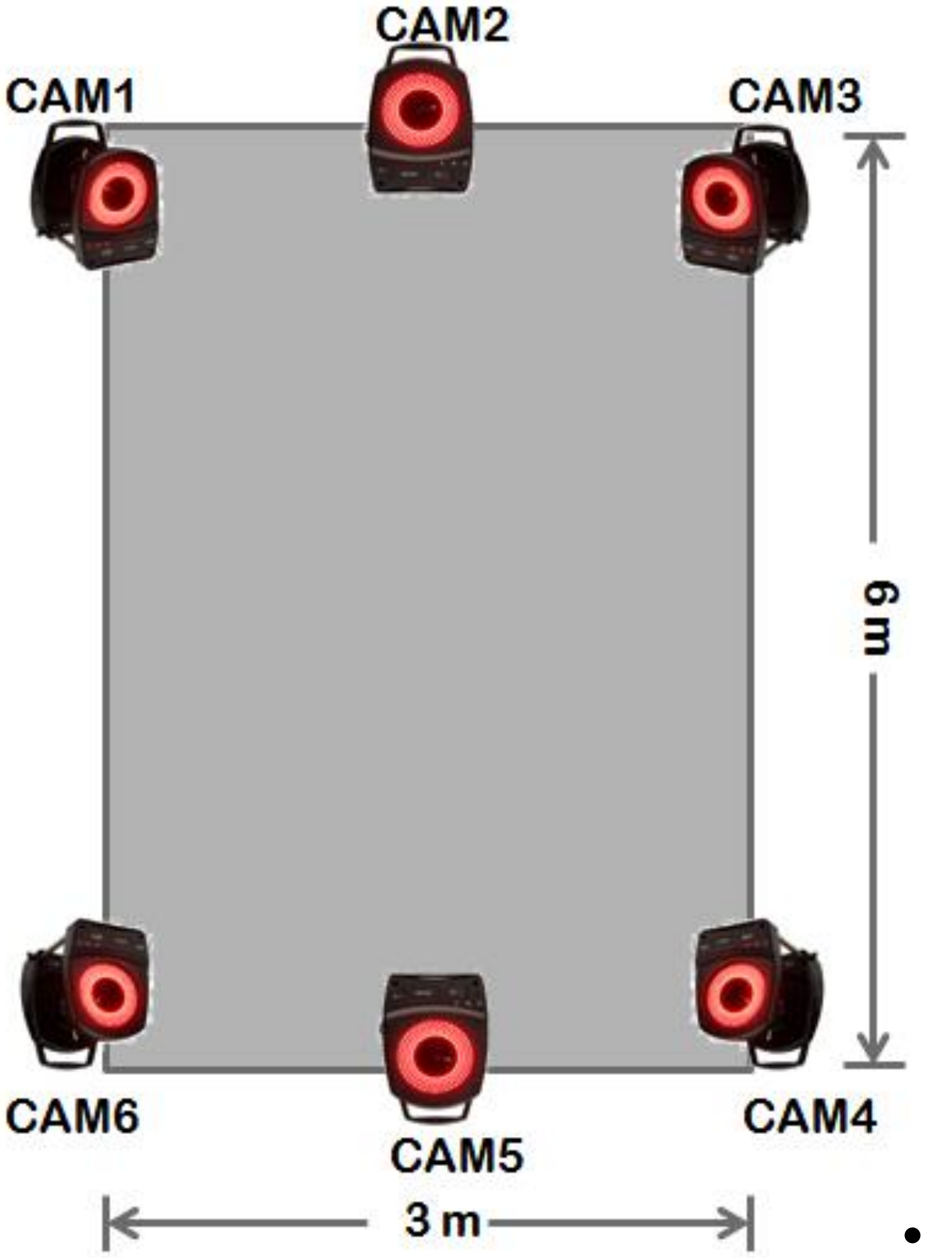
Sabian

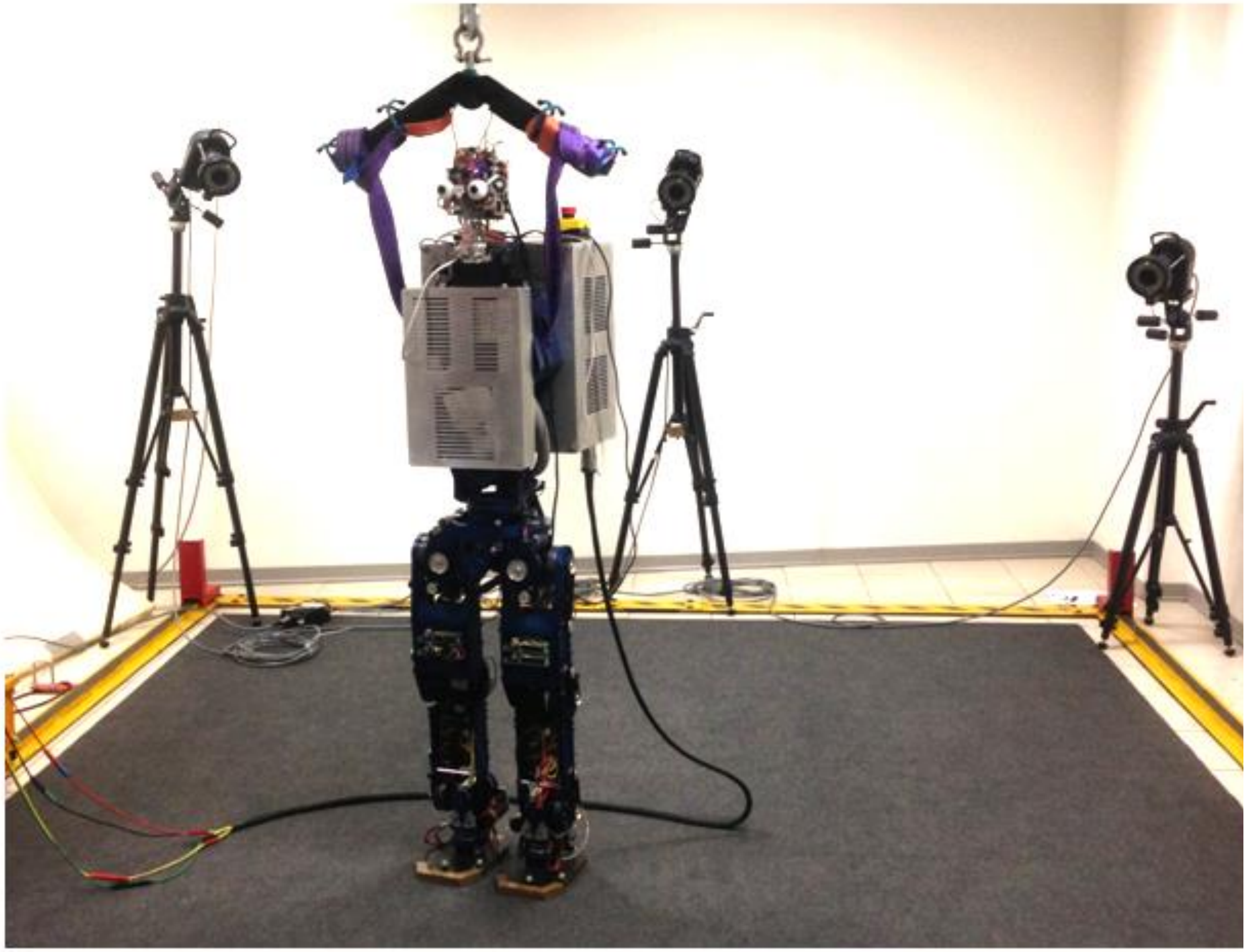
Wabian/Sabian

- height: 1475 mm
- weight: 64.5 kg.
- 6 DOF in the legs
- 2 DOF in the waist
- 2 DOF in the trunk
- 1 passive DOF in each foot

SABIAN's Parameters	Value
CoM Height	0.74 m
Leg Length	1 m
Velocity	0.3 m/s
Walking cycle	1 s/step
Step Length	0.3 m
Step width	0.18 m
Step Height	0.3 m

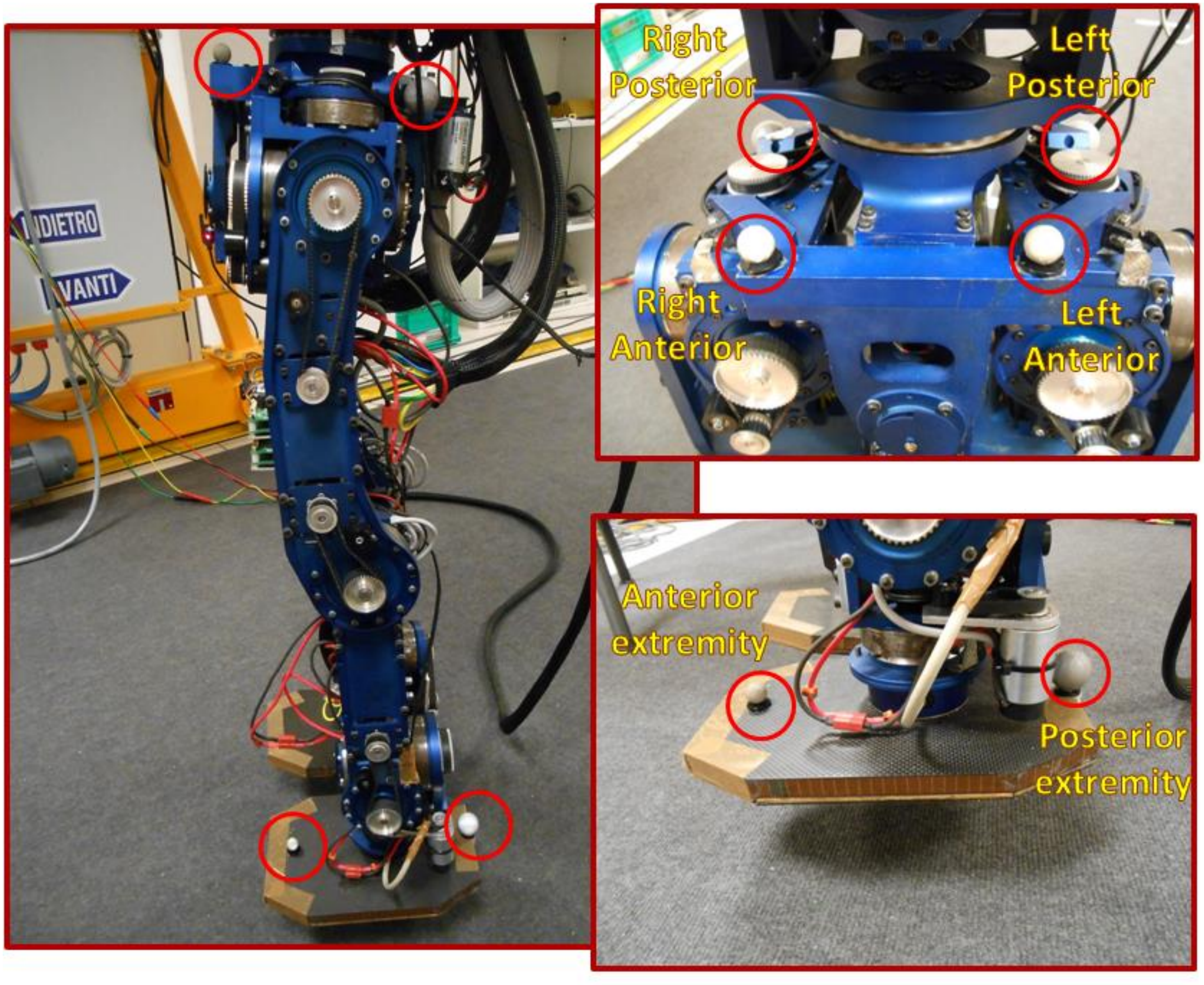
The experimental set-up
Motion Capture system





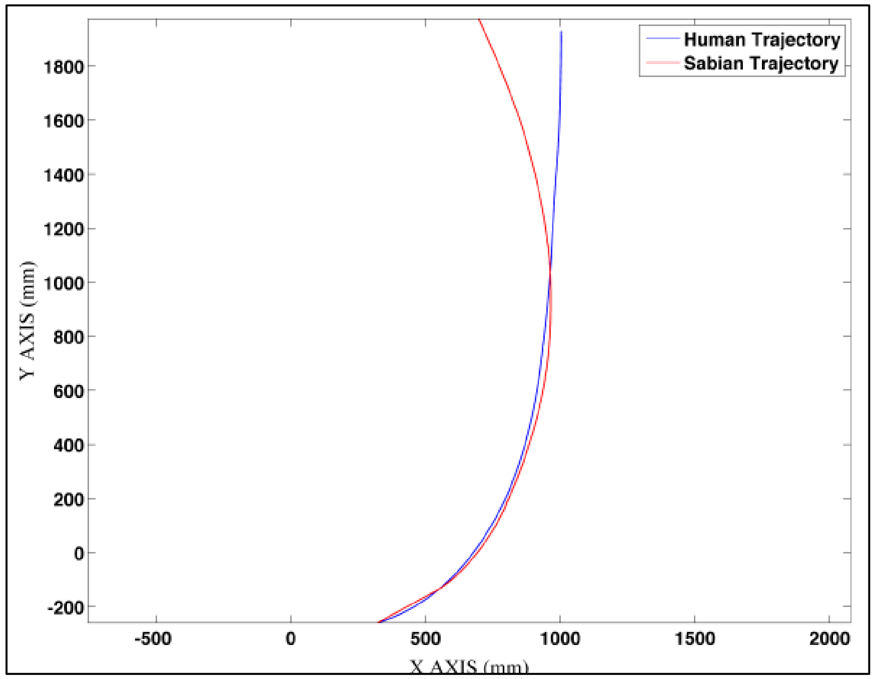
- Empty workspace of 6 x 3 meters
- Supporting device for the robot
- Vicon motion-capture system with 6 MX cameras at 100 Hz

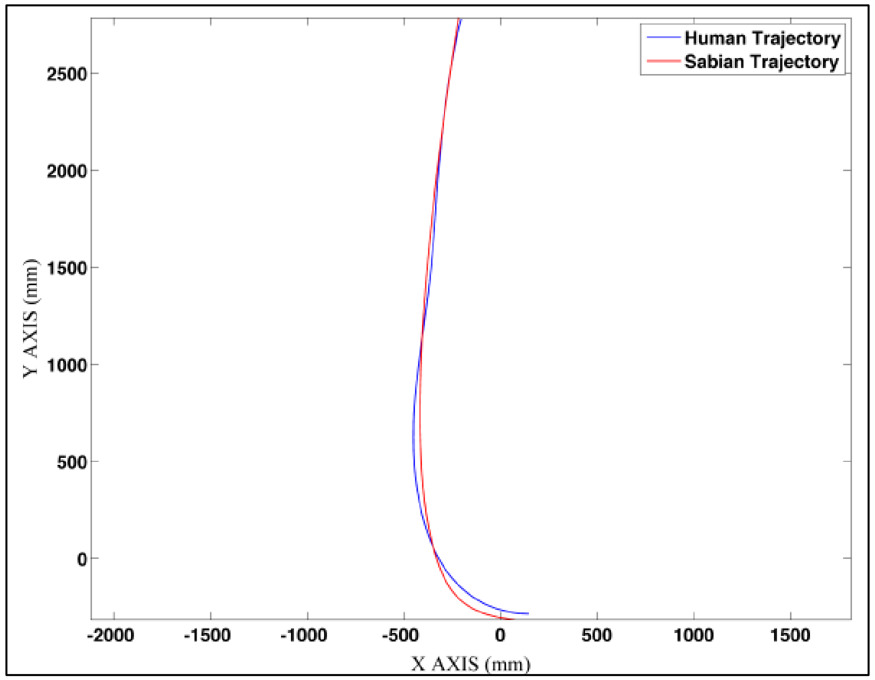
The Motion Capture system
Marker positions

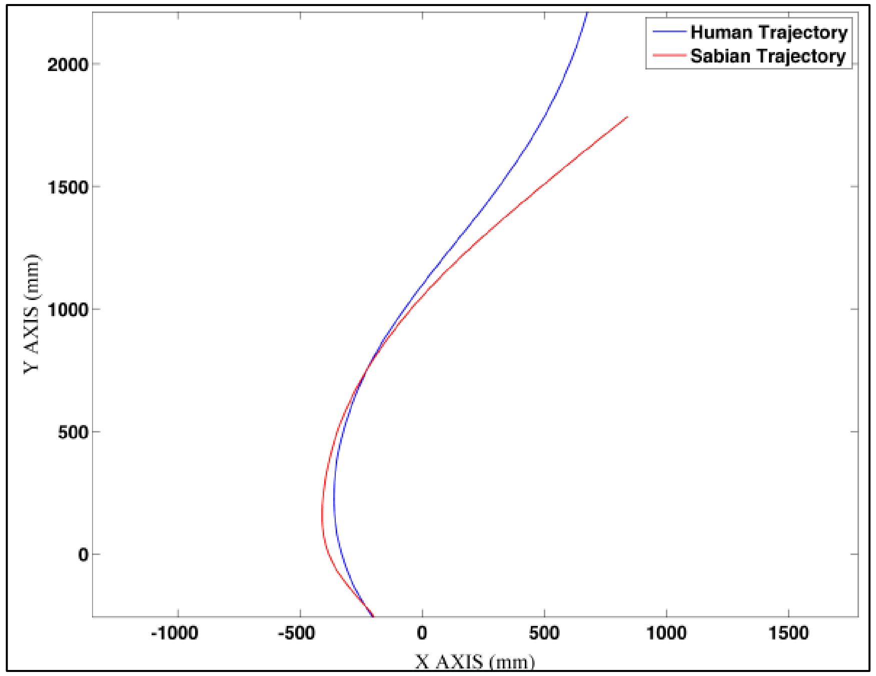


Experimental trials
Human-robot comparison

Trajectory







COMPARISON RESULTS IN TERMS OF SUM OF TRAJECTORY ERROR (STE) AND AVERAGE TRAJECTORY ERROR (ATE)

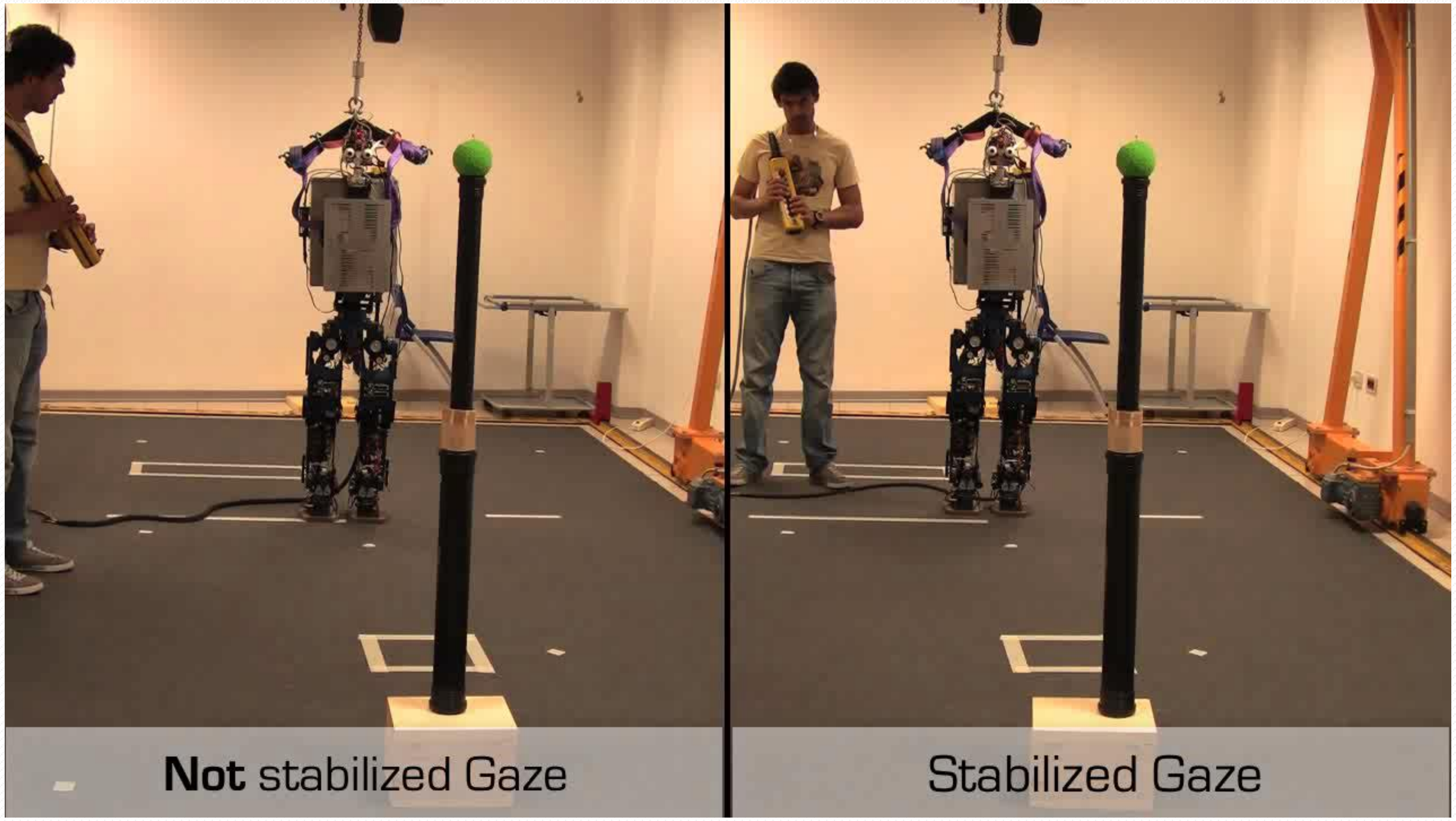
Phase Number	STE (mm)	ATE (mm)
Phase 1	45470	225
Phase 2	23565	83
Phase 3	55689	271

Straight walking to reach a visual target

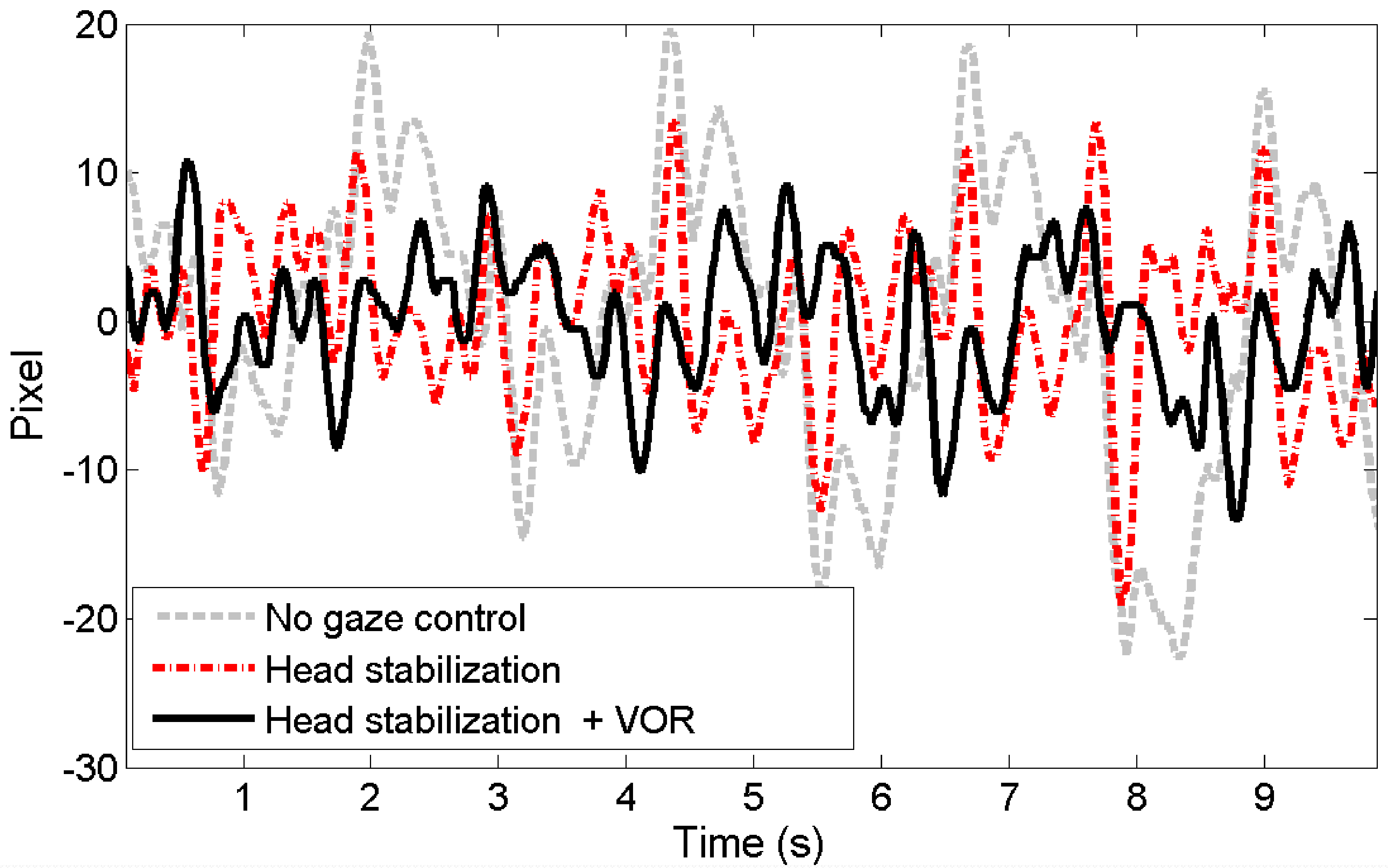
The robot is placed in front of a target at a distance of 3.2 meters.

Active modules:
Foot placement generation
Head stabilization
Gaze stabilization

Parameters	***Value***
Time to reach the target	20.1 s
Number of steps	20
ZMP x position error	0.012
ZMP y position error	0.015
Error of the target in the vision system	4.65 pixels

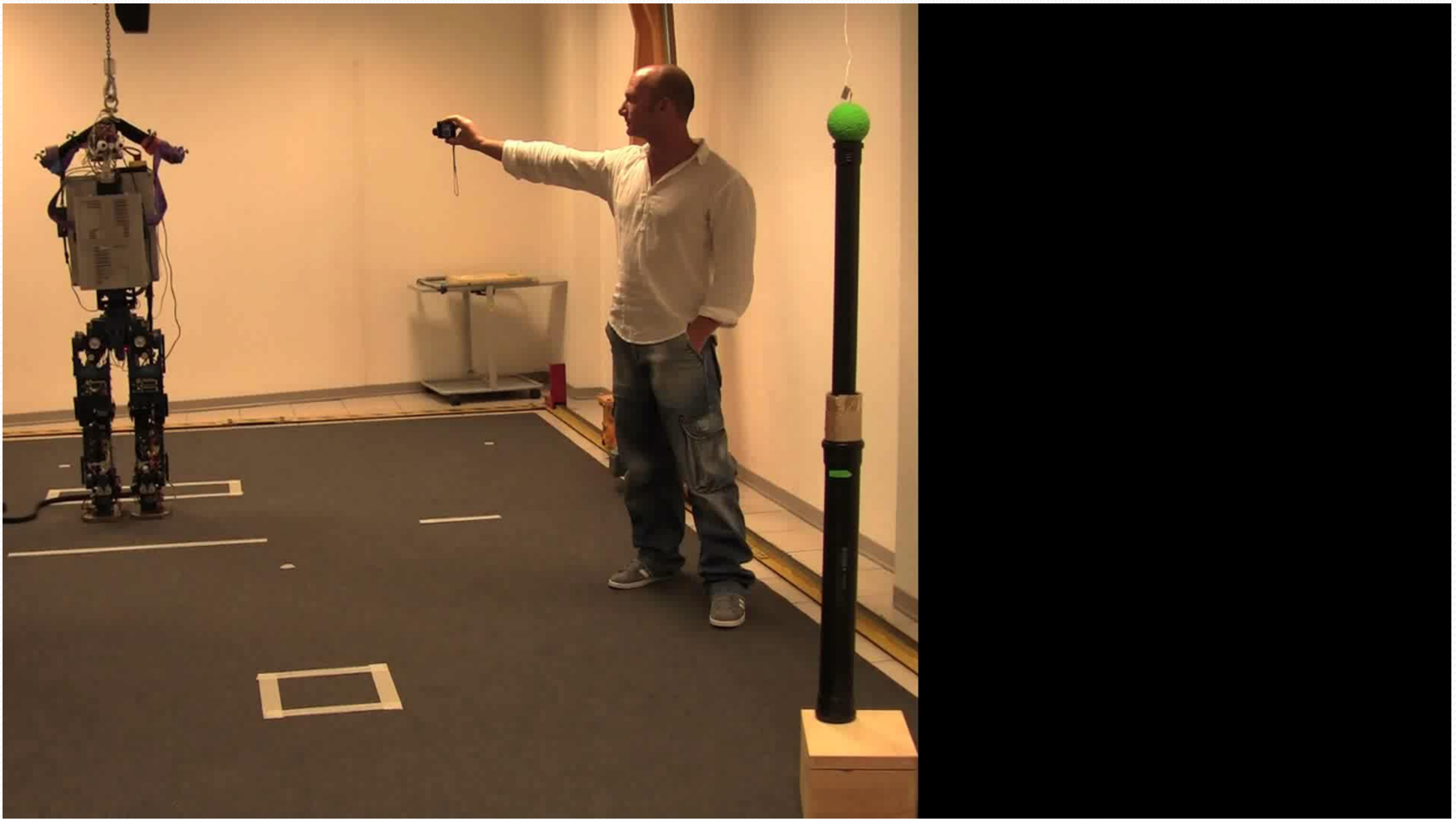


Straight walking to reach a visual target – gaze and head stabilization



Error in the camera image during three trials of a straight walking path. The errors of the different trials are superimposed and time aligned. We considered for this comparison only the middle part of the trials.

Not-straight walking to reach a visual target



Target position is at a distance of 2 m in front and 2 m on the left from the robot.

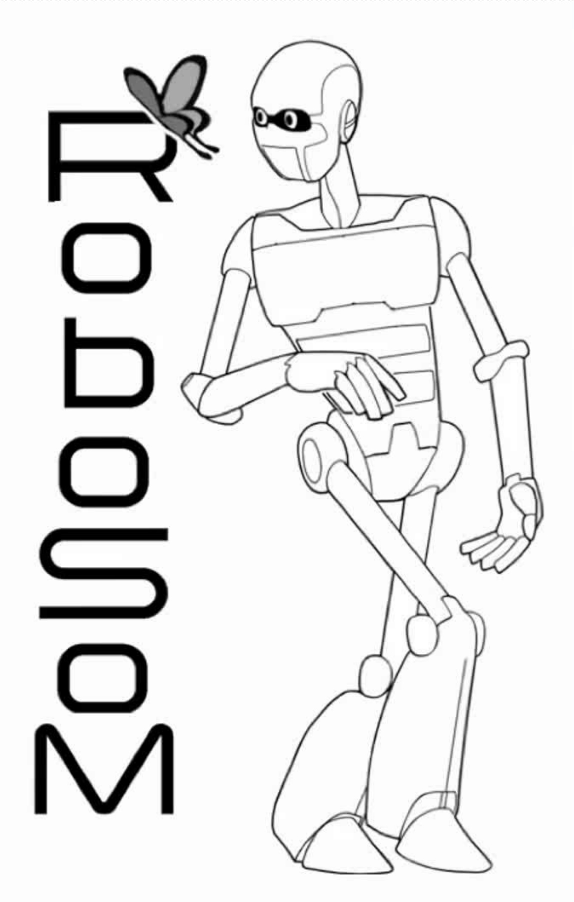
Active modules:
Foot placement generation
Trajectory planning

$$TE(t) = \sqrt{(x(t) - x_{pl}(t))^2 + (y(t) - y_{pl}(t))^2}$$

TE: Trajectory Error
STE: Sum of the TE
MTE: Mean of TE

Parameters	***Value***
Time to reach the target	23.2 s
Number of steps	25
STE	57.649
MTE (m)	0.057
ZMP x position error	0.0384
ZMP y position error	0.0370

Walking to reach a visual target with obstacles avoidance

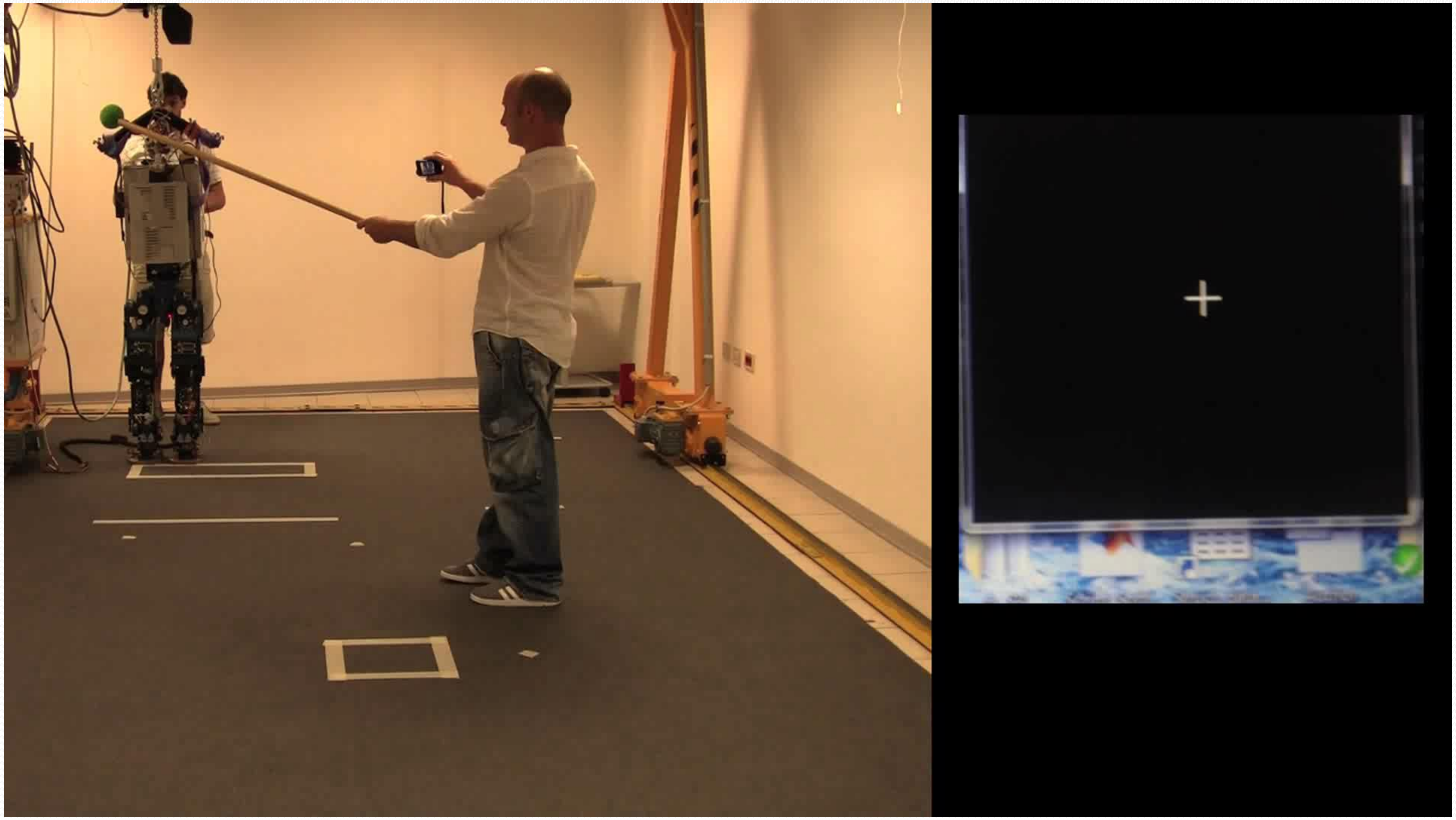


The visual target is at 2.675 m in front and 0.65 m on the right.
The obstacle (0.35 m x 0.350 m x 0.35 m) is 2 m in front and 0.65 m on the right.
Active modules:
Foot placement generation
Head/gaze stabilization
Trajectory planning

TE: Trajectory Error
STE: Sum of the TE
MTE: Mean of TE

Parameters	***Value***
Time to reach the target	26.34 s
Number of steps	24
STE (m)	387.465
MTE (m)	0.387
Minimum distance form the obstacle (m)	0.327

Following a moving target



The visual target is at 1.580 m in front and 0.6 m on the left. When the robot is near the first target position, the target is moved in another position (0, 3.5 m).

Active modules:

Foot placement generation
Head/gaze stabilization
Trajectory planning
Eye movements
On-line trajectory generation

Parameters	***Value***
Time to reach the target	28.8 s
Number of steps	27
ZMP x position error	0.047
ZMP y position error	0.038