Modeling eye movements

CoSMo 2017
Gunnar Blohm

Introduction

- Why move the eyes?

What we think we see

What we see

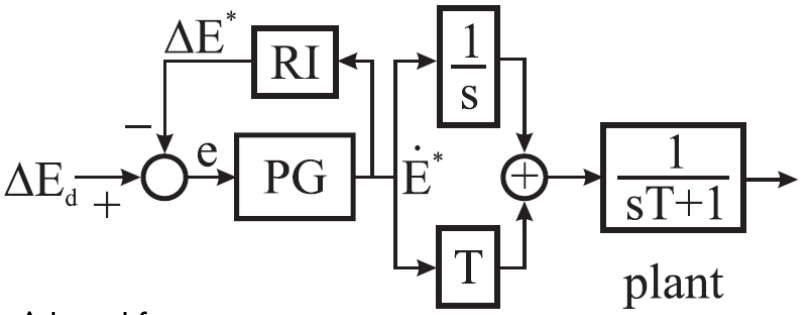
Lena, *Playboy* centerfold, Nov 1972
(standard test image in the field of image processing since 1973)

Introduction

- Why move the eyes?
  - Functional role of eye movements: optimize visual processing!
    - Image stabilization
      - Smooth pursuit of moving objects (low-pass)
      - Vestibulo-ocular reflex (VOR) compensates for head movements (high-pass)
      - Opto-kinetic nystagmus (OKN) stabilizes wide-field motion
    - Image exploration
      - Saccades re-orient gaze
  - Resulting constraints for the controller(s)
    - Minimize retinal error (position)
    - Minimize retinal image slip (velocity)
    - Be as fast and accurate as possible (role of predictions/anticipations…)

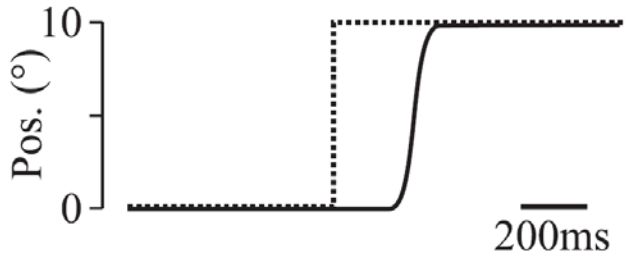
Introduction

- Example: saccade model



Adapted from:
Jürgens et al. 1981
Scudder 1988

Alfred Yarbus, 1967

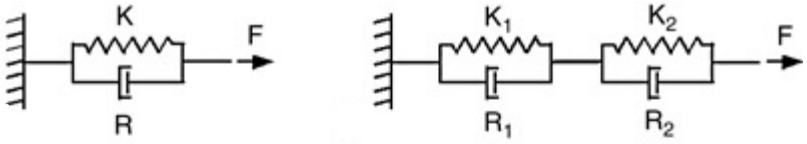


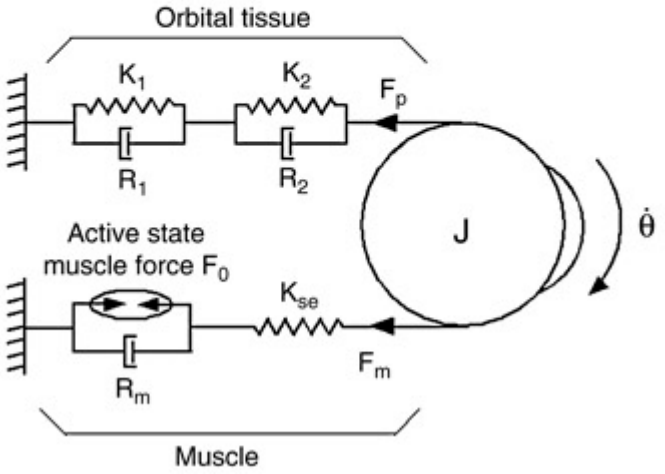
Where to start?

- 2 potential approaches
  - Blind approach
    - Straight use of systems identification tools
    - Model the system based on the measured input-output relationship
    - = Engineering approach
  - Informed approach
    - Model systems components (not the system as a whole)
    - Incorporate detailed knowledge about physiology, biomechanics etc
    - = Neuroscience approach

Eye/head plants

- Eye and neck muscles properties
  - Damped spring-mass system equivalent





Robinson (1964), Scudder (2009)

Equation of motion of eye ball:

$$J \cdot \frac{d^2\theta}{dt^2} + F_p = F_m$$

Muscle force applied:

$$F_m = F_0 - R_m \cdot \frac{d\theta}{dt} - \frac{R_m}{K_{se}} \cdot \frac{dF_m}{dt}$$

J: moment of inertia
F_p: passive force (muscle tissue)
F_m: active muscle force

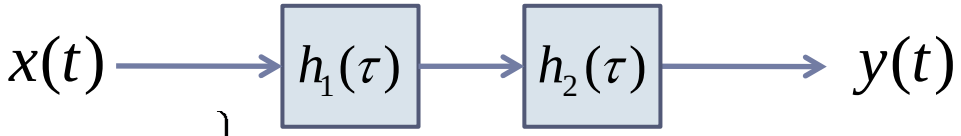
Passive muscle/tissue force:

$$F_p = \frac{R_1 R_2 \cdot \frac{d^2\theta}{dt^2} + (R_1 K_2 + R_2 K_1) \cdot \frac{d\theta}{dt} + K_1 K_2 \cdot \theta - (R_1 + R_2) \cdot \frac{dF_p}{dt}}{(K_1 + K_2)}$$

Modelling the eye

- Low inertia
- Viscous muscles (like elastic bands)

  → second-order linear system approximation



$$u(t) = \int_0^\infty x(t-\sigma)\cdot h_1(\sigma)\,d\sigma$$

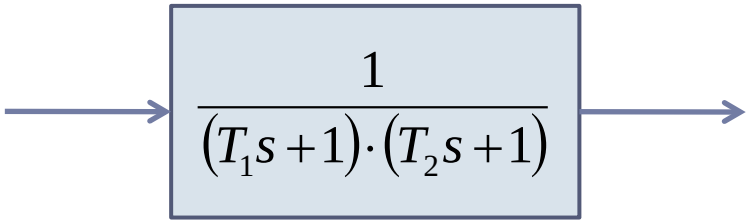
$$y(t) = \int_0^\infty u(t-\tau)\cdot h_2(\tau)\,d\tau$$

$$\Rightarrow y(t) = \int_0^\infty \int_\tau^\infty x(t-\sigma-\tau)\cdot h_1(\sigma-\tau)\cdot h_2(\tau)\,d\sigma\,d\tau$$

(leads to terrible expressions!)

$$y(t) = h_1(t) * h_2(t) * x(t)$$

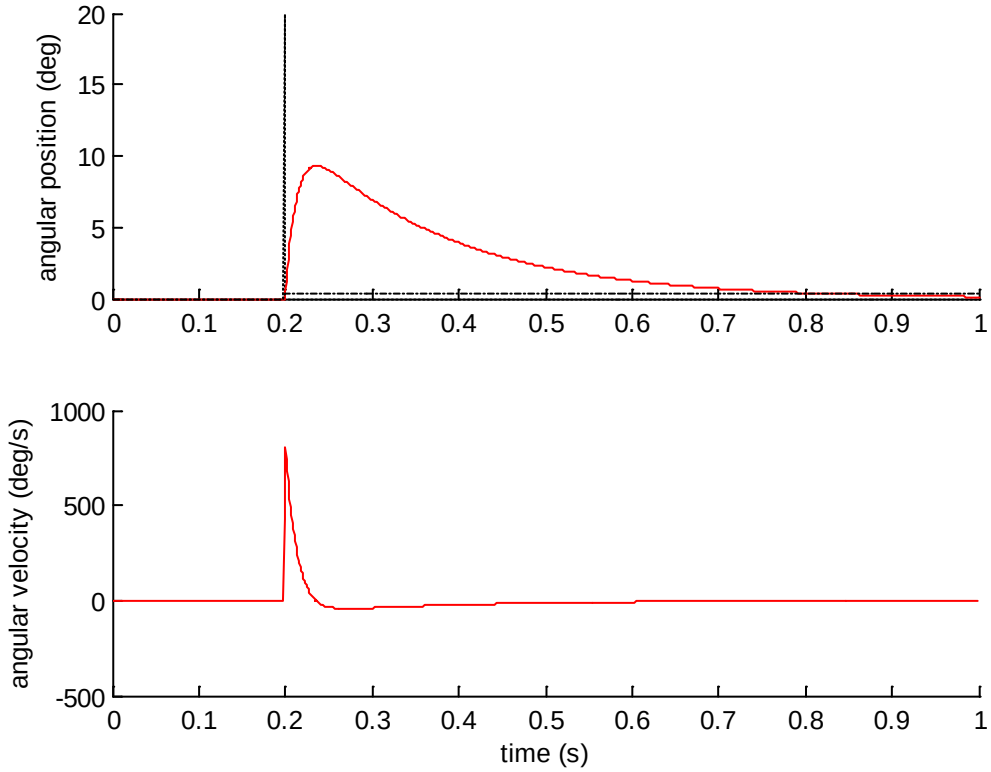
- T_1 = 175ms, T_2 = 13ms
- T_1: viscosity of the plant
- T_2: inertial properties of eye



Modelling the eye

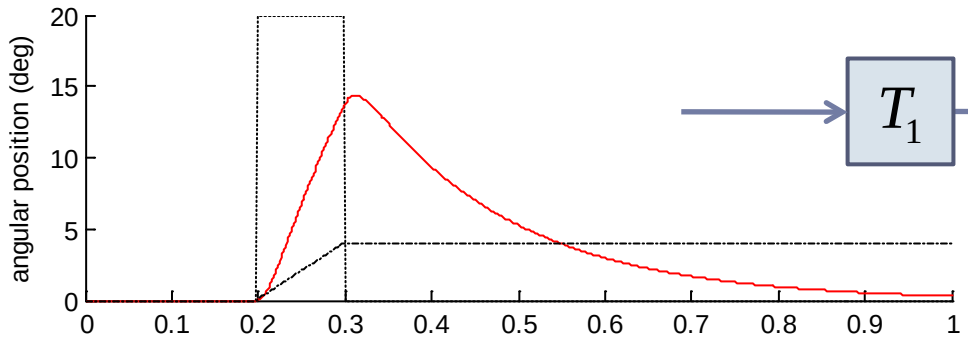
- Testing the model's impulse response

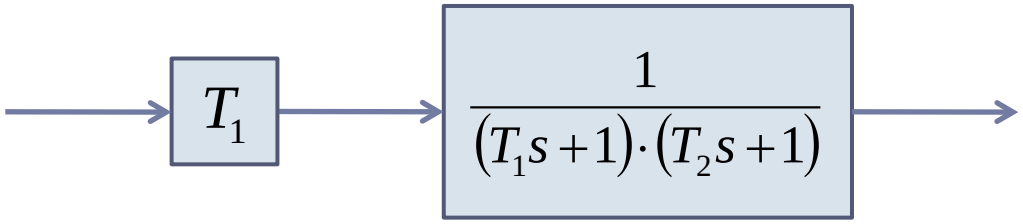
$$\frac{1}{(T_1 s + 1)\cdot(T_2 s + 1)}$$

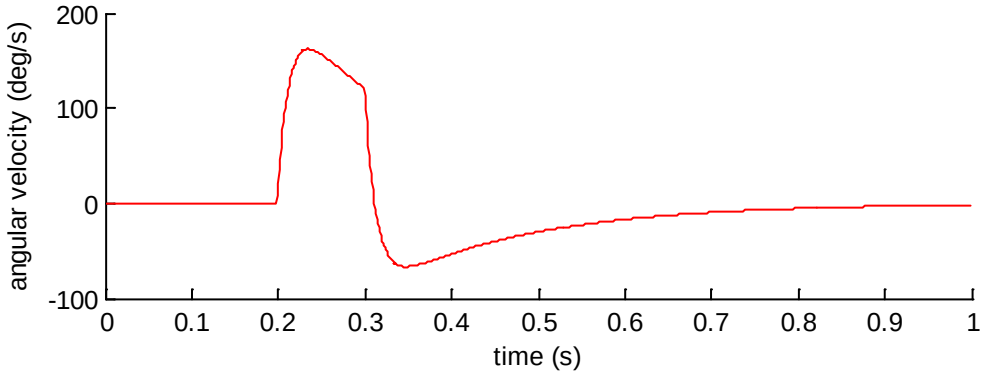


Moving the eyes

- We need a motor command (phasic) to move the eyes
  - Eye moves, but gaze cannot be held



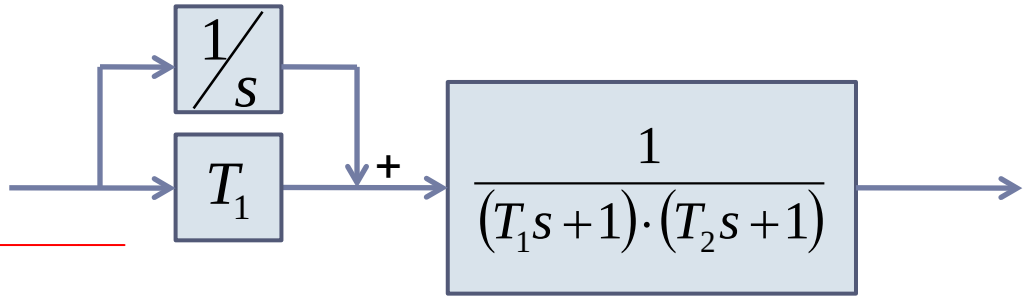


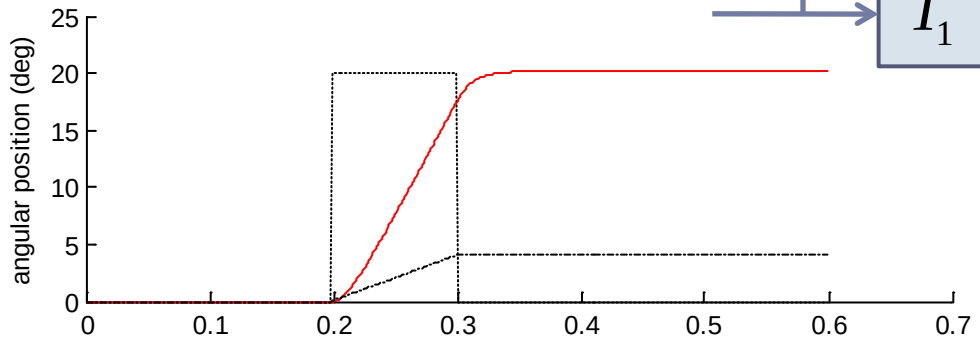


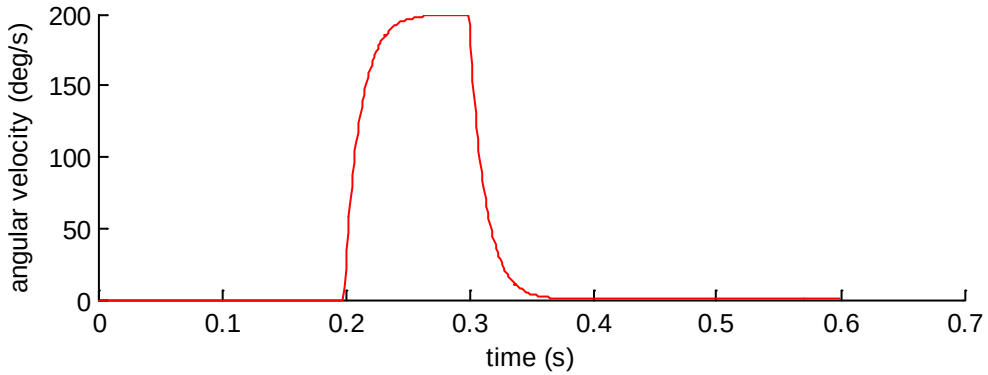
  - A tonic activation needed to maintain gaze

Gaze holding: the neural integrator

- How do we get the tonic portion?
  - Neural integrator

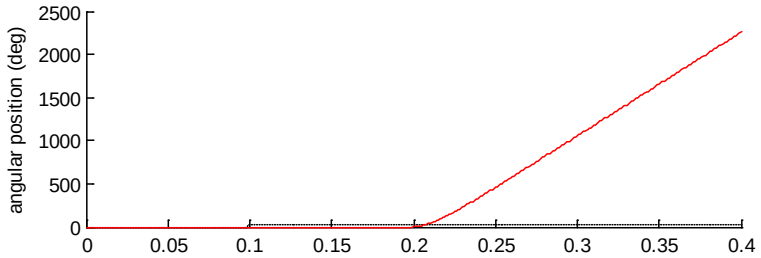


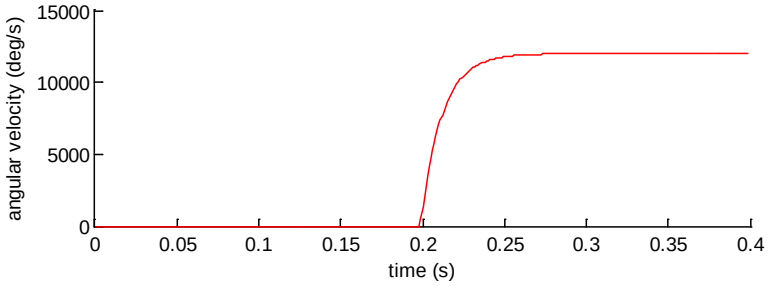


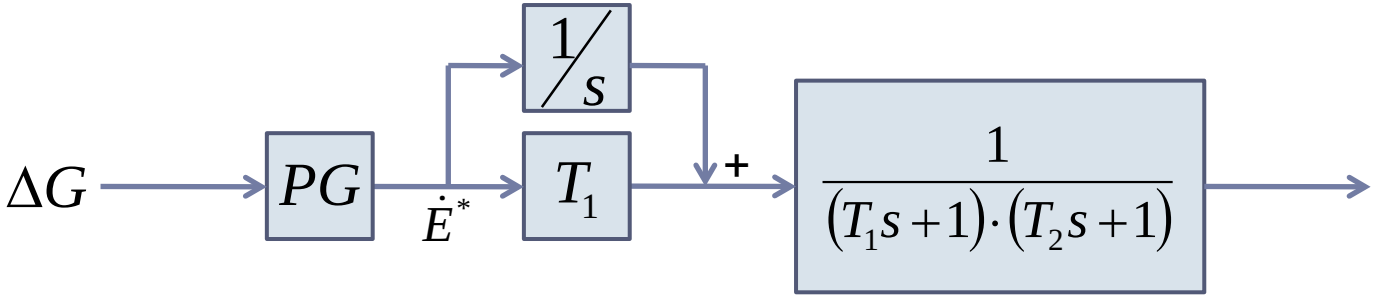


Motor command generation

- Problem: movement is not monitored...

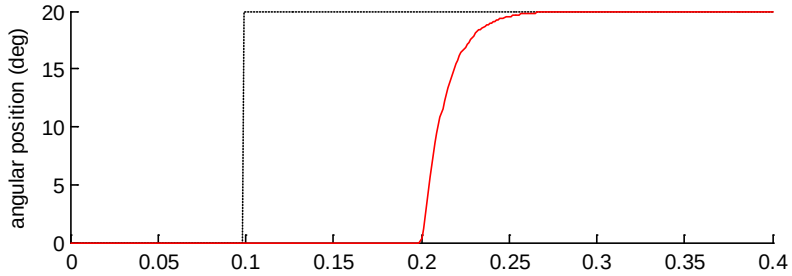


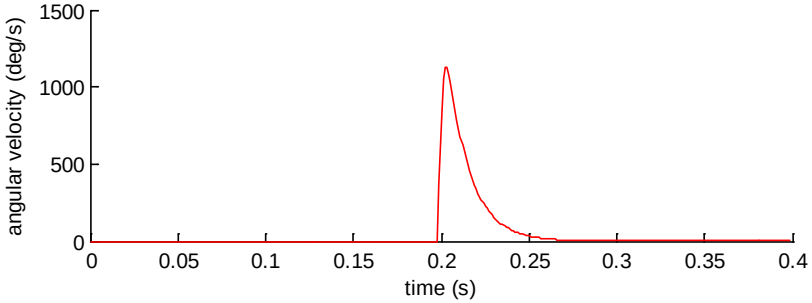


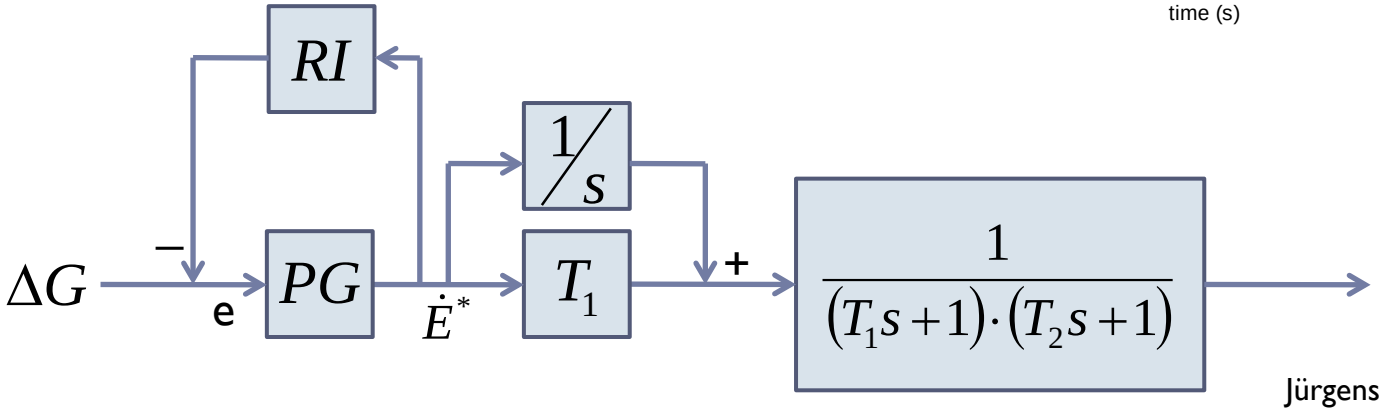


Motor command generation

- Solution: resettable integrator
  - Only remaining error e drives the eyes





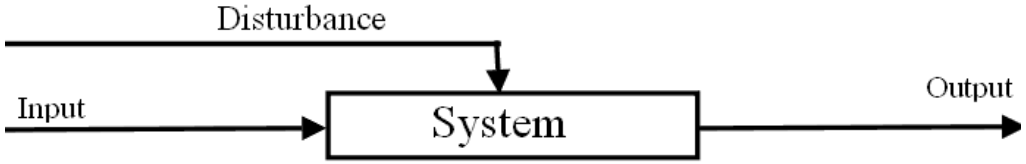


Jürgens et al. 1981
Scudder 1988

Control modes

Control modes

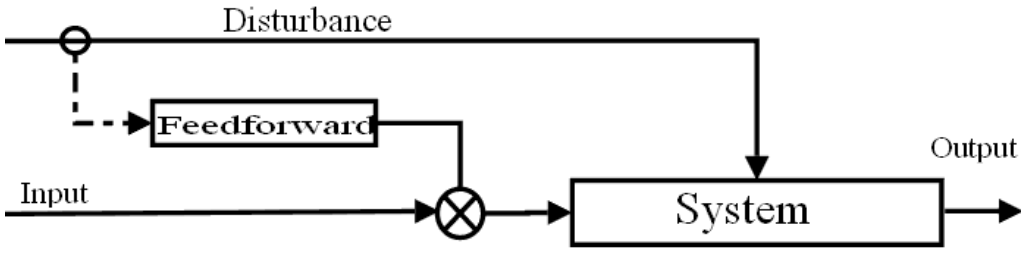
- Open-loop control models
  - control only possible when system is well-defined, i.e. there is a precise mathematical relationship between input and output
  - No knowledge of perturbations
  - No learning possible
  - Unstable!



Wikipedia

Control modes

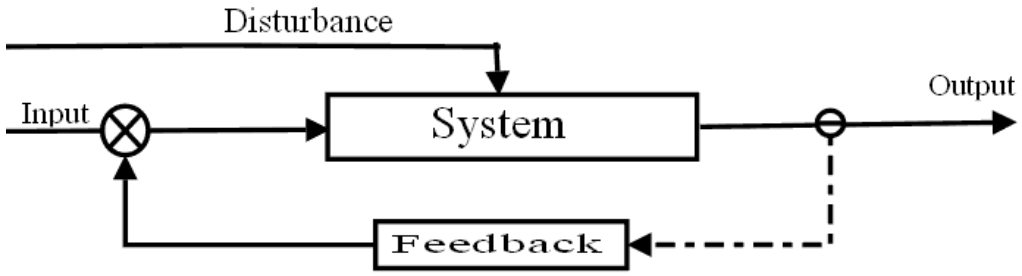
- Feed-forward control models (model predictive control)
  - Uses an inverse model of the plant physics
  - Control output only depends on internal (inverse) model of the plant physics, independently of actual plant reaction
  - Feed-forward control without feedback = ballistic
    - Anticipatory regulation required for optimal behaviour
    - Based on learning
    - Neural network analogy / implementation: Perceptron



Wikipedia

Control modes

- Feedback control models (closed-loop)
  - Uses output history to adjust future commands
  - Negative feedback
    - Helps maintaining stability in the system despite of external changes
    - Reduction of the input that caused the output
  - Positive feedback
    - Amplifies the event that caused the output
    - Auto-excitation: self-enforcing loop

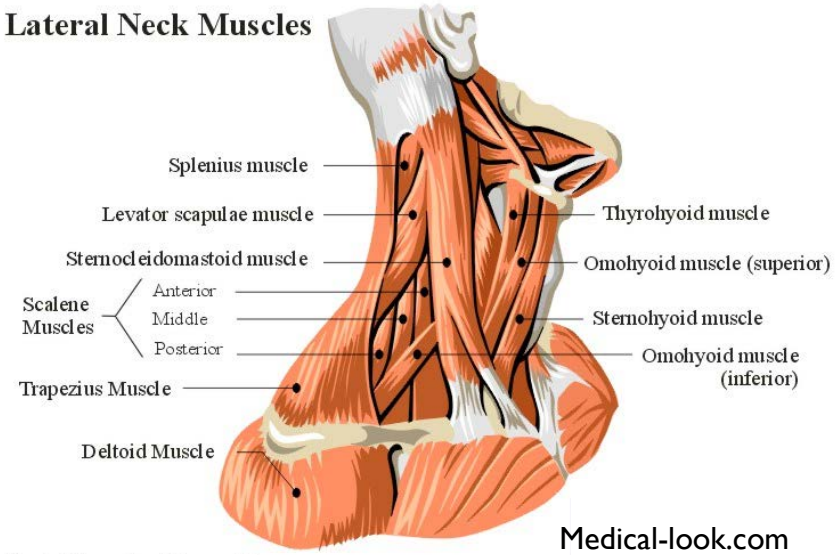


Wikipedia

Eye movement models

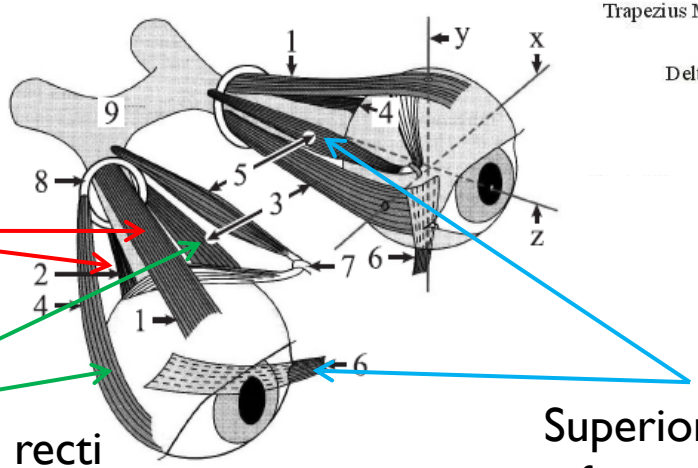
Eye movements

- Eye and neck muscles



Medical-look.com

Superior and inferior recti



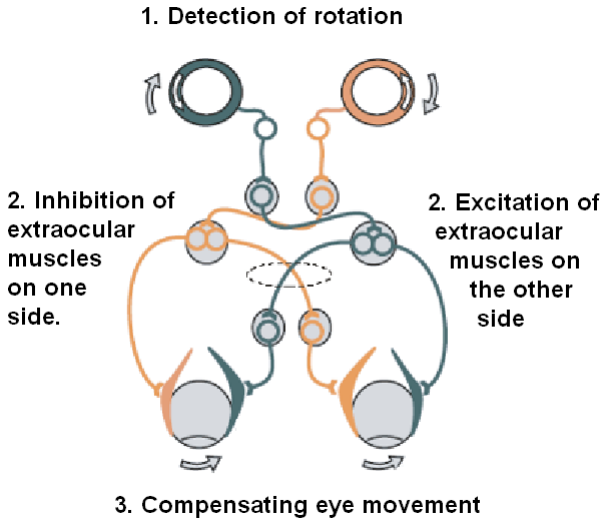
Medial and lateral recti

Superior and inferior obliques

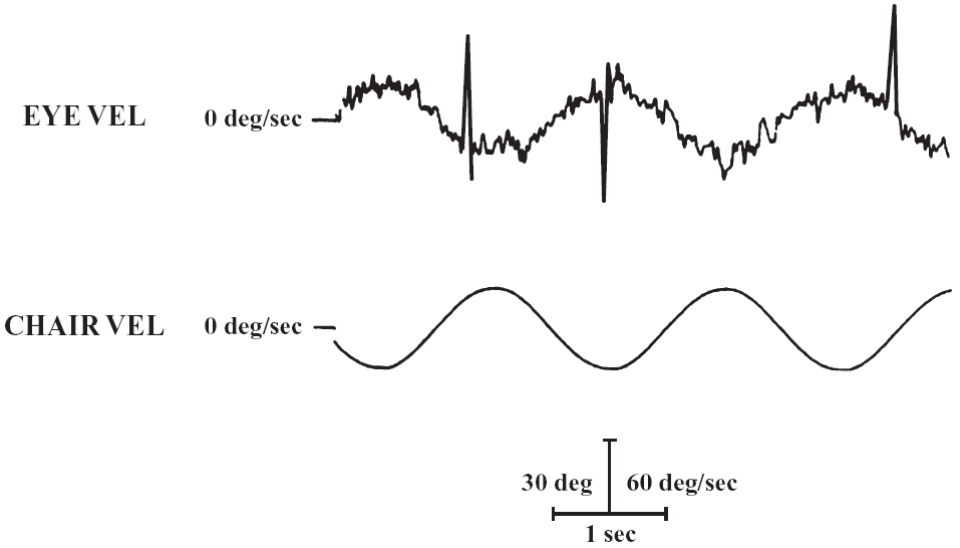
Blohm 2004

Eye movements

- Vestibulo-ocular reflex



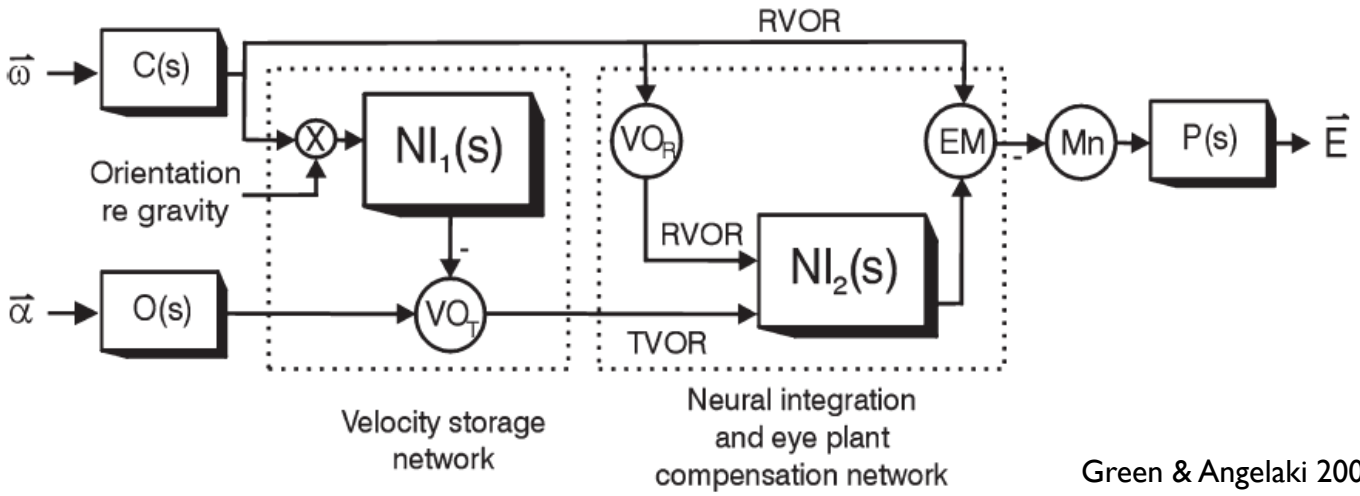
Wikipedia



Leigh & Zee 2006

Eye movements

- Vestibulo-ocular reflex

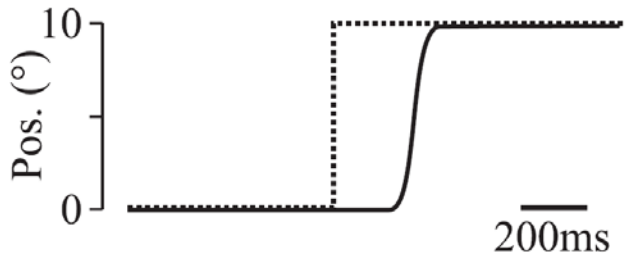


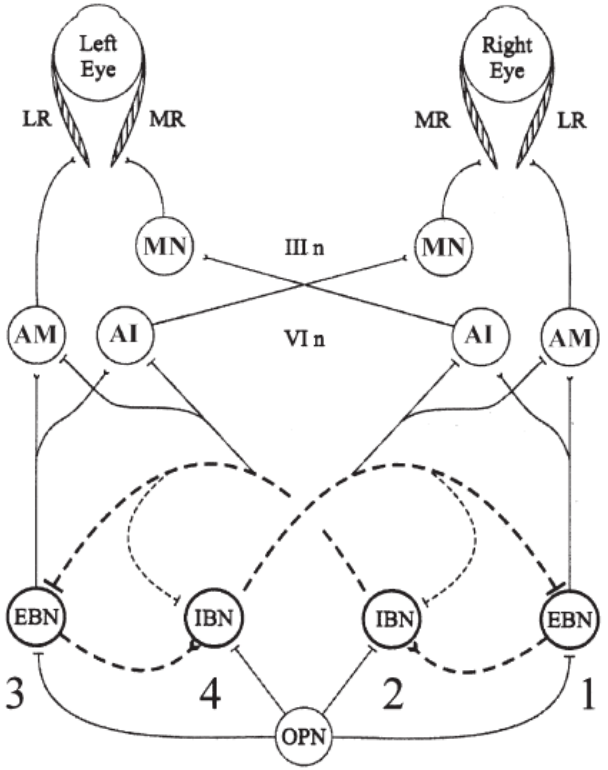
Green & Angelaki 2004

- Angular velocity from semi-circular canals: ω
- Linear acceleration senses by otolith organs: α
- VO: vestibular-only neurons
- EM: eye movement sensitive neurons

Eye movements

- Saccades:
  - Brainstem pathways



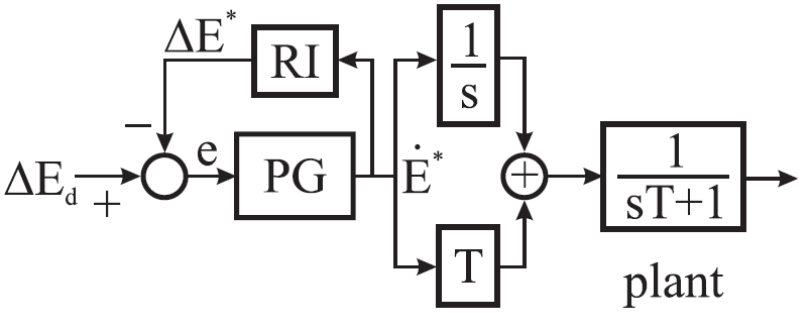


Ramat et al. 2005

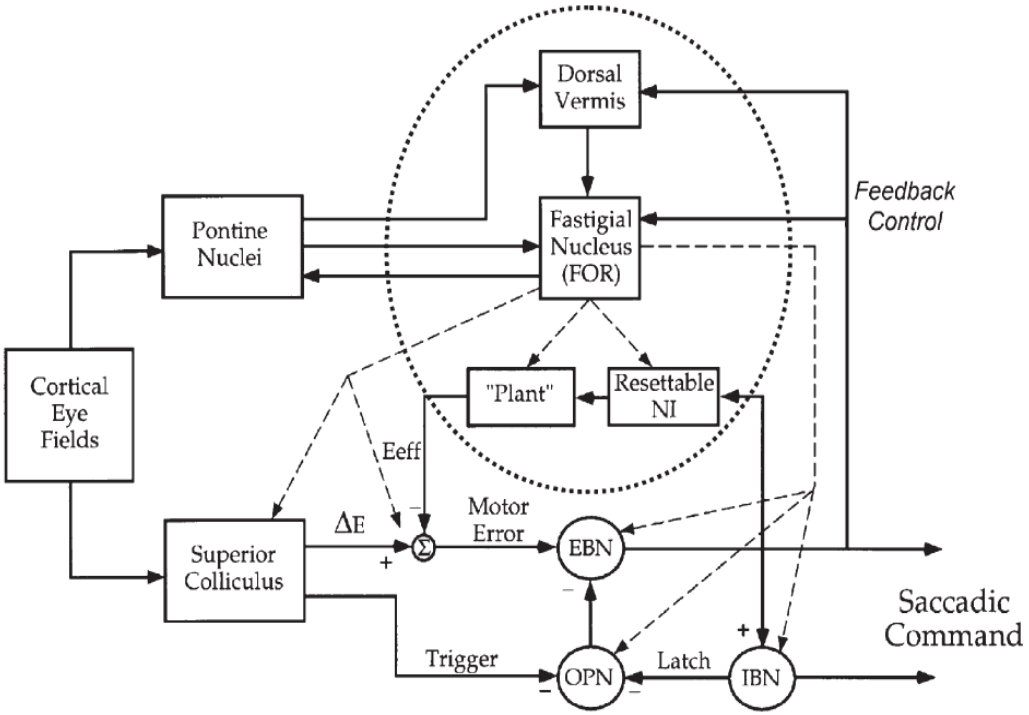
  - MN: motoneurons
  - AM: abducens motoneurons
  - AI: abducens interneurons
  - EBN: excitatory burst neurons
  - IBN: inhibitory burst neurons
  - OPN: omnipause neurons

Eye movements

- Saccades:
  - Executive control
    - Ballistic: Robinson model
    - Feedback control



Adapted from:
Jürgens et al. 1981
Scudder 1988

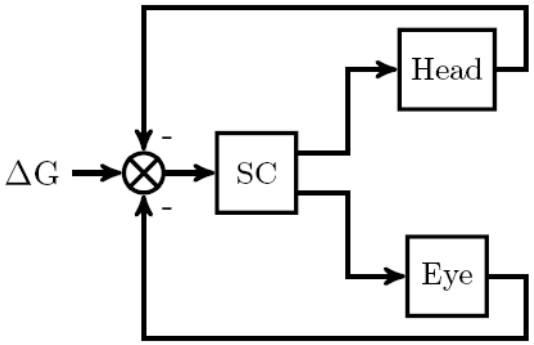


Leigh & Zee 2006

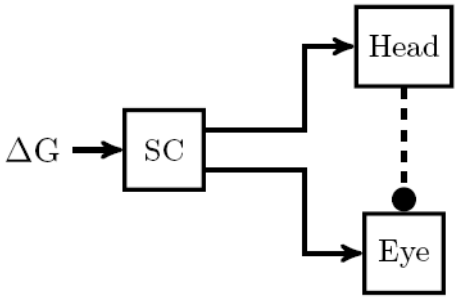
Eye movements

- Saccades:
  - Eye-head coordination: first models

Galiana, Lefèvre, Guitton (1992)



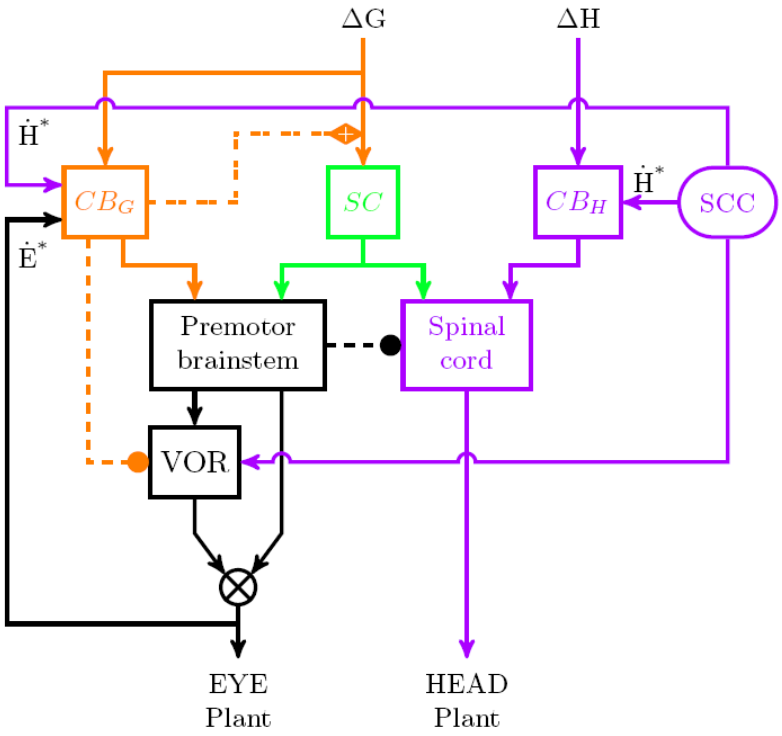
Freedman 2001, 2008



  - Cannot model separate gaze and head goals

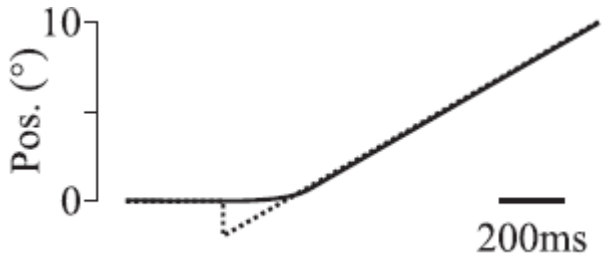
Eye movements

- Saccades:
  - Eye-head coordination: new nested control model
    - Daye, Optican, Blohm, Lefèvre (2014)

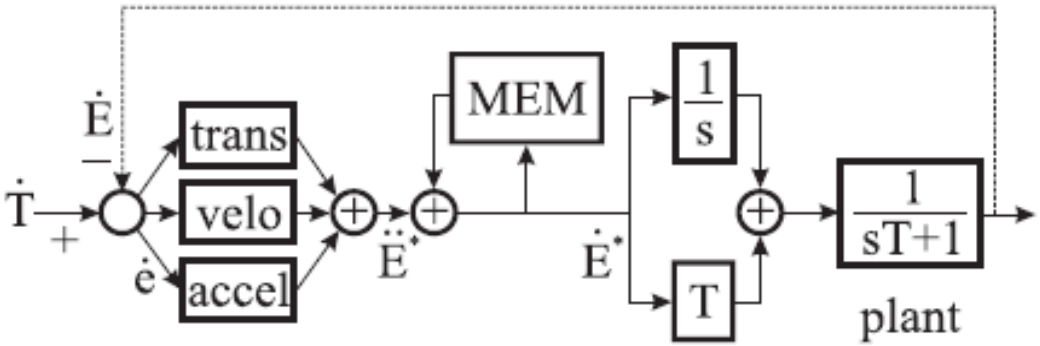


Eye movements

- Smooth pursuit
  - Visually-guided pursuit



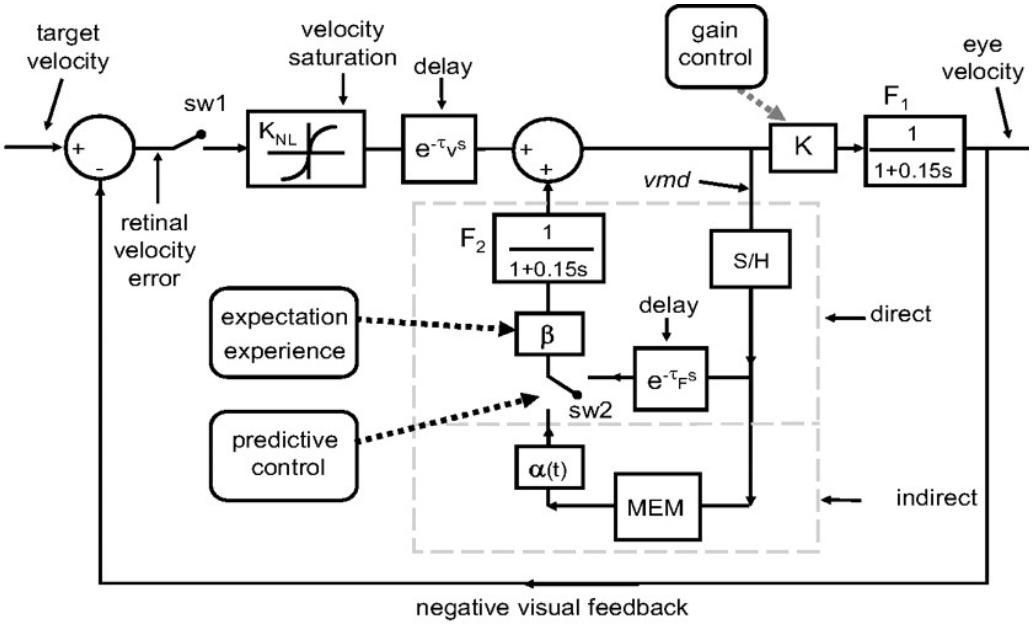
Blohm 2004

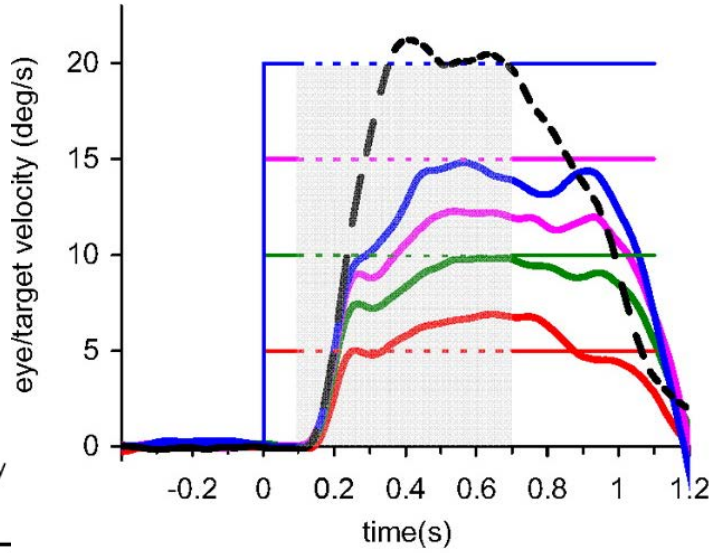


Adapted from Churchland et al. 2003

Eye movements

- Smooth pursuit
  - Anticipatory pursuit

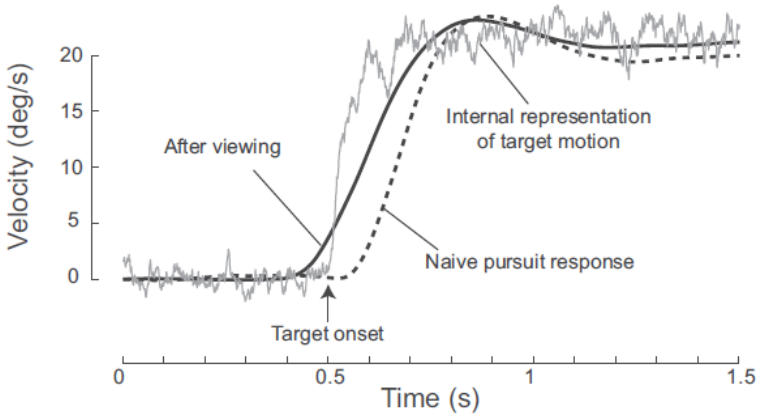


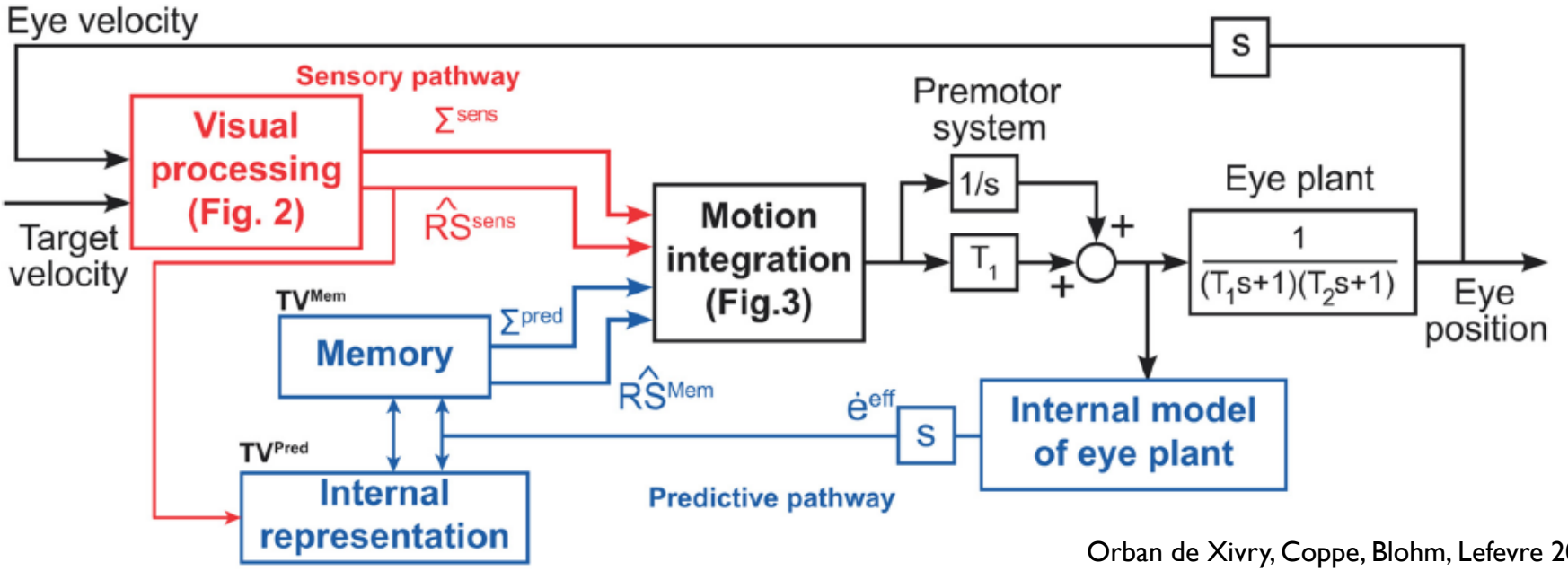


Barnes & Collins 2008

Eye movements

- Smooth pursuit
  - Stochastic pursuit model

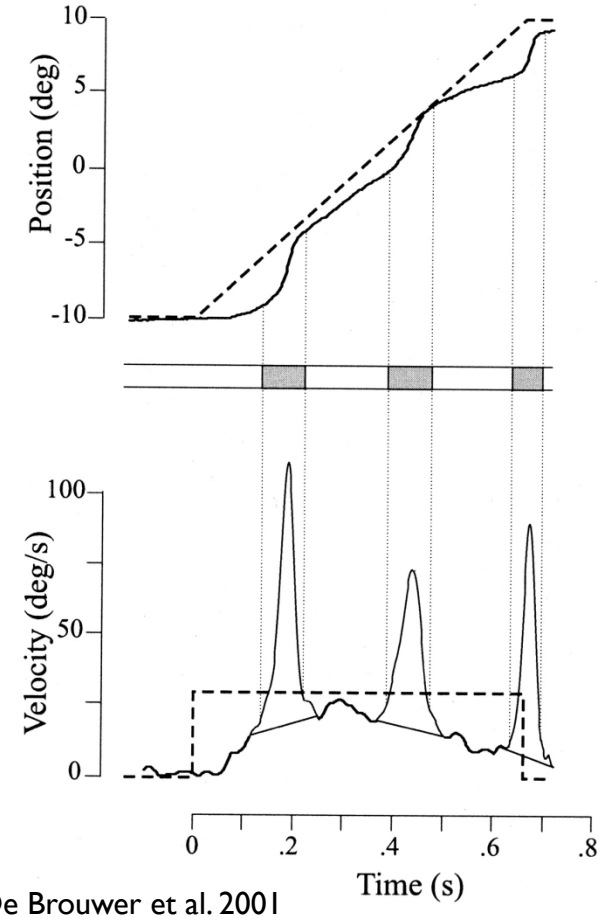




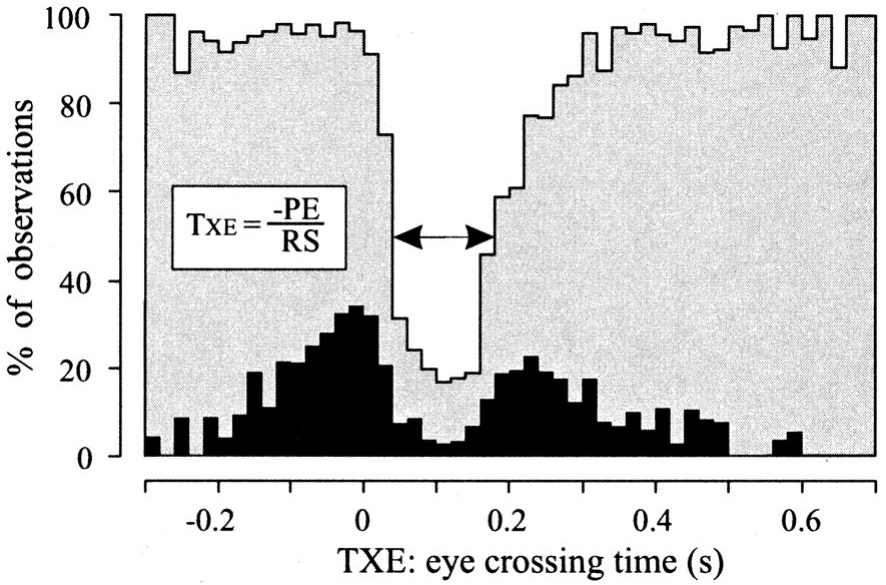
Orban de Xivry, Coppe, Blohm, Lefevre 2013

Eye movements

- Saccade-pursuit interaction



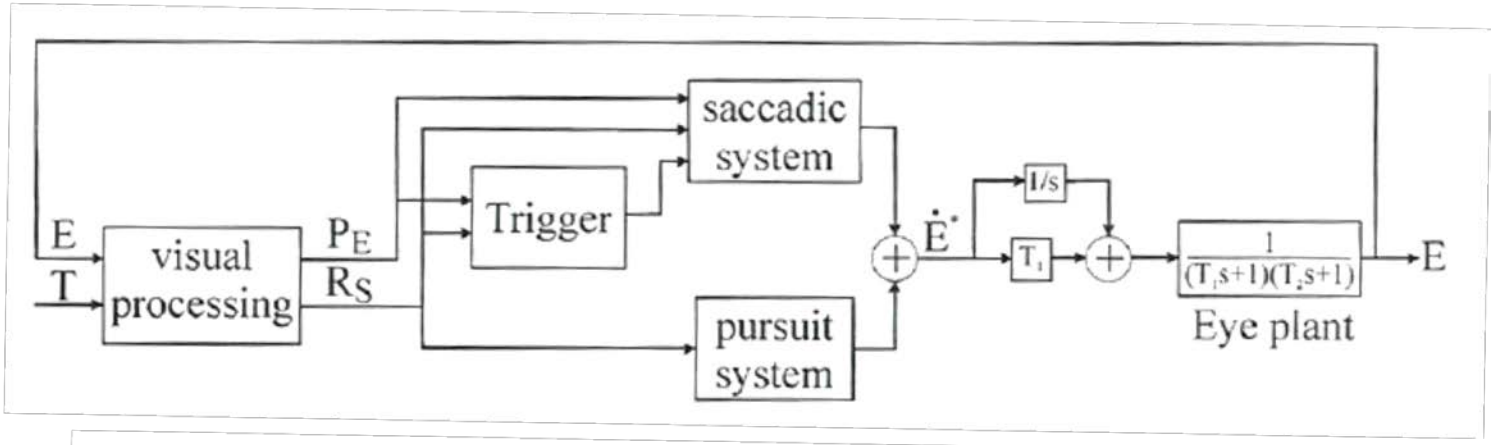
De Brouwer et al. 2001

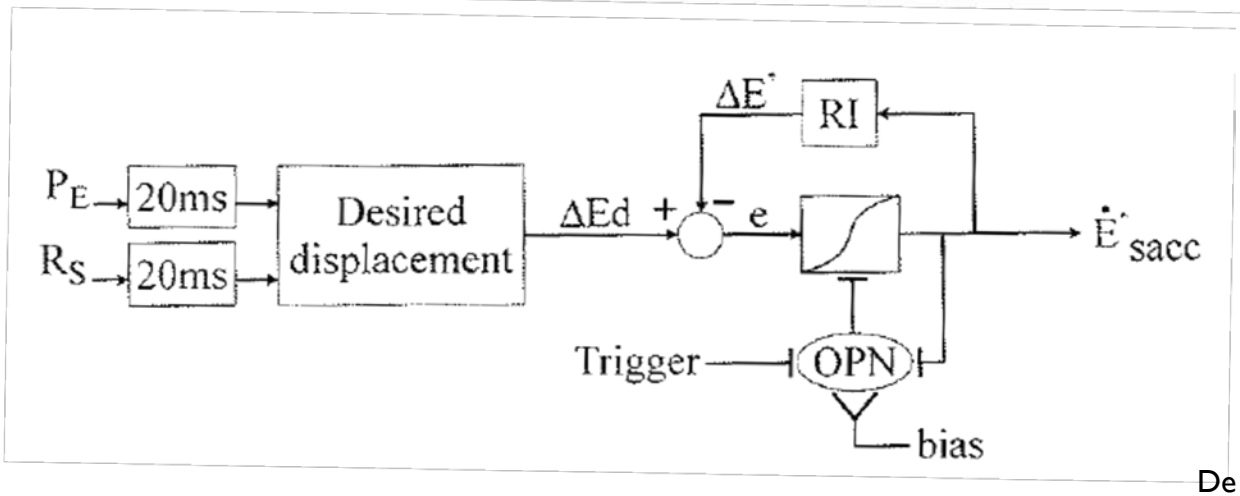


De Brower et al. 2002

Eye movements

- Saccade-pursuit interaction





De Brower et al. 2002


That's all Folks!