A cable-driven robotic eye for the study of oculomotor behaviors

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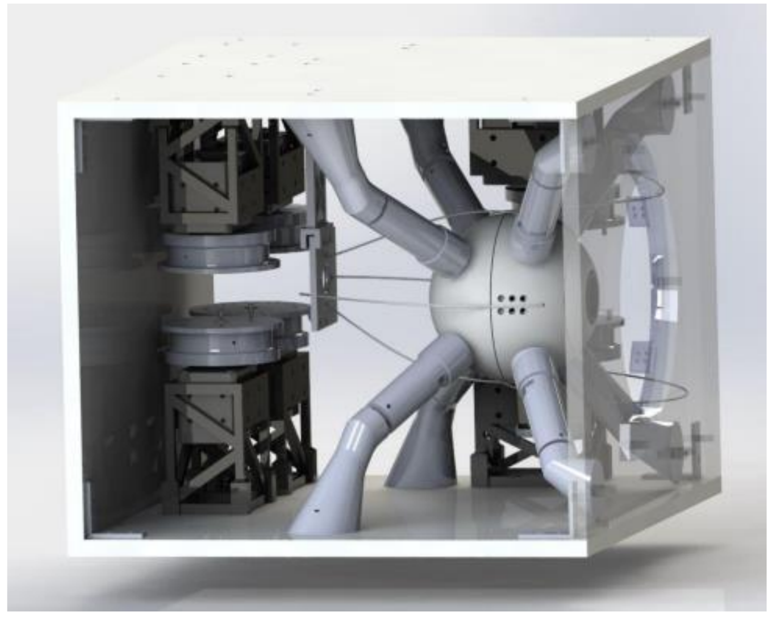
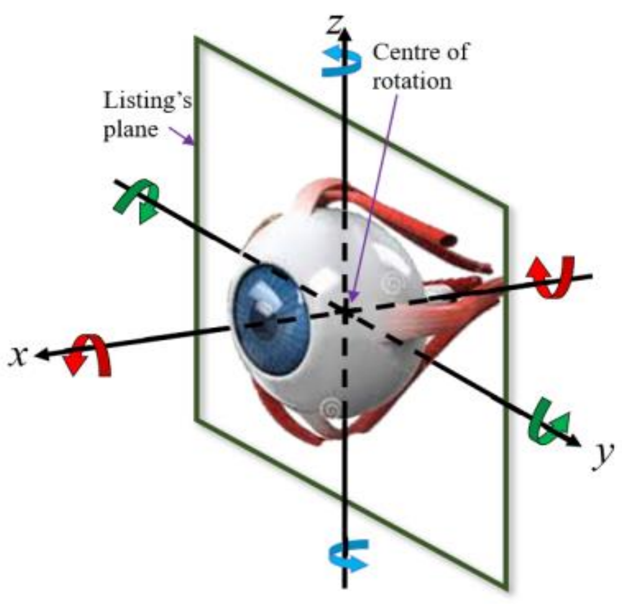


Background



Eye coordinate frame

- Eye is actuated by **6 extraocular muscles** in agonist-antagonist pairing to perform movements like saccades (rapid eye motion between fixation points)
- **Overdamped system** due to the viscous fatty tissues surrounding the eye and drag from the optical nerve
- Has 3 DoF, but restricts its orientation by rotation axes that lie in the YZ plane (**Listing's law**)

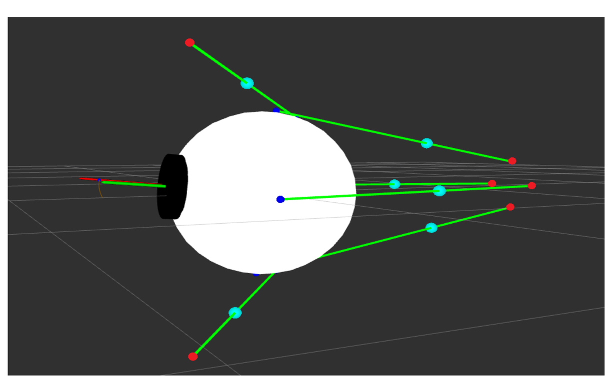
Objectives

- Develop a **biologically inspired** 3D model of the eye, actuated by 6 independent cables
- Study neural control of the oculomotor system through **open-loop optimal control** techniques
- **Replicate human behavior** like kinematic and dynamic characteristics with both linear and nonlinear models

Nonlinear Simulator

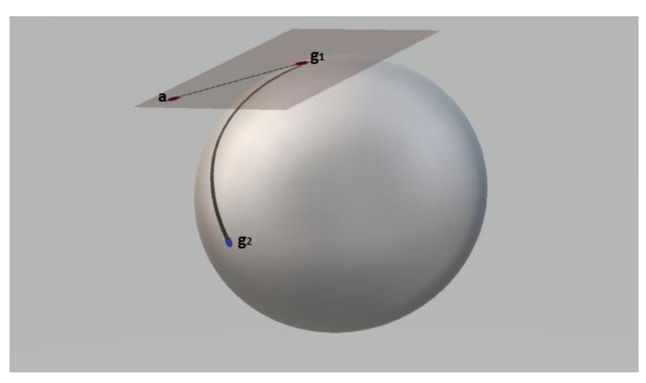
- Sphere with 6 cables ruled by rigid-body dynamics equation

$$\alpha = \mathbf{I}^{-1}(\boldsymbol{\tau}_{eye} - \boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega})$$


Graphical Simulator

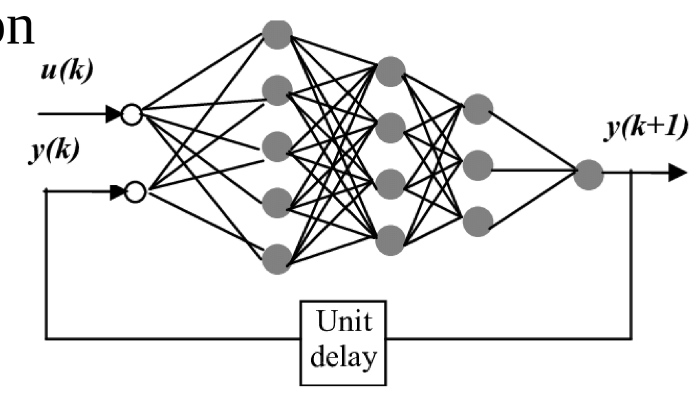
Linear Approximation

- Analytical approximation of dynamical equations using local derivative techniques
- Controller based on a linearized local state


Linear approximation schematic

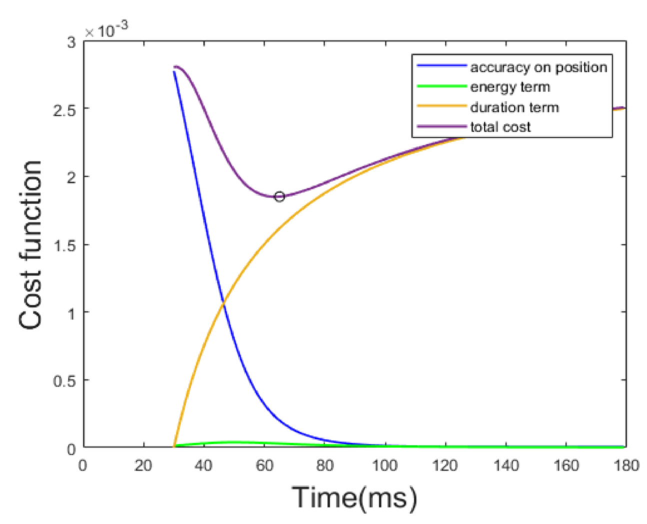
Nonlinear Approximation

- Model built using NN trained with data from the nonlinear simulator
- Controller based on nonlinear numerical optimization



NARX model diagram

Optimization



Cost function minimization convex solution

$$\min_{\boldsymbol{u},K} \; J(\boldsymbol{u},K) = \sum_{\alpha} \lambda_\alpha J_\alpha(\boldsymbol{u},K)$$

subject to

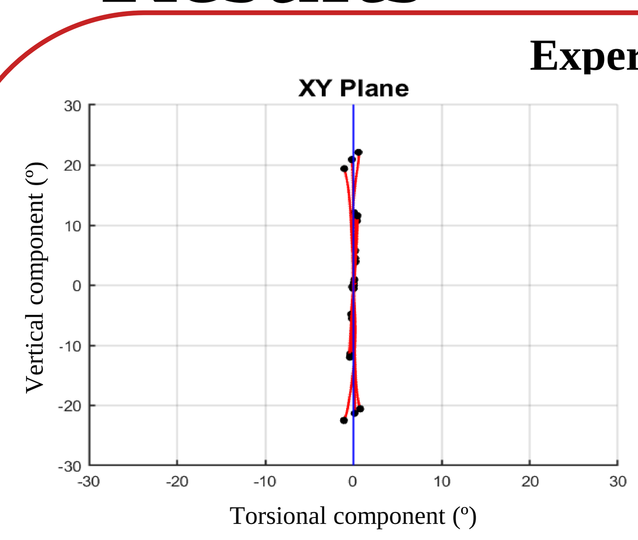
$$\boldsymbol{x}_{i+1} = f(\boldsymbol{x}_i, \boldsymbol{u}_i)$$

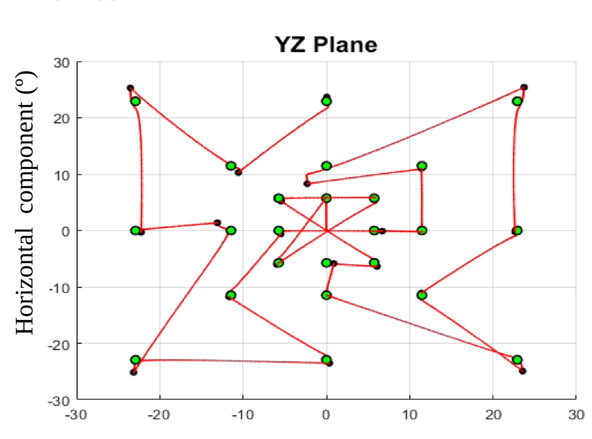
$\boldsymbol{u}$	Motor commands
K	Optimal saccade time
$\boldsymbol{\lambda}$	Individual cost weights
J	Cost terms
x	State

Both linear and nonlinear models minimize **Duration** and **Energy,** while maximizing **Accuracy**

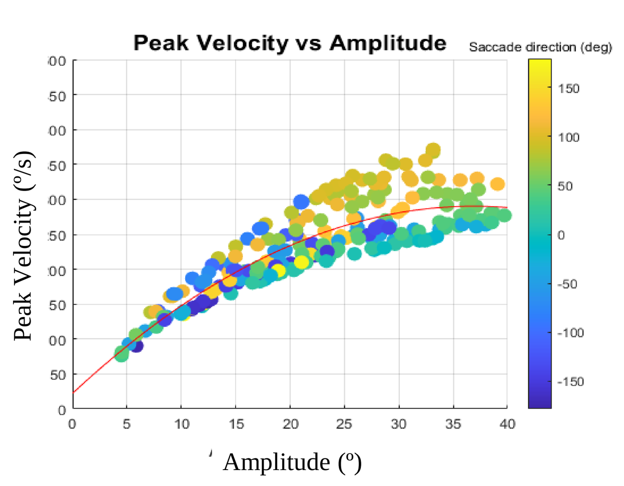
Results

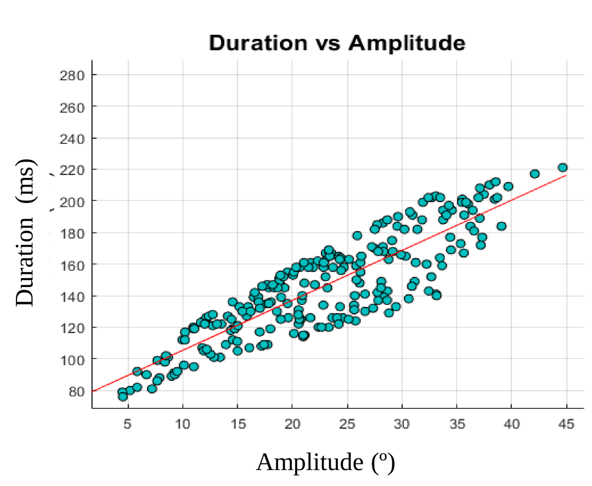
Experimental





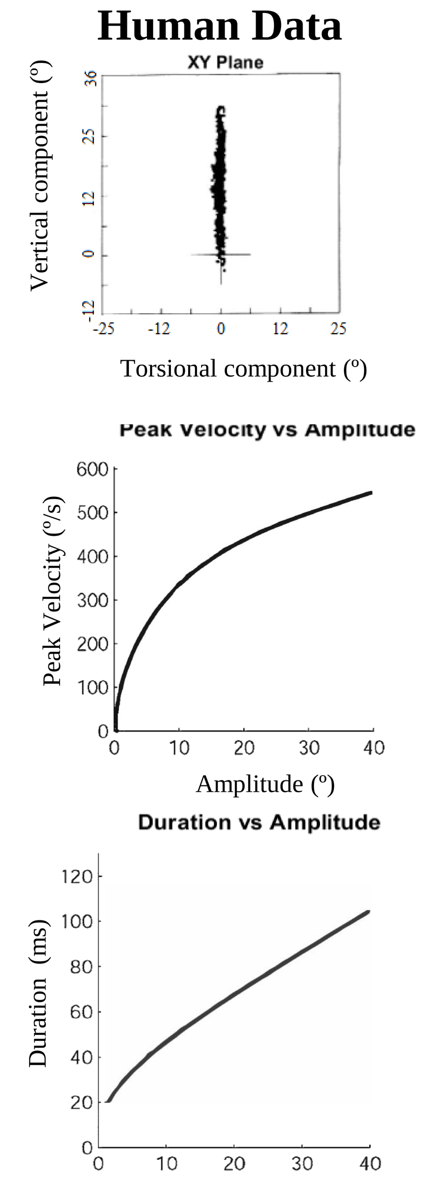
Listing's Plane from our models





Kinematic Properties

Human Data



Saccade	Listing's Plane error (degrees)	Computational time for 24 saccades (minutes)
Linear	0.63º	12
Nonlinear	0.18º	45

Conclusion

- **Co-contraction of the cables has a substantial effect on reaching equilibrium at goal orientation.**
- **Listing's Plane error increases with amplitude for both models, but nonlinear shows lower deviation from the plane**
- **Linear model is computationally faster than nonlinear**
- **Contributions: Showed optimizing specific costs produces biological behavior in a biomimetic eye**
- **Future work: Improving the modelling of friction and cables, implementing signal dependent noise with feedback control**

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Computer and Robot Vision Laboratory