ORF-MOSAIC for Adaptive Control of a Biomimetic Arm

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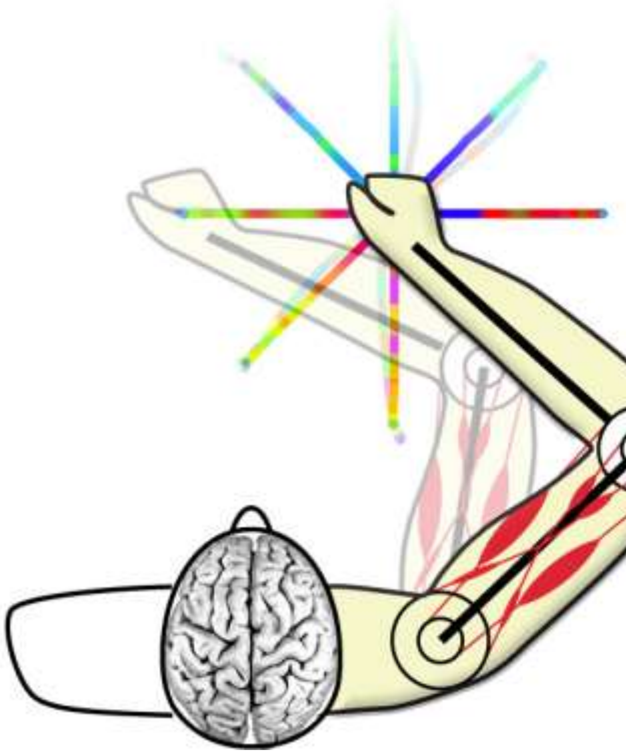
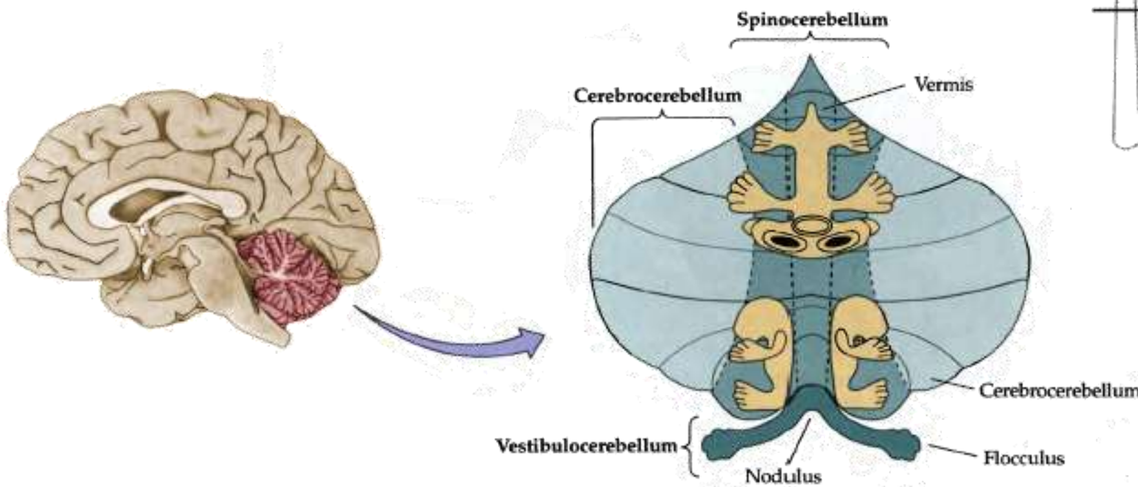
How it began!

Outline

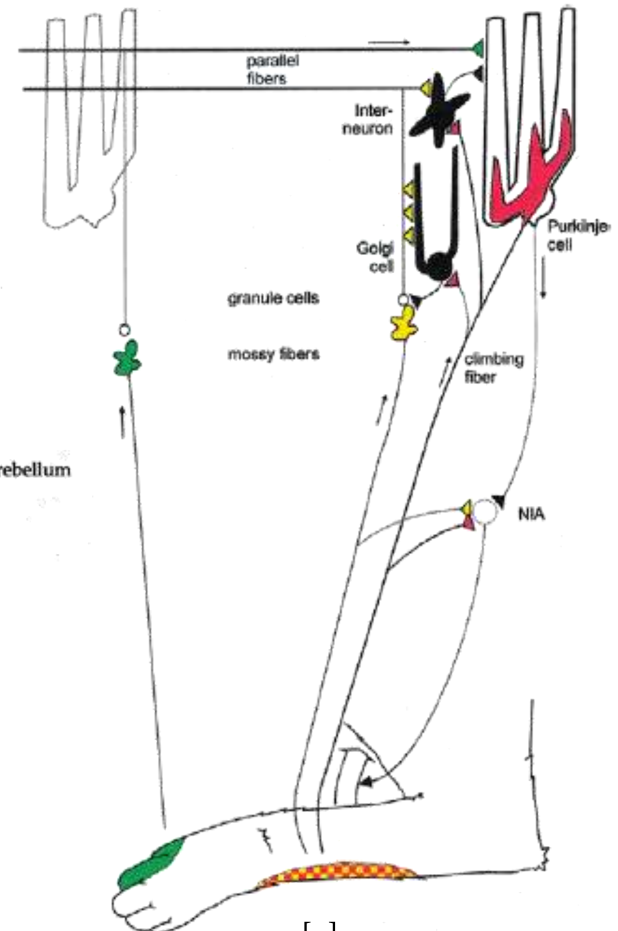
- Introduction
  - Cerebellum
  - Different cerebellar models
  - MOSAIC
- Problem formulation
- Modeling
- Methods
- Experimental Design
- Simulations
- Results
- Discussion
- Conclusions



Cerebellum and its Role



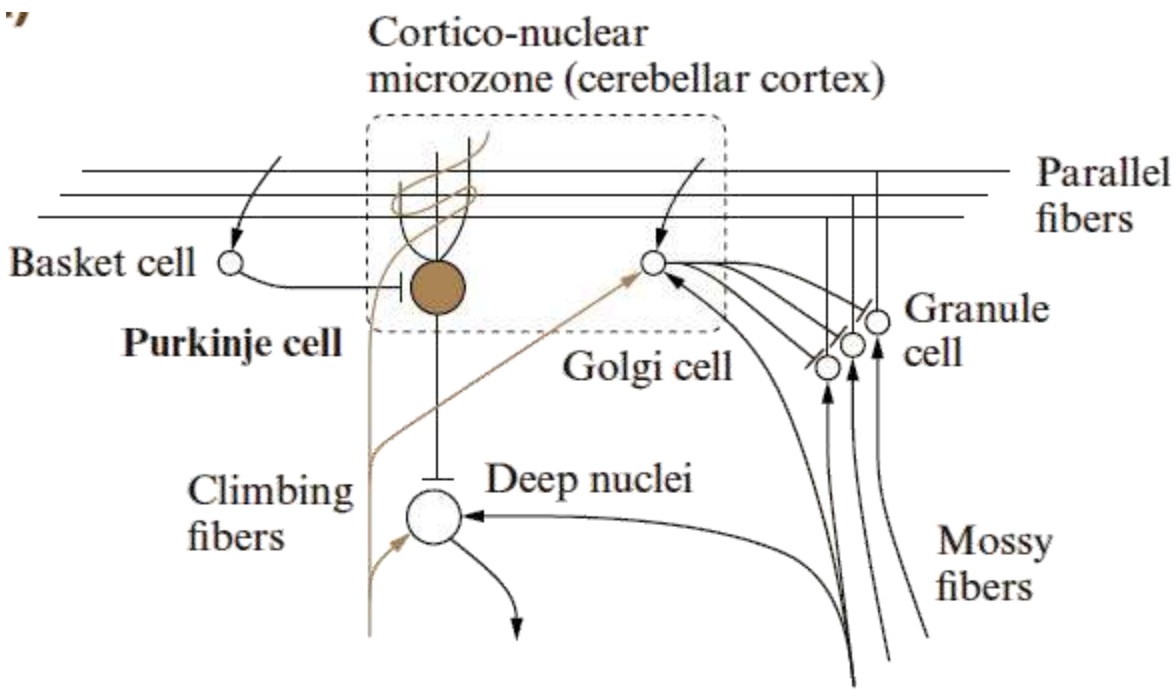
[1]



[2]

[1] Modified from Neuroscie, 3rd Ed.
[2] Courtesy of H.Jörntell

Microznoe circuitry



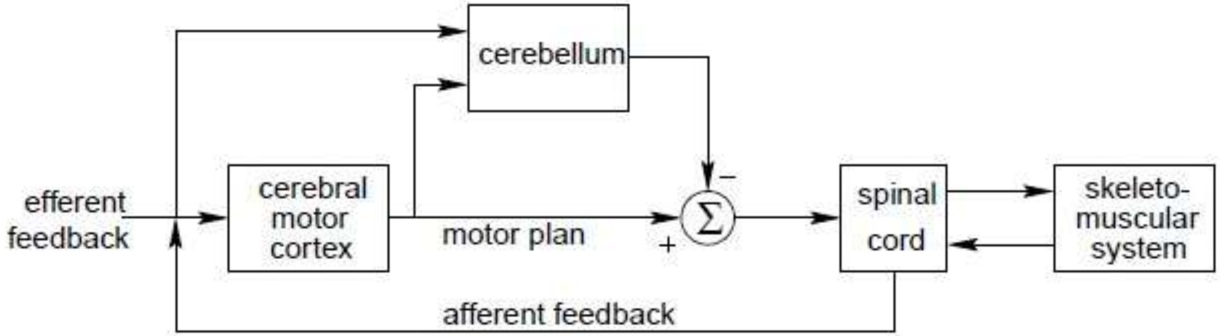
[1] Figure form Handbook of Robotics, Springer 2008,

Principles in Cerebellum

- Feedforward processing
- Divergence and convergence
- Modularity
- Plasticity

Computational Models

- Cerebellar Model Articulation Controller (CMAC)
- Adjustable Pattern Generator (APG)
- Schweighofer-Arbib
- Cerebellar feedback-error-learning model (CBFELM)
- Multiple paired forward-inverse model (MPFIM)

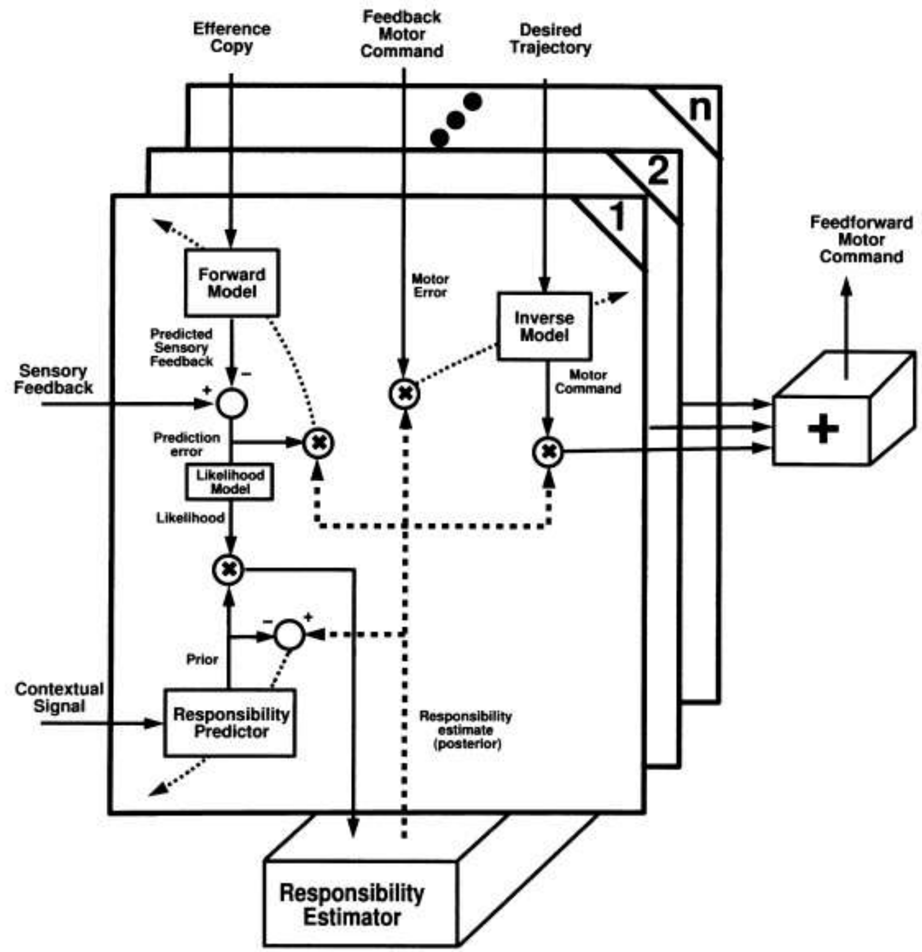


[1] Figure adapted form Handbook of Robotics, Springer 2008

MOSAIC Structure

- Internal Model
  - Forward Models
  - Inverse Models
- Modularity
- Adaptation
- Reduction of motor error
- Efference copy

- Spin-offs
  - HMM-MOSAIC
  - HMOSAIC
  - e-MOSAIC
  - MMRL
  - AMA-MOSAICI



[1] Figure from D.M. Wolpert and M. Kawato, Neural Net.,11:1325, 1998

MOSAIC based Models

- Original MOSAIC
  - Tested for switching between 3 objects, and generalizing to a new one
  - No of modules are manually tuned
  - Requires careful tuning of parameters
  - The quality of forward models are critical
- HMM MOSAIC
  - Same experiments as above
  - Probabilistic model using HMM
  - heavy computation
  - Fixed to linear forward models
  - Originally in batch mode
  - Improved parameter tuning and resp. estimation by EM

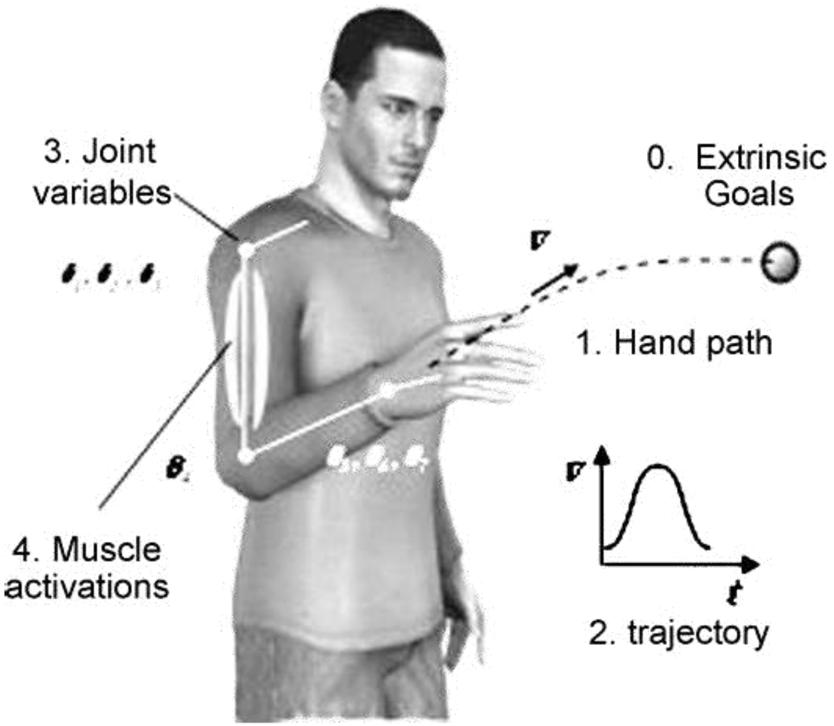
MOSAIC based Model

- HMOSAIC
  - Same experiments
  - Two layers of MOSAIC
  - Higher layer provides estimate of prior probabilities
- eMOSAIC
  - Humanoid robot control
  - LQG for controllers
  - Forward models replaced by Kalman filters
  - No adaptation
- AMA-MOSAICI
  - Sit-to-stand control
  - Clustering algorithm for determining no of modules
  - Clustering and training Off-line
- MMRL
  - Controllers are replaced by RL agents
  - Discrete and continuous case
  - Self-organization of modules
  - Haunting task in a grid world and controlling an inverted pendulum

MOSAIC based Model

- Toy problems
- More serious problems
  - Resorting to classic controllers or RL
  - Simplification
    - No dealy
    - No adaptation

Objectives



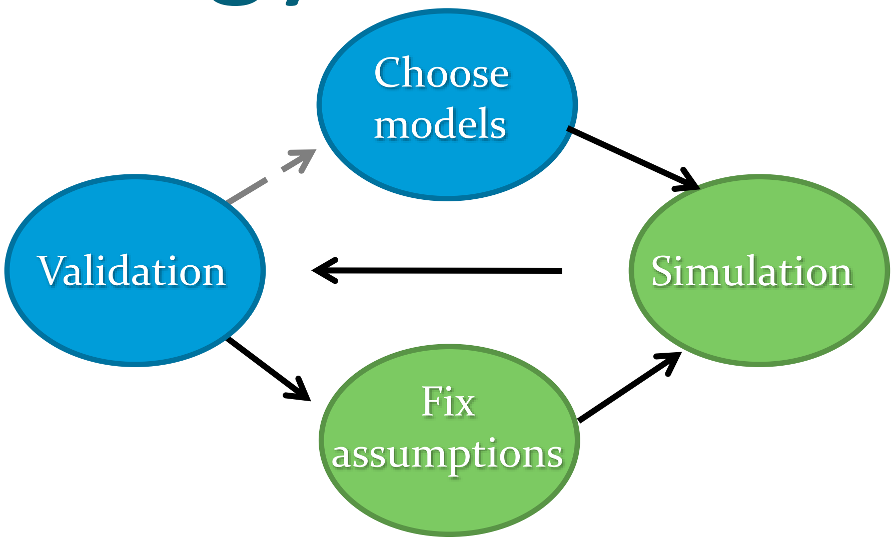
- Investigation of the applicability of a biologically inspired model of cerebellum to deal with:
- *More complex embodiments*
- *Less accurate models (delays, noise, …)*

[1] Figure from F.M.M.O. Camposa, J.M.F. Calado, Ann. Rev. In Control 33 (2009), 70

Problem Statement

ORF-MOSAIC as a biologically inspired cerebellar model to adaptively control a human-like robotic arm with potential delays

Methodology

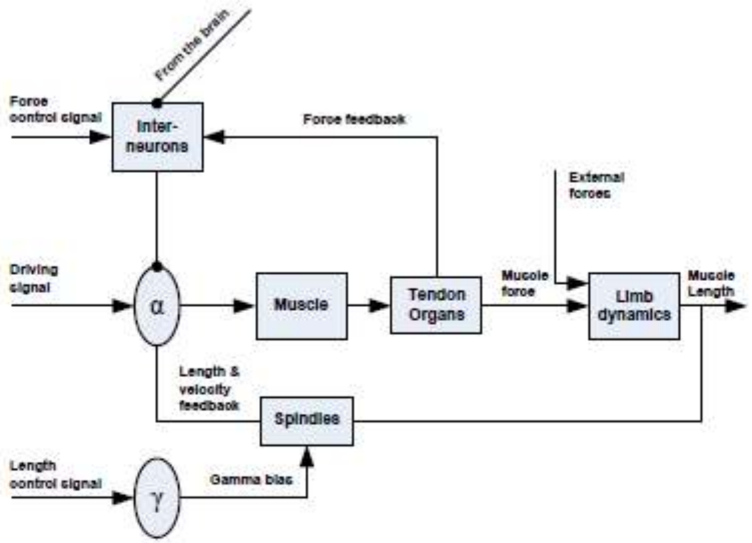


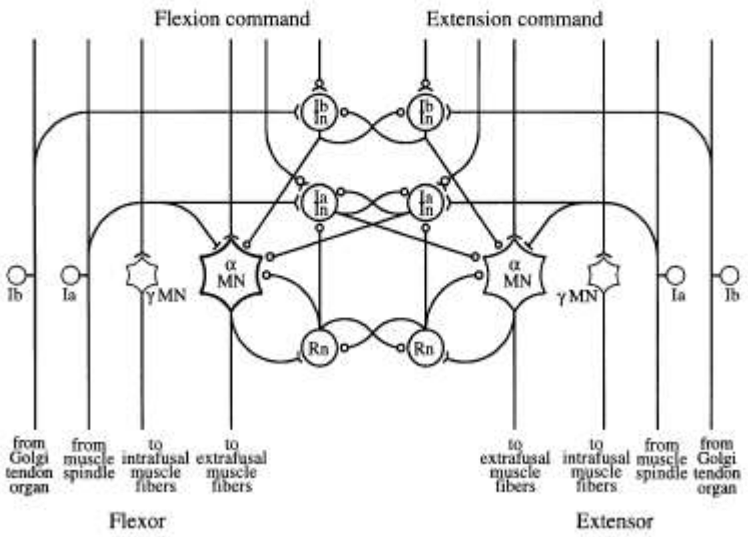
- Models as faithful as possible to biology
- Fixes according well-established theories in control engineering

Modeling

- Motor Cortex (Trajectory Generation, …)
- Cerebellum (MOSAIC)
- Sensory System and Lower Motor Control
- Arm
- Muscle Systems

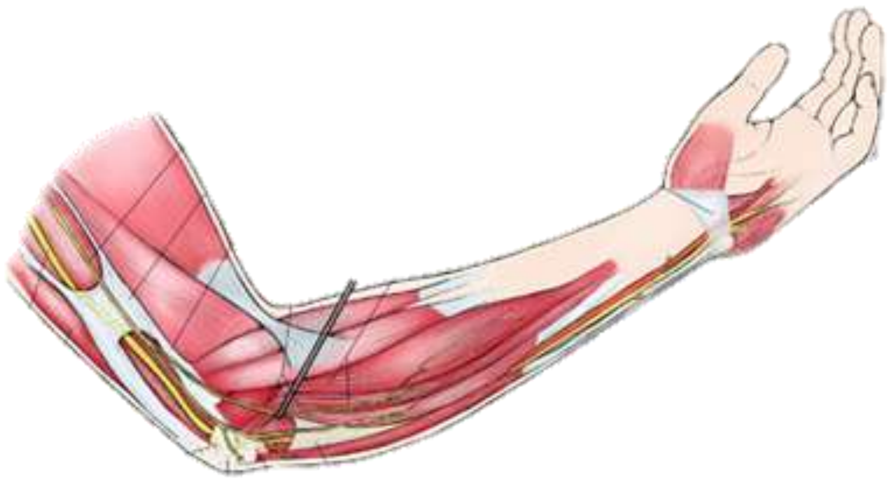
Lower Motor Control

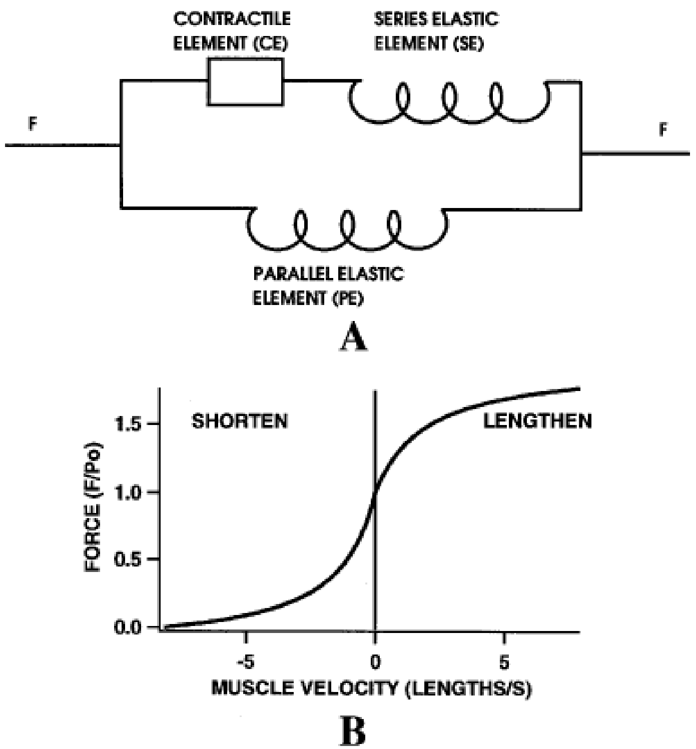




Musculoskeletal Model

- Preserves essential features of an arm
- Mono-articular and bi-articular
- Hill-type muscle model





[1] Figure from Handbook of brain theory, MIT press, 1995

Assumptions

- Minimum jerk trajectory by CTX
- Planning in task space, control in joint space and transformation to muscle space
- Minimum tension principle for muscle control
- Internal model

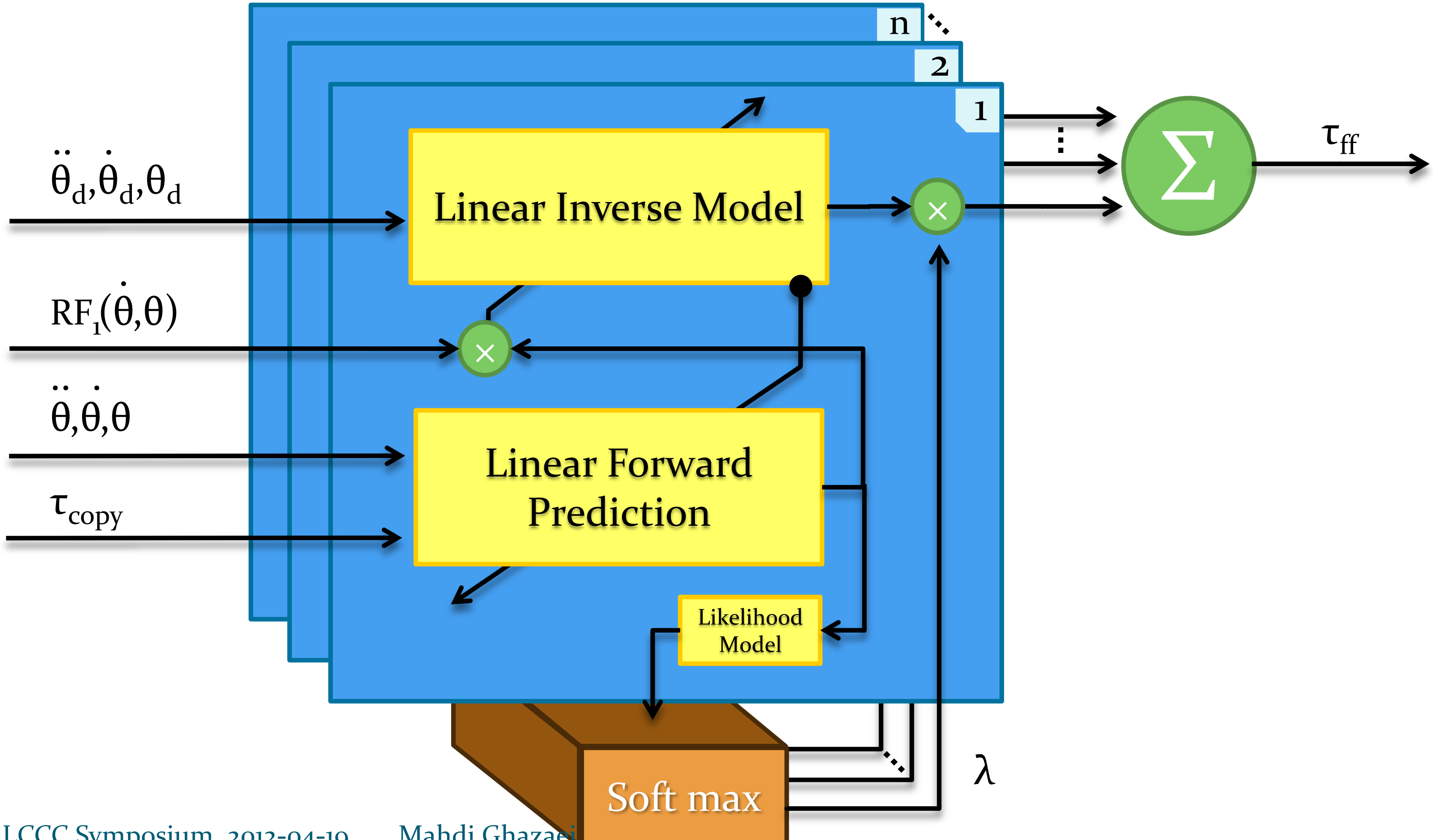
Methods

- Linear models representing cellular structure
- Low level control represented by a feedback controller and a transformation
- Approximation to known adaptive controllers

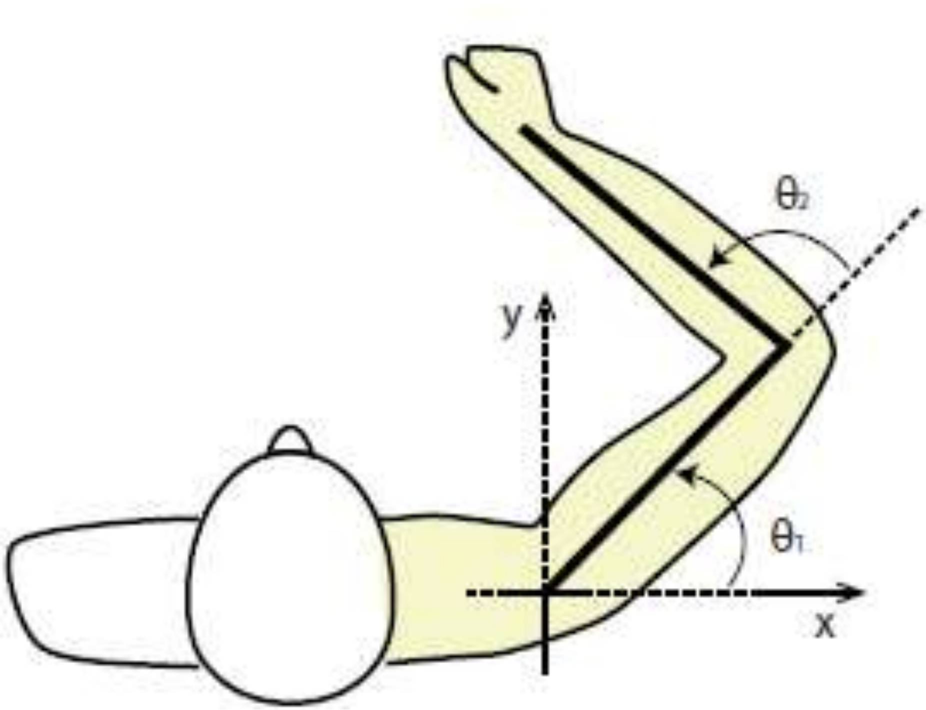
Customization of MOSAIC

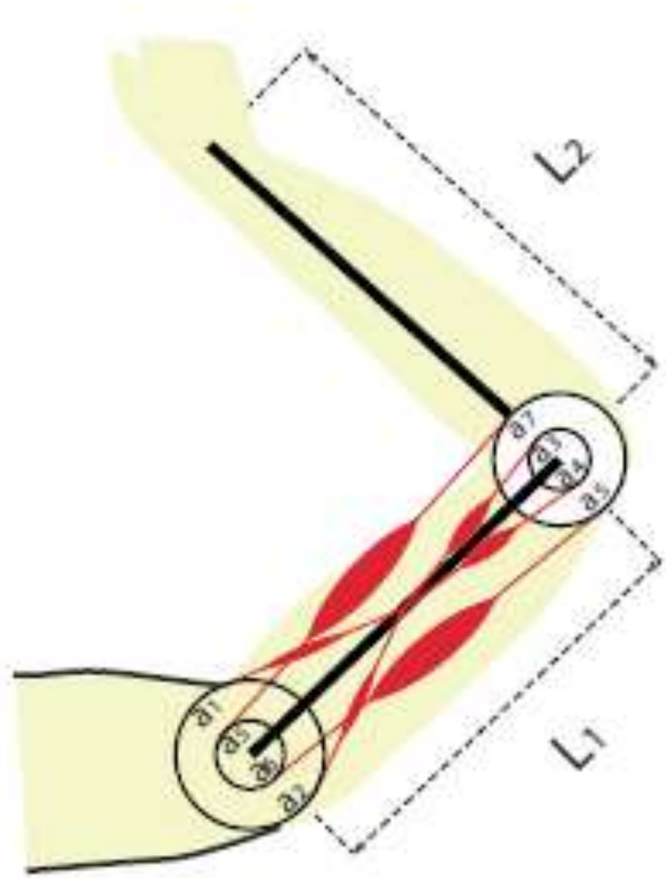
- Introduction of receptive fields for modules
- Dissociation of adaptation from control in a module
- Why different modules?
  - Taking care of different subtasks which are domains in state space
- Plasticity role?
  - Adapt existing internal models to cope with small changes in plant
  - To acquire new skills but no retention

Cerebellar Controller



Model of Arm



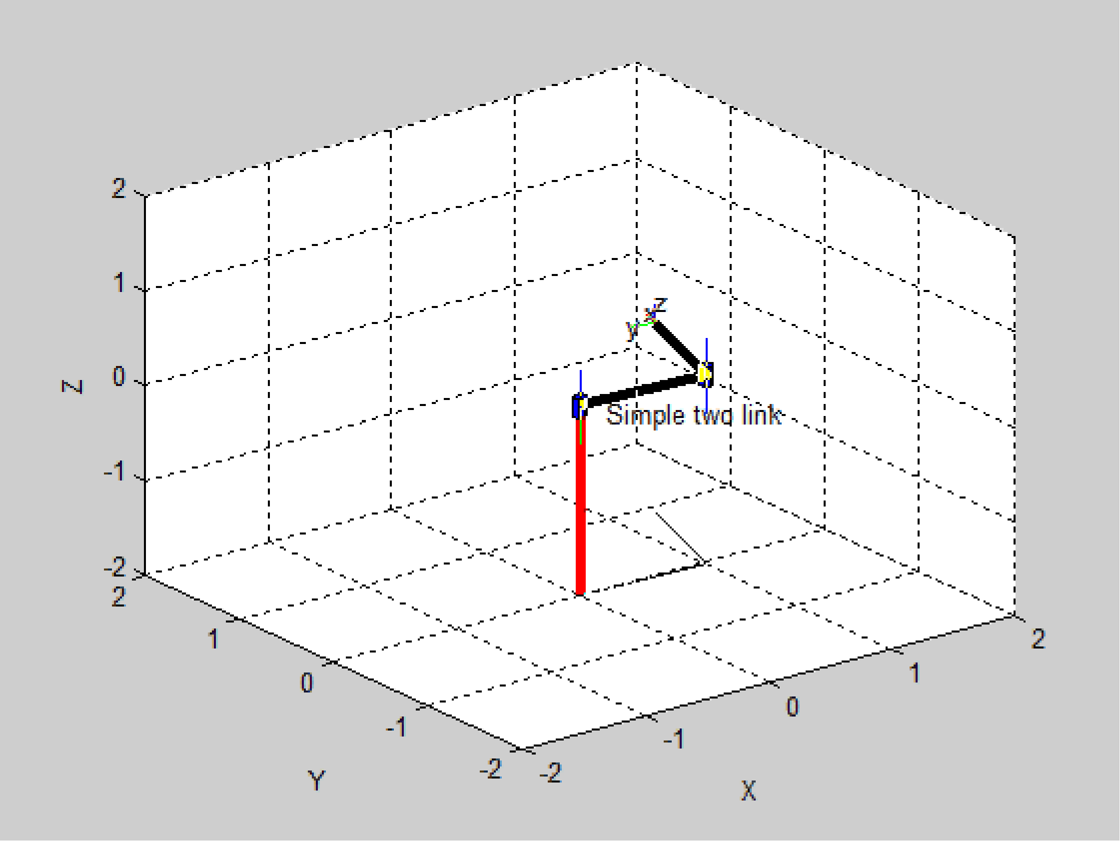


Minimum Tension Controller

$$\underset{u}{\text{minimize}}\ \frac{1}{2}T^T T \text{ subject to } 0 \leq u \leq 1 \text{ and } \tau = \tau_{sp}$$

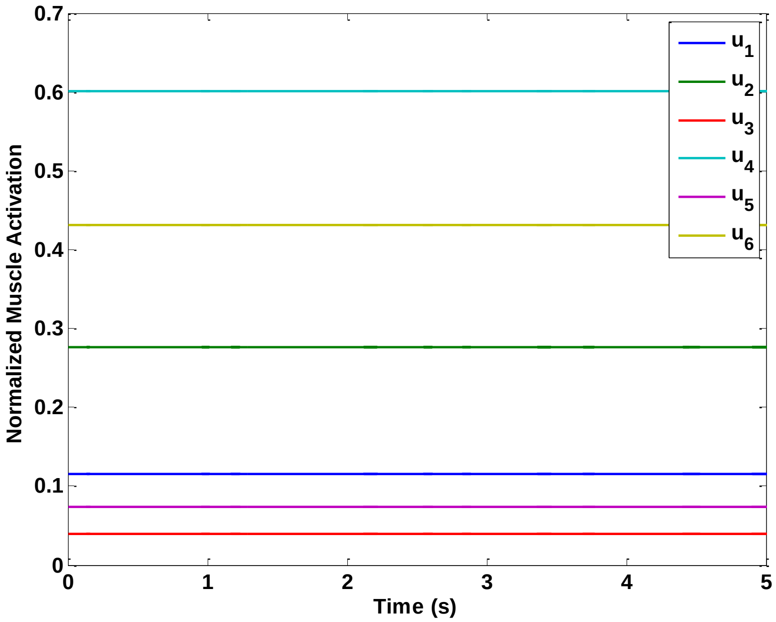
- Convex optimization
- With some mathematical tricks reformulated to a quadratic programming problem

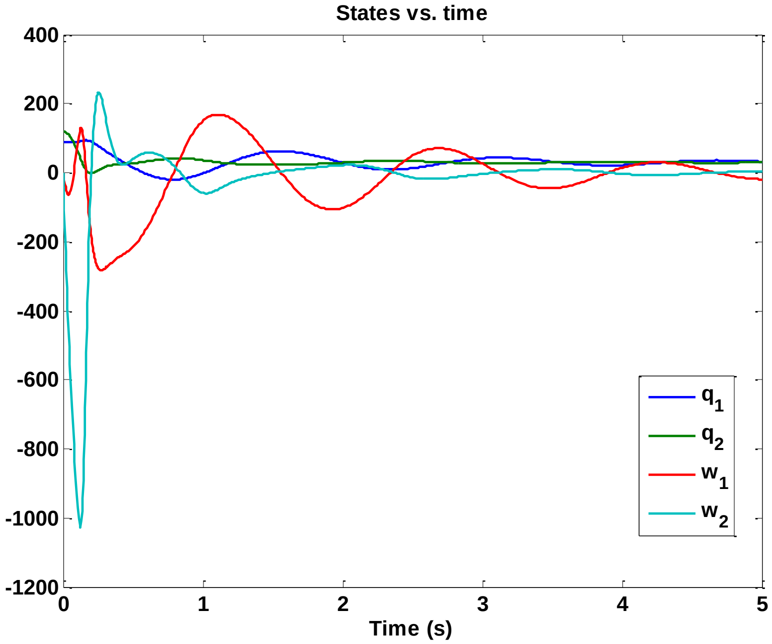
Simulation of Arm
Constant muscle activation



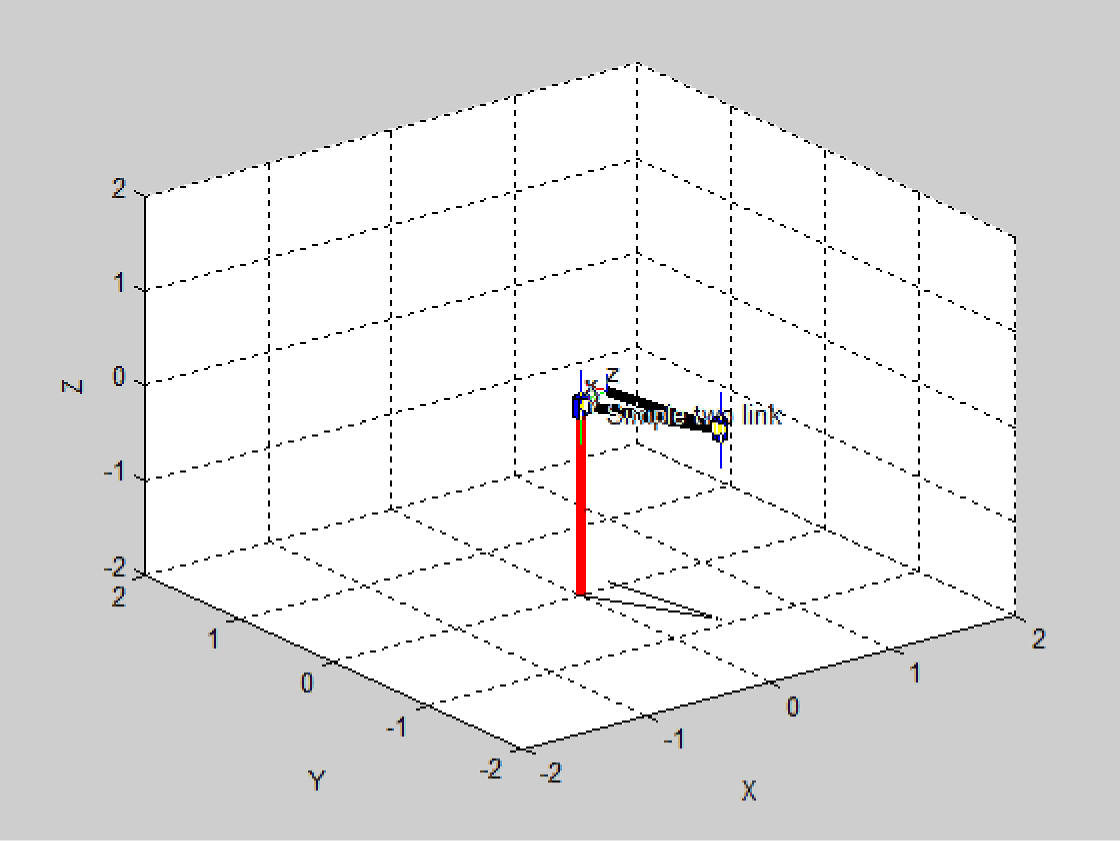
Simulation of Arm

Constant muscle activation



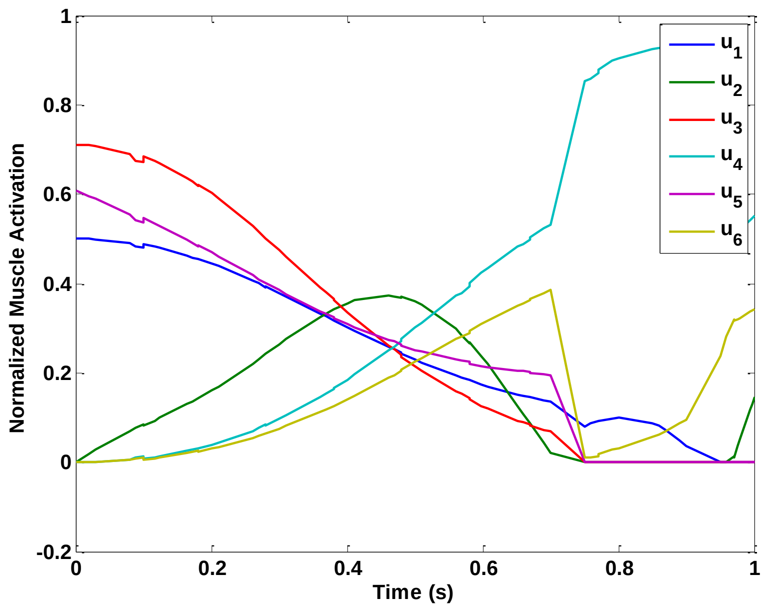


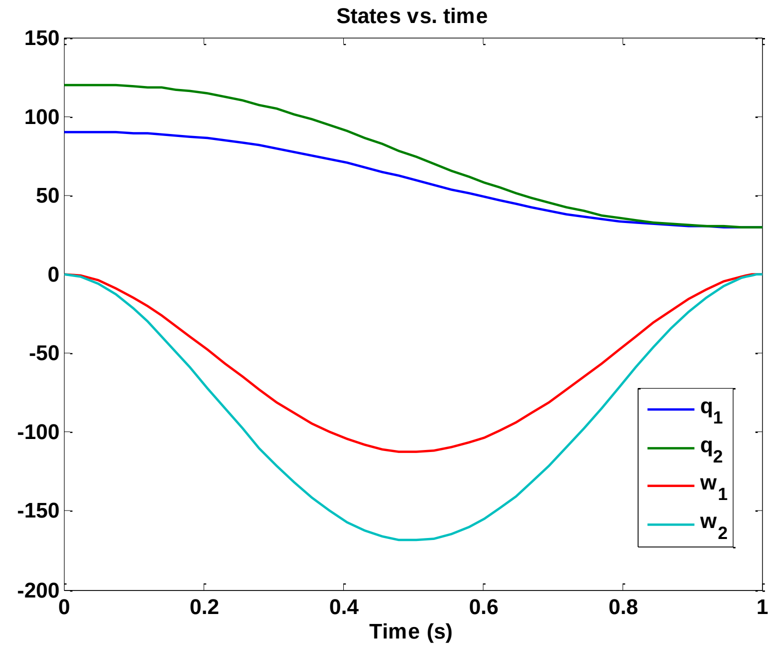
Simulation of Arm
Minimum Tension



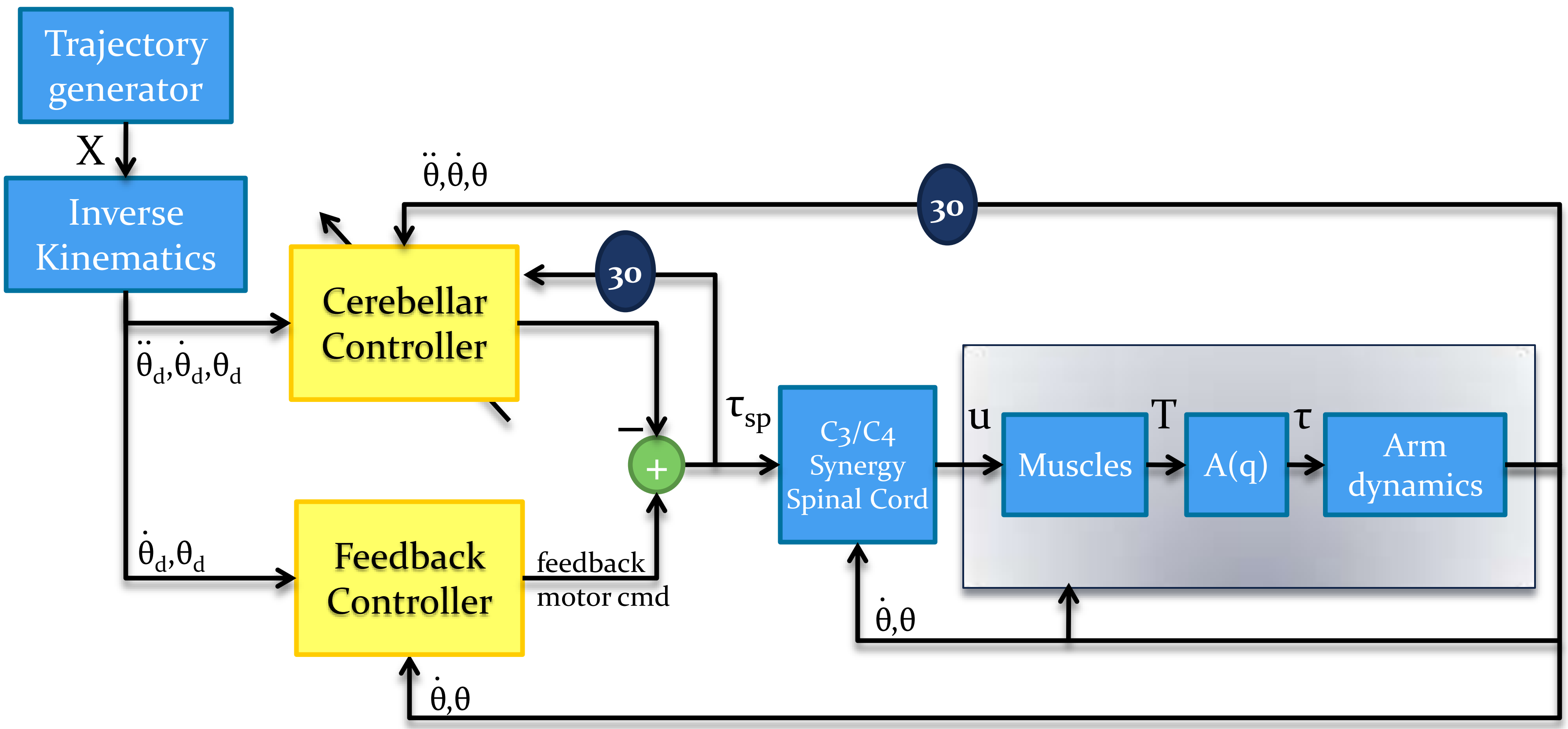
Simulation of Arm

Minimum Tension





End-2-end Simulation



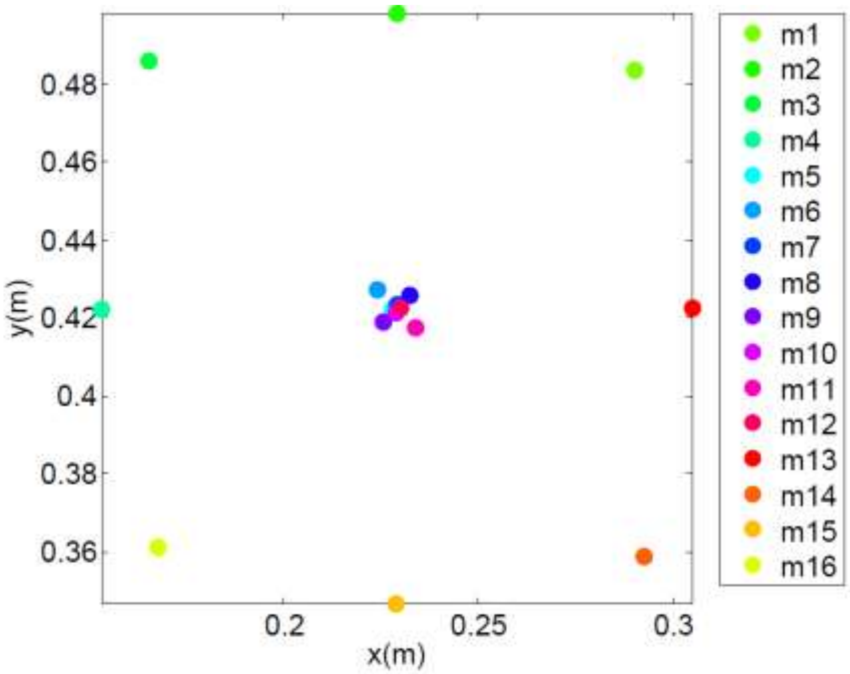
Final Experimental Design

- *30* [ms] delay in the path to the cerebellar controller
- PD controller with stiffness parameter of human arm and no delay
- Movement *0.65* [s] , wait for *0.65* [s]
- 16 modules in a15x15 [cm] workspace
- External translation invariant force field in task space

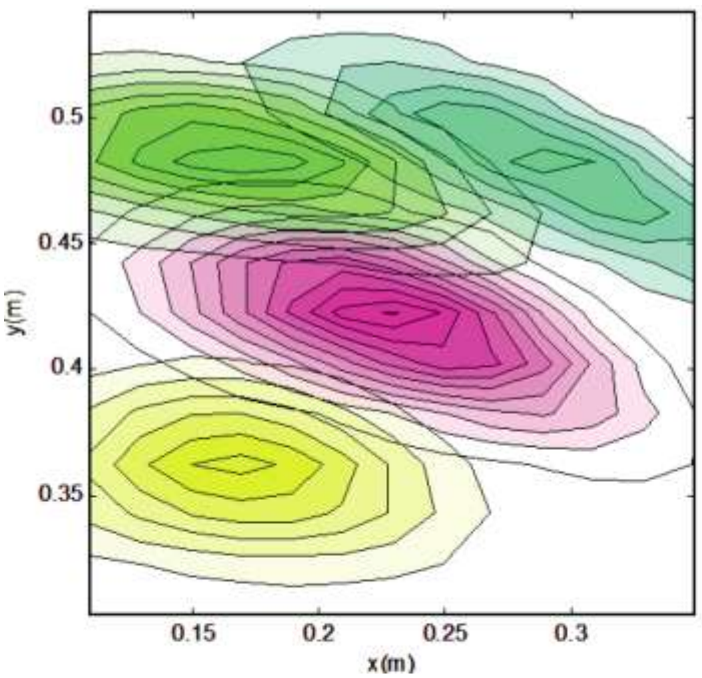
$$f = B\dot{x}, \qquad B = \begin{bmatrix} -2.525 & -2.8 \\ -2.8 & 2.775 \end{bmatrix} [\mathrm{Nsm}^{-1}].$$

- Object : *60* [cm] rod with *2* [Kg], perpendicular to the arm

Mapping of modules to workspace

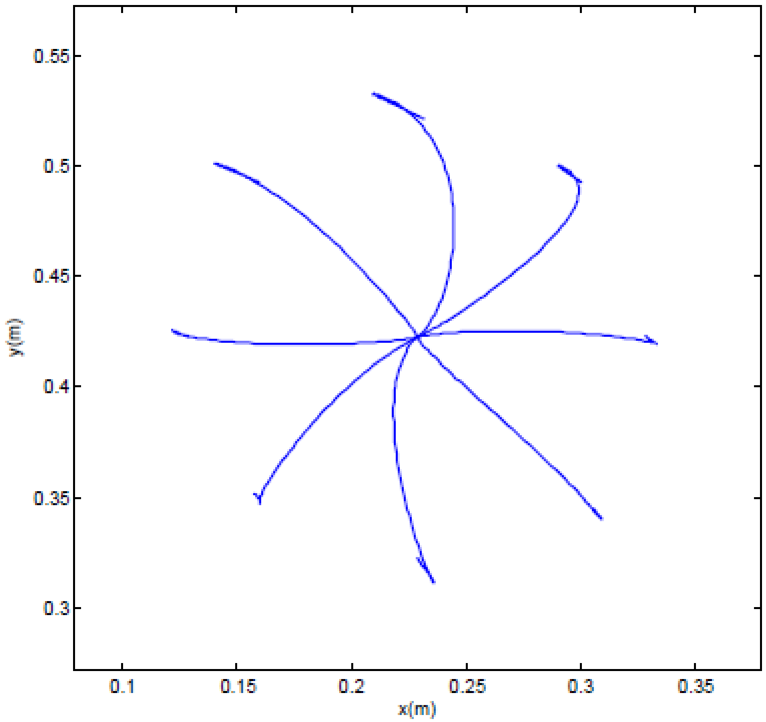


Numbering and color coding of modules

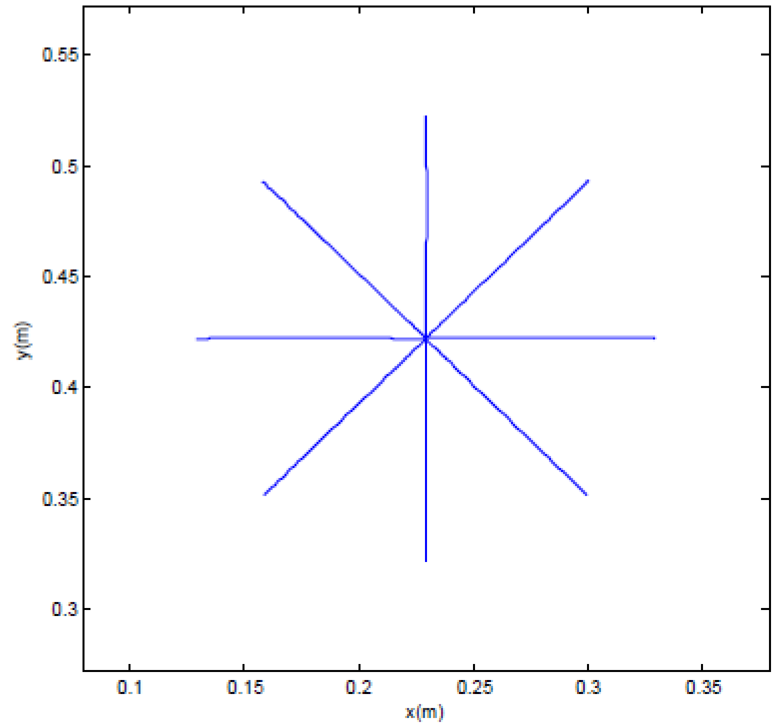


Samples of receptive fields in static configuration

Hand Trajectory

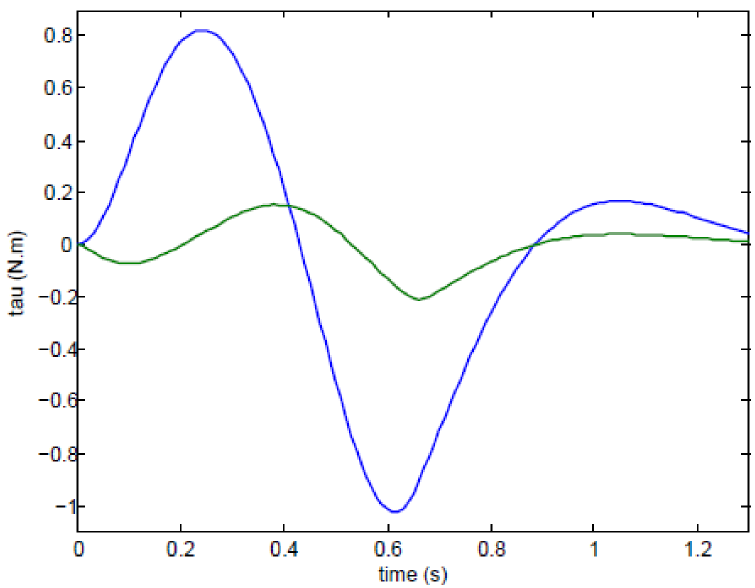


Before Training

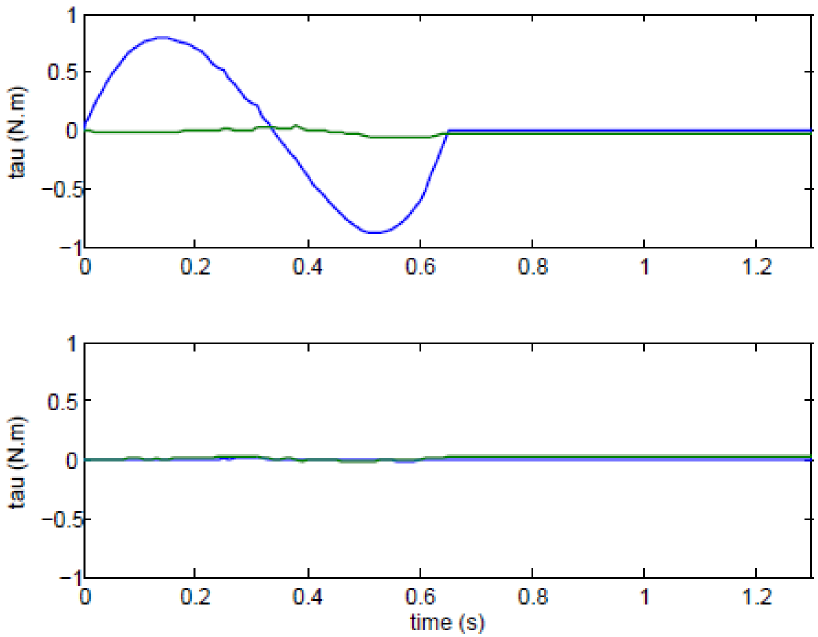


After Training

Feedback & Feedforward contributions

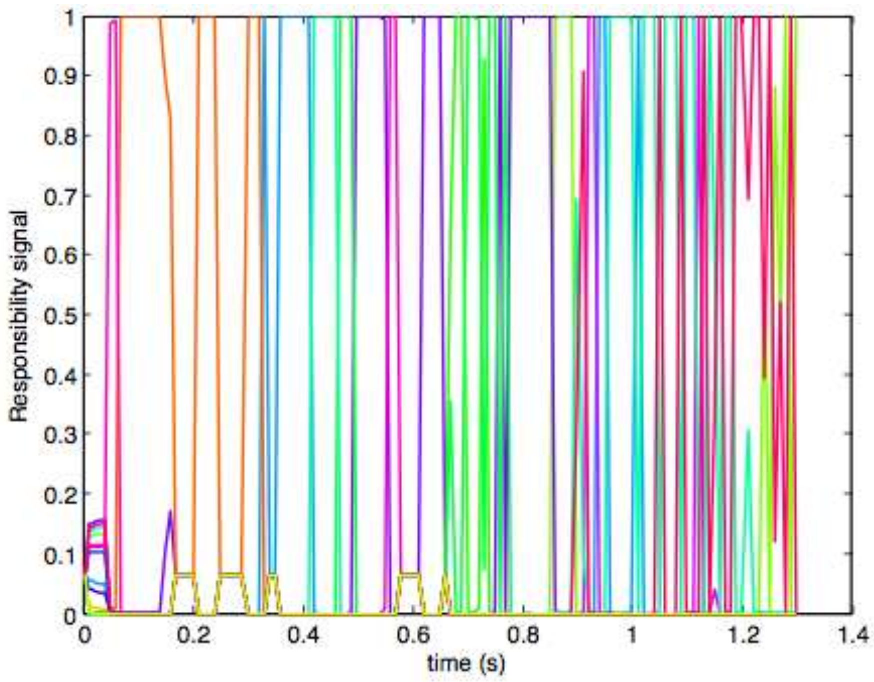


Before Training

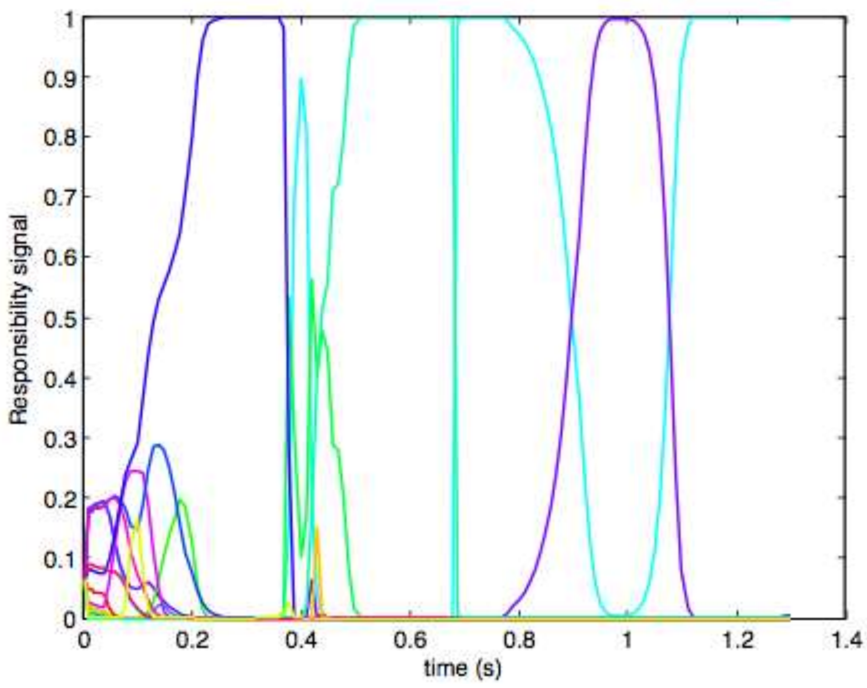


After Training

Contributions from modules

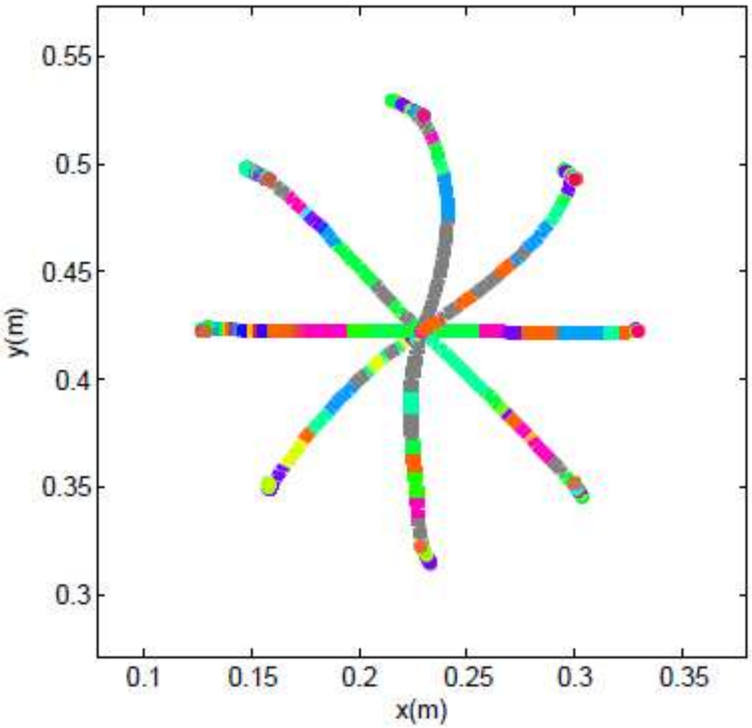


Before Training

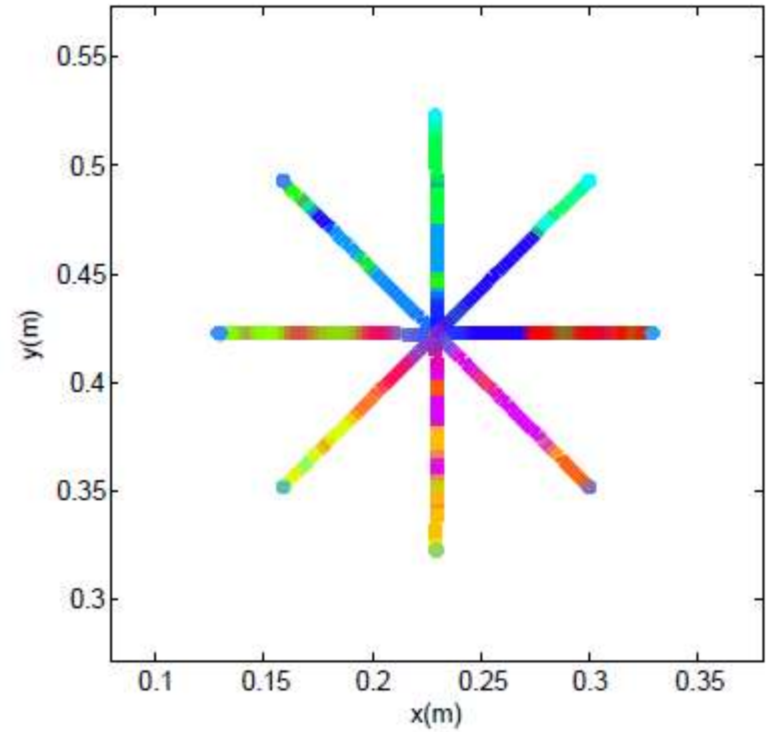


After Training

Controlling Modules

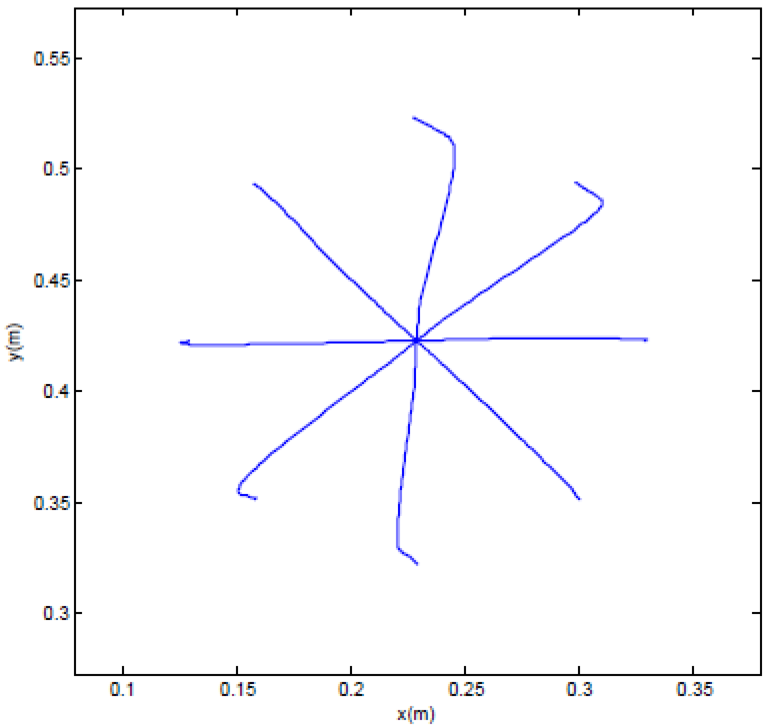


Before Training

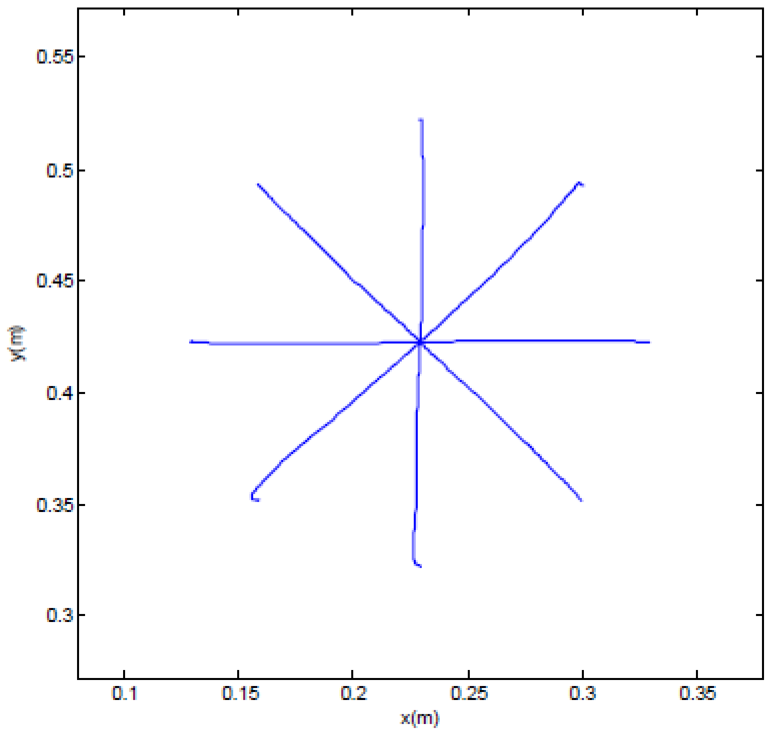


After Training

External Field Test

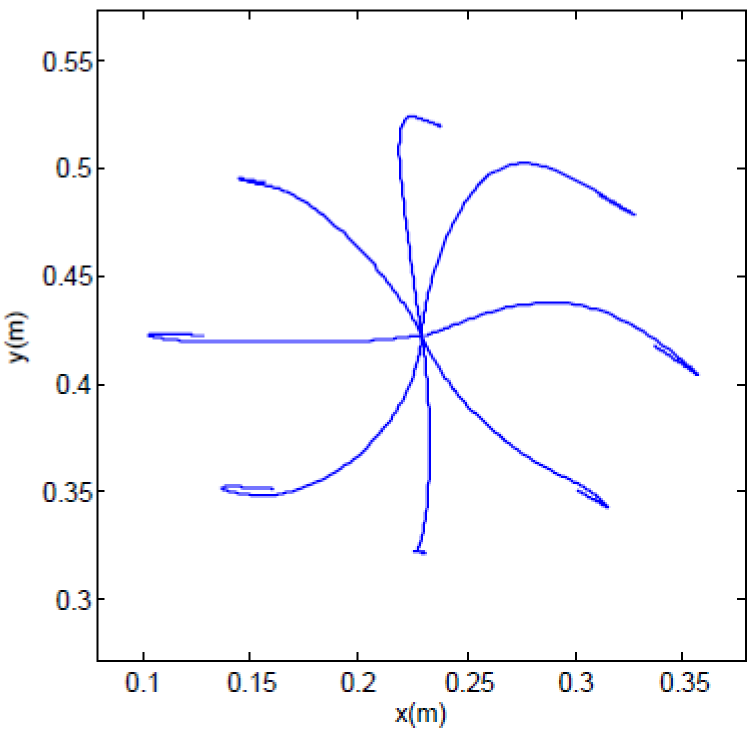


Before Training



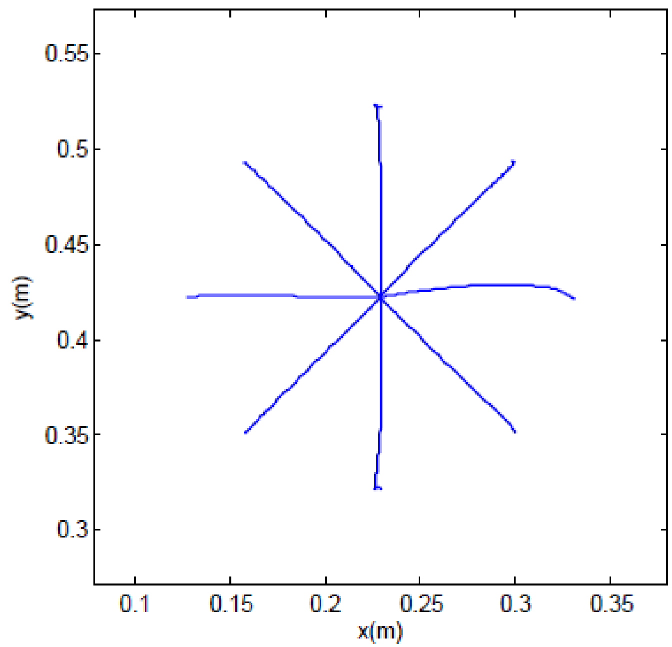
After Training

Handling an Object

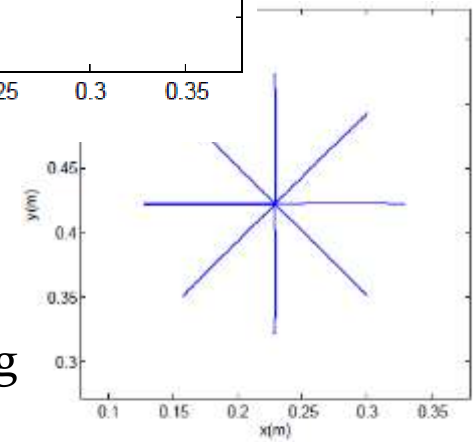


Before Training

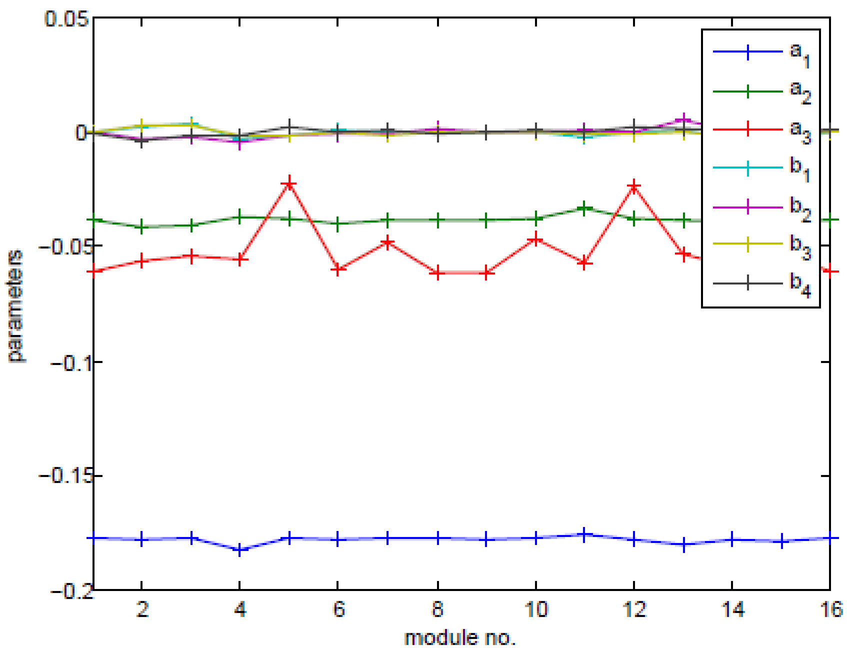
Adaptation



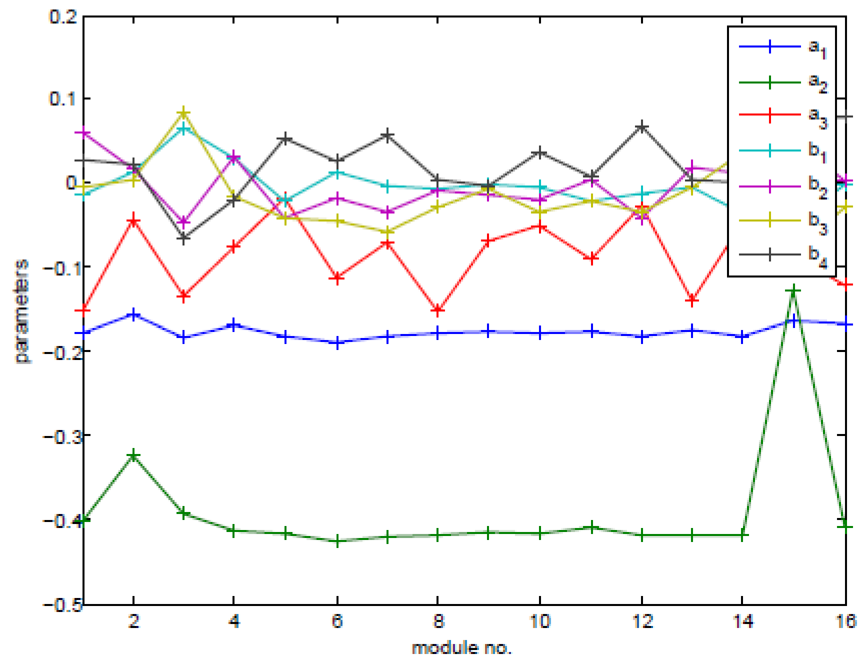
After Training



Parameters Across Modules

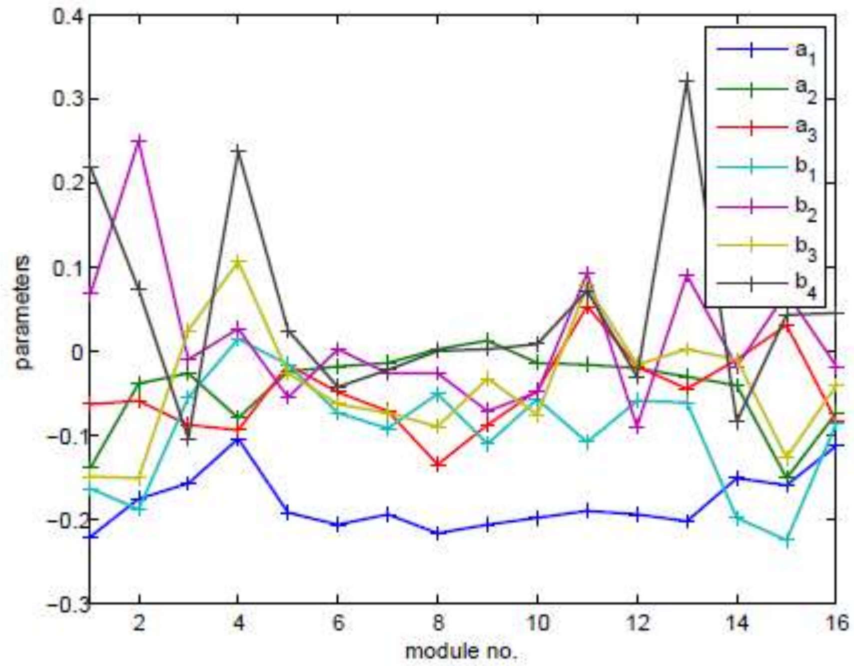


No object

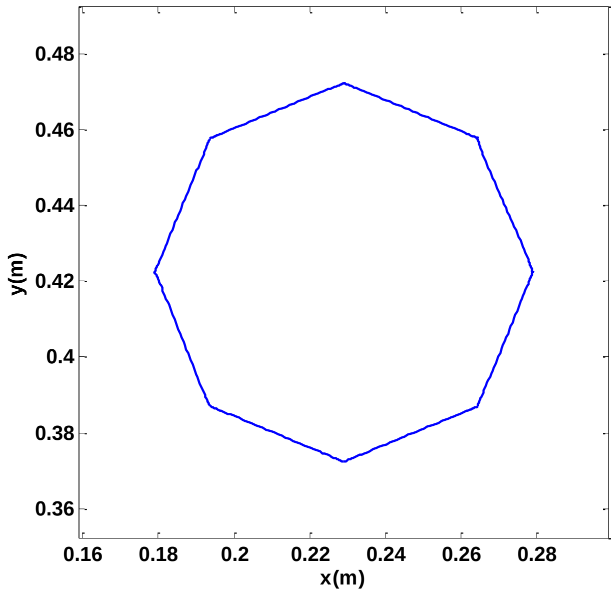


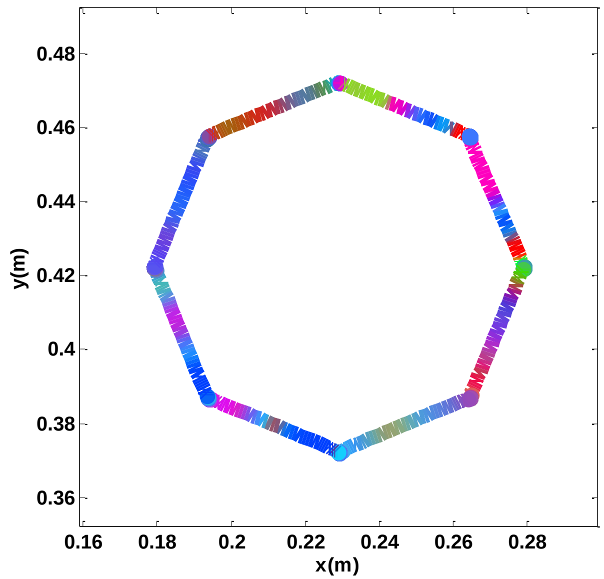
With an object

Parameters Across Modules
w/ External Field



Different trajectory





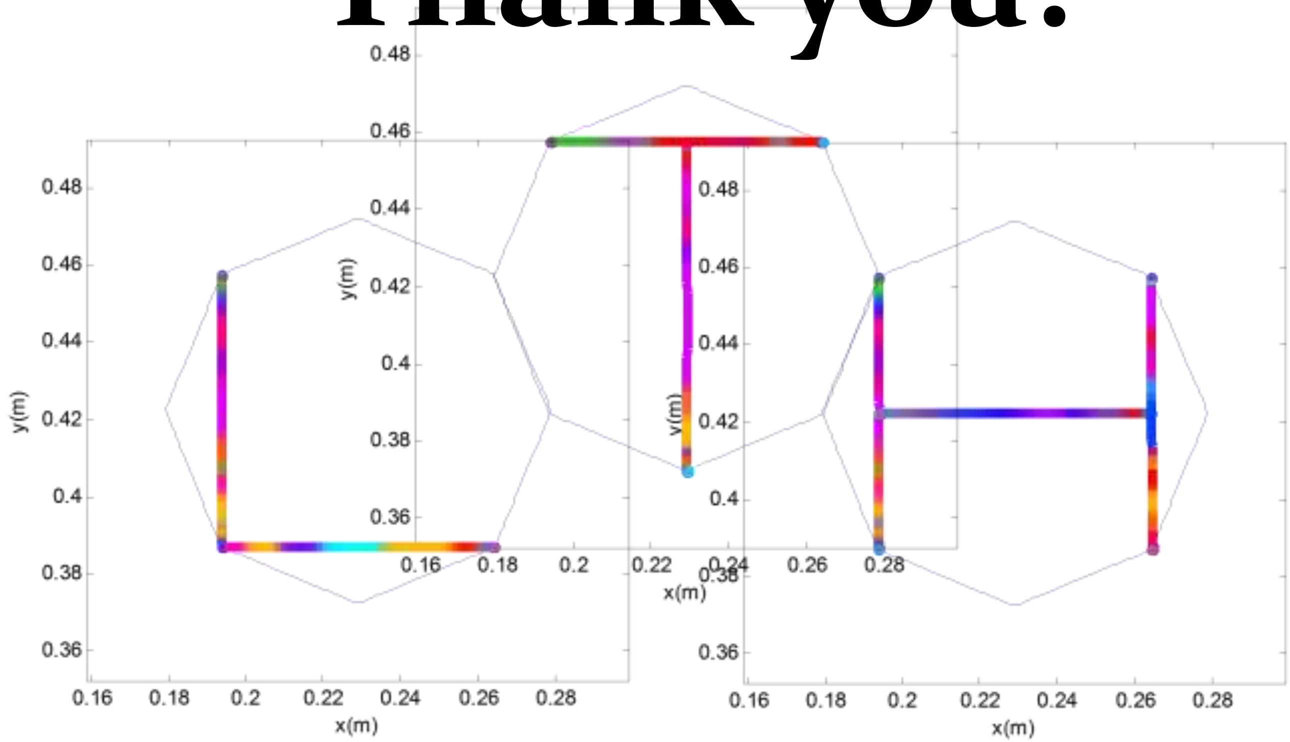
Discussion

- Learning of non-linearities by the cerbellar controller
- Specialization of modules with 7-parameters to different areas of the force field
- Trade-offs
  - Unit complexity vs. the number of modules
  - Unit adaptation vs. effective switching or combination
- How to localize the model in cerebellum and brain?
  - Microzones and modules
  - Biologically plausible signals

Conclusion

- Cerebellar Model for Control Inspired by the Microzonal Structure
- Arm Model with Musculo-skeletal structure
- Adaptation to the changes in the load and external disturbances despite delay
- Highly sparse representation with not full knowledge of the model as a priority
- Model for distributed control and adaptation

Thank you!



Questions…?