Developing the Cerebellar Chip as a General Control Model for Autonomous Systems

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Overview

1. The Cerebellum
2. The Cerebellar Chip
3. Control of General Plants
4. Control of Artificial Muscle
5. Conclusions and Future Work

The Cerebellum

- The cerebellum plays a key role in learning and executing skilled movements
- Cerebellar lesions disrupt but do not abolish function
- Importance of the cerebellum is highlighted by the fact it contains 80% of all brain neurons in humans*

** Herculano-Houzel, S. (2010) Frontiers in Neuroanatomy, 4, Article 12. doi: 10.3389/fnana.2010.00012*

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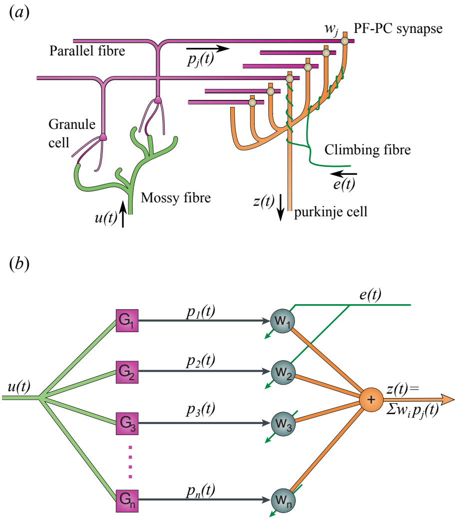
- Evidence for a cerebellar microcircuit that is uniform across the entire cerebellar cortex
- Suggests that the microcircuit implements an algorithm that is useful in many different contexts

The Cerebellar Microcircuit as an Adaptive Filter



- Adaptive filter algorithm first proposed as model for cerebellar microcircuit by Fujita (1982), derived from the ideas of Marr and Albus
- Most of the current models of the cerebellum that are concerned with behaviour appear to be based on the adaptive filter (Dean et al 2010)
- Adaptive filters are potentially very powerful and widely used in control and signal processing

Fujita, M. (1982) Biological Cybernetics, 45, 195-206.

Dean, P. et al (2010) Nature Reviews Neuroscience, 11(1), 30-43

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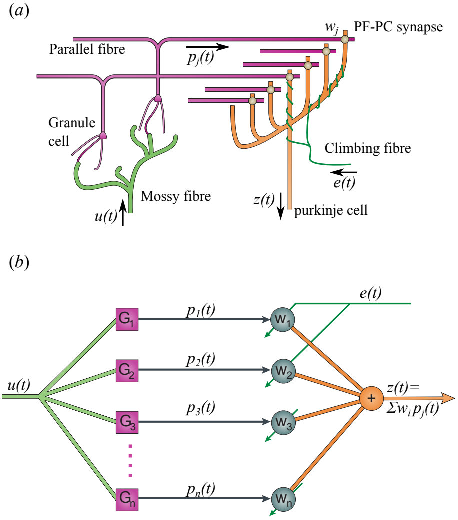
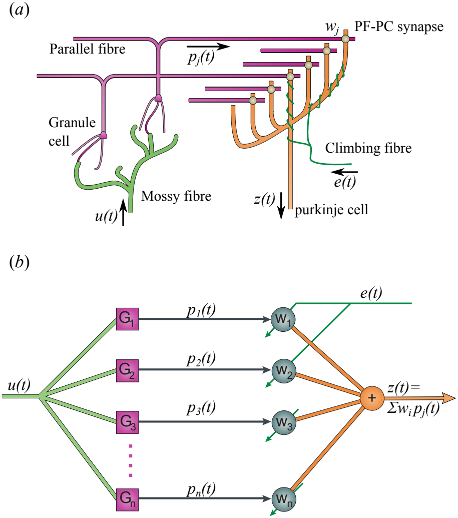


- Input analysis: granular layer generates component signals from input (mossy fibre) signals
- Component signals weighted by parallel-fibre Purkinje cell synapses
- Weights adjusted by climbing fibre signal
- Purkinje cell combines weighted components to produce output.

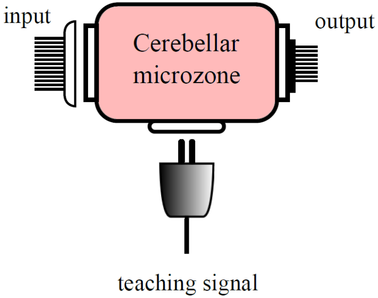
Biologically Plausible Learning Rule for PF/PC synapses



Covariance learning rule:

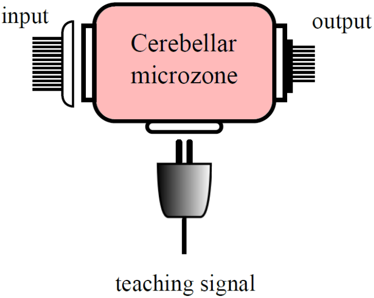
- Anti-Hebbian covariance learning rule $\delta w_i = -\beta \langle e(t) p_i(t) \rangle$
- identical to LMS learning rule of adaptive control theory
- with appropriate connectivity will minimise $\langle e(t)^2 \rangle$
- stops when each PF input $p_i(t)$ is decorrelated from error signal $e(t)$ - **decorrelation control**

The Cerebellar Chip



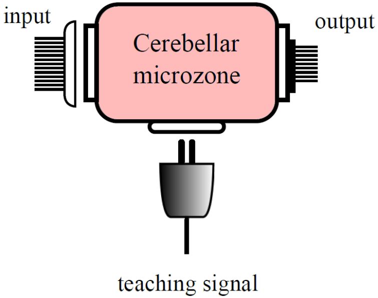
- The microcircuit can be thought of as a cerebellar chip
- Each cerebellar microzone has a similar internal organisation, but its own set of external connections.
- The function depends on both the signal processing capability of the generic chip and the particular architecture in which it is embedded.

The Cerebellar Chip



- Useful for a range of adaptive signal processing and motor control problems
  - Noise cancellation (e.g. electric fish)
  - Adaptive plant inversion (e.g. vestibular ocular reflex - VOR - adaptation)
  - Adaptive error feedback (e.g. optokinetic reflex - OKR - adaptation)
  - Predictive tracking (e.g. predictive smooth pursuit)
  - Optimal control (e.g. saccade optimisation)

The Cerebellar Chip



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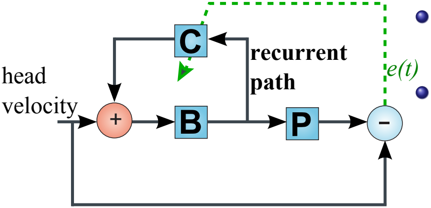
Adaptive Inverse Control : VOR Adaptation

- Retinal slip is produced by movements of the head, such as those that occur in locomotion
- The VOR counter-rotates the eyes to maintain stable gaze.
- Usually not aware when we use it.
- Cerebellum calibrates the accuracy of the VOR

Adaptive Inverse Control : VOR Adaptation

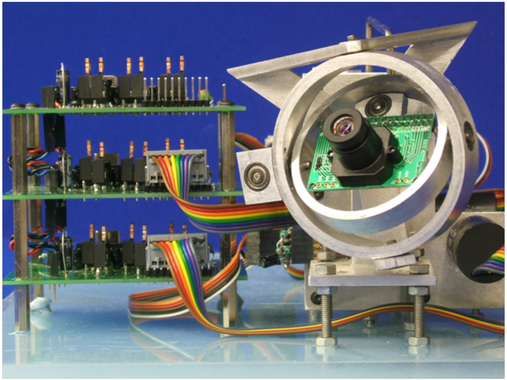


Simplified, linearised model of horizontal VOR

- **Recurrent Architecture** allows the sensory error signal $e(t)$ to be used to drive adaptation of the filter weights.
- Current engineering control often designed on case by case basis
- Biological system constrained as
  - cerebellar chip must operate in situ and function during learning
  - teaching signals must be biologically plausible - e.g. sensory error
  - learning rule fixed by characteristics of plasticity in microcircuit
- Biological systems appear to use relatively homogeneous structure to achieve remarkable control performance

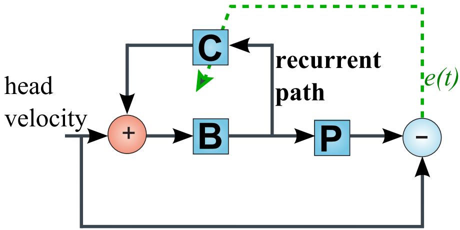
Previous Applications

Cerebellar inspired algorithm used to stabilise camera images in robot head



Lenz, A. et al. (2009) IEEE Trans Syst Man Cybern B Cybern, 39(6), 1420-1433

Control of General Plants



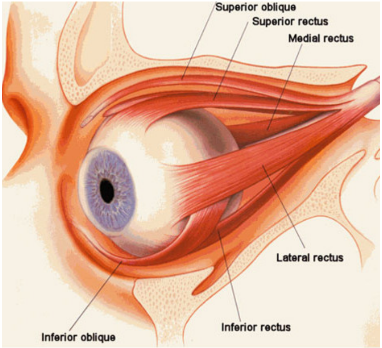
- Previously controlled plant have had equal poles and zeros
- Extend algorithm to apply to general plants with more poles than zeros - more generally applicable
- If plant has more poles than zeros the inverse plant compensator that is learnt will be improper
- Calculating output of improper plant has difficulties
  - Requires differentiators, difficult to realise, leads to noisy high freq performance, can lead to instabilities in learning rule

Control of General Plants

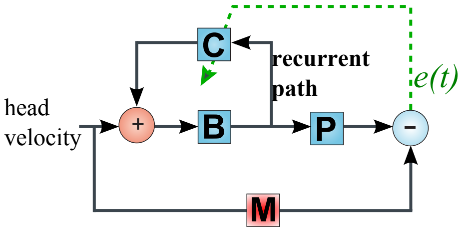
- For eye movements velocity is controlled
- Eye plant (extracelluar muscle and orbital tissue) can be modelled as

$$\frac{ks}{s + 1/T_p}$$

- Controlling position would require differentiators
- Difficult control for some inputs (e.g. step)



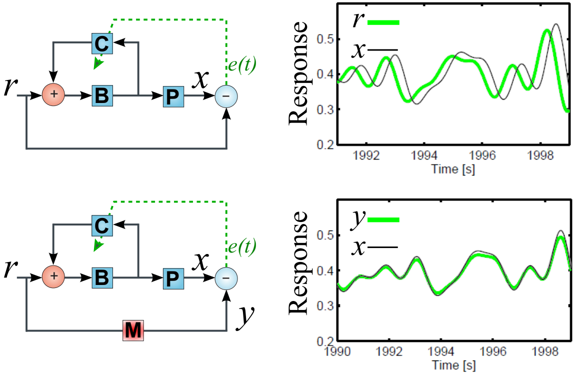
Control of General Plants



- Extend VOR circuitry to include reference model M which specifies the behaviour of controlled plant
- Reference model ensures that desired controller is well behaved and the reference trajectory is achievable
- Technical solution to the problem

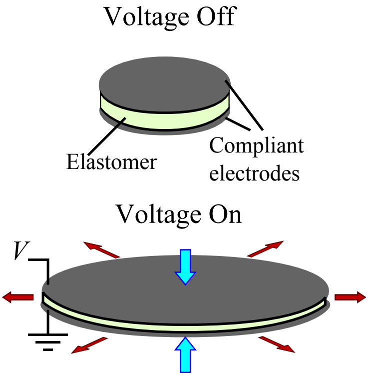
Control of Simulated Plant

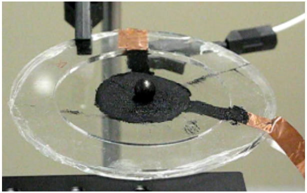
- Control of plant with four poles and no zeros



- Without reference model the actual response lags the desired response
- Reference model specifies a realistic response of the controlled plant

Artificial Muscle Actuators

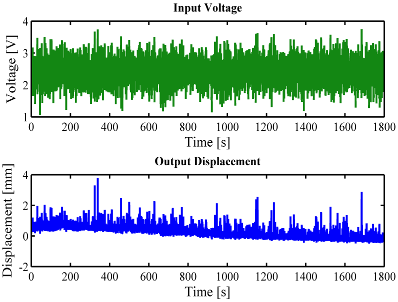




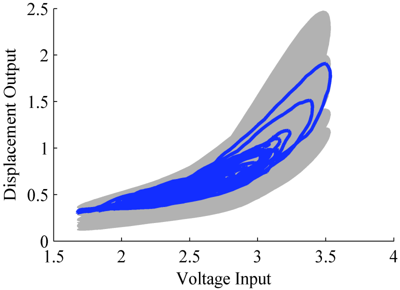
- Tested algorithm by tracking the displacement of a DEA (Dielectric ElectroActive Polymer)
- Electroactive polymers change shape or size in response to suitable electrical stimulation
- DEAs have the potential to provide lighter, more compliant actuators
- DEAs present new control challenges
  - Manufactured with wide tolerances
  - Subject to creep and time related aging
  - Respond in a nonlinear way

Behaviour of Artificial Muscle (DEA)

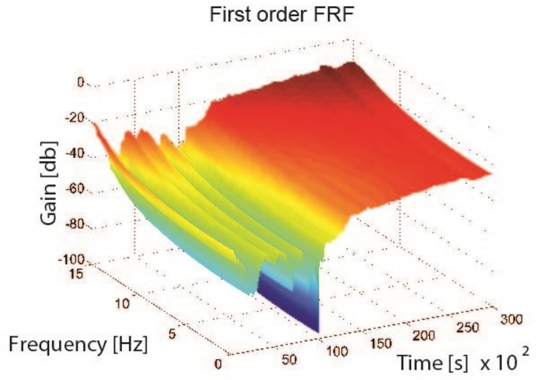
Change in response over time



Change in response across EAPs



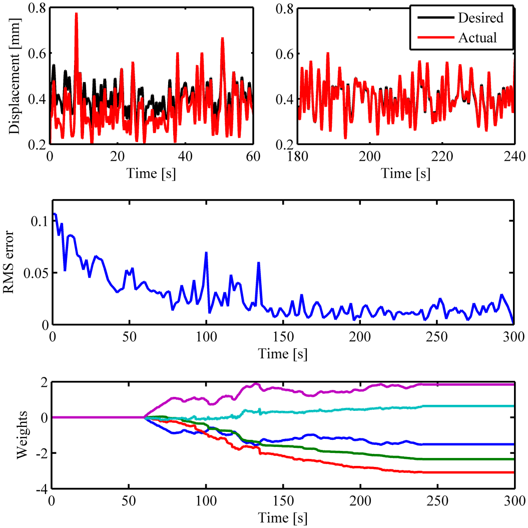
Behaviour of Artificial Muscle (DEA)

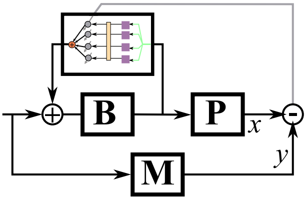


by W. R. Jacobs

- Dynamics of DEA change over time
- More details of this in Poster 'Control-oriented nonlinear dynamic modelling of dielectric electro-active polymers' *W. R. Jacobs et al.*

Control of Artificial Muscles

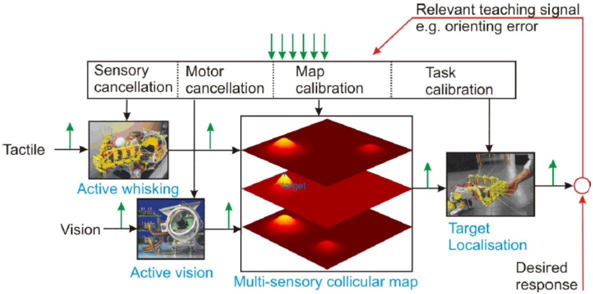




- Experimental results
- Sensory error is the difference between actual and desired displacement $x - y$
- Weights adjust over time to minimise error

Applying Cerebellar Chip to a Range of Tasks

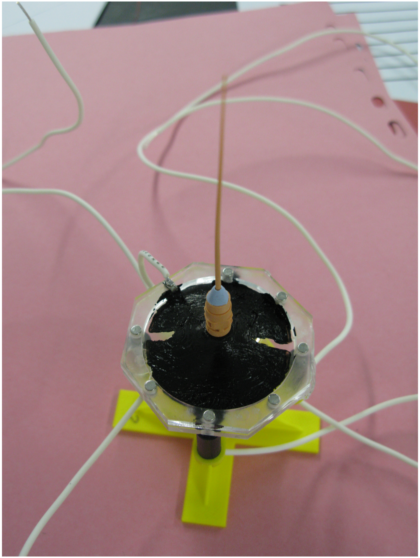
Part of the Bella Project (EPSRC Project)



- Four basic robotic tasks
  - Eye stabilisation
  - Whisker novelty detection
  - Sensory map calibration
  - Target acquisition
- Each task to be assigned its own cerebellar control module

Actuator Configurations

DEAs to drive sensory eye and whisker systems



Conclusions and Future Work

- To extend previous work on the cerebellar algorithm to the control of linear plants of different orders a reference model can be included in the control system
- Cerebellar inspired control potentially applicable to a range of control tasks
- Algorithm shown to work when applied a tracking task using a Dielectric ElectroActive Polymer actuator

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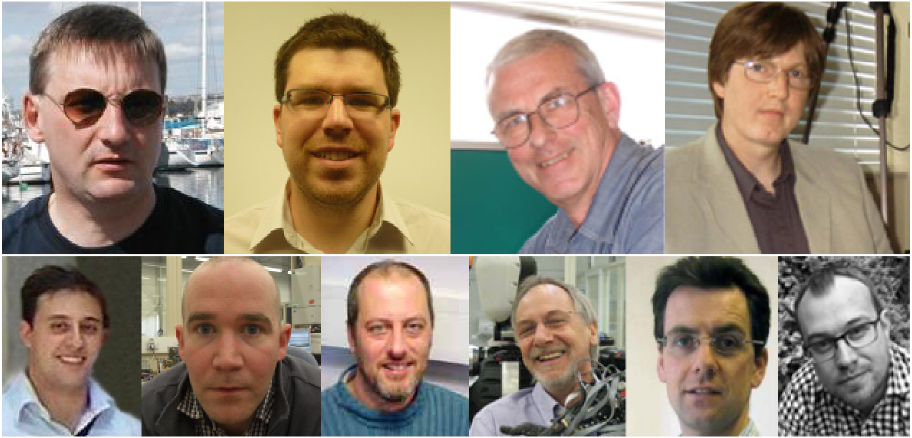
Future Work

- Nonlinear plants
- multi degree of freedom, multiple actuator systems
- map calibration
- integration of tasks



Thank You

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