Functions of distributed plasticity in a biologically-inspired control system: from electrophysiology to robotics

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1 Introduction

We describe here the progress of a multi-disciplinary collaboration to evaluate cerebellar-inspired control architectures for the adaptive control of mobile robots. Our example problem is the calibration of the vestibulo-ocular reflex (VOR), a reflex which stabilises the eyes during head movements, for which the cerebellum is known to be essential.

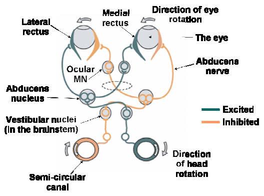
A puzzling feature of the cerebellar control network for the VOR is that it uses two sites of plasticity, one within the cerebellum itself and one in the brainstem, related to the neurons to which the cerebellum projects. We are examining the nature and function of this distributed plasticity with the following goals:
i) to characterise the properties of brainstem plasticity by electrophysiological recording
ii) to construct models of cerebellum and brainstem plasticity to investigate the computational properties of algorithms with brainstem plasticity
iii) to implement and evaluate biologically-inspired algorithms for the adaptive control of a robot-mounted camera.

2 The VOR: A Test-Bed System

The cerebellum is divided into thousands of modules, each with identical micro-circuitry but distinguished by unique connections with other parts of the brain.

Since the micro-circuitry of the cerebellum is so uniform, the choice of experimental model in which to investigate the cerebellar algorithm in motor control can be made on grounds such as tractability and generic significance.

The VOR is just such a problem. This is a reflex that drives the eyes in the opposite direction to head rotation to stabilise the image on the retina.



Biological representation of the VOR (Cerebellum not shown)

The very extensive experimental investigation of the VOR and its calibration makes it especially suitable for a multi-disciplinary evaluation of biological features that could contribute to superior motor control.

3 Project Aims and Objectives

Project Aims

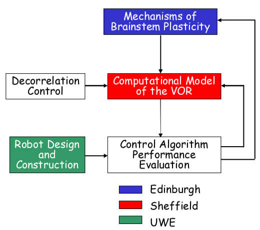
Elucidate and evaluate the function of distributed plasticity in order to:

- improve the understanding of the biological motor control system and
- determine the potential for improving traditional engineering solutions using biologically motivated methods.

Objectives:

1. Investigate rules of plasticity in the Brainstem through *in vitro* recording from medial vestibular nucleus (MVN) neurons.
2. Determine a computational model of the VOR to incorporate plasticity mechanisms, control algorithm and oculomotor plant dynamics.
3. Construct a robot to mimic the biological VOR system.
4. Evaluate performance of control in the robot to provide feedback on the success of the control algorithm from both a biological and engineering perspective.
5. Adjust investigation into plasticity mechanisms and computational VOR model based on findings from robot implementation.

Project Organisation

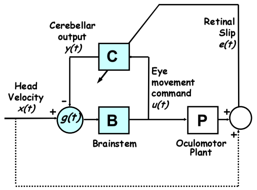


4 Learning Control By Decorrelation

Decorrelation is a generic principle of motor skill learning from sensory error:

Errors sensed during motor tasks that are correlated with motor commands indicate inaccurate motor commands.

Learning is driven by reducing the correlation between errors in motor control and motor commands.



The horizontal VOR system

The cerebellum can be represented as a discrete-time adaptive filter $C(z)$, which relates motor commands $u(t)$ to cerebellum output $y(t)$, i.e. $y(t) = C(z)u(t)$ (see above right).

The decorrelation algorithm updates the weights $w(t)$, of $C(z)$, according to the learning rule

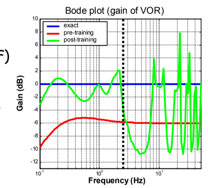
$$w(t+1) = w(t) - K\langle e(t),u(t)\rangle$$

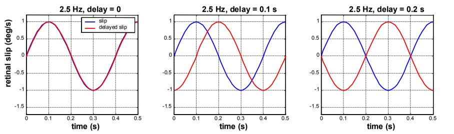
where K is a gain that affects the rate of learning and $\langle e(t),u(t)\rangle$ is the correlation between error and motor command.

5 Slip Delay Prevents HF Learning

- The retinal slip delay, which is 100 ms, would cause learning in the cerebellum to become unstable at high frequencies (HF) (right).
- Learning becomes unstable, because with a 100 ms delay the sign of the correlation reverses for motor command signals $u(t)$ above 2.5 Hz (below), i.e.

$$w(t+1) = w(t) + K\langle e(t),u(t)\rangle$$

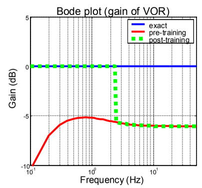


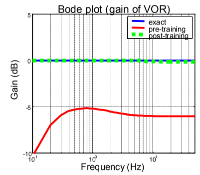


1. Stable Learning 2. Critically Stable 3. Unstable Learning

6 Brainstem Plasticity Enables HF Learning

- Learning in the cerebellum is stable for motor command signals $u(t)$ below 2.5Hz.
- Low-pass filtering the motor command signal (cut-off at 2.5Hz) leads to stable learning in the cerebellum (right).
- The high frequency gain is now learnt by the brainstem (below).





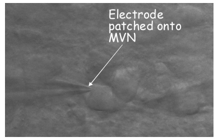
- The cerebellum provides the teaching signal to the brainstem.
- The correlation between cerebellar output $y(t)$ and the head velocity signal $x(t)$ is used to adjust the intrinsic gain $g(t)$ of the brainstem (see slide 4), i.e.

$$g(t+1) = g(t) - R\langle x(t),y(t)\rangle$$

Where R is a gain term.

7 In Vitro MVN Neuron Recording

We are investigating the cellular mechanisms which regulate the intrinsic excitability of MVNs, in brain-slice preparations *in vitro*.



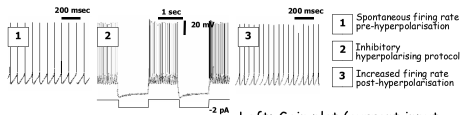
Using whole-cell patch clamp recordings from visualised MVN neurons, we have shown that the intrinsic excitability of the MVN cells can be regulated by patterns of inhibitory inputs applied to the cells (see slide 8).

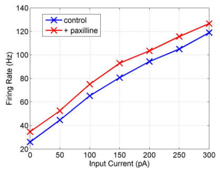
The increase in excitability is long-lasting, and has been shown to be mimicked by drugs that block specific potassium channels[1], e.g. paxilline (see slide 8). Drugs which open potassium channels reduce the intrinsic excitability of MVN neurons, indicating that the regulation of potassium channel function is one important way in which the firing rate gain of the MVN neurons may be regulated.

[1] A. B. Nelson, A. H. Gittis, S. du Lac, 2005, *Decreases in CaMKII Activity Trigger Persistent Potentiation of Intrinsic Excitability in Spontaneously Firing Vestibular Nucleus Neurons*, Neuron, Vol. 46, 623-631.

8 Possible Plasticity Mechanism

The intrinsic excitability of MVN cells is increased above normal following intermittent inhibitory hyperpolarising current injections which silence the action potential firing of the neurons (below).

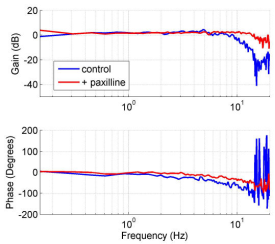




Left: Gain plot (current input (pA) v. steady state instantaneous firing rate) of a type B MVN cell. The neuron was exposed to step-wise increasing depolarising current injections from 0 to 300 pA in 50 pA steps. In the presence of 3 microM paxilline, the neuron's gain was unaffected (remains parallel) but there was an increase in sensitivity to a given current input.

9 Signal Transmission Improved

Right: Bode plot showing the increase in bandwidth of a type B MVN neuron in the presence of paxilline. The blockade of BK potassium channels by paxilline (at 3 microM) did not increase the low-frequency gain of the neuron. However, the corner frequency was shifted to the right. This corresponds to an increase in gain at higher frequencies, improving the signal transmission properties of the cell in the affected region.



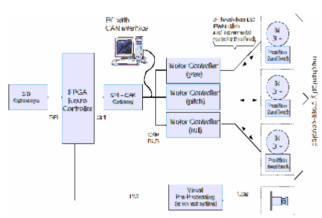
Proof of Concept:

It has been demonstrated that plastic effects on the signal transmission properties of MVN neurons are achievable *in vitro*.

10 Eye-Robot: Artificial VOR

A custom built 3 degree of freedom head movement simulator and camera platform rotates in 3 axes (yaw, pitch and roll).

The gimbal mounted camera is operated by 3 brushless DC motors each driven with a dsPIC® microcontroller including position feedback via incremental encoders.



Communication between the different driver modules is established via a Controller Area Network (CAN) operating at 1MBit/s. This interface is also employed to continuously observe the system state and evaluate the performance on a PC.

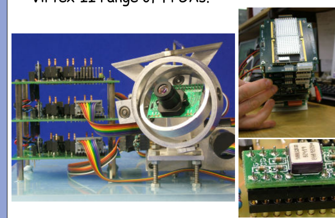
The connection between the Field Programmable Gate Array (FPGA), the sensors and the actuators is implemented using a serial peripheral interface (SPI) running at 5 MHz.

11 Robot Construction

A novel design of a 3-D gyroscopic system using three MEMS gyroscopes (ADXRS300 from Analog Devices®) emulates the mammalian vestibular system.

An embedded microcontroller generates realistic emulation of sensor/motor dynamics.

The neuro-controller is implemented on the XILINX Virtex II range of FPGAs.



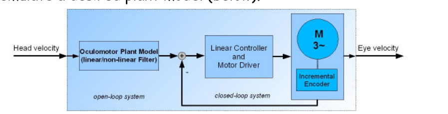
Top right: BenNUEY stack, on top are two Virtex II 2V8000 FPGAs with their heat-sinks.

Left: Gimbal mounted camera with driver boards for yaw, pitch and roll control.

Bottom right: 7x7 mm 1 axis gyroscope

12 Virtual Plant

A separate microcontroller drives each DC motor, corresponding to each axis of rotation, in a closed loop scheme. This architecture provides the freedom to add an 'arbitrary' filter in an open-loop manner so that each drive system as a whole can emulate a desired plant model (below).



Right: The response of a model of the oculomotor plant (simulated in Matlab) and the response of the mechatronic eye (including the same plant model) to a given reference signal. The oculomotor plant model utilised in this instance was a first order filter with a time constant $T=0.1s$.