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Structured control from self-organizing arm movements

Katja Fiedler*[1], Georg Martius[1,2], Frank Hesse[1,2] and J Michael Herrmann[1,2,3]

Address: [1]MPI for Dynamics and Self-Organization, Goettingen, Bunsenstr. 10, 37073 Goettingen, Germany, [2]Bernstein Center for Computational Neuroscience Goettingen, Bunsenstr. 10, 37073 Goettingen, Germany and [3]Inst. of Perception, Action and Behaviour, School of Informatics, University of Edinburgh, EH9 3JZ, UK

Email: J Michael Herrmann - michael.herrmann@ed.ac.uk

* Corresponding author

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Introduction

The organization of unconstrained arm movements in humans appears to be determined essentially by the biophysical properties of the limb [1], which, however, might imply as well that the underlying neural control mechanisms are perfectly adapted to controlled system. The stiffness of the arm with respect to perturbing forces [2] is caused by an active process that cannot be inferred from the biomechanics of the arm alone, and may thus reveal information about the underlying neural control mechanisms. We approach the problem by analyzing experimental measurements of stiffness in human subjects and by simulations of emergent control of a model of the human arm.

Physical simulations of a controlled human arm

Control is achieved by an algorithm for self-organizing control of sensorimotor loops [3] that establishes a dynamical system in the sensor space. The resulting dynamics is characterized by both the sensitive dependence on previous actions as well as the local predictability by an internal model. The algorithm merely follows the objective of conveying the sensorimotor loop into a marginally stable regime, which has been shown to suffice to generate a variety of behaviors in different robots [3]. Here we study the example of a four DOF model of a human arm. The controller creates a manifold of behaviors by an itinerant motion across the critical region of its parameter space. In order to identify "natural" behaviors a set of controllers is used. An effective controller can be selected by maximal learning progress [4] and upon convergence to a local optimum the active controller is stored as elementary behaviors in a premotor layer and can be reactivated by environmental affordances or by high-level planning.

Experiments on arm movements in human subjects

In parallel we have studied properties of human arm movements in a four-DOF setting (wrist-restrained) in three spatial dimensions using a high-performance haptic device. We have measured the stiffness based on the equilibrium point hypothesis by the motor response to a perturbing force and in dependence on the spatial position of the arm. In a second set of experiments we have studied trajectories in a self-referential task, where the subjects chase a target which is driven by a fast-learning controller. The controller learns to predict the subject's movement such that an increasing difficulty of the task is achieved and more complex movements can be expected.

Results

While at low complexity in the chasing task closed-loop control is sufficient, the subjects become more likely to use preexisting open-loop movement primitives at an increased task complexity. The primitives are extracted from the data by third-order statistics and share geometrical properties with the primitives that are produced by self-organizing multi-agent control of the simulated arm. The measurement of the stiffness allows us to derive a common explanation for the control-related aspects of the movement primitives in both experiment and simulation. Furthermore, the spatial heterogeneity of the extent and density of the primitives can be related to the stiffness estimates. Finally, we discuss application to prosthetics and suggest as a principle for the organization of the working range of arm movements that the entire sensorimotor space is partitioned into segments where the associated elementary behavior assumes optimal controllability.

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