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Robot control with biological cells

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Abstract

At present there exists a large gap in size, performance, adaptability and robustness between natural and artificial information processors for performing coherent perception-action tasks under real-time constraints. Even the simplest organisms have an enviable capability of coping with an unknown dynamic environment. Robots, in contrast, are still clumsy if confronted with such complexity. This paper presents a bio-hybrid architecture developed for exploring an alternate approach to the control of autonomous robots. Circuits prepared from amoeboid plasmodia of the slime mold *Physarum polycephalum* are interfaced with an omnidirectional hexapod robot. Sensory signals from the macro-physical environment of the robot are transduced to cellular scale and processed using the unique micro-physical features of intracellular information processing. Conversely, the response form the cellular computation is amplified to yield a macroscopic output action in the environment mediated through the robot's actuators.

Keywords: Autonomous robots; Molecular computing; Coupled oscillators; Biologically inspired robotics

1. Introduction

The prevalent approach to robot control is based on 'behaviour decomposition'. The interaction loop between robot and environment is decomposed and treated as individual modules. This concept simplifies controller design and proved successful in many robotic systems including humanoid robots (e.g., Fujita et al., 2003). With 'behaviour decomposition', the flexible selection of modules is critical for an adaptive and autonomous behaviour of the robot. One approach to address the decomposition problem disaggregates learning and interaction with the environment. While in learning mode, the robot learns or self-organises a proper module in terms of some environmental signal provided by a teacher, and subsequently uses this module in interaction mode.

The use of 'behaviour decomposition' enables robots to successfully work in either a stable work space or with the support of a teacher. The scheme can be implemented in localised (Tani and Nolfi, 1999) or distributed fashion (Tani et al., 2004). Without a teacher, however, delineating a boundary for the environment becomes an insurmountable challenge as the environment has no natural limit. In an unknown dynamic environment a disaggregation of learning mode and interaction mode is not useful unless this manifestation of the 'frame problem' (McCarthy and Hayes, 1969) can be overcome. In an attempt to address this difficulty, Brooks (1990) proposed the 'subsumption architecture' and implemented it in insect-like robots (Brooks, 1991). This route, however, proved difficult to scale up because of computational cost. Quite a number of extensions and modifications of the above architectures have been reported, but the quest for genuinely autonomous robot control, capable of coping with an unknown complex environment, has not yet been successful. Nonetheless,

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organisms seemingly do not face the difficulties encountered with robots. Cariani (1992) points to the plasticity of architecture and its ability to form appropriate sensory, computational, and effector structures in response to direct interaction with the environment. Whether it is possible to replicate this plasticity on a virtual level in a formal computational model for execution on digital machine is unclear. Undoubtedly, simulation is a powerful tool for studying design concepts. Ziegler et al. (1998) were among the first to consider the biochemical metaphor for robot control and employed simulation to evolve highly abstracted chemical controllers. More recently, Adamatzky et al. (2004) have taken steps towards the realisation of a chemically controlled robot based on reaction-diffusion computing with an excitable chemical medium (cf. Rambidi, 2005).

Conrad (1989, 1999) argued that the common digital mode of computation is fundamentally different from the context-sensitive mode of information processing found in biological systems and any attempt to emulate it on a digital computer would be inherently inefficient. If Conrad's assertion holds then robots that face an unknown complex dynamic environment cannot be successfully controlled with a conventional computer. This is the case because the requirement to act in real-time precludes the use of an architecture that trades efficiency for programmability (Conrad, 1995). The medium of computation becomes significant. On this basis we decided to explore an approach that recruits intracellular dynamics to autonomous robot control.

1.1. Intracellular computation

Ideas from biological information processing have influenced numerous robot control architectures. Most of them draw their inspiration from neural networks. As a matter of fact, however, almost all known biological information processing occurs at the subcellular level. In consequence of the tremendous success of single cell organisms in our biosphere, this is the case even if we set aside molecular level computation within neurons. The significance of intracellular information processing has been recognised three decades ago (Conrad, 1972; Liberman, 1979). The picture that emerged since then shows a host of biochemical processes in the cell and its membrane contributing to signal processing and computing. Thus, far the mechanisms that confer the enviable computation power to cells are not understood. It is possible, however, to discern properties of the intracellular medium that contribute. Two principles are pertinent. One is shape-based self-assembly: Brownian motion provides a search mechanism that in combination with free energy minimisation enables the recognition of specific molecular coded signals in a highly complex chemical background. The other is conformational state change: the complex electrostatic interaction network formed by the atoms within a macromolecule integrates the electrostatic environment of the molecule and in accordance therewith modulates the properties of the molecule. Self-assembly facilitates communication among distant molecules, but is limited by diffusion speed. It can serve for signal integration through the assembly of multi-component supramolecular structures. More typically, conformational state change mediates signal fusion. The conformational dynamics in a molecule can be very rapid and signal propagation along lines of molecules in direct contact is accordingly fast. The two principles above are implemented with a large number of specialised components that have been picked through evolution from a combinatorially vast space of potential combinations of building blocks. The building block scheme extends beyond the molecular level to the cells themselves. A myriad of different cells, each specialised to operate in a particular environment, are found in nature. Let us now turn to our cell of choice for the robot controller.

2. *Physarum polycephalum*

The amoeboid plasmodium of the slime mold *P. polycephalum* is a large multi-nuclear single-cellular organism (Fig. 1A). In a fully developed plasmodium flat sheet-like areas at the edge are connected by more centrally located tubular structures as visible in Fig. 1B. Being a single cell, the plasmodium – which can extend to over 20 m in diameter – does not possess a nervous system. It relies on intracellular information processing to integrate local sensory information and to generate an appropriate response to stimuli. Different areas within the plasmodium communicate by protoplasmic flow. This oscillatory flow of protoplasma is called shuttle streaming and provides a transport mechanism for nutrition and signals. A dynamically reconfiguring network of tubes, formed from gelled cytosol, directs the flow of protoplasma as well as the overall movement and growth direction of the cell. It has been observed that the rhythm of shuttle streaming is synchronised with intracellular oscillatory behaviours such as oscillations in ATP concentration, Ca^{2+} concentration, and the plasmagel/plasmasol exchange rhythm (Ueda et al., 1986). This oscillatory rhythm is known to increase in frequency in the presence of attractive stimuli (glucose, warmth) and, conversely, slows down if a repulsive stimuli (blue light, salt) is encountered (Durham and