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Real-time Requirements and Restricted Resources: The Role of the Computing Substrate in Robots

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1 Computation and its Implementation

Existing robots are crude and clumsy compared to organisms. Over the past decade it became increasingly evident that the physical properties of the structural components of organism are crucial to their extraordinary performance, and that many cognitive capabilities can only be understood from a system level perspective that integrates body, control, and envrionment. This insight led to robot designs that exploit the physical characteristics of a robots' body [1] and more recently gave rise to designs in which the properties of the robot's body are the basis on which control dynamics self-organises [2]. If one takes the direction of these investigations further, one arrives at the point where control is not only exploiting the physics of the body, but is in itself directly driven by physics.

Within computer science the role of the physical substrate used to implement computation has largely been ignored. Presumably this is the case because already at the dawn of practical computing devices Turing's universal machine indicated that the ultimate theoretical capability of all adequate computing mechanisms may be the same. Crucial to the notion of universality is the freedom from time and space constraints. If resources are limited and response time is critical, as it is typically the case for both organisms and robots, then it is far from clear that conventional computing methods are the most suitable mode of information processing. Computation driven directly by the physics of the implementation substrate may harbour a significant advantage [3]. Arguably it is the only route to achieve life-like behaviour and endurance in a compact artifical device [4]. In this context novel forms of robot control employing non-programmable and unconventional information processors (e.g, [2, 5]) are of particular interest. We have implemented an experimental setup to explore the material-based information processing of a living cell in a robot control setting.

2 Cellular Robot Control

For our experiments with a robot under control of a living cell we have chosen the large multinucleated cell of the plasmodial stage of the slime mold *Physarum polycephalum*. This cell can be grown on agar in desired shapes by means of a negative plastic mask (Fig. 1). The cell body of the plasmodium undergoes continual reorganisation as the cell moves through and adapts to its environment. The cell, even though it can reach macroscopic proportions acts as a single integrated organism. Core to the distributed intracellular information processing that enables this behaviour are biochemical oscillations with concomitant rhythmic flow of protoplasm through tubular structures within the cell [6]. Through shaping the

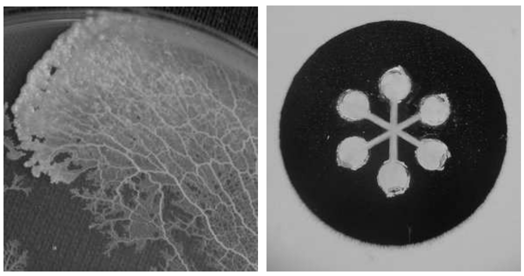

Figure 1: Plasmodium cultured on agar gel (left), and grown inside a black negative mask to form a coupled oscillator "physarum circuit" (right).

cell body by letting it grow within a plastic mask it is possible to implement a system of coupled oscillators [7]. The protoplasm flow gives rise to rhythmic changes in local thickness of the cell and allow for an optical readout of the oscillations by measuring the light transmission over the area of the cell. The ends of the six arms of the circuit shown in Fig. 1 each form an oscillator (1.5 mm diameter). These six oscillators exchange protoplasm with each other through tubular structures formed inside the narrow arms, and dynamically change their frequency, amplitude and phase. In nature sunlight is a repellent for *Physarum* and exposure of a plasmodium to white light will result in a change of its oscillations. It is therefore possible to interface the cell optically with white light for stimulation input and orange light for oscillation readout.

2.1 Experiments

The results discussed below have been obtained by simulating the motion of an omnidirectional robot; elsewhere we describe experiments with a real hexapod robot [8]. The simulator is designed to capture the behaviour of the real robot which comprises six legs with only one degree of freedom each, and six light sensors. In the simulations oscillations recorded from the plasmodium are mapped into locomotion of the simulated robot as follows:

$$\begin{pmatrix} X_{t+1} \\ \\ Y_{t+1} \end{pmatrix} = \begin{pmatrix} X_t \\ \\ Y_t \end{pmatrix} + \alpha \sum_{i=1}^{6} \mathrm{D}_t^i \, \mathrm{T}_t^i \begin{pmatrix} cos(\frac{\pi}{3}i) \\ \\ sin(\frac{\pi}{3}i) \end{pmatrix}$$

Where (X_t, Y_t) represents the position of the robot in the 2D space at time t, α is a scaling constant, D_t^i is the relative thickness value of i-th *Physarum* oscillator at time t, and T_t^i is regression coefficient of this oscillator's oscillation over the past 100 samples, equivalent to 200 s of measurements.

The investigation of the effect of light stimuli on the transitions among oscillatory patterns in physarum circuits are ongoing. The results described here are indicative of the behaviour of the robot in such experiments. The robot is simulated as a point moving in a plane and controlled by the oscillation data generated with a physarum circuit stimulated by white light. White light reduces the oscillation amplitude of stimulated oscillators while the amplitude of unstimulated oscillators increases. Optical measurements of the oscillations in the plasmodium cell provide the data used to update the position of the robot in the plane.

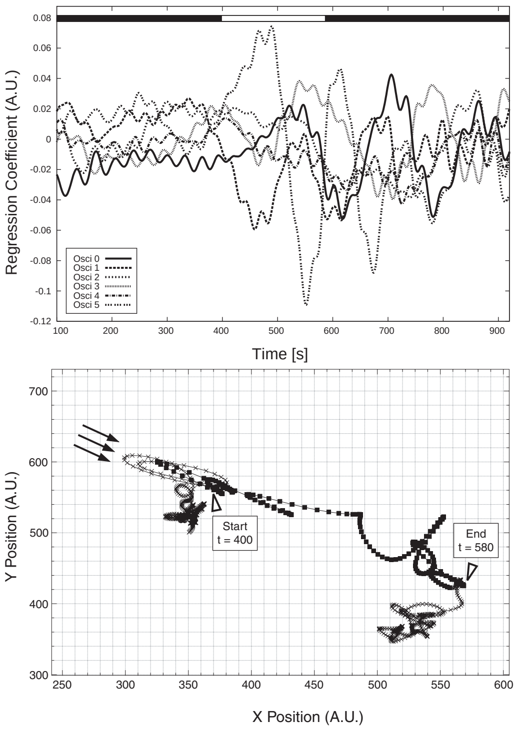

Figure 2: Negative phototaxis of the simulated robot controlled by a real cell. Change in regression coefficients for the six oscillators during irradiation of oscillator 1 (t = 400 s to t = 580 s), response to light exposure from the direction indicated by the arrows (bottom).

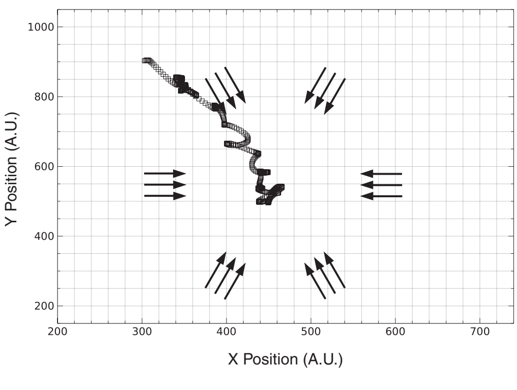

Figure 3: Escape from a trap with light exposure from all sides.

Figure 2 illustrates negative phototactic behaviour. Without light stimulation (t = 0 s to t = 400 s) the robot moves randomly. Upon stimulation of oscillator 1 through illumination with white light the oscillation pattern of the plasmodium changes (t = 400 s to t = 580 s). The resulting oscillation pattern gives rise to an effective motion away from the side of stimulation.

It is now interesting to consider the case in which the robot is surrounded by light sources from all directions. A robot exhibiting strict negative phototaxis would be trapped by its own behaviour. One of the astonishing features of many natural information processing systems is their ability to cope with unforseen challenges and to overcome even paradoxical situations. For the simulated robot controlled by oscillations recorded from a living cell we found that in many trials it will be trapped, but occasionally it escapes from the contradictory stimulation (Fig. 3).

2.2 Conclusion

Organisms spectacularly outperform artifical devices in their ability to succesfully negotiate an ambiguous, and unpredictable environment. The complexity of such tasks together with severe restrictions on material and energy that can be allocated to them renders conventional computing schemes unlikely candidates for closing this performance gap. Information processing concepts that exploit the physics of the implementing material directly are more likely to achieve the efficiency that will be required for robots with more life-like characteristics. Present technology, however, does not provide an easy means to implemnet such physics driven architecture. We have turned to the slime mold *Physarum polycephalum* to assemble a bio-hybrid system that uses intercellular information processing to explore the possibility of physics driven computation in robotics.

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