Integration of Cellular Biological Structures Into Robotic Systems

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1 Introduction

Ideas from biological information processing have influenced numerous robot control architectures. Most of them draw their inspiration from neural networks. 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]. 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.

Arguably this step is necessary to narrow the performance gap between man-made devices and biological systems. All organisms require information processing to defend their intricate organisation against the onslaught physical entropy. As a consequence organisms exhibit an intriguing sophistication in overcoming computationally difficult challenges. This is the case even for simple life forms and individual cells. Robots and organisms both need to process sensory information from a range of modalities and make decisions based on noisy ambiguous data. Not only do they need to process the sensory inputs and respond in real-time with appropriate actions, but they need to do this under the resource restrictions imposed by their size. Organisms approach this challenge by directly exploiting the physico-chemico properties of their molecular materials—in stark contrast to present computing technology the formalisms of which are defined in disregard of the physical substrate used to implement. Brooks observed that 'the matter that makes up living systems obeys the laws of physics in ways that are expensive to simulate computationally" [2] and Conrad argued that programmable computing is necessarily inefficient compared to nature's information processing [3, 4]. From what has been stated above, it appears worthwhile to give more attention to the role computational substrates may play in cognitive systems [5]. Taking heed of the clues from biology, macromolecular materials appear particularly attractive [6].

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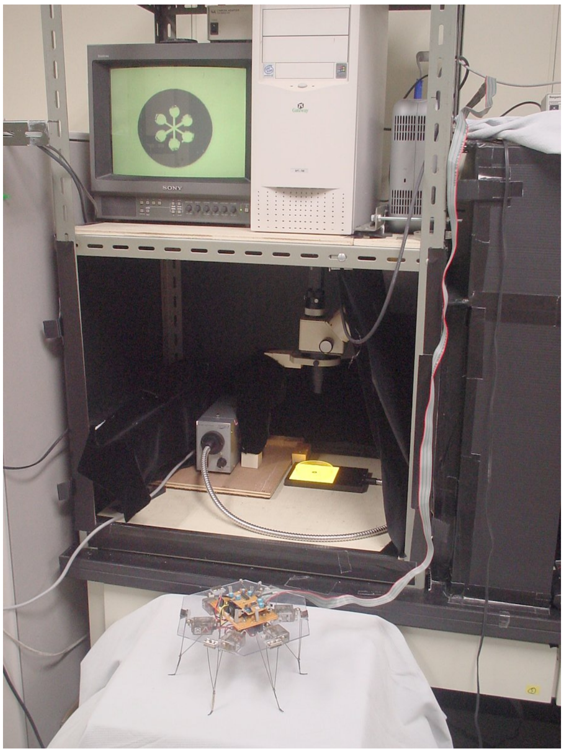

Figure 1: A tethered hexapod robot optically interfaced with a *Physarum polycephalum* cell [7].

2 On-board Cellular Robot Control

We endeavour to sketch a potential route to recruiting some of nature's information processing efficiency for technical applications: the integration of living cells into bio-electronic hybrid robot control devices. In this approach, selected features of the robot's environment are mapped into features of the environment of a living cell. Conversely, the response of the cell is mapped back onto the actuators of the robot. Fig. 1 shows an early implementation of this concept. The cell employed in the experiments is the plasmodial stage of the slime mould *Physarum polycephalum*. This large multinucleated cell can be found on decaying wood and feeds on bacteria and organic matter. Despite its macroscopic size (it typically grows to $>$100 cm^2) the cell acts as a single integrated organism. Too large to rely on diffusion, it uses rythmic contractions to distribute materials within its cell body [8, 9].

Central to our approach is the cell-robot interface. Both, optical and electronic interfaces for plasmodia of the slime mold have been implemented. Our first approach to cellular robot control had purposely set aside the question of whether it is practicable to integrate a cell-based controller into a small robot [10]. In recent work we have addressed this issue. The current architecture uses the oscillator design suggested by Takamatsu and Fujii [11] but with a mask on which electrodes have been patterned. The mechanical oscillations of the plasmodium that were previously detected as local changes in light transmission of the cell body, can also be detected by the change in impedance among the electrodes integrated in the mask [12, 13].

Fig. 2 shows a mask with two independent plasmodia (labeled *Physarum* in the figure). Each is grown into a cutout in the circuit board that acts as mask to confine the plasmodium into a dumbbell shape with a left and a right well connected by a channel. Two pairs of electrodes are available for each well [11]. The image shows the underside of the chip through a cutout in the circuit board with the circuit for measuring the impedance. During operation, this face of the mask would be covered with a layer of agar. To monitor the oscillations of the slime mould cell, we employ an integrated

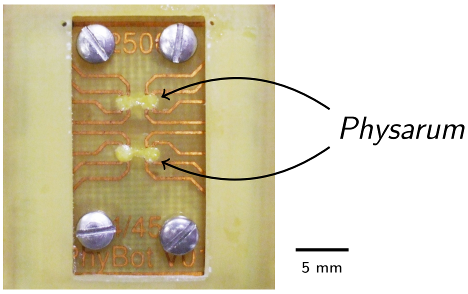

Figure 2: Electrical interfacing of the *Physarum* plasmodium.

circuit capable of measuring impedance at up to 100 kHz. For further details refer to the Methods section.

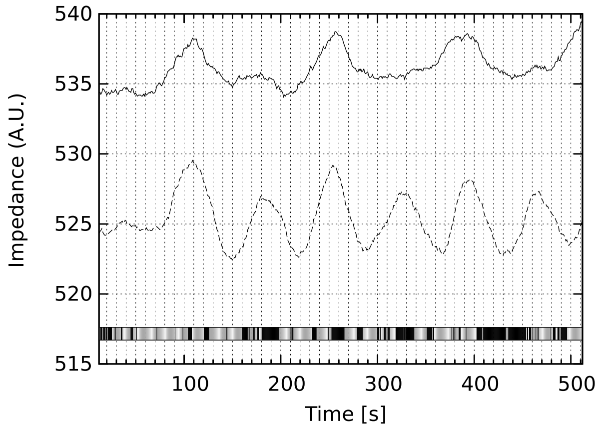

Figure 3: Change in impedance at 100 kHz concomitant with the volume oscillations of two parts of a single slime mould cell.

The impedance across each of the eight pairs of electrodes is measured once per second, the maximal rate our multiplexed setup permits. Fig. 3 shows the signals originating from two wells, i.e., two ends of a single cell, after a moving average filter has been applied to reduce noise.

The two curves show the moving averages over 15 samples, recorded from the right and left well of the plasmodium. The phase-relationship between the two wells is shown in the bar across the bottom of the figure where white and black indicate in- and out-of-phase, respectively. In the experiment described here, this binary phase-relation is used to steer a robot. The minimalist robot, pictured in Fig. 4, was inspired by Braitenberg's vehicles [14] and is designed as a test platform for unconventional controllers.

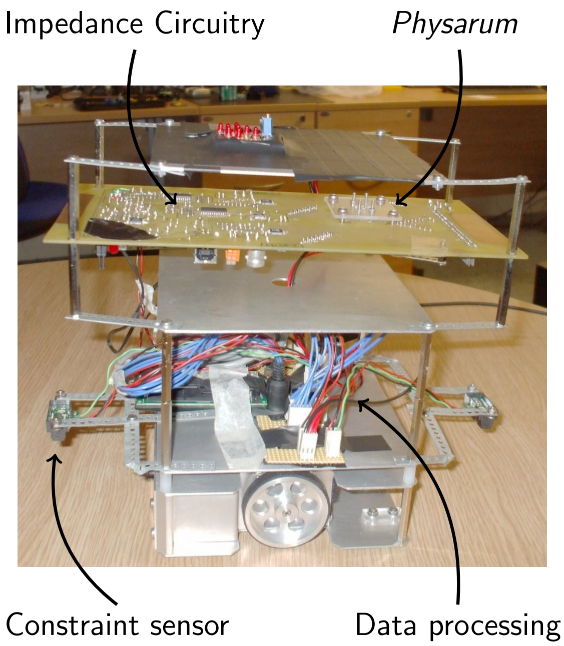

Figure 4: Robotic platform with the *Physarum* chip installed on the impedance circuit board.

In the present experiments a simple one bit actuator control patterned on the control of actuation in bacterial chemotaxis [15, 16] has been employed. The control bit toggles between the state of turning in a random direction or moving forward. The state is updated at a rate of 1 Hz, whereby in-phase oscillation of the two wells mapped to random turning and out-of phase oscillation is mapped to straight moves. A typical segment of a trajectory without stimulation is shown in Fig. 5. An illuminated target on the robot is tracked for position and orientation with an overhead camera. If the robot reaches the boundary of the arena, forward commands are ignored and only turns are executed.

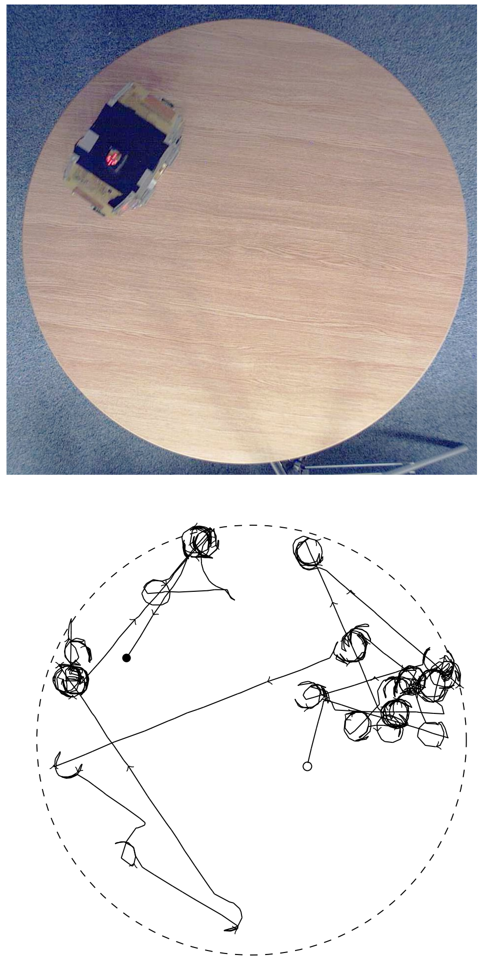
A
B

Figure 5: The arena to which the robot is confined in the view of the tracking camera (A), and the trajectory of the robot corresponding to the signals shown in Fig. 3; ∘ marks the start and • the end of the segment (B).

So far this prototype only implements the actuator side; the facility to transmit the sensory stimulation to the slime mould is not yet completed. Nevertheless, preliminary tests indicate that in principle the integration of living cells into a robot is feasible.

3 Vision: Living Devices

Microbial cells are routinely employed in many engineered processes. Their ability to self-reproduce offers a cheap and fast route to deploy complex nano-scale systems. Parallel to the progress in molecular biology, the traditional breeding (e.g., to optimise baker's yeast) has been augmented with direct modification of cell lines to introduce new capabilities (e.g., production of human insulin). What started as metabolic engineering with static changes to the genome of the cells, is now, as "synthetic biology," on the way to engineer dynamic control structures and may eventually allow the design of application specific cells [17]. In addition to self-reproduction, cells provide quality control and testing at the point of assembly for many of their macromolecular products and can replenish their components and thus operate under adverse conditions.

Another important development is the increasing sophistication of lab-on-chip and microfluidic technologies that make it possible to maintain a controlled microenvironment for a cell. The confluence of both of these lines of research opens up a new engineering direction where living cells are tightly integrated with conventional technology. In the resulting devices, living cells are an essential component. Examples are "living sensors" [18, 19] and "living pumps" [20, 21]. In the coming decades such an approach will almost certainly be explored for elementary cognitive systems and we see the ongoing work described in the previous section as a small step in this direction.

4 Potential for Space Applications

The key features of cells that may be of potential interest in the space field are:

1. Self-repair capability
2. Self-reconfiguration capability
3. Efficient in material requirement
4. Efficient in energy usage

Cells, in general, will recognise a wide variety of damages and take steps to repair themselves. Some extremophile microbes, in particular, posses elaborate innate mechanisms to actively maintain their molecular organisation. The material efficiency of cells usually permits redundancy of functional components (especially proteins) and information carriers (double stranded DNA) and thus enables them to autonomously recover from many injuries. A slime mould plasmodium can contain many millions of redundant copies of its genetic information within a single cell. Potentially cells could offer a unique solution to the problem of transporting a complex functional system over a long period though a harsh environment when shielding is impractical due to weight constraints. It is also possible to imagine applications of cells to grow a functionalised surface such as a sensory-skin for a robot. Only a small volume of seed cells (or spores) would need to be protected from radiation damage during transit and after formation such a surface may be able to self-heal when damaged.

Of course there are also problems. Devices containing living cells pose the danger of spreading organisms from Earth or may interfere with the search for indicators of non-terrestrial life. Cells do have different requirements from inanimate materials, have a quite restricted operating temperature range, need to be protected against loss of moisture, and in general have idiosyncratic supply needs.

5 Conclusion

Robots and organisms face the same problem: they need to act in real-time in a complex environment and are severely restricted in material and energy that can be allocated to their information processing needs. Organisms, however, spectacularly outperform current robots. It appears increasingly likely that the choice of computational substrate is critical to their success.

The integration of living cells into robotic systems is feasible, albeit at its infancy. Cells offer many properties that are unlikely to come within reach of conventional technologies within the foreseeable future, in particular self-reproduction and self-repair of complex heterogeneous structures. Devising bio-hybrid architectures in which cells confer their unique characteristics in a beneficial manner to the system as a whole, will be among the key challenges in this field.

Conceivable early application domains in space research may lie in non-critical subsystems where the integration of living devices potentially offers the opportunity to deploy systems of high complexity with a reasonable chance to recover, or grow functionality after extended periods of exposure to high electromagnetic radiation flux. It goes without saying that any application scenario needs to exclude the possibility of contaminating celestial bodies.

Methods

Electrodes were patterned on a small circuit board (PCB); the wells drilled (cf., Fig. 2) and a channel cut between each pair of wells. The design of the electrode pattern allows for two independent plasmodia. Each plasmodium is in a dumbbell configuration with two 1.6 mm diameter wells at a centre-distance of 2.5 mm and connected by a 0.4 mm wide channel. Two pairs of electrodes are available on each well for a total of 16 electrodes on the board. The copper side of the circuit board is laminated except at the areas where it connects to the impedance circuit. To provide the plasmodium with a moist surface the board is placed with the laminated side on layer on agar. *Physarum polycephalum* was cultured on 1.5% agar gel and fed with oat flakes. It is possible to let the slime mould grow onto the agar surface masked with the circuit board. However, to accelerate the preparation for the experiments we proceed as follows. First a tubular section of a plasmodium is excised from a large culture and implanted into the channel. Next the wells, i.e., the holes drilled in the circuit board are filled with material from the anterior, fan-like parts of the culture. By covering the top side of the circuit board with a thin, gas-permeable PDMS membrane the plasmodium is fully enclosed, which enables experiments of several hours duration. A perspex frame holds the layers together. We refer to this stack of agar sheet, laminate, (copper layer) PCB and PDMS as a “chip”. After an incubation period of 2–3 h in the dark, during which the material in the dumbbell shaped mask fuses into a single plasmodial cell, the chip is ready for experiments. We typically prepare several plasmodia in chips and select those that show a strong oscillation signal.

A custom circuit based on an impedance converter/network analyser (AD5933, Analog Devices, www.analog.com) and two multiplexers (ADG732, Analog Devices) in combination with custom software enables the monitoring of the cellular oscillations through either a universal serial bus or I^2C interface [22]. The actual implementation of the circuit used in the experiments described here, is a prototype with easy access to all components and the ability to isolate blocks for testing. We expect to reduce the layout to less than a quarter of its current size (cf. Fig. 4). Impedance is measured at 100 kHz applying an excitation of $\approx$1 V peak-to-peak.

The impedance circuit is connected through I^2C to a gumstix computer (www.gumstix.com), which samples all eight electrode pairs at $\approx$1 Hz and stores the information in flash memory. The data from all electrodes on both plasmodia on the chip is recorded for later analysis. For driving the robot, however, one of the plasmodia is selected. For each of the two wells filled by this plasmodium, only the data from the pair of electrodes that show the stronger oscillation is selected for further processing. To reduce noise the moving average over 15 samples is computed (curves in Fig. 3). This provides a sufficient signal even though not much provision for screening against noise was made in the prototype, except separating the power supply for the impedance circuitry from the supply of the robot and gumstix. After the noise filtering, the drifting-component in the signal is removed by subtracting the 15 s delayed signal. Then the phase-relationship between the two signals originating from the left and right well is classified according to whether both signals have equal or opposite sign (bar at the bottom of Fig. 3).

The impedance circuit board carrying the *Physarum* chip and the gumstix are mounted on custom designed wheeled robot base [23]. A simple rule is used to map the phase-relationship between the two wells onto the motion of the robot: If the signs of the signals are equal the robot takes a random turn, if the signs differ the robot moves straight forward. Within the 1 second period between state updates the robot can move at most 9 cm. The robot is confined to a round table with 1 m diameter by means of an infrared sensor. If the sensor moves off the table, further “forward” commands are ignored by the low-level driver circuit of the robot until a rotation brings this constraint sensor back onto the table surface. For tracking of the robot a network camera (AXIS 206M, www.axis.com) is mounted above the table and images captured at a rate of 3 frames per second. An illuminated arrow-shaped target mounted on the robot is located automatically in the frames to obtain the trajectory of the robot.

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