Information-Theoretic Aspects of Control in a Bio-Hybrid Robot Device

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Abstract

Information processing in natural systems radically differs from current information technology. This difference is particularly apparent in the area of robotics, where both organisms and artificial devices face a similar challenge: the need to act in real time in a complex environment and to do so with computing resources severely limited by their size and power consumption. The formidable gap between artificial and natural systems in terms of information processing capability motivates research into the biological modes of information processing. Such undertakings, however, are hampered by the fact that nature directly exploits the manifold physical characteristics of its computing substrates, while available theoretical tools in general ignore the underlying implementation. Here we sketch the concept of bounded computability in an attempt towards reconciling the information-theoretic perspective with the need to take the material basis of information processing into account. We do so in the context of *Physarum polycephalum* as a naturally evolved information processor and the use of this organism as an integral component of a robot controller.

Introduction

Technological progress makes ontological distinctions between classes of entities, like those between the natural and the artificial, or between the living and the non-living, more and more porous. Unconventional computing devices contribute to this process. Hybrid artifacts, for example, try to overcome the theoretic and physical limits of information processing in solid-state realisations of digital von Neumann machines by exploiting the self-organisation of naturally evolved systems in engineered environments (Zauner, 2005). Biological systems evolved enviable computing capabilities to cope with noisy and harsh environments and compete with rivalling life forms. Information processing in biological systems, from single-cell organisms to brains, directly utilises the physical and chemical processes of cellular and intracellular dynamics. Arguably, therefore, if one aims at narrowing the still formidable performance gap between artificial and biological systems, the material basis of their information processing cannot be ignored. An information-theoretic analysis of hybrid computational systems must, hence, take the physical properties of material substrates used for computation into account. By 'information theory' is meant here, not only Shannon's statistical theory of communication (Shannon and Weaver, 1949), but the structural science that constructs mathematical models of the form, meaning, and use of information and applies them to empirical phenomena. The empirical diversification of information theory would allow the engineering of unconventional computers to utilise empirical knowledge of naturally evolved systems more efficiently since the requirements for particular computational tasks could then be stated directly in terms of physical specifications of computational media (Tsuda et al., 2006a).

To explore the border zone between information theory and the physics of self-organising systems, it is necessary to elaborate a *theory of bounded computability* that relates generic traits of information-processing systems, not with general time and space bounds (as in the theory of computational complexity (Papadimitriou, 1994)), but with specific physico-chemical constraints on the realisation of such systems in different classes of computational media (analogously to the theory of bounded rationality (Simon, 1997)). In a theory about possible relations between material media and computational functions of physical information-processing systems, the concept of information must integrate the distinction between the behavioural structure of a system, its functional structure, and the structure of its material medium. Otherwise, the complex structural interplay of matter, function, and behaviour that constitutes the very nature of information, could not be adequately analysed and the concepts of information theory would add nothing new to physics and chemistry. For example, the more medium and function are considered being inseparable, the less it is reasonable to use information theory and its fundamental distinction between form and 'in-formed' media. Not only must one and the same information be regarded as representable by different physical entities; various material substrates must also be considered being possible media for the same information-processing function.

If computers will develop along an increasing number of technological ramifications, a theory of bounded computability must become more and more empirically diversified. On the other hand, the theory has also to define its basic concepts more and more generally to let a unified approach to the analysis and construction of computers appear still promising. This paper first introduces some information-theoretic ideas that might be useful for constructing a general architecture of unconventional computing systems from elements already tried and tested in the architecture of conventional ones. Such a rather reformist approach of step-by-step generalisation is, of course, not the only one possible; alternatively, the theory might start from scratch by introducing a most general mathematical framework in which more revolutionary concepts that try to capture essential aspects of self-organising systems can be defined and compared exactly (Tsuda et al., 2004). The utility of an information-theoretic framework is to be tested by using it in the analysis and synthesis of real information-processing systems. Thus, a particular unconventional computing system based on the true slime mould *Physarum polycephalum* and used as a bio-hybrid robot controller will be presented. Finally, information-theoretic aspects of the bio-hybrid controller will be described on a coarse-grained level using the ideas introduced first. By showing that the processes in such a controller can be systematically categorised from a general information-theoretic perspective, this description is meant to be a preliminary step towards a theory of bounded computability.

Syntactic, Semantic, and Pragmatic Representation of Information

A full-fledged concept of information integrates the distinction between the behavioural structure of a system, its functional structure, and the structure of its material medium. Information is not a concrete entity that can be localised in a particular part of a system; it is an abstract structure that covers the complex systemic interplay of matter, function, and behaviour. Basic information-theoretic concepts that are general enough to describe this interplay for a spectrum of systems as broad as possible, are the concepts of syntax, semantics, and pragmatics (Artmann, 2008). In the following, they are considered denoting different ways of representing physical systems from a unified information-theoretic point of view.

First, information can be represented *syntactically* by the material structure of a physical system. The spatio-temporal organisation of the material components of a system is then regarded as an actualisation of the syntactic structure of information in a physical medium. The material structure of the medium actually stands for the syntactic structure of information that is constituted by the set of relations of its elements. The dynamics of self-organisation of the physical medium drives the processing of the syntactic representation of information, but does not require a specific information-theoretic explanation. An important criterion for classifying computational media from a syntactic perspective is how efficient media are in processing syntactic representations of information to perform specific computational tasks.

Second, information can be represented *semantically* by the functional structure of a physical system. The causal order between the material components of a system is then regarded as an implementation of the semantic structure of information by a physical medium. This semantic structure is constituted by codes. A code connects two syntactic structures with each other. 'Code' is the information-theoretic name of a mapping that relates, in case of encoding, each of the possible syntactic elements of a message to a possible element of a signal and, in case of decoding, each of the possible syntactic elements of a signal to a possible element of a message (Cover and Thomas, 2006). The dynamics of self-organisation of the physical medium implements the semantic structure of information by encoding and decoding syntactic structures in physical processes. From the perspective of semantics, it is necessary to interpret the present state of (a part of) a system as encoding the future state (of another part) of it. An important semantic criterion for classifying computational media is how general the codes used in a medium to implement semantic representations of information are, i.e., to which degree the codes are able to differentiate between possible messages under given boundary conditions.

Third, information can be represented *pragmatically* by the behavioural structure of a physical system. The pattern of interaction between the system and its environment is then regarded as an effectuation of the pragmatic structure of information through the agency of a physical medium. The pragmatic structure is constituted by transformations of boundary conditions on coding. When is a message selected for being encoded, when is a signal decoded, and how does the code originate? Generalising the idea that information is constituted pragmatically by the effect of a signal on its receiver (MacKay, 1969), the definition of the pragmatic structure of information involves at least two syntactic orders and one semantic mapping. The dynamics of self-organisation of the physical medium changes internal and external conditions of information processing in the system. From the perspective of pragmatics, it is necessary to interact with the present behaviour of a system in order to let its dynamics lead it to a particular future behaviour. An important criterion for classifying computational media from a pragmatic perspective is how versatile media are in effectuating transformations of the system's behaviour under changing boundary conditions, i.e., to which degree the behaviour of the system is able to adapt itself to different environments.

A theory of bounded computability, which relates generic traits of information-processing systems with specific physico-chemical constraints on the realisation of such systems in different classes of computational media, must deal with the interplay of syntactic efficiency, semantic generality, and pragmatic versatility. To get a first idea of this interplay, a real computing system whose further development requires information-theoretic backing, should be analysed. For this purpose, the following section introduces a naturally evolved information processor, and the section after the next describes how it is used in a bio-hybrid robot controller.

Physarum polycephalum as Information Processor

The plasmodium of the true slime mould, *Physarum polycephalum*, is an amoeba-like unicellular organism, whose body size ranges from several hundred microns to a radius of more than one meter (Fig. 1). Despite its large size, the single cell acts as an integrated organism and is known for its distributed information processing.

A plasmodial cell of *Physarum polycephalum* consists of an ectoplasm tube that encloses an endoplasmic core. The former is a gel membrane layer, while the latter is a more fluid state of the protoplasm (Wohlfarth-Bottermann, 1979). In the ectoplasm tube, cytoplasmic actomyosin periodically aggregates to form sheet-like structures and then unravels into fibrils. These structural changes create a hydrostatic pressure gradient within the cell, and eventually give rise to a flow of ectoplasm shuttling from one location in the cell to other parts of the cell and back. If a cell is not stimulated, this contractile rhythm is synchronised throughout the cell. However, when a local part of a cell is exposed to an external stimulus such as food or white light, it leads to desynchronisation of the rhythm. The frequency of the oscillating rhythm at the stimulated part increases if it is an attractive stimulus, or decreases if it is repulsive. Such local frequency change affects oscillations of other parts through protoplasmic streaming and forms a spatial phase pattern in the cell (Hejnowicz and Wohlfarth-Bottermann, 1980; Matsumoto et al., 1986; Tanaka et al., 1987). The emerging global phase pattern eventually determines the direction of migration, i.e., the behaviour of the organism (Matsumoto et al., 1988).

This mode of information processing affords scalability to the plasmodium. As long as the plasmodium is able to form the phase gradient of the contractile oscillation rhythm within its single-cell body, it reacts to various external stimuli in the same fashion no matter how large it grows. Central to this size-invariant behaviour is the spatial phase pattern of the oscillation rhythm formed within a cell. It emerges from the interaction of the intracellular dynamics of the plasmodium and the environment triggered by a contact with an external stimulus and the plasmodium. Several theoretical models have been proposed to explain the behaviour (Miura and Yano, 1998; Miyake et al., 1996) based on the theory of positional information (Gierer and Meinhardt, 1972). It is interesting to note, that the information processing in the cell can access information about past states. Nakagaki and his colleagues found if it is exposed to periodic environmental changes the plasmodium is able to anticipate the next change by changing its behaviour at the time a periodic change is next due to occur; the memory persists over several hours (Saigusa et al., 2008).

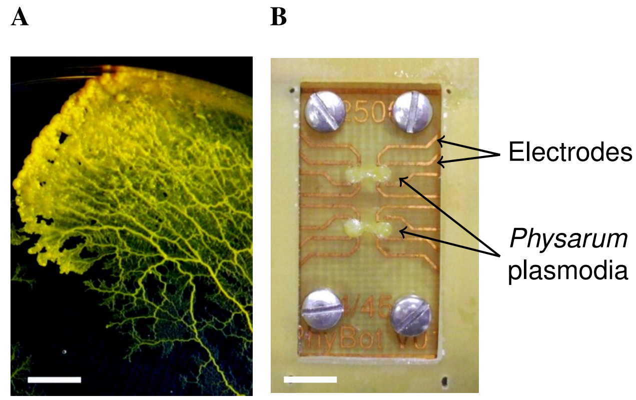

Figure 1: The plasmodium of the true slime mould *Physarum polycephalum* growing on the 1.5 % agar gel plate (A) and growing in the *Physarum* chip (B). A white bar on each panel is 5 mm.

Cellular Robot Control

The information-processing abilities of the plasmodium together with its humble requirements, suggest to use this simple organism in hybrid systems that fulfil some function for the generation of adaptive behaviour in engineered systems. For this purpose, the contractile oscillation dynamics of the cell was employed to control a robot.

Previously we worked on a bio-hybrid robot system controlled by the plasmodium, in which a robot and the plasmodium are connected with a bi-directional optical interface (cf. Tsuda et al., 2006a,b). However, the optical interface design sets the limit for the complete integration of the cell into bio-hybrid robot devices because the robot was remotely controlled by the plasmodium, which was located under a microscope in a humidity-controlled chamber.

Our recent work addresses this issue. As seen in other robotic systems using uncomventional computing devices (Adamatzky et al., 2004), we focused on an on-board robot controller design to integrate the plasmodium into an autonomous robot. For implementing the design, a new interface between the robot and the cell is required. The optical measurement of the plasmodium's oscillations required bulky equipment and it was therefore desirable to explore other technologies for monitoring the activity of the plasmodium. A custom circuit board for electrical impedance spectroscopy (EIS) has been developed (Macey, 2007) and mounted on a small wheeled robot platform (Jones, 2006).

Figure 2 shows the new setup of the bio-hybrid robotic system. The system consists of four components: a

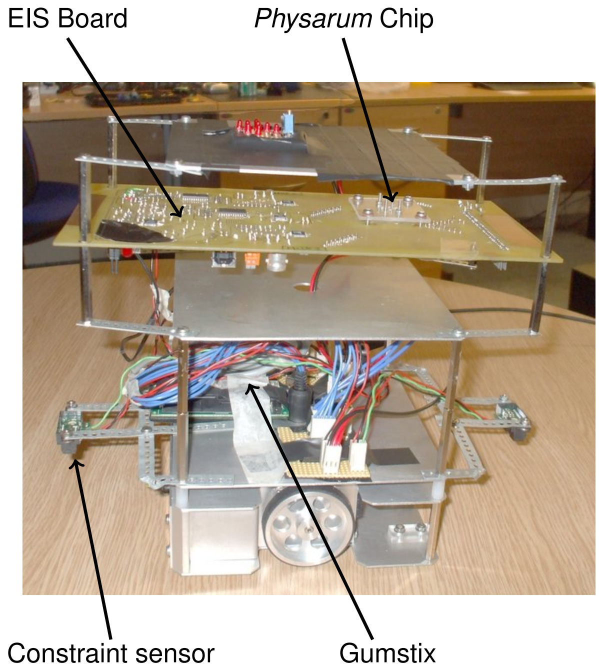

Figure 2: The complete setup of the robotic system driven by the *Physarum* plasmodium.

Physarum chip (Fig. 1B), the EIS board, a small gumstix computer, and a wheeled robot base. In this configuration the cell's oscillations are read through impedance measurements and mapped onto the wheel motion of the robot base. The current implementation of the un-tethered robot still lacks the interface between the cell and sensors on the robot, i.e., the robot is driven by the cell's oscillating pattern without any feedback to the cell.

The *Physarum* chip is a small printed circuit board (PCB) containing two plasmodial cells and mounted with a plexi glass frame to the EIS circuit board. Each plasmodium is confined in a dumbbell-shaped cut-out of the PCB sheet, as shown in Fig. 1B. The dumbbell-shape design follows (Takamatsu et al., 2000a,b) who studied the oscillation patterns of the plasmodium confined to this shape.

The impedance measurement circuitry (EIS board) allows for non-invasive monitoring of the plasmodium's oscillation activity. Fig. 3A and B show signals from two consecutive time periods of a single experiment. The two curves show the magnitude of the impedance from the left and right circular areas (wells) of the dumbbell shaped plasmodium after a noise filter has been applied. Measured impedance data from the EIS board is converted into commands for the robot control and stored for subsequent analysis by the on-board gumstix computer.

It is known that the plasmodium if confined to the dumbbell shape show in-phase and out-of-phase oscillation patterns between the two wells (cf. Takamatsu et al., 2000b). Based on this observation, we introduced a simple mapping from oscillations to robot movement. The mapping is inspired by the motor-control in bacterial chemotaxis (Adler and Tso, 1974; Scharf et al., 1998): If the signal from the left well and the signal from the right well are in synchrony, the robot pivots either left or right randomly, otherwise the robot moves straight. The update cycle from impedance measurement to change of robot behaviour is once per second; for details see the materials and methods section at the end.

The trajectories of the robot that results from this mapping are shown in Fig. 3C and D. During the time period shown in panel A of Fig. 3, the oscillations of the two parts of the plasmodium cell are predominately synchronised and accordingly the robots trajectory shows many random pivot turns (Fig. 3C). On the other hand, in the period shown in panels B and D, the robot runs straight more often because the oscillation pattern switched to an out-of-phase mode about midway through the period shown in (Fig. 3B).

Although the current implementation of the bio-hybrid robot has only a one-directional interface from the plasmodium to the robot, the preliminary experiments indicate the feasibility of integrating a living cell into the controller of an autonomous robot. The next required step is the implementation of the converse interface from the robot to the cell, i.e., inputs to the plasmodium. This may be achieved by illuminating the cell with white or blue light from LEDs according to signals from sensors on the robot. This part of the interface is still under investigation, however we expect it to be much simpler to realise than the cell-to-actuator interface described above.

To close the interaction loop of artificial control, natural organism, and environment so that it can be used for the construction of an adaptively behaving robot, this loop can be analysed in terms of information theory. In the following, it will be described on a coarse-grained level that allows for a general differentiation between the syntactic, semantic, and pragmatic representation of information. The focus is on the plasmodium as a medium that does bounded computation under specific internal and external physico-chemical constraints on information processing.

Application of Information-Theoretic Framework to the Bio-Hybrid Robot

The following general information-theoretic description of the interaction loop of artificial control, natural organism, and environment assumes a bidirectional interface between the organism and the robot's sensor and actuators as already implemented in the earlier, tethered robot (Tsuda et al., 2007). As mentioned above, a bi-directional interface for the robot with the integrated cell is still under development. For the following discussion, however, it is not crucial whether the plasmodial cell is located in the robot; for practical applications of course it is.

Where is information represented semantically in the interaction loop? First and foremost, in the code-based func-

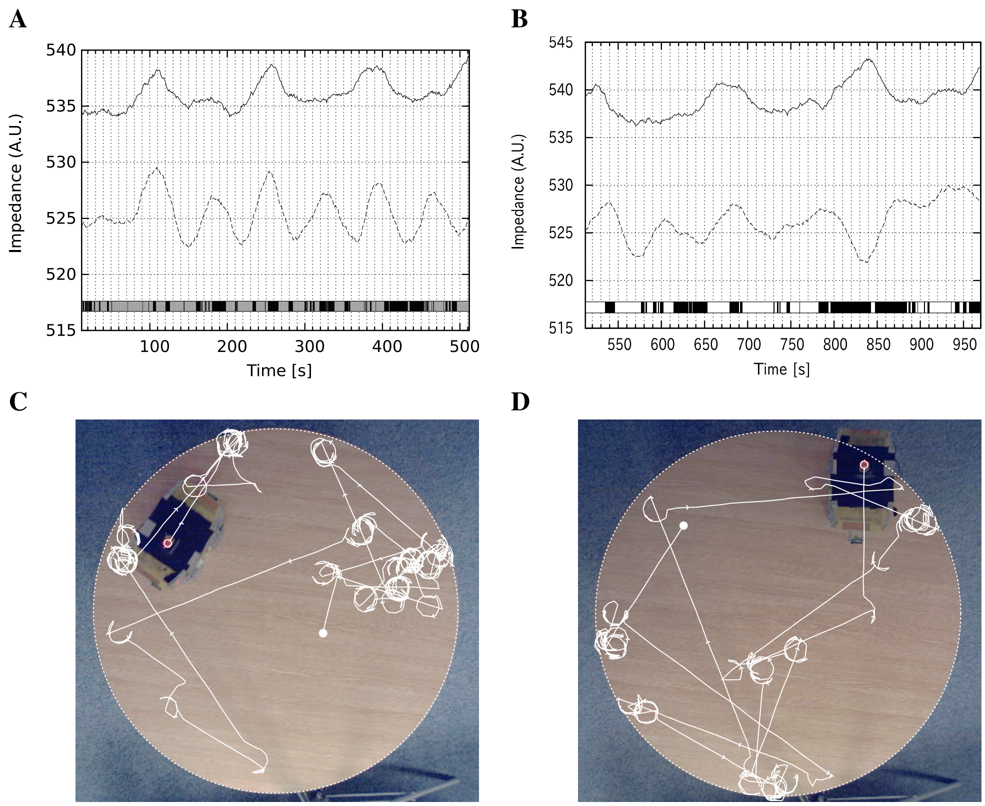

Figure 3: Oscillation of a plasmodium in a *Physarum* chip and the corresponding trajectories of the robot. The moving-averages of the magnitude of the impedance at 100k Hz are plotted for 30–500 s (A) and 500–970 s (B). The solid and dotted curves in the plots correspond to oscillations of the plasmodium from right and left wells, respectively. The phase relationship between two wells are shown in the bottom of the plots as black (in-phase) and white (out-of-phase) vertical lines. The behaviour of the robot is determined according to the phase relationship as traced in panel (C) for 30–500 s and panel (D) 500–970 s. A solid circle indicates the start and an open circle the end of the trajectory.

tional structure of the artificial control. Encoding happens when stimuli from the robotic light sensors are transduced to white light signals for the cell. Decoding occurs when amplitude signals calculated from measured data of the plasmodium oscillators are processed by software to alter the motion of the robot actuators. The control software acts as a decoding device that semantically relates a syntactic representation of information (plasmodium oscillation signals) to another syntactic representation of information (robot motor signals). All in all, four syntactic representations of information (external light signals, white light signals for the plasmodium, oscillation signals from the plasmodium, and robot motor signals) are related by two semantic representations of information (namely, the code used for encoding the light sensor data into white light signals and the code used for decoding the oscillation data into motor signals). In-between, the plasmodium connects the two semantic representations by bounded computation (see Fig. 4).

Where is information represented pragmatically in the interaction loop? First, the behaviour of the robot that results from decoding plasmodium oscillation signals into robot motor signals, changes the boundary conditions on encoding since the effects of the robot's activity on the environment are perceived by the robot's light sensors whose data is then encoded into white light signals for the cell. Second, the plasmodium behaves according to its own dynamics in its direct environment, i.e. in the artificial control. This environment receives the behaviour of the plasmodium in form of oscillation data that is decoded into robot motor signals. The pragmatic interaction of the plasmodium with its engineered environment is, thus, semantically represented in the very same environment and then pragmatically represented by the behaviour of the robot in its real-world environment. Connecting the relation of the robot to its real-world environment with the relation of the plasmodium to its artificial environment, it results that the semantic structure of the robot control device (in short, its *control semantics*) is given by the two codes mentioned above. They map two different pragmatic representations of information to each other, namely the behaviour of the plasmodium and the behaviour

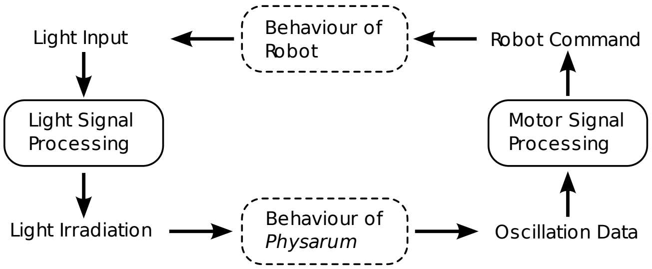

Figure 4: Interaction loop of *Physarum*-controlled robot. Each part of the diagram corresponds to either syntax (no box), semantics (solid box), or pragmatics (dotted box).

of the robot (see Fig. 4).

Given a particular control semantics and a specific environment, the behaviour of the robot can be anticipated by an external observer. This does not necessarily mean the bio-hybrid robot system would always behave as its designer or observer expects. The key issue here is how we can exploit the cell's self-organising dynamics to achieve a fully autonomous robot. Arguably, biological cells outperform conventional autonomous robots in many features by exploiting pragmatic versatility, i.e. the high degree to which the cells are able to adapt their behaviour to different environments.

In fact, several researchers have observed that the plasmodium is able to spontaneously change its behaviour pattern against external stimuli to overcome unfavourable conditions (Aono and Hara, 2007; Nomura, 2001; Takamatsu et al., 2004). For example, Takamatsu found that if the plasmodium is entrained to oscillate at a fixed frequency by external periodically-changing stimulus, it spontaneously deviates from the frequency after a certain period even if the stimulus is maintained. She speculated that such spontaneous change might stem from multistability or chaotic behaviour of the plasmodium's dynamics and may contribute to the diversity of behavioural modes of the plasmodium, such as food-searching mode and feeding mode (Takamatsu et al., 2004).

Although physiological mechanisms underlying such behaviour are yet to be investigated, these observations point to richness of the cell's internal dynamics. However, they also point to the lack of theory about relations between the dynamics of physico-chemical material structures and their use as computational media. The conventional computing paradigm assumes perfection of each part in a system. It is, therefore, inadequate when we want to harness the pragmatic versatility of the plasmodium, which results from the richness of its self-organised processing of syntactic representations of information, by a control semantics that allows the robot to adapt its behaviour to a real-world environment.

The development of a control semantics for devices like the plasmodium-based robot controller is an important engineering contribution to the construction of a general architecture for unconventional computers. This architecture could be described in the conceptual framework of a theory of bounded computability that relates generic traits of information-processing systems with physico-chemical constraints on the realisation of such systems in different classes of computational media.

The information-theoretic sketch of some processes in the bio-hybrid controller given above hints at general features that seem to be fundamental to the architecture of such devices, and perhaps of other unconventional computing systems, too. However, the largely varying physico-chemical properties of the computational media used in those systems make it difficult to propose bold yet reasonable generalisations. The following remarks that address syntactic efficiency, semantic generality, and pragmatic versatility try to make a virtue out of necessity by drawing some consequences from the significance of specific physico-chemical properties of unconventional computational media.

First, the material features of computational media like the plasmodium appear, from the perspective of the controller, as constraints on the processing of syntactic representations of information. Information processing by the computational medium has, of course, also internal semantic and pragmatic aspects. There exist, e.g., semantic representations of information in the cell like the organic code that structures the expression of genetic information in the plasmodium (Barbieri, 2003). Yet from the perspective of the controller those cell-internal aspects are to be considered just as constraints on the efficiency of processing syntactic representations of information that are actualised in the cell's environment. Therefore, the syntactic effectiveness of the computational medium shows itself in its pragmatic versatility, i.e. the degree to which its behaviour is able to adapt itself to changing boundary conditions that bear information syntactically.

Second, the semantic substructures of the controller, the codes used for encoding external stimuli and for decoding internally collected measurement data, are pragmatically connected by the behaviour of the computational medium, i.e. by how it measurably reacts to the encoded stimuli. To encode information means in pragmatic respect that the control device sets the boundary conditions on how the computational medium processes syntactic representations of information. To decode information means that the control device semantically represents the pragmatic results of the information processing by the computational medium. This functionally differentiated interplay of semantics and pragmatics in the controller is as important as the syntactic efficiency of the isolated organic computational medium, since it is the means by which the pragmatic versatility of the cell is also detectable in the behaviour of the robot.

Third, from the perspective of the computational medium, the control device is a behaviour amplifier. The microscopic behaviour of a cell is amplified to the macroscopic behaviour of a robot by semantic means. This suggests to think about the generality of codes, i.e., about the degree to which they are able to differentiate between possible messages under given pragmatic boundary conditions, in terms of the graininess of behaviours between which the implemented codes can differentiate. The finer the behavioural differences of the cell that a code can semantically represent are, the more general the code is in respect to this particular control setting.

These remarks highlight some features of the interplay between syntactic, semantic, and pragmatic representations of information in unconventional computing systems. They indicate to which information-theoretic problems, not only the further development of the plasmodium-based robot controller, but also the construction of a general architecture of unconventional computers should concentrate its attention.

Materials and Methods

Plasmodia of *Physarum polycephalum* were cultured on 1.5 % agar gel plate and fed with oat-flakes. They were starved for more than 24 hours before the experiment. When plasmodia are transferred into the chip, tip portions of the cell taken from the anterior region of a thin-spread culture are used. The chip, shown in Fig. 1B, can host two independent plasmodia for monitoring. Each plasmodium cell is confined in a dumbbell-shaped cut-out of a thin sheet of printed circuit board (470 μm). To maintain the moisture required by the cell, the PCB is covered on one side with an approximately 0.5 mm thick layer of 1.5 % agar gel, and on the other side with an approximately 50 μm thick sheet of the gas-permeable elastomer polydimethylsiloxane (PDMS). The copper side of the PCB with its patterned electrodes faces the agar gel and is insulated from it with laminate. The stack of PDMS–PCB–Agar is clamped with a plexiglass frame. This assembly, referred to as "*Physarum* chip", completely encloses the plasmodial cell and provides the necessary humidity and adequate oxygen supply to keep the cell active for more than 5 hours.

The dumbbell-shaped design, two 1.6 mm diameter circular holes at a centre-distance of 2.5 mm connected by a 0.4 mm wide channel, is modelled on the design reported in Takamatsu et al. (2000b). A prepared *Physarum* chip is mounted on the EIS board and left to stand in a dark place for 2–3 hours or more until the cell starts steadily oscillating in the chip. The PCB sheet is equipped with a total of eight pairs of electrodes for the two plasmodia samples, two electrode pairs for each well (Fig. 1B). During the incubating period, electrical impedances of plasmodia at 100 kHz AC frequency are constantly monitored via these electrodes to trace the oscillatory activity of the cells. Based on the strength of the oscillation signal recorded, one of two plasmodia is selected to be used for the control of the robot.

In the robot control experiment, impedances of the plasmodia at the eight points are measured once per second and saved in the flash memory of the gumstix computer. Although the data from all eight electrode pairs are recorded throughout the experiment, only one of two electrode pairs available at each well is selected for the control of the robot. As in the case of selecting a plasmodium, the criterion is the strength of the oscillation signal received from the electrode pair.

The robot carries a computer $8{\times}3.5{\times}2$ cm^3 in size on which a customised Linux kernel has been installed (`www.gumstix.com`). This computer serves for signal processing and as a data logger, recording the impedance measurements in flash memory for off-line analysis. To this end the computer configures the EIS board over an I^2C bus, configures the impedance circuitry, controls the analog-switches that multiplex among the electrodes and retrieves the impedance measurements. After the signal processing described below, the computer sends commands to a microcontroller in the wheeled robot base.

The wheeled robot base is a minimalist design based on the Braitenberg vehicles (Braitenberg, 1984). It allows for the *Physarum* chip, the EIS board, and the gumstix computer to be mounted, and accommodates the necessary power supplies. The base has its own microcontroller that translates simple commands (forward, left, right) to the drive level of the stepper motors. The microcontroller also monitors two infra-red proximity switches and ignores forward commands if one of these switches detects a cliff. This effectively constrains the robot to the area of the table that serves as arena for experiments.

A two-step process converts the measured impedance signals into drive commands for the robot base: Signal processing to recover the oscillation state of the cell from the impedance measurements, and mapping of the cells oscillation state into actuator commands.

First, the moving average over 15 samples ($\approx$ 15 seconds) of recorded data is calculated to reduce noise in the impedance measurements. At present the circuitry on the robot has not been optimised to reduce noise, but the signals are strong enough that the simple moving average filter works sufficiently well for our purpose. The curves in Fig. 3A and B show the signals after the noise filtering step. Next a differential of the averaged signal is computed by subtracting the 15 s delayed signal to remove the long-term trend of the signals (Nakagaki et al., 1996).

After the signal processing, a command to drive the robot is determined according to the phase relationship between the differential signals from both wells: If the two wells are in phase (synchronised mode), the robot takes a random turn. If they are out of phase (phase delayed mode), then it moves straight. The phase relationship is classified by the following simple rule: If the signs of the two differential signals are equal (both oscillations are increasing or both are decreasing) the oscillation state is classified as synchronised mode. If the signs of the differential signals differ the oscillation state is classified as phase delayed mode. The former is mapped into a random choice of either a "left" or a "right" command, the latter is mapped into a "forward" command. The whole conversion cycle is performed once per second and commands for the robot's actuators are issued accordingly.

The robot system was tested on a 1 m diameter round table, the robot being constraint to this area by the cliff sensing described above. Position and direction of the robot are tracked by an Ethernet camera mounted above the table using an illuminated target pattern on top of the robot.

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