Sensors and Actuators B 188 (2013) 38–44

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Slime mould tactile sensor

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ARTICLE INFO

Article history:
Received 13 April 2013
Received in revised form 11 June 2013
Accepted 16 June 2013
Available online xxx

Keywords:
Slime mould
Bionic
Bioengineering
Sensor

ABSTRACT

Slime mould *Physarum polycephalum* is a single cells visible by unaided eye. The cells shows a wide spectrum of intelligent behaviour. By interpreting the behaviour in terms of computation one can make a slime mould based computing device. The Physarum computers are capable to solve a range of tasks of computational geometry, optimisation and logic. Physarum computers designed so far lack of localised inputs. Commonly used inputs — illumination and chemo-attractants and -repellents — usually act on extended domains of the slime mould's body. Aiming to design massive-parallel tactile inputs for slime mould computers we analyse a temporal dynamic of *P. polycephalum*'s electrical response to tactile stimulation. In experimental laboratory studies we discover how the Physarum responds to application and removal of a local mechanical pressure with electrical potential impulses and changes in its electrical potential oscillation patterns.

1. Introduction

Tactile sensors are quint-essential components of modern robotic devices. Most robots, especially those built for medical applications, rely on a vital information from their tactile sensors when physically interacting with their environment, human operators and subjects [20,27,12,22,21,20,5]. Novel and original implementations of tactile sensors include

- arrays of piezo-electric polymers with auxiliaries, converting force into voltage [6],
- arrays of electro-active polymers [33],
- polymer hair cell sensors [8],
- force sensitive conductive rubber [26],
- elastomers filled with carbon nanotubes [7],
- POSFET tactile arrays [6],
- pressure sensitive conductive rubber [18], and
- ionic polymer metal composites [34].

With a rise of bio-inspired and hybrid wetware-hardware robots [9,10,1,25,11] interest in technological developments drifted away from solid materials to a soft matter [32]. Successful implementations of bio-inspired and soft sensors include

- a bio-mimetic sensor, which employs a conductive fluid encapsulated in elastic container and uses deformation of the elastic container in transduction [35],
- flexible capacitive micro-fluidic based sensors [36],
- patterns of micro-channels filled with eutectic gallium-indium [23,24],
- live cell sensors [31], and
- bio-hybrid sensors encapsulating living fibroblasts as a part of transduction system [4].

In a series of previous works, see overview in [2], we developed a concept and fabricated experimental laboratory prototypes of amorphous bio-computing devices — Physarum machines. A Physarum machine is a programmable amorphous biological computing device experimentally implemented in plasmodium of *Physarum polycephalum*. *P. polycephalum* belongs to the species of order *Physarales*, subclass *Myxogastromycetidae*, class *Myxomycetes*, division *Myxostelida*. It is commonly known as a true, acellular or multi-headed slime mould. Plasmodium is a 'vegetative' phase, a single cell with a myriad of diploid nuclei. The plasmodium is visible to the unaided eye. The plasmodium looks like an amorphous yellowish mass with networks of protoplasmic tubes. The plasmodium behaves and moves as a giant amoeba. It feeds on bacteria, spores and other microbial creatures and micro-particles [30]. The plasmodium's foraging behaviour can be interpreted as a computation: data are represented by spatial distribution of attractants and repellents, and results are represented by a structure of Physarum's protoplasmic network. In such specification a plasmodium can solve computational problems with natural parallelism, including optimisation on graphs, computational geometry, logic and robot control, see details in [2].

A Physarum machine is programmed by configurations of repelling and attracting gradients: chemical substances, temperature and illumination. These quantities are often difficult to localise, which makes a precise, fine-grained, input of spatial data into

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http://dx.doi.org/10.1016/j.snb.2013.06.050

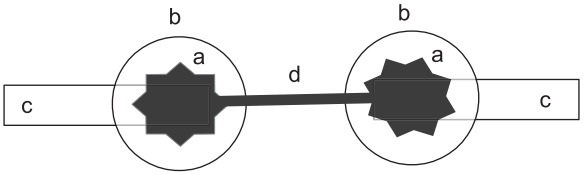

Fig. 1. A scheme of experimental setup: (a) Physarum, (b) agar blobs, (c) electrodes and (d) protoplasmic tube. All parts of Physarum shown in dark grey form a single cell.

Physarum machines problematic. A tactile input of information could be a solution. Thus in present we evaluate a feasibility of Physarum to act as a transducer: to transform a tactile stimulation or a mechanical pressure to a distinctive pattern of an electrical activity. We study how parameters of the oscillations change in response to an application and removal of a solid light-weight insulators to Physarum's protoplasmic tubes or sheet-shaped parts.

2. Methods

Plasmodium of *P. polycephalum* was cultivated in plastic lunch boxes (with few holes punched in their lids for ventilation) on wet kitchen towels and fed with oat flakes. Culture was periodically replanted to a fresh substrate. Electrical activity of plasmodium was recorded with ADC-24 High Resolution Data Logger (Pico Technology, UK). A scheme of experimental setup is shown in Fig. 1. Each electrode is made of a conductive aluminium foil, 0.07 mm thick, 8 mm wide, 50 mm (inclusive part protruding outside Petri dish) long. Two blobs of agar 2 ml each (Fig. 1b) were placed on electrodes (Fig. 1c) stuck to a bottom of a plastic Petri dish (9 cm). Distance between proximal sites of electrodes is always 10 mm. Physarum was inoculated on one agar blob. We waited till Physarum colonised the first blob, where it was inoculated, and propagated towards and colonised the second blob. When second blob is colonised, two blobs of agar, both colonised by Physarum (Fig. 1a), became connected by a single protoplasmic tube (Fig. 1d). We discounted experiments more than one tube was formed between the blobs because patterns of oscillation were affected by interactions between potential waves travelling along interlinked protoplasmic tubes. Petri dished were kept in darkness before and during recordings.

Loads were applied either to a protoplasmic tube (Fig. 1d) connecting the blobs or to a sheet of Physarum covering agar blob on recording electrode. The following events of tactile stimulation were studied in the experiments.

- TR(w): a piece of glass capillary weighting w g, $w = 0.01, 0.05, 0.1, 0.15$, is applied across a protoplasmic tube (Fig. 1d) connecting two blobs of agar colonised by Physarum,
- TA(w): a piece of glass capillary weighting w g is lifted (c. 10 min after application) of a protoplasmic tube,
- BA(w): a plastic load w g, $w = 0.05, 0.2, 0.35, 3$ is applied to a Physarum colonising agar blob on a recording electrode, weights are 0.5–2 mm thick plastic discs, 5–7 mm in diameter, and Blue-Tak ball weighting 3 g,
- BR(w) — a load w g is lifted (c. 10 min after application) from Physarum colonising agar blob.

Control experiments were conducted to check if potential deformation of agar gel or domains of gel contact with electrodes affect the electrical activity. Blobs of agar without slime mould were connected by a wire and stimulated with loads. We did not observe impulses or oscillations similar to those recorded in experiments where agar blobs were inoculated by Physarum and connected by protoplasmic tubes.

Table 1
Characteristics of a high-amplitude impulse response, calculated in 21 experiments. V is an average amplitude of Physarum electrical potential response, in mV, W is an average duration of the response, in seconds. $\sigma(\cdot)$ is a standard deviation. SNR$(\cdot)$ is a signal to noise ratio calculated for amplitude and width of the impulse.

	V	$\sigma(V)$	W	$\sigma(W)$	SNR(V)	SNR(W)
TA(0.01)	5.8	7.0	120	106.1	12.9	1.3
TR(0.01)	8.1	10.2	93	33.9	9.5	1.1
TA(0.05)	8.1	10.0	68.3	20.2	20.3	0.8
TR(0.05)	11.4	20.1	94.5	89.7	24.8	1.4
TA(0.1)	1.7	0.6	100.5	19.5	9.4	1.5
TR(0.1)	3.0	0.2	144.5	113.5	8.6	2.1
TA(0.15)	2.0	0.8	79.3	32.3	4.8	1.6
TR(0.15)	2.2	1.1	69.0	46.0	7.9	0.8
BA(0.2)	4.2	5.0	203.3	177.7	42	1
BR(0.2)	3.5	2.7	72.0	38.7	31.8	0.4
BA(0.35)	2.1	0.7	216.0	144.0	5.4	1.7
BR(0.35)	2.9	1.1	325.5	105.5	10	2.9
BA(3)	0.7	0.3	157.0	88.8	3.5	1.8
BR(3)	0.9	0.4	156.5	44.5	4.8	1.8

3. Results

Undisturbed Physarum exhibits periodic changes, or oscillations, of its surface electrical potential. A typical normal oscillation of a surface potential has amplitude of 0.1–5 mV, could be less subject to location of electrodes, and period 1–4 min [15–17]. Exact pattern of electric potential oscillations depends on a physiological state and age of Physarum culture and particulars of experimental setups [3]. In 1939 Heilbrunn and Daugherty discovered that peristaltic activity of protoplasmic tubes is governed by oscillations of electrical potential propagating along the tubes [14]. An exact nature of correlation between electrical and contractile oscillation of plasmodium is still unclear, there is a view that these two oscillations are governed by the same mechanism but may occur independently on each other [29].

A typical response of Physarum towards application of a load is shown in Fig. 2. Physarum exhibits more or less classical oscillations before stimulation (Fig. 2a), shape of oscillatory waves is a bit distorted, possibly due to minor branches of the tube connecting the blobs and electrodes (Fig. 1d). A segment of a glass capillary is placed across protoplasmic tube (Fig. 1d) at 5370th second from the beginning of recording (Fig. 2s). Physarum demonstrates two types of responses to application of this load: an immediate response with a high-amplitude impulse (Fig. 2b) and a prolonged response with changes in oscillation pattern (Fig. 2c). The immediate response is a high-amplitude spike: its amplitude is 12.33 mV and its duration is 150 s. The prolonged response is an envelop of increased amplitude oscillations. An average amplitude of oscillations before stimulation, in the example shown in Fig. 2, was 2.3 mV and duration of each wave was 120 s. The amplitude of waves in the prolonged response became 5.29 mV with a duration of a wave slightly increased to 124 s.

An example of Physarum responses to repeated cycle of applying and removing loads — events TA(0.05) and TR(0.05) — is shown in Fig. 3. A segment of capillary tube, 0.05 g, was applied and removed twice. Physarum reacted to first application with a spike of amplitude 11.5 mV and duration 121 s. Next minor spike of 3 mV (marked 'b' in Fig. 3) was due to the protoplasmic tube partially collapsing. A response impulse to removal of the load has amplitude 9.7 mV and duration 158 s (Fig. 3c). In this example, an impulse response to a second application of 0.05 g load was a bit less pronounced: c. 3.6 mV amplitude and 71 s duration (Fig. 3d). Response to second removal of the load was as strong as the response to first removal: 8.1 mV amplitude and 135 s duration (Fig. 3e).

Parameters of the high-amplitude impulse calculated in 21 experiments, are shown in Table 1 and Fig. 4. Large values of standard deviation is the first thing one could notice in Table 1,