SLIMY HAIRS:
HAIR SENSORS MADE WITH SLIME Mould

ANDREW ADAMATZKY

UNIVERSITY OF THE WEST OF ENGLAND, BRISTOL, UK
ANDREW.ADAMATZKY@UWE.AC.UK

Abstract. Slime mould Physarum polycephalum is a large single cell visible by unaided eye. We design a slime mould implementation of a tactile hair, where the slime mould responds to repeated deflection of hair by an immediate high-amplitude spike and a prolonged increase in amplitude and width of its oscillation impulses. We demonstrate that signal-to-noise ratio of the Physarum tactile hair sensor averages near 6 for the immediate response and 2 for the prolonged response.

Keywords: slime mould, bionic, bioengineering, sensor

1. Introduction

Tactile sensors are ubiquitous in robotics and medical devices [10, 15, 25, 22] and thus development of novel types of these sensing devices remains a hot topic of engineering, material sciences and bionics. Novel designs and implementations, see overviews in [30, 22], include arrays of electro-active polymers and ionic polymer metal composites [39, 40], piezoelectric polymer oxide semiconductor field effect transistors tactile arrays [11], pressure sensitive conductive rubber [21, 29], flexible capacitive micro-fluidic based sensors [42], and patterns of micro-channels filled with eutectic gallium-indium [27, 28]. Recently an interest in technological developments started to move away from solid materials to soft matter implementations, see overview in [37], and bio-inspired and hybrid implementations: bio-mimetic sensors which employ a conductive fluid encapsulated in elastic container and use deformation of the elastic container in transduction [41], carbon nanotube filled elastomers [12], polymer hair cell sensors [13].

Live cell sensors [36] and bio-hybrid sensors encapsulating living fibroblasts as a part of transduction system [9] are of particular interest because they open totally new dimension in engineering sensing technologies. The living substrates used in sensor design are too dependent on a ‘life-support’ system, they need supply of nutrients and removal of waste. Therefore we decided to consider an autonomous living creature which does not require sophisticate support bandwidth and can survive for a long period of time without a laboratory equipment. This is a vegetative stage, a plasmodium of acellular slime mould Physarum polycephalum.

Physarum 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 single cell with a myriad of diploid nuclei. The plasmodium is visible to the naked eye (Fig. 1). The plasmodium
Figure 1. Plasmodium of *P. polycephalum* on a data set, planar configuration of oat flakes, on an agar gel in a Petri dish 8 cm diameter. (a) A virgin oat flake. (b) An oat flake colonised by the plasmodium. (c) A protoplasmic tubes. (d) An active zones, growing parts of 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 [35].

Plasmodium of *P. polycephalum* consumes microscopic particles, and during its foraging behaviour the plasmodium spans scattered sources of nutrients with a network of protoplasmic tubes (Fig. 1). The plasmodium optimises its protoplasmic network that covers all sources of nutrients and guarantees robust and quick distribution of nutrients in the plasmodium’s body. 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 protoplasmic network [3]. Plasmodium can solve computational problems with natural parallelism, e.g. related to shortest path [26] and hierarchies of planar proximity graphs [1], computation of plane tessellations [34], execution of logical computing schemes [38, 2], and natural implementation of spatial logic and process algebra [33]. In [3] we experimentally demonstrated that slime mould *P. polycephalum* is a programmable amorphous biological computing substrate, capable for solving a wide range of tasks: from computational geometry and optimisation on graphs to logics and general purpose computing.

In our previous paper on slime mould’s tactile sensors [4] we experimentally studied how Physarum reacts to application of a load to its fine network of tubes or a single tube. We demonstrated impulse and pattern of oscillation responses and characterised sensorial abilities of Physarum. We found, however, that it is not practical to allow
Figure 2. Scheme of experimental setup. Electrodes (r) and (e) are fixed to a bottom of polyurethane Petri dish. A hair (h) is fixed to one electrode with epoxy glue. Agar blobs (b) are placed on electrodes. The hair penetrates through the centre of one agar blob. Physarum (p) colonises both agar blobs, propagates across bare plastic substrate (s) and connects two blobs with a protoplasmic tube (t). Root of the hair is partly colonised by Physarum.

Physon tum tactile sensor to be in a direct contact with a load, because the slime mould starts colonising the load and becomes attached to the load and the sensor could be damaged when the load is lifted. Thus some intermediary mechanical medium is required an object causing tactile stimulation and the Physon tum. Looking for alternative solutions we encountered Engel and colleagues design of a spider artificial hair made of polyurethane and fixed to a flexible substrate. Being inspired by their approach we implemented a slime mould-based analog of a spider tactile hair outlined in present paper.

2. Methods

Plasmodium of Physarum 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 fresh substrate. A scheme of experimental setup is shown in Fig. 2. A planar aluminium foil electrodes (width 5 mm, 0.04 mm thick, volume resistance 0.008 Ω/cm²) are fixed to a bottom of a plastic Petri dish (9 cm), see Fig. 2er, where ‘r’ is a reference electrode and ‘e’ is recording electrode. Distance between proximal sites of electrodes is 10 mm. One or more hairs (either human hairs or bristles from a toothbrush), 10 mm lengths, were fixed by upright to electrode ‘e’ using epoxy glue. Then 2 ml of agar was gently and slowly powered onto the electrodes to make a dome like blobs of agar (Fig. 2b). An oat flake occupied by Physon tum was placed on an agar blob, residing on a reference electrode ‘r’. Another oat flake not colonised by Physon tum was placed on an agar blob on electrode ‘e’. Physon tum exhibits chemotaxis behaviour and therefore propagates on a bare bottom of a Petri dish from blob ‘r’ to blob ‘e’, usually in 1-3 days. Thus in 1-3 days after inoculation of Physon tum on blob ‘r’, both blobs became colonised by Physon tum (Fig. 2p), and the blobs became connected by a single protoplasmic tube (Fig. 2t). Experiments where more than one tube connected blobs with Physon tum develop were usually discounted because patterns of oscillation were affected by interactions between potential waves travelling along interlinked protoplasmic tubes. Electrical activity of plasmodium was recorded with ADC-24 High Resolution Data Logger (Pico Technology, UK), a recording is taken...
3. Results

In 1-3 days after inoculation of Physarum to an agar blob on a references electrode it propagates to and colonises agar blob on a recording electrode. A living wire — protoplasmic tube — connecting two blobs of Physarum is formed (Fig. 3a). In most cases Physarum ‘climbs’ onto hairs/bristles and occupies one third to a half of their length (Fig. 3b). In many cases a sub-network of protoplasmic tubes is formed around the base of the hair/bristle (Fig. 3c). In some cases Physarum occupies the whole hair/bristle, from the bottom to the top (Fig. 3d).

An undisturbed Physarum exhibit more or less regular patterns of oscillations of its surface electrical potential (Fig. 5a, A). The electrical potential oscillations are more likely controlling a peristaltic activity of protoplasmic tubes, necessary for distribution of nutrients in the spatially extended body of Physarum [31, 17]. A calcium ion flux through membrane triggers oscillators responsible for dynamic of contractile activity [23, 14]. It
is commonly acceptable is that the potential oscillates with amplitude of 1 to 10 mV and period 50-200 sec, associated with shuttle streaming of cytoplasm [18, 19, 20, 23]. In our experiments we observed sometimes lower amplitudes because there are agar blobs between Physarum and electrodes and, also, electrodes were connected with protoplasmic tube only. Exact characteristics of electric potential oscillations vary depending on state of Physarum culture and experimental setups [6].

A typical response of Physarum to stimulation is shown in Fig. 5. The response is comprised of an immediate response (Fig. 5a, B): a high-amplitude impulse and a prolonged response (Fig. 5a, C). See experimental recording in Fig. 6a. High-amplitude
Figure 5. (a) Stages of electrical potential dynamics: period 'A' is a normal oscillator activity, 'S' is a moment of whisker repeated deviation, 'B' is an immediate response, high-amplitude spike, 'C' is a prolonged response, an envelop of waves. (b) Scheme of parameters measured: \( V \) is an amplitude of a high-amplitude response spike, \( V' \) and \( V'' \) are amplitudes of oscillations before and after stimulation, averaged by closest oscillations; \( D \) is a width of a high-amplitude response spike, and \( D' \) and \( D'' \) are average widths of oscillations before and after stimulation. Amplitudes are measured in mV and widths in seconds.

Impulse is always well pronounced, prolonged response oscillations can sometimes be distorted by other factors, e.g. growing branches of a protoplasmic tube or additional strands of plasmodium propagating between the agar blobs. Responses are repeatable not only in different experiments but also during several rounds of stimulation in the same experiment. An example is shown in Fig. 6b. Physarum responds with a high-amplitude impulse to the first package of stimulation, 890 sec, yet prolonged envelope response is not visible. Subsequent packages of hair deflection receives both immediate and well pronounced prolonged responses (Fig. 6b).
Figure 6. Typical responses of Physarum to deflection of hairs. Vertical axis is an electrical potential value in mV, horizontal axis is time in seconds. (a) Physarum responds with a high-amplitude impulse and envelop of four to five waves. Moment of hair deflection is shown by arrow. (b) Hair deflected, 30 times per each stimulation, at 890 sec, 3390 sec, 5630 sec and 6680 sec, moments of stimulation are shown by asterisks.
Figure 7. Physarum’s response deflecting hairs in turns. Vertical axis is an electrical potential value in mV, horizontal axis is time in seconds. (a) and (c) Hair on recording electrode is deflected 30 times. (b) and (d) Hair on reference electrode is deflected 30 times.

Table 1. Statistics of Physarum response to deflection of hairs calculated in 25 experiments.

|        | Average | Std deviation | Median |
|--------|---------|---------------|--------|
| V      | 4.0     | 2.1           | 3.1    |
| V′     | 0.7     | 0.5           | 0.5    |
| V″     | 1.51    | 1.36          | 0.94   |
| D      | 135.9   | 72.0          | 129.0  |
| D′     | 104.7   | 25.9          | 95     |
| D″     | 112.9   | 17.9          | 1.21   |
| e      | 3.15    | 1.21          | 3      |

In 25 experiments we calculated the following characteristics, see Fig. 7: amplitudes of oscillations before $V'$ and after $V''$ stimulation, and of the immediate response impulse $V$, and width of impulses before $D'$ and after stimulation $D''$, and of immediate response $D$. Statistics of the characteristics is shown in Tab. 1. In our particular setup, keep in mind that signal’s strength is reduced due to agar blobs and a single protoplasmic tube connecting electrodes, average amplitude of oscillations before stimulation is 0.7 mV.
and after oscillations, in the envelop of waves, is 1.51 mV. Amplitude of the immediate response is 4 mV in average. A prolonged response envelop has 3-4 waves. Width of oscillation impulses becomes slightly shorter after stimulation. Dispersion of amplitude and width values around average values are substantial (Tab. 1). This may be because electrical activity of Physarum and its response is determined by exact topology of a protoplasmic network wrapping agar blobs, and geometry of branching of the protoplasmic tube connecting the blobs.

Signal to noise ratio (SNR) is an important characteristic of a sensor. Physarum’s electrical potential constantly oscillates. Thus we assume a ‘noise’ is a background oscillatory pattern of an undisturbed Physarum and ‘signal’ is an immediate response (Fig. 5a, B) and a prolonged response, an envelop of waves (Fig. 5b, C). Maps of SNR obtained in laboratory experiments are shown in Fig. 8. Experimental plots of immediate response’s SNR are well grouped around average SNR of amplitude 5.7 and SNR of width 1.29 (Fig. 5a). SNR of amplitude of a prolonged response varies from 1 to almost 3 with average 2.2, while SNR of width is around 1 (Fig. 8b). Analysis of SNRs shows that amplitudes of immediate and prolonged responses are robust indicators of stimulation response.

4. Hairy balls and slimy whiskers

Will slime mould based tactile hairs work in a less ideal, than described in the previous section, environment? To evaluate validity of the approach we assembled Physarum tactile hair setups on ping-pong balls (Fig. 9) and a rubber mouse (Fig. 10). The balls were equipped with planar aluminium foil electrodes (the same as used in original setup) and the mouse with a hook-up wire electrodes (silver plated single core wires, cross-section area 0.23 mm\(^2\), resistance 23.6 Ω/1000ft). The wire electrodes were fixed to the mouse using silicon glue (Silastic medical adhesive silicon Type A, Dow Corning). Hairs on the balls were made of human hairs and whiskers on the mouse of polyurethane bristles fixed to the objects’ surface using Silastic silicon glue. We have not collected statistics but rather undertook few experiments to evaluate feasibility of the approach.

In the ping-balls setup Physarum linked blobs of agar on electrodes with a single protoplasmic tube. In experiments with mouse, tubes connecting agar blobs in the base of whiskers sometimes propagated across the mouse’s nose bridge but sometimes infra-maxillary. In most experiments hairs and whiskers were partly colonised by Physarum. Degree of colonisation varied from one sevenths of a bristle to almost (Fig. 9) over the half of the hair/whisker length (Fig. 10b).

Examples of responses to repeated deflections of hairs and whiskers are shown in Figs. 11 and 12. The responses are variable. Thus, Physarum hairs on a yellow ping-pong ball (Fig. 9b) reacted with an impulse of 4.3 mV to a repeated deflection of hairs (Fig. 11b). When hairs on agar blobs on recording and reference electrodes are deflected in turns Physarum responds, with impulses of different signs but the same amplitude of 0.5 mV (Fig. 11b). In a response illustrated in Fig. 12, baseline of electrical potential drops by 0.2 mV but recovers its original value after 270-300 seconds. A response impulse shown in Fig. 12 is twice of amplitude of the background impulses.
Figure 8. Maps of signal to noise ratios (SNR) of an immediate response (a), and prolonged response (b) in 25 experiments. (a) SNR of the immediate response is calculated as $V/V'$ and $D/D'$. (b) SNR of the prolonged response is calculated as $V''/V'$ and $D''/D'$. 
SNRs of the responses illustrated are 15 in Figs. 11a, 2 in Figs. 11b, 0.9 in Figs. 12a and 2 in Figs. 12b. Thus in most cases response signal is well distinguishable from background impulses.
Figure 10. Rubber mouse equipped with Physarum whiskers. (a) Top view of the setup. (b) Whiskers are partly colonised by Physarum.
Figure 11. Physarum response to hairs deflection on a ping-pong balls (Fig. 9). Vertical axis is an electrical potential value in mV, horizontal axis is time in seconds. (a) Hairs on agar blob on recording electrode of yellow ball (Fig. 9b) are deflected 60 times at c. 7900 sec of experiments. (b) Hairs on agar blob on recording electrode of white ball (Fig. 9a) are deflected 60 times at c. 290 sec and hairs on reference electrode are deflected 60 times at c. 580 sec, both moments of hairs deflections are shown by asterisks.
Figure 12. Physarum whiskers response on a mouse (Fig. 10). Vertical axis is an electrical potential value in mV, horizontal axis is time in seconds. (a) Whiskers are deflected vertically 60 times at c. 1900 sec. (b) Whiskers are deflected vertically 60 times at c. 1320 sec. Moments of stimulation are marked by asterisks.
In laboratory experiments we designed a bio-hybrid system imitating some features of a tactile hair of a spider. A neuron transducing a mechanical deflection of a chair into an electrical response is physically imitated by slime mould *Physarum polycephalum*. Two types of responses are detected: immediate response with a high-amplitude impulse and a prolonged response in a form of a wave envelop. The slime mould tactile hairs show a reasonable value of a signal to noise ratio: around 6 for an immediate response and 2 for a prolonged response. We have also installed Physarum hairs and whiskers on a non-planar objects and demonstrated that a signal to noise ratio of at least 2 is reached. Thus, we can claim that Physarum based tactile hairs and whiskers might play a significant role in future designs of bio-hybrid robotic devices.

Our designs of slime mould based tactile hairs make an elegant addition to existing prototypes of bio-hybrid sensors incorporating live cells as parts of transduction system [25, 26] and open totally new dimension in engineering sensing technologies. Living substrates used for the bio-hybrid systems require connective pathways to deliver nutrients and remove products of cell metabolism [22]. Some approaches to deal with this problem are based on micro-fabrication of vascular networks [32]. Slime mould based sensors does not require any auxiliary 'life support' system, the cell propagates on the electrodes, consumes nutrients from sources of food supplied and damps waste products in a substrate by itself.

Advantages of the proposed Physarum hairs are self-growth of sensors, low-power consumption, almost zero costs, reasonably good sensitivity, and a high signal to noise ratio. Disadvantages include the Physarum hairs/whiskers response dependence on a morphology of protoplasmic tubes and networks (which are in a state of continuous flux), susceptibility to temperature, light and humidity change, and relatively short period of functionality (usually 3-4 days).

The devices described in the paper are instances of wetware of a secondary class of living technologies [8]. Rephrasing, Bedau et al. [8], we can say that Physarum tactile hairs proposed are artificial because they are created by our intentional activities yet they are totally natural because they grow and respond to environmental stimuli by their own biological laws.

Further research in the slime mould based tactile hairs will aim to answer the following questions. What are biophysical mechanisms of hair/whisker to Physarum to electrical output transduction? Do cellular membrane and outer wall of Physarum’s protoplasmic tubes react to stretching and twisting in same manner as e.g. bacteria do [16]? How does a response’s strength (in amplitude and duration) depends on a number of hairs/whiskers deflected? How to keep the ‘slimy whiskers’ functioning for weeks and months? What is an adaptability pattern of the Physarum hairs when they are exposes to repeated rounds of stimulation?

References

[1] A. Adamatzky, Developing proximity graphs by Physarum Polycephalum: Does the plasmodium follow Toussaint hierarchy? Parallel Processing Letters 19 (2008), 105–127.
[2] A. Adamatzky, Slime mould logical gates, arXiv:1005.2301v1 [nlin.PS] (2009).
[3] A. Adamatzky, Physarum Machines: Making Computers from Slime Mould, World Scientific, 2010.
[4] Adamatzky A. Physarum tactile sensor, April 2013 (Submitted)
[5] Achenbach F. and Weisenseel M. H. Ionic currents traverse the slime mould Physarum. Cell Biol Int Rep. 1981 (5) 375–379.
[6] Acheubach U. and Wohlfarth-Bottermann K.E. Synchronization and signal transmission in proto-plasmic strands of Physarum. Planta 151 (1981) 574–583.
[7] Barth F. G. Spider mechanoreceptors. Current opinion in neurobiology. 14 (2004) 415–422.
[8] Bedai M.A., McCaskill J. S., Packard N. H., Rasmussen S. Living technology: exploiting life’s principles in technology. Artificial Life 16 (2010) 89–97.
[9] Cheneler, D., Buselli, E, Oddo, C. M., Kaklamani, G., Beccai, L, Carrozza, M. C., Grover, L., Anthony, C., Ward, M. C. L. and Adams, M. Bio-hybrid tactile sensor and experimental set-up for investigating and mimicking the human sense of touch. Proceedings of HRI2012, Boston, USA, 3rd March 2012.
[10] Cutkosky M. R., Howe R. D., Provancher W. R. Force and Tactile Sensors. In: Siciliano B. and Khatib O. (Eds.) Springer Handbook on Robotics (Springer, 2008).
[11] Dahiya R.S., Valle M., Metta G., Lorenzelli L. Bio-inspired tactile sensing arrays, Proc. SPIE 7365, Bioengineered and Bioinspired Systems IV, 73650D (May 20, 2009);
[12] Engel J., Chen J., Chen N., Pandya S., Liu C. Multi-walled carbon nanotube conductive elastomers: materials and application to micro transducers. Micro Electro Mechanical Systems, 2006. MEMS 2006 Istanbul. 19th IEEE International Conference on, 246–249.
[13] Engel J. M., Chen J., Liu C., Bullen D. Polyurethane rubber all-polymer artificial hair cell sensor. J Microelectromechanical Systems 15 (2006) 729–736.
[14] Fingerle J. and Gradmann D. Electrical Properties of the plasma membrane of microplasmodia of Physarum polycephalum J. Membrane Biol. 68 (1982) 67–77.
[15] Hamil O. P. and Martinac B. Molecular Basis of Mechanotransduction in Living Cells. Physiol Rev 81 (2001) 685–740.
[16] Heilbrunn L. V. and Daugherty K. The electric charge of protoplasmic colloids. Physiol. Zool. 12 (1939) 1–12.
[17] Iwamura T. Correlations between protoplasmic streaming and bioelectric potential of a slime mould, Physarum polycephalum. Botanical Magazine 62 (1949) 126–131.
[18] Kamiya N. and Abe S. Bioelectric phenomena in the myxomycete plasmodium and their relation to protoplasmic flow. J Colloid Sci 5 (1950) 149–163.
[19] Kashimoto U. Rhythmicity on the protoplasmic streaming of a slime mold, Physarum Polycephalum. I. A statistical analysis of the electric potential rhythm. J Gen Physiol 41 (1958) 1205–1222.
[20] Kato Y. and Mukai T. Tactile sensor without wire and sensing element in the tactile region using new rubber material. In: Rocha J.G. and Lanceros-Mendez S. (Eds.) Sensors, Focus on Tactile, Force and Stress Sensors (In-Teh, Vienna, Austria, 2008), 399–408.
[21] Kato Y. and Mukai T. Tactile sensor without wire and sensing element in the tactile region using new rubber material. In: Rocha J.G. and Lanceros-Mendez S. (Eds.) Sensors, Focus on Tactile, Force and Stress Sensors (In-Teh, Vienna, Austria, 2008), 399–408.
[22] Lucarotti C., Oddo C. M., Vitiello N., Carrozza M.C. Synthetic and bio-artificial tactile sensing: A review Sensors 2013, 13, 1435–1466.
[23] Meyer R. and Stockem W. Studies on microplasmodia of Physarum polycephalum V: Electrical activity of different types of micro- and macroplasmodia. Cell Biol. Int. Rep. 3 (1979) 321–330.
[24] Muhammad H.B., Oddo C.M., Beccai L., Recchiuto C., Anthony C.J., Adams M.J., M.C. Carrozza, D.W.L. Hukins, M.C.L. Ward. Development of a bioinspired MEMS based capacitive tactile sensor for a robotic finger. Sensors and Actuators A 165 (2011) 221–229.
[25] Mukai T., Hirano S. and Kato Y. Fast and accurate tactile sensor system for a human-interactive robot. In: Rocha J.G. and Lanceros-Mendez S. (Eds.) Sensors, Focus on Tactile, Force and Stress Sensors (In-Teh, Vienna, Austria, 2008), 305–316.
[26] T. Nakagaki, H. Yamada, A. Toth, Maze-solving by an amoeboid organism, Nature 407 (2000), 470–470.
[27] Park Y.-L., Majidi C., Kramer R., Béard P., Wood R.J. Hyperelastic pressure sensing with a liquid-embedded elastomer. J. Micromech. Microeng. 20 (2010) 125029 (6pp).
[28] Park Y.-L., Chen B., Wood R.J. Soft artificial skin with multi-modal sensing capability using embedded liquid conductors 2011 IEEE SENSORS Proceedings (October 2011) 81–84.
[29] Ohmukai M., Kami Y., Matsuura R. Electrode for force sensor of conductive rubber. Journal of Sensor Technology 2 (2012) 127–131.
[30] Rocha J.G. and Lanceros-Mendez S. (Ed.) Sensors, Focus on Tactile, Force and Stress Sensors (In-Teh, Vienna, Austria, 2008).
[31] Seifriz W. A theory of protoplasmic streaming. Science 86 (1937) 397–402.
[32] Shin, M.; Matsuda, K.; Ishii, O.; Terai, H.; Kaazempur-Mofrad, M.; Borenstein, J.; Detmar, M.; Vacanti, J.P. Endothelialized networks with a vascular geometry in microfabricated poly(dimethyl siloxane). Biomed. Microdevices 6 (2004) 269–278.
[33] A. Schumann and A. Adamatzky, Physarum spatial logic, New Mathematics and Natural Computation 7 (2011), 483–498.
[34] T. Shirakawa, A. Adamatzky, Y.-P. Gunji, Y. Miyake, On simultaneous construction of Voronoi diagram and Delaunay triangulation by Physarum polycephalum, Int. J. Bifurcation Chaos 9 (2009), 3109–3117.
[35] S. L. Stephenson and H. Stempen, Myxomycetes: A Handbook of Slime Molds, Timber Press, 2000.
[36] Taniguchi A. Live cell-based sensor cells. Biomaterials 31 (2010) 5911–5915.
[37] Twana M. I., Redmond S. J., Lovell N. H. A review of tactile sensing technologies with applications in biomedical engineering. Sensors and Actuators A 179 (2012) 17–31.
[38] S. Tsuda, M. Aono, and Y.P. Gunji, Robust and emergent Physarum-computing, BioSystems 73 (2004), 45–55.
[39] Wang J., Xu C., Taya M., Kuga Y. Bio-inspired tactile sensor with arrayed structures based on electroactive polymers. SPIE Proceedings Vol. 6927. Electroactive Polymer Actuators and Devices (EAPAD) 2008, Yoseph Bar-Cohen, Ed., 69271B.
[40] Wang J., Kimura M., Taya M. Bio-inspired design of tactile sensors based on ionic polymer metal composites ICCM International Conferences on Composite Materials?’2009.
[41] Wettels N., Santos V.J., Johansson R.S., Loeb G.E. Biomimetic tactile sensor array. Advanced Robotics 22 (2008) 829–849.
[42] Wong R.D.P., Posner J.D., Santos V.J. Flexible microfluidic normal force sensor skin for tactile feedback. Sensors and Actuators A 179 (2012) 62 69.

(Adamatzky) UNIVERSITY OF THE WEST OF ENGLAND, BRISTOL, UNITED KINGDOM