Materials Science and Engineering C 30 (2010) 1211–1220

Contents lists available at ScienceDirect

Materials Science and Engineering C

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

Manipulating substances with *Physarum polycephalum*

Andrew Adamatzky

University of the West of England, Bristol BS16 1QY, United Kingdom

ARTICLE INFO

Article history:
Received 22 December 2009
Received in revised form 23 June 2010
Accepted 24 June 2010
Available online 7 July 2010

Keywords:
Biological transport
Unconventional computation
Physarum polycephalum

ABSTRACT

The plasmodium of *Physarum polycephalum* is a large single cell capable for optimal spanning of food sources and avoidance of harmful stimuli. The sophisticated foraging behavior of the plasmodium can be interpreted in terms of computation. When propagating on a substrate with distributed sources of food the plasmodium simulates a general-purpose storage modification machine, approximates varieties of proximity graphs and imitates calculation of shortest path and plane tessellation. The plasmodium's behaviour is determined by the space–time distribution of attracting and repelling sources, and immediately guided by the waves of excitation traveling inside the plasmodium. Due to cytoplasmic streaming a harmless colored substance can be naturally ingested by the plasmodium and distributed inside the protoplasmic network. We show that by controlling the plasmodium's propagation over an uncolored substrate we can 'fill' specified areas of the substrate with the color transported by the plasmodium. We experimentally demonstrate that the plasmodium of *P. polycephalum* excels in adaptive transportation, mixing and transformation of colored food particles. We uncover a range of operations implementable by the plasmodium over color set, and design methods to control mixing and transportation of colors.

1. Introduction

The plasmodium of *Physarum polycephalum*[1] is a single cell with many diploid nuclei. The plasmodium feeds on microbial creatures and microscopic food particles. When placed in an environment with distributed sources of nutrients the plasmodium forms a network of protoplasmic tubes connecting the food sources. Nakagaki et al. [18–21] showed that the topology of the plasmodium's protoplasmic network optimizes the plasmodium's harvesting on the scattered sources of nutrients and makes more efficient flow and transport of intra-cellular components.

The plasmodium's behavior is determined by external stimuli and excitation waves traveling and interacting inside the plasmodium [17]. The plasmodium can be considered a reaction–diffusion [3] or an excitable [1] medium encapsulated in an elastic growing membrane. Thus the plasmodium joins the *Kunstkammer* collection of natural computing substrates complementary to existing reaction–diffusion chemical processors [2].

The plasmodium can be interpreted as a massive-parallel amorphous computer with parallel inputs and outputs. The plasmodium-computer takes data in the form of spatially distributed sources of nutrients. The plasmodium-computer provides results of computation as a configuration of its entire body of protoplasmic network. The plasmodium is capable for approximation of shortest path [20], computation of planar proximity graphs [7] and plane tessellations [25], primitive memory [23], basic logical computing [28], and control of robot navigation [29]. In principle, the plasmodium can be considered a general-purpose computer because the plasmodium simulates Kolmogorov–Uspenskii machine — the storage modification machine operating on a colored set of graph nodes [4].

Reaction–diffusion chemical [2] and plasmodium [18–21]-computers are the most famous and, probably, the most elaborate non-linear media experimental computing devices. They solve a wide range of tasks from mathematical morphology and computational geometry to implementation of functionally complete logical circuits. The plasmodium of *P. polycephalum* has an advantage over reaction–diffusion chemical computers: the plasmodium can exert a substantial, relative to the plasmodium's morphology and metabolism, force on the objects it is attached to.

Few years ago we proposed that, if properly controlled, the plasmodium can be viewed as a biological implementation of virtual artificial amoeba proposed by Yokoi et al. in 1992 [24,31,32]. The proposition was verified in experiments. We have shown that the plasmodium can – in a controllable and programmable manner – propel small floating objects [5] and manipulate (first step towards intelligent assembly) several floating objects simultaneously [6].

The plasmodium of *P. polycephalum* constructs a range of proximity graphs — spanning trees, relative neighborhood graphs, Gabriel graphs, Delone diagram [7], and approximate Voronoi diagram [25]. Structures developed by the plasmodium can form a basis for an intelligent adaptive network of distributing, mixing and manipulating chemical substances (which are relatively harmless for

E-mail address: andrew.adamatzky@uwe.ac.uk.

[1] Order *Physarales*, subclass *Myxogastromycetidae*, class *Myxomecetes*.

0928-4931/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.msec.2010.06.020

the plasmodium at least in a short term). Such an intelligent network may act as 'lab-on-a-plasmodium' for experiments in biological micro-fluidics, drug testing devices [27], bio-sensors and distributed amorphous delivery system.

In the present paper we apply our ideas of plasmodium-based amorphous robotics to the manipulation of substances by the plasmodium's protoplasmic network. Due to cytoplasmic streaming [11–14,22,26] a relatively harmless colored substance can be naturally ingested by the plasmodium and distributed inside the protoplasmic network. By controlling the plasmodium's propagation over an uncolored substrate we can 'fill' specified areas of the substrate with the color transported by the plasmodium.

The paper is structured as follows. In Sect. 2 we show how experiments are implemented and what materials and equipment are used. A simple method for the controllable transportation of a colored substance to a specified location is presented in Sect. 3. In Sect. 4 we discuss mixing and modification of colors in the protoplasmic network produced during the merging of two differently colored plasmodia. We show how to transport mixed colors in Sect. 5. Principle findings and directions of further studies are outlined in Sect. 6.

2. Aims and methods

We aim to develop a procedure of controllable transfer of colors between spatial domains and mixing of colors by the plasmodium of *P. polycephalum*. Let X, Y and L be the finite compact domains of the Euclidean plane. Given that X and Y domains are filled with colors c_X and c_Y and domain L is uncolored, we wish to color the domain L either with the color c_X or c_Y or a compound color c mixed of c_X and c_Y.

To demonstrate that color can be mixed and transferred in a controllable manner (pioneer experimental results on mixing colored substances were presented in [18]) we should experimentally implement basic operations (Fig. 1):

TRANSFER (X,L): the plasmodium is inoculated in domain X and transport the color c_X to domain L (Fig. 1a, see experimental results in Sect. 3),

MIX (X,Y): the plasmodia are inoculated in colored domains X and Y, the plasmodia merge and mix colors c_X and c_Y (Fig. 1b, see experimental results in Sect. 4),

and their superpositions:

MIX (TRANSFER (X,L), TRANSFER (Y,L)): the plasmodia are inoculated in colored domains X and Y, each plasmodium independently guided towards domain L, the plasmodia merge with each other in domain L and the colors they brought into the domain are mixed (Fig. 1c, see experimental results in Sect. 5).

TRANSFER (MIX (X,Y), L): the plasmodia are inoculated in colored domains X and Y, the plasmodia are encouraged to merge their protoplasmic networks and to mix their colors, the joint plasmodium is then guided towards domain L (Fig. 1d, see experimental results in Sect. 5).

The plasmodium of *P. polycephalum* is cultivated in plastic containers, on paper towels sprinkled with still water and fed with oat flakes[2]. The experimental substrate is 2% agar gel[3] poured in 9 cm glass Petri dishes. All experiments discussed in the paper are done using nutrient-free agar.

The nutrient-free agar is used to 'program' the localized transfer of substances. The plasmodium's behavior strongly depends on a presence/absence of nutrients in the substrate [9]. On a nutrient-rich substrate, e.g. corn-meal agar, the plasmodium grows in all directions, expanding circularly. On a nutrient-free substrate (by 'nutrient-free' we mean that no nutrients are added in the agar itself during the preparation of gel), e.g. agar or a humid filter paper, the plasmodium propagates only in certain directions, mostly towards the sources of nutrients (oat flakes placed scarcely on the gel's surface).

Oat flakes are saturated with SuperCook Food Colorings [4]:

- Green (tartazine colors E102, green S E142),
- Yellow (tartazine E102, sunset yellow E110, Ponceau 4R E124),
- Blue (brilliant blue E133 and azorubine E122),
- Red (sunset yellow E110 and azorubin E122).

The flakes are quickly dried after saturation. Depending on particular experiments, few colored oat flakes, and one uncolored oat flake colonized by the plasmodium, are placed on agar gel. To prevent the diffusion of colorings from colored flakes to agar, closed cuts in agar immediately surrounding the flakes are made. The plasmodium moves through the cuts in agar without problems while the diffusion of colorings is restricted. In the experiments on controlling plasmodium propagation with repelling fields, we use grains of coarse sea salt.[5]

The Petri dishes are kept in the dark, at temperature 22–25C°, except for observation and image recording. Periodically the dishes

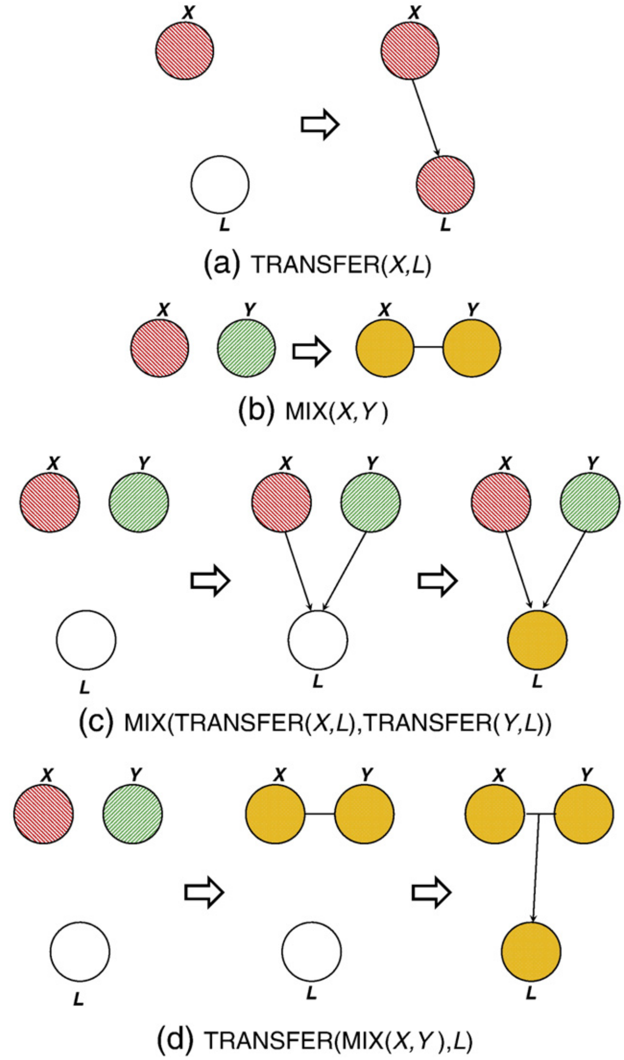

Fig. 1. Basic operations to be realized by the plasmodium of *P. polycephalum*: the plasmodia are placed in colored domains X and Y, and domain L is initially uncolored.

[2] Asda's Smart Price Porridge Oats.
[3] Select agar, Sigma Aldrich.
[4] www.supercook.co.uk.
[5] Saxa coarse grain sea salt, RHM Foods, CW10 0HD, UK.