Robotic cell surface mechanics

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Abstract

In swarm robotics simple identical robots have to be made to coordinate in such a way that they can perform a task. Multi-cellular organisms similarly during development have to be able to create spatial patterns using many identical components (cells) without being able to draw on an absolute frame of reference. Finding and understanding existing solutions to the latter problem might therefore be a promising route to solving the former. Cell-surface mechanics, i.e. cell movement based on surface tension or adhesion is a mechanism that is known to be involved in many basic processes of morphogenesis. We implemented a simplified model of cell surface mechanics on the kilobot, a small robot with limited computational power and without any spatial orientation capabilities. Using only distance measurements to their neighbours kilobots were able to perform various morphogenetic tasks.

Introduction

In the last decades miniaturization and efficiency increases in processor and battery technology have led to the rise of swarm robotics (Brambilla et al., 2013). It is built on the promise that for many tasks a single complicated and expensive custom robot can be replaced by a potentially more robust swarm of simple and cheap off-the-shelf units (Barca and Sekercioglu, 2012).

Kilobots have been developed as a new platform with the explicit aim to make swarm robotics affordable for individuals or institutions with a limited budget (Rubenstein et al., 2012). Accordingly their design prioritizes simplicity and low hardware costs resulting in very limited capabilities.

While great advances have been made on the hardware side, programming robot swarms is still a challenge (Rubenstein et al., 2014). Swarm members have to differentiate from essentially identical initial states to a structured entity where different units or group of units perform different activities, solely based on local communication.

A similar challenge is faced by most multicellular organisms during ontogeny. Starting with identical units of limited complexity that only have access to local information and communication they have to create spatial and temporal patterns in order to develop differentiated tissues and organs.

Mixed masses of animal cells of different tissue types will over time rearrange leading to a number of different spatial configurations (Glazier and Graner, 1993). This sorting process is based on properties of the cells and their membranes. Although its biophysics are not completely understood, phenomenologically it can be modelled with a high degree of accuracy (Brodland, 2004; Marée et al., 2007).

In the past, various attempts have been made to translate biological mechanisms of pattern formation into robots (e.g. Zahadat et al., 2013). Here we will present an implementation of a cell surface mechanics-like system on the kilobot platform enabling basic morphogenetic processes.

Methods

Cell surface mechanics is based on the idea that interfaces between cells differ in their adhesion and/or surface tension depending on the types of the cells on both sides. In analogy to the formalisms applied e.g. in modelling foams, the free energy of a given membrane configuration can then be calculated. Local thermodynamic fluctuations in membrane state will produce stochastic changes in membrane configuration with a corresponding change in free energy. Assuming that changes to a lower energy state are more likely, the system as a whole will tend towards a decrease in free energy. Depending on the combination of cell types three main equilibrium patterns have been found: Cells will arrange in a *mixed* or checkerboard pattern, they can *separate* by type into two clusters or one cell type can form a layer *engulfing* the other one (Glazier and Graner, 1993).

Various different types of formalisms with different degrees of abstraction have been used to model cell surface mechanics (see review by Brodland, 2004). Some models track microscopic changes in membrane configuration and thus enable large scale changes in cell shape, others operate on the level of entire cells and provide less flexibility.

For our system we chose single cells as the basic unit of abstraction. We let each bot represent the centre of a cell with a circular "virtual cell" of a fixed radius extending around it. If the virtual cells of two bots overlap we assume they form an interfacial membrane on the line between the

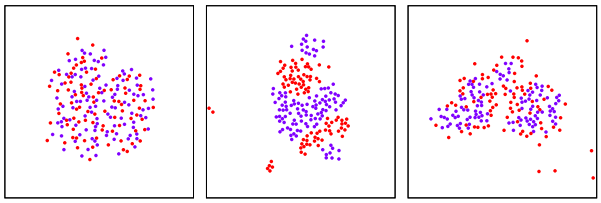

Figure 1: Robot positions after 50k seconds for *mixing* (left, $J_{1,1} = 8$, $J_{2,2} = 8$, $J_{1,2} = 2$), *separation* (middle, 2, 2, 8) and *engulfment* (right, 2, 12, 8). $J_M = 10$ in all cases.

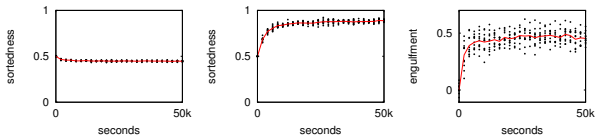

Figure 2: Sortedness or degree of engulfment, respectively, over time in 10 random replicates for *mixing* (left), *separation* (middle) and *engulfment* (right).

two intersection points of their circular cell surfaces. We use the standard formulation of the Hamiltonian to calculate energy for a given set of bot positions and resulting membrane configuration. Given segment lengths l_i, surface energy constant J and cell types at segment i, $\tau(i)$ and $\tau'(i)$, respectively, we obtain: $H = \sum_i J(\tau(i), \tau'(i)) \cdot l_i$

Kilobots can measure the distance to their neighbours, but are not able to determine their own or their neighbours' absolute position. We therefore approximate the degree to which the overlap between neighbouring interface segments reduces overall cell surface by calculating segment length as $l_i = l_{i,\text{orig}}/(1 + \sum l_{\text{orig}}/c)$.

Minimization of the energy state of the system happens by means of a Monte Carlo process: Each robot measures distances to its neighbours and from that calculates its current surface configuration. Then it performs a random movement step (within the limits of the kilobots' locomotion), after which it measures distances again. Based on this information the change in surface lengths and consequently the change in energy is calculated. If the result is favourable (i.e. $H' < H$) the robot maintains its position. Otherwise it moves back to its starting point.

In simulations of real cells different equilibrium states of a cell cluster will be reached depending on specific combinations of values of the surface energy constants $J(a, b)$ (Glazier and Graner, 1993). Using a freely available, accurate kilobot simulator (Jansson et al., 2015) we tested values of J corresponding to each of the end configurations *mixing*, *separation* and *engulfment*. We simulated 200 robots (100 per cell type) moving for 50,000 simulated seconds starting from random initial positions.

Results

For all three configurations (*mixing*, *separation* and *engulfment*) the spatial configuration of the robots clearly corresponds to the expected pattern (see fig. 1). Emergence of the patterns is robust against starting conditions (fig. 2)

Conclusion

We have successfully implemented a key morphogenetic process in a low capability swarm robot system. Despite the high stochasticity and the lack of information on absolute or relative position membrane-based changes in local potential energy lead to large-scale patterning in the robot swarm analogous to those observed in real tissues.

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