Modelling the growth of a soft-body system from a single cell and temporal adaptation to the environment

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This paper presents the adaptation process of a soft-body system based on the spring interactions between the cells that make up the system, to the user-defined environment. The soft-body system is generated by consecutive mitosis a single-cell system whereas the environment includes desired and undesired regions. The cells undergo apoptosis under certain conditions: two cells overlapping each other, a cell that is not interacting with another cells, and the cells that positioned on the undesired regions. If none of the conditions for apoptosis is met, the cells that have interactions less than a predetermined value undergo mitosis and newborn cells are generated. This paper also investigates the effect of cell diameter on adaptation process.

INTRODUCTION

Soft-body systems that consist of cell-like structures were previously investigated in detail, where the development of a 2D system from a single-cell and transformation of the obtained system into a solid structure by assigning muscle-like elements provided insights on the soft-body robotics [1]. These kinds of systems were also investigated in 3D, however the outcomes showed that the accessible complexity of the system decreases rapidly and the simulations become computationally expensive [2]. Recent works on the soft-body adaptation is based on the previously developed algorithm of development and locomotion for 2D soft-body systems, where the assignment of static and dynamic muscle-like elements is done based on the total distance covered in locomotion given as a cost function to the neural networks [3, 4].

In this project, unlike the previous implementations of soft-body systems using physics simulation libraries which was followed easily with neural networks, the physics engine for the soft-body interactions was developed from scratch. Due to this, this project does not include adaptation of the soft-body systems by learning, using a gene-regulatory network or a neural net, but rather includes the adaptation of the system to the user-provided environment by cell deaths under certain rules.

METHODS AND IMPLEMENTATION

The development of the algorithms were inspired from the previous works on soft-body dynamics [1–4], however, the details of each algorithm and the adaptation stage to the environment were developed independently expect the fact that both systems start from a single-cell structure.

The developed physics engine solved the equations of motion associated with each cell using the velocity-Verlet algorithm with a timestep of $\Delta = 0.1$ for the simulations presented in the project, where the equations of the position and velocity at the next timestep may be determined as follows:

$$x(t+\Delta t) = x(t) + v(t)\Delta t + \frac{1}{2}a(t)\Delta t^2 \tag{1}$$

$$v(t+\Delta t) = v(t) + \frac{1}{2}[a(t) + a(t+\Delta t)]\Delta t \tag{2}$$

Construction of the soft-body was done by the spring model, where the interaction between each cell with each another was used while computing the magnitude and vector of the resultant force on a particular cell. The interactions were saved in a variable called *Interaction Matrix*, which consisted of either 1 or 0s (interacting or not). The *Interaction Matrix* was constructed using the distances between two cells, which is also saved in a variable called *Distance Matrix*.

$$a_i(t) = \sum_{j,\ i\neq j} \text{Interaction Matrix}(i,j,t)\frac{k}{m}(x_i - D_{cell}) \tag{3}$$

where D_{cell} is the cell diameter.

Note that, by definition, the *Interaction Matrix* and *Distance Matrix* are symmetric matrices. If the distance between two selected particles is smaller than a predetermined value, $1.5 \times \mathrm{D}_{cell}$ for the simulations presented in this project.

To give the soft-body system time for relaxation, the interaction between the cells were updated not in each timestep but in a predetermined number of timesteps, which is 10 for the simulation presented in this project. The collision between the cells were dealt by conserving the momentum, however a parameter for possible momentum loss is also implemented into the code so that the system may be forced to lose energy.

The basics of the soft-body system is designed to let a single-cell to undergo mitosis, and following the initial mitosis, the mother cell and the newborn cell to continue undergoing mitosis for generations. After each generation, that is called as *event*, the soft-body system is checked for various conditions that may require programmed cell death, *apoptosis*.

FIG. 1. Visualization of mitosis event. (Green cells: Total interaction count < 2, Yellow cells: Total interaction count $= 3$, Red cells: Total interaction count > 3)

The conditions for the cell to be selected as deleted are based on three conditions:
- The condition with the highest priority is the cells that position themselves in undesirable regions. After each event, if the number of alive cells in the system is > 50, the algorithm determines the index of these cells, and if they are present, selects one of the cells to undergo apoptosis.
- The condition with the second highest priority is the cells that are interacting with none of the cells in the system. After each event, if the number of alive cells in the system is > 16, the algorithm determines the index of these cells, and if they are present, selects one of the cells to undergo apoptosis.
- The condition with the lowest priority is the cells overlapping with another cell which creates nonphysical structures. Similarly, after each event, without any count limitation, the algorithm determines the index of these cells, and if they are present, selects one of the cells to undergo apoptosis.

Given priority order enables the fix the nonphysical formations in the system in the beginning, and then let the non-interacting cells to die out as the system size increases a bit, and lastly let the system adopt to the user-defined environment.

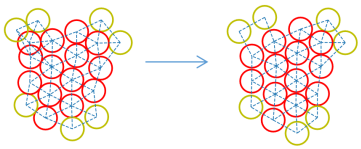

FIG. 2. Visualization of apoptosis event.

Regarding the user-defined environment, the project includes a paint application in which the input of the user is taken for the desirable and undesirable (white and red) regions. As the user saves the drawing, and continues with the next code block, the drawing gets transformed to a mapping of 1 and 0s between -10 and 10 in both x and y coordinates. If the coordinates of a particular cell takes place in the region corresponding to the undesirable region, the index of the cell is added into a list. Since after each apoptosis event there are a predetermined number of timesteps, 25 for this project, to be taken, a cell that is previously in the list can position itself to be in the desirable region and can be removed from the next list, and vice versa.

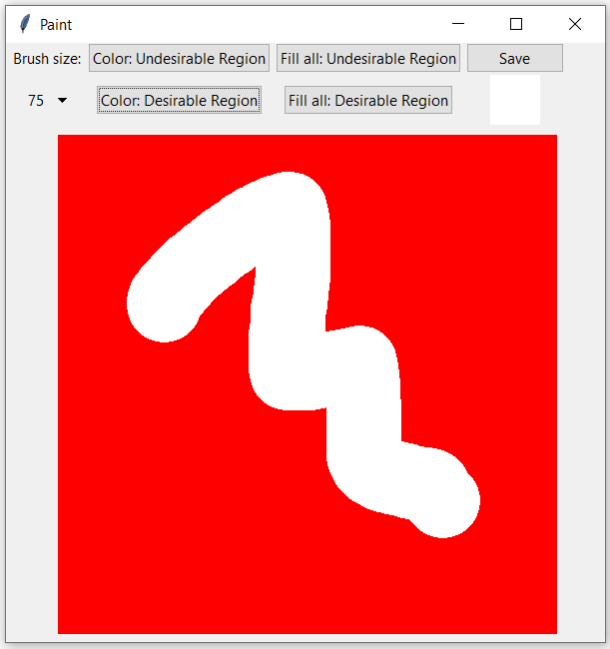

FIG. 3. An exemplary drawing on the painter program.

Lastly, the visualization of the simulation is done after the computation of the positions and interactions of each cell in a particular event. The positions of the cells were shown by circles in the plot, and the spring interactions were shown by blue lines. The coloring of the cells are as Figure 1 suggests. Since the interactions are given to be evaluated not at each timestep but with a given update frequency, the coloring of the cells are updated with the same frequency as well. Due to inefficiency of the used plotting library in terms animations, the update frequency of the plot is also given as a user input. As the number of cells in the system increases, plotting of the computed positions and interactions become computationally expensive, although there is no further computation is necessary during the plotting stage. The visualization is expected to become smoother as the computational power of the computer increases.

SIMULATIONS AND RESULTS

Following the methodology that is explained, the following parameters were provided to the system for the simulations done as a part of this project.

TABLE I. Simulation Parameters

Parameter	Value
Cell diameter (D_{cell})	[0.8, 0.85 0.9, 0.95 1.0]
Spring constant (k)	0.5
Cell mass (m)	1
Timestep (Δt)	0.1
Number allowed interactions to undergo mitosis	3
Final system size	$\geq$ 128 cells
Interaction range	1.5 ($\times$ D_{cell})
Interaction update frequency	10 timesteps
Momentum conservation: Collision	1 (elastic)
Momentum conservation: Division	1 (elastic)
Total number of steps in event: Mitosis	50 timesteps
Total number of steps in event: Apoptosis	25 timesteps

To test the adaptation of the soft-body system to the environment, the following 4 environments were given as an input to the program, resembling the letters U, N, A, M. The effect of cell diameter is investigated:

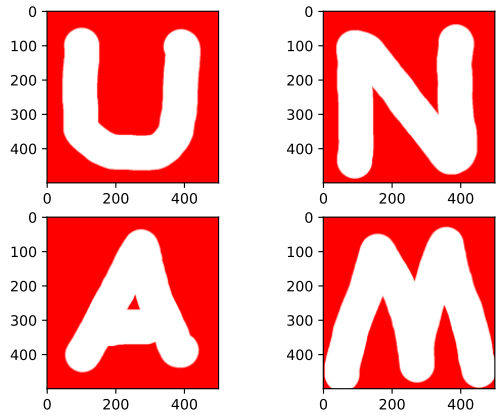

FIG. 4. 4 environments to be tested for soft-body adaptation. (White color: Desirable region, Red color: Undesirable region)

The effect of cell diameters becomes significant during mitosis event, where the distance between two recently divided cells is set to 1, rather than the cell diameter. Being 1 distance unit away from the other cell becomes significant for the system to maintain the spring interactions. By giving the systems to run for a total of 999 events, regardless of the system is undergoing the mitosis or apoptosis event, the adaptation success and the number of cells undergo apoptosis are investigated. One may find the final states of adaptation simulations on the drawings given in Figure 4 below. In each figure, 4 independent simulations were done using a different environment with different cell diameter.

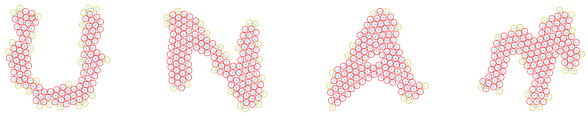

FIG. 5. Final states of 4 simulations with $D_{cell} = 1$.

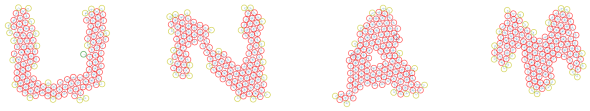

FIG. 6. Final states of 4 simulations with $D_{cell} = 0.95$.

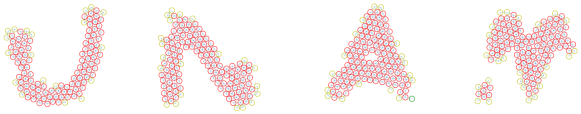

FIG. 7. Final states of 4 simulations with $D_{cell} = 0.90$.

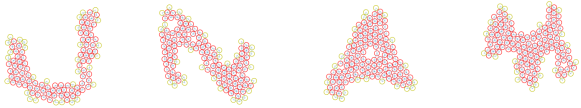

FIG. 8. Final states of 4 simulations with $D_{cell} = 0.85$.

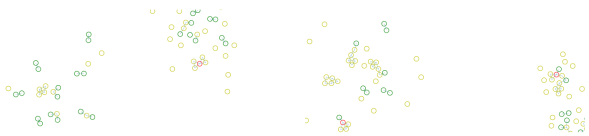

FIG. 9. Final states of 4 simulations with $D_{cell} = 0.80$.

From the trend in the adaptation process, one may see that for a cell diameter in between 0.80 and 0.85, the system faces its stability-instability limit. Regarding the simulations given in Figures 5-9, the number of alive cells in the final state of the system and the number of apoptosis events that is performed can be investigated, separately for each environment.

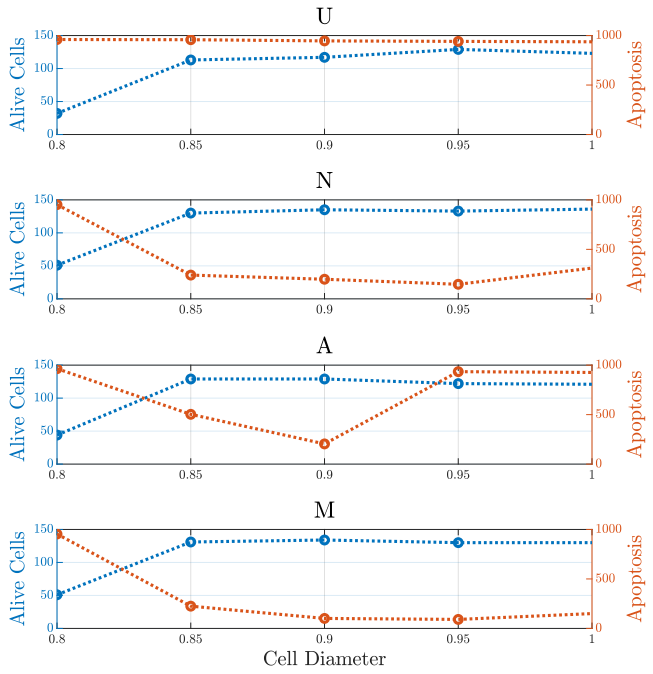

FIG. 10. Number of alive cells and number of apoptosis events vs cell diameter for each environment.

As Figure 10 implies, the number of alive cells show similar trend for different environments. All of the systems reach the success limit that is around 128 cells as the cell diameter increase, or at least be higher than 0.80.

On the other hand, the apoptosis events show different trends for different environments:
- For the environment resembling the letter U, the system mostly undergoes apoptosis and the amount of apoptosis events cover most of its 999 event allowances. As the cell diameter increases, the number of apoptosis events starts to decrease slightly.
- For the environment resembling the letter N, the system undergoes apoptosis at most for the cell diameter of 0.80. This is expected since the system becomes unstable for this diameter. As the diameter increase, the number of apoptosis decreases to considerably small numbers. Moreover, the system undergoes the minimum number of apoptosis events for the cell diameter of 0.95, meaning that the decrease in the apoptosis events does not simply correlated with the cell diameter and it reaches its minima before reaching to the cell diameter of 1.
- For the environment resembling the letter A, the system shows a sharp trend in apoptosis, where neither the cell diameter of 0.80 nor 0.95 (and 1.0) is ideal for this system. The number of apoptosis events reaches its minima for the cell diameter of 0.90, which supports the claim of no simple correlation between the cell diameter and the number of apoptosis events given for the letter N.
- For the environment resembling the letter M, the system shows a very similar trend to the letter N, however the system undergoes the minimum number of apoptosis during the adaptation to the letter M.

DISCUSSION

The analysis done on the adaptation based on the number of apoptosis events and alive cells may be used to claim that the systems with high cell diameter shows better adaptation to linear shapes that are present in letters N and M. On the other hand, the adaptation to the hollow shapes requires specific cell diameters to enhance the adaptation success.

For the further implications of these claims, one must note that the cell diameter that is defined in the simulation does not effect the distance between two cells after mitosis which is kept constant as 1. Hence, the change in the cell diameters may also be interpreted as the separation between two cells after each mitosis, where the interaction between two cells still depend on the cell diameter by the relation $1.5 \times D_{cell}$.

[1] Joachimczak, Michał, et al. (2014). Fine Grained Artificial Development for Body-controller Coevolution of Soft-bodied Animats.
[2] Joachimczak, Michał & Wróbel, Borys. (2012). Open Ended Evolution of 3D Multicellular Development Controlled by Gene Regulatory Networks.
[3] Joachimczak, Michał, et al. (2015). Improving Evolvability of Morphologies and Controllers of Developmental Soft-Bodied Robots with Novelty Search.
[4] Joachimczak, Michał & Wróbel, Borys. (2010). Evolving Gene Regulatory Networks for Real Time Control of Foraging Behaviours.