Evolving Vascular Morphogenesis Controller to Demonstrate Locomotion

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Abstract—Locomotion can be a result of coordination of movements between well-shaped limbs of an organism, or it can be an emerging effect of local interactions between several simple agents forming an aggregated swarm that can move around in the environment. In this paper, we apply a distributed morphogenesis approach to develop a mobile growing artificial organism. The morphogenesis approach works based on a competition between several agents at growing positions that strive to get larger fractions of a limited shared resource needed for growth. The morphology develops from the local competitions and interactions of such agents with each other and with their environment. The locomotion driven by this approach is the result of growing new agents at one side and retracting agents from the other side of the overall swarm-based organism. The morphogenesis controller is successfully evolved here for generating a growing organism that moves towards a target.

Keywords-component; vascular morphogenesis controller; developmental process, generative encoding, resource distribution; locomotion; evolutionary computation; swarm intelligence

I. INTRODUCTION

Locomotion is a topic of interest in a vast variety of disciplines for the obvious reason of its importance for survival of organisms. In robotics and artificial intelligence, locomotion is investigated from different perspectives including coordination mechanisms and control. In many biological organisms in nature, movement is accomplished by means of muscular contractions, where locomotion is the result of coordination between distinct body part, e.g. limbs of the animals.

In the field of distributed control and self-organization in robotics, for example in modular robotics, many different methods have been applied for generating self-organized motion inspired by the mechanisms of muscular locomotion [1][23][24]. But muscles are not the only means of locomotion in biological systems. A different mechanism for locomotion is called amoeboid locomotion which is a leaderless crawling motion of organisms without distinct shape of body (no head, tail, or limbs). The motion in this case is accomplished by advancing pseudopodium at some points on the surface of the organism while the substances forming the pseudopodium are withdrawn from other parts causing the displacement of the organism. This type of continuous swarm-like motion is a very primitive motion that is found in some organisms such as amoeba, and slime-molds. Another comparatively similar type of locomotion is the leaderless flocking behavior in animal swarms. The flexible locomotion of the group in this case is the result of coordination of orientation and speed between the individual members of the group in response to the motion status of their neighbors and environmental cues.

In the field of swarm intelligence and swarm robotics, self-organized coordinated locomotion is investigated mostly by inspiration from similar behaviors in nature. For example, flocking algorithms inspired from the group motion of birds are introduced by simulating agents following simple rules of interaction with their neighbors [9]. In [19], coordinated locomotion of a swarm results from mechanisms inspired by slime-molds and fireflies.

A related line of research is the self-organized formation of shapes and morphology in swarms. In [15], a decentralized algorithm is implemented in a large swarm of simple robots. The required predetermined shape uses diffusion mechanisms and repositioning of the robots that move along the surface of the aggregate and find a fitting place to stay.
The development of morphology in natural organisms and their huge diversity of patterns and adaptability [7][1][22] is a result of the interplay between their genomes, the environment, and the physical and chemical rules of interactions. For morphogenesis in artificial systems, various bio-inspired approaches have been developed [3]. Many of them (e.g. [2][4]) employ the concepts of embryogenesis and cell development [10][21]. Some others [17][9] take more abstract approaches of generative encodings, e.g. L-systems [12] where basic units are recursively extended by applying a set of context-free developmental rules.

In this paper, we take a recently introduced morphogenesis approach, Vascular Morphogenesis Controller (VMC) [25], inspired by competition for growth between branches of a plant and hormone signaling [13]. Individual branches in a plant act as autonomous members of a swarm [6] and compete for receiving a higher share of the limited common resource (i.e., water and minerals from the roots) that is necessary for their growth. The process of growth and the plant’s morphology is the result of the interplay between the parameters encoded in the genome, environmental modalities, and the competition between the growing tips of the branches.

VMC has been previously implemented for developing artificial structures [25] in the context of the EU-funded project flora robotica [5][8]. The method has also demonstrated adaptive maze solving capabilities [26]. In this work, for the first time, we apply VMC for generating an amoeboid-like motion of a swarm-based organism by allowing the root of the organism to move within its body (see below). The VMC-parameters are evolved for the locomotion of an organism towards a target while the target generates a linear gradient in the environment to be used as an environmental cue for the organism. The results are demonstrated by investigating the behavior of an evolved organism in dynamic setups.

II. VASCULAR MORPHOGENESIS CONTROLLER

Vascular Morphogenesis Controller (VMC) is a distributed controller that is inspired from the competition between branches of a plant for more resources and consequently more growth. In biological plants, vascular strands are responsible for transporting common resources, i.e. water and minerals that are necessary for growth, from the roots to all over the plant. The vascular system is regulated by the dynamics within different branches and the quality of the regions they reach [11][16]. The branches located in more promising regions get

![Diagram of Vascular Morphogenesis Controller](image-url)
thicker vessels than the others. The information about the quality of the region a branch is located in is relayed by the amount of a hormone, called auxin, that is produced at the tip of the branch. A branch that gets a high amount of light, produces higher levels of auxin than a branch at in a dark region. The auxin flows along the branches towards the root and on its way, it reinforces the thickness of the branch vessels. A branch with thicker vessels gets a larger share of the common resource which leads to more growth for the branch and eventually allowing the branch to reach even better regions. On the other hand, the branches in worse regions of the environment, get less share of the resource and may cease to grow and even die after some time, which in turn leaves more resource for the rest of the plant. These positive and negative feedback mechanisms form the branch competition, and lead to a continuous global adaptation of the shape of the plant.

In VMC, we have abstracted these processes into a distributed controller of morphology for artificial structures and organisms. VMC can be represented as an acyclic directed graph that is distributed over the body of the growing organism (see Fig.1). Every leaf of the graph represents a growable point of the organism (like the branch tips of a plant). By analogy with the plant hormone auxin, “successin” is produced at every leaf of the graph as a function of the local sensor inputs and a set of constant parameters. The edges between the nodes represent the vessels. The successin flows in the opposite direction of the edges and moves from the leaves towards the root. In its way, successin adjusts the thickness of the vessels (i.e., the weight of the edges). A quantity of a limited resource initiates at the root of the graph and flows along the edges towards the leaves. At every internal node, the resource is distributed between the children of the node proportional to the thickness of their vessels. The amount of resource reaching a leaf determines the potential for growth at that leaf. The dynamics of the successin and the thickness of vessels at the nodes are determined by the sensor inputs, a set of constant parameters encoded in the VMC genome, and the topology of the graph.

At every leaf $i$, a quantity of successin $S_i$ is produced as follows:

$$S_i := w_{\text{const}} + \sum_{s \in \text{sensors}} (w_s \cdot I_s)$$  \hspace{1cm} (1)

where $I_s$ is the input from sensor $s$. The parameters $w_{\text{const}}$ and $w_s$ represent the production rate of successin at the leaf, independent of and dependent on the sensor inputs, respectively.

As successin flows towards the root, the value of successin at every parent node is a function of successin values at its children, as follows:

$$S_i := g(r_{\text{const}} + \sum_{s \in \text{sensors}} r_s \cdot I_i) \cdot \sum_{b \in \text{branches}} S_b$$  \hspace{1cm} (2)

where $r_{\text{const}}$ and $r_s$ are parameters of the successin transfer rate via the nodes. The parameters are respectively independent of and dependent on the sensor inputs. In this implementation, $g(x)$ is a sigmoid function that maps the input to the range of $(0,1)$.

The value of successin passing through the nodes, leads to an update of the vessel thicknesses (associated with the edges between the nodes). The adjustment rule of the vessels at every time step is based on the amount of successin passing the vessel:

If $S_i \geq V_i$ then:

$$V_i := \min(S_i \cdot (1-c) \cdot V_i + b + a \cdot (S_i - V_i))$$  \hspace{1cm} (3)

Otherwise: $V_i := \max(S_i \cdot (1-c) \cdot V_i)$

where $a$ is the adjustment factor, $b$ is the constant addition rate, and $c$ is the constant decay rate of the vessels.

The thickness of vessels determines the distribution of resource between the children of every node. The resource is initiated at the root flowing towards the leaves. The resource value reaching a node $m$ ($R_m$) is decreased by 1 unit (as if it partially consumed at the node) and the rest is divided between the children of the node.
the children of the node according to their vessel thicknesses. This consumption of the resource at the node puts a constraint on the maximum size of the VMC tree. The resource distribution is represented by the following:

\[
R_i := (R_m - 1) \cdot \frac{V_i}{\sum_{b \in \text{branches}} V_b}
\]

where \( R_i \) is the share of resource at the child \( i \) of the node \( m \).

III. IMPLEMENTATION OF VMC FOR A MOVABLE GROWING STRUCTURE

To create an organism with an amoeboid-like locomotion, we have implemented the VMC in a growing structure that is allowed to move. For that, a simulation is developed in the Processing framework with the Box2D physics engine.

The simulated organism starts with a single node running the controller. This node is the root of a VMC graph with size 1. Every time the organism grows, every new node - which is a new leaf of the graph - holds an independent VMC controller. All the controllers run independently and update their state values (successin, resource and vessel thicknesses) asynchronously.

The common resource is constant all over the experiment and its value is 100 at the root. Whenever the resource value at a leaf of the graph is higher than a constant threshold (here 3.0), the node grows by making two branches and becomes an internal node of the graph. For a node that all of its children are leaves of the graph, whenever the resource value of all the children is lower than a constant threshold (here 1.0), the children are removed altogether and the node becomes a leaf again. In the current implementation, the nodes grow by getting exactly two children which are apart from each other with an angle of 120° between them. Nodes can push each other around: the connections between the nodes are constant in length but the orientation can change by being pushed by the others. If a leaf is in contact with another node, its production of successin is suppressed which can lead to a cessation of growth at that leaf.

Unlike the previous implementations of VMC [25][26] where the root of the graph was assigned to a particular fixed node during the whole process, here the node containing the root can pass the root to one of its children. If the ratio between the resource values reaching the two children of the root node is higher than a threshold (here 3.0), the root of the graph is passed to the child with a higher resource value. In the current implementation, this action is restricted to every 20th time-step. Once the root is shifted to the child, all the input edges to the new root node (the child) are reversed and therefore the child becomes the root of the graph. Thus, the old root node can potentially become a leaf at some point in time and consequently it can be removed from the graph. This way, the organism as a whole is capable of moving by growing new leaves at one side and losing old leaves at the opposite side.

IV. EXPERIMENTAL SETUP

Here we evolve the VMC genome for allowing an organism to move towards a given target in a square environment. The organism starts as a single circular node at the position (0,0). The connection length between a node and each child is 21 pixels. The target is positioned at the corner of the environment at (400,400) coordinates and it produces a gradient that can be perceived by the sensors of the nodes. The gradient is linearly decreasing with the highest concentration of 600 at the target and zero at the distance of 600 pixels. For larger distances, the concentration is set to zero.

A. Evolutionary Setup

A genetic algorithm is used to evolve the VMC parameters. All the parameters of the VMC are encoded in a genome as a sequence of floating point values. In this implementation, we evolve the following parameters: \( (w_{\text{const}}, w_s, r_{\text{const}}, a, b, c) \) (see section II for the description of the parameters).

The population size of the genetic algorithm is 15 and the populations are evolved for 25 generations. The experiments are repeated for 15 independent evolutionary runs. Elitism of one genome and a crossover rate of 20% are implemented. All the genomes (except the elite) are mutated with a step-size \( \sim N(0,0.2) \). The genomes are randomly initialized between \([-1,1]\) for the sensor-related parameter \( w_s \), and between \([0,1]\) for the other parameters. For evaluating the fitness, each genome is used to grow the organism for 1000 time-steps and the fitness is evaluated as:

\[
\text{fitness} := \text{distance of the root to the target}
\]
Each genome is evaluated in three independent runs and the fitness is the minimum of the three evaluations.

V. RESULTS

Fig. 2 represents the fitness trajectory of the evolutionary populations collected from all 15 evolutionary runs. In order to get an impression of the behaviors of the organisms controlled by the evolved VMC genomes, we choose an arbitrary evolutionary run and present the behavior of its developing organism. Fig. 3 represents the behavior by depicting the organism in the environment in a sequence of snapshots for a period of 2300 steps (recall that the genomes controlling the organism were only evolved for a period of 1000 steps). As represented in the figure, the organism in the initial step consists of a single node. It then grows into a larger organism by developing additional nodes over time. As a result of addition and removal of nodes, as well as the possibility of the root node to move within the organism, the organism moves towards the target following the environmental gradient. The behavior is considered visually comparable with the motion of *dictostelium discoideum* slime-molds (consisting of several autonomous cells) following food.

To test whether the organism is reactive to the environmental modality, in the next step, we take the same evolved genome and let the organism develop in a different setup. In this setup, a target disappears after a fixed period of 2000 steps and immediately reappears at a new position. The process is iterated for 30,000 time steps. The target is initially positioned at coordination (400,0) and reappears in a sequence of new positions (400,-400), (0,-400), (0,0), back to (400, 0). Fig. 4 represents the trajectory of the locomotion over time. Every pixel in the trajectory...
depicts the position of the center of mass of the organism. The figure demonstrates the reactivity of the organism to the position of the target as the organism moves towards the target regardless of the direction.

VI. DISCUSSION

VMC is a novel distributed controller originally introduced for developing artificial structures. Here we have implemented the controller for developing an artificial organism capable of locomotion in response to environmental modality. It relates to an interesting topic in Evolutionary Robotics (ER), which is the parallel evolution of morphology and controllers. It is suggested [20] that applying developmental processes is beneficial for this approach even in real world robots. Here we take a swarm intelligence developmental approach where several simple agents react locally to their neighbors and their environment resulting in emergent behavior of the whole system. Every cell (node) in the body of our organism contributes to developing the morphology as well as providing sensory information. Although each cell can only sense its local environmental modality without any directional information, the directionality emerges as an implicit result of the interactions between the cells leading to the seemingly purposeful locomotion of the organism.

The approach will be further investigated in the future for developing more complex organisms including organisms with neural network controllers.

ACKNOWLEDGMENT

This work was supported by EU-H2020 project ‘florarobotica’, no. 640959.

REFERENCES


