Vascular Morphogenesis Controller: A Distributed Controller for Growing Artificial Structures

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It is a challenging task to develop morphologies of structures in response to dynamic environmental factors and constraints. In the context of the EU-funded project *flora robotica* [1] we are interested in developing self-organized methods that combine local considerations and global requirements and drive the development of structures. Embryogenetic development of biological organisms and cell differentiation are studied for a long time in evolutionary developmental biology (EvoDevo) [2], [3]. Some of the mechanisms from that field are already applied to pattern formation [4] and development of body morphologies [5], [6] and controllers [7] in evolutionary robotics [8] and modular robotics [9]. In this work, vascular system and branching dynamics of plants are used as the source of inspiration for designing a novel algorithm called "Vascular Morphogenesis Controller" (VMC) that is applied to morphological development of modular structures. Plant vessels develop in the stems and roots. They transport water and minerals from the roots to the leaves, and sugars and photosynthates from the leaves to other parts of the plant [10]. There are evidences [11], [12] suggesting that there is a competition between different branches over the vascular growth. The branches that are in better situations (e.g., get more light) produce more photosynthates that flow back from the leaves. The higher flow rate leads to more vascular tissues in the branch and therefore more water and minerals from the roots reach the branch. More water and minerals facilitate the growth of the branch and the branch may end up in an even better situation which in turn reinforces the growth. Different branches with their different local conditions compete over production of new vessels. On the other hand, global resources (i.e., water) are limited and the vessels are subject to degradation as well. Based on the positive and negative feedback loops established by this competition and limitation, a dynamic system of vessels shape the growth of the plants.

1. Vascular Morphogenesis Controller

The VMC uses a similar concept as the branching competition in plants in order to develop the morphology of an artificial structure. The algorithm directs the morphology by controlling the branching of the structure. Every unit of the structure that is potentially capable of holding a branch is considered a controller node of a tree-like (acyclic directed graph) structure. At each node, a state variable G is defined representing the "growth motivation". The value of G at a leaf indicates its willingness for growth. Each leaf senses its local environment and generates a value, namely "Flow", that is then communicated to the parent node. To every child i of a node, a state variable W_i is assigned that is similar to the quality of the vessels at a branch of a plant. The W_i is updated based on the flow coming from the children nodes (branches or leaves) and a set of local parameters. The flows that are coming from all the children of a node, are summed up at the node and pass through a function of local sensors and internal parameters at the node. The output is the flow passing from the node to its parent. The processes are running in parallel at every node leading to the update of the W at all the nodes. The values of the W along the organism are the key variables that are used for distributing the limited resource of growth motivation. Since the growth motivation is limited, a competition occurs between different branches. Fig. 1 represents a schematic example of the different variables in the interacting nodes. The G value (growth motivation) at the root is constant. It is then split into fractions according to the values of W assigned to each

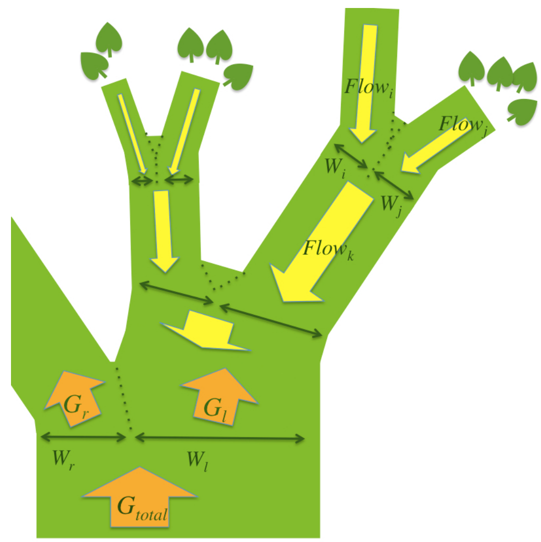

Figure 1. Vascular Morphogenesis Controller is running in parallel at every potential branching point.

branch of the root. The fractions are transmitted to the nodes in the branches where the same process occurs. The process runs at every branching node up to the leaves distributing the G value between the leaves. The amount of G reaching each leaf determines its motivation for further growth. The following equation represents how the G value of a node i is updated based on the G value of its $parent$ node (G_{parent}) and the W values assigned to itself and its siblings at the parent node.

$$G_i = G_{parent} \cdot \frac{W_i}{\sum_{b \in branches} W_b} \tag{1}$$

The $Flow$ at a $leaf$ is generated according to the following equation:

$$Flow_{leaf} = \omega_{const} + \sum_{s \in sensors} \omega_s \cdot I_s \tag{2}$$

The value of $Flow$ at internal (non-leaf) node i is updated based on the $Flow$ values coming from its branches ($Flow_b$) and a function f as follows:

$$\begin{aligned} Flow_i &= f(sensors) \cdot \sum_{b \in branches} Flow_b \\ f(sensors) &= g(\rho_{const} + \sum_{s \in sensors} \rho_s \cdot I_s \end{aligned} \tag{3}$$

The $Flow$s coming to a node from its branches are used for adjusting the Ws of the respective branches as follows:

$$\Delta W_i = \begin{cases} -c \cdot W_i + \beta + \alpha \cdot (Flow_i - W_i) & \text{if } W_i < Flow_i \\ -c \cdot W_i & \text{otherwise} \end{cases} \tag{4}$$

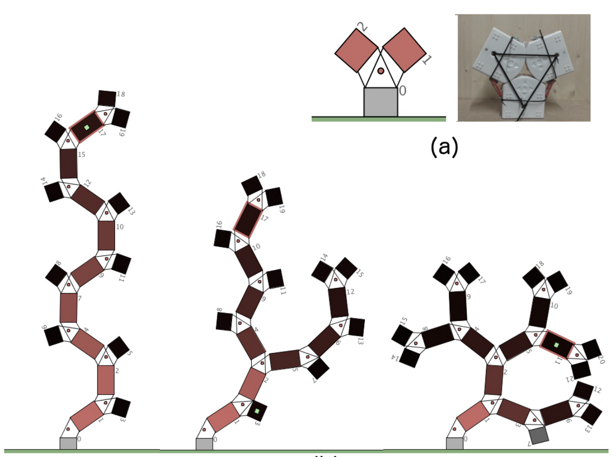

Figure 2. Different robot morphologies grown by using different parameters

2. Growing a Modular Robot

VMC is implemented to develop the morphology of a growing modular robot under physical effects such as gravity and elasticity. The simulation is developed with Box2D physics engine after a physical modular robot was built using a mobile robot called Thymio and elastic bindings (Fig. 2(a)). The growth of the robot starts from a base module that makes a tilted flexible starting point for the growth. All the other modules of the robot are branching modules. The accelerometers at the modules indicating the direction of the gravity vector are used as the sensors at the leaves. In every step of simulation, the leaf with the highest growth motivation is chosen as the branch to grow. The parameters of the controller are evolved for growing tall against gravity in a calm environment (Fig. 2(b) left), in a shaking environment (Fig. 2(b) middle), and also for growing bushy (Fig. 2(b) right).

3. Conclusion

A novel morphogenesis controller based on competition between branches of a structure is proposed and successfully implemented to grow a modular robotic structures in different conditions.

Acknowledgments

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