Development of Morphology Based on Resource Distribution: Finding the Shortest Path in a Maze by Vascular Morphogenesis Controller

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Morphogenesis in biological systems is controlled by the parameters encoded in the genomes and rules of interaction between different components of the system and the environment. Several methods are proposed for developing morphology of artificial structures (Doursat et al., 2013). Some of them are inspired by embryogenesis (Wolpert, 1996) in biological organisms, i.e. Cussat-Blanc and Pollack (2014). Others (Hornby and Pollack, 2001; Sims, 1994) use more abstract generative encodings such as variances of L-systems (Lindenmayer, 1975). Our approach to morphogenesis is based on the distribution of a common resource between competing components of a growing system. The novel distributed controller called Vascular Morphogenesis Controller (VMC) is inspired by the growth process of plants and more specifically the competition between different branches for developing vessels and thus for further growth. The initial algorithm is introduced in Zahadat et al. (2017) for modular robots. Here we use it to solve a maze.

Model: Vascular Morphogenesis Controller

The vascular system of plants is responsible for transporting common resources necessary for growth (e.g., water and minerals) from the roots to branches. A hormone called Auxin is produced at the tips of branches and flows back towards the root. On its way along the branch vessels, Auxin regulates vessel production. Branches that are in better positions (e.g., in light) produce more Auxin and develop more vessels leading to more common resource and growth (Leyser, 2011). VMC abstracts these concepts (Fig. 1). A VMC is an acyclic directed graph overlaid on the growing structure. The leaves of the graph act as the growable tips of a plant and produce Successin (in analogy with Auxin). The Successin flows towards the graph's root and along the way, it regulates the thickness of edges (analogous to plant vessels). The thicknesses are then used for distribution of a limited value (common resource) between branches. The share of this value reaching a tip motivates its growth.

At every leaf i, Successin S_i is produced as:

$$S_i := \omega_{const} + \sum_{s \in sensors} \omega_s \cdot I_s \tag{1}$$

where I_s is the input from sensor s. The ω_{const} and ω_s are constant and sensor-dependant production rates.

Successin flows towards the root. The value of S at a junction (internal node) i is updated as:

$$S_i := g(\rho_{const} + \sum_{s \in sensors} \rho_s \cdot I_s) \cdot \sum_{b \in branches} S_b \tag{2}$$

where $g(x)$ is a sigmoid function. The ρ_{const} and ρ_s are constant and sensor-dependant transfer rates of Successin and contribute to the effect of distance from the root on the share of resource reaching the leaves.

For every edge connecting a node to its child i, V_i is adjusted at every time step based on the Successin flowing through it. If S_i is more than V_i, V_i is likely to increase (depending on the parameter values). Otherwise, V_i decreases by a constant decay rate down to the value of S_i.

$$V_i := \begin{cases} min(S_i, (1-c) \cdot V_i + \beta + \alpha \cdot (S_i - V_i)) & \text{if } S_i \geq V_i \\ max(S_i, (1-c) \cdot V_i) & \text{if } S_i < V_i \end{cases} \tag{3}$$

where c is the decay rate, β is the addition rate, and α is the adjustment rate. The values of these parameters influence the intensity of competition between different branches.

The limited common resource R initiates at the root node. The R_m for a node m is proportionally divided between its children simply based on the thickness of their edges:

$$R_i := R_m \cdot \frac{V_i}{\sum_{b \in children} V_b} \tag{4}$$

Implementation and Results

Fig. 2 shows the growth of a structure controlled by VMC in a maze. The structure grows from an initial seed at the bottom of the maze. Every branch can grow into two branches with 90° angle in between. Branches can bend due to the walls. The structure grows until it reaches the exit at top-right (Fig. 2a). The colors of nodes represent the amount of common resource available. After reaching the exit, a wall at the bottom-left is removed to offer a shorter path out of

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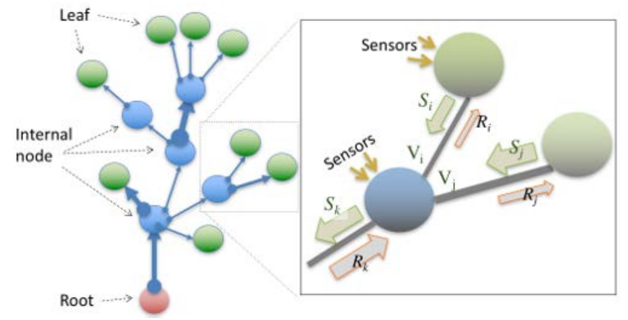

Figure 1: An example network of controller nodes in VMC.

the maze (from the root). The structure detects the change and reacts by giving more share of resource and thus growing faster at the shorter path (Fig. 2b). The older top parts of the structure are now deprived of resource, because the new better path is taking almost all of it now. Fig. 2c and 2d represent the resource intensity over the maze accumulated from 10 independent runs. Every run takes 6000 simulation steps and the resource distribution over the maze is depicted for the last 1000 steps.

In the current implementation, the value of R_m at the root is set to $1 + S_{root}$ where S_{root} is the amount of Successin reaching the root at every time step. At a tip i, the R_i is accumulated and a forgetting factor (λ) is applied as follows: $G_i = \lambda \cdot G_i + R_i$ while G_i is initially set to 1. The tip decides to grow if $G_i > TH_g$ and it is removed from the structure if $G_i < TH_r$. The parameter values of this implementation are represented in Table 1.

α	β	c	ω_{const}	ω_s	ρ_{const}
0.95	0.1	0.05	0.15	1	0.85
ρ_s	I_{inside}	$I_{outside}$	λ	TH_g	TH_r
0	0.01	0.02	0.99	6	0.1

Table 1: Parameter values

Conclusion

A novel controller of growth inspired from branch competition in plants is implemented in a structure growing in a maze. The results show that the distributed controller successfully allows the structure to choose the exit with shortest distance from the initial point of growth indicating the capacity of VMC for collective decision making in dynamic environments which is comparable to the behavior of slime-mold growing in a maze (Nakagaki (2001)).

Acknowledgements

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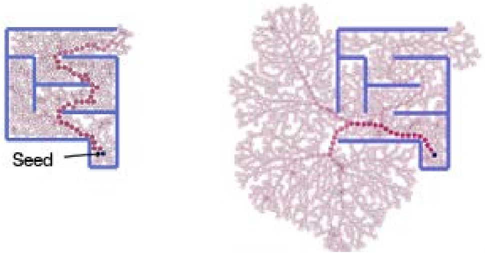
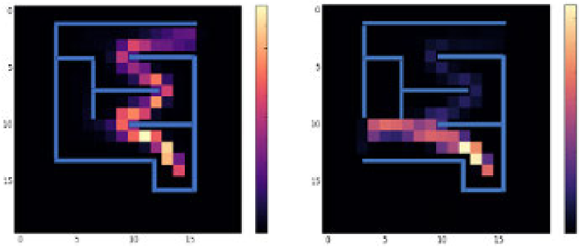


(a) Growth in the maze with one exit

(b) Growth after adding the second exit in a shorter distance



(c) Resource histogram inside the maze with one exit

(d) Resource histogram inside the maze after adding the second exit

Figure 2: Growing in maze in different conditions.

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