Hybrid Mass-Spring L-System for modelling tree interactions with environment

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Keywords: tree growth, physics-based simulation, gravitropism, phototropism

Introduction

Tree model accuracy in digital twin cities is increasingly crucial for urban planning. Specifically, a tree model that considers the growth process and its responses to the environment may inform decision makers and provide recommendations on tree management and safety issues such as falling trees, obstructing branches, tree pruning and shades.

Existing L-System-based tree modelling techniques (Yi et al., 2018) (Stava et al., 2014) focus on implementing tree growth processes without accounting for the trees' continued mechanical responses to external forces and tropisms, after growth. Accounting for such responses will allow for more accurate tree models, which is important for urban tree planning. On the other hand, (Moulton et al., 2020) and (Hädrich et al., 2017) resolve this by modelling tree stems as inextensible elastic rods and particles respectively but neither integrates the domain knowledge of botanical growth processes such as branching patterns. (Jirasek et al., 2000) is similar to our work and they incorporate L-Systems while using equations involving moments to compute the rotation of the internodes. However this model does not account for the tree parts becoming stiffer and the possibility of branch breaking. Our model of incorporating L-Systems and the Mass-Spring system will allow us to keep track of nodal information while accounting for both biological growth processes and mechanical processes, thus it is more suitable for urban tree planning.

Methods

We generate our hybrid tree models based on species modelling work in (Gobeawan et al., 2021): stems are constructed by stacking and extending short cylindrical internodes over time according to L-System growth rules. Subsequently, mechanical responses are incorporated through a mass-spring system, where nodes and internodes are represented by point masses and connecting springs, consecutively. Springs connecting alternate point masses are also added for tree structure support. This is described in the following pseudocode.

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for number of age timesteps:
    tree grows for 1 unit of age by L-System production rules;
    for number of substeps:
        calculate forces acting on each node in mass-spring system;
        calculate and update new position of each node;
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To grow the tree until a target age, the system iterates for a number of age timesteps, each producing a new growth pair of internode and node at each active bud. Within an age timestep, for a number of substeps, forces on each node are calculated iteratively to update its position. Forces considered here include the tree's own weight and responses to environmental stimuli (phototropism and gravitropism), along with spring forces (elastic force and damping force) of the mass-spring system. To account for material changes from non-woody to woody branches, the spring constant for each branch varies with respect to its age.

Our model implementation uses L-Py (Boudon et al., 2012) and PlantGL for the L-Systems and its graphical representations. We implemented the mass-spring system (Baraff and

Witkin, 1999) using the implicit Euler (Mesit et al., 2007), gravitropism based on the sine law (Dumais, 2013), and phototropism by pulling stem tips towards the light source.

Results and Discussion

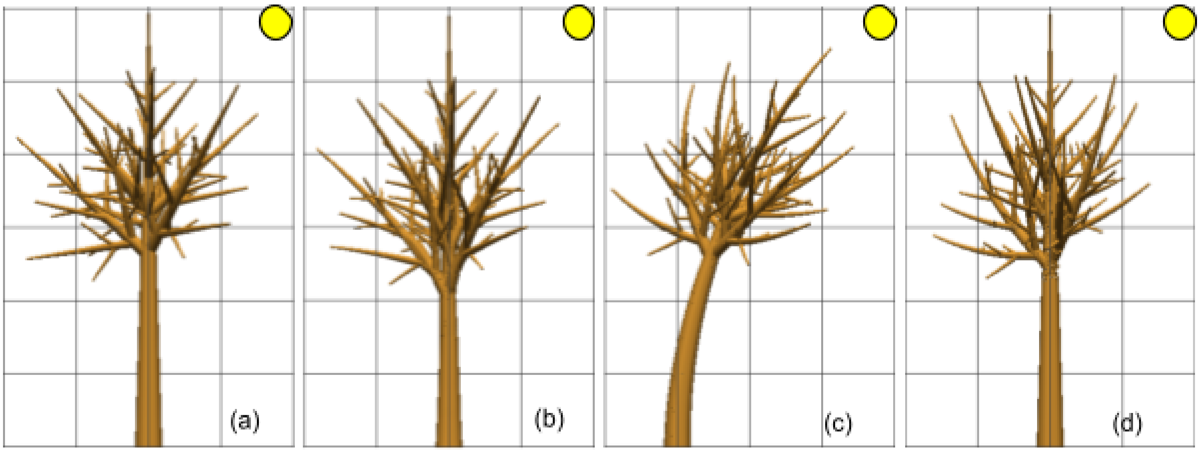

Figure 1. Simulated 25-year-old *Hopea odorata* tree considering: (a) no forces, (b) tree's weight ($g = 9.81\, m\, s^{-2}$), (c) response to phototropism ($0.01N$), (d) response to gravitropism ($maximum\ 0.1N$). The yellow dot represents a light source.

Fig. 1 shows several scenarios of a hybrid 25-year-old *Hopea odorata* model. For every age timestep which is set as 1/24 of a year, the positions of all nodes were updated for 25 substeps of $8 \cdot 10^{-4}$ seconds. In Fig. 1(d) where the tree responds to all forces, its tips pull the stems towards a light source while its weight pulls them down, illustrating our model's response to environmental stimuli. However, our implementation requires small time steps for simulation stability. Inherently, our model requires relatively intensive computing resources to run long, accurate simulations.

Conclusion

We have developed a hybrid tree model involving species-specific L-System growth rules and mechanical responses to environmental factors such as gravity and light sources. The hybrid model shows typical reactions to these factors, given that realistic values were used for most parameters such as the spring constant. More work is required to investigate the different parameter values (e.g. magnitude of tropism forces). We have tested that our model can be used to investigate the strain acting on each node of the tree, and allow automatic branch breaking after the strain reaches a certain threshold. However, more work can be done to validate these models using data, and thereby make further improvements.

Acknowledgement

This research/project is supported by the National Research Foundation, Singapore under its Industry Alignment Fund – Pre-positioning (IAF-PP) Funding Initiative. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of National Research Foundation, Singapore.

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