Modeling Trees as Kinematic Stucture with Spring & Damper System

Moonyoung Lee (moonyoul), Kwang Kyun Kim (kwangkyk)

Abstract— There is a growing need for automation in agriculture as reports of labor shortages increase. However, using robots to harvest from trees is challenging because the dynamics models of trees are often unknown, which can lead to unsafe robot interaction with the tree. We propose to model a tree as a series of kinematic chain similar to a robot arm. With this model simplification, branches can be modeled as a rigid link where motions are then constraint to revolute motion around its joints. We then observe tree's response to an applied external disturbance in simulation. We investigate how the response of the spring-damping tree model system varies as we increase the number of branches in a tree. Our experimental results show that fully grown tree with 13 links reach steady state in 43% of the time compared to that of a less mature tree with only 7 links when an external disturbance is applied.

I. Introduction

With increasing labor shortages, labor-intensive fruit harvesting tasks are becoming more and more costly. Therefore, there is an increasing demand to have robots perform these types of tasks. However, performing robot manipulation tasks in heavily cluttered environments, such as dense canopies, remains an open problem. Automating manipulation in dense canopies is challenging due to the extensive robot contact with the environment to perform the needed picking task. Traditionally, many approaches used in the robot manipulation community impose two simplifying assumptions regarding contacts. First, with the exception of the object to grab, contact with rest of the environment is treated as collision that should be avoided. Second is that the canopy environment perceived through a vision-system is assumed to be quasi-static. However, human laborers demonstrate extreme dexterity in dense canopies by frequently making contact with the environment and even pushing them aside in order to obtain a better view of the fruit to be picked. Thus, this implies the need to investigate robotic contact interaction with trees as observed from the dexterous manipulation demonstrated by human laborers on the field.

Frequent interaction between agricultural robots and the farm environment naturally then creates demand for a more simulated farm environment with accurate dynamics. This would bring a number of benefits in agricultural robotics. First, obtaining a physical model of a tree can be used to better reason about contacts rather than simply treating all point-cloud obtained from the vision-system as collision particles to avoid. In a robotics perspective, this work is important because this approach can greatly increase the perceived workspace of the robot close to the actual reachable workspace even when operating in cluttered canopy areas. Second, acquiring contact data becomes easier in the simulator, while as in the field, the robot would have to interact with real plants where sensor measurements are required.

All authors are with The Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213, USA {moonyoul, kwangkyk}@andrew.cmu.edu

Fig. 1: CMU Agriculture robot interacting with tree vines

However, we have yet to observe a simulator that has both photorealistic visualization and accurate dynamics. For example, 3D animators segment a 3D modeled tree into parts, and then input noises or twists intuitively to realistically visualize trees in wind. Lacking the dynamics with the external wind, however, such approach makes a group of trees in the wind look very unnatural as each tree oscillate in an arbitrary direction. Modeling trees with spring and damping system allows dynamic interactions with wind, and improves visualization of a group of trees in the wind more natural and plausible.

This paper investigates how trees can be modeled as a kinematic chain with a spring-damper system. We then explore how the stability of the spring-damping tree model system with respect to the external force varies as the number of branches in the model reduces. The results are compared to the changes in the oscillation observed from actual trees in the wind as the number of branches differ.

II. Related Work

There have been a wide coverage of studies done for agriculture automation but many studies can be categorized into robot perception for tasks such as fruit counting [1],[2],[3], or motion planning and control to pick fruits [4], [5]. Many of the manipulation planning approaches however, drastically simplify the complexity of the manipulation problem by simply disregarding any contact with the environment.

The underlying assumption to this approach is that obstacles such as leaves and twigs don't drastically affect the robot trajectory. This assumption only works for limited cases of well-pruned canopies, or where fruits are clearly exposed for picking in a contact-free motion, but performs poorly in real field environments where the plant growth is less controlled and inevitable contacts could damage the plants. In order for the robot to have safe interactions with trees before harvesting fruits is to know the tree dynamics model a priori. Knowing how much a tree would deform (or in contrast, how much the tree would resist to the robot's contact) is important because prior knowledge of the tree model can be used to create a safer control loop during the interaction.

There are two studies we found in our literature review that guided our tree modelling project. The authors of [6] showed the tree's geometric representation can be modeled as a collection of articulated rigid bodies, or as a series of cylinders. Each rigid body represents either a trunk, branch, or a twig. Spherical joints are placed between bodies to connect the parent and child body, except the root rigid body, which has a zero parent body. Spherical joints are constructed to have zero translation between three separate revolute joints which gives three rotational degrees of freedom. The second study [7] showed how trees modeled as rigid bodies can act as coupled mass with spring and damping properties. An external force like wind influences the spring and damping response of the trees. In an actual tree, the spring and damping coefficients are calculated from measuring varying vibration of the tree with strain meter and accelerometers. K, C coefficients are different depending on the method and modeling, but one finding shows that the vibration of the tree in wind increases as the number of branches decreases. Based on these studies, our research goal is to model and observe a similar dynamics behavior in our 3D modeled tree.

III. Modeling Method

A. Kinematics

The methodology of modeling a tree starts by geometrically representing the tree as links and point revolute joints as done in [6]. Trunk and branches are abstracted as links and a spherical joint between the links let each articulated rigid bodies of trunk and branches rotate about the joint. A spherical joint is implemented by setting the distance between revolute joints about x, y, and z-axis as zero, which overlaps the joints as a spherical joint. We manually created the basic tree model as a 3-link simple tree as a URDF (Universal Robot Description File) first, and then extended the model to a 13-link full tree as shown in Fig. 4. The URDF file was created using the URDF generator visualization tool.

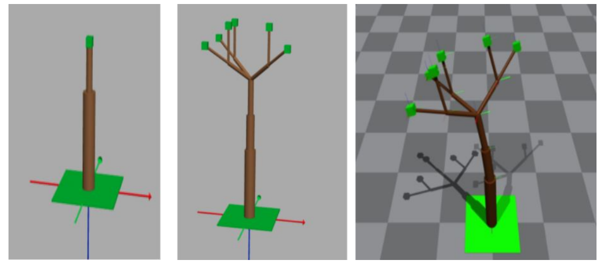

Fig. 2: Creating a simple 3 link tree URDF model as links and joints (left) Creating fully grown 13 link tree URDF model (middle) Loading URDF file in Simulation to observe deformation under force (right)

Modeling the kinematic structure of the tree has posed some implications on the trade-offs in different types of transformation representation. Using Euler angles (RPY) required less effort in modeling as it only needed the least number of parameters of roll, pitch, and yaw. It is also a form of representing the model in an intuitive way. However, when the created URDF model was inputted to two different simulators, the two simulators returned slightly different shaped trees even though they shared the same parameters as shown in Fig. 3. The two simulators showed two differently shaped trees because different simulators parameterize the Euler angles in different sequences from each other. The different expression implies that Euler angle transformation representation cannot be a unique one unless the rule of composition is included in modeling. Fundamentally, least parameter representation cannot avoid singularities in any 3D representation of SO(3). On the other hand, employing exponential coordinates to map the rotation in SO(3) to twists in SE(3) can generalize the transformation

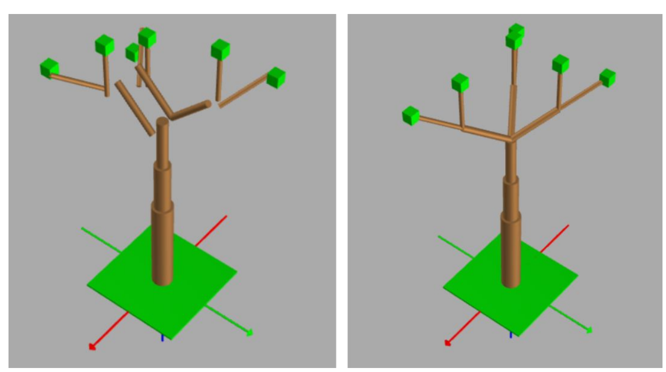

Fig. 3: URDF model using Euler angles for transformations, and therefore leading to undesired behavior of non-unique transformations for two different simulators

matrices as a unique solution.

B. Dynamics

Now that we have formulated the kinematic model of the tree motion, we are interested in observing the dynamic motion of the tree when an external disturbance is applied to it. As learned in class, the equation of motion (EoM) can be described as

$$M(q)\ddot{q} + C(q, \ddot{q})\dot{q} + g(q) = \tau. \qquad (1)$$

Wind, or the external disturbance applied on the tree, would exert corresponding torque $\tau$to each joint of the tree, and $q, \dot{q}, \ddot{q}$ capture the response motion of the tree. M, C, g are determined by the Isaac Gym Simulator given the mass, inertia, link length parameters parameterized in the URDF model of the tree. As we are interested in observing how much the tree deforms under external disturbance, we investigate the effect of the K, D coefficients that reflect the spring damper system. As the tree is modeled similar to a robot arm in a URDF file, there are no parameters that define K, D directly for the joint motors. However, given a desired joint reference position q_{ref} in the simulator, there is a joint controller that observes the real load on each joint. Therefore, the stiffness coefficient of the joint controller determines how much the tree should bend under pressure (emulating the spring behavior) and the damping coefficient determines how quickly the kinetic energy is absorbed when the external load is released (emulating the damping behavior). As the resulting motion trajectory heavily depends on how the force is transferred to the rigid body of the tree, it is imperative to select a simulator with accurate physics engine like NVIDIA Isaac Gym. Every cylinder link of the URDF is represented as a collision mesh that make direct contact with an external disturbance. The external disturbance in Isaac Gym is parameterized as a single point contact with force $F = [Fx, Fy, Fz]$ where the F vector contains both the disturbance magnitude as well as the contact direction. The K, D coefficients were fine-tuned by visually inspecting how "naturally" the tree would bend in simulator in response to the applied force. If the coefficients were too low compared to the applied F, the tree would wildly swing like a loose spring. If the coefficients were too high compared to F, the tree would not react to the applied F. We visually inspected the tree movements and then determined the K, D coefficients.

IV. Experimental Results

One method to assess whether a tree model behaves similarly to the real tree is by performing the "pluck test" [7] to determine if tree damping effect become reduced as the number of branches are removed as shown in Fig. 5 (left). We emulated this experiments by applying a 'push and release' disturbance to the tree. Similar to the results the authors of [7] obtained on real trees, we observed

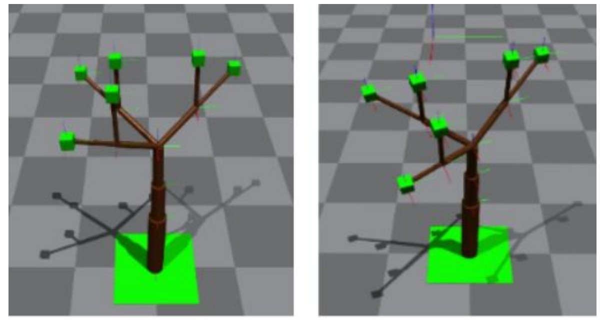

Fig. 4: Before and after external force is applied to the tree. The contact location is shown with the big TF coordinate in the right

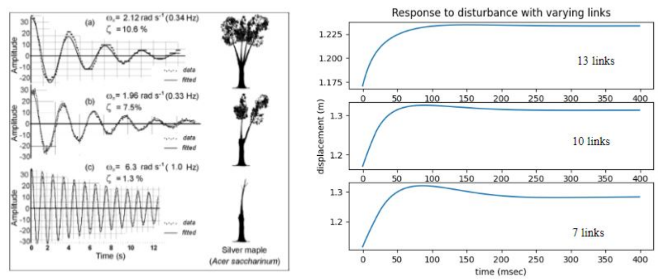

Fig. 5: Response under disturbance as number of branches vary shown with real data (left) and with our model (right)

that our spring-damper modeled tree in simulator also showed less damping effect as the number of branches reduced. More specifically, the tree with 13 links reached steady state in 0.15 seconds while it took the tree with just 7 links 0.35 seconds to reach steady state, which took 42% less time comparatively. This aligns with our intuition that increased number of branches adds to the inertia of the tree body, as well as introducing additional dampers to more quickly absorb the velocity term. This experiment is important because it shows how a simple tree kinematics can be represented with series of links and joints, while the dynamics can be represented as a spring damper system.

V. Conclusion

In this project, we investigated how a simple tree can be modeled as a kinematic chain and it's dynamics represented as a spring-damper system. After manually creating URDF model of the simplified 13 link tree, we applied external disturbances to the tree in a physics accurate simulator called Nvidia Isaac Gym. To determine whether the simulated tree motions are "natural", we performed a "pluck test" similar to [7]. Through this experiment, we were able to observe how the simplified model of the tree does indeed show similar response behaviors to a real tree. The authors believe this preliminary shows exciting results that we would like to further investigate by extending the number of links to a more full grown scale. The scientific questions to further investigate would be how the dynamics computation load would scale as we vary the number of links in our simulator.

References

[1] F. Yandun, A. Silwal, and G. Kantor, "Visual 3D Reconstruction and Dynamic Simulation of Fruit Trees for Robotic Manipulation," in IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops, 2020, pp. 54–55.

[2] A. A. Author, B. B. Author, and C. Author, "Title of article," Title of Journal, vol. 10, no. 2, pp. 49–53, 2005.

[3] Y.-Y. Zheng, J.-L. Kong, X.-B. Jin, X.-Y. Wang, T.-L. Su, and M. Zuo, "Cropdeep: The crop vision dataset for deep-learning-based classification and detection in precision agriculture," Sensors, vol. 19, no. 5, 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/5/1058

[4] S. Mghames, M. Hanheide, and A. Ghalamzan, "Interactive movement primitives: Planning to push occluding pieces for fruit picking," in 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, pp. 2616–2623.

[5] Z. Nemlekar, Heramb. Liu, S. Kothawade, S. Niyaz, B. Raghavan, and S. Nikolaidis, "Robotic Lime Picking by Considering Leaves as Permeable Obstacles," in International Conference on Intelligent Robots and Systems, 2021.

[6] K.R.James and N.Haritos, "Brances and damping on trees in wind," 23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23), 2014.

[7] J. H. W. L. Ed Quigley, Yue Yu and R. Fedkiw, "Real-time interactive tree animation," IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS, vol. 24, no. 5, pp. 1717–1727, 2018.