Toward Digital Fabrication of Preformed Vine Robots

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***Abstract*— Vine robots are a class of soft robots that grow via tip eversion. Their compliance allows them to squeeze through small gaps and adapt to obstacles. They can be mechanically programmed to follow a desired path by preforming the vine robot's body material. Here, we present a method of optimizing a desired path given an environment, a planner for fabricating vine robots to grow along a path, and an assessment of the vine robots resulting from three fabrication methods.**

I. INTRODUCTION

Preforming a vine robot involves setting its mechanical structure so it everts into a desired shape [1] [2]. This is useful in reducing interactions with known environments, but there is limited work on assessing accuracy of the deployed shape. We address this gap for preformed vine robots with discrete bends. We present a planner for fabricating preformed vine robots based on robot diameter, fabrication method, and desired Denavit-Hartenberg (D-H) parameters. We model a vine robot as an R^n fixed manipulator with n links, allowing us to represent its shape with D-H parameters. We assess growth and shape matching capabilities of vine robots resulting from three fabrication methods.

II. METHODS

Path Generation: Similar to the approach take by Exarchos et al. [3], we use a path generation algorithm to obtain a set of desired vine robot poses. We solve the inverse kinematics problem with an evolutionary algorithm that includes hard constraints on obstacle collision and bounds on the environment. The algorithm outputs an optimal design in terms of vine robot segment lengths and bend angles to reach a target while avoiding obstacles (Fig. 1a). Obstacles are modeled as circles, and collisions add a static penalty to the fitness function solving the inverse kinematics. The algorithm finds a (sub)optimal solution in reasonable time, with a single iteration running in $\mathcal{O}(n \log n)$ with the number of targets and obstacles in the environments.

Fabrication Methods: We investigate three methods that operate by connecting two points along the axial length of the vine robot to create a discrete bend in a desired direction (Fig. 1b): (i) a method used by Greer et al. that tapes folds along the length of the robot [2]; (ii) a new method that ultrasonically welds folds of material together; and (iii) a new method that integrates loops along the length of the vine robot that can be connected or disconnected as desired. We apply these methods to two materials: low-density polyethylene (LDPE) and TPU-coated rip-stop nylon.

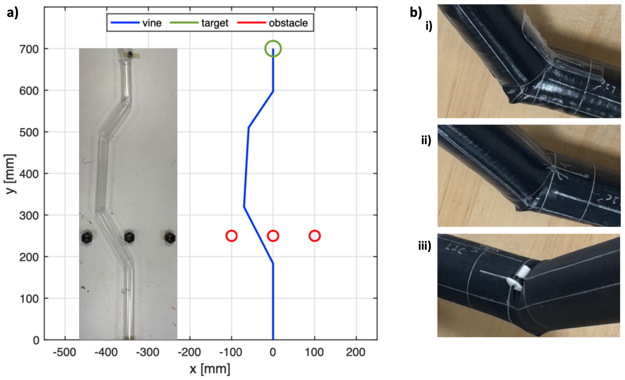

Fig. 1. **a)** Path generated for a desired tip pose, implemented using tape on LDPE material. **b)** Examples of joints created on vines made of Nylon ripstop material using (i) tape, (ii) ultrasonic welding, and (iii) connected loops embedded in the vine.

Mechanical Programming Planner: We present a planner that takes a D-H representation of the desired vine robot shape and converts it to fabrication parameters based on fabrication method and robot diameter. The fabrication parameters define (i) the distance between pairs of points that create a joint, (ii) the axial distance between two sets of pairs, and (iii) the circumferential distance between two sets of pairs. We assess the effectiveness of our planner on each manufacturing method in terms of D-H parameter matching, growth speed, and minimum growth pressure.

III. PRELIMINARY RESULTS

We match desired D-H parameters with errors as low as 5 mm for link length, 5 degrees for link twist, and 3 degrees for joint angle. Future work will evaluate these manufacturing methods for automation, i.e. digital fabrication.

REFERENCES

[1] N. Agharese, T. Cloyd, L. H. Blumenschein, M. Raitor, E. W. Hawkes, H. Culbertson, and A. M. Okamura, "Hapwrap: Soft growing wearable haptic device," in *IEEE International Conference on Robotics and Automation*, 2018, pp. 5466–5472.

[2] J. D. Greer, L. H. Blumenschein, R. Alterovitz, E. W. Hawkes, and A. M. Okamura, "Robust navigation of a soft growing robot by exploiting contact with the environment," *The International Journal of Robotics Research*, pp. 1724–1738, 2020.

[3] I. Exarchos, B. H. Do, F. Stroppa, M. M. Coad, A. M. Okamura, and C. K. Liu, "Task-specific design optimization and fabrication for inflated-beam soft robots with growable discrete joints," in *IEEE International Conference on Robotics and Automation*, 2022, pp. 7145–7151.

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