Geometrical Analysis of Simple Contours Deposited by a 3D Printing Hexacopter

Alexander Nettekoven[a], Nicholas Franken[b], Ufuk Topcu[b]

[a] *Walker Department of Mechanical Engineering, The University of Texas at Austin, 204 E. Dean Keeton Street, Austin, 78712, TX, USA*
[b] *Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 2617 Wichita Street, Austin, 78712, TX, USA*

Abstract

Current limitations in vertical and horizontal mobility for ground robots in 3D printing of medium to large-scale objects have recently led to the development of a 3D printing hexacopter testbed at the University of Texas at Austin. This testbed can fly to a desired location and deposit polylactic acid on flat surfaces. A previous study has shown the feasibility of this approach but has not yet quantified the testbed's printing capabilities. In this paper, we quantify the printing capabilities. We print square contours of different sizes and quantify the printed results based on their geometric dimensions. We also quantify the testbed's trajectory tracking to assess the testbed's positioning accuracy during printing. In quantifying the testbed, we lay the groundwork for using aerial robots in printing applications of medium to large-scale objects, such as concrete printing.

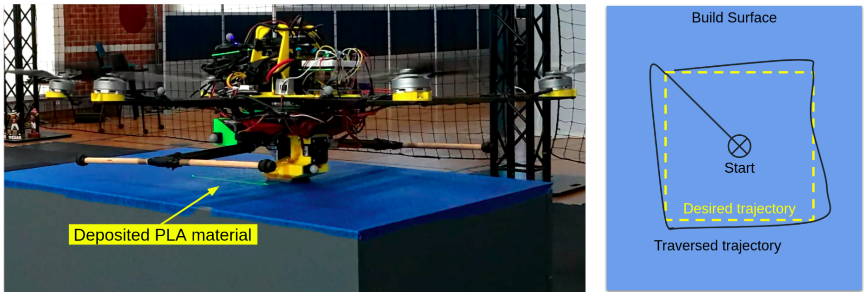
---

1. Introduction

Ground robots are increasingly used in 3D printing of medium to large-scale objects [1, 2, 3, 4, 5]. Pairing a robot's versatility with 3D printing significantly increases the process's flexibility and an engineer's design freedom to manufacture arbitrarily complex objects [5]. However, a lack of vertical mobility and sometimes horizontal mobility still prevents these 3D printing processes from maximizing their potential [2, 5, 6]. For example, the limitations in mobility usually require the ground robots to be larger than the to-be-printed objects [6]. This requirement prevents these systems from scaling to arbitrarily large objects. Another limitation is a ground robot's dependency on the terrain and the surroundings. For example, a ground robot cannot print a large cylindrical structure from its center without being trapped inside.

To overcome these limitations, we recently developed a 3D printing hexacopter testbed at the University of Texas at Austin (see Figure 1(a)) [7]. This testbed is a small-scale proof of concept for combining 3D printing technologies with unmanned aerial vehicles (UAV). The testbed uses fused deposition modeling to 3D print during flight. The advantage of combining 3D printing with UAV technology is the added mobility in the vertical direction and the lower dependency on the terrain and the surroundings. We previously demonstrated the feasibility of this approach by successfully printing different contours of polylactic acid (PLA) on a flat surface during flight. However, these tests were primarily qualitative.

In this paper, we analyze the system's printing capabilities quantitatively. We perform multiple print trials and measure the geometric dimensions of the print results. Since 3D printing applications such as concrete printing require 3D printing at specific locations, we also analyze



(a) 3D Printing Hexacopter Testbed (b) Top view schematic

Figure 1: The 3D printing hexacopter is depositing polylactic acid on a flat surface according to the desired trajectory on the right. A video of previous experiments with the testbed can be found at https://youtu.be/tEooDpE2TyE.

the testbed's positioning accuracy. In performing these quantifications, we lay the groundwork for further development of this novel process and enable benchmarking with other 3D printing processes in future research.

The remainder of this paper is structured as follows. In Section II, we introduce the methods for quantifying the current printing capabilities of the testbed. In Section III and IV, we present our results from multiple print trials and discuss their relevance. In Section V, we provide our conclusions and discuss the next steps.

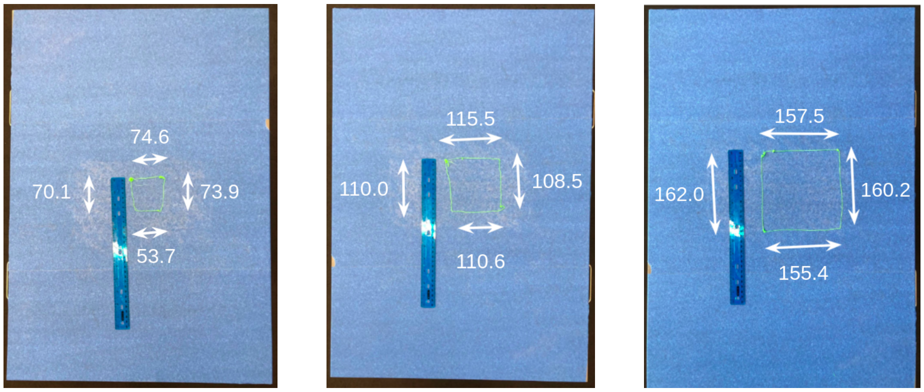
2. Methods

To quantify the printing performance of the testbed, we print three contours of different sizes on a flat surface (see Figure 1). Note that we focus on single-layer geometries in this paper since multi-layer printing has not been tested yet. The desired edge lengths of the three square contours are 60 mm, 100 mm, and 150 mm. We then use two different methods to analyze the testbed's printing performance. The first method focuses on the geometric dimensions of the printed contours, while the second method focuses on the testbed's positioning accuracy.

For the first method, we measure the edge lengths of each printed square contour with a digital caliper and then compare the measured edge lengths to the desired edge lengths. The caliper's tolerance is 0.03 mm. For the second method, we record the testbed's position throughout the print trials and compare the measured positions with the positions given by the desired trajectories. In comparing the positions, we determine how accurate the positioning of the testbed is. This analysis is crucial since large-scale printing applications, such as concrete printing, often require printing at a specific print location. To measure the testbed's position, we use a motion capture system with submillimeter position accuracy.

3. Results

We present the successful print results of the square contours in Figure 2. Each square is marked with the corresponding edge measurements in millimeters. As indicated by the measurements, we find that all but one edge are larger than the desired lengths. We calculate the root mean square error (RMSE) for the 60 mm × 60 mm, 100 mm × 100 mm, and 150 mm × 150 mm



(a) 60 mm × 60 mm square contour with an RMSE of 12.17 mm.

(b) 100 mm × 100 mm square contour with an RMSE of 11.49 mm

(c) 150 mm × 150 mm square contour with an RMSE of 9.12 mm

Figure 2: Square contours printed by the 3D printing hexacopter. A 30-centimeter ruler is placed alongside the squares for comparison. The marked measurements of the edge lengths are in millimeters.

squares to be 12.17 mm, 11.49 mm, and 9.12 mm, respectively. The total RMSE for all edges is 10.8 mm.

The positioning accuracy of the testbed has a root mean square error of 4.3 mm. This positioning error is considerably lower than the deviations in the edge lengths. However, the maximum position error of the testbed, averaged over the three print trials, is 11.2 mm. From our experiments, we find that the largest position errors, including the maximum position error for each trial, occur at the corners of the square contours and are caused by the testbed overshooting the desired corner setpoints during the print trials (similar to the exemplary traversed trajectory in Figure 1(b)).

4. Discussion

We find that the testbed achieves approximately four-millimeter positioning accuracy during printing. This accuracy is between double and triple the reported positioning accuracy for some commercial concrete printing machines that use large-scale gantry or robotic systems. These machines can have positioning accuracies of one to two millimeters [8]. However, the current testbed setup is using an idealized laboratory environment, which reduces outside disturbances, such as wind gusts, and relies on submillimeter position estimation from a motion capture system for the flight controllers. To achieve similar results in outdoor environments, future research needs to investigate the robustness of the testbed outside of the laboratory setting.

When considering the geometric dimensions of the printed contours, the testbed's tracking performance does not translate to similar accuracy in the edge lengths. The discrepancy between accuracy in positioning and geometric dimensions is largely due to the testbed overshooting at the corners of the square contours. Since the testbed uses PID controllers for the positioning, complex interactions between the testbed and the build surface, such as ground effects and the stick-slip phenomenon, pose significant challenges for these controllers. To achieve millimeter accuracy in the edge lengths, the testbed requires advanced controllers that can model the testbed's dynamics and account for the testbed's interactions with the build surface.

An additional observation we make is that the edge length RMSE for each square contour does not grow with the size of the square contours. In fact, the RMSE slightly decreases. This characteristic may suggest that the error in the edge lengths is independent of the contour size and can be scaled to arbitrarily large dimensions. However, the number of print trials is insufficient to make any definitive claims.

Overall, the testbed can achieve approximately four-millimeter positioning accuracy and can print contours with approximately one-centimeter tolerances. Future research will aim to improve the single-layer printing capabilities and also test multi-layer printing.

5. Conclusion

A recently developed 3D printing hexacopter testbed can deposit polylactic acid on flat surfaces during flight. To quantify the testbed's printing capabilities, we printed square contours of different sizes and analyzed the printed results based on their geometric dimensions. We also analyzed the testbed's positioning accuracy during printing. We find that the testbed's positioning accuracy has a tolerance of a few millimeters with a root mean square error of 4.3 mm. However, we find that the printed edges are approximately 1 cm larger than the desired edge lengths. These length deviations are mainly due to the testbed overshooting at the corners of the square contours. In future research, we will improve the positioning accuracy and address the overshoot problems by developing advanced control algorithms.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No. 1646522 and 1652113.

References

[1] K. Wong, A. Hernandez, A Review of Additive Manufacturing, ISRN Mechanical Engineering 2012 (08 2012). doi:10.5402/2012/208760.

[2] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing, Virtual and Physical Prototyping 11 (2016) 1–17. doi:10.1080/17452759.2016.1209867.

[3] A. Paolini, S. Kollmannsberger, E. Rank, Additive manufacturing in construction: A review on processes, applications, and digital planning methods, Additive Manufacturing 30 (2019) 100894. doi:https://doi.org/10.1016/j.addma.2019.100894.

[4] S. H. Ghaffar, J. Corker, M. Fan, Additive manufacturing technology and its implementation in construction as an eco-innovative solution, Automation in Construction 93 (2018) 1–11. doi:https://doi.org/10.1016/j.autcon.2018.05.005.

[5] N. Labonnote, A. Rønnquist, B. Manum, P. Rüther, Additive construction: State-of-the-art, challenges and opportunities, Automation in Construction 72 (2016) 347–366. doi:https://doi.org/10.1016/j.autcon.2016.08.026.

[6] B. Nematollahi, M. Xia, J. Sanjayan, Current Progress of 3D Concrete Printing Technologies, 2017. doi:10.22260/ISARC2017/0035.

[7] A. Nettekoven, U. Topcu, A 3D Printing Hexacopter: Design and Demonstration, in: 2021 International Conference on Unmanned Aircraft Systems (ICUAS), 2021, pp. 1472–1477. doi:10.1109/ICUAS51884.2021.9476759.

[8] N. Watson, N. Meisel, S. Bilén, J. Duarte, S. Nazarian, Large-scale additive manufacturing of concrete using a 6-axis robotic arm for autonomous habitat construction, 2019.