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# Design and Prototyping of Root-inspired Soft-growing Robot

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## ABSTRACT

This paper introduces RootBot, a bio-inspired excavation robot modeled after plant root growth. Utilizing inflatable soft plastic tubes, RootBot emulates root-like propulsion, allowing flexible navigation through complex underground pathways. The prototype consists of propulsion, excavation, and discharge modules. It demonstrates straight excavation capabilities at an advance rate of 0.82 cm/min in wet sand, along with high-curvature steering and retraction in meter-scale experiments. We discuss RootBot's scalability for easy adaptation to specific tasks and the necessary iterations to enhance performance. With continued development, RootBot could provide a versatile tool in geotechnical engineering, enabling precise excavation and effective navigation around unexpected underground obstacles.

## INTRODUCTION

Urban environments, with various subsurface structures, often call for directional tunneling. Excavation robots with steering capabilities are needed to navigate complex paths and avoid unexpected obstacles. In response, ongoing efforts focus on developing robotic excavation systems inspired by biological organisms like clams (Huang, 2020; Tao et al., 2020), earthworms (Cortes & John, 2018; Isaka et al., 2019), and moles (Lee et al., 2019). Despite these efforts, limitations remain in path selection and high-curvature steering (Brundan & Danno, 2020; Silva Rico et al., 2017).

Soft-growing robots inspired by vine-like plants have evolved since the first proposal by Mishima et al. (2006) and the further research (e.g., Hawkes et al., 2017; Jeong et al., 2020; Kim et al., 2021). These robots grow from a base, continuously expanding by adding material at their tip. Owing to their flexibility and compliance, soft-growing robots can adapt to various environments and navigate confined or challenging spaces, making them ideal for excavation tasks (Coad et al., 2019).

We present RootBot, a root-inspired soft growing excavation robot with steering and directional tunneling capabilities. RootBot advances forward, retract, and steer while excavating and growing freely in space. A prototype was fabricated and tested in various excavation scenarios using a meter-scale soil box. While detailed information is available in Han et al. (2024), this paper focuses on RootBot's steering capability and limitations.

## DESIGN AND PROTOTYPING OF ROOTBOT

**Propulsion module.** RootBot mimics root locomotion by extending its body through the inflation of two soft plastic tubes (Fig. 1A). First, a soft tube is fed through a roller, where air pressure inflates it, providing propulsion. Before the roller, the tube remains uninflated, but after passing through, it inflates and drives the robot forward. This mechanism allows continuous growth with the sustained tube supply. RootBot uses two tubes with independently controlled air pressure (Fig. 1B). By adjusting the pressure in each tube, the robot can move forward, retract, and steer its excavation module at the front. The propulsion force is applied to the front, mimicking root growth, and is efficiently transmitted even when the tubes curve or contact the ground, with minimal friction loss. The propulsion module controls the tube feed and air pressure to manage steering and growth. We used polyester fabric tubes, capable of withstanding air pressures up to 0.7 MPa (Fig. 1C).

**Excavation module.** The excavation module uses two circular cutterheads powered by electronic servo motors (Fig. 2A). By regulating DC voltage inputs, the rotational speed of the cutterheads can be controlled. The cutterhead measures 20 cm wide and 10 cm high, and the entire module, including cutterheads, motors, and discharge chamber, is 8.7 cm long. During excavation, the cutterheads rotate in an opposite direction. If they rotate in the same direction, unwanted torque could cause the whole module to rotate. The cutterheads feature protruding scrapers, and openings for muck discharge, similar to tunnel boring machine (TBM) designs. As the cutterheads rotate, the scrapers cut the soil, which is then funneled into the discharge chamber.

**Discharge module.** Continuous excavation demands the discharge of accumulated soil, known as muck discharge. Unlike typical tunnel boring machines (TBM) that use screw conveyors, RootBot employs a two-line plumbing system (Fig. 2B). The upper tube line sprays water to lubricate the excavation module, while the lower tube line uses suction to remove the soil-water mixture. One water pump and one vacuum pump are connected to these lines, allowing continuous excavation without soil buildup in the discharge chamber. This system ensures efficient muck removal, maintaining a steady excavation speed.

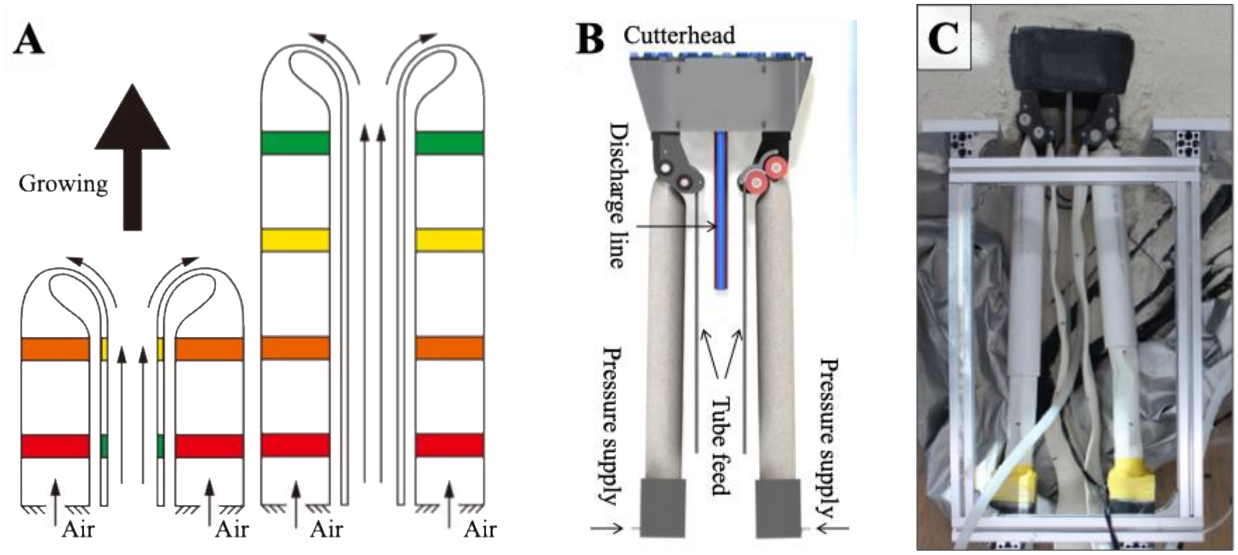


**Figure 1. A** Bio-inspired soft-growing robot, **B** top view of the prototyped RootBot, and **C** a digital photo of RootBot (adopted from Han et al., 2024).

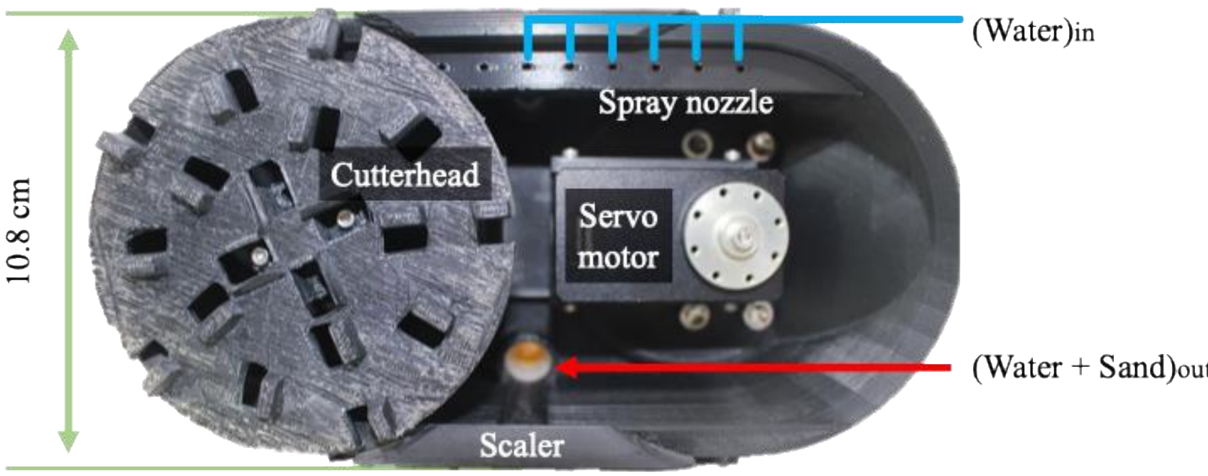


**Figure 2.** The excavation module.

## EXPERIMENTAL STUDY

**Experiment setup.** We conducted experiments using a soil box (1 × 1 × 0.25 m, width×length× height; Fig. 3). We filled the box with moist fine sand at 11–14% water content, achieving a compacted void ratio of 0.83–0.84 and relative density of 56–59%. We then placed a transparent acrylic lid on top, which applied $\sigma_v$ = ~1 kPa, allowing us to monitor RootBot's advancement.

We prepared peripheral equipment for compressed air, tube feeding, cutterhead rotation control, water supply and vacuum suction. Water was sprayed on excavated soil in the discharge chamber. The muck was retrieved to a suction trap by a vacuum pump connected to the discharge plumbing. Compressed air was provided to the tubes, and the air pressure was controlled with pressure regulators, up to 300 kPa. In this study we fixed the cutterhead rotation speed at 30 RPM during excavation, while the tube feeds were regulated with two winches. We measured the cutterhead speeds, motor torques, and tube air pressures, and monitored RootBot's advancement using a digital camera.

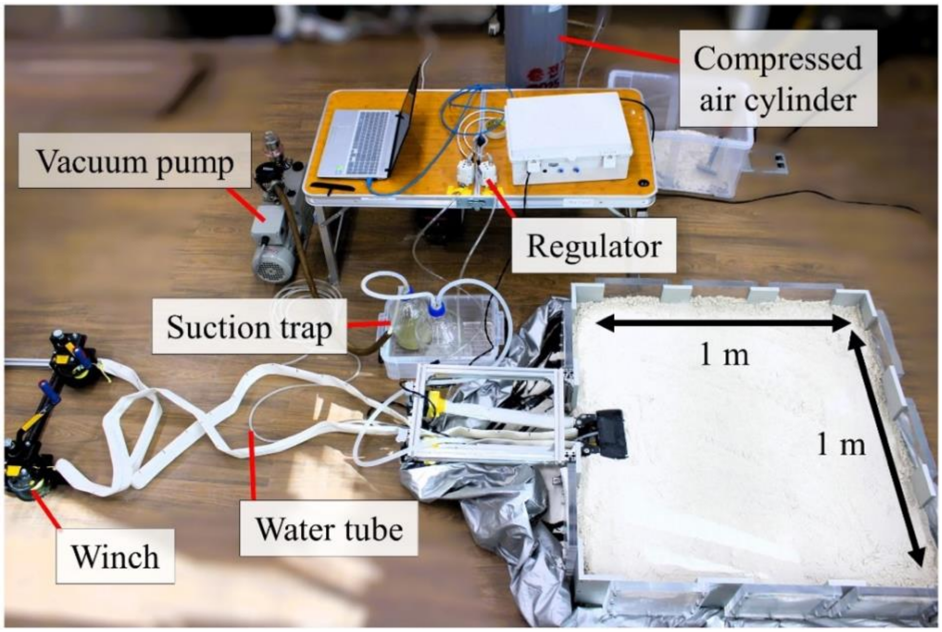


**Figure 3.** Mock-up excavation test setup.

**Excavation scenarios.** In this paper, we present three excavation scenarios (Fig. 4): straight excavation, low-curvature directional excavation (less than 30°), and high-curvature directional excavation (greater than 60°). First, RootBot excavated straight, achieved by supplying equal air pressure to both tubes (Fig. 4A). We monitored the distance advanced over time with a cutterhead speed of 30 RPM and air pressure of 120 kPa. Next, RootBot performed a moderately curved excavation by varying the air pressure in the tubes (Fig. 4B). In the beginning, the pressures were equal at 50 kPa. The pressure in one tube then increased to 100 kPa while keeping the other at 50 kPa, which steered the excavation face. Finally, a simultaneous increase in one tube's pressure and a decrease in the other enabled sharper turns. In this scenario (Fig. 4C), RootBot demonstrated high-curvature directional excavation. We began with equal pressures of 50 kPa, then increased one tube to ~100 kPa while reducing the other to ~10 kPa to generate a sharp rotation.

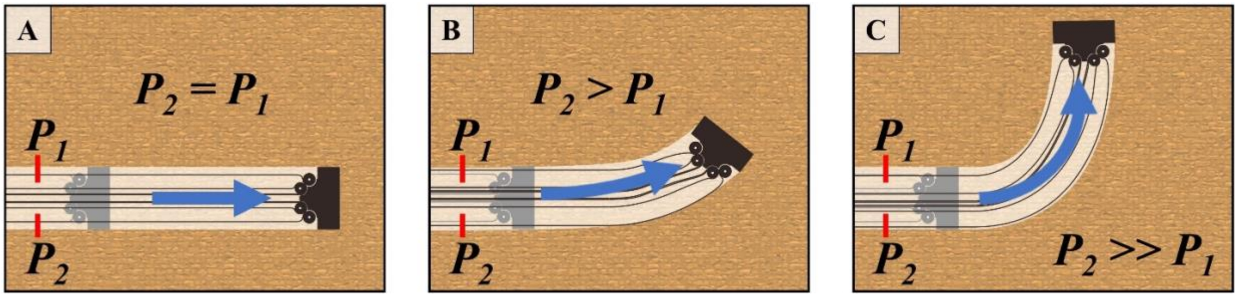


**Figure 4.** Excavation scenarios: **A** straight excavation, **B** low-curvature directional excavation, and **C** high-curvature directional excavation. Note that $P_1$ and $P_2$ are the air pressure applied through each tube.

# EXPERIMENT RESULTS

**Scenario A.** We assessed the forward excavation speed of RootBot during straight excavation tests (Fig. 5). The cutterhead created a rectangular excavation face (Fig. 5A). With the air pressure of 120 kPa and a cutterhead speed of 30 RPM, RootBot achieved a forward excavation speed of 0.82 ± 0.17 cm/min (Fig. 5B). The maximum advancement rate may vary based on ground conditions and operational controls, including tube air pressure and cutterhead speed.

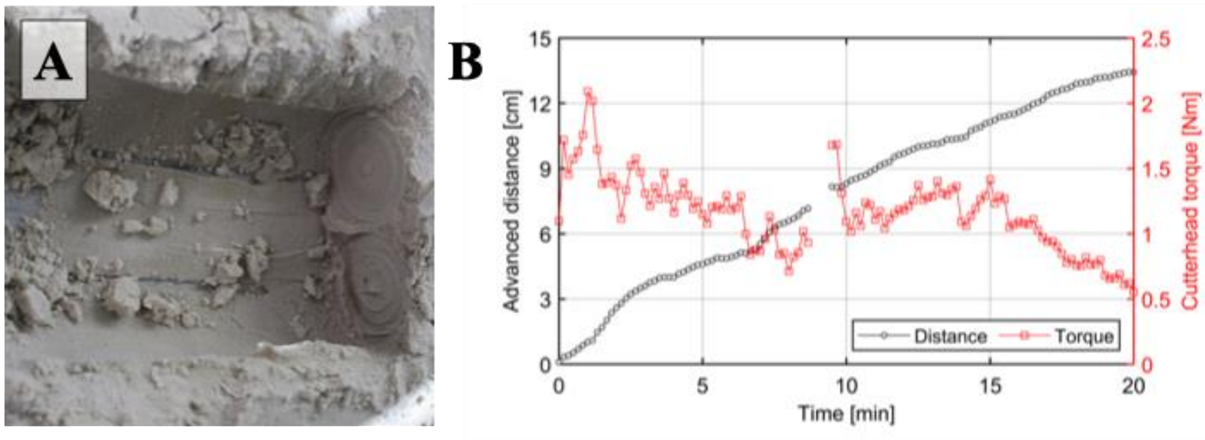


**Figure 5.** Straight excavation: **A** the excavated trace, and **B** the result on excavation performance. The data are taken from Han et al. (2024).

**Scenario B.** We conducted directional excavation with the cutterhead rotation speed constant at 30 RPM, as shown in Fig. 6. Initially, we maintained equal pressures at ~45 kPa for a straight excavation of 10 cm. We then increased the left tube pressure to 90 kPa and the right tube pressure to 60 kPa, causing RootBot to moderately rotate at an 18° steering angle. Further adjustments resulted in a final steering angle of 41°. When equalizing the both side pressures at 60 kPa, RootBot returned to straight excavation (Fig. 6B).

**Scenario C:** We tested sharp steering angles, as shown in Fig. 7. Initially, we performed a straight excavation with balanced pressure at approximately 50 kPa. We then induced a sharp turn by elevating the left tube pressure to ~100 kPa and reducing the right tube pressure to ~10 kPa, resulting in a steering angle of 44°. Maintaining the differential pressure > 50 kPa further increased the steering angle to greater than 90° during advancement (Fig. 7B). Despite buckling in the left-side tube due to the high curvature, RootBot continued to excavate effectively by growing from the soft tube feeds. This capability allows RootBot to navigate complex, curved routes while excavating soil. Figure 7C illustrates the resulting path, confirming a steering angle > 90°.

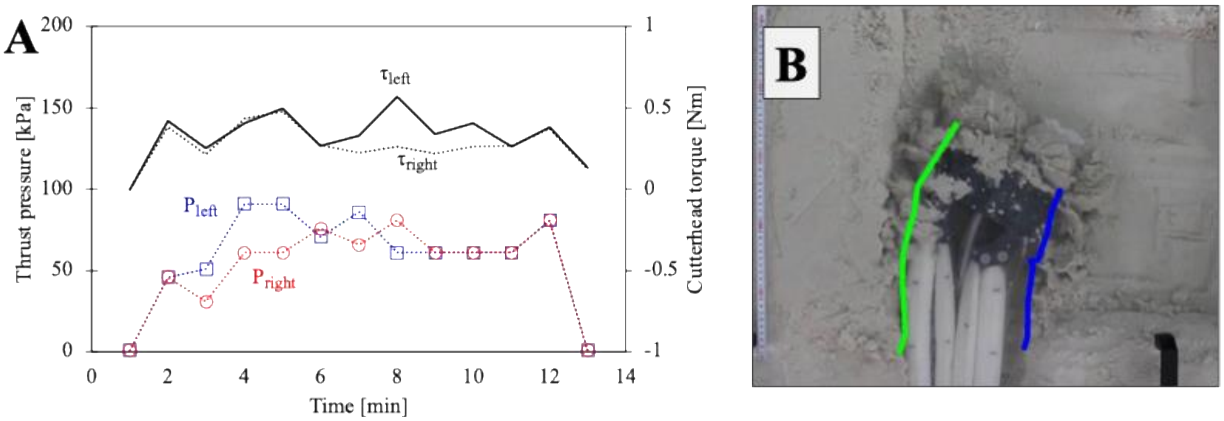


**Figure 6.** Low-curvature Directional excavation: **A** the pressure manipulation and cutterhead torque, and **B** the steering and excavation route. The data are taken from Han et al. (2024).

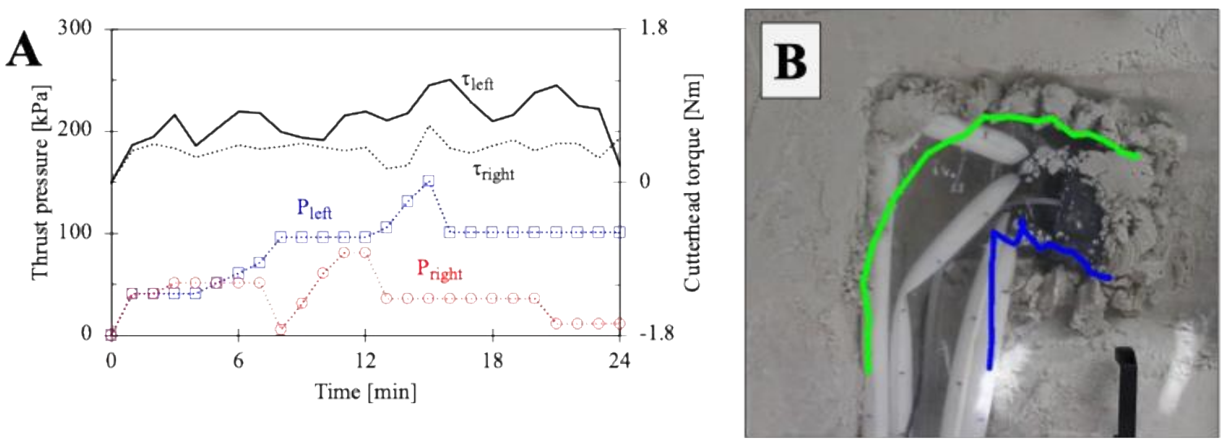


**Figure 7.** High-curvature directional excavation: **A** the pressure manipulation and cutterhead torque, and **B** the steering and excavation route. The data are taken from Han et al. (2024).

## CONCLUSION AND IMPLICATIONS

This study introduces RootBot, a soft-growing robotic system designed for tunneling in complex and confined spaces with a small cross-section. The prototype shows a straight excavation speed of 0.82 cm/min in wet-compacted sand while demonstrating high-curvature steering capabilities. RootBot's scalability allows for easy adaptation to specific tasks, as alternative tube materials could enable higher pressures, and various fluids, such as water or oil, could enhance thrust. While this study presents a rectangular excavation section for the prototype, it can be modified in shape and size. Additionally, utilizing a more viscous fluid with dispersants in the discharge system may improve the transport of excavated muck and reduce clogging in the discharge tubes.

Further research is essential to address limitations and enhance performance. Currently, RootBot's locomotion is confined to planar motion due to its two soft growing tubes. Future iterations could incorporate three-dimensional excavation through cutterhead rotation, additional vines and cutterheads, or non-rotating methods like waterjet nozzles. To prevent collapses in the excavated space, grouting or casing may be required in the rear section, similar to tunnel construction. The tube buckling problems could be mitigated with a feedback system that includes motion sensors to improve maneuverability post-buckling. Additionally, a quantitative assessment of how pressure, cutterhead speed, and torque impact excavation performance is necessary, as these factors significantly influence operational strategies. RootBot's versatility should be examined across different excavation sections, cutterhead designs, sizes, and ground types.

## ACKNOWLEDGEMENT

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