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Design of an Autonomous Pipe-Cleaning Robot for Small-Scale Hydroponic Systems

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ABSTRACT

Hydroponic farming offers a sustainable solution to food insecurity, especially in developing countries, by enabling high-yield crop production with minimal land and water usage. However, one major challenge in hydroponic systems is the frequent clogging of PVC pipes due to debris from growing media and the buildup of algae, which thrives under high humidity and limited sunlight. These blockages not only reduce system efficiency but also increase the risk of plant diseases that can compromise entire harvests. To address this issue, this research focuses on the design and development of a compact mobile robot capable of cleaning hydroponic pipes. The robot is designed using SolidWorks and simulated in Tinkercad, targeting a 4-inch (110 mm) diameter PVC pipe with a length of 3 feet. It incorporates the HC-SR04 ultrasonic sensor to detect obstacles and uses acrylic as the structural material. The performance of the robot was tested against three types of common pipe obstructions: small stones, sand and grass roots. Experimental results show that the robot can navigate through the hydroponic pipe and partially remove debris, although complete cleaning remains challenging due to space constraints and the complexity of internal pipe conditions. This work demonstrates a low-cost, automated solution for maintaining hydroponic systems and highlights areas for further optimization in design and control.

Keywords: Acrylic Plastic, Cleaning Devices, Hydroponic, Mobile Robot, Pipeline

1. INTRODUCTION

Hydroponics is a soilless agricultural technique that enables precise control over plant health by regulating nutrient delivery and water usage. These systems promote high growth rates, improve crop quality, and significantly reduce chemical usage, making them an environmentally friendly alternative to traditional farming methods [1].

A hydroponic system only requires water and minimal space, making it suitable for both urban and rural settings. It typically consists of a reservoir that stores nutrient solutions and delivers them to plant roots via an inert medium. Optimal levels of oxygenation, salinity, pH, and conductivity must be maintained to ensure healthy plant growth [2].

Hydroponically grown vegetables, herbs, and flowers benefit from controlled environments that facilitate faster growth and higher yields [3]. However, maintaining hygiene in these systems is critical. The sterile nature of hydroponic environments makes them highly vulnerable to contamination—minor traces of bacteria, algae, or pathogens can spread rapidly and devastate

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an entire crop within hours or days [4]. Algae, in particular, pose a significant challenge due to their ability to grow on any surface. Once established, algae can clog pipes, damage pumps, emit foul odors, and compromise overall system functionality [5]. Another common issue is clogging caused by growing media debris that accumulates and blocks water flow within the pipes [6].

Several studies have explored in-pipe cleaning technologies to address such issues. Ana Sakura Zainal Abidin et al. [7] tested cleaning tools on various clog types, achieving over 95% removal for soft materials like tissue, but showing reduced effectiveness against stubborn debris such as plasticine. Aditya Pratap Singh et al. [8] measured cleaning efficiency in terms of residual dirt per square meter, showing significant improvements up to 98.22%. Kelemen et al. [9] focused on chimney sweepers adapted for inspection and cleaning. Feng et al. [10] developed a robust wheeled robot with strong traction to overcome in-pipe obstacles, though it required higher torque. Hashem et al. [11] demonstrated a low-cost cleaning robot with improved water quality outcomes, noting a trade-off between torque and cleaning pressure. Kazeminasab et al. [12] highlighted navigation challenges, where in some cases, robots failed to reach target locations due to signal loss or unexpected pipe geometry.

Motivated by these challenges, this project aims to design and develop a compact, low-cost mobile robot capable of navigating and cleaning narrow hydroponic PVC pipes. The robot integrates an HC-SR04 ultrasonic sensor for obstacle detection and is fabricated using lightweight acrylic. Simulated in Tinkercad and designed in SolidWorks, the robot targets small-scale hydroponic systems that are especially common in urban farming. This study investigates the robot's ability to detect obstructions and remove common debris—such as sand, small stones, and plant roots—to support cleaner and more efficient hydroponic operations.

2. MATERIAL AND METHODS

This section outlines the systematic approach taken to design, simulate, fabricate, and test the proposed mobile robot for cleaning hydroponic pipes. The methodology includes both software and hardware aspects—starting from conceptual design and simulation using SolidWorks and Tinkercad, through to component selection, circuit development, and physical prototyping. The testing phase involved evaluating the robot’s performance in a controlled hydroponic pipe environment, focusing on its ability to detect obstacles, navigate confined spaces, and remove common debris. Each stage was carried out with the aim of creating a compact, low-cost, and sensor-guided robot suited for small-scale hydroponic systems.

2.1 Project Workflow

After reviewing related studies and completing the literature review, this project was developed through several systematic phases—from concept development to design, prototyping, and testing. A structured project workflow ensures organized execution and logical progression throughout each stage. The entire process is summarized in the flow chart shown in Figure 1.

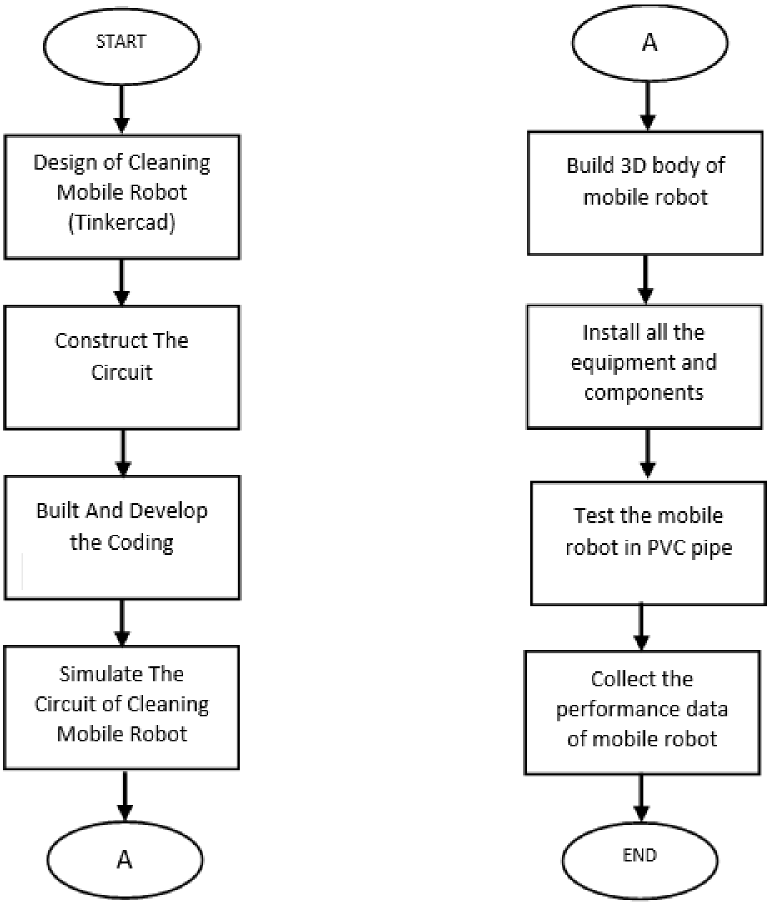


Figure 1. Project Workflow

2.2 Software

To minimize design errors and potential hazards during implementation, simulation and design software were employed before building the actual prototype. Autodesk Tinkercad was used for circuit design and simulation, while SolidWorks was utilized for 3D mechanical design and assembly of the mobile robot model.

2.2.1 Component

Selecting appropriate components is crucial to ensuring the robot functions correctly inside a confined pipe system. Table 1 lists all the hardware components used in the prototype mobile robot.

Table 1 List of components

No.	Component	Quantity
1	Ultrasonic Distance Sensor	1
2	Hobby Gearmotor	1
3	H-bridge Motor Driver	1
4	Arduino Uno R3	1
5	9V Battery	1
6	DC Motor	1

2.2.2 Circuit Simulation

The control system circuit was developed and tested using Tinkercad. Since the Arduino Nano is not available in the simulation environment, the Arduino Uno R3 was used as a substitute. Microcontrollers like Arduino Uno R3 can provide efficient control logic for basic autonomous robots [14][15]. The system uses the HC-SR04 ultrasonic sensor to detect nearby obstacles. Ultrasonic sensors such as the HC-SR04 are widely used for obstacle detection in compact autonomous systems [13]. When the sensor detects an object within a preset distance, the microcontroller signals the DC motors to reverse or adjust movement accordingly. DC motors are preferred for brush actuation due to their high-speed and torque control capabilities [16][17]. This circuit drives two motors: one for wheel propulsion (gear motor) and another for the cleaning brush (DC motor). Gear motors assist with taction in confined pipe environments, although they may limit manoeuvrability in tight turns [18].

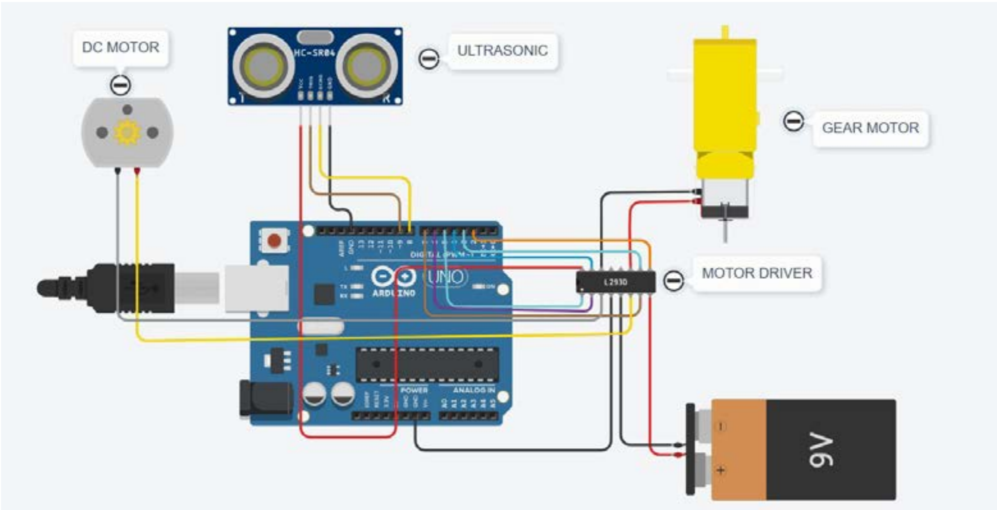


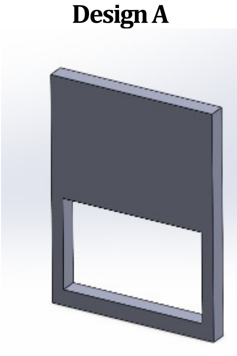
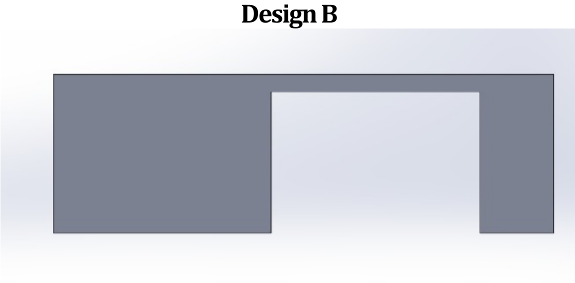
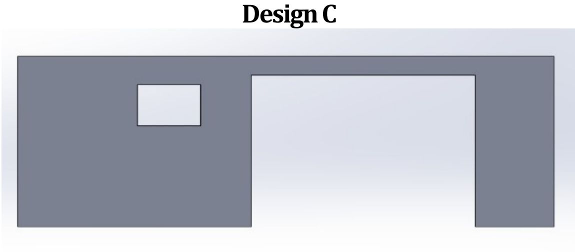
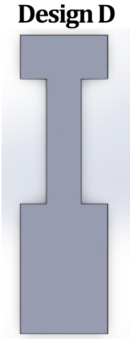
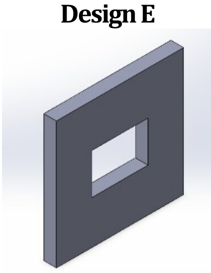
Figure 2. Circuit of the system

2.2.3 Design Development

The mechanical design was created in SolidWorks, consisting of five main 3D parts. These parts were designed to fit within a standard 4-inch (110 mm) PVC hydroponic pipe. Table 2 outlines the characteristics and dimensions of each component.

Figures 3 to 5 illustrate the assembled 3D design, the robot's external appearance, and its internal component layout. The final design dimensions are 75 mm (H) × 55 mm (W) × 170 mm (L). The wheels used are 30 mm in diameter.

Table 2 3D prototype parts

Design Part	**Characteristic**	**Dimension (Height x Width X Length) (mm)**
Design A 	Casing for HC-SR04 ultrasonic sensor	50 x 5 x 50
Design B 	Left side of mobile robot with space for wheel	54 x 2.5 x 170
Design C 	Right side of mobile robot with space for wheel and switch	54 x 2.5 x 170
Design D 	Base for mobile robot	170 x 3 x 50
Design E 	Casing for DC Motor. This also have 2 part represents stand for DC Motor	50 x 5 x 50

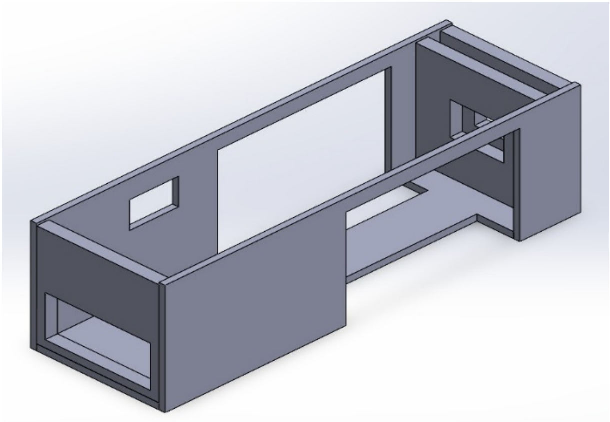


Figure 3. 3D prototype overview

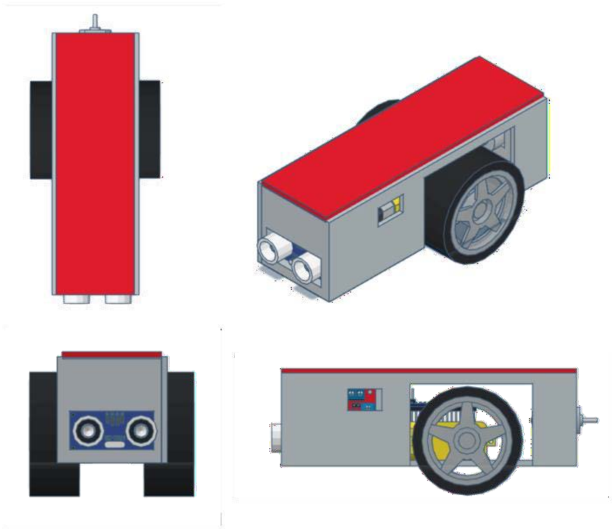


Figure 4. View of mobile robot

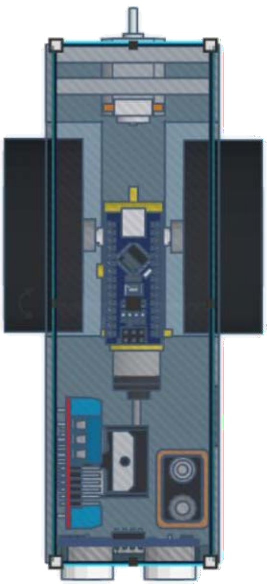


Figure 5. Prototype overview inside the body

This mobile robot is distinct from most existing in-pipe robots, which are typically larger, externally powered, or designed for industrial water or sewage systems. In contrast, this robot is compact, fully self-contained, and optimized for small-scale hydroponic farming, especially in narrow PVC pipelines. Its use of lightweight acrylic and a single-sensor control mechanism reflects a cost-effective and accessible solution for agricultural applications.

2.3 Prototype Model

The mobile robot prototype was fabricated using acrylic, chosen for its durability, light weight, and ease of cutting. Acrylic offers durability and lightweight characteristics, making it a suitable material for small robotic platforms [19][20]. The parts were laser-cut to the specified dimensions and assembled into the full robot body. Figures 6 and 7 show the fabricated acrylic components and the fully assembled robot.

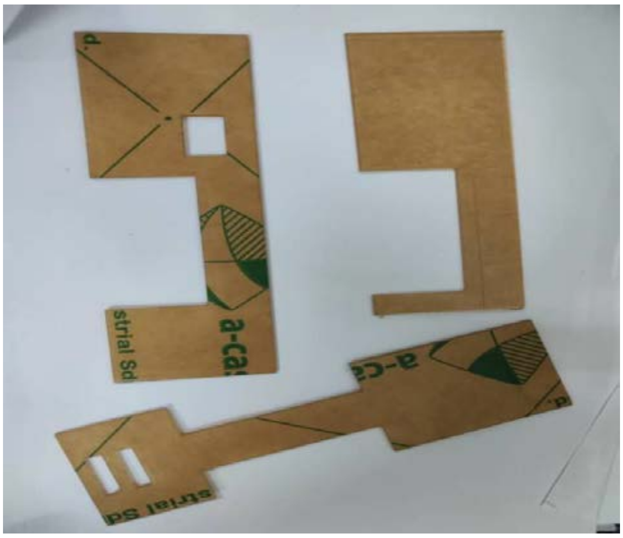


Figure 6. Acrylic after cut

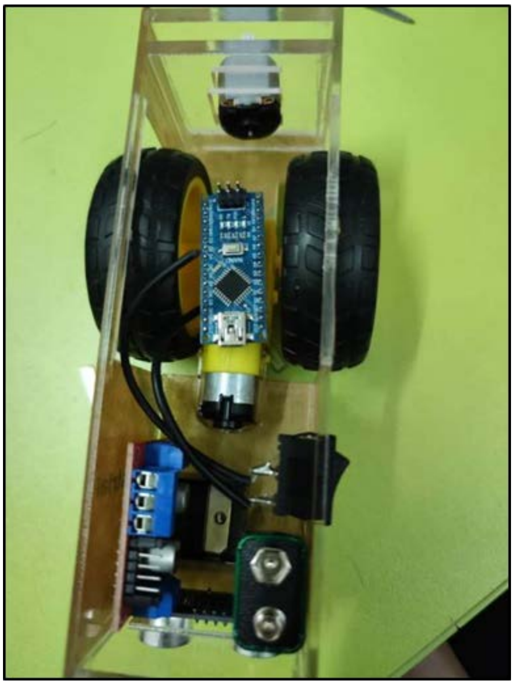


Figure 7. Final prototype model

2.4 Robot Testing in PVC Pipe

To evaluate the robot’s effectiveness in real-world conditions, a test setup was conducted using a 3-foot-long PVC pipe with a 4-inch inner diameter, replicating a typical hydroponic system. The robot was inserted into the pipe, and its movement was observed as it encountered various materials simulating pipe blockages such as small stones, sand, and grass roots.

The robot's ultrasonic sensor detected pipe walls and obstructions, triggering the gear motor to stop and reverse briefly before proceeding, as programmed. The cleaning brush (DC motor) remained active throughout, agitating and pushing debris forward.

This testing demonstrated that the robot could: 1) Navigate through straight, narrow pipes autonomously; 2) respond to obstacles in real-time using sensor feedback; and 3) partially remove soft to moderate debris, although complete removal of heavier or embedded materials remained a challenge.

These results validated the robot’s potential as a functional, low-cost cleaning system for maintaining hydroponic pipe cleanliness especially in small farms where manual cleaning is labour intensive and impractical.

3. RESULTS AND DISCUSSION

This chapter discusses the outcomes from both simulation and hardware testing of the mobile robot. Simulations were first carried out to verify motor control logic based on ultrasonic sensor inputs. Upon successful simulation, the robot was fabricated and tested in a hydroponic pipe environment to evaluate its real-world cleaning performance.

3.1 Initial Result

The circuit and code were simulated in Tinkercad to test the response of the DC motors to varying distances detected by the HC-SR04 ultrasonic sensor. The results are shown in Table 3.

Table 3 Motor movement based on ultrasonic

DISTANCE BETWEEN ULTRASONIC (cm)	MOTOR (rpm)		GEAR MOTOR CONDITION
	DC MOTOR	GEAR MOTOR	
2.5	15636	-239	REVERSE
49.5	15636	-239	REVERSE
100.5	15636	-239	REVERSE
124.6	-15636	239	FORWARD
202	-15636	239	FORWARD

As seen in the table, when the ultrasonic sensor detects an object within 100 cm or less, the robot reverses by setting the gear motor to -239 rpm. When no obstacle is detected within this range, the robot moves forward with a positive gear motor speed of 239 rpm. The DC motor controlling the brush maintains high rotational speed (±15,636 rpm) to agitate debris regardless of direction.

3.2 Prototype Testing in Hydroponic Pipe

The prototype was tested in a 3-foot-long PVC hydroponic pipe with a 4-inch inner diameter to simulate real operating conditions. The robot was evaluated based on: 1) obstacle detection using the ultrasonic sensor; 2) ability to move through the pipe; and 3) effectiveness in removing three types of debris: pebbles, sand, and grass roots. Figures 8 and 9 show the robot's position in the hydroponic pipe, and Table 4 highlights the testing conducted.

Figure 8. Mobile robot in hydroponic pipe

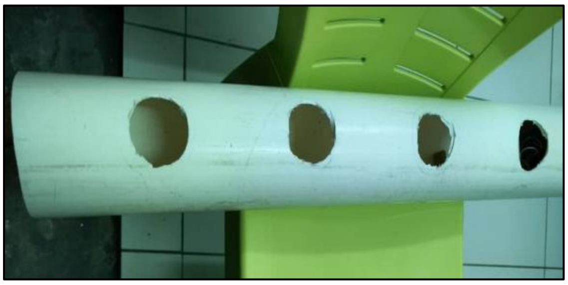


Figure 9. Mobile robot test in hydroponic pipe

Table 4. Test mobile robot with ultrasonic sensor

MATERIAL	SENSOR STATUS	ULTRASONIC SENSOR		ACTION
		DC MOTOR ACTION	GEAR MOTOR	
Pebbles	Active	Running	Move Forward	Some pebbles still stay in the hydroponic pipe
Sand	Active	Running	Move Forward	Mostly sand can be removed but still have some balance sand on the inside piping
Grass Roots	Active	Running	Move Forward	A large root clung to the bush, and after the mobile robot moved, a litter of small root debris fell out of the bush
Wall	Active	Running	Stop and reverse	The gear motor will stop a while after that reverses before keep moving forward

The robot successfully navigated the pipe and responded to obstacles as programmed. The ultrasonic sensor reliably detected walls and triggered a temporary pause followed by reverse motion, demonstrating basic autonomous navigation capability. However, full cleaning was not achieved, particularly with heavier materials like pebbles and fibrous roots. The brush spacing and limited torque were likely responsible for this limitation.

3.3 Key Observations and Limitations of the prototype

The HC-SR04 ultrasonic sensor demonstrated reliable performance in detecting pipe walls; however, its accuracy was less dependable when encountering soft or low-profile debris, which may not reflect ultrasonic waves effectively. In terms of motor performance, the high-speed DC motor used for the cleaning brush provided strong agitation and contributed to partial debris removal. Nonetheless, the use of a single gear motor for propulsion limited the robot's manoeuvrability, particularly during turns or when attempting to dislodge heavier obstructions. A significant design constraint is the robot's size, which closely matches the inner diameter of the hydroponic pipe. This minimal clearance restricts its ability to execute complex movements such as reversing or realigning within the pipe. Compared to traditional in-pipe robots typically larger, caterpillar driven, externally powered, and designed for industrial pipelines this robot offers a self-contained and compact alternative. It is specifically designed for small-scale hydroponic applications and emphasizes affordability, simplicity, and ease of use, making it particularly suitable for urban or vertical farming systems.

4. CONCLUSION

This project successfully developed a compact mobile robot for cleaning hydroponic pipes, incorporating a mechanical design modelled in SolidWorks and an electronic control system simulated in Tinkercad. The robot is equipped with a DC motor-driven brush for debris removal, an HC-SR04 ultrasonic sensor for obstacle detection, and an Arduino Nano (represented by an Uno in simulation) as the main microcontroller. A L298N motor driver is used to enable bi-directional control of the motors based on sensor input. Fabricated using acrylic, the robot demonstrated its ability to autonomously navigate and perform cleaning tasks within a 4-inch PVC pipe, targeting common clogging issues in hydroponic systems such as blockages caused by sand, small stones, and plant roots. Testing showed that while the robot was capable of partial debris removal and reliable wall detection, its performance was limited by factors such as narrow internal spacing, debris adhesion, and the absence of adaptive control mechanisms.

In comparison to existing in pipe cleaning robots many of which are caterpillar-based, externally powered, or designed for industrial-scale use and this design stands out due to its compact form factor, sensor-guided autonomous motion, and the use of simple, low-cost components. These characteristics make it particularly well-suited for small-scale hydroponic systems often found in urban or vertical farming setups. Regular maintenance is essential for hydroponic systems to ensure optimal plant health and longevity. By automating the cleaning process, this mobile robot supports sustainable agriculture and helps reduce labour costs, offering value in developing regions where food security is a growing concern. For future improvement, the robot could benefit from a dual-motor drive system to enhance manoeuvrability, a more aggressive or adaptable brush mechanism for thorough cleaning, and the integration of advanced sensor fusion technologies such as infrared or visual cameras for improved obstacle recognition and navigation.

Hydroponic farming can operate year-round without seasonal limitations, enabling consistent production of fresh, high-quality vegetables. Automated maintenance tools like the proposed robot play a crucial role in maintaining these systems and can contribute meaningfully to global efforts toward sustainable and reliable food production.

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