Autonomous Construction Robot with Telescopic Arm for Drywall Panel Installation

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Abstract–
Conventional techniques for installing panels face several problems, such as human errors, time inefficiency, and safety risks. The panel installation robot, outfitted with sophisticated mechanical, electronic, and software technologies, proficiently addresses these challenges. The robot employs omnidirectional motion mechanisms, a telescopic robotic arm, and precision installation tools, including drills and nail guns, to facilitate the accurate and safe execution of installation operations. The robot's positioning system, with advanced cameras and image processing technology, can precisely identify the runners' location and modify the arm's movements accordingly. The semi-automatic control via a web user interface enables operators to remotely monitor and control the installation process. Furthermore, the robot's safety mechanism, utilizing distance sensors and cameras, averts collisions with obstacles, so guaranteeing safer operation. This unique design decreases installation time by 10% to 30%, depending on the length of the panel, while simultaneously enhancing productivity, precision, and addressing environmental concerns.

Keywords –
Construction Robotics, Automation in Construction, Drywall Panel Installation, and Telescopic Robotic Arm

1 Introduction

The incorporation of Building Information Modeling (BIM) as a holistic tool for design, planning, and project management within the construction sector, alongside significant advancements in robotics, has generated novel prospects for utilizing robots in unstructured settings like construction sites [1]. These developments allow robots to adapt effectively to the intricate and dynamic conditions characteristic of construction environments, ensuring dependable and efficient performance. In the last thirty years, construction robotics has advanced significantly, being utilized in tasks such as painting, welding, exterior cladding installation, major component assembly, precast concrete panel manufacture, and site cleaning [2,3]. Drywall installation, which demands high levels of accuracy and technical expertise, is typically performed by experienced workers. However, installation complexity, and human error make this process challenging. Incorrect measurements, cutting, and drywall misalignment cause uneven surfaces and gaps, increasing repair and rework expenses. Furthermore, the time-consuming nature of drywall installation usually causes delays in large construction projects. To address these challenges, robotic technologies have emerged as an innovative solution, particularly in the installation of interior panels like drywall. The robot studied in this research is specifically designed for the installation of various types of building panels. The robot features a fully automated system for installing drywall panels, which, unlike semi-automated or operator-dependent systems in previous studies, requires no human intervention and offers higher safety and installation speed [4,5]. By automating the installation process, robots not only reduce the dependency on skilled labor but also minimize errors and ensure consistent quality in construction projects. This efficiency is not only about speed but also about the ability to work continuously without the need for breaks, thereby streamlining the construction process. The robot presented in this study (Wall-bot) is designed to operate on various surfaces and install different types of panels, such as drywall. Unlike many previous systems that were limited to specific materials or a particular type of installation, this robot is equipped with two distinct installation tools—an electric drill for metal and a nail gun for concrete [6-8]. These features enhance installation efficiency and align with the evolving requirements of the construction industry. The innovative design of Wall-bot met the requirements of construction tasks. It aims to provide fundamental design elements while addressing panel installation limitations. Ultimately, this system is market-ready and can reduce installation time, which is a significant advantage compared to systems that are still in the experimental stage or operate slower than manual methods [9]. By decreasing project time and the need for specialized labor, overall costs are significantly reduced. These features enhance installation efficiency and align with the evolving requirements of the construction industry.

2 Design and Implementation

This section details the conceptual design and implementation of various components of the robot, which has been specifically developed for the installation of panels in construction environments. The robot's design incorporates mechanical, electronic, and software systems that operate seamlessly and with high precision to efficiently perform the panel installation process.

2.1 Conceptual design

A robotic system has been designed and developed to overcome the obstacles associated with the installation of panels. The complete process is designed to resolve critical issues and enhance the installation process. Drywall panels are an ideal choice for automation technologies due to their lightweight structure, ease of transportation and installation, and lower execution costs. However, the installation process of these panels faces challenges, such as the need for high precision, ensuring safety in construction environments, and a significant demand for time and labor. In this study, a robotic system that is equipped with advanced technology has been developed to facilitate the installation of panels with superior precision, speed, and efficiency. This section details the conceptual design and implementation of various components of the robot, which has been specifically developed for the installation of panels in construction environments.

One of the most notable features of this robot is its advanced telescopic arm. This arm is specifically designed to provide precise adjustment of the angle and position of panels based on the ceiling-to-floor distance. With five degrees of freedom, the telescopic arm is fully automated for the transportation, positioning, and installation of non-load-bearing building panels. The robotic arm has two linear actuators arranged in parallel along the vertical axis. These actuators are designed to adjust the height of the panel. Additionally, the arm has a linear actuator that enables the forward and backward movement of the entire robotic arm. This actuator, in conjunction with another actuator connected via a metal linkage—one end attached to the robot's body and the other end to the telescopic arm—enables angular adjustments in the robotic arm. Another significant design challenge was the transportation of panels during the installation process. To address this, the robotic arm is equipped with a panel gripper, enabling it to perform all stages of transportation, positioning, and installation fully automatically, without requiring manual labor. For mounting panels onto ceilings, walls, and floors, the telescopic arm is equipped with two types of installation tools designed for attaching panels to both metallic and concrete surfaces. This system operates as an electric drill and a nail gun, guaranteeing accurate and secure panel installation.

The robot is equipped with an advanced positioning and control system specifically designed for panel installation operations in complex construction environments. This system utilizes advanced technologies, such as smart cameras, image processing, and a web user interface (Web UI), to ensure precise movement of the robot and accurate panel installation. Smart cameras are used to ascertain the precise positions of runners (structures onto which panels are affixed). These cameras capture both chromatic pictures and three-dimensional information about the surrounding environment. The collected data is processed to analyze the geometric features of the surfaces, boundaries, and lines. This analysis enables accurate determination of the panel installation positions. The Edge Detection algorithm is used to identify the boundaries and lines of the runners, thereby determining the exact locations for panel installation. The main problem in the installation of building panels is the need for high accuracy and flexibility in complex environmental conditions. This procedure is traditionally performed manually, often resulting in increased installation time, less precision, and possible safety hazards for workers. To address these challenges, an advanced control system has been designed for Wall-bot, automating several tasks, such as guiding the robot to predetermined locations while also allowing manual control by an operator when necessary. The technology employs a web user interface (Web UI) that enables the operator to precisely control the robot in various work conditions and determine the exact locations of the runners. The Web UI, functioning via a local network, synchronizes the robot's wheels and arm, enabling users to control the robot using any device connected to a wireless network. The Web UI includes three primary components:

- **Camera Live View:** It provides live video streams from the cameras mounted at the center of the robot's arm. The strategic positioning of this camera provides the user with a precise view of the working area, enabling more accurate management of operations.
- **Robot Wheel Control:** This section is designed for managing the movement and positioning of the

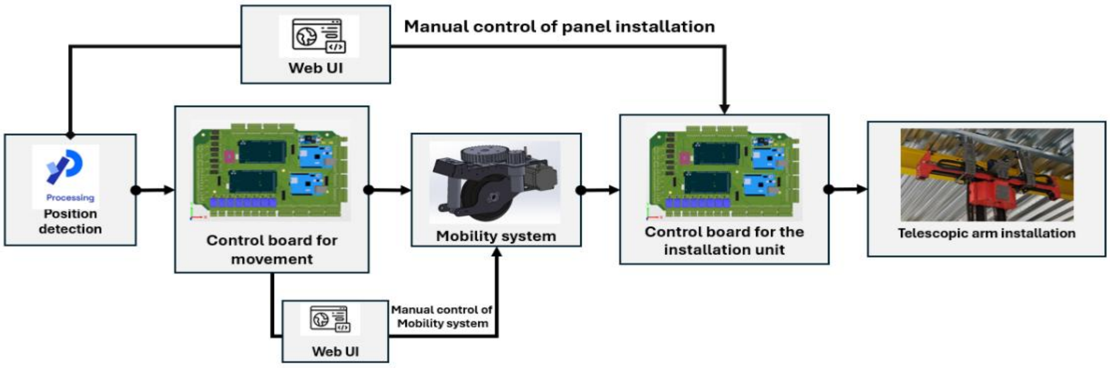


Figure 1. Block diagram illustrating the process of the panel installation. The process begins with position detection using an image processing system and cameras. The mobility system, controlled by an advanced system, enables accurate movement to the target location. Sensors enhance safety and prevent collisions. Finally, the telescopic arm securely installs the panel. Manual control via a Web UI for necessary adjustments.

robot's wheels. Default Modes presents five images, representing the default angles of the wheels. Users can select their preferred image and click the 'Run' button to transmit the angle data to the robot, thereby initiating the movement of the wheels to the desired location. This feature is designed for quick and simple adjustments. The sixth image enables the manual modification of each wheel's angles and robot’s linear speed for long-distance straight movements, providing flexibility for users to set the desired speed based on their specific requirements. Furthermore, an emergency 'Stop' button is included to immediately halt the robot in critical situations.

- **Robot Telescopic Arm Control:** This section focuses on the control of the robotic arm and its attached equipment. A set of buttons is designed to restore the motors to their initial positions, which is especially beneficial during startup or while reconfiguring the arm. Additionally, the user can precisely designate the position of each arm motor by inputting numerical values. Once the settings are applied and the execute button is pressed, the arm moves to the specified position. This functionality is ideal for accurate operations. Three toggle buttons are provided for the operation of the auxiliary equipment attached to the robotic arm. These three toggle buttons serve specific functions: they allow precise positioning of the laser pointer, activate the magnet for holding metallic parts, and enable the lighting system to improve visibility in low-light environments. Additionally, the 'Install Runner' button is used to activate the telescopic arm mechanism. At this stage, the arm's motors elevate the runner towards the ceiling, guaranteeing its adherence to the surface and proper positioning. Upon installation, the tools shoot fasteners to affix the runner to the ceiling. After completing the operation, the motors automatically stop for safety and efficiency.

The robot's mobility system is a crucial element of its design. The robot's mobility system, featuring four driven wheels, enables autonomous navigation on construction sites. Each wheel moves linearly and rotates about its vertical axis, providing omnidirectional motion for enhanced maneuverability in complex interior spaces.

A belt and pulley system has been integrated to transfer power from the motors to the wheels. This mechanism guarantees accuracy and increased torque transfer, allowing the robot to function efficiently in various conditions.

A spring-damper system is crucial for enabling smooth and steady robot movement in construction sites with sloped or uneven surfaces, as it absorbs undesirable vibrations during transportation and panel installation. Thus, the robot is equipped with four hydraulic shock absorbers, located next to the wheels due to space limitations for installation.

In addition to the mechanisms that are specifically designed for the working environment, the robot must be equipped with sensors that are capable of detecting obstacles. These sensors measure the distance to obstacles to avoid accidents, ensuring safe and efficient operation in dynamic construction sites. As shown in Figure 1, the panel installation robot follows a designed operation procedure to guarantee the precise and efficient positioning of panels. The procedure begins with the identification of the panel installation position through the use of an image processing system and cameras.

Following the determination of the position, the robot employs its omnidirectional mobility system, which is managed by advanced control systems to guarantee smooth and accurate movement, to navigate to the desired destination. Additionally, sensors are integrated into the system to guarantee safety and prevent collisions during operation. Finally, the telescopic arm, equipped with advanced installation tools, precisely attaches the panels in place. This integrated design optimizes the quality of the project, reduces construction time and costs.

2.2 Implementation of the Robot

Wall Bot is equipped with advanced mechanisms, including mobility systems, a robotic arm, and installation tools, enabling high-speed and precise installation of building panels. Figure 2 illustrates the robot's entire structure and its mechanisms. These mechanisms, enable transportation through difficult pathways, adjust angles and heights, and install panels with accuracy and reliability. The integration of advanced control systems with precise positioning capabilities and an efficient user interface enhances the accuracy and efficiency of the installation process.

A detailed explanation of its main mechanisms is provided below:

2.2.1 Robotic Arm and Motion Mechanism

The Cartesian robotic arm is an essential component of the robot, capable of autonomously positioning, and installing panels at diverse heights and angles. This arm is designed to accurately adjust its position, guaranteeing efficient and precise operation throughout the panel installation procedure. The following information describes the primary mechanics of this arm:

- **Telescopic Mechanism:** The robotic arm is equipped with an advanced telescopic mechanism that enables variable adjustment of height and depth

Figure 3. Detailed View of the Telescopic Mechanism in the Robotic Arm

of motion. To achieve precise and linear movement, a stepper motor with a torque of 85 kg·cm is employed. This motor, in conjunction with a ball screw featuring a 16 mm diameter and a 5 mm pitch, provides highly accurate and controlled linear motion (see figure 3).
- **Motion Mechanisms:** The robotic arm utilizes advanced mechanisms, including stepper motors and ball screws, to achieve accurate vertical and horizontal motions. This mechanism employs a stepper motor with a torque of 45 kg·cm, paired with a ball screw that has a diameter of 16 mm and a pitch of 5 mm. This combination facilitates the accurate and delicate motions, enabling the arm to properly install panels in various positions.
- **Rails and Connections:** Various components of the robotic arm affixed to linear rails and carriages, facilitating the arm's vertical and horizontal motions. These mechanisms enable the arm to transport panels along different paths with accuracy.
- **Panel Gripper:** The robotic arm is equipped with an advanced panel gripper responsible for holding and stabilizing panels during installation operations. This gripper can position panels in various orientations and, with the help of linear actuators and stepper motors, precisely adjust their angles before securely installing them in the desired location. The gripper's design prevents damage to the panels during handling and ensures a safe and highly accurate installation process.
- **Angle Adjustment Mechanisms:** The robotic arm is equipped with an advanced mechanism comprising a linear actuator and a metallic linkage. The linear actuator is responsible for moving the arm forward and backward, while the metallic linkage is connected on one side to the robot's body and on the other side to the telescopic arm structure. These two mechanisms can operate either synchronously or independently. When operating in synchronized mode, the robotic arm moves directly forward and backward without any angular deviation. However, if the two mechanisms operate at different speeds or directions, a positive or negative angle relative to the

vertical axis is generated, allowing the arm to be adjusted at various angles. This mechanism, by combining horizontal and vertical movements, enables the arm to achieve a wide range of angular adjustments, ensuring precise positioning of the panels. The angular adjustment mechanism of the robot is particularly effective for installing panels in locations where direct installation is not feasible due to obstacles on the ceiling or floor of the building.

2.2.2 Installation Tools

The accurate and efficient operation of installation tools is one of the key features of Wall bot. These tools must operate precisely and impeccably in many construction areas, including uneven surfaces, varying heights. The robot's installation tools are specially designed for various conditions.

- **Electric Drills and Nail Guns:** The robotic arm is equipped with two types of installation tools, enabling the installation of panels on ceilings, walls, and floors.

1. Installation on Metal Surfaces: For metal ceilings, the system employs an electric drill using self-tapping screws. These screws automatically install the runner (the panel support structure) to the metal ceiling without the need for additional pre-drilled holes.
2. Installation on Concrete Surfaces: The robot employs a nail gun system for concrete ceilings. This tool accurately embeds nails into the concrete substrate to firmly fasten the panels. The nail gun technology functions similarly to industrial nailers, facilitating rapid and secure installation of panels on robust and resilient ceilings. Furthermore, each tool is affixed to a linear system that enables positional adjustment according to the unique requirements of the ceiling. This capability allows the robot to do installations with enhanced precision at any location on the ceiling, considering its type and condition.

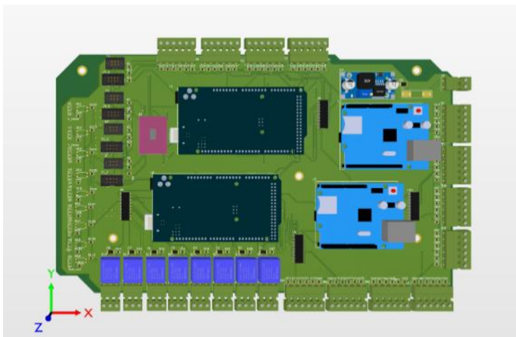
2.2.3 Cameras for Runner Positioning and Sensors

The runner's location on the ceiling and the robot's movement across obstacles are achieved by two complimentary techniques:

- **Smart Cameras**: Cameras mounted to the robot capture the surrounding environment and transmit this data for image processing. This processed data directs the robot to the precise area for panel installation by determining the runner's position on the ceiling. The robot is equipped with RGB cameras
- and 3D depth cameras, crucial for analyzing the geometric characteristics of the surroundings. The robot's cameras map the area to identify obstacles and determine safe, efficient pathways.
- **Sensors:** The robot's operation in construction environments necessitates the top priority of preventing collisions with obstacles and ensuring safety. The robot's positioning system is designed to autonomously detect obstacles and modify its trajectory using cameras and supplementary sensors. LiDAR (Light Detection and Ranging) sensors provide intricate 3D mapping of the surroundings, allowing the robot to identify obstacles, measure distances, and move securely. These sensors augment the robot's spatial awareness and enable accurate mobility in congested areas. Moreover, the device sends audible and visual alerts to the operator upon the detection of a possible threat. This capability is vital in construction settings, where many impediments and risks may exist. Through the integration of cameras and sensors, the robot has an advanced safety system, guaranteeing secure functionality in dynamic and difficult conditions.

3 Electronic Circuit Board of Wall-Bot

Wall-bot is an advanced machine for drywall installation. The robot must move along the surface and install each panel at the desired positions. This robot has a total of 12 stepper motors, 4 DC motors, 2 drills, and several additional sensors, including two distinct control systems. A Control Board have been designed to make the connections between the microcontroller boards, Ethernet connections, sensors and actuators (see figure 4). The board comprises two distinct Atmega2560 processing boards integrated to facilitate connections. Two boards connect to each other over the Ethernet Cables though a router and then connect to a PC with another Ethernet Cable. The board is required a 12V Main Power supply to run with Maximum current of 10 Amps. A buck switching converter transforms the power into the requisite 5V for the majority of digital components. Given the presence of two control boards within the unit, each board can be reviewed separately.



3.1 Main control for the movement

Four DC motors are coupled to BTS7960B external drivers, each connected with the board via 2x4 IDC connectors. These DC motors are mounted on four stepper motors, which rotate the DC motors to enable the robot to move in any direction across the surface. The stepper motors are controlled with TB66xx series drivers, with each driver connected through a 6-pin, 0.2-inch pitch terminal socket. To accurately measure motor speed, AS5600 Magnetic Angle Encoder are used to precisely measure the motor speed of all tires. The Encoder link to the Arduino processor via 2x3 IDC connectors, with the connection facilitated by the TCA9845 multiplexer. This design guarantees accurate speed measurement and effective motor control. The robot's movements are controlled by a singular ATmega2560 Arduino processor, which implements the control algorithms and manages communication. Commands are sent from the primary PC by a W5100 Ethernet module, facilitating uninterrupted and instantaneous control of the robot's motions. The robot is equipped with advanced communication components, stepper motors, and DC motors, which are incorporated to enhance its adaptability, precision, and mobility for intricate positioning tasks.

3.2 Main control for the installation unit

This unit consists of five actuators driven by eight stepper motors, nine proximity sensors for positioning, and many relays for the control of auxiliary equipment such as drills and fans. The system is controlled by an ATmega2560 Arduino board, which regulates motor function and sensor feedback for accurate operation. The main PC and a router are connected through an Ethernet module in this device, which allows for real-time monitoring and control. Buffer gates and ULN2xxx driver circuits are used to guarantee reliable connection and avert interaction problems among components. These devices provide electrical stability, hence augmenting the system's resilience and reducing possible interference among components. The seamless integration of actuators, sensors, and communication modules guarantees accurate performance, making the unit very efficient for intricate operations. The incorporation of gate ICs in electronic board design offers substantial protection for the primary processor by reducing potential damage. Nevertheless, to attain full electrical isolation and protection against electrostatic discharges (ESDs) and electrical shocks, optocouplers are utilized. These components guarantee strong isolation and improved system reliability, especially in electrically noisy settings. One of the key advantages of this design is the implementation of a dual-processor system. By employing two processors simultaneously, conflicts between movement control and the primary tasks of the robot are effectively prevented, resulting in smoother operation and task execution. A further advantage is the reduction of interference among I²C sensors, since the design has a specialized I²C module. Furthermore, all proximity sensors are completely isolated, guaranteeing precise sensor functionality and reducing the risk of signal disruption. The board is equipped with robust protection mechanisms on the power lines, including safeguards against overvoltage, overcurrent, and polarity mismatches. These protections improve its durability and resilience under challenging operating conditions.

Table 1 Denavit-Hartenberg (D-H) parameters of the robotic arm.

parameter	α_{i-1}	a_{i-1}	θ_i	d_i
i=1	0	0	0	d_1
i=2	0	0	0	$d_2 + l_1$
i=3	0	0	θ_1	l_2
i=4	$-\frac{\pi}{2}$	0	0	$d_3 + l_3$

4 Kinematic Modelling for the Telescopic Arm

For both forward and inverse kinematic analysis, this section models the telescopic arm as a 4-DOF robotic arm with three prismatic joints and one revolute joint, neglecting the fifth degree of freedom, which enables the angle adjustment of the telescopic arm, to simplify the analysis.

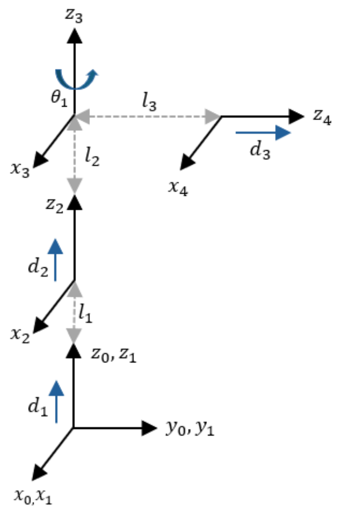


Figure 5 Assigned coordinate frames for each link of the robotic arm

4.1 Forward kinematics model

Forward kinematics calculates the position and orientation of the end-effector in 3D space by using the joint variables, such as joint angles or linear displacements. This calculation is performed by applying homogeneous transformation matrices that describe how the robot's joints and links are connected [10]. The Denavit-Hartenberg (DH) convention is a widely used approach for modeling robotic arms. It defines four parameters to represent the kinematic chains of robotic arms: twist angle, link length, link offset, and joint angle. Fig 5 depicts a coordinate frame attached to each link of the robotic arm. Table 1 lists DH parameters for the telescopic arm. The homogenous transformation matrix (see Equation (2)) that relates the global coordinate system is derived from Equation (1):

$$T_{06} = T_{01}\, T_{12}\, T_{23}\, T_{34}\, T_{45}\, T_{56} \tag{1}$$

$$T_{04} = \begin{bmatrix} \cos(\theta_1) & 0 & -\sin(\theta_1) & -\sin(\theta_1) * (d_3 + l_3) \\ \sin(\theta_1) & 0 & \cos(\theta_1) & \cos(\theta_1) * (d_3 + l_3) \\ 0 & -1 & 0 & l_1 + l_2 + d_1 + d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Based on the transformation matrix, five points within the range of motion for each joint, including the initial and final points, were analysed. The position values for the selected points were calculated using MATLAB code and are presented in Table 2.

4.2 Inverse kinematics model

Inverse kinematics is the method of calculating the joint parameters required for a robotic arm to reach a desired position and orientation, functioning as the reverse of forward kinematics. There are two methods for solving inverse kinematics: the geometrical method and the algebraic method. The algebraic method is more complex than the geometrical method, as it involves solving a set of mathematical equations derived from the robot's kinematic chain. The joint values for the telescopic arm are determined from following equations using the geometrical method shown in Figure 1. θ_1 is derived from Equation (3), and d_3 is derived from Equation (4). To determine d_1 and d_2 from the equation, one of the values must be predefined by the operator. It is recommended to initially set d_2 at its maximum displacement (80 cm), and then derive d_1 from Equation (5).

$$\theta_1 = \tan^{-1}\left(-\frac{x}{y}\right) \tag{3}$$

$$d_3 = \sqrt{x^2 + y^2} - l_3 \tag{4}$$

$$d_1 + d_2 = z - l_1 - l_2 \tag{5}$$

The telescopic arm has vertical movement along the Z-axis, while the horizontal link rotates along the Z-axis. Additionally, the radius of the installation tools is adjustable. The combination of these movements results in the installation range forming a hollow cylinder, as shown in figure 6.

5 Conclusion

This study demonstrates that the developed robot has the potential to revolutionize the construction industry, particularly in panel installation. The robot enhances efficiency, minimizes human errors and physical strain, and guarantees superior quality and precision in operations by automating the installation procedure. The advanced image processing technology integrated into the robot not only improves accuracy in panel placement but also highlights its high flexibility in installing panels of diverse sizes and weights. The robot's standout features, such as precise environmental analysis, the design of flexible arms, and coordinated movements enable it to effectively perform complex tasks in dynamic and challenging environments. Moreover, its ability to interact and coordinate with other robots facilitates the execution of larger projects with greater efficiency and speed. Future advancements in machine learning algorithms could enhance the robot's decision-making capabilities and adaptability to diverse conditions. Energy sustainability is expected to be incorporated into these systems in the future. Optimizing the robot's energy consumption through advanced energy management technologies, such as intelligent consumption control algorithms, can maximize its operational efficiency. Additionally, integrating the robot with renewable energy sources would enable more

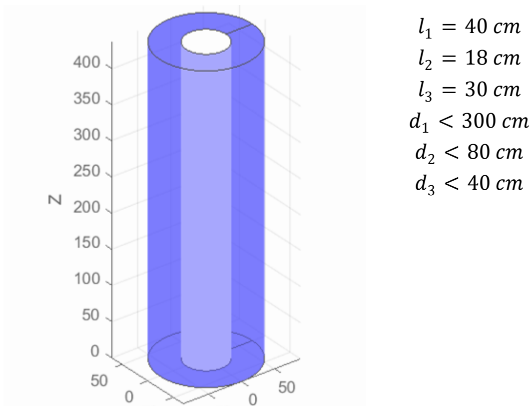


Figure **6** The installation range of the robotic arm, formed as a hollow cylinder

Table 2 Calculated position values for five selected points within the range of motion for each joint

parameter	x (cm)	y (cm)	z (cm)
$d_1 = 0, \quad d_2 = 0$ $d_3 = 0, \quad \theta = 0$	0	30	58
$d_1 = 75, \quad d_2 = 20$ $d_3 = 10, \quad \theta = 7.5^{\circ}$	-5.2	39.66	153
$d_1 = 150, \quad d_2 = 40$ $d_3 = 20, \quad \theta = 15^{\circ}$	-12.94	48.3	248
$d_1 = 225, \quad d_2 = 60$ $d_3 = 30, \quad \theta = 22.5^{\circ}$	-22.96	55.43	343
$d_1 = 300, \quad d_2 = 80$ $d_3 = 40, \quad \theta = 30^{\circ}$	-35	60.62	438

sustainable and environmentally friendly project implementation. Furthermore, it is expected that the integration of robotics with 3D printing technology will be a key focus of future advancements. This integration could provide opportunities for designing and constructing complex building components. With 3D printing, it would become possible to produce parts that are precise, fast, and minimally wasteful, while robots could be equipped to install and assemble these components with high accuracy. This future development is anticipated to reduce costs, expedite project schedules, and align with sustainable construction standards. In terms of social aspects, this technology reduces laborious and repetitive tasks, allowing human workers to focus more on the creative and strategic aspects of projects. This shift not only enhances job satisfaction but also emphasizes the necessity of implementing safety standards and professional ethics to increase human-robot interaction. The Wall-bot, with its distinctive features, provides an innovative shift in civil engineering techniques. Utilizing this innovation may optimize project schedules, improve building quality, and foster robust and sustainable infrastructure, so offering greater prospects for the construction sector. Due to continuous developments, these robots are anticipated to function with enhanced speed, precision, and efficiency, significantly influencing the future of construction.

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