ECE 445

Magnetic-Wheeled Pipe Climbing Robot for PowerTool Rust Removal

Team #20

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1 Introduction

1.1 Goals

The goal of this project is to address the limitations of conventional manual rust removal on external steel pipelines. In current maintenance practice, rust removal is often labor-intensive, hazardous, and difficult to perform consistently, especially on pipes located in elevated, confined, or otherwise hard-to-access environments. In addition, insufficient or inconsistent surface preparation may reduce coating adhesion and long-term corrosion protection. Since corrosion of steel infrastructure continues to cause significant economic and operational loss, there is a strong need for safer, more efficient, and more repeatable maintenance methods [1]. Furthermore, standards such as ISO 8501-1 and SSPC-SP 11 show that power-tool cleaning remains an important and practical rust-removal method when abrasive blasting is not suitable [2], [3]. Therefore, this project aims to develop a robotic solution that can improve safety, reduce manual effort, and achieve more repeatable rust-removal performance on external steel pipe surfaces.

1.2 Functions

The proposed product is a magnetic-wheeled pipe-climbing robot designed for power-tool rust removal on external steel pipes. The robot is expected to adhere to ferromagnetic pipe surfaces, move reliably along the pipe, and carry a rust-removal end effector during operation. It should also maintain stable tool-to-surface contact while cleaning so that the rust layer can be removed effectively under curved and uneven surface conditions. In addition, the system is intended to support experimental comparison of different abrasive tool materials in order to evaluate their influence on cleaning effectiveness and resulting surface condition. These required functions are motivated by prior studies on magnetic adhesion mechanisms for climbing robots and robotic grinding systems with force-position control [4], [5], [6].

1.3 Benefits

This project can provide several important benefits to clients and maintenance operators. First, it can reduce direct human exposure to hazardous rust-removal environments by replacing or assisting manual cleaning tasks with robotic operation. Second, it can improve the repeatability and consistency of rust removal, which is important for achieving coating-ready surface preparation. Third, the robotic platform may improve maintenance efficiency by combining adhesion, locomotion, and cleaning functions into one integrated system. Overall, the system is expected to support safer, more reliable, and more controllable pipe maintenance procedures. These advantages are also consistent with the practical motivation behind robotic pipe-maintenance systems reported in previous work [7].

1.4 Features

The proposed system is differentiated from existing solutions by its integrated focus on adhesion, contact stability, and surface-preparation quality. Unlike systems that only address wall climbing or only study grinding behavior in a fixed setup, this project combines magnetic-wheeled locomotion with a rust-removal end effector designed for stable operation on curved steel pipes [4], [5], [6]. Another distinguishing feature is the inclusion of abrasive-tool comparison as part of the system evaluation, allowing the project to study not only whether the robot can move and clean, but also how tool selection affects rust-removal effectiveness and final surface quality [8], [9], [10]. This combination makes the project more application-oriented and better aligned with the practical requirements of external steel pipe maintenance.

1.5 High-Level Requirements

Based on the project objective and the intended application scenario, the following high-level requirements (HLRs) are defined for the proposed magnetic-wheeled pipe-climbing rust-removal robot:

1. The robot shall adhere securely to external steel pipe surfaces during operation without detachment or uncontrolled slipping.

2. The robot shall be capable of moving along the surface of an external steel pipe while carrying the rust-removal end effector and associated onboard components.

3. The system shall maintain stable tool-to-surface contact during rust removal so that repeatable cleaning performance can be achieved on curved steel pipe surfaces.

4. The system shall remove rust effectively enough to prepare the pipe surface for subsequent coating, inspection, or maintenance treatment.

5. The robot shall reduce direct operator exposure to hazardous rust-removal environments by enabling robot-assisted or remotely assisted operation.

2 Design & Requirements
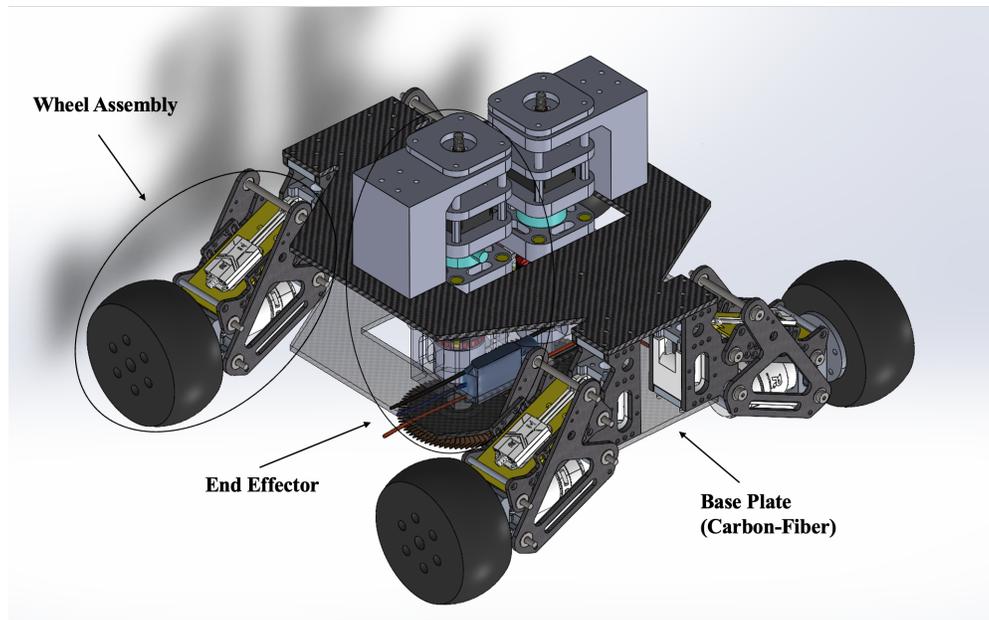
2.1 Physical Diagram Description

Figure 1: Overall view of the magnetic-wheeled rust-removal robot

The robot comprises a compact four-wheeled magnetic climbing chassis, four side wheel assemblies, a central drive support frame, and two vertically mounted rust-removing heads on top of the chassis. The chassis is designed to traverse the outer surface of ferromagnetic steel pipes, maintaining sufficient adhesion and traction during movement and rust removal operations. The top plate provides a rigid mounting interface for the end effector module, while the lower frame houses the drive, support, and wiring structures.

This physical design enhances the robot's overall functionality in three ways. First, the four-wheeled layout distributes the robot's weight and workload across multiple contact points, improving stability on curved pipe surfaces. Second, the four magnetic wheel assemblies provide passive adhesion and traction without requiring a continuous vacuum, consistent with the magnetic adhesion method proposed in this project. Third, the modular, top-mounted rust-removing heads allow the robot to perform grinding and cleaning while the chassis maintains stable movement on the pipe surface.

Each wheel assembly includes a magnetic wheel, structural side plates, a motor-driven transmission section, and a compliant or adjustable support structure connecting the module to the main chassis. The function of this assembly is to generate both normal adhesion force and tangential traction force on the steel pipe surface. The magnetic wheel provides passive attraction to the ferromagnetic pipe, while the motorized wheel rotation produces forward or reverse motion. The wheel module contributes to overall
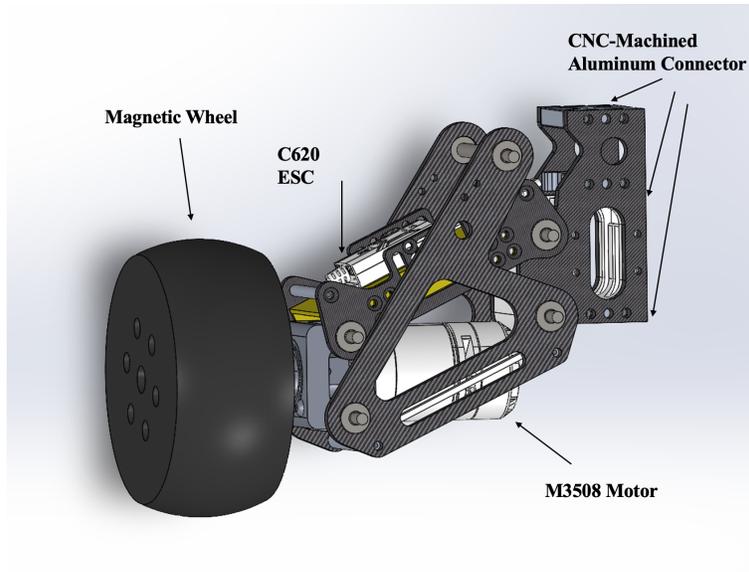
Figure 2: Wheel assembly

functionality by ensuring that the robot can resist gravity, tool reaction forces, and disturbances during cleaning. In addition, the mechanical structure around the wheel is intended to control wheel alignment and maintain a small air gap variation when the robot passes over pipe curvature changes, weld seams, or uneven rust layers. This is consistent with the proposal's requirement to design a wheel-magnet module compatible with pipe curvature and to account for air-gap-sensitive adhesion and slip margin under grinding load.
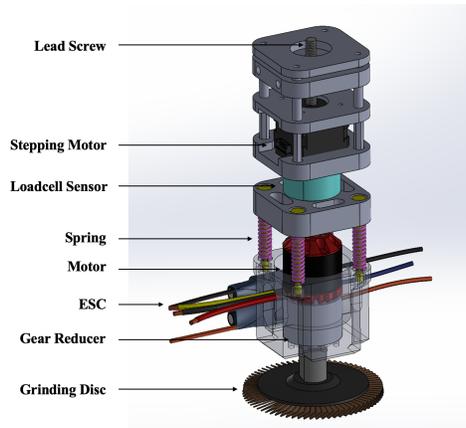
Figure 3: Rust-removal head

Figure 3 shows the rust-removal head, which consists of a lead screw, stepping motor, load cell sensor, spring, DC motor, ESC, gear reducer, and grinding disc. The stepping motor and lead screw are used to adjust the position of the grinding head in the normal direction, while the load cell sensor measures the contact force between the tool and the pipe surface. The spring provides compliance to reduce force fluctuation caused by vi-

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bration, weld seams, and surface irregularities. The DC motor, ESC, and gear reducer drive the grinding disc to perform the rust-removal process. This subsystem is the key processing module of the robot because it combines position adjustment, force sensing, compliant support, and abrasive cleaning, which together help maintain stable contact and improve the consistency of rust removal on curved steel pipe surfaces.
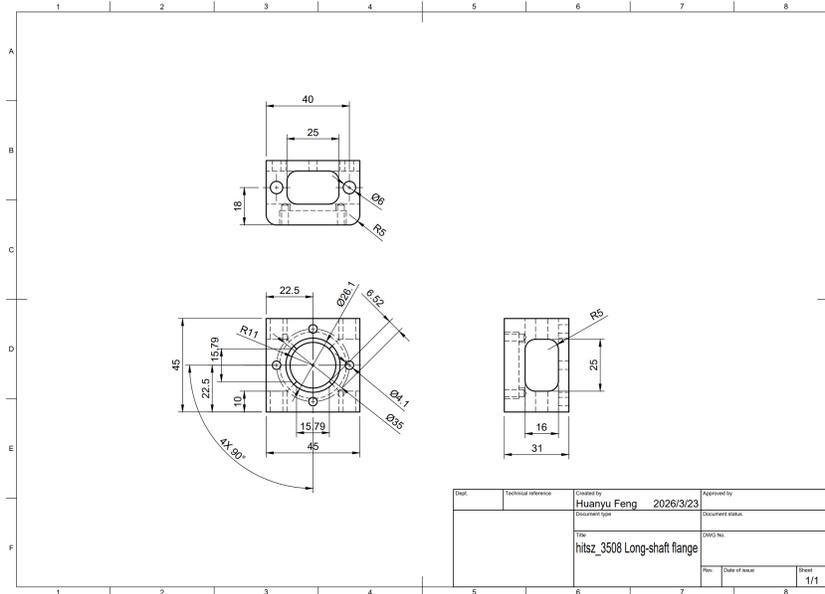
Figure 4: Engineering drawing of the M3508 long-shaft flange

The engineering drawing of the 3508 long-shaft flange defines the mounting interface between the motor output and the rust-removal head structure, ensuring accurate alignment, concentric transmission, and reliable assembly of the rotary grinding subsystem. Its specified hole pattern and overall dimensions also provide the dimensional basis for manufacturing and integration with the upper actuator and drive components.
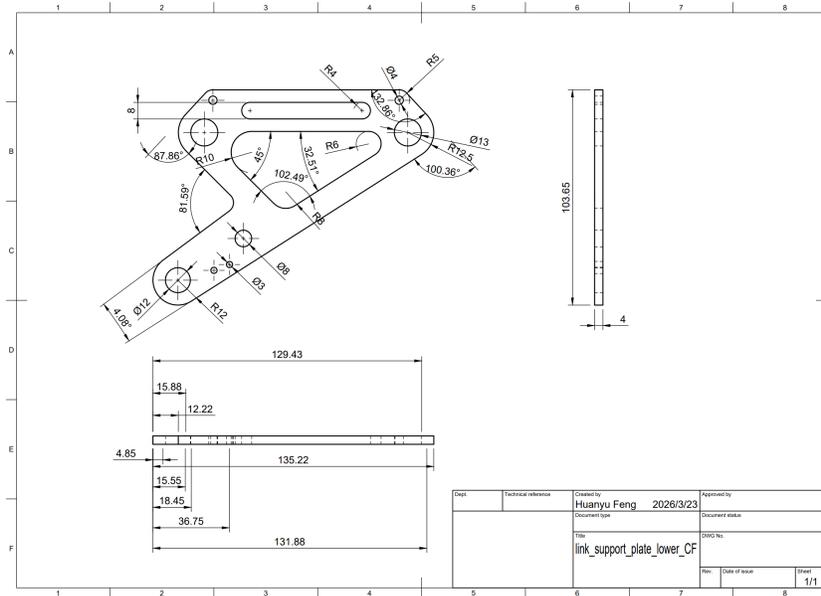
Figure 5: Engineering drawing of the lower carbon-fiber link support plate

The engineering drawing of the lower carbon-fiber link support plate defines the geometry of the wheel-support linkage, including the main mounting holes, slot features, and overall thickness, which are critical for maintaining structural stiffness and correct wheel-module kinematics. This part contributes directly to the stability of the locomotion and magnetic adhesion system by supporting the wheel assembly and transmitting loads between the chassis and the wheel linkage.

2.2   Physical Diagram Description

Figure 6: Proposed Block Diagram of Magnetic Rust-Removal Robot

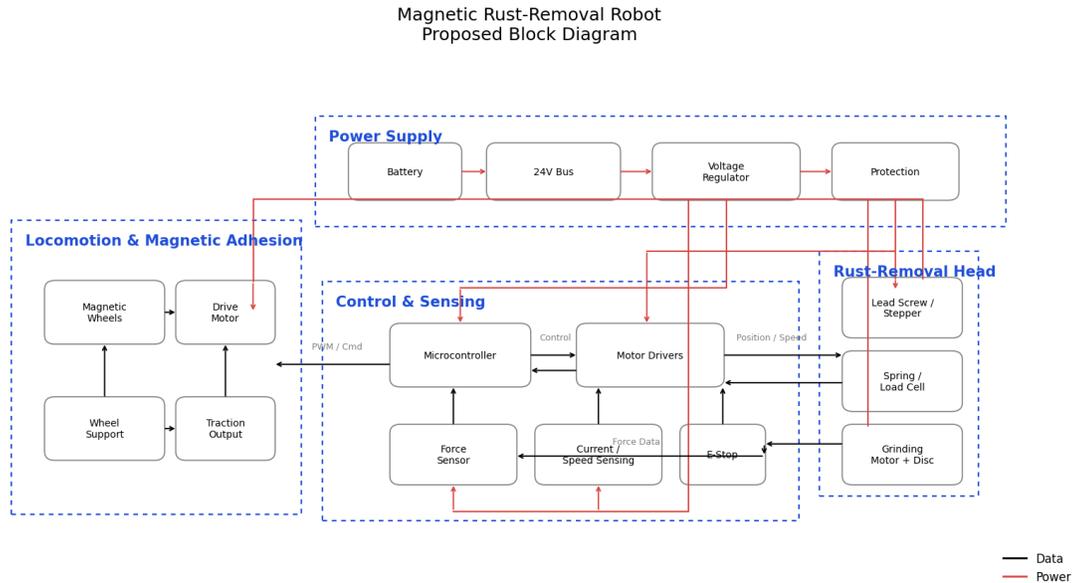The Locomotion and Magnetic Adhesion Module supports the robot body on the steel pipe and provides mobile positioning for the end effector. The Rust-Removal End-Effector Module receives mechanical support and positioning from the chassis while receiving rotational power from its motor. The Normal-Force Adjustment and Compliance Module mechanically connects the abrasive head to the robot frame and regulates the tool-surface contact force. The Sensing and Measurement Module sends force, current, and motion-related feedback signals to the Control and Safety Module. The Control and Safety Module then commands the locomotion motors and the normal-force adjustment actuator to maintain stable climbing and consistent rust removal.

Each block contributes to the overall functionality as follows: the adhesion/motion sub-system ensures the robot remains attached to the pipe; the end effector removes rust; the compliance and force-regulation subsystem stabilizes contact; the sensors quantify robot and process state; the controller coordinates all actions and activates protection logic when abnormal events occur. This modular organization directly supports the project objective of combining adhesion design, force control, and abrasive-process evaluation in a unified pipe-maintenance robot.

2.3   Component Requirements

2.3.1   Magnetic Adhesion and Locomotion Module

- **Requirement A1**: The robot shall operate on external ferromagnetic steel pipes with diameters from 0.8 m to 10 m.

- **Requirement A2**: The four-wheel magnetic adhesion system shall provide a total nominal adhesion force of at least 392 N under standard contact conditions.

- **Requirement A3**: The locomotion system shall support a total robot mass of 15 kg without detachment from the pipe surface during static attachment and low-speed motion.

- **Requirement A4**: The wheel-traction system shall resist a combined external tangential load of at least 307 N, corresponding to robot weight and the estimated total grinding reaction force in the worst-case climbing condition.

- **Requirement A5**: The wheel module shall maintain attachment when local gap variation caused by curvature change, welds, or rust thickness reaches up to 2 mm.

2.3.2   Rust-Removal Head Module

- **Requirement B1**: Each rust-removal head shall be powered by a 24 V DC motor with rated power not less than 200 W.

- **Requirement B2**: Each rust-removal head shall provide a rated rotational speed of 1200 rpm under nominal input voltage.

- **Requirement B3**: The two rust-removal heads together shall tolerate a total estimated tangential grinding reaction force of at least 160 N during operation.

- **Requirement B4**: The rust-removal head shall support interchangeable abrasive tools for comparative evaluation of different tool materials and abrasive systems.

- **Requirement B5**: The rust-removal head shall maintain continuous operation for at least 10 min under nominal load without structural loosening or thermal shutdown.

2.3.3   Normal-Force Sensing and Compliance Module

- **Requirement C1**: The force sensing subsystem shall measure tool contact force over a range of 0 N to 200 N.

- **Requirement C2**: The normal contact force command for each rust-removal head shall be maintained within a controllable operating range of 20 N to 80 N.

- **Requirement C3**: The force measurement error shall not exceed ±5 N over the operating range used in closed-loop control.

- **Requirement C4**: The compliant support mechanism shall provide sufficient travel and flexibility to maintain contact during local surface disturbances such as welds, pits, and curvature change.

- **Requirement C5**: The contact-force control loop shall detect overload conditions when the measured force exceeds 120 N and trigger protective logic.

2.3.4 Power Module

- **Requirement D1**: The power subsystem shall supply 24 V DC to each rust-removal motor under nominal operating conditions.

- **Requirement D2**: The power subsystem shall support a total rust-removal motor power of at least 400 W for two simultaneously operating heads.

- **Requirement D3**: The power subsystem shall provide protected low-voltage outputs for the controller and sensor modules with voltage variation within ±5% of nominal values.

- **Requirement D4**: The system shall include overcurrent protection for drive motors and rust-removal motors.

2.3.5 Control and Safety Module

- **Requirement E1**: The controller shall coordinate locomotion and rust-removal operation simultaneously during pipe-surface cleaning.

- **Requirement E2**: The controller shall receive force measurements from the 0–200 N force sensor and use them for contact-state monitoring.

- **Requirement E3**: The control system shall trigger a protective stop if measured contact force exceeds 120 N, if sudden adhesion loss is detected, or if tool jamming occurs.

- **Requirement E4**: The emergency stop function shall cut power to motion-producing actuators within 0.5 s of activation.

- **Requirement E5**: The system shall support repeatable experiments by fixing and recording tool speed, locomotion speed, and contact-force setpoint during testing.

2.4 Risk: traction margin may be insufficient under vertical climbing and grinding load

For a 15 kg robot, the gravitational load is approximately 147 N. The estimated total tangential grinding reaction force from two rust-removal heads is 160 N. Therefore, the worst-case tangential load that must be resisted during vertical operation is approximately:

$$F_{req} = 147 + 160 = 307 \, \text{N} \tag{1}$$

The total nominal magnetic adhesion force of the four wheels is approximately:

$$F_{adh} = 4 \times 10 \times 9.81 = 392 \, \text{N} \tag{2}$$

Assuming traction is limited by friction, the available tangential traction is $F_{fric,max} = \mu F_{adh}$. To avoid slip, $\mu F_{adh} \geq F_{req}$, thus:

$$\mu \geq \frac{307}{392} \approx 0.78 \tag{3}$$

This means the wheel-pipe interface must provide an effective friction coefficient of at least **0.78** in the worst-case operating condition. Because this value is relatively high for dusty or rusted steel surfaces, the traction margin is a major technical risk. To mitigate this risk, the design should consider increasing effective adhesion force, reducing tangential grinding force, optimizing wheel tread material, or limiting operation to lower-speed / lower-load conditions during vertical climbing. This analysis is consistent with the proposal's identification of adhesion margin, traction margin, and tool-reaction coupling as the central challenges of the system.

3 Ethics and Safety

3.1 Ethics

Our team will follow both the IEEE Code of Ethics and the ACM Code of Ethics throughout the design, testing, and reporting of this project [11], [12]. The main ethical motivation of this project is to reduce human exposure to hazardous rust-removal work on external steel pipes. Traditional manual grinding and wire brushing can expose workers to heights, confined spaces, dust, vibration, and inconsistent tool contact. A robot that performs this task should therefore be designed and evaluated in a way that genuinely reduces risk rather than merely shifting risk from a human operator to an inadequately tested machine.

A first ethical concern is overclaiming system capability. Our project depends on magnetic adhesion, traction under tangential grinding loads, and stable tool-to-surface contact on curved and irregular pipe surfaces. Prior research shows that magnetic wheel performance is sensitive to air gap and that robotic grinding quality depends strongly on force stability and contact regulation [4], [6]. Because of these coupled effects, it would be unethical to claim that the robot is field-ready unless we have validated adhesion margin, traction margin, contact-force stability, and abnormal-event handling under representative conditions. In this proposal and in later reports, we will clearly distinguish between intended functionality and experimentally verified performance.

A second ethical concern is responsible deployment. Previous work on robotic rust removal for exterior gas pipes shows that real deployment conditions introduce practical constraints beyond what is seen in a laboratory prototype [7]. For this reason, our team will treat the current system as a supervised prototype rather than a fully autonomous field product. We will begin with controlled testing on pipe sections in a laboratory environment, and we will define clear operating limits such as pipe curvature range, allowable surface condition, tool speed range, and required adhesion margin before considering more demanding scenarios. This approach is consistent with the obligation to prioritize public welfare and avoid harm [11], [12].

A third ethical concern is honest reporting of results. Since this project includes both system integration and abrasive-tool evaluation, there is a risk of selectively emphasizing successful trials while ignoring unstable or unfavorable outcomes. We will instead report failed runs, measurement uncertainty, tool wear, slip events, and any gap between target and achieved surface condition. This is especially important because surface-preparation quality directly affects later coating performance. Ethical engineering requires that limitations, uncertainty, and remaining risks be disclosed clearly rather than hidden behind optimistic claims [11], [12].

3.2 Safety

The first major safety concern is the rotating abrasive tool. Attachments such as wire brushes, fiber discs, and nonwoven conditioning discs can eject debris, snag on surface

irregularities, or injure nearby users if operated improperly. OSHA notes that hand and power tools can cause severe injuries when used or maintained improperly [13]. To reduce this risk, our design will use a protective guard around the tool whenever possible, enforce speed and torque limits, and include stall detection and an emergency-stop function. During testing, operators will keep a safe distance from the spinning tool and will not touch the robot until power is fully removed.

The second major concern is detachment and falling-object risk. Because the robot is intended to climb steel pipes using magnetic wheels, a sudden loss of adhesion or traction could cause the platform to slip or fall. This risk becomes more serious when tangential grinding forces, welds, curvature variation, or surface debris reduce the available safety margin. Existing magnetic wheel studies emphasize the importance of adhesion capability and air-gap sensitivity, while field-oriented pipe-maintenance robots highlight the need for conservative design in real operating conditions [4], [7]. Therefore, all early experiments will be performed on low-height or ground-level pipe fixtures, and the robot will use a secondary tether or catch mechanism during climbing tests. Fall protection principles must be respected whenever testing is performed above ground level [14].

The third concern is dust, debris, and possible coating residue exposure. Grinding and rust removal can generate airborne particles, and CDC-NIOSH notes that cutting or grinding metal can produce lead dust in some work settings [15]. Even when lead is not present, airborne dust and debris are still harmful to eyes and the respiratory system. For this reason, tests should be conducted in a well-ventilated area, preferably with local vacuum extraction or debris collection. Operators should wear safety glasses or a face shield, gloves as appropriate, and respiratory protection whenever airborne dust cannot be adequately controlled [16], [17].

The fourth concern is noise and mechanical disturbance. Grinding tools can produce sustained high noise levels and repeated vibration during operation. OSHA notes that noise exposure above 85 dBA can damage hearing over time [18]. Accordingly, hearing protection should be used during powered testing, especially for repeated trials. In addition, the robot should be shut down immediately if severe vibration, abnormal sound, or tool chatter is observed, since these may indicate poor contact conditions, imbalance, or tool damage.

The fifth concern is electrical and control-system safety. Our project includes drive motors, a tool motor, force sensing, and closed-loop protection logic. Wiring faults, unstable control behavior, or delayed shutdown could cause overheating, unintended motion, or tool jamming. To mitigate these hazards, the prototype should use insulated wiring, secure connectors, current limiting or fusing, and a clearly accessible emergency-stop switch. Protection logic should also detect abnormal events such as sudden adhesion loss, excessive vibration, or tool jam conditions and immediately disable tool motion when necessary. These precautions are consistent with good laboratory practice for powered mechanical systems and with the controlled force-regulation approach discussed in prior robotic rust-removal work [6], [13].

Overall, safety in this project is not limited to one subsystem. It depends on safe tool operation, conservative magnetic-adhesion design, proper personal protective equipment, ventilation, controlled laboratory procedures, and reliable emergency shutdown. Our team will therefore evaluate the system in a staged manner and prioritize operator safety over aggressive performance testing at every stage [11], [16].

References

[1] Association for Materials Protection and Performance (AMPP), *From rust to risk: Global campaign urges action on corrosion crisis*, Apr. 22, 2025, Apr. 2025. [Online]. Available: https://www.ampp.org/blogs/webmasternaceorg/2025/04/22/global-campaign-urges-action-on-corrosion-crisis.

[2] *Preparation of steel substrates before application of paints and related products — visual assessment of surface cleanliness — part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings*, International Organization for Standardization.

[3] *Power tool cleaning to bare metal*, SSPC / NACE.

[4] W. Song, H. Jiang, T. Wang, and S. Zhu, "Design of permanent magnetic wheel-type adhesion-locomotion system for water-jetting wall-climbing robot," *Advances in Mechanical Engineering*, vol. 10, no. 7, 2018. DOI: 10.1177/1687814018787378.

[5] A. Sahbel, A. Abbas, and T. Sattar, "Experimental and numerical optimization of magnetic adhesion mechanism," *International Journal of Mechanical Engineering and Robotics Research*, 2019. [Online]. Available: https://www.ijmerr.com/uploadfile/2018/1228/20181228035802817.pdf.

[6] T. Li, Q. Sun, C. Wang, X. Yuan, and K. Wang, "A robot floating grinding and rust removal approach based on composite force-position fuzzy control," *Sensors*, vol. 25, no. 7, p. 2204, 2025. DOI: 10.3390/s25072204.

[7] K. H. Koh et al., "Teleoperated service robotic system for on-site surface rust removal and protection of high-rise exterior gas pipes," *Automation in Construction*, vol. 125, p. 103 609, 2021. DOI: 10.1016/j.autcon.2021.103609.

[8] S. Korga, K. Żyła, and J. Józwik, "Analysis of the abrasive-type influence on the effectiveness of rotary cleaning of machine parts with complex geometric features," *Materials*, vol. 13, no. 22, p. 5144, 2020. DOI: 10.3390/ma13225144.

[9] A. Kim, S. Kainuma, and M. Yang, "Surface characteristics and corrosion behavior of carbon steel treated by abrasive blasting," *Metals*, vol. 11, no. 12, p. 2065, 2021. DOI: 10.3390/met11122065.

[10] D. J. Varacalle, D. P. Guillen, D. M. Deason, W. Rhodaberger, and E. Sampson, "Effect of grit-blasting on substrate roughness and coating adhesion," *Journal of Thermal Spray Technology*, vol. 15, no. 3, pp. 348–355, 2006. DOI: 10.1361/105996306X124347.

[11] IEEE. "IEEE Code of Ethics," Accessed: Mar. 22, 2026. [Online]. Available: https://ewh.ieee.org/cmte/substations/posted_documents/ieee_codeofethics.pdf.

[12] Association for Computing Machinery. "ACM Code of Ethics and Professional Conduct," Accessed: Mar. 22, 2026. [Online]. Available: https://www.acm.org/code-of-ethics.

[13] Occupational Safety and Health Administration. "Hand and Power Tools - Overview," Accessed: Mar. 22, 2026. [Online]. Available: https://www.osha.gov/hand-power-tools.

[14] Occupational Safety and Health Administration. "Fall Protection - Overview," Accessed: Mar. 22, 2026. [Online]. Available: https://www.osha.gov/fall-protection.

[15]   Centers for Disease Control and Prevention. "Understanding Your Risk for Lead Exposure," Accessed: Mar. 22, 2026. [Online]. Available: https://www.cdc.gov/niosh/lead/risk-factors/index.html.

[16]   Occupational Safety and Health Administration. "Personal Protective Equipment - Overview," Accessed: Mar. 22, 2026. [Online]. Available: https://www.osha.gov/personal-protective-equipment.

[17]   Occupational Safety and Health Administration. "Respiratory Protection - Overview," Accessed: Mar. 22, 2026. [Online]. Available: https://www.osha.gov/respiratory-protection.

[18]   Occupational Safety and Health Administration. "Occupational Noise Exposure - Overview," Accessed: Mar. 22, 2026. [Online]. Available: https://www.osha.gov/noise.