

ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

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# Magnetic-Wheeled Pipe Climbing Robot for Power Tool Rust Removal

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## Team #20

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# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Problem Statement . . . . .	1
1.2	Solution Overview and Visual Aid . . . . .	1
1.3	High-Level Requirements . . . . .	2
<b>2</b>	<b>Design</b>	<b>4</b>
2.1	Physical Design Overview . . . . .	4
2.2	Block Diagram and System Architecture . . . . .	8
2.3	Subsystem Design, Interfaces, and Requirements . . . . .	8
2.3.1	Magnetic Adhesion and Locomotion Module . . . . .	8
2.3.2	Rust-Removal End-Effector Module . . . . .	9
2.3.3	Normal-Force Sensing and Compliance Module . . . . .	10
2.3.4	Power Module . . . . .	11
2.3.5	Control and Safety Module . . . . .	12
<b>3</b>	<b>Calculations and Tolerance Analysis</b>	<b>14</b>
3.1	Critical Function and Nominal Force Balance . . . . .	14
3.2	Traction Margin and Safety Factor . . . . .	14
3.3	Sensitivity to Adhesion Loss . . . . .	15
3.4	Sensitivity to Grinding Reaction Load . . . . .	16
3.5	Design Implications . . . . .	17
<b>4</b>	<b>Cost Analysis</b>	<b>18</b>
<b>5</b>	<b>Schedule</b>	<b>19</b>
<b>6</b>	<b>Ethics and Safety</b>	<b>21</b>
6.1	Ethics . . . . .	21
6.2	Safety . . . . .	21

# 1 Introduction

## 1.1 Problem Statement

Corrosion on external steel pipelines remains a persistent maintenance problem in many industrial environments. In current practice, rust removal is often performed manually or with handheld power tools, which can be labor-intensive, hazardous, and difficult to execute consistently, especially on pipes located in elevated, confined, or otherwise hard-to-access areas. In addition to exposing workers to dust, vibration, and other hazards, manual cleaning may also lead to non-uniform surface preparation, which can reduce coating adhesion and shorten the service life of the repaired structure. 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].

When abrasive blasting is impractical because of environmental constraints, workspace limitations, or field deployment conditions, power-tool cleaning remains an important alternative. Standards such as ISO 8501-1 and SSPC-SP 11 provide widely used guidance for acceptable surface preparation outcomes and show that power-tool cleaning is a practical rust-removal method when more aggressive surface treatment methods are not suitable [2], [3]. However, effective robotic rust removal on curved steel pipe surfaces requires multiple engineering challenges to be addressed at the same time. The system must maintain reliable adhesion to the ferromagnetic pipe surface, generate sufficient traction to resist tangential reaction forces from the cleaning tool, and sustain stable tool-to-surface contact so that rust can be removed effectively without excessive damage to the substrate. Prior work on magnetic climbing mechanisms and grinding-force control also suggests that adhesion, locomotion, and contact regulation must be considered together rather than as isolated functions [4], [5], [6].

Therefore, the problem addressed in this project is the design of a robotic system that can perform safer, more repeatable, and more effective power-tool rust removal on external steel pipelines than conventional manual methods.

## 1.2 Solution Overview and Visual Aid

To address this problem, this project proposes a magnetic-wheeled pipe-climbing robot for power-tool rust removal on external steel pipes. The robot is designed to adhere to ferromagnetic pipe surfaces using magnetic wheel assemblies, move stably along the pipe, and carry a rust-removal end effector during operation. A compliance and normal-force sensing mechanism is used to help maintain stable contact between the abrasive tool and the curved pipe surface, while the control subsystem coordinates locomotion, sensing, and safety interlocks. The power subsystem provides regulated electrical power for the drive motors, end-effector motor, sensors, and controller.

At the system level, the robot operates as follows. Magnetic wheels provide the normal adhesion force required for attachment and also support traction during locomotion. The locomotion subsystem drives the robot along the steel pipe surface, while the rust-

removal end effector applies mechanical abrasion to the corroded region. Meanwhile, the compliance and sensing mechanism helps maintain an appropriate contact force despite pipe curvature variation, weld seams, surface irregularities, and vibration. The controller monitors operating conditions and issues protective shutdown commands when unsafe conditions are detected. This type of integrated robotic maintenance approach is consistent with the practical motivation of prior pipe-maintenance and teleoperated cleaning systems, which seek to reduce direct operator exposure while improving consistency and controllability of maintenance tasks [7]. In addition, the proposed design is motivated by previous studies on magnetic adhesion mechanisms for climbing robots and robotic grinding systems with force-position control [4], [5], [6].

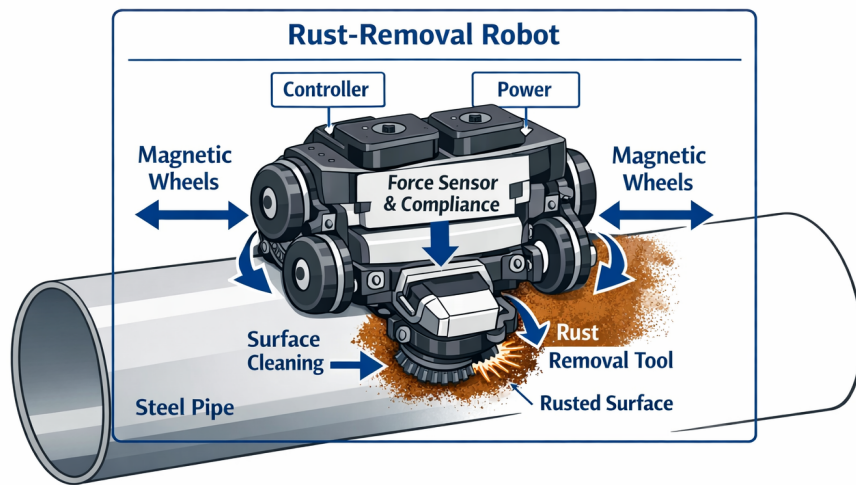


Figure 1: Visual Aid

### 1.3 High-Level Requirements

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

1. **Adhesion and traction requirement:** The robot shall maintain magnetic adhesion and vertical climbing mobility on ferromagnetic steel pipes, supporting its 15 kg mass and resisting a worst-case combined tangential load of 307 N without detaching or experiencing uncontrolled traction slip. This requirement is motivated by prior work on magnetic climbing mechanisms and the need for sufficient adhesion and traction margin in pipe-climbing applications [4], [5].
2. **Rust-removal and contact-force requirement:** The robot shall maintain tool-to-surface contact force within  $\pm 5$  N of the target operational setpoint during clean-

ing, while effectively removing corrosion on the pipe surface to achieve a visual cleanliness grade consistent with ISO 8501-1 St 3 or SSPC-SP 11 over the intended operational path [2], [3], [6].

3. **Safety requirement:** The control subsystem shall actively monitor load-cell feedback and trigger an emergency actuator shutdown within 0.5 s if the measured contact force exceeds the 120 N overload threshold or if sudden adhesion loss is detected, so that direct operator exposure to hazardous rust-removal conditions can be reduced through robot-assisted or remotely assisted operation [7].

## 2 Design

### 2.1 Physical Design Overview

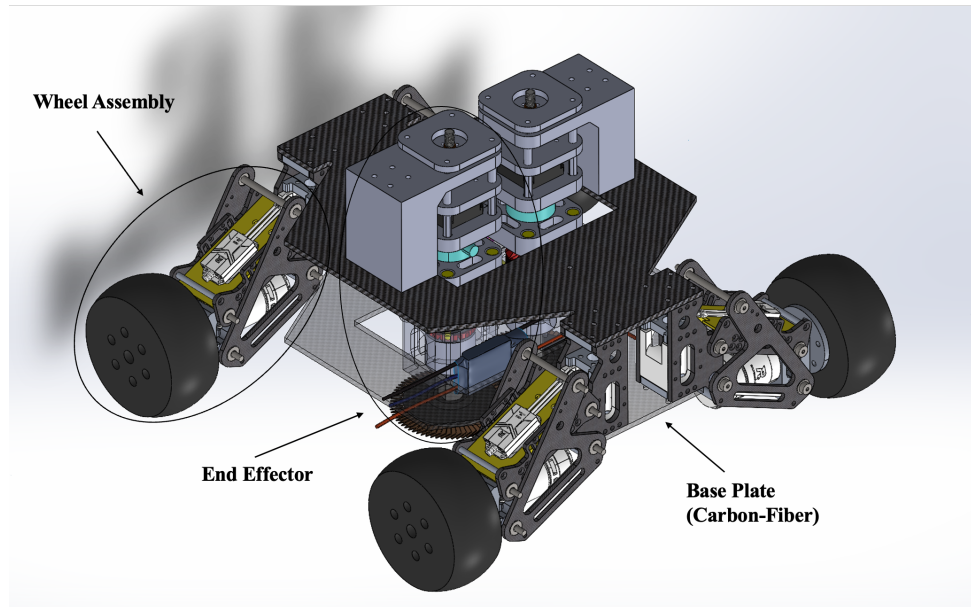


Figure 2: Overall view of the magnetic-wheeled rust-removal robot.

The robot comprises a compact four-wheeled magnetic climbing chassis, four side wheel assemblies, a central drive support frame, and two vertically mounted rust-removal heads on top of the chassis. The chassis is designed to traverse the outer surface of ferromagnetic steel pipes while maintaining sufficient adhesion and traction during movement and rust-removal operation. 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-removal heads allow the robot to perform grinding and cleaning while the chassis maintains stable movement on the pipe surface.

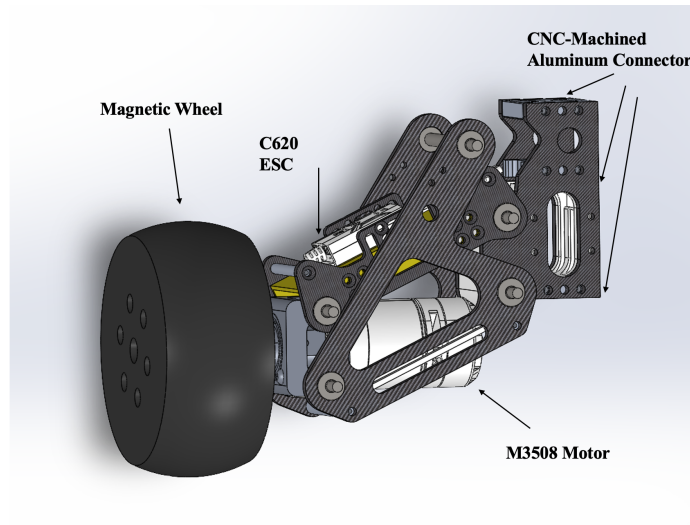


Figure 3: Wheel assembly.

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 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.

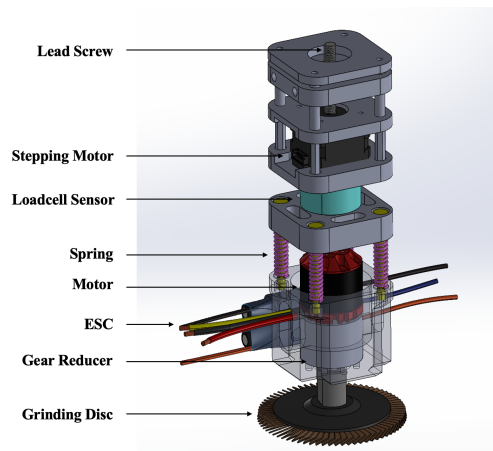


Figure 4: Rust-removal head.

Figure 4 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 vibration, 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.

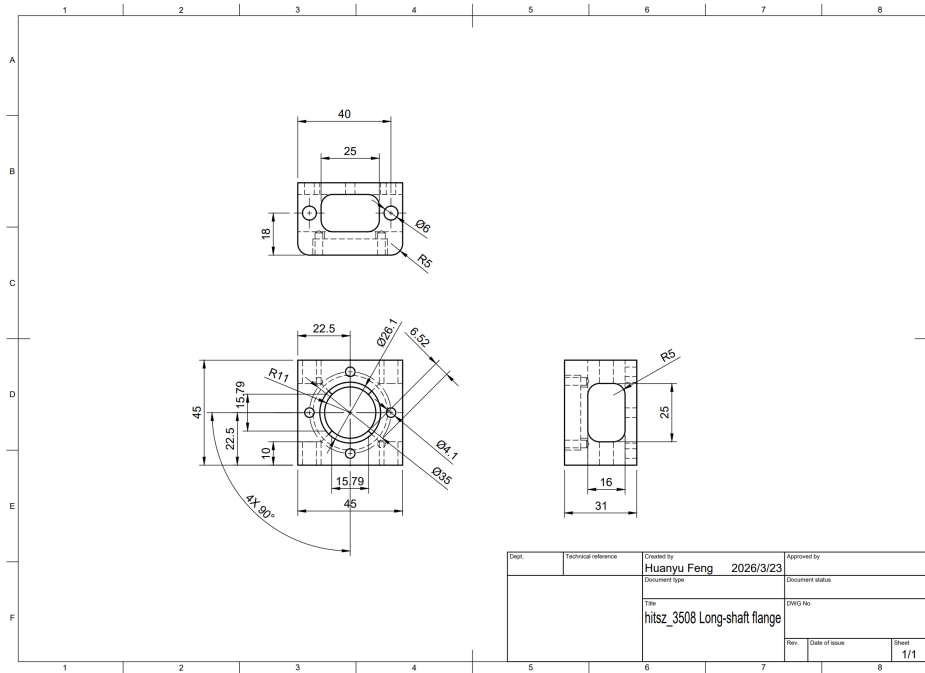


Figure 5: Engineering drawing of the M3508 long-shaft flange.

The engineering drawing of the M3508 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.

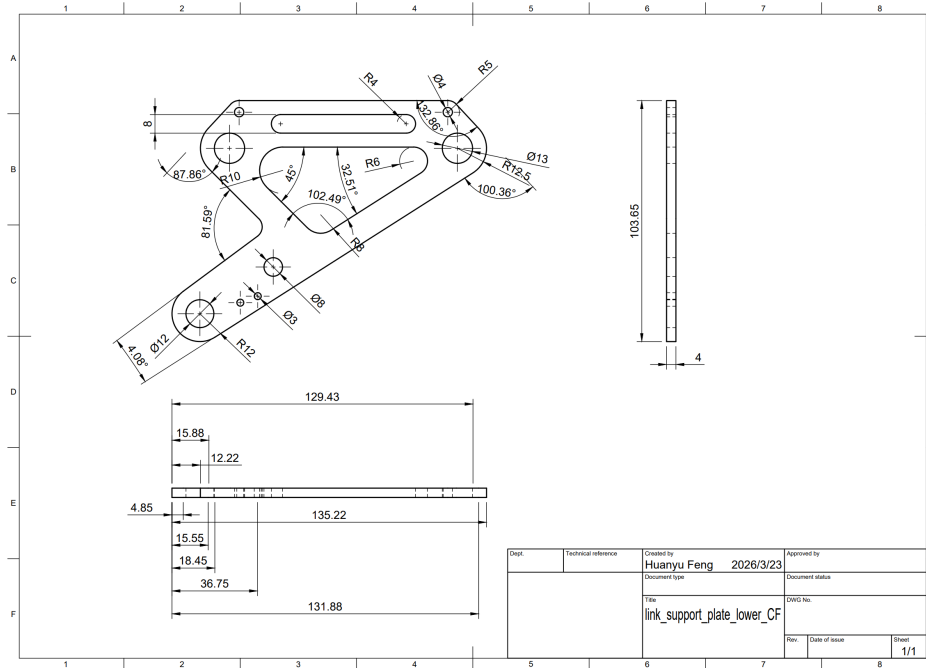


Figure 6: Engineering drawing of the lower carbon-fiber link support plate.

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 Block Diagram and System Architecture

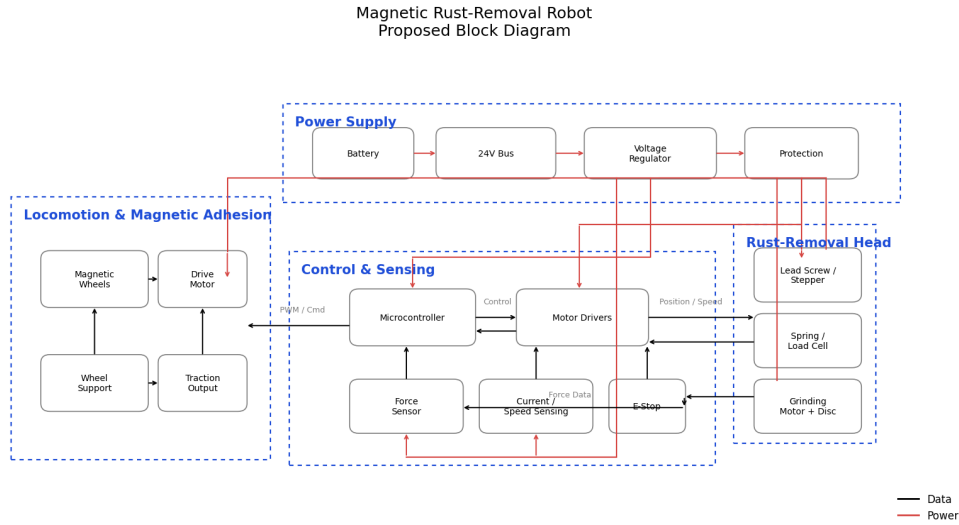


Figure 7: Proposed block diagram of the magnetic rust-removal robot.

The top-level system is divided into five main modules: the Locomotion and Magnetic Adhesion Module, the Rust-Removal End-Effector Module, the Normal-Force Adjustment and Compliance Module, the Power Module, and the Control and Safety Module. 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 performs material removal. The Normal-Force Adjustment and Compliance Module regulates tool-to-surface contact. The Sensing and Measurement paths provide force, current, and motion feedback to the controller. The Control and Safety Module then commands the locomotion motors and the normal-force adjustment actuator to maintain stable climbing and consistent rust removal.

## 2.3 Subsystem Design, Interfaces, and Requirements

### 2.3.1 Magnetic Adhesion and Locomotion Module

Each wheel assembly includes a magnetic wheel, structural side plates, a motor-driven transmission section, and a compliant or adjustable support structure connecting the wheel module to the chassis. The magnetic wheel generates passive attraction to the ferromagnetic pipe, while the driven wheel rotation produces forward and reverse motion. This design is justified by the ferromagnetic nature of the target surface and the need for a compact adhesion mechanism that avoids continuous vacuum generation.

Requirements	Verification
<ol style="list-style-type: none"> <li>1. The module shall support the full robot mass of 15 kg on a ferromagnetic steel pipe without detachment during static and powered operation.</li> <li>2. The module shall resist a tangential external load of at least 307 N during climbing and cleaning without uncontrolled slip.</li> <li>3. The robot shall climb 1.0 m vertically with cumulative slip not exceeding 10 mm.</li> <li>4. The wheel assembly shall maintain stable contact on all intended test pipe diameters.</li> <li>5. The module shall achieve position repeatability within <math>\pm 20</math> mm over a commanded 1.0 m travel.</li> </ol>	<ol style="list-style-type: none"> <li>1. Place the fully assembled robot on a representative steel pipe and verify that no detachment occurs during a 5-minute hold and low-speed motion test.</li> <li>2. Apply an opposing tangential load with a calibrated fixture during climbing and verify that the robot does not detach or slip before 307 N.</li> <li>3. Command a 1.0 m vertical climb and verify from a fixed scale that cumulative slip is no more than 10 mm.</li> <li>4. Test the robot on all representative pipe diameters and verify that continuous wheel engagement is maintained throughout motion.</li> <li>5. Repeat a 1.0 m travel test at least five times and verify that the final stopping error in each trial is within <math>\pm 20</math> mm.</li> </ol>

Table 1: Requirements and verification for the magnetic adhesion and locomotion module.

### 2.3.2 Rust-Removal End-Effector Module

The rust-removal head 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 adjust the grinding head position in the normal direction. The load cell measures contact force between the abrasive tool and the pipe surface. The spring provides compliance to reduce force fluctuation caused by vibration, weld seams, and surface irregularities. The DC motor, ESC, and gear reducer drive the grinding disc. This subsystem is the primary processing module of the robot because it must generate sufficient abrasive action to remove rust while also maintaining stable and controllable contact with a curved surface.

Requirements	Verification
<ol style="list-style-type: none"> <li>1. The end-effector shall maintain tool speed within <math>\pm 10\%</math> of the commanded setpoint under nominal contact load.</li> <li>2. The subsystem shall clean the processed region to a visual cleanliness grade consistent with ISO 8501-1 St 3 or SSPC-SP 11.</li> <li>3. The subsystem shall support controlled comparison of at least two abrasive tool materials under identical operating conditions.</li> <li>4. The tool mount and rotary drive shall remain mechanically stable during nominal and maximum intended operating speeds.</li> <li>5. The end-effector shall complete a continuous cleaning path of at least 300 mm without stalling or losing effective contact.</li> </ol>	<ol style="list-style-type: none"> <li>1. Measure the tool speed under nominal load and verify that the steady-state speed remains within <math>\pm 10\%</math> of the command.</li> <li>2. Perform a controlled cleaning trial on a rusted coupon or pipe section and verify from inspection images that the cleaned region meets the selected surface standard.</li> <li>3. Repeat identical cleaning trials with at least two abrasive tools and verify that tool performance can be compared under fixed speed, force, and travel conditions.</li> <li>4. Run the end-effector at nominal and maximum speed and verify that no visible runout, loosening, or abnormal vibration prevents operation.</li> <li>5. Command a cleaning pass of at least 300 mm and verify that the subsystem completes the pass without stalling or contact loss.</li> </ol>

Table 2: Requirements and verification for the rust-removal end-effector module.

### 2.3.3 Normal-Force Sensing and Compliance Module

The normal-force regulation subsystem consists of the lead screw actuator, load cell, spring element, and associated support structure. Its purpose is to regulate the contact condition between the grinding disc and the pipe surface. The actuator provides controlled displacement, the load cell provides force feedback, and the spring introduces compliance to reduce the effect of local geometric disturbance and vibration. This design is justified because rust-removal performance depends strongly on maintaining a usable contact force range.

Requirements	Verification
<ol style="list-style-type: none"> <li>1. The subsystem shall regulate tool-to-surface contact force to within <math>\pm 5</math> N of the target setpoint during nominal cleaning.</li> <li>2. The subsystem shall maintain controllable contact across representative curvature changes and weld-like surface irregularities.</li> <li>3. The sensing path shall provide repeatable force measurements suitable for closed-loop control.</li> <li>4. The compliance mechanism shall prevent the measured contact force from exceeding the 120 N overload threshold during nominal operation.</li> <li>5. The actuator shall provide sufficient normal-direction travel for contact engagement, maintenance, and release.</li> </ol>	<ol style="list-style-type: none"> <li>1. Record the load-cell output during nominal cleaning and verify that the measured force remains within <math>\pm 5</math> N of the setpoint.</li> <li>2. Traverse representative curved and irregular pipe sections and verify that the tool remains in controlled contact without shutdown.</li> <li>3. Apply repeated known loads to the sensor and verify that the measured output is repeatable across trials.</li> <li>4. Record force data during operation over irregularities and verify that transient force spikes stay below 120 N.</li> <li>5. Measure the available actuator travel and verify that the subsystem can engage, maintain, and release contact over the intended geometry range.</li> </ol>

Table 3: Requirements and verification for the normal-force sensing and compliance module.

### 2.3.4 Power Module

The power subsystem supplies high-power drive energy for the rust-removal motors and regulated low-voltage power for sensing, control, and logic electronics. A separate regulated rail is used for controllers and sensors to isolate them from motor noise and transient current draw.

Requirements	Verification
<ol style="list-style-type: none"> <li>1. The power subsystem shall provide all required regulated supply rails for the motors, sensors, controller, and end-effector.</li> <li>2. Each regulated output shall remain within <math>\pm 5\%</math> of its nominal voltage under expected load conditions.</li> <li>3. The subsystem shall support simultaneous operation of all major subsystems without brownout or power interruption.</li> <li>4. The subsystem shall include fault protection sufficient to limit damage risk during overload or wiring faults.</li> <li>5. The subsystem shall provide an accessible power shutoff for safe testing.</li> </ol>	<ol style="list-style-type: none"> <li>1. Measure each output rail during powered operation and verify that all required subsystems receive the intended supply.</li> <li>2. Measure each regulated output under light, nominal, and worst-case load and verify that the voltage stays within <math>\pm 5\%</math> of nominal.</li> <li>3. Operate the locomotion, sensing, control, and end-effector subsystems simultaneously and verify that no unintended shutdown occurs.</li> <li>4. Perform a controlled protection test and verify that the fault-limiting mechanism activates as intended without unsafe damage.</li> <li>5. Trigger the power shutoff during a powered bench test and verify that power is removed as intended.</li> </ol>

Table 4: Requirements and verification for the power module.

### 2.3.5 Control and Safety Module

The controller coordinates locomotion and rust-removal operation simultaneously during pipe-surface cleaning. It reads force measurements, supervises actuator commands, records test parameters, and executes safety logic. The control subsystem is essential because the project is both a mobility platform and an experimental rust-removal platform.

Requirements	Verification
<ol style="list-style-type: none"> <li>1. The control module shall acquire essential sensor signals and generate actuator commands during integrated operation.</li> <li>2. The control module shall trigger emergency shutdown within 0.5 s when the measured contact force exceeds 120 N.</li> <li>3. The control module shall transition the system to a safe state within 0.5 s after sudden adhesion loss or equivalent instability is detected.</li> <li>4. The controller shall maintain stable closed-loop force regulation during nominal operation.</li> <li>5. The subsystem shall support repeatable start, stop, and emergency-stop behavior.</li> </ol>	<ol style="list-style-type: none"> <li>1. Run the sensing and actuation loop during an integrated test and verify that valid sensor inputs and actuator outputs are maintained.</li> <li>2. Apply a controlled overload above 120 N and verify that shutdown is commanded within 0.5 s.</li> <li>3. Simulate an adhesion-loss event and verify that the system enters the defined safe state within 0.5 s.</li> <li>4. Record force and actuator response during nominal operation and verify that no sustained oscillation or runaway behavior occurs.</li> <li>5. Execute repeated start, stop, and emergency-stop commands and verify that the system responds correctly in every trial.</li> </ol>

Table 5: Requirements and verification for the control and safety module.

## 3 Calculations and Tolerance Analysis

### 3.1 Critical Function and Nominal Force Balance

The most critical mechanical risk in this project is loss of traction during vertical climbing while the rust-removal tool is engaged. In this operating condition, the robot must not only support its own weight, but also resist the tangential reaction force generated by the abrasive tool. Therefore, the critical subsystem function considered in this analysis is no-slip climbing under simultaneous gravity and grinding load.

Let the robot mass be  $m$ , gravitational acceleration be  $g$ , the tangential grinding reaction force be  $F_{\text{grind}}$ , the total available magnetic adhesion force be  $F_{\text{adh}}$ , and the effective wheel–pipe friction coefficient be  $\mu$ . The total required tangential holding force is

$$F_{\text{req}} = mg + F_{\text{grind}}. \quad (1)$$

Using the current design target of  $m = 15$  kg and a worst-case grinding reaction of  $F_{\text{grind}} = 160$  N,

$$F_{\text{req}} = 15 \times 9.81 + 160 \approx 307 \text{ N}. \quad (2)$$

The maximum available friction-limited traction force is

$$F_{\text{fric,max}} = \mu F_{\text{adh}}. \quad (3)$$

To avoid slip, the available traction must satisfy

$$\mu F_{\text{adh}} \geq F_{\text{req}}. \quad (4)$$

Assuming the nominal total magnetic adhesion force is

$$F_{\text{adh}} = 392 \text{ N}, \quad (5)$$

the minimum required effective friction coefficient is

$$\mu_{\text{req}} = \frac{F_{\text{req}}}{F_{\text{adh}}} = \frac{307}{392} \approx 0.783. \quad (6)$$

This result shows that, under the nominal design assumptions, the wheel–pipe interface must provide an effective friction coefficient of at least approximately 0.78 to prevent traction slip during vertical cleaning.

### 3.2 Traction Margin and Safety Factor

To quantify how robust the design is beyond the no-slip threshold, two additional metrics are defined: traction margin and traction safety factor. The traction margin is

$$M = \mu F_{\text{adh}} - F_{\text{req}}, \quad (7)$$

and the traction safety factor is

$$SF = \frac{\mu F_{\text{adh}}}{F_{\text{req}}}. \quad (8)$$

The no-slip requirement is satisfied when

$$M \geq 0 \quad (9)$$

or equivalently when

$$SF \geq 1. \quad (10)$$

For example, if the effective friction coefficient is  $\mu = 0.80$ , then

$$F_{\text{fric,max}} = 0.80 \times 392 = 313.6 \text{ N}, \quad (11)$$

so the corresponding traction margin is

$$M = 313.6 - 307 = 6.6 \text{ N}, \quad (12)$$

and the safety factor is

$$SF = \frac{313.6}{307} \approx 1.02. \quad (13)$$

Although this nominal case satisfies the no-slip condition, the resulting margin is very small, which indicates that the design is sensitive to changes in adhesion force, surface friction, and tool reaction load.

### 3.3 Sensitivity to Adhesion Loss

In practice, the nominal magnetic adhesion force may not be fully available because of air gap, wheel misalignment, pipe curvature variation, weld seams, rust thickness, or surface coating. To account for these non-ideal effects, an adhesion retention factor  $\eta$  is introduced such that

$$F_{\text{adh,eff}} = \eta F_{\text{adh,nom}}, \quad (14)$$

where  $0 < \eta \leq 1$  and  $F_{\text{adh,nom}} = 392 \text{ N}$ .

Under this model, the no-slip condition becomes

$$\mu \eta F_{\text{adh,nom}} \geq F_{\text{req}}, \quad (15)$$

and the required friction coefficient becomes

$$\mu_{\text{req}} = \frac{F_{\text{req}}}{\eta F_{\text{adh,nom}}}. \quad (16)$$

Using  $F_{\text{req}} = 307 \text{ N}$  and  $F_{\text{adh,nom}} = 392 \text{ N}$ , the required friction coefficient under several adhesion-loss cases is:

$$\eta = 1.0 \Rightarrow \mu_{\text{req}} = \frac{307}{392} \approx 0.783, \quad (17)$$

$$\eta = 0.9 \Rightarrow \mu_{\text{req}} = \frac{307}{0.9 \times 392} \approx 0.870, \quad (18)$$

$$\eta = 0.8 \Rightarrow \mu_{\text{req}} = \frac{307}{0.8 \times 392} \approx 0.979. \quad (19)$$

These results show that even moderate adhesion degradation can significantly increase the required friction coefficient. In particular, a 20% reduction in available adhesion raises the required effective friction coefficient to nearly 1.0, which may be difficult to guarantee on a rusty or irregular steel surface.

Adhesion retention factor $\eta$	Effective adhesion force (N)	Required friction coefficient $\mu_{\text{req}}$
1.0	392.0	0.783
0.9	352.8	0.870
0.8	313.6	0.979

Table 6: Sensitivity of the no-slip condition to adhesion loss.

### 3.4 Sensitivity to Grinding Reaction Load

The tangential reaction force from the rust-removal tool may also vary during operation because of tool wear, local surface roughness, aggressive engagement, or changing contact conditions. Since

$$F_{\text{req}} = mg + F_{\text{grind}}, \quad (20)$$

an increase in grinding load directly reduces the available traction margin.

Assuming  $\mu = 0.85$  and  $F_{\text{adh}} = 392$  N, the maximum available traction is

$$F_{\text{fric,max}} = 0.85 \times 392 = 333.2 \text{ N}. \quad (21)$$

Then the safety factor under several grinding loads becomes:

$$F_{\text{grind}} = 140 \text{ N} \Rightarrow F_{\text{req}} = 147 + 140 = 287 \text{ N}, \quad SF = \frac{333.2}{287} \approx 1.16, \quad (22)$$

$$F_{\text{grind}} = 160 \text{ N} \Rightarrow F_{\text{req}} = 147 + 160 = 307 \text{ N}, \quad SF = \frac{333.2}{307} \approx 1.09, \quad (23)$$

$$F_{\text{grind}} = 180 \text{ N} \Rightarrow F_{\text{req}} = 147 + 180 = 327 \text{ N}, \quad SF = \frac{333.2}{327} \approx 1.02. \quad (24)$$

This result indicates that the system is also sensitive to increases in tool reaction force, especially when the design is already operating near the minimum no-slip threshold.

Grinding reaction force $F_{\text{grind}}$ (N)	Required tangential force $F_{\text{req}}$ (N)	Safety factor $SF$
140	287	1.16
160	307	1.09
180	327	1.02

Table 7: Sensitivity of traction safety factor to grinding reaction load for  $\mu = 0.85$  and  $F_{\text{adh}} = 392$  N.

### 3.5 Design Implications

The above analysis shows that the no-slip climbing requirement is only marginally satisfied under nominal assumptions, and that the traction margin decreases quickly when adhesion is reduced or grinding load increases. Therefore, robust operation requires more than simply meeting the nominal adhesion target. The mechanical design should minimize air gap between the magnetic wheels and the steel surface, maintain wheel alignment over curved or irregular pipe regions, and use tread materials that maximize effective friction on rusty steel. In addition, the rust-removal process should avoid unnecessarily large tangential tool loads during vertical climbing, and the control strategy should detect overload or traction degradation early enough to trigger safe intervention.

Overall, this tolerance analysis shows that traction margin is a critical subsystem constraint for the robot and justifies conservative design choices in the magnetic wheel assembly, mechanical structure, and control limits.

## 4 Cost Analysis

Table 8 shows the preliminary cost estimate for the prototype. These values should be updated after final component procurement.

Table 8: Preliminary prototype cost estimate.

Item	Estimated Cost	Notes
Magnetic wheel assemblies and drive motors	\$400	Four wheel modules
Rust-removal motors, ESCs, and grinding heads	\$200	Two end-effectors
Stepper motor, lead screw, and force-sensing components	\$40	Force-control subsystem
Controller, wiring, low-voltage electronics, and sensors	\$80	MCU, ADC, protections
Battery or power-supply components	\$10	24 V bus and regulated rails
Carbon-fiber or aluminum structural parts and machining	\$200	Custom fabricated parts
Fasteners, connectors, and assembly materials	\$20	Miscellaneous hardware
<b>Total Parts Cost</b>	<b>\$960</b>	
Estimated labor (course prototype)	\$240	

## 5 Schedule

Table 9 show the proposed weekly project schedule.

Table 9: Weekly schedule.

Week	Xuhao Yang	Huanyu Feng	Xiaocheng Zhang	Junxiang Qin
1	Finalize chassis plates and release manufacturing drawings.	Finalize magnetic wheel geometry and magnet mounting layout.	Finalize controller architecture and define the integrated I/O map.	Finish HX711 interface, sensor readout pipeline, and motor-control support.
2	Assemble chassis frame and mount wheel and end-effector interfaces.	Bench-test wheel adhesion on steel pipe sections and record force data.	Implement the initial closed-loop force/PID framework.	Integrate sensor acquisition with the actuator test bench.
3	Debug mechanical fit, alignment, and mounting rigidity.	Optimize the magnet-pipe gap and validate continuous wheel contact.	Implement four-wheel coordinated locomotion control.	Calibrate the force sensor and tune pressure-loop filtering.
4	Complete full prototype mechanical assembly.	Validate adhesion robustness over target pipe diameters and irregularities.	Complete subsystem integration and debug controller-actuator communication.	Validate load-cell repeatability and refine motor behavior under load.
5	Prepare the mock-demo mechanical setup and backup hardware.	Verify climbing stability and adhesion during mock-demo scenarios.	Lead integrated mock-demo testing and fix major software issues.	Support end-effector sensing tests and collect mock-demo data.
6	Revise the structure and mounting based on mock-demo feedback.	Finalize the wheel and magnet configuration for the final prototype.	Add video transmission and improve integrated control robustness.	Implement overload protection logic and shutdown handling.
7	Perform final mechanical validation and assembly lock-down.	Complete final adhesion and climbing verification tests.	Run the final integrated system test and demo sequence rehearsal.	Validate sensing response, actuator safety, and cleaning-head performance.
8	Prepare mechanical figures, final poster/demo hardware, and presentation section.	Prepare adhesion and locomotion results, figures, and presentation section. 20	Prepare control architecture/results slides and the live demo script.	Prepare sensing/safety results, final document edits, and presentation section.

## 6 Ethics and Safety

### 6.1 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 [8], [9]. 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 design document 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 [8], [9].

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 [8], [9].

### 6.2 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 [10]. 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 [11].

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 [12]. 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 [13], [14].

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 [15]. 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], [10].

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 [8], [13].

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