Inspection Robot for Confined Spaces

Requirements Justification

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Document Purpose

This document is complementary to the specification document, providing detailed justifications for the selection of the various components used in the Inspection Robot for Confined Spaces. While the specification document outlines the technical requirements and design parameters, this document focuses on the analytical and engineering rationale behind the chosen components, ensuring that the design meets the operational requirements effectively and efficiently.

Contents

Introduction

The proposed tracked robotic system is designed for navigation in confined and challenging environments, integrating Lidar, cameras, and multiple sensors for autonomous operation. Given its mission-critical requirements, the different parts have been carefully selected to balance mobility, stability, and payload capacity. This report provides a formal justification for maintaining these dimensions while optimizing weight, power consumption, and maneuverability.

1 Justification of Dimensions

The dimensions of **40x50x30 cm** were chosen to ensure **stability, traction, and maneuverability** in confined and uneven environments. Key considerations include:

- **Height (30 cm):** Ensures operation within confined spaces (maximum height: **60 cm**), providing clearance for sensors and mechanical extensions while maintaining flexibility.
- **Low Center of Gravity:** The **30 cm height** reduces tipping risks on slopes, rough terrain, or obstacles, enhancing stability during dynamic movements.
- **Footprint (40x50 cm):** A larger contact surface improves **traction** by distributing weight evenly across the tracks, preventing sinking in soft or uneven surfaces.
- **Track Proportion:** A balanced **50 cm length** and **40 cm width** optimize weight distribution, maximizing grip while minimizing turning resistance for better maneuverability.
- **Load Distribution:** The wider frame reduces pressure on individual track sections, minimizing wear and improving obstacle handling, especially with modular 3D-printed tracks.

These dimensions balance **stability, traction, and maneuverability**, ensuring effective operation in confined spaces without compromising structural integrity or mobility.

2 Justification of the Simplified Track System and Worm Drive Mechanism

The choice of the propulsion system is a critical factor in ensuring the robot's effectiveness in confined environments. Instead of a traditional **tank-like track system with multiple road wheels**, a **simplified track system with two primary drive wheels** was selected. Additionally, a **worm drive mechanism** was implemented to optimize torque transmission. The rationale behind these choices is outlined below.

2.1 Simplified Track System

The simplified track system, driven by two large wheels, offers several advantages over traditional tank-like mechanisms:

- **Reduced Complexity and Friction:** Eliminates multiple contact points, reducing mechanical complexity and friction losses for improved energy efficiency.
- **Compatibility with Modular 3D-Printed Tracks:** Ensures uniform track engagement and reduces mechanical stress on 3D-printed components, avoiding misalignment issues.
- **Efficient Torque Transfer:** Directs motor torque through two main drive wheels, ensuring effective power delivery.
- **Enhanced Maneuverability:** Reduces unnecessary contact points, enabling smoother turns and better adaptability in tight spaces.

2.2 Worm Drive Mechanism

The worm drive mechanism provides critical benefits for the robot's operation:

- **High Torque and Low-Speed Output:** Offers significant gear reduction, increasing torque while reducing speed—ideal for controlled movement.
- **Self-Locking Capability:** Prevents back-driving, enhancing stability on inclined surfaces when motors are inactive.
- **Compact and Robust Design:** Simplifies the drivetrain by eliminating the need for multi-stage gear reductions, making it suitable for confined spaces.

3 Fabrication Method Selection

3.1 Sheet Metal Design for Chassis

The chassis is fabricated using **sheet metal design** due to its superior strength-to-weight ratio, cost-effectiveness, and ease of forming. This method is particularly well-suited for creating large, flat components like the chassis, ensuring precise and durable structures. Sheet metal fabrication allows for efficient production through processes such as **metal cold forming** and **metal press forming**, which are ideal for achieving the required structural integrity and lightweight design necessary for confined-space navigation. Compared to alternatives like casting or 3D printing, sheet metal offers better scalability and faster production for large parts.

3.2 3D Printing for Wheels and Tracks

For the wheels and tracks, **3D printing** is employed to leverage its ability to produce complex geometries and lightweight structures. This method is particularly advantageous for creating intricate designs that require flexibility and durability, such as modular tracks and custom wheel shapes. Unlike traditional manufacturing, 3D printing allows for rapid prototyping and customization, making it ideal for small, complex components. The process also reduces material waste and enables the use of high-strength polymers or composites, which are essential for optimizing the performance of the wheels and tracks in confined environments.

4 Material Selection Justification

By selecting a simplified track system and incorporating a worm drive, the design ensures an optimal balance between **mechanical efficiency, stability, and adaptability**, making it well-suited for confined-space navigation.

4.1 Minimum Required Yield Strength Calculation

To ensure the base plate can support a **20 kg** load over the **40 cm × 50 cm** span with minimal deformation, we determine the minimum required **yield strength** (σ_y) based on bending stress. The maximum bending stress in a uniformly loaded rectangular plate can be approximated as:

$$\sigma = \frac{M}{S} \tag{1}$$

where:

- $M = \alpha PL$ is the maximum bending moment,
- $S = \frac{bh^2}{6}$ is the section modulus of the plate,
- $P = mg = (20 \times 9.81)$ N is the total applied force,
- $L = 0.50$ m is the longest span of the plate,
- $b = 0.40$ m is the plate width,
- $h = 0.005$ m is the plate thickness.

Assuming a worst-case scenario with $\alpha = 0.125$ (for a uniformly distributed load on a simply supported beam), the bending moment is:

$$M = 0.125 \times P \times L \tag{2}$$

Substituting $P = 196.2$ N:

$$M = 0.125 \times 196.2 \times 0.50 = 12.26 \text{ Nm} \tag{3}$$

Now, computing the section modulus:

$$S = \frac{bh^2}{6} = \frac{0.40 \times (0.005)^2}{6} = 1.67 \times 10^{-6} \text{ m}^3 \tag{4}$$

Thus, the bending stress is:

$$\sigma = \frac{12.26}{1.67 \times 10^{-6}} = 73.5 \text{ MPa} \tag{5}$$

4.2 Material Selection

To select a material that meets the required strength, we analyzed the **CES selection graph**, where the **x-axis represents the Price × Density** product. This metric helps balance weight reduction and cost effectiveness while ensuring structural integrity.

From the CES graph (Figure 1), the selected Aluminum 2024-T36 offers the following:

- A yield strength of approximately **300-500 MPa**, which exceeds the required **73 MPa**, ensuring a safety factor of 4-7.
- A relatively **low Price × Density** product compared to other high-strength alloys such as **tungsten or rhodium**, making it an economical yet strong choice.
- A high **stiffness-weight ratio**, which minimizes deflection and enhances stability, ensuring reliable performance in confined space environments.
- **Excellent suitability for sheet metal forming**, including metal cold forming and metal press forming, as indicated in the selection report. This makes it an ideal choice for applications requiring precise and durable sheet metal components.

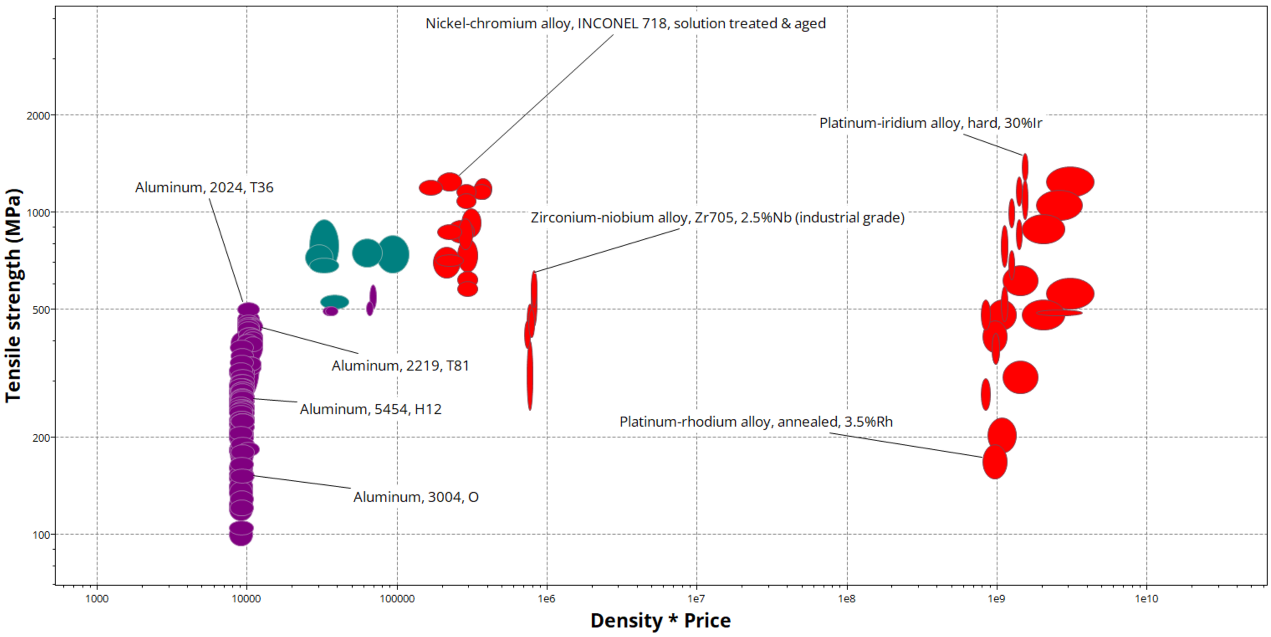

Figure 1: CES selection graph.

By selecting Aluminum 2024-T36, the robot achieves an optimal balance of **stiffness, durability, and lightweight design**, ensuring reliable operation in confined space environments. The significant safety margin provided by the material ensures robust performance even under unexpected loads or dynamic conditions.

4.3 Maximum Deformation Calculation

To calculate the maximum deformation of the plate, we use the formula for the deflection of a simply supported rectangular plate under a uniformly distributed load:

$$\delta = \frac{5qL^4}{384EI} \tag{6}$$

where:

- $q = \frac{P}{b \times L} = \frac{196.2}{0.40 \times 0.50} = 981$ N/m is the load per unit length,
- $L = 0.50$ m is the longest span of the plate,
- $E = 73.1$ GPa $= 73.1 \times 10^9$ Pa is the Young's modulus of Aluminum 2024-T36,
- $I = \frac{bh^3}{12} = \frac{0.40 \times (0.005)^3}{12} = 4.17 \times 10^{-9}$ m^4 is the moment of inertia of the plate.

Substituting the values:

$$\delta = \frac{5 \times 981 \times (0.50)^4}{384 \times 73.1 \times 10^9 \times 4.17 \times 10^{-9}} \tag{7}$$

$$\delta = \frac{5 \times 981 \times 0.0625}{384 \times 73.1 \times 4.17} \tag{8}$$

$$\delta = \frac{306.5625}{117,073.92} \approx 0.00262 \text{ m} = 2.62 \text{ mm} \tag{9}$$

The maximum deformation of the plate is approximately **2.62 mm**, which is within acceptable limits for most engineering applications, ensuring the plate remains stable and functional under the applied load.

5 Motor Selection Justification

To ensure the robot can operate effectively in confined spaces, we calculated the required torque and justified the selection of the **63ZYT04A-IP67** DC motor with a **1:100 worm gear reduction**. The calculations include gravitational, acceleration, and frictional forces, as well as a safety factor to account for uncertainties.

5.1 Force Calculation

The total force required to move the robot includes the following components:

- **Gravitational Force** (F_g): The force required to overcome gravity on an incline.
- **Acceleration Force** (F_a): The force required to achieve the desired acceleration.
- **Frictional Force** (F_f): The force required to overcome static and kinetic friction.

The total force is given by:

$$F_{\text{total}} = F_g + F_a + F_f$$

5.2 Component Forces

1. **Gravitational Force**:

$$F_g = mg\sin(\theta)$$

where:

- $m = 20\,\text{kg}$ (mass of the robot),
- $g = 9.81\,\text{m/s}^2$ (acceleration due to gravity),
- $\theta = 45^\circ$ (maximum incline angle for safety margin).

Substituting the values:

$$F_g = 20 \times 9.81 \times \sin(45^\circ) = 138.7\,\text{N}$$

2. **Acceleration Force**:

$$F_a = ma$$

where:

- $a = 0.5\,\text{m/s}^2$ (desired acceleration).

Substituting the values:

$$F_a = 20 \times 0.5 = 10\,\text{N}$$

3. **Frictional Force**:

$$F_f = \mu mg\cos(\theta)$$

where:

- $\mu = 0.5$ (coefficient of friction, static and kinetic).

Substituting the values:

$$F_f = 0.5 \times 20 \times 9.81 \times \cos(45^\circ) = 69.3\,\text{N}$$

5.3 Total Force with Safety Factor

The total force required is:

$$F_{\text{total}} = F_g + F_a + F_f = 138.7 + 10 + 69.3 = 218\,\text{N}$$

To account for uncertainties and dynamic loads, a safety factor of **1.5** is applied:

$$F_{\text{total, safety}} = 218 \times 1.5 = 327\,\text{N}$$

5.4 Torque Calculation

The torque required at the wheels is:

$$T = F_{\text{total, safety}} \times r$$

where:

- $r = 0.15\,\text{m}$ (wheel radius).

Substituting the values:

$$T = 327 \times 0.15 = 49.05\,\text{Nm}$$

For two motors, the torque per motor is:

$$T_{\text{motor}} = \frac{49.05}{2} = 24.53\,\text{Nm per motor}$$

5.5 Motor Justification

The selected **63ZYT04A-IP67** DC motor has the following specifications:

- Rated torque: $0.5\,\text{Nm}$,
- Rated speed: $3000\,\text{RPM}$,
- Gear reduction: $1:100$.

The motor's output torque after gear reduction is:

$$T_{\text{motor, out}} = T_{\text{motor}} \times \text{Gear Ratio} = 0.5 \times 100 = 50\,\text{Nm}$$

The motor provides **sufficient torque** ($50\,\text{Nm} > 24.53\,\text{Nm}$) to meet the requirements, even with the safety factor.

5.6 Linear Speed Calculation

The linear speed of the robot is calculated as:

$$v = \omega \times r$$

where:

- ω is the angular speed of the wheel in rad/s,
- $r = 0.15\,\text{m}$ is the wheel radius.

The motor's rated speed is $3000\,\text{RPM}$. After a $1:100$ gear reduction:

$$\omega_{\text{wheel}} = \frac{3000}{100} = 30\,\text{RPM}$$

Converting RPM to rad/s:

$$\omega_{\text{wheel}} = 30 \times \frac{2\pi}{60} = 3.14\,\text{rad/s}$$

The linear speed is:

$$v = 3.14 \times 0.15 = 0.471\,\text{m/s} = 47.1\,\text{cm/s}$$

The **63ZYT04A-IP67** DC motor with a **1:100 worm gear reduction** is well-suited for the robot, as it provides sufficient torque ($50\,\text{Nm}$) to meet the requirements ($24.53\,\text{Nm}$) and achieves a linear speed of **47.1 cm/s**. The calculations include a safety factor of **1.5** to account for uncertainties and dynamic loads, ensuring reliable operation in confined spaces.

6 Battery Selection Justification

The selection of the battery is a critical decision that directly impacts the robot's performance and operational duration. The chosen battery specifications are as follows:

- **Voltage**: 24V
- **Capacity**: 30Ah
- **Total Energy**: 720Wh

Rationale:

1. **Voltage Compatibility**: The 24V battery aligns with the voltage requirements of the DC motors and other high-power components, ensuring efficient power delivery without the need for additional voltage step-up mechanisms.
2. **Energy Capacity**: With a total energy capacity of 720Wh, the battery provides sufficient power to support the robot's operations for the required duration.
3. **Operational Duration**: Based on the estimated total power consumption of 370W (320W for motors and 50W for electronics), the battery can support approximately 1.95 hours of continuous operation under full load. This meets our defined requirement of a 2-hour operating time, considering potential variations in load and usage patterns.

7 Power Consumption Analysis

The power consumption of the robot is divided into two main categories: the **DC motors** and the **sensors and electronics**. The total power consumption is designed to be **370W**, with a safe margin included in the estimates. A detailed breakdown is provided below.

- **DC Motors**:
  - Power: 160W each (320W total for two motors)
- **Sensors and Electronics**:
  - **Jetson Orin**: 15W (for processing)
  - **Nucleo STM32 Development Board**: 3W (for low-level control and interfacing)
  - **LiDAR (Slamtec RPLIDAR)**: 8W (for environment mapping and navigation)
  - **Stereo Camera (Intel Depth Camera D415)**: 8W (for depth perception and object detection)
  - **Temperature and Humidity Sensor (SHT31)**: 0.2W (for environmental monitoring)
  - **Gas Sensors (MQ-136 ZYMQ-135)**: 3W (for gas detection)
  - **Encoders**: 1.5W (for tracking wheel rotation and speed)
  - **RF Receiver (RadioMaster ELRS)**: 1.5W (for wireless communication)

  Total Sensors and Electronics: 50W

Calculations:

1. **Total Energy Available**:

$$\text{Total Energy} = \text{Voltage} \times \text{Capacity} = 24V \times 30Ah = 720Wh$$

2. **Total Power Consumption**:

$$\text{Total Power Consumption} = \text{Motor Power} + \text{Electronics Power} = 320W + 50W = 370W$$

3. **Estimated Runtime**:

$$\text{Runtime} = \frac{\text{Total Energy}}{\text{Total Power Consumption}} = \frac{720Wh}{370W} \approx 1.95 \text{ hours}$$

Considerations:

- **Variable Load**: The actual runtime may extend beyond 2 hours if the motors are not continuously operating at full load.
- **Peak Power**: The system is designed to handle peak power demands, such as during motor startups or direction changes, without compromising performance.

The power management system of the Inspection Robot for Confined Spaces is logically designed to meet the defined energy requirements. The selection of a 24V, 30Ah battery ensures that the robot can operate for at least 2 hours under full load, aligning with our operational goals. The calculations demonstrate that the system respects our requirements and provides a solid foundation for the robot's successful deployment in confined spaces.

Summary

In conclusion, the selected components—including the 63ZYT04A-IP67 motors, 24V 30Ah battery, and Aluminum 2024-T36 material—have been carefully justified based on their ability to meet the robot's operational requirements in confined spaces. The proposed equipment ensures a balance of performance, durability, and cost-effectiveness, making it essential for the successful deployment of the inspection robot. We recommend proceeding with the purchase of these components to meet project timelines and objectives.