Heterogeneous Robot Teams for Search and Rescue

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Abstract—**To explore these hazardous and unpredictable environment, we are developing a team of robots with complementary capabilities: Rescue Rollers (centimeter-scale spherical robots) and Vine Robots (large inflatable robots). Vine robots extend and navigate through complex environments by inflating their large scale flexible bodies, whereas Rescue Rollers use their compact profile to move through or past obstacles which makes the combination ideal for tasks such as search and rescue and minimally invasive procedures. This paper focuses on determining which wheel designs generate the highest force across various terrains and understanding how different geometries perform under varying external conditions. Additionally, we develop a mechanism to allow the robot to transform from a spherical shape to one capable of maneuvering through challenging landscapes. This mechanism incorporates springs/magnets, linkages, and the conversion of kinetic and potential energy produced by the joint pieces.**

Index Terms—**compact, linkages, expandable, mechanism, navigate**

I. INTRODUCTION

A. Motivation

In the aftermath of natural disasters, the ability to investigate and navigate rough terrain is critical for effective rescue operations. However, these environments pose significant safety risks to humans due to their inherent instability and hazardous conditions. To mitigate these risks and enhance the capabilities of rescue missions, we are developing robotic systems known as Rescue Rollers in collaboration with Vine robot to operate in such challenging environments.

Our project focuses on the creation of centimeter-scale spherical robots, known as Rescue Rollers. These robots are designed to navigate challenging terrain where traditional rescue methods are impractical or impossible. In some rescue missions, the environment is too confined or dangerous for human intervention. Rescue Rollers, being small and compact, can maneuver past obstacles that humans cannot, making them effective in such rescue operations.

Vine robots excel in navigating confined spaces and avoiding obstacles due to their flexible, growth-based movement, making them ideal for exploring tight and complex environments [1]. Their adaptability allows them to get damaged and still continue with the rescue mission, and they are energy efficient. However, Vine robots have limited steering which is not in this scenario. This is where the Rescue Roller complements the Vine robot as it can explore in all directions and climb obstacles. It can even help steer the Vine bot as well.

Rescue Rollers are low-cost and perform well when deployed in large numbers. Many of them can be used simultaneously during search and rescue missions. They could be equipped with sensors, enhancing their versatility for applications such as search and rescue operations for later study. However, their small size limits their push and pulling force, and they face challenges with power consumption. Despite these limitations, Rescue Rollers offer valuable capabilities in scenarios where traditional robots might struggle, particularly in tasks requiring agility and adaptability in confined or difficult environments [2].

Our robots can effectively explore and assess areas that are otherwise inaccessible. The Rescue Rollers push outside the Vine robot for it to buckle and move in a certain direction around obstacles. Also, the Rescue Rollers can roam around the environment independently in areas the Vine bot can't reach. This coordinated approach enhances their ability to navigate and assess challenging terrains effectively.

B. Key Contributions

Our research is driven by several key objectives:

1) **An in-depth analysis of the impact of wheel geometry and scale on robot performance**: This involves investigating how different wheel geometries and scales affect the robots' ability to navigate various terrains, such as loose soil, rocky surfaces, and debris-strewn areas.
2) **Evaluation of force production capabilities across diverse terrains**: We measure the force generated by each wheel during pushing and pulling actions to ensure effective movement and manipulation of the environment. The spherical shape is limited in its capabilities to climb obstacles and produce force, therefore, we are testing wheels with different geometries. The goal is to find the most effective wheel geometry across various terrains.
3) **Design and development of transformative mechanisms for enhanced navigation**: We design a mechanism that allows the Rescue Roller to transform from a spherical shape to a more adaptable form, improving its ability to navigate complex and challenging landscapes.
4) **Creation of a flexible PCB for efficient wireless charging**: We develop a flexible printed circuit board (PCB) that facilitates wireless charging, ensuring efficient and reliable energy transfer for the robots' sustained operation during extended rescue missions.

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II. DESIGN AND PROTOTYPING

A. *Design Evolution*

We developed a mechanism to allow the robot to transform from a spherical shape to one capable of maneuvering through challenging landscapes. The system is connected to the drive motor shaft, and when the motor rotates, it causes the shell of the spherical bot to unlock and pop open. The original mechanism is composed of a spring driven four-bar. Its hardware configuration consists of several 3D-printed components, including wheels, linkages, a shaft bracket piece, and a spring. The limitation of this design led to the spring bunching up which could lead to it getting stuck.

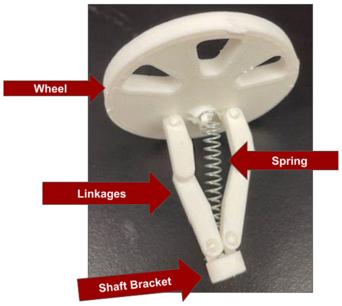

Fig. 1. Physical Spring Mechanism

To address the issue of the spring getting bunched, we replaced the spring with cube-shaped magnets, which produced the same effect without the risk of the spring becoming tangled. We positioned the magnets in a way that they would repel each other, allowing the wheels to extend outward. We also re-designed the inside linkages closest to the wheel with a curved profile to position itself better inside the spherical wheels.

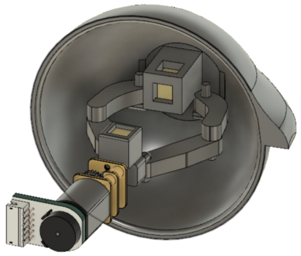

Fig. 2. Magnetic Mechanism 3D Design

III. WHEEL FORCE TESTING

We also evaluate the performance of various wheel designs and geometries to identify which configurations generate the highest force across different terrains. By identifying the wheel that generates the most force, it will produce a more effective collaboration with the Vine bot. This collaboration consists of the Rescue Roller enhancing the Vine robots maneuverability. Once we determine the optimal wheel design, we can finalize the wheel selection for the robot final design, balancing force generation and other factors.

We conducted a series of tests to understand how different wheel geometries perform under a range of external conditions. The testing process involved several types of surfaces and methods to capture a comprehensive view of each wheel design's capabilities.

A. *Testing Surfaces and Methods*

1) **Terrains Tested:**
   - **Turf:** Representing softer and more flexible terrain, turf is useful for assessing how wheels perform on surfaces that simulate natural grass or unpaved ground.
   - **Rocky Surface:** This surface includes an uneven and rough ground to test wheel performance under irregular conditions.
   - **Acrylic Plate:** A smooth and hard surface that provides insight into how wheels perform under controlled, low-friction conditions.
   - **MDF:** Medium-Density Fiberboard (MDF) offers a consistent and moderately rough surface to test wheel interaction.
   - **MDF with Tape:** This surface features an additional rough tape layer known as Life Grip Tape to simulate high-friction conditions and assess how wheels handle increased resistance.

3illustrates the different test surfaces used:

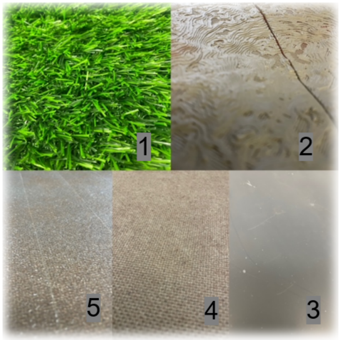

Fig. 3. Terrains: [1] Turf, [2] Rocky Surface, [3] Acrylic, [5] MDF w/ Tape

2) **Testing Procedures:**
   - **Pulling Test:** For the pulling test, we equipped the robot with a hook attached to its tail. This hook was connected to a load cell, which measured the force exerted by the wheels in Newtons. The load cell was interfaced with an Arduino Uno, which was programmed to record the force data.
     The setup involved pulling the robot along each type of terrain to measure how effectively the wheels could generate traction and handle different resistances.
   - **Pushing Test:** In the pushing test, the load cell was mounted directly onto the robot. The robot was then driven into a vertical wall to measure the force exerted during impact. This test assessed the

Fig. 4. Wheel Pull Force Testing

pushing capability of the wheels, including how well they could handle direct force application against a stationary obstacle. The results highlighted which wheel designs could maintain stability and avoid oscillations.

Throughout the tests, we observed variations in performance among different wheel designs. Some wheels exhibited unstable oscillations, particularly when pushing against the wall, while others demonstrated greater stability and consistent force generation across all surfaces.

B. Application of Data

By analyzing the force measurements and performance across various terrains, we can identify the most effective wheel configurations for different conditions. This information will be used in future iterations of the project to finalize the wheel design, ensuring that it produces sufficient force to interact effectively with the inflatable Vine robot and perform optimally in real-world scenarios.

After gathering data from each wheel across different terrains the most effective wheel was the concentric wheels. We took 3 trials for pushing and pulling data, and the concentric wheel produced the highest average force and the most stable force when analyzing the oscillations.

Figures 5 and 6 shows samples of data we collected during testing.

IV. CIRCUITRY

A. Power Distribution

To operate during prolonged periods and cover long distances, the robots require wireless charging to sustain their performance throughout the rescue mission. Wireless charging is necessary for this system as the robots will be roaming around large unknown areas, in which a wire might be too short to charge the robots. As well as the setup is to avoid alignment issues for the robot to plug in. The wireless charging works so long as the coils are relatively close and aligned it will charge which is less of a positioning requirement than wired charging. Also, it ensures the Vine robot maintains its soft, flexible texture necessitates the use of a flexible PCB for transmitting power.

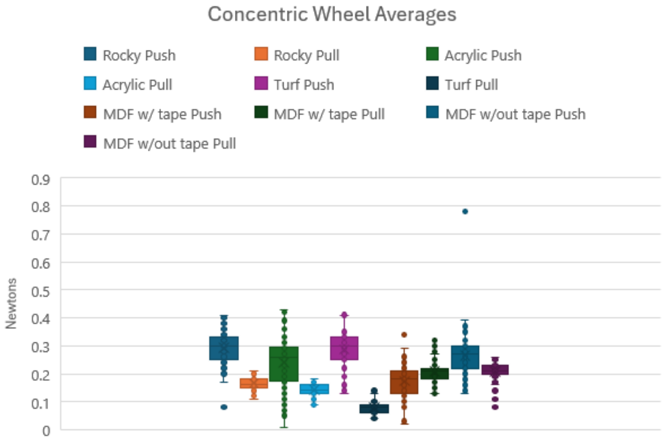

Fig. 5. Concentric Wheel Force Averages

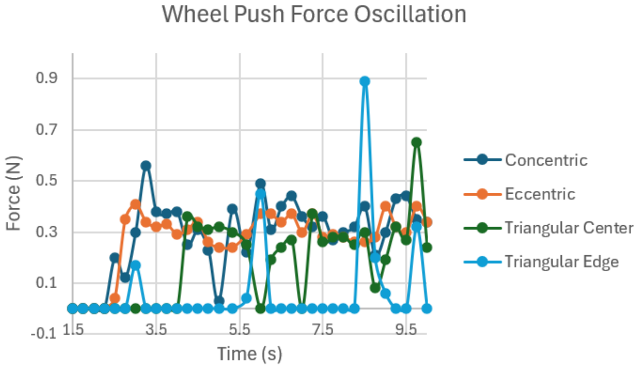

Fig. 6. Wheel Force Oscillation Example

Commercially available wireless chargers often utilise ferrite sheets to enhance the power transfer efficiency. However, ferrite is an inflexible material and would prevent our desired interface with the soft vine robot. We then researched circular coils which generate more uniform and symmetrical magnetic field, which are crucial for efficient energy transfer [3]. The uniform field ensures that the magnetic flux is evenly distributed across the coil, maximizing the efficiency of inductive coupling between the charger and the device. This uniformity is less achievable with square-shaped coils, which do not provide as consistent a magnetic field. Consequently, We design a circular coil on a PCB using EasyEDA, which can be wired to the transmitter and connected to the Vine robot which you can see in Figure 7.

While examining wireless charging transmitters and receivers available online, we ordered and tested several units, measuring the inductance to be a certain value to use later. To design the coil that would be most efficient for this project, we first need to determine the optimal number of turns. Through comparisons with commercially available designs, we settled on a 14-coil configuration and had a value of 40mm for r (radius) to go along with the dimensions of the robot. To reach our desired power distribution target (5V, 1A), we intend to combine multiple layers of the flexible PCB, similar to the several coils utilised in traditional chargers. To determine the number of layers, we measured the inductance of our manufactured coil and set that value equal to L in equation 1 to find the thickness l [4].

$$L \approx \frac{\mu_0 N^2 r^2}{2r + l} \tag{1}$$

By using the measured inductance value of off-the-shelf products, we ensured that our coil design would meet the necessary specifications for efficient wireless charging. The implementation of a circular coil with 14 turns on a flexible PCB enhances the robot's ability to maintain a consistent power supply, thereby extending its operational duration and range during critical rescue missions.

This process involved iterations of design and testing to optimize the coil's performance. Once we found an optimal coil pattern, the next step was to scale down the transmitter to fit to the diameter of the Vine robot. By integrating these features into the robot's design, we aim to improve energy efficiency by transmitting power to the Vine robot. By doing this, it can continue the rescue mission in challenging unknown environments.

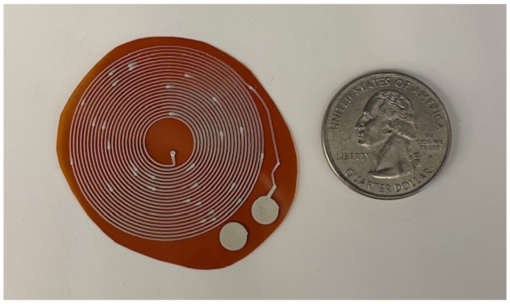

Fig. 7. Flexible PCB Wireless Charger

V. DISCUSSION

A. Future Work

In the ongoing development of our Rescue Roller robots, we have made significant progress in understanding and optimizing various design aspects to enhance their performance in challenging environments. However, there remains considerable work to be done to fully realize the potential of these robots. Our future work will focus on several key areas:

1) **Finalized Wheel Design:** We aim to integrate the most effective wheel designs identified during our research into a final prototype. This process will involve synthesizing the best features from different wheel configurations to create a versatile and robust wheel capable of navigating a wide range of terrains. The finalized design will be tested rigorously across various environments, including loose soil, rocky surfaces, and debris-strewn areas, to ensure its effectiveness and durability. The objective is to develop a wheel system that provides optimal traction, stability, and maneuverability under diverse conditions.
2) **Jumping Tail Mechanism:** To enhance the robot's ability to overcome obstacles and navigate vertical challenges, we will develop and integrate a jumping tail mechanism [5]. This tail will be engineered to provide additional propulsion, allowing the robot to leap over tall obstacles or climb over barriers. The design will focus on ensuring that the tail mechanism is both lightweight and powerful enough to provide the required thrust without compromising the robot's overall balance and stability. Testing will include various jump heights and obstacle types to validate the effectiveness of this feature.
3) **Coupling Mechanism:** An essential aspect of the robot's functionality involves the efficient application of power and electronics. We will design and implement a sophisticated coupling mechanism that facilitates seamless integration of power systems and electronic components within the robot. This mechanism will ensure reliable power distribution and efficient communication between different parts of the robot, including the sensors, actuators, and control systems. Special attention will be given to minimizing energy losses and optimizing power management to extend the robot's operational duration.
4) **Integrating Sensors:** The addition of air quality sensors is a critical enhancement to the robot's capabilities. These sensors will be integrated into the robot's system to provide real-time environmental data, which is crucial for assessing hazardous conditions in disaster-stricken areas. We will explore various sensor types and configurations to ensure accurate and reliable measurements. The integration process will involve developing software to process and interpret sensor data, which will be used to guide the robot's navigation and decision-making processes.

In summary, our future work will focus on refining the design and functionality of our Rescue Roller robots to improve their performance and adaptability. By addressing these key areas, we aim to enhance the robots' effectiveness in performing rescue operations and navigating complex environments. Through continued innovation and rigorous testing, we are committed to advancing the capabilities of these robots to better support disaster response efforts and improve safety in challenging scenarios.

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