Heterogenous Collaboration: A new approach for search and rescue operations

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***Abstract*— Urban search and rescue (USAR) remains a challenging application domain despite recent and rapid advancements in robotics. Navigating complex environments is difficult for robotic architectures due to the variation in surface composition and the range of terrain feature sizes. This variety of scenarios incentivize creating a range of different robot designs, but how to effectively use these robots together remains uncertain. Soft robots and centimeter (cm) scale robots have been studied for their potential uses in USAR operations due to their ability to pass through narrow spaces by deforming to adapt to the environment or by virtue of their small size. However, both classes still poses significant challenges in control, limited operational domain, and runtime. In this paper, we demonstrate how collaborative behavior of Vine Robots, i.e. soft inflatable growing robots, and RESCUE Rollers, i.e. cm-scale mobile robots, can expand the reachable area for each robot in rescue-like operations. We accomplish this expansion by equipping the Vine robot to carry and deploy the RESCUE Rollers, and by using the RESCUE Rollers to improve the maneuvarability of Vine Robots by external steering. Through experimental characterization of the necessary interaction forces and an example scenario of collaborative behavior to reach the top of a ramp, we demonstrate that this approach of physical heterogeneous collaboration can lead to increased capabilities of all systems involved.**

I. Introduction

Urban search and rescue (USAR) scenarios are notoriously challenging to navigate and operate within [1], [2]. Structural collapses turn environments into chaotic debris-filled spaces with constrained access points, leading to complications when trying to access or traverse the search area. Environmental uncertainty, in combination with small access points, makes exploration by humans dangerous and potentially impossible. Robotic systems offer a promising solution to enhance search efficiency and safety in these situations [1], [3], [4], with considerable focus paid to new designs that optimize locomotion through these complex environments. Some proposed systems represent relatively small modifications on established reliable robot designs, such as shape-changing wheels [5], [6], while others have been designed specifically with the challenges of search and rescue in mind, such as snake-inspired robots [7], [8]. However, the range of abilities that a robot must have, from navigating across unstructured piles of rubble and up and down stairs or ramps to accessing and capitalizing on small gaps, remaining pipes and other unconventional routes [9], still present a challenge for any one autonomous system.

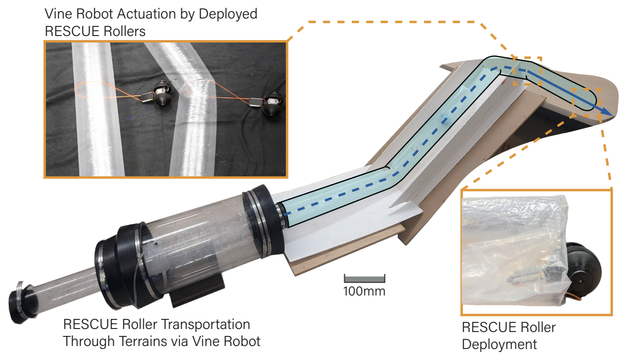

Fig. 1: The Vine Robot is a soft growing robot capable of traversing large distances. It can carry RESCUE Roller robots and deliver them to previously inaccessible desired locations. The RESCUE Rollers are centimeter-scale robots capable of assisting steering of the Vine Robot.

One proposed approach to address tasks with a wide range of requirements, like those found in search and rescue, is to create teams of robots with distinct strengths; these heterogeneous robots teams, which are made of robots with different roles or capabilities, can work together to improve overall team performance when compared to single robots or homogeneous robot teams [10]–[12]. Previously, these systems have been made distinct by their task or role in the team, their sensor or actuator configurations, their overall morphology, or some combination. A primary feature of these heterogeneous teams has been that they interact with each other primarily in their communication and data sharing, meaning the potential benefits of heterogeneity remain confined to an additive success of each robot approaching the USAR task independently. In search and rescue however, the complexity of the task often cannot be solved in parallel like this, one system may be capable of squeezing through a tight gap but then may find an insurmountable vertical traversal on the other side. The solution then is to find a way for heterogeneous teams to share locomotion capabilities, in addition to data and sensing information.

In this paper, we investigate a heterogeneous team of robots designed to physically interact and share navigation capabilities, resulting in an increased ability to solve navigation tasks in search and rescue environments. We select two

This work is supported in part by National Science Foundation grant 2308653 and 2308654.

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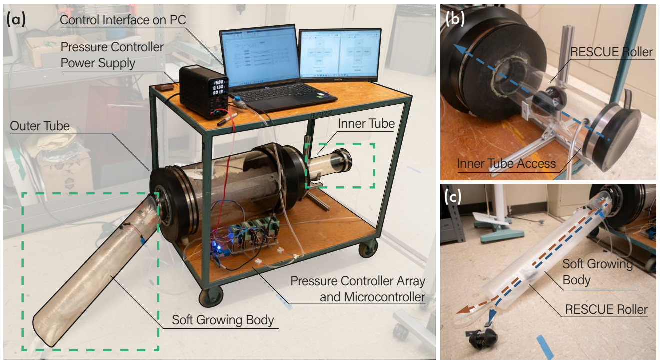

Fig. 2: Deployment-Capable Vine Robot consisting of an acrylic pressurized tube, an inner material storage tube, flexible end caps, and a thin-walled compliant tube. The design can carry and deploy payloads inserted through the material storage tube.

classes of robots which have shown promise in recent years for tackling challenging portions of USAR: soft growing robots [13] and centimeter (cm)-scale robots [14], [15] (Fig. 1). Soft growing robots, also known as Vine Robots, show beneficial passive kinematics for moving through cluttered environments [16] and even burrowing through soil [17], leading to recent designs focused on search and rescue, including one capable of extending 17 m through a simulated search and rescue environment [18]. These Vine Robots are highly capable at vertical and horizontal traversal [19], but still experience challenges when trying to steer around tight corners or quickly change the direction of growth [20]–[22]. Centimeter-scale robots can have high maneuverability and can be relatively inexpensive to deploy in large numbers, allowing sensor or communication payloads to be distributed [14], [23], [24]. However, these individual robots inherently cannot traverse features larger than their body length [25], [26], at least not without specialized designs to allow jumping or other high energy navigation systems [27]. Given the complementary nature of these capabilities and challenges, these robotic platforms serve as a test case of integrating and designing for physical interaction in heterogeneous teams. In this work, we modify the designs of these systems to physically collaborate and share their beneficial capabilities, resulting in superior navigation for each robot.

The remainder of this paper is as follows. Section II details the design of the Deployment-Capable Vine Robot and the Rapid Emergency Search in Cluttered and Unstructured Environments (RESCUE) Roller (Figure 1). Section III presents the analysis and demonstration of the collaborative robot capabilities. Lastly, Section IV discusses the findings and evaluation of this paper's results.

II. Robot Design and Fabrication

Before discussing the combined interactions, we describe each system's designs and limitations including modifications made to their design to achieve beneficial interactions.

A. Deployment-Capable Vine Robot design

The Vine Robot is part of a class of robots which moves by growing [13], [19], extending in length by adding new material at the tip of the previously grown robot body. To achieve this motion, a thin-walled tube is inverted back on itself, and then, when pressurized, the inverted material will “evert" out the tip of the robot, pushed by the internal pressure. This eversion creates extension without sliding against the environment, meaning Vine Robots can easily operate in tightly cluttered spaces or move through gaps. Vine Robots will also create self-supporting structures with the deployed body, allowing them to easily climb stairs or cross gaps. To steer the Vine Robot, soft length-changing actuators can be added along the full length of the robot [19], [20]. When these actuators shorten, either through pressure or cable tension, the Vine Robot will bend in the direction of whichever actuators were activated. While this approach to steering creates easily controlled bending in any direction, the actuators generally result in a turning of less than 2.5° per centimeter body length [28], putting a limit on the smallest radius of curvature the Vine Robot can achieve.

In our heterogeneous robot team, we aim to share the Vine Robot's ability to move through tight spaces and over gaps, while addressing the limitations experienced in steering. To do this, we design the Deployment-Capable Vine Robot, a Vine Robot which can carry and deploy RESCUE Rollers to environments that the RESCUE Rollers cannot reach on their own. Carrying the RESCUE Rollers with the Deployment-Capable Vine Robot gives the RESCUE Rollers the opportunity to contribute to the steering of the Vine Robot as described in Section II-B.

The design of the Deployment-Capable Vine Robot is shown in Fig. 2. The stored material is folded around an internal acrylic tube and linearly scrunched (Fig. 2 (a)), a material storage method first demonstrated by Ryu et al. [29], to allow an access point through which RESCUE Rollers can be loaded inside the Vine Robot (Fig. 2 (b)). The acrylic material packing tube is connected to an acrylic tube which forms the pressurized vessel by two rubber couplers (Quik Cap, Fernco). This main pressure chamber measures 30.48 cm in diameter, while the material storage tube measures 10.16 cm in diameter. In this work we use Low-Density Polyethylene (LDPE) thin-film tubing (129 mm diameter, 50 μm wall thickness, Uline) as the Vine Robot body for the convenience of visualizing the payload being carried and deployed. Unaided steering of the Vine Robot is achieved by series pouch motors [30], [31]. Given the size of the robot body, these actuators can only achieve a bend radius of 1.22m at the operating pressure of the vine (1.03kPa) and the pouch motors (13.8kPa). All pressures are controlled using pressure regulators (QB3, Proportion-Air).

B. RESCUE Roller design

Small-scale wheeled robots have generally been favored for their size, tight maneuvering, and relatively inexpensive manufacturing, allowing multiple to be used in a single team [23], [24]. While some more exotic movement forms have been suggested [27], two-wheel differential drive offers a simple design while maintaining the capacity for quick direction changing and a small package size. The obstacle

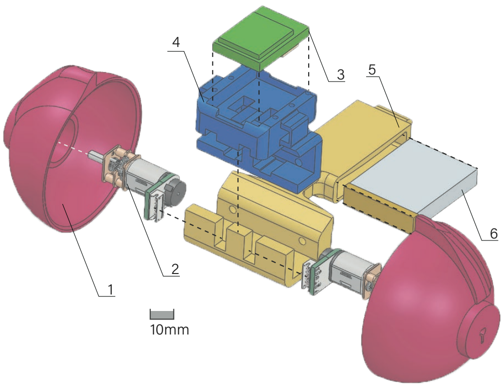

Fig. 3: Exploded view of the RESCUE Roller showing 1) hemispherical snail cam wheels, 2) motors with encoders, 3) custom PCB, 4) main chassis, 5) tail, and 6) battery.

height that can be scaled by these robots will be limited by the wheel size, often bounded by the wheel radius.

Within the heterogeneous team, we want a cm-scale robot that remains small enough to be carried by the Vine Robot but is capable of traversing rough terrain with high maneuverability and has the ability to apply forces on the Deployment-Capable Vine Robot to share that maneuverability. To accomplish this, we designed RESCUE Roller (Fig. 3) as a two-wheeled small-scale robot with actuators capable of generating enough force to help a Vine Robot steer. RESCUE Roller uses a two-wheel differential drive system with hemispherical wheels and an extended tail to allow high maneuverability and stability. The wheels are shaped like snail cams with a diameter of 60 mm and a step of either 7.5 mm or 10 mm, allowing the robot to surmount obstacles up to 30 mm tall. This is over twice the height of what standard circular wheels could achieve. High friction tape (Gripping Material GM400, 3M) is used to further increase the friction of the wheels for better obstacle climbing and force production. The wheelbase of the RESCUE Roller is 84 mm wide and the extended tail gives the robot an overall length of 120 mm. In addition to increasing stability and reducing the incidence of the robot overturning, the rectangular profile produced by the tail also allows the RESCUE Rollers to maintain a set orientation when being carried and deployed by the Deployment-Capable Vine Robot. The tail carries a 3.7 V 1000 mAh Lithium Polymer cell to power the robot. The wheels are driven by miniature gear motors (250:1 12 V HPCB Micro Metal Gearmotor, Pololu), powered through a 10.8 V, 2 A dual H-bridge (DRV8833, Texas Instruments). A microcontroller with built in camera and microphone (Xiao ESP32-S3 Sense, Seeed Studio) provides on-board control and communication over Wi-Fi for remote operation. To maintain low cost and ease of development, the chassis is constructed from 3D-printed PLA using a Bambu Labs P1S. The fully assembled system weighs approximately 114 g.

III. Experiments and Results

This section demonstrates the collaboration between the RESCUE Rollers and the Vine Robot and characterizes elements of their performance. We first evaluate the target

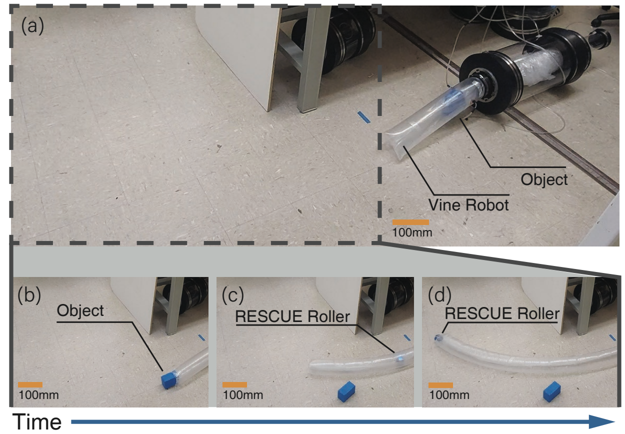

Fig. 4: The Deployment-Capable Vine Robot deploying multiple objects in succession. (a) The passive payload and cm-scale robot are placed in the material storage tube from the back end of the base station, and the Vine Robot starts growing. (b) The Vine Robot deploys the passive payload. (c) The Vine Robot steers and keeps growing while the cm-scale robot drives into the material stream. (d) The Vine Robot deploys the cm-scale robot.

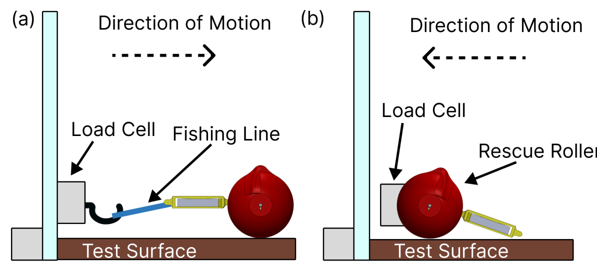

Fig. 5: RESCUE Roller (a) pulling and (b) pushing force experimental setups. The experiments were performed on five test surfaces with different friction, compliance, and roughness.

capabilities separately, examining payload deployment with Deployment-Capable Vine Robots and steering of inflated tubes with a single RESCUE Roller, before presenting a demonstration of the collaborative navigation of both robots types together through a simplified environment.

A. Multiple Payload Deployment

To characterize the payload carrying and deployment of the Deployment-Capable Vine Robot, we tested a range of passive and active payloads, focusing on payload size, payload weight, number of payloads, and deployment location control. The payload delivery was tested on a range of slopes up to 60^o in angle, and the Vine Robot was able to consistently deploy payloads up to 1 kg in weight and ranging in size from 40 mm diameter spheres up to RESCUE Roller size (84 mm by 67.5 mm by 120 mm). Fig. 4 shows both a passive payload and an active cm-scale robot payload (BOLT Coding Robot, Sphero) being deployed. At the start, we placed the passive object and the BOLT inside the inner tube of the Vine Robot, with the passive object in contact with the growing material. As the Vine Robot grows (Fig. 10(a)) the passive rectangular object is carried and eventually deployed (Fig. 4(b)), at which point the BOLT is moved forward to be carried by the Vine Robot. The deployment

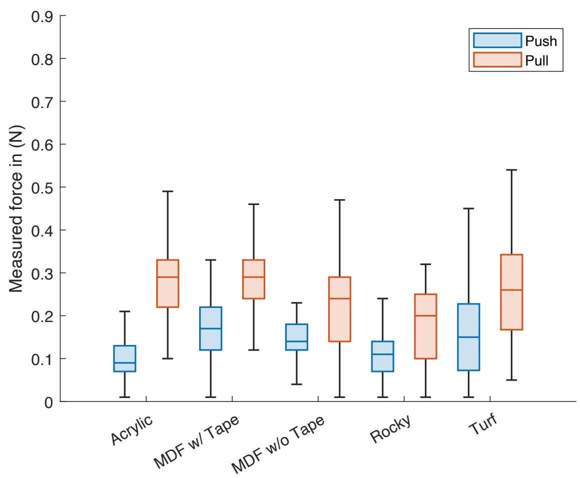

Fig. 6: Applied force on acrylic, medium density fiber board (MDF), MDF surfaced with Life Grip Tape, an artificial rocky terrain, and artificial turf by a RESCUE Roller robot with 10mm step snail cam wheels.

location can be controlled by steering the Vine Robot (Fig. 4(c)-(d)) and controlling when the cm-scale robot is moved into the Vine Robot.

B. *External Actuation by RESCUE Rollers*

1) Characterizing RESCUE Roller Force Application: To evaluate a RESCUE Roller's ability to steer the Vine Robot, we first establish the push and pull forces the RESCUE Roller can apply on different surfaces. Fig. 5 (a) To assess the pulling force we used a 0-500g force transducer (Precision Gram Load Cell, Transducer Techniques) with one side fixed to an upright surface and the other side attached to the robot with a fishing line loop. The robot drove away at full power for 10 second while data was recorded. The pushing force of a RESCUE Roller was measured in a similar manner, but with the transducer attached to the RESCUE Roller, and the robot driven towards the upright surface, again at full power for 10 seconds (Fig. 5(b)). These tests were performed on surfaces of varying friction, compliance, and roughness, including: an acrylic sheet, medium density fiberboard (MDF) with a Life-Grip Anti Slip Tape on, MDF without the tape, a 3D printed rough or rocky surface (variance of 3mm [32]), and an artificial turf of uniformly distributed 1 inch long plastic strips. Fig. 6 presents a side-by-side comparison of push and pull force capability while traversing on these materials. Across all surfaces, the average pulling and pushing forces are 0.245 N and 0.138 N, respectively. The minimum median pulling force is 0.2 N (acrylic), while the maximum reaches 0.29 N (on both MDF with tape and an artificial rocky surface). For pushing forces, the minimum median is 0.09 N (acrylic), and the maximum is 0.17 N (MDF with tape).

2) Characterizing Vine Robot Bending Stiffness: For the RESCUE Rollers to actuate the Vine Robot, they need to counter-act the tension in the Vine Robot material shell, which can be calculated as a restoring moment at the point where the Vine Robot bends with a magnitude proportional to the axial tension in the material [33]. When pulling long

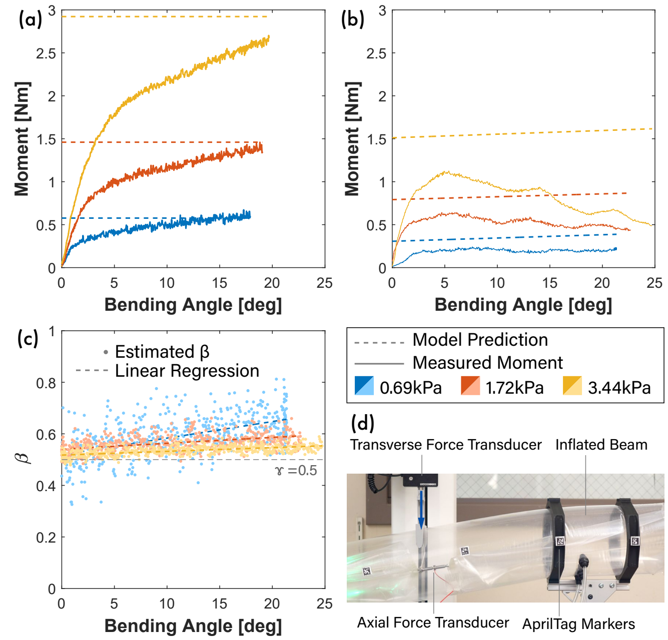

Fig. 7: Measured and modeled bending moments at various pressure levels for (a) a simple inflated beam and (b) a Vine Robot segment with uneverted material in tension (i.e. stopped form extending). (c) The fraction of total pressure force held by the axial material tension, β, calculated from the measured axial tension in the uneverted material. (d) Testing setup for bending moment and axial tension.

lengths of Vine Robot, the RESCUE Rollers will additionally need to overcome friction between the Vine Robot and the surface. The total force that the RESCUE Rollers need to pull, F_{act}, can be summarized as:

$$F_{act} = \frac{\beta \pi P R^3}{l_0} + \int_0^{l_0} x f_{fric}(x) dx \quad (1)$$

where P, R are the internal pressure and radius of the Vine Robot, l_0 is the distance between the RESCUE Roller and the bend point, $f_{fric}(x)$ is the friction per unit length, and $\beta \in (0, 1]$ is the proportion of the pressure force balanced by the material axial tension. This β modifies previous derivations of inflated beam bending [33] to account for portion of the generated tension which is balanced by the uneverted material. When the Vine Robot is stopped from extending, this will be approximately 0.5. Equation (1) represents an upper limit on the force required to bend the Vine Robot, which will occur when the bend point fully loses axial tension all around the robot circumference.

We verified the bending moment term in Equation (1) by deforming an inflated beam and measuring the induced force. The bending angle was measured with AprilTag markers (Fig. 7d) and force measured with a force transducer and stand (MR03-5 and EM-303, Mark-10). Beams with uneverted material were also tested to demonstrate the different β values, and tension in the uneverted material was measured with a tensiometer (FSH04400, Futek). Results (Fig. 7(a)) indicate that the moment required to deform an inflated beam without uneverted material will increase with bend angle to be about equal to the constant moment model [33].

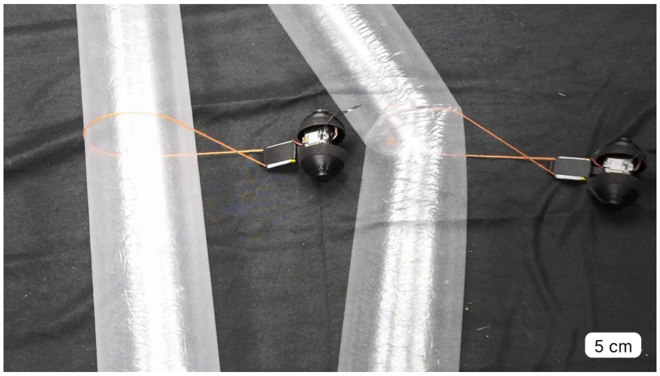

Fig. 8: The demonstration shows the RESCUE Roller driving on a black cloth while attached with a loop of yarn to a Vine Robot pressurized to approximately 0.8 kPa. The Vine Robot is anchored at both ends, about 0.7 m away from the RESCUE Roller. The RESCUE Roller pulling force wrinkles the surface of inflated tube and displaces the pulled point 26 cm. The initial configuration and the result after 3 seconds are superimposed.

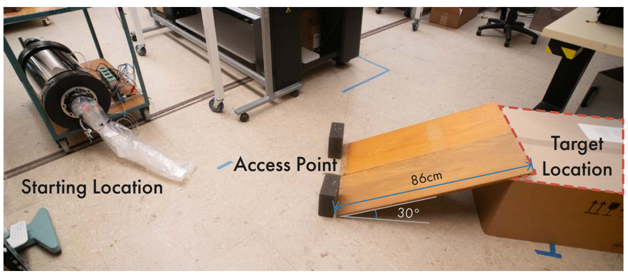

Fig. 9: Experiment Setup to demonstrate the concept of heterogeneous collaboration. The Vine Robot will carry a RESCUE Roller to the target location,which the roller is normally unable to reach due to a ramp with 30° angle.

With uneverted material (Fig. 7(b)), the bending moment is reduced by about half, and uneverted material tension is consistent with $\beta = 0.5$ (Fig. 7(c)). The moment does begin to reduce with increasing angle, but this is likely an unintended effect of eccentric loading wwith the internal material. The reduction when the uneverted material is present indicates a method for RESCUE Rollers to more easily deform the Vine Robot.Assuming negligible friction, and using the highest median pulling force of the RESCUE Roller, 0.29 N, a single RESCUE Roller can bend a 1.5 m section of Vine Robot pressurized to 1.03 kPa (Fig. 8).

C. Vine Robot and RESCUE Rollers collaboration:

Finally, we demonstrate the combined Deployment-Capable Vine Robot and RESCUE Roller team to showcase the full collaborative movement capabilities in a single scenario. The demonstration is carried out on a course that includes a ramp and a platform, as shown in Fig. 9. In the demonstration, the Vine Robot extends with one RESCUE Roller inside for 35 seconds (Fig. 10(a)). At 79 seconds, Fig. 10(b) shows the first RESCUE Roller successfully deployed, while tethered to the Vine Robot by a string. It then moves from right to left, steering the Vine Robot to face the incline opening, stopping at 110 seconds. Next, a second RESCUE Roller is inserted to be carried by the Vine Robot, and the Vine Robot grows up a 30-degree incline (Fig. 10(c)). Finally, the Vine Robot deploys the second RESCUE Roller atop the incline (237 seconds), and the RESCUE Roller can drive around on the surface (Fig. 10(d)).

IV. Discussions and Conclusions

We presented the designs and resulting collaborative behaviors of the Deployment-Capable Vine Robot and RESCUE Roller. These robots complement each other's capabilities and combining them allows delivery of the RESCUE Rollers to previously inaccessible locations, and more extreme steering of the Vine Robot. Our key takeaway is how robots of distinct capability can be designed to synergistically interact and explore unstructured environments.

The Deployment-Capable Vine Robot can carry multiple payloads of up to 1 kg of weight, and, with active injection of the RESCUE Rollers into the internal material to be carried, RESCUE Roller payloads can be deployed at desired points. On the other hand, for a single RESCUE roller to steer the Vine Robot, its median pulling output force of 0.29 N can bend a 1.5 m long Vine Robot. The bending characterization indicates that lowering the pressure, stopping the Vine Robot extension, or leveraging multiple RESCUE Rollers should allow us to steer larger bends or shorter Vine Robot lengths.

The collaborative approach demonstrated in this paper between the Vine Robot and RESCUE Rollers offers a cost-effective and efficient method for deploying multiple robots in search and rescue operations for distributed exploration and sensing. This demonstrated collaborative design does not even represent the full possibilities; the Vine Robot, for example, could be used to deliver power to other robots or essential supplies to victims, while the RESCUE Rollers could be diversified and specialized through varying mapping, communication, and sensing capabilities. Physical collaborative behavior among heterogeneous robots opens new pathways for researchers and engineers to think about robot-robot collaboration for search and rescue operations. In the future, we will explore additional capabilities of this new collaboration and apply these capabilities to enhance simulated search and rescue operations in real-world settings.

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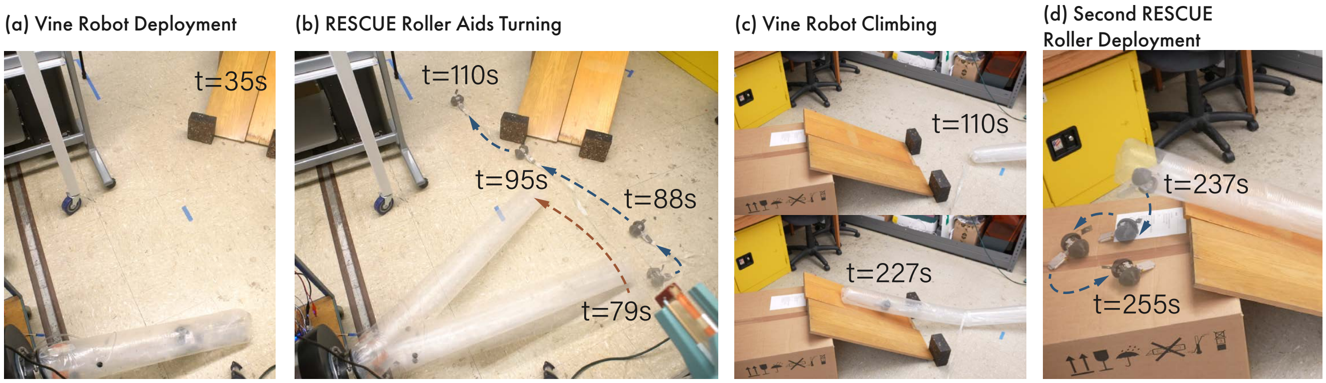

Fig. 10: Demonstrating the Deployment-Capable Vine Robot deploying multiple RESCUE Rollers and the RESCUE Rollers helping the Vine Robot to steer. (a) The Vine Robot starts to grow with a RESCUE Roller to deploy already inside the growing body. (b) The Vine Robot deploys the first RESCUE Roller, which is tethered to the robot. The RESCUE Roller then pulls the Vine Robot to steer it towards the ramp where it then (c) grows up the ramp to carry the second RESCUE Roller atop the platform and (d) finally, deploy the second RESCUE Roller in the target area.

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