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Human-Centered Design and Control of Vine Robots for Disaster Scenarios

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14. ABSTRACT
This project aimed to increase efficacy of humanitarian assistance and disaster relief through robust and portable designs and advanced human¬-robot interaction applied to a new class of soft continuum robots: Vine Robots. In contrast to traditional robots that move based on flight or repeated contacts with a surface (e.g., walking, running, rolling), vine robots are soft robots that achieve movement through growth, on time scales much faster than their biological counterparts. They achieve this growth by “eversion,” or turning inside out, of their body material due to internal fluid pressure. As vine robots grow, they expand from the tip, allowing
them to use their newly established “stem” as a base from which to traverse gaps, climb vertically, and grow to over 100 times their original length. Because they do not rely on contact with the environment to achieve movement, they can navigate over rough, slippery, sticky, and sharp terrain. Growth from the tip of a robot also enables it to withstand being stepped on and extend through gaps a quarter of its height. Within its region of growth, a vine robot can provide not only sensing, but also a physical conduit, such as a water hose that grows to a fire or an oxygen tube that grows to a trapped disaster victim. Vine robots could also protect trapped victims and infrastructure by gently wrapping themselves around unstable rubble or grasping a gas valve to be pulled shut. A main goal of this project has been the development of new vine robot designs and capabilities for humanitarian assistance and disaster relief. Our vine robot design objectives were to: (1) Characterize and optimize vine robot performance in terms of reach, payload, and robustness in relevant environments, (2) Improve the reach and control of vine robots using two methods of tip control previously
developed: tip bending and curved growth, (3) Implement portable vine robots using a compact base station and two driving media (compressed air and water), and (4) Develop sensing modules, including intrinsic and extrinsic sensing. Over the course of this project, we made major contributions in all three areas described above.

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Human-Centered Design and Control of Vine Robots for Disaster Scenarios
Final Report for Award #FA2386-17-1-4658
June 10, 2020, Revised October 22, 2021

PI: Allison Okamura, Stanford University
Collaborating PI: Jee-Hwan Ryu, KAIST (formerly KOREATECH)

1. Project Goals

This project aimed to increase efficacy of humanitarian assistance and disaster relief through robust and portable designs and advanced human-robot interaction applied to a new class of soft continuum robots: Vine Robots. In contrast to traditional robots that move based on flight or repeated contacts with a surface (e.g., walking, running, rolling), vine robots are soft robots that achieve movement through growth, on time scales much faster than their biological counterparts. They achieve this growth by "eversion," or turning inside out, of their body material due to internal fluid pressure.

As vine robots grow, they expand from the tip, allowing them to use their newly established "stem" as a base from which to traverse gaps, climb vertically, and grow to over 100 times their original length. Because they do not rely on contact with the environment to achieve movement, they can navigate over rough, slippery, sticky, and sharp terrain. Growth from the tip of a robot also enables it to withstand being stepped on and extend through gaps a quarter of its height. Within its region of growth, a vine robot can provide not only sensing, but also a physical conduit, such as a water hose that grows to a fire or an oxygen tube that grows to a trapped disaster victim. Vine robots could also protect trapped victims and infrastructure by gently wrapping themselves around unstable rubble or grasping a gas valve to be pulled shut.

A main goal of this project has been the development of new vine robot designs and capabilities for humanitarian assistance and disaster relief. Our **vine robot design objectives** were to: (1) Characterize and optimize vine robot performance in terms of reach, payload, and robustness in relevant environments, (2) Improve the reach and control of vine robots using two methods of tip control previously developed: tip bending and curved growth, (3) Implement portable vine robots using a compact base station and two driving media (compressed air and water), and (4) Develop sensing modules, including intrinsic and extrinsic sensing. Over the course of this project, we made major contributions in all three areas described above.

Human-in-the-loop control of vine robots is necessary in the uncertain and complex environments to be encountered. Our **human-in-the-loop control objectives** were to: (1) Design an intuitive human interface for effective teleoperation that maximizes the human operator's control ability while minimizing the cognitive workload, (2) Develop a situational awareness improvement module to help the operator understand the state of the vine robot and the environment, and (3) Create a vine robot teleoperation training simulator for providing diverse training environments considering realistic disaster situations. The human-in-the-loop control aspects of this work were led by our collaborators at KAIST (PI Jee-Hwan Ryu), and the submitted their final report to KOREA MOTIE.

2. Summary of Project Contributions

In this project, we modeled the interaction of vine robots with their environment [1, 5], as well as the shapes that can be created through various actuation schemes [2, 9], and the dynamic behaviors of vine robots [10, 11]. We studied teleoperation schemes for vine robots and developed a custom-designed flexible joystick that mimics the shape of the vine robot body [3]. We developed designs and control schemes for a vine robot system that carries a camera and can steer and grow simultaneously [4], and we successfully designed, built, and deployed a compact, portable vine robot system at a soft robot navigation competition based on a mock disaster scenario and in the field for exploration of an archeological site in Chavín, Peru [6]. We explored the use of the unique shape change abilities of vine robots to create reconfigurable and deployable antennas [7]. We developed new vine robot capabilities through the addition of a device to retract the robot body after growth without undesired buckling [8] and through the addition of a tip mount capable of supporting high loads in tension [12]. Kinematic and dynamic models of vine robots allow for design optimization and control [9, 10, 11]. Finally, we wrote a review of much of the recent work on vine robots [13], discussing their design, control, modeling, and application.

Throughout this project, Stanford and KAIST teams met biweekly via video conference, and the PIs and a subset of the students met in person twice per year at conferences. Our collaboration resulted in three joint publications: one on a human interface for vine robot teleoperation [3], a second on design and deployment of a field-ready vine robot system [6], and a third on vine robot tip mount design [11], with future joint publications likely to come out of our ongoing work (Section 4). From August 2019 through January 2020, KAIST student Sang-Goo Jeong spent six months visiting Stanford through the International Student Exchange Program (ISEP), resulting in much fruitful transfer of vine robot knowledge and cultural exchange, as well as our collaborative publication [11] on vine robot tip mount design, and continued collaboration on two subsequent projects.

The following sections describe in detail the work completed in the final year of the project, as well as our ongoing work and continued collaboration with KAIST researchers. Finally, we list the papers published or submitted during this project.

3. Final Year Contributions

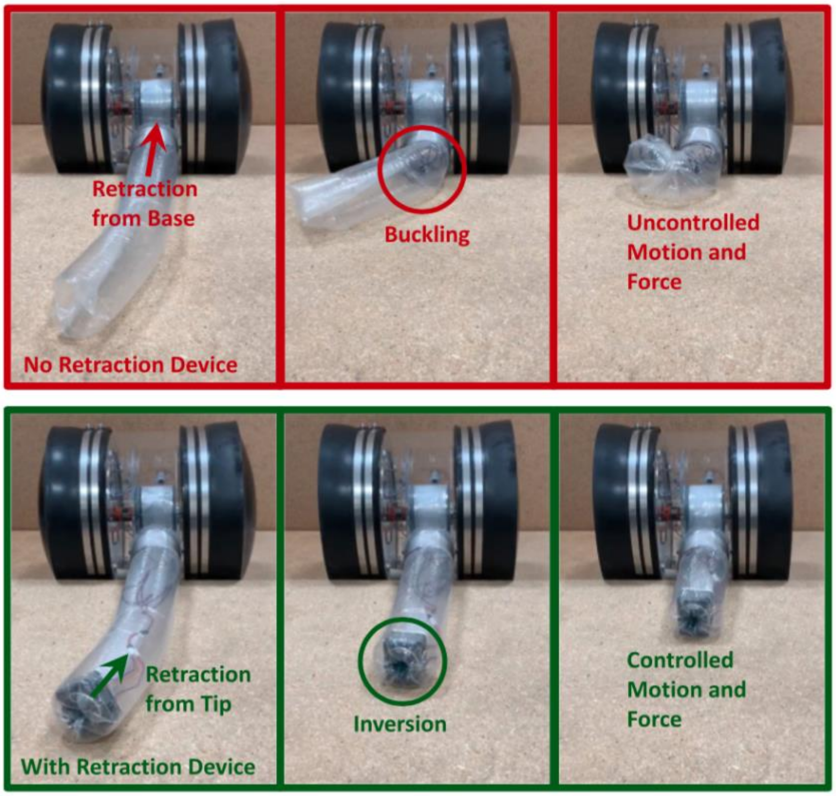

Figure 1. Demonstration of our device to enable controlled retraction of a soft growing robot. After the robot grows from the base through eversion of its body material, retraction is attempted via tension applied on the internal robot body material with a motor in the base (top), and with a motorized retraction device at the tip (bottom). Without the device, the soft robot body often buckles, resulting in a lack of control over its motion and force, but with the device, the soft robot body inverts successfully, allowing control over its motion and the force applied to the environment.

a. Retraction of Soft Growing Robots without Buckling

This work [8] focuses on understanding and solving the problem of undesired buckling during retraction of vine robots. Vine robots have demonstrated applications in exploration of cluttered environments. During growth, the motion and force of the robot tip can be controlled in three degrees of freedom using actuators that direct the tip in combination with extension. However, when reversal of the growth process is attempted by retracting the internal body material from the base, the robot body often responds by buckling rather than inverting the body material, making control of tip motion and force impossible. We presented and validated a model to predict when buckling occurs instead of inversion, and we introduced an electromechanical device (Figure 1) that can be added to a vine robot to prevent buckling during retraction, restoring the ability of steering actuators to control the robot's motion and force during inversion. Using our retraction device, we demonstrated three previously impossible tasks: exploring different branches of a forking path, reversing growth while applying minimal force on the environment, and bringing back environment samples to the base without disturbing the environment.

We extended this work (Section 3.d) by integrating the control of our retraction device into the control of the overall vine robot system, as well as combining this device with designs for mounting of sensors and tools at the vine robot tip to allow retraction of vine robots equipped with items for interacting with the environment.

b. Geometric Solutions for General Actuator Routing on Inflated-Beam Soft Growing Robots

This work [9] focuses on modeling the shapes produced by generally routed actuators on a vine robot body. Continuum and soft robots can leverage complex actuator shapes to take on useful shapes while actuating only a few of their many degrees of freedom. The addition of vine-like growth increases the range of potential shapes that can be actuated and enables easier access to constrained environments. Existing models for describing the complex kinematics involved in general actuation of continuum robots rely on simulation or well-behaved stress-strain relationships, but the non-linear behavior of the thin-walled inflated-beams used in vine robots makes these techniques difficult to apply. We derived kinematic models of single, generally routed tendon paths on a soft pneumatic backbone of inextensible but flexible material from geometric relationships alone. This allows for forward modeling of the resulting shapes with only knowledge of the geometry of the system (Figure 2). We showed that this model can accurately predict the shape of the whole robot body and how the model changes with actuation type. We also demonstrated the use of this kinematic model for inverse design, where actuator designs are found based on desired final robot shapes. We deployed these designed actuators on vine robots to show the benefits of simultaneous growth and shape change, including the ability of the vine robot to tie itself in a knot.

Future work includes developing models and algorithms that allow control over different parts of the resulting actuation, i.e., matching a desired movement of the robot tip or matching multiple target shapes with a single actuator. We would also like explore the interaction of multiple actuators and the effects of external forces, so as to increase the design space and allow design of actuation strategies for carrying a payload or interacting with obstacles.

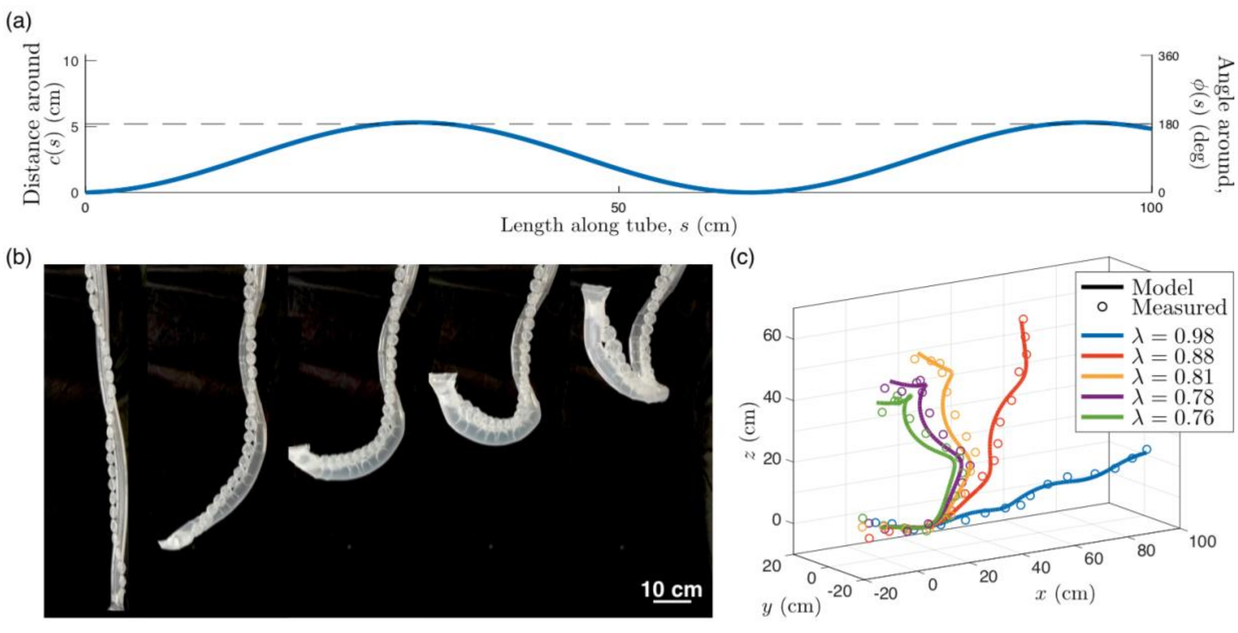

Figure 2. Comparison of modeled and measured shapes for general actuation of a pneumatic backbone using a series pneumatic artificial muscle (sPAM) actuator. (a) The actuator is attached in a sinusoidal pattern along the backbone. (b) The physical prototype changes its shape as the actuator contraction ratio λ is changed. (c) The modeled and measured shapes of the robot body match well, with RMSE less than or equal to 3.20 cm for all values of λ.

c. Dynamic Characterization of Soft Growing Robots

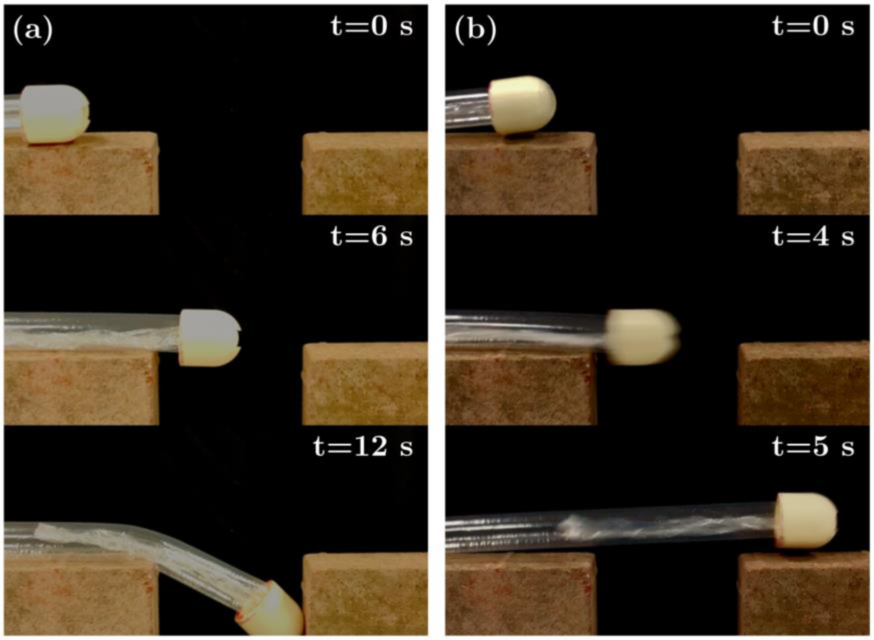

Figure 3. A vine robot crosses a gap under the influence of gravity. (a) Without consideration for robot dynamics, certain obstacles, such as a gap in the floor, may appear to be impassable. (b) Proper characterization of robot dynamics can show how these obstacles are in fact passable.

This work [10, 11] focuses on characterizing and modeling the dynamic behaviors of vine robots in growth and bending. Soft continuum robots are well suited for navigating complex terrain because their inherent compliance allows them to passively adapt to the environment. Moreover, due to their growth-based movement, vine robots can access locations that are unreachable by other types of robots. However, their compliance can result in undesirable deformations, which may prevent the robot from reaching its target. Dynamic maneuvers coupled with local planning may overcome this challenge (Figure 3). Toward this goal, we characterized the dynamics of growth and bending for vine robots. We developed experimental methods for measuring the dynamic responses of a thin-walled inflated beam under growth and bending, and we presented measured dynamic responses for a range of geometries and pressure inputs. We fit lumped parameter dynamic models to the measured behaviors, and we demonstrated trends of dynamic parameters with respect to geometry and pressure. A publicly available dataset (https://stanford.box.com/v/vine-dynamics-data-2020) allows testing of future models.

Next, we developed a dynamics simulator. Simulating soft robots in cluttered environments remains an open problem due to the challenge of capturing complex dynamics and interactions with the environment. Furthermore, fast simulation is desired for quickly exploring robot behaviors in the context of motion planning. We present a dynamics simulator that captures general behaviors, handles robot-object interactions, and runs faster than real time for soft growing vine robots. The simulator framework uses a simplified multi-link, rigid-body model with contact constraints. To bridge the sim-to-real gap, we developed methods for fitting model parameters based on video data of a robot in motion and in contact with an environment. We created examples of simulations, including several with fit parameters, to show the qualitative and quantitative agreement between simulated and real behaviors. Our work demonstrates the capabilities of this high-speed dynamics simulator and its potential for use in the control of soft robots.

d. A Tip Mount for Transporting Sensors and Tools using Soft Growing Robots

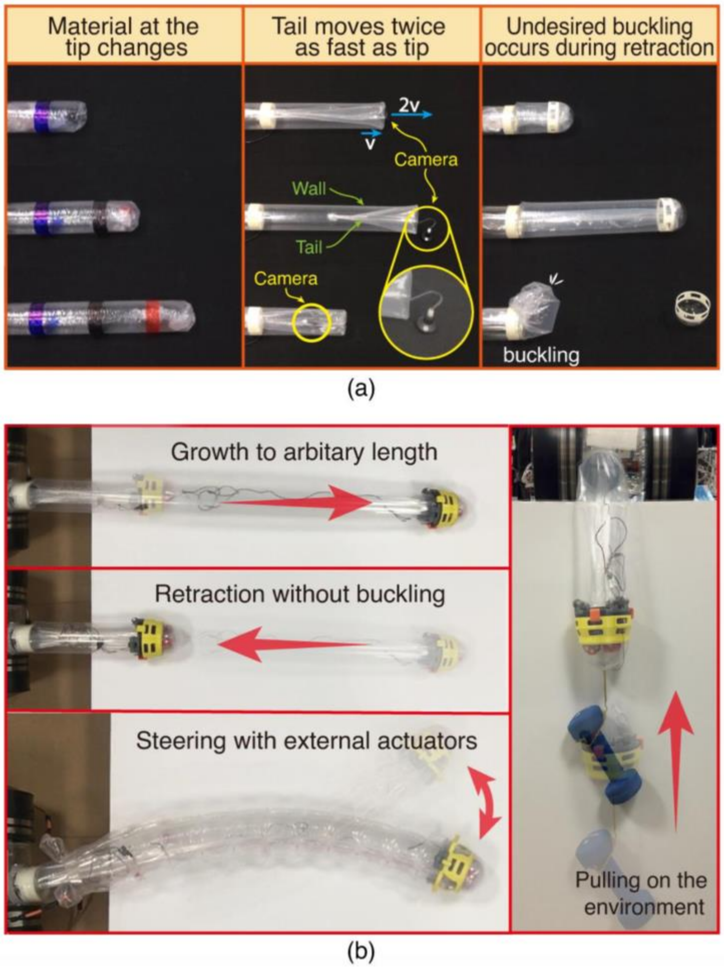

Figure 4. Challenges related to mounting to the tip of vine robots, and our tip mount solving these challenges. (a) The material at the robot tip changes during growth and retraction, so anything affixed to the tip material will not remain at the tip. The inner material (the "tail") moves at twice the speed of the robot tip relative to the base, so anything packaged within the tail will be ejected during growth and engulfed during retraction. When retracted from the base, vine robots often undergo undesired buckling. (b) Our current tip mount design remains at the robot tip during growth to arbitrary lengths, incorporates our device to retract the robot without undesired buckling, does not interfere with steering of the robot body using external actuators, and can apply significant pulling forces to the environment.

This work [12] focuses on the design of a new tip mount for vine robots that allows more useful motion and interaction with the environment. Vine robots are well-suited for navigation in confined spaces. Adding the ability to interact with the environment using sensors and tools attached to the robot tip would greatly enhance the usefulness of these robots for exploration in the field. However, because the material that is at the tip of the robot body continually changes as the robot grows and retracts, it is challenging to keep sensors and tools attached to the robot tip during actuation and environment interaction. We analyzed previous designs for mounting to the tip of soft growing robots, and we presented a novel device (Figure 4) that successfully remains attached to the robot tip while providing a mounting point for sensors and tools. Our tip mount incorporates and builds on our previous work on a device to retract the robot without undesired buckling of its body. Using our tip mount, we demonstrated two new soft growing robot capabilities: (1) pulling on the environment while retracting, and (2) retrieving and delivering objects. Finally, we discussed the limitations of our design and opportunities for improvement in future soft growing robot tip mounts.

Future work includes addressing the limitations of vine robot tip mount designs to date, especially in their tradeoff between reliable attachment to the robot tip and encumbering the robot's ability to move without sliding relative to its environment. Additionally, we have a new project exploring the use of vine robots as true manipulators (National Science Foundation Grant NRI: FND: Computational and Interactive Design of Soft Growing Robot Manipulators, Award Number:2024247, PI: Allison Okamura).

f. Design, Modeling, Control, and Application of Vine Robots

This work [13] reviews much of the recent work on vine robots. Since 2017, there has been much research on vine robots, in large part because of this grant and other related ones, as well as the high potential for vine robots to be useful in real world applications. We broke down the recent work on vine robots into four categories. First, we examined the design of vine robots, highlighting tradeoffs in material selection, actuation methods, and placement of sensors and tools. These tradeoffs have led to application-specific implementations. Second, we described the state of and

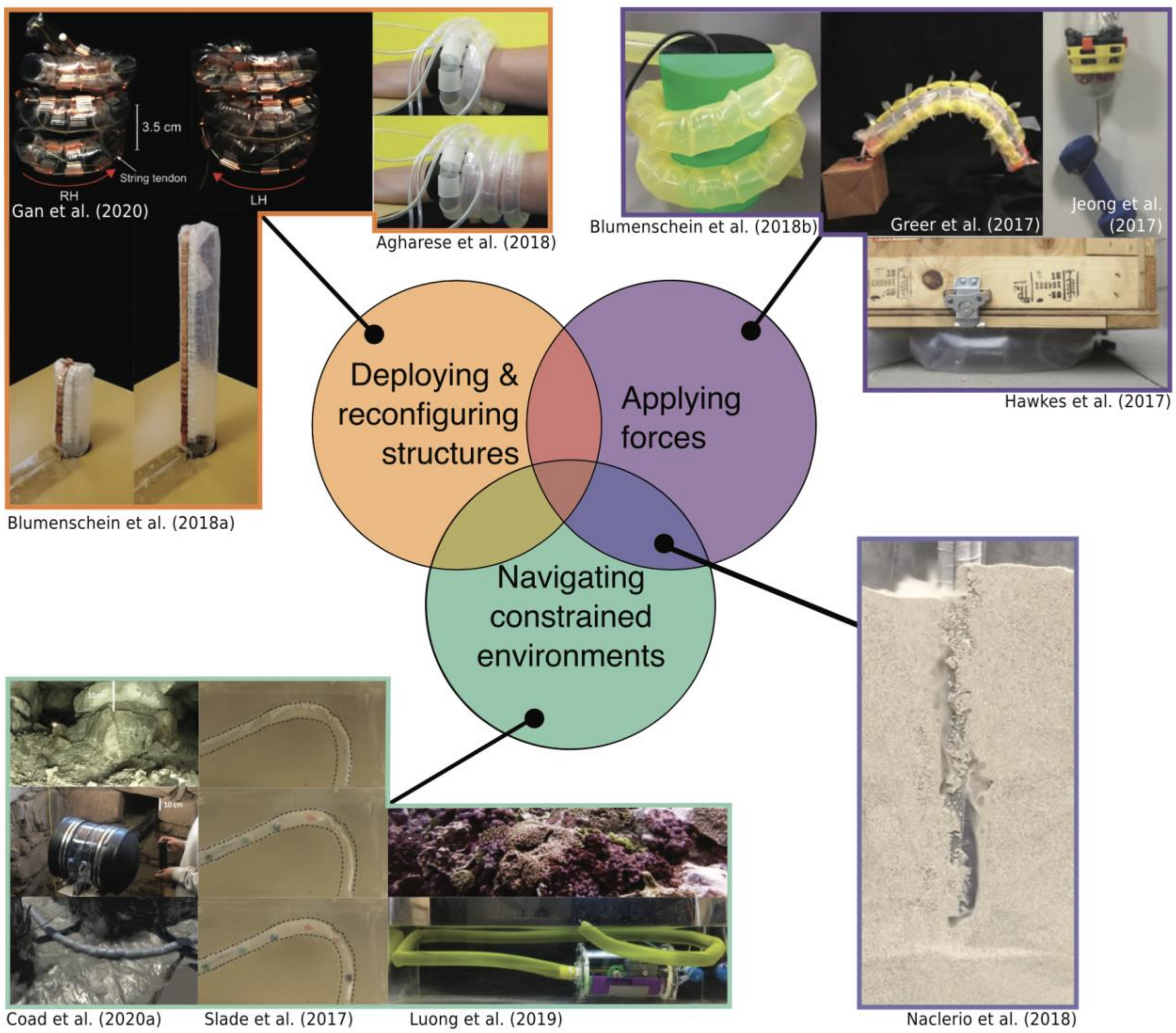

Figure 5. Vine robot applications organized by the function of the vine robot in the application. The grown structure of the vine robot can be used for deploying and reconfiguring structures for RF antennas and wearable haptic devices. Movement by growth allows vine robots to navigate constrained environments without damaging the environment or the robot, allowing exploration of archaeological sites, deployment of medical devices, and monitoring of delicate underwater environments. Lastly, the structure of the vine robot can be used to apply forces to the environment in a variety of ways–squeezing, pushing, pulling, or expanding. Some applications incorporate multiple functions, like vine robot burrowing, where the robot navigates the highly constrained environment of a granular material while applying outward force to keep the newly formed path from collapsing.

need for modeling of vine robots. Quasi-static models of growth and retraction and kinematic and force-balance models of steering and environment interaction have been developed that use simplifying assumptions and limit the involved degrees of freedom. Third, we reported on vine robot control and planning techniques that have been developed to move the robot tip to a target, using a variety of modalities to provide reference inputs to the robot. Fourth, we highlighted the benefits and challenges of using this paradigm of movement for various applications (Figure 5). Vine robot applications to date include deploying and reconfiguring structures, navigating confined spaces, and applying forces on the environment. We concluded by identifying gaps in the state of the art and discussing opportunities for future research to advance vine robots and their usefulness in the field.

4. Ongoing Work

Building on the work begun during this project and the ISEP, we are continuing to collaborate with our colleagues at KAIST on two ongoing projects.

First, we are continuing development of a vine robot system for exploration and monitoring of very small underground spaces, with a particular application in exploring the underground habitat of the endangered California Tiger Salamander on Stanford's campus. This work builds on our development of a field-ready vine robot system that was used in 2018 to explore an archeological site in Chavín, Peru [6]. Key challenges for this work include miniaturization of the robot and the development of a new tip mount (building on our work in Section 3.d) that carries a camera and does not encumber the robot's ability to navigate tortuous paths as small as 2 cm in diameter.

Second, we are continuing our work on the use of vine robots as manipulators, with particular application for safe manipulation in human environments. Key challenges for this work include the development of actuation schemes and tip mount designs (building on our work in Section 3.d) that allow maneuverability of payloads over a large workspace.

Additionally, we obtained a DURIP (AFOSR) to purchase an optical frequency domain reflectometry (OFDR) sensor for sensing of the vine robot shape, as well as an ultrasonic welding machine for manufacturing a flexible housing/attachment for the sensor, and we will conduct research into how the addition of this type of sensing can aid in control of vine robots and the situational awareness given to the human operator.

Our work continues to develop the capabilities vine robots for real application to search and rescue scenarios. We are in contact with search and rescue professionals and have plans to test our field-ready vine robot systems with potential end-users to understand the needs for future vine robot research towards this application.

5. Publications

[1] J. D. Greer, L. H. Blumenschein, A. M. Okamura, and E. W. Hawkes, "Obstacle-Aided Navigation of a Soft Growing Robot," *IEEE International Conference on Robotics and Automation*, pp. 4165-4172, 2018. Paper available at https://doi.org/10.1109/ICRA.2018.8460777 and video available at https://youtu.be/Tf5P4L6b7OY

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[12] S.-G. Jeong*, M. M. Coad*, L. H. Blumenschein, M. Luo, U. Mehmood, J. H. Kim, A. M. Okamura, and J.-H. Ryu, “A Tip Mount for Transporting Sensors and Tools using Soft Growing Robots.” IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 8781-8788, 2020. Paper available at https://doi.org/10.1109/IROS45743.2020.9340950 and video available at https://youtu.be/eBKRbu_LSYA *These authors contributed equally to this work.

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