Design, Control, and Modeling for Soft Growing Robot Deployment for Nuclear Material Inspection

Yimeng Qin[1], Allison M. Okamura[1], and Marco Salathe[2]

[1]*Stanford University, 450 Jane Stanford Way, Stanford, CA, 94305, USA.*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA.*

Abstract

We present the design of a soft continuum robot that grows via pressure-driven eversion, referred to as a "vine robot", toward deployment in radiation-contaminated environments. Vine robots mimic plant-like tip extension by emitting material that turns inside out via internal fluid pressure. With a compliant body constructed from durable fabric and unique tip growth mechanism, vine robots can be deployed into narrow, cluttered, and tortuous spaces due to propulsion transmitted at the tip and minimal friction with respect to the environment. Unlike traditional robots that require onboard power and communication, the vine robot centralizes operation and deployment at its base, which is located away from the robot tip. The base station compactly stores the fabric material, deploys it in a controlled fashion, and includes mechanisms to enable steering of the robot body. Sensing systems integrated at the robot tip enable real-time inspection of unknown environments, data collection, and robot localization and mapping. The vine robot system can be operated via human-in-the-loop teleoperation or autonomous control. We designed specialized vine robots with three-dimensional growth and steering capabilities and used them to acquire remote video data inside pipes and around and over mock nuclear material containers.

1 Introduction

Nuclear material management is crucial for ensuring public security, safety, and regulatory compliance. Regular and precise nuclear material accounting and control (NMAC) prevents material loss, mitigates accidents, and supports regulatory adherence, which is vital for non-proliferation efforts [1][2]. Current methods rely on specially trained personnel and embedded tracking devices, which are labor-intensive, operationally risky, and cost inefficient. Robotic systems have the potential to enhance nuclear facility safety by minimizing human exposure to hazardous environments, providing precise nuclear material detection and localization, and enhancing overall efficiency [3].

Most robots can operate in relatively open areas [4][5][6], but have limited ability to navigate in confined environments due to their large size and lack of flexibility and adaptability. Numerous confined spaces within nuclear facilities, from narrow service tunnels to densely packed storage areas, present significant challenges for robotic operations. For example, interim storage facilities, which store nuclear materials in tightly stacked containers, require regular inventory checks and confinement monitoring [7]. Additionally, most nuclear power plants (NPPs) feature extensive and tortuous pipelines essential for cooling, waste management, and transmission of reaction chemicals. Both exterior and interior pipe conditions should be inspected [8], requiring robots able to perform 3D navigation and adaptable maneuvering inside confined spaces.

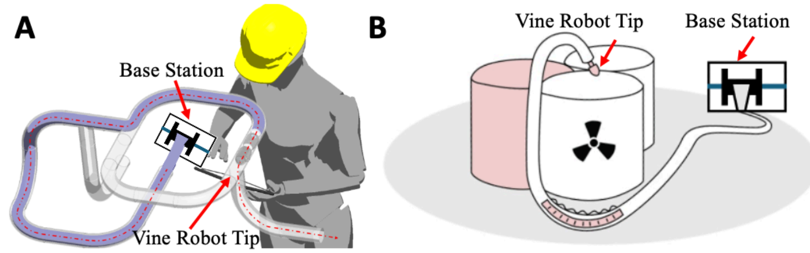

Figure 1: Conceptual illustrations of continuum robot deployment for nuclear material inspection: (A) Operation inside a pipeline, (B) Operation in an open 3D space.

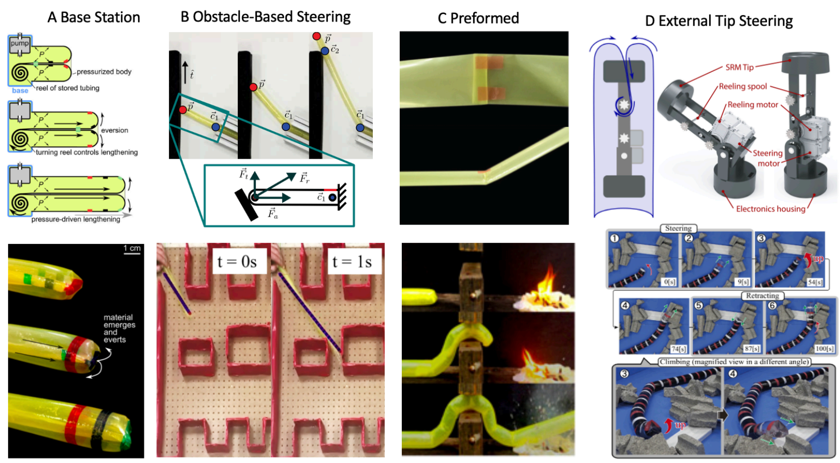

Figure 2: Vine robot eversion and steering methods appropriate for in-pipe navigation: (A) A base station deploys the body material in a controlled fashion (modified from [9], reprinted with permission from AAAS). (B) Obstacle-based steering changes the vine robot body shape via environmental contacts (modified from [10], reprinted with permission from Sage Publishing). (C) Preformed steering involves shaping the vine robot body to follow predetermined paths when the environment is known in advance (modified from [9][10], reprinted with permission from AAAS and Sage Publishing). (D) External tip steering devices control the tip direction (modified from [11][12], ©IEEE 2021).

In contrast to traditional rigid robots, soft robots are constructed from flexible materials, which allow them to maneuver through tight spaces. To perform inspection tasks, the robots need to perform 3D navigation and transport sensors to sites of interest. This can be achieved by continuum robots (continuous robotic structures with infinite degrees of freedom) that can enter confined spaces and support their own body weight and climb over obstacles and gaps (Figure 1).

One type of soft continuum robot, called the “vine robot”, is particularly well suited for confined space navigation [9], as shown in Figure 2A. Vine robots mimic plant-like tip extension by emitting material inside out due to internal fluid pressure. With a compliant body and unique tip growth mechanism, vine robots can be deployed into narrow, cluttered, and tortuous spaces due to propulsion transmitted at the tip and minimal friction with respect to the environment. A vine robot body can be constructed from low-cost, disposable fabrics or durable, radiation-resistant materials for long-term use. The base station integrates a motorized spool and pneumatic control system, which allows operators to control the robot several meters or more from the robot tip. Integration of a sensing system at the tip enables the robot to inspect unknown environments, collect data, and perform mapping and localization. This paper presents an overview of the design, control, and modeling of vine robot deployment for nuclear material inspection. We discuss designs specialized for two scenarios for nuclear material inspection: navigating inside pipelines and in open spaces.

2 General Vine Robot Design Concepts

Material Selection and Fabrication: A vine robot main body must be constructed from material that is inextensible in the radial direction such that, instead of expanding in the radial direction, applied internal pneumatic pressure will cause tip eversion, such that new "tail" material is pulled through the body and everted at the tip. The material must be sealable and impermeable to form a closed pneumatic vessel. Standard vine robot materials include low-density polyethylene (LDPE), nylon ripstop coated with thermoplastic polyurethane (TPU), and silicone-coated nylon [13]. All thermoplastic, or thermoplastic-coated, material can be sealed via heat sealing or ultrasonic welding, and thermoset-coated material can be sealed via adhesives.

Actuating Growth Length: The vine robot length can increase or decrease by changing the traveling direction of the tail material. Eversion occurs when the tail material is fed toward the tip, and the material is turned inside out via internal pneumatic pressure, such that tail material becomes wall material. Retraction occurs when the tail material travels in the opposite direction, and the wall material inverts and becomes the tail. A base station design [9], including a pressure vessel and body material motorized spool, is used to control the vine robot actuating growth length, as shown in Figure 2A.

Actuating Growth Direction: Enabling control of growth direction, i.e., steering, significantly enhances the vine robot's usefulness for tasks such as targeted location inspection [9][10][11][14][15][16], pipe branch-junction selection, and climbing over and around unconstrained environments, as shown in Figure 1. Various steering actuator designs have been proposed in the literature, with most focusing on achieving buckling and creating curvature in the vine robot material locally or globally (as shown in Figures 4B, 4C, and 4D). Because different design principles are used for steering in open and confined spaces, steering designs tailored to each scenario are discussed in the following sections.

Sensor Tip Mount Designs: Integrating sensors or tools at the vine robot tip is important for tip localization, state estimation, environment interaction, and data collection during navigation and exploration. Because the tip material of a vine robot continuously changes, the tip mount cannot be permanently attached to the body material and must travel with the everting tip. Several different mechanisms have been proposed in the literature, including cable inside the tail [9][17], friction fit on the external body [13], and interlock mechanism [18][19][20]. Because the tail material travels at twice the speed of the wall material, a cable inside the tail material will travel faster than the tip. Kim et al. folded the cable/tail material in an origami fashion, allowing independent control of cable speed [21]. Most tip mount designs involve rigid mechanisms, which decrease the robot's ability to enter confined spaces. Due to the force limitations of current steering methods, the weight of the sensors and tools attached at the tip limit 3D steering capability, confined space navigation, and low contact friction with the surrounding environment. These issues present design challenges discussed below.

3 In-pipe Vine Robot Design

Complex and dense pipe systems within nuclear facilities transport materials vital to facility operation, including delivering cooling solutions to nuclear reaction vessels, transporting steam vapor to the main power generator, and supplying fuel and lubricating oil to maintain the emergency diesel generator [22]. The geometry of pipe systems presents a critical challenge for performing inspection and maintenance of the pipe interiors – pipelines vary in length and diameter, and can follow tortuous paths. The lack of an efficient method to access the pipe interior can lead to failures that result in prolonged facility downtime, sustainability impacts, economic losses, and unsafe conditions [23].

Commercial in-pipe inspection devices include bore scopes and endoscopes, rovers, drones, and pipeline intervention gadgets (PIGs). These devices are inherently limited in their propulsion force to propel themselves of the material they carry forward. They also usually require a tether cable for power and communication, which severely limits their ability to traverse inside a tortuous pipeline with varying diameter. Due to their soft continuum nature, vine robots have an advantage in navigating such confined environments. In this section, we describe a vine robot design optimized for a pipe environment.

Eversion Pressure Modeling: For in-pipe vine robots, workspace analysis is performed to determine how far a vine robot can travel forward given the pipe geometry and vine robot parameters. The vine robot pressure must be high enough to overcome tip mount and tail friction to enable eversion and forward motion, while not being so high as to cause the vine robot to burst. To assess the deployment feasibility of the vine robot within a confined pipeline, we need to determine both the required eversion body pressure and the optimal diameter of the robot for a given robot material. Blumenschein et al. derived an eversion pressure equation that accounts for material yield pressure, tip velocity, and curvature-dependent friction [24]. The confined interiors and tortuous paths of pipelines restrict movement of the robot's tail material, causing it to slide against the interior of the vine robot wall material. This interaction, exacerbated by large curvature-dependent friction, limits the distance the vine robot can travel within the pipeline. To illustrate the practical application of Blumenschein et al.'s theoretical analysis, consider a pipeline used to transmit chemical products. This pipeline, with a radius of 10 inches, extends 760 feet long and includes four 45-degree turns. There are no existing navigation and inspection tools due to pipeline's lengthy distance, turns (including turns that go against gravity), and lack of flow during inspection. Applying Blumenschein et al.'s eversion pressure calculation to a vine robot constructed from low-density polyethylene (LDPE), the required eversion pressure decreases dramatically from 58.0 psi to 0.2 psi as the robot's radius increases from 0.5 inches to the pipeline's internal diameter of 10 inches. Given the burst pressure of LDPE, the vine robot's radius needs to be at least 2.7 inches to ensure safe operation and prevent material failure.

Actuating Growth Direction: The confined in-pipe environment naturally supports the vine robot's body. Therefore, rather than steering the entire body, which requires continuous actuation and is difficult to scale to arbitrary lengths, controlling the tip orientation is a more efficient and effective method. Figures 2B, 2C, and 2D show three steering methods suitable for in-pipe navigation [9][10][11][12][25]. Figure 2B shows how vine robots can use intentional collisions with the environment to steer [10]; a vine robot that is constrained to grow within a pipe with turns is an extreme example of this (i.e., Figure 1A). Figure 2C shows how the vine robot body can be preformed to create single and multiple bends to achieve passive steering without relying on environmental contacts [9]. Figure 2D depicts a rigid mechanical device for steering that is integrated at distal vine robot's tip location.

Debris Removal and Sample Collection: Beyond navigation and inspection, the vine robot is also capable of applying pushing and pulling forces to the environment, e.g. for unblocking a pipe. Previous work demonstrated that a gripper tip mount attached on vine robot can transmit 25 N of pulling force over a short distance, which is only 10 percent of the maximum force the vine robot body material can withstand [20] (Figure 3A). The pushing force, which is proportional to the propulsion force, can be increased by increasing the internal pneumatic pressure of the vine robot (up to the material burst pressure). Additionally, task-specific tools can be attached at the tip to apply force to a target more effectively (e.g., carrying a rotary drill). Although the interior pipe wall provides natural support to the vine robot body, the risk of collapsing or buckling can be minimized by mechanisms that push on the pipe's interior wall for stabilization. Future work is needed on modeling and control of stabilization mechanisms to maximize force transmission.

To analyze the interior condition of the pipe and materials causing blockage, it is desirable for the vine robot to acquire samples from the environment. In prior work, we added a gripper to the tip mount to retrieve small objects [20] (Figure 3B). The modular tip mount design can be modified for task-specific applications. Additionally, the vine robot body itself can be used to collect scattered debris by adding an adhesive layer on the body material. Figure 3C depicts the vine robot moving to a target location, and then inverting and engulfing debris samples [26].

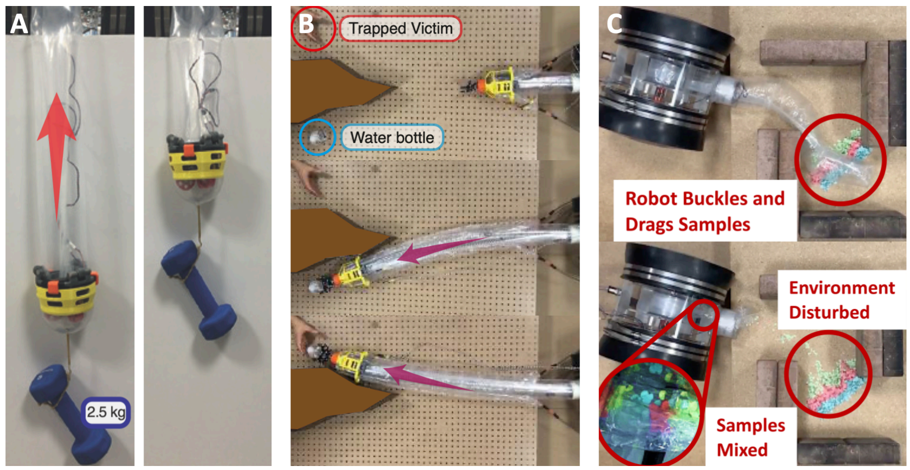

Figure 3: Methods of debris removal and sample collection [20][26]: (A) A tip mount designed to provide large pulling force in the retraction direction. (B) A vine robot can invert and engulf the debris samples to achieve sample collection during retractions. (C) A gripper attached on a tip mount is used to retrieve an objects. Modified from [26] ©IEEE 2020 and [20] ©IEEE 2020.

4 Open Space Vine Robot Design

Inspection in open spaces within nuclear facilities, such as material storage areas, cooling pools, and reactor halls, is necessary to ensure operational integrity and regulatory compliance. The challenges of performing such inspections include nuclear hazards, the vastness of the area, and the need to maneuver around delicate equipment and hazardous material. Traditional inspection methods involve humans carrying sensors and data recording equipment into facilities, with the aim of achieving direct line of sight to all areas requiring inspection. While well-trained operators are capable of collecting high-quality data, the inherent complexity and hazards of these operations can result in inefficiencies and safety risks. Existing robotic inspection solutions, such as mobile robots and drones, have limited 3D maneuverability and battery capacity. Vine robots are highly maneuverable and can reach far into spaces that need to be inspected, while being inherently tethered to power. They can travel up and over structures that block viewing of areas of interest. Their low inertia and ability to be easily disposed enables safe contact with objects in the environment. In this section, we will discuss our recent work on design, modelling, and control of a multi-segment vine robot. Each segment of the multi-segment vine robot can be independently controlled to curve in any direction, allowing a high degree of 3D maneuverability.

Actuating Growth Direction: Pneumatic artificial muscles introduce distributed strain on actuated sections, which effectively creates continuous bending on the backbone, i.e. the centerline of the long axis of the main body (Figure 4A). To this end, researchers have developed various distributed pneumatic artificial muscles, including cylindrical pneumatic artificial muscles (cPAMs), fabric pneumatic artificial muscles (fPAMs), series pneumatic artificial muscles (sPAMs), and embedded pneumatic artificial muscles (ePAMs) [15][16]. Kuebler et al. demonstrated a vine robot equipped with three lines of cPAM actuators, where each line is continuous from the base to the tip. Such a robot can navigate by interacting with objects in the environment, but it is limited in freespace due to only having four controllable degrees of freedom (growth and bending in three directions). To enhance maneuverability, our vine robot is designed with multiple segments, each featuring a distributed pneumatic artificial muscle that can be controlled to move with four independent degrees of freedoms (DOF). Thus, a vine robot with n segments possesses $4n$ bending degrees of freedom, plus the growth degree of freedom. The ePAM design was chosen for its durability and scalability. Other steering methods that are suitable for 3D navigation and will be explored in future work include various shape locking mechanisms and concentrated strain. Shape locking allows a vine robot to achieve more complicate shapes by discretizing the soft body's infinite degrees of freedom, and locking them individually [14][27] (Figure 4B). Furthermore, some researchers utilize tendons, usually routed from base to tip, to steer the vine robot body via buckling due to concentrated strain [28][29] (Figure 4C).

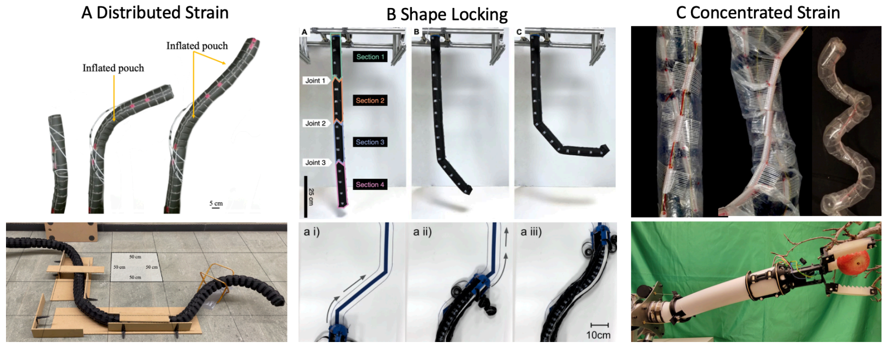

Figure 4: Methods of controlling and steering everting vine robots in open space: (A) Distributed strain uses series pneumatic artificial muscles to bend the vine robot body (modified from [16] ©IEEE 2021 and [15] ©Mary Ann Liebert, Inc.). (B) Shape locking forces the soft robot shape into finite degrees of freedom (modified from [14] ©IEEE 2023 and [27] ©Mary Ann Liebert, Inc.). (C) The concentrated strain method uses tendons routed from the base station to the actuated location (modified from [28] ©IEEE 2018 and [29] ©IEEE 2024).

Modeling: Understanding vine robot kinematics is necessary to predict robot shape and tip location, which are important for path planning. Models describing soft robot kinematics are often inaccurate due to the robots' infinite degrees of freedom. Compared to traditional elastomer-based soft robots, vine robots are made from inflated beams whose geometry can be more easily predicted when they are fully inflated. We use a constant curvature model (CCM) to model the shape of each segment of our multi-segment vine robot body [30]. The robot's distal tip location can be analytically described by applying a series of Constant Curvature Models (CCMs), one for each segment, where the end of one segment serves as the starting point for the next. The assumption for the CCM model is the each actuator array is parallel to backbone of the vine robot. Blumenschein et al. developed a closed-form geometric solution to characterize the bending of an inflated tube steered using cable-based actuators [28]. However, for the distributed strain actuators used on our vine robot, the steering workspace is affected by increased stiffening of the main body with increased pressure. This creates a trade-off between stability and steerability, to be addressed in future work.

Control: Vine robots can be controlled via teleoperation by a human operator or to operate autonomously. Sensor systems, including inertial measurement units (IMUs) and lightweight monocular/depth cameras, have been integrated in a tip mount of our multi-segment vine robot. These data are used to reconstruct the 3D environment and localize the tip. With robot kinematic modeling, the multi-segment vine robot can use these sensors to autonomously navigate. Autonomous control has been demonstrated in [32], which used an image-space Jacobian to minimize the image feature error and map back to the robot joint space, which allowed a robot to follow an object or light source in a closed control loop. In our project, we have utilized the design sensor system at the tip to perform simultaneous localization and mapping (SLAM), enabling effective path planning and obstacle avoidance. For teleoperation, we have in the past used a specialized flexible joystick that matches the shape of the vine robot [31], and used this system to explore an archeological site in Peru (Figure 5A) [13]. To control the additional degrees of freedom in our multi-segment vine robot, we use a standard commercial Xbox joystick (Microsoft) to enable our vine robot to climb into a 3D space and inspect its surroundings, as shown in Figure 5B.

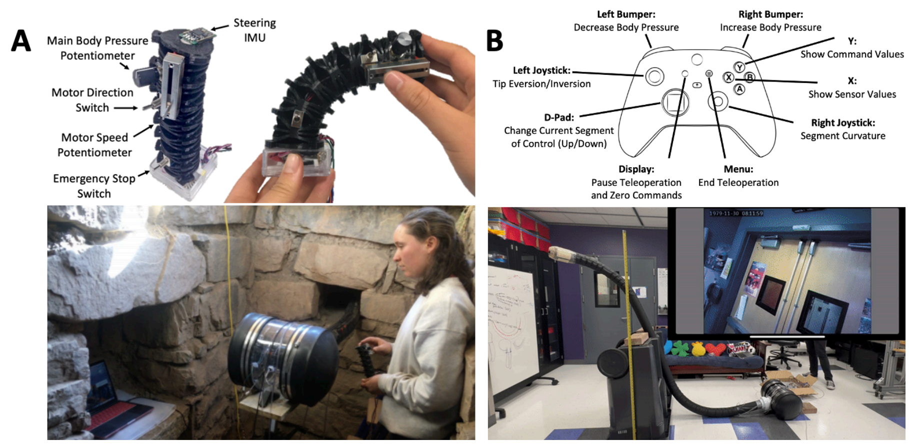

Figure 5: Direct teleoperation provides control commands to the vine robot to perform navigation and inspection work. (A) An intuitive flexible joystick controls the vine robot to navigate inside an archaeology site (modified from [31] ©IEEE 2019). (B) A human operator employs a Microsoft Xbox joystick to navigate the vine robot against gravity, performing the inspection of the surrounding three-dimensional space.

5 Conclusions and Future Work

In this paper, we presented the basic mechanisms and general merit of soft growing vine robots for nuclear material inspection. We summarized the state-of-art pain points for nuclear material inspection and highlight potential usages of soft robots. Specifically, we presented a review of design, control and modeling for vine robots that are specialized for two challenging scenarios inside nuclear facility, in-pipe and open space environment operation.

Additional considerations are required for operations in nuclear facilities, to be addressed in future work. In some environments, the fabric material used for the main robot body must be radiation resistant. High energy particles, such as gamma rays and neutrons, can cause chemical degradation and embrittlement, especially for long periods of exposure over the lifetime of the robot [33] [34]. To control contamination after deployment, the material needs to be designed for one-time use, prevent the attraction of radioactive particles, or be easily cleaned post-use.

In pipe environments, the internal friction between the tail material and the wall material limits the deployment length of the vine robot within very long and tortuous pipe systems. In such environments, mechanisms are needed to reduce tension in the tail. Additionally, pipe interiors are often GPS-denied. The sensors at the tip must communicate data back to the base via internal cables or multiple short-distance Wi-Fi transmitter and receiver systems, and consider data communication latency and accuracy.

To optimize inspection operations in open spaces, we need better theoretical or numerical modeling related to 3D steering. General and precise modeling of distributed strain actuators would better predict the workspace and ability to handle payloads, enabling optimization of design parameters. Concurrently, novel actuator designs with improved stress-strain performance should be developed. Furthermore, a model predicting potential buckling locations in 3D space would be useful for enhancing stability during 3D navigation.

Acknowledgments

This work was supported in part by U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) under Grant DE-AC02-05CH11231 and in part by Lam Research Corporation and the National Science Foundation under Grant 2024247.

References

[1] *Nuclear Material Accounting Handbook*, https://www.iaea.org/publications/7828/nuclear-material-accounting-handbook, Last accessed July 1 2024.

[2] "Basics of IAEA Safeguards," https://www.iaea.org/topics/basics-of-iaea-safeguards, Last accessed July 1 2024.

[3] R. Haddal and N. K. Hayden, "Autonomous Systems Artificial Intelligence and Safeguards." Sandia National Lab. Albuquerque, NM (United States), Tech. Rep. SAND2018-8193C, July 2018.

[4] "Data collection in nuclear environments," https://bostondynamics.com/solutions/safety/nuclear-decommissioning, Last accessed July 1, 2024.

[5] K. Groves, E. Hernandez, A. West, T. Wright, and B. Lennox, "Robotic Exploration of an Unknown Nuclear Environment Using Radiation Informed Autonomous Navigation," *Robotics*, vol. 10, no. 2, p. 78, 2021.

[6] "KUKA solutions for nuclear decommissioning facilities," https://www.kuka.com/en-us/industries/solutions-database/2017/08/nuclear-decommissioning, Last accessed July 1, 2024.

[7] "Storage of Spent Nuclear Fuel," https://www.nrc.gov/waste/spent-fuel-storage.html, Last accessed July 1, 2024.

[8] "Backgrounder on Underground Pipes at Nuclear Reactors," https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/buried-pipes-fs.html, Last accessed July 1, 2024.

[9] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, and A. M. Okamura, "A soft robot that navigates its environment through growth," *Science Robotics*, vol. 2, no. 8, p. eaan3028, 2017.

[10] J. D. Greer, L. H. Blumenschein, R. Alterovitz, E. W. Hawkes, and A. M. Okamura, "Robust navigation of a soft growing robot by exploiting contact with the environment," *The International Journal of Robotics Research*, vol. 39, no. 14, pp. 1724–1738, 2020.

[11] D. A. Haggerty, N. D. Naclerio, and E. W. Hawkes, "Hybrid Vine Robot With Internal Steering-Reeling Mechanism Enhances System-Level Capabilities," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 5437–5444, 2021.

[12] T. Takahashi, K. Tadakuma, M. Watanabe, E. Takane, N. Hookabe, H. Kajiahara, T. Yamasaki, M. Konyo, and S. Tadokoro, "Eversion Robotic Mechanism With Hydraulic Skeletonto Realize Steering Function," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 5413–5420, 2021.

[13] M. Coad, "Design, Modeling, and Control of Vine Robots for Exploration of Unknown Environments," PhD Thesis, Stanford University, June 2021.

[14] R. Jitosho, S. Simón-Trench, A. M. Okamura, and B. H. Do, "Passive Shape Locking for Multi-Bend Growing Inflated Beam Robots," in *IEEE International Conference on Soft Robotics (RoboSoft)*, 2023.

[15] A. M. Kübler, C. d. Pasquier, A. Low, B. Djambazi, N. Aymon, J. Förster, N. Agharese, R. Siegwart, and A. M. Okamura, "A Comparison of Pneumatic Actuators for Soft Growing Vine Robots," *Soft Robotics*, 2024.

[16] T. Abrar, F. Putzu, A. Ataka, H. Godaba, and K. Althoefer, "Highly Manoeuvrable Eversion Robot Based on Fusion of Function with Structure," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2021, pp. 12 089–12 096.

[17] J. D. Greer, T. K. Morimoto, A. M. Okamura, and E. W. Hawkes, "A Soft, Steerable Continuum Robot That Grows via Tip Extension," *Soft Robotics*, vol. 6, no. 1, pp. 95–108, 2019.

[18] F. Stroppa, M. Luo, K. Yoshida, M. M. Coad, L. H. Blumenschein, and A. M. Okamura, "Human Interface for Teleoperated Object Manipulation with a Soft Growing Robot," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2020, pp. 726–732.

[19] J. Luong, P. Glick, A. Ong, M. S. deVries, S. Sandin, E. W. Hawkes, and M. T. Tolley, "Eversion and Retraction of a Soft Robot Towards the Exploration of Coral Reefs," in *IEEE International Conference on Soft Robotics (RoboSoft)*, 2019, pp. 801–807.

[20] 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," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2020, pp. 8781–8788.

[21] J.-h. Kim, J. Jang, S.-m. Lee, S.-G. Jeong, Y.-J. Kim, and J.-H. Ryu, "Origami-inspired New Material Feeding Mechanism for Soft Growing Robots to Keep the Camera Stay at the Tip by Securing its Path," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 4592–4599, 2021.

[22] "IE Circular No. 80-05, Emergency Diesel-Generator Lubricating Oil Addition and Onsite Supply," https://www.nrc.gov/reading-rm/doc-collections/gen-comm/circulars/1980/cr80005.html, Last accessed July 1, 2024.

[23] "Pipe Rupture at Surry Nuclear Plant Kills Four Workers," 2018, https://blog.ucsusa.org/dlochbaum/pipe-rupture-at-surry/, Last accessed July 1, 2024.

[24] L. H. Blumenschein, A. M. Okamura, and E. W. Hawkes, "Modeling of Bioinspired Apical Extension in a Soft Robot," in *Biomimetic and Biohybrid Systems*, M. Mangan, M. Cutkosky,

A. Mura, P. F. Verschure, T. Prescott, and N. Lepora, Eds. Cham: Springer International Publishing, 2017, pp. 522–531.

[25] R. Jitosho, N. Agharese, A. M. Okamura, and Z. Manchester, "A Dynamics Simulator for Soft Growing Robots," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2021, pp. 11 775–11 781.

[26] M. M. Coad, R. P. Thomasson, L. H. Blumenschein, N. S. Usevitch, E. W. Hawkes, and A. M. Okamura, "Retraction of Soft Growing Robots without Buckling," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 2115–2122, 2020.

[27] B. H. Do, S. Wu, R. R. Zhao, and A. M. Okamura, "Stiffness Change for Reconfiguration of Inflated Beam Robots," *Soft Robotics*, 2024.

[28] L. H. Blumenschein, M. Koehler, N. S. Usevitch, E. W. Hawkes, D. C. Rucker, and A. M. Okamura, "Geometric Solutions for General Actuator Routing on Inflated-Beam Soft Growing Robots," *IEEE Transactions on Robotics*, vol. 38, no. 3, pp. 1820–1840, 2022.

[29] C. Ninatanta, R. Cole, I. Wells, A. Ramos, J. Pilgrim, J. Benedict, R. Taylor, R. Dorosh, K. Yoshida, M. Karkee, and M. Luo, "Design and Evaluation of a Lightweight Soft Electrical Apple Harvesting Gripper," in *IEEE International Conference on Soft Robotics (RoboSoft)*, 2024, pp. 479–484.

[30] R. J. Webster and B. A. Jones, "Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review," *The International Journal of Robotics Research*, vol. 29, no. 13, pp. 1661–1683, 2010.

[31] M. M. Coad, L. H. Blumenschein, S. Cutler, J. A. R. Zepeda, N. D. Naclerio, H. El-Hussieny, U. Mehmood, J.-H. Ryu, E. W. Hawkes, and A. M. Okamura, "Vine Robots: Design, teleoperation, and deployment for navigation and exploration," *IEEE Robotics & Automation Magazine*, vol. 27, no. 3, pp. 120–132, 2020.

[32] J. D. Greer, T. K. Morimoto, A. M. Okamura, and E. W. Hawkes, "Series Pneumatic Artificial Muscles (sPAMs) and Application to a Soft Continuum Robot," *IEEE International Conference on Robotics and Automation*, pp. 5503–5510, 2017.

[33] E. G. Souza, K. Kruger, C. D. Nascimento, C. Aguzzoli, G. Hoff, A. C. B. K. Moraes, R. G. Lund, P. S. Nascente, C. E. Cuevas-Suárez, E. Piva, and N. L. V. Carreno, "Development of Lead-Free Radiation Shielding Material Utilizing Barium Sulfate and Magnesium Oxide as Fillers in Addition Cure Liquid Silicone Rubber," *Polymers*, vol. 15, no. 22, p. 4382, 2023.

[34] Y. Ohki, Y. Miyazaki, H. Zhou, M. Sumita, T. Someya, and N. Hirai, "Mitigation of Degradation in Polymers by Gamma Rays," in *IEEE International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, 2021, pp. 89–92.