Tip-Growing Robots: Design, Theory, Application

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***Abstract*—Growing robots apically extend through material eversion or deposition at their tip. This endows them with unique capabilities such as follow the leader navigation, long-reach, inherent compliance, and large force delivery bandwidth. Tip-growing robots can therefore conform to sensitive, intricate, and difficult-to-access environments. This review paper categorises, compares, and critically evaluates state-of-the-art growing robots with emphasis on their designs, fabrication processes, actuation and steering mechanisms, mechanics models, controllers, and applications. Finally, the paper discusses the main challenges that the research area still faces and proposes future directions.**

***Index Terms*—Soft robotics, growing robot, vine robot, eversion, continuum robotics.**

I. Introduction

DRAWING inspiration from the apical extension of plants' roots and branches, tip-growing robots deploy through their environment by transporting material from their base to their tip. This new material then forms the body of the robot, onto which new transported material can be added. To date, there have been two main working principles for bio-inspired, tip-growing robots: (a) pressure-driven eversion, and (b) material deposition via additive manufacturing, both represented in Fig. 1. Navigation via apical extension enables the robot tip to advance while limiting the relative translation between the trailing body and the surrounding environment. The working principles above, especially when combined with fabrication using soft and compliant materials, make tip-growing robots attractive for deployment within sensitive and difficult-to-reach sites. Notably, growing robots have been proposed for applications ranging from burrowing, to search and rescue applications within debris, to intraluminal interventions.

Pressure-driven eversion leads to tip elongation by the unfolding and outward rolling of the material stored within the robot body. The mechanism emulates eversion in certain animal species, such as the octopus retina when blinking [1], snail eye extension/retraction in response to light [2], and muscle contraction in spine-headed worms [3].

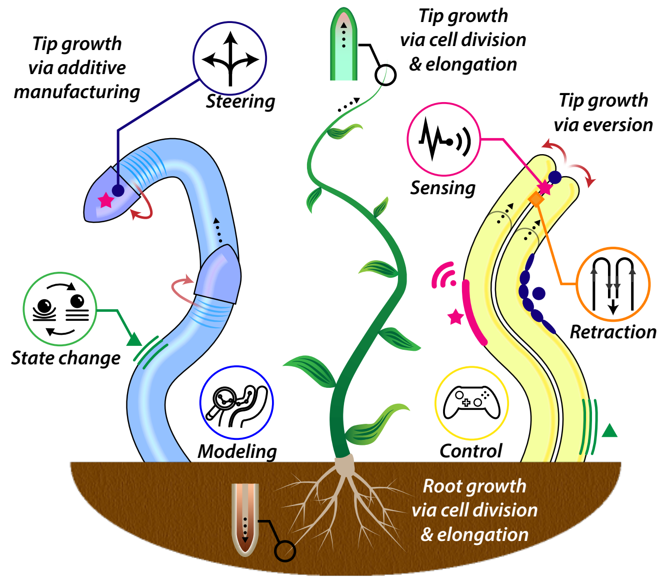

Figure 1. Representation of the two main tip-growing robot working principles proposed in the literature, i.e. material deposition via additive manufacturing (on the left) and pressure-driven eversion (on the right), and their bio-inspiration source, with a growing plant (middle).

Efforts to design eversion-based systems originate in the piping industry in 1977 for the renewal and repair of pipelines [4]. The eversion mechanism later started emerging in medical technologies to facilitate vascular catherisation [5], endoscopy [6], [7], and colonoscopy [8]. Industrial inspiration from the trenchless piping methods and eversion-based medical devices drew the attention of roboticists, eventually leading to eversion-based growing robots.

The first eversion robot, i.e. a mechanism with built-in actuation, sensing, and low control framework, was introduced in 2006 by Mishima *et al.* [9] in the context of "SlimeScope", a pneumatically expandable arm that navigated through rubble for search and rescue operations. Eversion growing robots were further developed by Tugokashi *et al.* [10] into an "active hose", a multi-degree of freedom steerable eversion growing robot with high flexibility and low external friction. More recently, Hawkes *et al.* [11] reinvigorated research on eversion growing robots, drawing inspiration from prior efforts and showcasing a wealth of physically intelligent behaviors.

Additive manufacturing was introduced as a growth mechanism by Sadeghi *et al.* [12], who deployed a 3D printer at the head of a robot. Further advancements facilitated sensing [13]–[15], passive morphological adaptation [16], and coiling

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motions (climbing) [17]. Robots that grow via additive manufacturing can modify their shapes by tuning the printing parameters, may self-support their own weight, and demonstrate soft bending capabilities.

Comprehensive reviews of the literature on tip-growing robots were provided in [18], and [19], in 2020, covering growth by eversion, and by additive manufacturing, respectively. Over 80 new papers have been published since then, detailing new designs, fabrication, actuation, sensing, modeling, and control approaches of these classes of robots. Our manuscript revisits the research landscape to take a deeper look into the contemporary state-of-the-art, consolidating existing research and identifying trends and gaps in the field.

Our method of study was as follows. First, we defined keywords relating to the topic, e.g. "eversion growing", "soft growing", "bioinspired robotics", "growing robot" and "vine robot". These keywords were entered into academic databases, including "Web of Science", "Google Scholar" and "IEEE-Xplore" to guide the search, in addition to volume-by-volume exploration of key academic journals and conference proceedings. The forward and backward citations of each identified publication were tracked to ensure no relevant manuscript was missed. We limited the scope of this paper to the predominant approaches to tip-growth, i.e. everting and additive-manufacturing robots, illustrated in Fig. 1. Other tip-growing robots, such as chain-block [20] and tape-measure [21] designs were excluded. Publications related to eversion outside the context of tip-growth, such as toroidal eversion robots, e.g. [22], [23], were also excluded. The search led to a total of 135 relevant manuscripts that are categorised, compared and critically assessed within the manuscript. In addition, our contribution includes the creation of and keeping up-to-date an online public resource that provides details on the existing tip-growing robots[1].

The rest of this paper is organized as follows. Sec. II provides an overview of growing robot design, showing the different growth mechanisms that have been deployed, and the materials and features used in their fabrication. Sec. III highlights the steering, variable-stiffness and shape-locking research, and Sec. IV details the work on perception and functionalization via sensor and tool integration. Sec. V describes the modeling and Sec. VI discusses the control approaches. Sec. VII showcases the application domains of growing robots, namely the healthcare, subterranean, and inspection fields, and deployable structures. Finally, Sec. VIII summarizes the review and highlights gaps and potential future directions.

II. Working Principle and Fabrication

This section presents the working principles, design landscape, and materials used for developing tip-growing robots. Fig. 2 illustrates the main growing mechanisms and their similarity to a living plant as source of bioinspiration. See Table I subscript for the acronyms in this Section.

[1]https://cgirerd.github.io/tip_growing_robots.html

A. Eversion-Based Growth

- Concept and Working Principle: Everting growing robots navigate their environments through pressure-driven eversion, whereby they unroll and deploy from the tip as internal pressure is applied to the system [11]. In such cases, the base of the robot remains in a fixed position with respect to the environment and only the tip undertakes relative motion, reducing the friction associated with body translation within the environment. To achieve this, the material of the everting body has first been stored at the robot base, in a motorized spool [11]. However, this approach limits the use of the central robot lumen as a working channel. An alternative approach has been to store the inverted (or tail) material straight, to maintain an open lumen for the passage of tools, or the inclusion of a working channel [24]–[27]. However, since the tail material translates at twice the speed of the components inside it, the friction between the tail and the components limits the growth length of such robots. More recently, the concept of origami-inspired material scrunching (or gathering and folding) was introduced, where the tail material can be scrunched at the tip [28] to maintain a working channel regardless of eversion length and curvature. Also, a design was proposed, with the body of the robot being a sleeve inside which individual small everting robots grow, following a circular pattern, and enabling a central working channel [29]. While everting growing robots are typically pneumatically actuated, research has also reported hydraulic actuation with more viscous working fluids to exhibit buoyancy forces required for underwater operation [30], achieve higher actuation forces and speeds [31], reduce buckling by increasing contact forces with the surface [32], or improve the safety in intraluminal applications [27].

Different robot architectures and configurations have been explored, with the most common being a single-cavity, single-path robot. Helical structures have also been utilized to enable shape reconfiguration for deployable structures, such as antennas [33] and wearable haptics [24]. In [34], a bi-cavity robot was proposed, comprised of two vine robots arranged concentrically, able to grow independently. The outer vine robot everts, enabling deployment in the environment without friction forces, while the inner one can evert or invert, enabling the grasping of an object.

In addition to single-path everting robots, multiple branching configurations have been proposed to enhance the robot's navigation capabilities. Blumenschein *et al.* [33] proposed a branching design made by pre-forming the robot with branches perpendicular to the main body, which evert and lengthen. The length of the branches was controlled through internal tendons. Similarly, Glick *et al.* [35] created branching robots by Thermoplastic Polyurethane (TPU) laser-welding an everting tube to create a 2D branched body with a single open end. It was inverted, mounted to the robot base, and the non-deployed branches were crumpled and stored at the base to prevent overlapping and jamming.

- Materials and Fabrication: The materials used in everting robots are characterised by their high compliance, low hysteresis, flexibility and, in most cases, inextensibility. Inextensible materials ensure that the pressure applied to evert the tip does

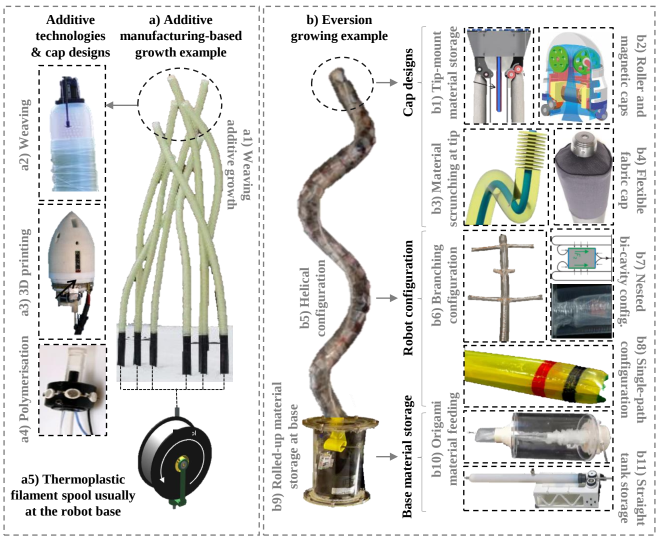

Figure 2. Design overview of tip-growing robots. (a- left) Additive-manufacturing robots [36] grow from the tip via (a1, a2) weaving [37], (a3) 3D-printing [17] or (a4) polymerisation [38]. They rely on material deposition at the tip, typically with (a5) filament spool storage at the base [17]. (b- right) Eversion robots grow by unfolding from the tip as pressure is applied [11]. They showcase different cap designs to (b1) store material at the tip [39] or to integrate tools and sensors into the robot via (b2) rigid outer caps [40], (b3) soft fabric caps [41] or (b4) tip-material scrunching (also known as origami folding or material gathering) [28]. Different eversion robot configurations have been deployed, such as (b5) helical configuration [33], (b6) branching of the robot body [33], (b7) nested bi-cavity structure [34] or (b8) single-cavity, single-path straight configuration [11]. Material storage in eversion robots is achieved via (b9) spooling at the base [11], (b10) material folding at the base [25] or (b11) straight material storage in a long, air-tight tank [42].

not cause radial expansion or longitudinal stretching of the robot body and allows for shape change without requiring high energy [18]. Examples of such materials include thermoplastics, synthetic fabrics and thermosets, as reported in Table I and Fig. 3 with the material properties.

Thermoplastics are the most commonly used, as they are inexpensive and available in various diameters and lengths as seam-free layflat tubing. An alternative to off-the-shelf tube is to form the tubular everting structure in-house via heat-sealing [27], laser-welding [43], or ultrasonic-welding [44]. The high tensile strength and flexibility of Low Density Polyethylene (LDPE) make it a popular material choice. Borkar *et al.* [45] compared the eversion performance of transparent LDPE, black LDPE, and tarpaulin High Density Polyethylene (HDPE). Although the transparent LDPE was the quickest and easiest to prototype, the lengthening rate of the HDPE-based eversion robot was significantly less dependent on the eversion pressure and tube diameter, providing more consistent growth. HDPE is also stronger and more tear-resistant than LDPE [46], which tends to fatigue easily after multiple eversion cycles due to its low strain limit [18]. LDPE also tends to retain its shape when stored on a reel, resulting in curves upon inflation [47]. Other work explored the use of other thermoplastics, such as laser-welded [35] or heat-welded [48] TPU, or heat-sealed polypropylene [31], due to their higher strain limits.

Synthetic fabrics, such as nylon and polyester, are highly compliant, flexible and robust. Coating nylon fabrics with a silicone or TPU layer [49] can make the fabrics airtight and waterproof. The fabric can be sealed into a tube using silicone (if silicone-coated) or natural rubber adhesive (e.g. polyurethane), adhesive tape, or if TPU-coated, through heat-sealing or ultrasonic-welding [44], [50]. Overall, the use of ripstop fabric makes the tubular everting structures more durable and tear-resistant [51]. In particular, the high tensile strength of Nylon [52] and the high tear-resistance of polyester make them popular choices [39]. Composite materials made of polyester with a mesh of reinforcement fibers in between have been used in the case of material scrunching [28]. The thinness of the material enabled high compression ratios for material storage in scrunched vine designs, while the reinforcement fibers provided high burst pressures by enabling high tear and tensile strength in the composite material. Finally, double-layered tubes have been proposed, where the inner LDPE layer provides a good air seal while the outer nylon layer increases the system's durability and robustness [53], [54].

An alternative class of materials is hyperelastic thermosets, such as latex. Early work [55], [56] demonstrated that latex can erode quickly at high temperatures, has a tendency to burst, and can have limited repeatability due to its viscoelastic properties. However, recent work [57] demonstrated possible shape-locking capabilities, control of the robot diameter at different locations through bulging, and reduction in tail tension, which lowers the robot's tendency to buckle, improving its retraction capabilities.

More recently, several eversion robot designs have made use of inhomogeneous materials or structures to create an imbalance across the robot body, which can be utilized for steering or maintaining tools at the tip [51], [58]. Suukler *et al.* [58] fabricated the everting tube using a cotton weave for the lower half of the structure and cotton mixed with elastane for the upper half. The material imbalance allowed the more elastic half of the robot to stretch and the less elastic half to relatively shorten, achieving thus directional steering.

B. Additive Manufacturing-Based Growth

- Concept and Working Principle: An alternative way of achieving apical extension is by building the robot body *in situ* at the tip via additive manufacturing. A common approach entails installing a customized, miniaturized 3D printer at the tip of the robot, as introduced by Sadeghi *et al.* [12]. Such systems can actively alter the viscoelastic properties of their material, allowing them to achieve sufficient rigidity required for some applications, such as burrowing [12]. Their intrinsic state change properties can also be exploited for obstacle avoidance strategies and contact-assisted steering [16].

Weaving as an alternative method of growth via additive manufacturing was demonstrated in [37]. The growing robot consisted of a fiber-winding system, using soft fiberglass and Ultra Violet (UV)-curable resin for the fabrication. The system functioned by inflating a silicone tube from the base and weaving the fiber-reinforced composites along the exterior surface of the tube. After the composites were cured, the silicone tube was deflated, leaving behind the composite structure. The robot could be steered before weaving the subsequent segment, allowing for control of the tube geometries and

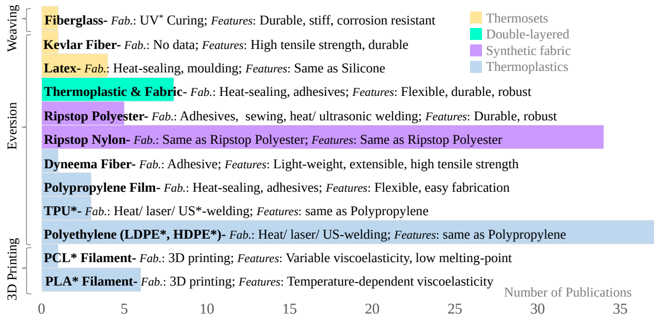

Figure 3. Growing robot material range, fabrication (Fab.) method, main features, and application frequency in literature. *See Table I subscript.

patterns through the fabrication sequence. This mechanism could build self-supporting, potentially interwoven, structures, with use cases in building walls and bridges.

More recently, Hausladen *et al.* [38] facilitated additive growth via local polymerisation by supplying the system with a constant flow of a monomer solution and solidifying it at the tip, then illuminating desired regions to enable the growth of the tip at the specified area. By tuning the chemistry in such system, the mechanical and physical properties can be regulated.

- Materials and Fabrication: 3D printing-based growing robots conventionally use Polylactic Acid (PLA) material, depositing and cooling the melted layers sequentially [12], [14], [16], [59], [60] or cooling the layers all at once to speed up the process via extrusion printing [36]. PLA's viscoelastic properties are temperature dependent, which poses an advantage when the tip encounters obstacles, as it can be heated to its ductile phase, allowing it to squeeze through barriers. Meder *et al.* [60] highlighted that while PLA provides desirable mechanical properties, its melting point of $150-180$ °C [60], [61] stresses the system by reducing motor efficiency, and can affect soil moisture in subterranean applications. Polycaprolactone (PCL) was suggested as an alternative 3D printing material due to its lower melting point (60 °C). However, this reduced thermal exchange within the system makes it more difficult to achieve cooling. Moreover, PCL is highly adherent, which can lead to slippage during growth, resulting in uneven growth.

UV-curable composites have also been explored, e.g. a mixture of fiberglass with UV-curable resins released from a nozzle to form interwoven structures [37]. The produced structures were highly durable, stiff and weather-resistant. In [38], a PDMS-PEA monomer underwent a UV-curing process to form a solid polymer during robot growth. The photopolymerisation process provides the advantage of modulating the mechanical properties (e.g. stiffness) of the growing body simply by tuning the chemistry of the solution (molar ratio and concentration). The materials and fabrication methods of eversion and additive manufacturing-based growing robots are reported in Table I and the graph of Fig. 3.

III. Steering, State Change, and Retraction

In addition to the forward growth of the robot, various actuators and mechanisms have been integrated to enable additional functionalities such as steering, state-change (including stiffening of the robot body), and retraction. See Table II subscript for the acronyms used in this Section.

Table I
Manufacturing methods to construct the growing element.

Mechanism (Material)	Features (+) & Limitations (-)
Welding:	
Heat welding (thermoplastic films*, latex, silicone, TPU*-coated fabrics) [27]	+ Quick, low cost, high strength - Thick weld, microfabrication issues
CO_2 Laser-welding (thermoplastic films) [43]	+ Repeatable, microscale, thin weld, bespoke shapes - Low tear strength
US*-welding (TPU-coated fabrics, thermoplastic films) [44], [50]	+ Quick, efficient, repeatable, High strength - Forms thick welds leading to microfabrication issues
Adhesives:	
Silicone adhesive (silicone-coated fabrics) [49]	+ Fast curing time, bespoke shapes - Materials specific, low repeatability
Polyurethane adhesive (TPU, TPU-coated fabrics) [62]	+ Bespoke shapes - Long curing time, low strength, low repeatability
Adhesive tape (fabrics, TPU, polypropylene) [44]	+ Quick, simple - Microfabrication issues, low strength
Stitching:	
Sewing (fabrics) [63], [64]	+ Repeatable, quick, bespoke shapes, high strength - Sealing & microfabrication issues
Additive Manufacturing:	
3D printing (PLA*, PCL*) [12]	+ Robust, active stiffness modulation - Microfabrication issues, limited use-cases due to fabrication speed & friction exertion
Weaving & UV*-curing (fiberglass) [37]	+ Durable, Self-weight support - As 3D printing

*Thermoplastic films include LDPE, HDPE, TPU and polypropylene. **TPU**: Thermoplastic Polyurethane, **PLA**: polylactic Acid, **PCL**: Polycaprolactone, **LDPE**: Low Density Polyethylene, **HDPE**: High Density Polyethylene, **UV**: Ultra-Violet, **US**: Ultra-Sound.

A. Steering

Both passive and active steering solutions have been proposed for tip-everting robots. They are described hereafter, and are represented in Fig. 4 and reported in Table II.

1) Passive and Environment-Assisted Steering: Passive steering methods do not rely on active control of actuators and sensors. They can include pre-defined morphology, which uses the robot's inherent design to guide movement, contact-assisted steering, which leverages environmental interactions to steer the body, and material response to external stimuli.

- Pre-defined Morphology: A simple approach for steering eversion-based growing robots is to pre-form the body of the robot prior to its deployment. This can be achieved by placing adhesive tape along the desired bending points [44], [65], directly soldering or welding the bends onto the material [31], creating a pre-shaped tube [55], [62], [66], or fastening rigid connectors together to create bends [44]. Pre-defined steering simplifies the system and allows the robot to freely grow along the path, but can only be applied to known static environments.

- Contact-Assisted Passive Steering: While obstacles are usually seen as hindering robot motions, recent works include utilizing obstacle interactions to steer and aid navigation. This includes model-based contact-assisted steering by predicting the robot path and obstacle collisions in a cluttered environment [65], [67]–[70]. See Sec. VI for further discussion.

Alternatively, growing robots can passively adapt their morphology upon contact with the surroundings. For eversion robots, this can be in the form of self-interactions in highly constrained environments, or wall-contact, as characterised in [71]. Additive manufacturing-based growing robots, can also be passively steered by utilizing the compliance of the robot body [12] or heating the PLA head to its ductile phase [16] to adjust the robot path as it encounters an obstacle.

- Material Response to External Stimuli: With material-level responsiveness, steering of growing robots can be achieved in response to external stimuli without input from the central robot controller. For the eversion-based growing robots, passive steering using Photo-Thermal Phase-Change Series Actuators (PPSA) was demonstrated in [72]. A low boiling point working fluid (Novec-7000) was encased in pouches that were arranged along the sides of the robot body. As the working fluid changed its phase from liquid to gas due to external stimuli (infrared light), the pressure inside the pouch increased and steered the robot. In the case of additive growth, local polymerisation, previously highlighted in Sec. II.B, was utilized as an actuation mechanism for achieving growth. This mechanism can simultaneously be used to achieve directional steering by polymerising the material at arbitrary points through UV-light curing [38].

2) Active Steering: Growing robots with active steering enable a larger variety of shapes. Different mechanisms have been proposed for distributed steering of the entire robot backbone, or for articulation of the robot tip or individual locations along the robot body.

a) Distributed Steering: Several steering methods that deform a significant length of the robot have been shown for eversion-based growing robots.

- Tendon-Driven: Typically, tendon-driven steering features multiple tendons routed outside the robot body, along its entire length. In order to ensure uniform deformation of the robot along its length, the tendons are routed inside guides evenly spaced along the robot body. Pulling the tendons shrink the regions of the robot between the guides, which come into contact. The tendons have been placed either axially along the robot [73], enabling bending of the robot body, or helically around the robot, to produce bending and torsion of the robot body, leading to helical shapes [74]–[76]. Tendon-driven steering is repeatable, precise, and can enable reversible shape change [50]. However, tendons may create friction forces against the environment, and the guides need to withstand the eversion process at the tip.

- Pneumatic Artificial Muscles (PAMs): PAMs are a class of inflatable contractile actuators. They turn potential energy from compressed gas to mechanical energy [77]. As PAMs contract the robot body locally for long lengths, they provide more uniform bending along the length compared to the use of tendons and tubular guides. In addition, they are entirely soft and do not translate with respect to the environment [78].

One example is series PAMs (sPAMs) or pouch motors (SPMs), which consist of a tube with partial seals that form radial constraints (sPAMs) or flat surfaces (SPMs) along its width, repeated along its length. These tubes are attached along the robot's pneumatic backbone. Upon inflation, the pouches balloon and contract the robot body [77], [79]–[81]. Internal attachment of the pouches has been shown to improve bending by 133% compared to external attachment [78], and adjusting the sPAM configuration (number of pouches and arrangement) directly impacts the achievable bending angles [82]. Another class of PAMs are fabric PAMs (fPAMs), which leverage the patterns in ripstop fabrics. Introducing a bias-cut in the fabric provides the actuator with elastic properties, compared to the inextensibility presented with straight cuts, i.e. when cutting along major thread lines [49]. The fabric bias permits fPAMs to simultaneously expand radially and contract laterally as they are pressurised [49]. As fPAMs use low-friction fabrics to create a single tube, they are easy to evert and demonstrate quicker response times than alternative PAMs [50]. Inverse PAMs (iPAMs) comprise a latex rubber tube that lengthens when pressurised, while fibers wrapped around the actuator limit its radial expansion. By tuning the pressure of the iPAM, the helical shape of a robot can be held or reconfigured [33]. The use of elastic material in iPAMs produces a non-linear stress-strain graph, complicating control [51]. Eversive PAMs (ePAMs) use an airtight fabric that folds inside out and everts when pressurised. A pulling force is generated by pulling on an internal tendon. EPAMs have a linear force-pressure relationship and their stiffness increases as a function of pressure [51]. Cylindrical PAMs (cPAMs) are constructed by integrating a set of cylindrical pouches directly onto the robot body to act as the upper layer, increasing their robustness [50], [78]. Compared to alternative PAMs (e.g. sPAM), cPAMs are not constrained by the folded material along the edges. Both parameters enhance cPAMs bending performance, as they undergo significant cross-sectional deformations as the pouches are inflated [50].

- Magnetic Steering: Magnetic steering is of interest to reduce the space requirements inside the robots. To enable it, Davy *et al.* [83] proposed to coat the LDPE robot body with a Neodymium-Iron-Boron (NdFeB) magnetic powder-doped silicone layer, and to control the steering direction using an external permanent magnet. This approach has potential for miniaturization, but requires the magnetic platform to be placed within very close proximity to the robot in order to achieve a sufficient magnetic moment for steering.

- Additive Manufacturing-based Steering: 3D-printed growing robots can steer by changing the growth orientation. In [13], [17], three printing parameters, i.e. heating temperature, speed of incoming filament, and speed of head rotation, were tuned to change the viscoelastic properties (i.e. stiffness) of the PLA filament, resulting in active steering of the growing robot. The filament was made rigid to navigate through gaps and self-support when required, or made soft to speed up robot growth and to facilitate plant-like twining (i.e. circling as it climbs upwards). Upon sensing external stimuli (e.g. gravity, light, and shade), the embedded additive manufacturing mechanism triggered an adaptive growth behavior [17].

b) Localized Steering: Steering mechanisms that articulate specific/ selected locations along a growing robot, e.g. in the form of a local sharp bend, are discussed here.

- Latches: One of the first active steering mechanism proposed relies on mechanical latches, which retain some robot material in their locked configurations. Upon some pressure in external chambers around the eversion robot body, the latches snap, and release the stored material, thus lengthening the corresponding robot side [11]. We note that such steering is not reversible.

- Magnetic Valves for PAMs: Compared to the serially con-

Table II
STEERING MECHANISMS IN GROWING ROBOTS

Mechanism and Methods	Advantages (+) and Limitations (-)
Passive Steering:	
- Pre-defined [66]	+ Simple; no actuators needed for steering - Not-steerable on-demand; path should be known
- Contact-based: model-based [67] or passive morphological adaptation [16]	+ Simple deployment, possible precise shape control for model-based additive growth - Not deployable in open environments; reachable path is limited by obstacle arrangement; high shear forces against the environment
Passive adaptation by external stimuli	
- PPSA* [72]	+ Material-level responsiveness; instant response - Deployment only in open environments
- Local polymerisation [38]	+ Possible anisotropic growth; tunable mechanical and physical properties - Slow response; limited eversion length
Active Steering:	
Distributed steering	
- Tendon-driven [27]	+ Simple modeling and control; constant curvature bend - Tendon-routing friction; non-uniform curvature
- Pneumatic Artificial Muscle (PAM*): SPM* [80], sPAM* [77], fPAM* [49], iPAM* [33], ePAM* [51]	+ Entirely soft design, minimal friction; variable stiffness with fPAM - Non-linearity for stretchable fabric; limited steerability due to serial connection; can occupy large volumes
- Magnetic [83]	+ Scalable; embedded as the robot skin - Requires close magnet-robot proximity; repeatability limited by bonds between robot layers
Localized steering	
- Latches [11]	+ Entirely soft actuator; simple fabrication and control - Irreversible
- Magnetic valves for cPAM* [84]	+ Selective pouch steering; highly bendable; high lateral forces - Large volume with slow response
- Internal device: rigid articulated links [85], TSA* [86], continuum robot [64], reeling [87], heat welding [88]	+ High payload; sharp and precise bends at arbitrary points; often facilitates buckling-free retraction - Heavy; rigid components limit compliance e.g. for passing narrow openings
- Additive: e.g. FDM* [17]	+ Fully-autonomous; variable stiffness; speedy growth; self weight support; 3D steering - Slow; irreversible; not retractable

***PPSA**: photothermal phase-change series actuator; **SPM**: series pouch motor; **PAM**: pneumatic artificial muscles; **sPAM**: series PAM; **fPAM**: fabric PAM; **iPAM**: inverse PAM; **ePAM**: eversive PAM; **cPAM**: cylindrical PAM; **TSA**: twisted string actuator; **FDM**: fused deposition modeling printing.

nected PAMs described above, which are limited to constant curvatures along the entire body, Kubler *et al.* [84] proposed to connect cPAMs in parallel to a pressure supply line, enabling independent actuation of the pouches for local steering. Each pouch had an embedded 3D printed magnetic valve that could selectively open and close via an external magnetic field. By selectively inflating individual pouches, local bends could be achieved, enabling higher degrees-of-freedom with few control inputs.

- Internal-device Steering for Eversion Robots: Another approach is to introduce rigid devices inside the robot to achieve localized steering. For instance, this can be in the form of a steering-reeling device that enables bending by rotating two internally placed segments [87]. Another method is to integrate a continuum robot inside the front segment of the everting body [64] to provide it with three degrees-of-freedom. Rigid links, tendons and twisted string actuators (TSAs) have also been used to achieve localized bending by shortening one side of an internal mechanism [48], [85], [86]. Finally, heat-welding mechanisms can also be incorporated into internal-steering devices in order to construct bending structures in real-time, based on wall-contact or pre-programming [52], [88], [89]. The difference in length between the welded and unwelded sides causes bending towards the welded side.

While steering using internal devices can enable large

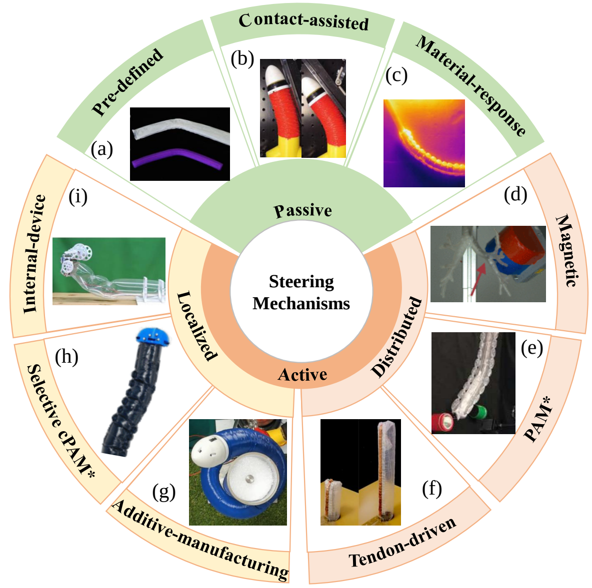

Figure 4. Steering mechanisms deployed in growing robots. **Passive steering:** (a) Pre-forming the robot body by molding and heat-sealing [66], (b) Contact-based steering, where PLA changes its viscoelastic properties to turn around obstacles [16], (c) Robot body-material response to light and heat [72]. **Active distributed steering:** (d) Magnetic skin [83], (e) Pneumatic Artificial Muscles (PAM) [77], (f) Tendon-driven steering [33]. **Active localized steering:** (g) Tuning printing parameters via additive-growth [17] (h) Localized pouch inflation e.g. cylindrical PAM (cPAM) [84] (i) Steering eversion robots via internal-device, e.g. adjusting path based on real-time heat-welding [52]. *See Table II subscript.

bending angles and tight curvatures at the tip, such devices to date require rigid components, limiting the robot's compliance and increasing its size and weight.

B. State Change for Steering and Force Transmission

Growing robots, like other continuum robots, are reconfigurable and have infinite degrees-of-freedom. In constrained pathways, multiple bends can be achieved upon contact with the environment by conforming to an available path. However, in an open environment, the limited number of actuators in growing robots makes it difficult to activate their degrees-of-freedom, unless additional external hardware components are integrated into the robot body. Shape locking and/or stiffening concepts can control the robot's structural deformation to achieve the required degrees-of-freedom.

1) Shape-Locking: Multiple mechanisms for active shape locking have been proposed, where multiple bends along the body are maintained. In general these approaches require additional actuation controls, which can increase the robot complexity. For example, shape-locking segments were passed through the guide-tubes along the body of a tendon-driven robot, everting independently of the main body, locking the curves in position [73]. Another proposed approach for active locking involves the use of magnetic valves [84], where cPAMs were selectively actuated to achieve bends at desired locations. Active shape locking can also be coupled with variable stiffness mechanisms [90], [91]. The use of non-reversible latches for steering can also be viewed as a shape-locking mechanism [11].

Passive shape-locking has been more recently demonstrated with simpler design approaches, commonly in the form of

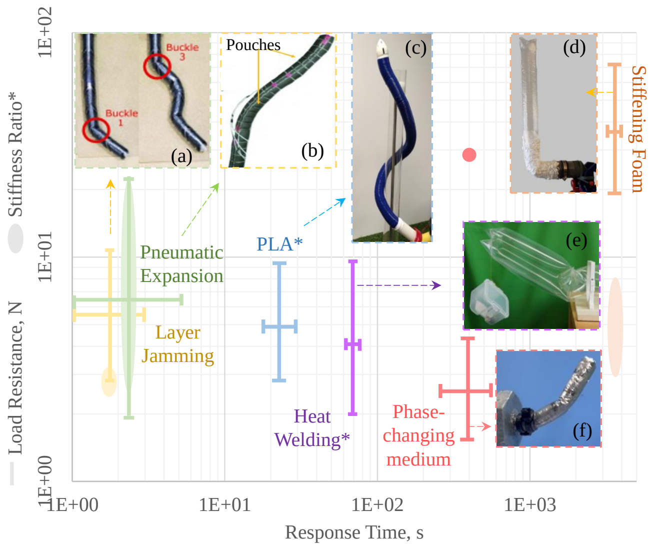

Figure 5. Controlling stiffness in growing robots through **(a)** layer jamming [90], **(b)** pneumatic expansion [78], **(c)** PLA (polylactic Acid) property change [17], **(d)** stiffening foam [94], **(e)** heat-welding [52], and **(f)** phase-changing alloy [95]. The graph indicates the relationship between load resistance (line), stiffness ratio (oval), and response time for all mechanisms. All data was retrieved and averaged from the respective papers. *No stiffness ratio data on heat-welding and PLA.

Table III
VARIABLE STIFFNESS MECHANISMS DEPLOYED IN GROWING ROBOTS

Mechanism	Advantages (+) and Limitations (-)
Pneumatic expansion [54], [56], [66], [78]–[80], [96]	+ High stiffness ratio - Limited by pouch geometry, limited accuracy at low pressures
Layer jamming [90], [97], [98]	+ Simple deployment - Limited efficacy, miniaturisation issues
Heat-welding [52], [89]	+ Shape-locking, reversible variable stiffness - Limited by the number of shape-locking bodies, irreversible steering
Foam-based [94]	+ Passive shape-locking - Slow response, environmental damage upon solidification
Phase-changing medium [95]	+ High stiffness ratio, dual functionality as stiffening and actuation medium hence simple integration - Slow response time, requires continuous heating, forms sharp edges when solidified

loops that enclose the robot body in the desired locking point. In [92], a passive tip mount deploys a hook-and-loop fastener at a certain distance from the tip, locking the proximal length of the robot body, while the distal region is able to bend. Similarly, Bianchi *et al.* [93] used re-closeable velcro straps to form flexible rings around the robot, permitting multi-bend shape locking by controlling the location of the Velcro straps.

2) Variable Stiffness: The inherent compliance of eversion growing robots affects tool stability, force exertion, and their tendency to buckle under high loads. Variable stiffness mechanisms enable systems to maintain their ability to conform to complex pathways, while improving the aforementioned capabilities. Although variable stiffness is important when using growing robots in sensitive and intricate applications, it can be challenging to achieve due to their continuously changing morphology. Table III and Fig. 5 compare the different variable stiffness methods that have been implemented to date.

The use of pneumatic actuators in eversion robots can be leveraged to control stiffness [54], [78], [79] by tuning the relative pressures between the robot body and its actuators. Lowering the actuator pressure and increasing the pressure in the main chamber increases stiffness [78] and improves trajectory tracking [79]. This can also improve force exertion [56], [66], [80], [96], while maintaining a soft body during the deployment stage. Pneumatic expansion has been used together with tendon-driven steering [96], where simultaneously controlling the air pressure and a central tendon tension enabled stiffness modulation. However, with pneumatic expansion, stiffness control is limited by pouch geometry and may present time delays due to the time taken to fill the pouches.

Layer jamming, a technique that leverages the friction between two or more layers, can also be used to control stiffness. Pouches containing layers are arranged in series, forming the robot's body. By controlling the inflation pressure, the sequential jamming and unjamming of the pouches allows for stiffness control, enabling smaller tip deflection [90], [97] and higher force exertion [98] during the jammed state. Layer jamming can also be utilized to improve active distributed steering by simultaneously stiffening one side and stretching the other, uniformly-wrinkled side, allowing it to bend and achieve tight curvatures [98]. While the execution of layer jamming is relatively simple, the technique introduces time delays when switching between states and has demonstrated a limited stiffness ratio of only 2 in [90].

Temperature change has also been used to vary the stiffness of growing robots. For example, heat welding has been used to create wrinkles in thermoplastic tubes at specific points to reduce the stiffness and form bends [52], [88]. While this technique can enable steering, it is irreversible and is limited by the critical temperature value. Another recent example achieved variable stiffness via a phase-changing alloy, a binary, thermoactive stiffening approach [95]. The alloy was used as the working fluid to actuate and pressurize the everting robot, and once everted, it served the secondary purpose of stiffening when solidified. The mechanism showed the ability to resist much higher forces than jamming-based variable stiffness and occupied less space within the robot body, but the design did not enable continued growth while in the stiff state.

An alternative approach is to deposit variable-stiffness material [17], [94]. For example, additive manufacturing-based growing robots can inherently tune their stiffness by changing the viscoelastic properties of the deposited filament, enabling them to sustain their own weight without collapsing, while still showing ability to make sharp bends [17]. One approach proposed for everting growing robots was to install a tip-mounted nozzle that sprayed an expanding polyurethane-based insulation foam that stiffens when it dries [94]. The foam could passively maintain rigidity and structure, but suffered from a slow response time (approximately 1 hour) and may not be suitable for sensitive/fragile environments.

C. Retraction Mechanisms

Eversion-based growing robots have the ability to reverse growth by inverting the tip to reduce their length (retract/ invert). Successful retraction allows the robot to remove its body from the environment without causing damage. However, retraction is particularly challenging for growing robots at longer lengths, due to their tendency to buckle and collapse under retraction forces applied to their tail, leading to limited motion control and potential application of undesired forces on the environment [99].

There have been several attempts to reduce buckling during retraction. The first class of solutions consists of integrating rigid reeling mechanisms directly at the tip of the robot instead of the base [40], [87], [99], [100]. They enable an artificial reduction of the length of the everting robots submitted to the buckling force, reducing tail tension along the robot and expanding the conditions under which retraction without buckling occurs.

In order to axially stiffen the robot and pull on the tail material at the base, a solution proposed by Pi *et al.* [101] integrated a flexible, incompressible tube between the body and tail of the robot along its entire length. Moving the tube backwards while maintaining tail tension, the incompressibility of the tube ensured no buckling and collapsing of the robot body. Limitations of this system include increased friction between the tube and the robot body and tail in curved paths.

While the previous solutions involve rigid elements, a solution proposed by Takahashi *et al.* [32] consisted of using water instead of air as the working fluid that induced robot eversion. In this case, the robot body maintained contact and friction with the ground during retraction, preventing it from buckling. However, the contact dependence of the robot increased its weight and limited its application to 2D environments (planar contact constraint) only.

Similarly, Kim *et al.* [63] presented a growing robot with a central retraction tube, negating the need for additional hardware and complex control. As the retraction channel was inflated, a sealing ring moved forward. When the channel was depressurised, the sealing ring moved backwards, automatically inverting and retracting the robot, allowing for self-retraction. Larger channels enabled stronger retraction but jamming could occur. Smaller channels reduced tail tension effects but required higher retraction pressures and complicated the effect of high inversion forces.

As highlighted above, research on retraction mechanisms focused on eversion-based growing robots. Robots that grow via additive manufacturing do not facilitate retraction, making it a major limitation of their mechanism as the robot is required to be pulled out of the environment, generating high forces against the surroundings. This confines the use of additive-manufacturing techniques mostly to open environments.

IV. Environment and State Perception, and Robot Functionalization

Sensors and tools, discussed in this section, are paramount in enhancing the navigation, performance and usability of growing robots in confined spaces. A variety of them, proposed in the literature, are visible in Fig. 6.

A. Sensing and Perception

Various proprioceptive and extereoceptive sensors have been used within growing robots. Proprioceptive sensors record the state of the robot (e.g. position and orientation) via internal or external means, and exteroceptive sensors perceive

Figure 6. Sensor integration and implementation in growing robots (as in **(a)** [84]). Distributed sensing: **(b)** Sensors embedded into steering pockets along robot body [102] or **(c)** Sensors along the exterior surface of robot [103]. Local tip-sensing: **(d)** String-mount [11], **(e)** Tip-mount outer cap design [40], **(f)** Origami-inspired tooltip design [25]. Proprioceptive sensing can be distributed along the body to measure strain as in **(g)** [104] and **(h)** [105] or localized at the tip to capture the robot's position, e.g. via magnets as in **(i)** [106]. Exteroceptive sensing (always local), e.g. **(j)** to measure soil conditions in [12] or **(k)** to provide visual feedback via camera [81].

the surrounding environment, providing information on the environmental conditions or responding to external stimuli.

1) Proprioceptive (Robot State) Sensing: Proprioceptive sensors can be used to provide information on the robot's position or orientation. For instance, Watson *et al.* [106] integrated a fixed ring-shaped permanent magnet at the robot's tip, complemented by an array of magneto-inductive sensors in the environment, to localize the tip position and orientation, albeit within limited range due to proximity constraints. Similarly, optical markers [84], [107] and accelerometers [108] have been placed on tip-mounts to enable real-time localization of the tip as the robot grows. Another approach used IMUs on sensor bands distributed along the robot's length, with the IMU orientations feeding into a model to estimate the 3D shape of the structure [103]. More recently, Raines *et al.* [109] introduced an acoustic approach, detecting pressure and acoustic signals at the robot base to infer environmental changes, e.g. localizing the robot position when travelling through tunnels of varying sizes.

Recent work has also investigated sensing information beyond position and orientation of the robot. Mitchell *et al.* [102] integrated flexible pressure sensors into the steering pockets to provide contact force information. Flexible resistance sensors that determine local curvature have also been considered to localize single point contacts and perform tactile-based obstacle detection [105]. Additionally, optical wave-guides have been placed along the length of the robot to provide local bending information, for grasping applications [104].

2) Exteroceptive (Environmental State) Sensing: Vision-based sensing, exemplified in works such as [9], [11], [30], [77], [81], uses tip-mounted cameras to provide direct and real-time visual feedback of the environment. Such sensors can be challenging to mount due to their weight, limits placed on the growing length [11], [77], or due to bulky housing [9]. To address this, a more compact, tethered camera-mounting design was presented in [81]. Light and heat sensing mechanisms, as in [72], utilized a thermoresponsive liquid (photoabsorber) as working fluid in growing robots to initiate a sensing-steering control loop, steering the robot by contracting its body towards the direction of the source. Another demonstration of sensing-steering control loops in growing robots was demonstrated by Del Dottore *et al.* [17], where a sensorised tip comprising photoreceptors was placed at the robot apex, along with the actuation unit (FDM printer). By sensing light, the growth orientation could be adjusted. Finally, there have been several examples of sensorised tip-mount caps, such as in the "plantoid" of [12], [13] and the robot of [60], that consisted of temperature, humidity, chemical and water content measurement (reflectance) sensors to monitor environmental conditions, e.g. for deep soil penetration.

B. Robot Functionalization: Component Integration

The integration of the sensors described above, in addition to tools that functionalize growing robots, involves various designs and strategies, focusing on tip-mount components and component distribution along the robot's body. This includes different cap designs, such as string-mounts, magnetic caps and soft caps, working channels or sensor distribution.

1) Tip-mount Components: Mounting sensors and tools at the tip provides direct and localized feedback during the deployment of growing robots. However, fixing tools to the tip is difficult as they have to follow the new material added to the tip. Placing a rigid tool at the tip also increases the weight and diameter of the growing element, limiting maneuverability and restricting motion to apertures larger than the diameter of the tip. Several cap designs have been featured in growing robots, further detailed in [40]. The mount can be placed at the tip of the robot, within the pressurised area or passed along a working channel.

- Tethered Cap Design: Tethered design was proposed, where the sensors were directly tied to a string that runs through an everting robot body [11], [77], [110], [111]. As the string moved twice as fast as the tip, it had to be pulled back from the base. In such cases, the tail material could not be stored in a spool and the growth length was limited due to friction forces between the string and the tail material [40]. To limit the length where friction forces apply, Kim *et al.* [25] proposed to store the tail material at the base via an origami folding and feeding mechanism. Alternatively, string management mechanisms such as a wire rewinding tool [9], and a zipper pocket mechanism that runs along the robot length [81] have been implemented. The mechanism in [81] was coupled with a rigid outer cap, whereby the friction between the cap and the tip held the tools in place independent of length change. However, the lack of friction between the cap and tip during retraction caused the cap to detach. Furthermore, additive-based growing robots commonly use a tethered design, given the high power consumption required for material feeding and deposition. Such designs combine the actuation and sensing unit within a tip-mount cap as in [12], [13], [17], [37].

- Untethered Cap Designs: To remove the constraints of a tether, several outer cap designs that are mechanically fixed onto the tip have been proposed. For instance, in [30], [112], a magnetic mount was placed inside the pressurised area to maintain its position at the tip during growth and retraction. However, weak magnetic forces may cause the outer part to detach. Combining previous designs, Jeong *et al.* [40] developed a tip mount composed of an outer cap for sensors, a retraction device, and a magnetic interlock. This design used an electromechanical roller-based design with a hook attaching the outer cap to the inner segment, preventing it from physically separating. The use of electromechanical rollers, however, limited the speed of growth, the compliance of the robot, and increased its weight. Heap *et al.* [100] presented an internal camera mount design, utilizing ball bearings and a PTFE ball. The design demonstrated reduced friction against the surroundings and lighter weight, enabling the robot to squeeze through tighter gaps. Soft fabric caps [41], [58] and origami-inspired tool-feeding mechanisms [25] also offer alternatives for securing tools at the tip without relying on rigid components.

- Tool Delivery via a Working Channel: Tools and sensors can also be passed to the tip of an eversion robot through a working channel (hollow tube). One proposed design consists of the tip of the working channel attached to and moving with the base of the tail until reaching the robot tip at the end of the deployment [62]. This limits accessing the robot tip at any time during deployment. A design which enables access to the tip at any time is possible if the working channel is inserted inside the robot tail. However, since the tail translates at twice the speed of the working channel, the working channel needs to be held back at the base, generating friction forces between the working channel and the tail. This can be addressed by implementing a duty-cycle controller to align the tool transmission with the robot pressurisation/depressurisation cycles [27], [113], or by constantly blowing air between the working channel and the inner channel to reduce drag forces [114]. Alternatively, passing a semi-rigid channel along the robot body can prevent airflow into the central core [63]. Finally, a tip-scrunching design was proposed in [28] to overcome the working channel scaling and length limitations while allowing tool deployment at any point during eversion.

2) Component Distribution Along the Robot Body: Placing sensors along the length of the robot body can be useful for localization, obstacle detection, and long-term monitoring of the confined path the robot navigated through, for instance. Examples of such are seen by distributing sensors along the length of the robot [102], [103], [105] or within the robot's branches [35]. Distributive sensing can be particularly useful for force and shape sensing purposes. Adhering the sensors externally and directly on the robot's body can result in

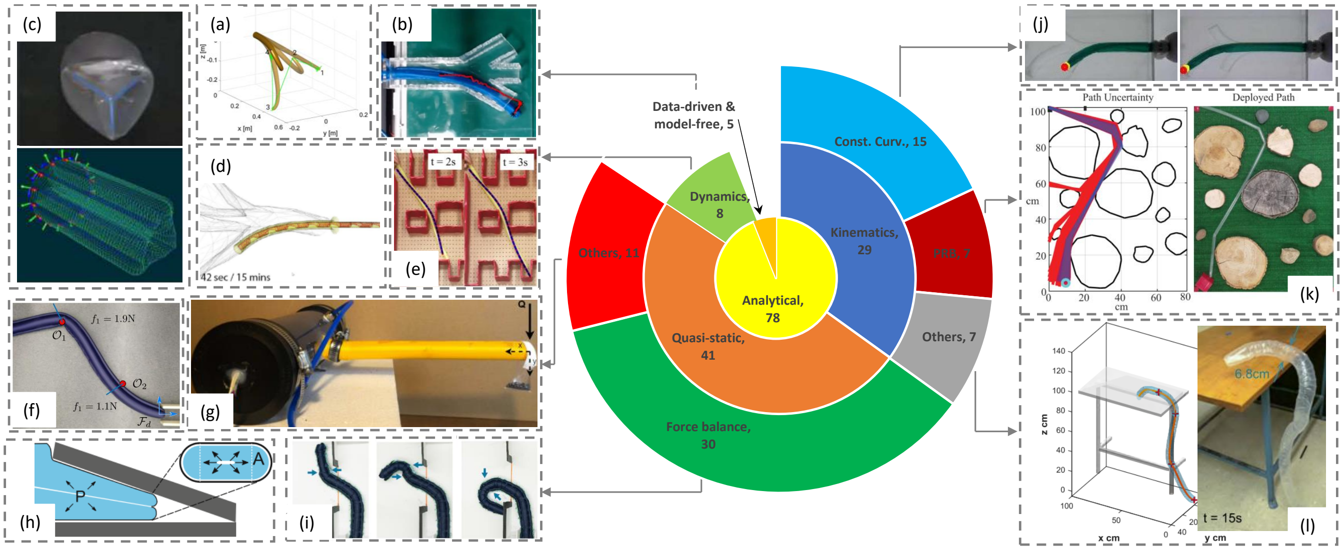

Figure 7. Number of publications that use a specific modeling technique and their example applications: **(a)** data-driven controllers tested in simulation (using *SoroSim* software) [115], and **(b)** experiments [116]; **(c)** Finite Element Analysis (FEA) using *SOFA-Framework* for physics-based eversion growth [117], and **(d)** environmental interactions [42] dynamics; **(e)** Pseudo Rigid Body (PRB) dynamics implemented in *Vine_Simulator* software [118]; **(f)** quasi-static models based on Cosserat rod model for obstacle-interaction planning [70], **(g)** inflated beam model to predict the robot collapse under external load [47], and **(h)** force balance model for growth through a slanted gap [119] and **(i)** comparing growth with and without shape locking [73] methods; **(j)** kinematic models based on Constant Curvature for closed-loop control [113], **(k)** PRB for navigation by exploiting environmental contacts [65], and **(l)** shape function approximation for robot geometric design [120].

stiffness mismatches and intervene with the robot's motion and functionality [103]. Improving upon this, the sensors can be distributed along the robot body by embedding them within the steering pouches [102] or within individual sensor pouches to allow for material wrinkling, reducing the stiffness mismatches along the robot length [105].

V. Modeling

Due to their continuously changing morphology, their tendency to buckle, and their non-linear dynamics, modeling of growing robots is challenging. Fig. 7 and Table IV show the main features and the frequency at which the mentioned techniques have been used in the literature. See Table IV subscript for the acronyms in this Section.

A. Kinematics

Several kinematic models have been proposed for growing robots. The Pseudo Rigid Body (PRB) (also referred to as joint-space representation) method approximates continuum robot backbones by a series of conventional rigid-body links and joints, e.g. a prismatic-revolute-prismatic configuration. This method was revised to accommodate the growing robot length change by updating the number of joints and rigid links, hence the equation of motion states [87]. These models have been used for design optimisation [97], [121], [122], obstacle-aided path planning [65], [67], contact localization [108], shared control [123], and in an open-source dynamic simulation software [118].

Alternatively, constant curvature models can predict motion through geometric constraints in actuators that are parallel to the backbone [76]. Greer *et al.* [67] developed a kinematic model for an sPAM actuated growing robot, considering the effect of pressure on tip displacement. Del Dottore *et al.* [14] presented a similar kinematic model for robots that grow incrementally by means of additive manufacturing. The model was further developed by considering the motion in configuration space [15] to describe the motion of the robot and to define suboptimal 3D trajectories.

While PRB and constant curvature models can accurately describe the geometry of simple systems, they are unable to capture the complex highly nonlinear motions of slender soft systems. Therefore, variable-curvature models based on Cosserat rod theory [76], Piecewise Variable Curvature (PVC) method, i.e. concatenation of segments with variable curvature expressed by a shape function [115], and reduced order shape fitting by a shape function [27], [120] were introduced. For example, Blumenschein *et al.* [76] used variable curvature and geometric constraints formulations to develop a kinematic model for helically actuated pneumatic growing robots. Wang *et al.* [120] split the representation of the system into a spatial curve describing the geometry of the robot, and a reduced-order kinematic representation (approximation) of the spatial curve that was designed using piecewise cubic Bezier curves. As such, the models position accuracy increased. A similar approach was proposed by Allen *et. al* [107] based on a polynomial representation of the robot continuous curvature (here only bending angle).

B. Quasi-Statics Models

The aforementioned kinematic models only considered geometric parameters such as the robot radius and the location of its steering actuators to describe the robot shape. In the case of everting robots, quasi-static models have been proposed to integrate the impact of internal and external forces, such as those related to the internal pressure and external contact. They are applied to modeling of growth, retraction, and buckling of growing robots, neglecting their dynamics to assist in understanding their movement capabilities [18], [52].

The main approach has been to use a force balance derivation [119] to relate the actuation pressure to the robot length, bending angle, buckling threshold, growth force and cumulative resistance to eversion. A comprehensive review of this class of models was presented in [18]. The growth models were later extended to consider the integration of working channels inside these robots [28], [124]. Alternatively, beam theory [79], [80], inflated beam models [47], [56], and the principle of virtual work (PVW) were employed [78], [113]. These models, however, did not consider the stiffening effect of internal pressure.

Tuctu *et al.* [56] used constant curvature kinematic and inflated beam bending mechanic models which were updated with deformations based on an iterative process. Results on the robot's geometry were coupled with a quasi-static model to precisely predict tip deflection. A similar method was employed by Hwee *et al.* to model the robot displacement and curvature under external contact and load. Beam theory has also been employed to model magnetic steering [83], and low melting point alloy-based stiffening [95] mechanisms for eversion growing robots.

C. Dynamics

Pressure changes or external impulses due to interactions may result in rapid growth and bending motions of growing robots, prompting the need for dynamic models. Dynamic models predominantly relate to everting robots, since robots growing through tip-material deposition do not usually exhibit rapid and transient effects.

Assuming constant curvature kinematics and all mass concentrated at the tip, El-Hussieny *et al.* [125] presented a dynamics model for everting robots using the Euler-Lagrange formalism. The model demonstrated the coupling between the bending angle and the extension of the tip in different scenarios. Jitosho *et al.* [118] presented a dynamic simulator using an impulse-velocity formulation that assumed the everting robot was a series of rigid prismatic joints and links. This model was also defined using the Lagrange multiplier formulation.

The model of [27] was capable of capturing eversion dynamics by modeling the stationary and sliding parts of an everting robot as a pair of length-varying concentric tubes. The TMT dynamic method from [126] was used for the derivations of the system dynamics.

D. Finite Element Modeling

Although studied experimentally, the limiting factors on the dimensional scale and performance of growing robots are not fully known, e.g. the possible implications of everting geometry on friction with internal structures. High-fidelity models based on Finite Element Analysis (FEA) have helped shed light to these questions.

Wu *et al.* [42] developed the first physics-based model for tendon-driven growing robots, considering the effects of internal pressure, tip force, and tendon tension on the robot's stiffness, growing speed, and steering behaviours. The model was implemented in the SOFA framework [127], [128], but its simplicity resulted in low accuracy when compared to experiments.A more accurate model of an eversion sheath was presented in [117] based on strands of Cosserat rods capable of capturing randomly, triangularly, and linearly-shaped tip eversion patterns observed in experiments. Still, high computational cost, and simulation instability at larger time steps and velocities is a challenge when FEM is considered.

Table IV
MODELING, PATH PLANNING, & CONTROL METHODS.

Domain/Method	Study type[1] (error%)	Planning & control methods	Features (*open access software*)
Analytical			
Kinematics			
Const. Curv. [12], [14], [15], [17], [31], [34], [53], [54], [56], [73], [79]–[81], [84], [89], [99], [113], [125], [129]–[133]	SE 2,3D (2-20% model, 0.5-3% control)	Switching, Jacobian inverse, Predictive, Moving horizon, Force control, Path planning, Teleoperation	Simplicity
PRB* [65], [67], [87], [97], [108], [118], [121]–[123]	SE 2,3D (5-6% pos., 5% angle)	Path planning, Contact obs., Shared-control	Design opt. (*Vine_Simulator*)
Variable Curv. [33], [76]	SE 3D (5%)	ND	Design opt.
Shape func.[2] [27], [107], [120]	SE 3D (1.4-5%)	ND	(*TMTDyn*)
Others[3] [17], [42], [70], [72], [93], [115], [121], [134]	SE 2,3D (ND)	Obstacle-aided navigation, closed-loop, Jacobian	Design opt. (*SoroSim*)
Quasi-statics			
Force balance [22], [32], [48], [52], [55], [57], [63], [72], [79], [81], [86], [87], [92], [94], [98]–[100], [119], [135], [136], [10], [11], [28], [34], [50], [64], [69], [73], [75], [93], [114], [137], [138]	SE 2,3D (6% pos., 5% angle)	Force control	Buckling, thermal model, burrowing
Beam (Inflated) [47], [56], [71], [79], [80], [83], [95], [105]	SE 2D (15-20% model, 6.5-8.5% force loc.)	Jacobian inv., Force localization, Observer	Accurate actuator model
PVW* [78], [113]	SE 2D (0.7-1.1%)	Switching closed-loop	Suitable for complex systems
Cosserat rod [70]	SE 2D (1.3%)	Obstacle-interaction navigation	Accurate backbone model
Dynamics			
Lumped par., Lagrangian [118], [125], [129]	SE 2D (ND)	ND	Simplicity, (*Vine_Simulator*)
Inv. dynamics, PVC* [115]	S 3D (ND)	Jacobian controller	(*SoroSim*)
Hamiltonian, PVW* [27], [139]	SE 1,3D (4.4%)	Energy shaping controller	Physics-based, (*TMTDyn*)
FEA* [42], [117]	SE 1,3D (6-24% pos., 51% speed)	ND	Physics-based, (*SOFA-Framework*)
Data-Driven			
Jacobian Corr. [115], [116], [140]	SE 3D (0.7-4%)	Closed-loop	Accurate, efficient
Deep RL* [133], [140]	S 2D (2%)	Trained controller	Accurate, adaptive

[1]S/E: Simulation/Experimental studies, 1-3D: motion dimentionality, pos.: position, ND: No Data. [2]Piecewise Cubic Bezier & polynomial spline Curves, [3]Finite Element, trapezoidal mesh, Piecewise Variable Curvature, case-specific trigonometric relations, etc. ***PRB**: Pseudo Rigid Body (e.g. Joint-space representation & Prismatic-Revolute-Prismatic), **PVW**: Principle of Virtual Work, **PVC**: Piecewise Variable Curvature, **FEA**: Finite Element Analysis, **RL**: Reinforcement Learning.

VI. CONTROL AND PLANNING

This section reviews the model-based and model-free path planning and control methods for growing robots. Table IV and Fig. 7 summarise the state-of-the-art in these areas.

A. Path Planning and Environment Mapping

Sliding-free motion and compliance of everting growing robots enable effective exploitation of environmental contacts for their steering and path planning. The idea was introduced by Greer *et al.* [65], [67] for a non-steerable robot. A recursive 2D path planning method adjusted the robot length and base direction to achieve the desired tip contact angles, and hence contacting forces, with known obstacles to reach a target location. A similar technique was used for additive manufacturing-based growing robots [16]. Selvaggio *et al.* [70] further developed this idea for a steerable, yet under-actuated, everting robot with controllable overall bending angles.

When local bending and shape setting is possible, e.g. via heat welding, standard path planning techniques such as Rapidly-exploring Random Tree star (RRT*) algorithms can be used [89]. The development of more effective local steering can enable further implementation of similar standard techniques in the future. Finally, Fuentes *et al.* in [68] showed that when prior knowledge of the environment is not available, the robot's interaction with the environment along the deployed length can be used for mapping.

B. Model-based Control and Observation

Compensating for model uncertainties with adaptive terms can make closed-loop control of growing robots more accurate by improving their transient response, avoiding overshoots and considering disturbances (e.g. due to pressure change and external forces) [80], [139].

Ataka *et al.* [79] presented the first model-based controller for fPAM-actuated everting robots, taking into account their ability to change their structural stiffness using pressure. They extended their work in [80] to estimate the unknown parameters using an observer based on a Kalman filter. The observer used pressure and bending values returned from sensors to control position and orientation at different stiffnesses with improved accuracy.

El-Hussieny *et al.* [130] applied a non-linear model predictive control scheme in conjunction with Monte-Carlo simulation to increase the controller robustness and to enable the guidance of growth direction.

Franco *et al.* [139] developed a 1D model that used a Hamiltonian formulation for ideal gas and a nonlinear observer to take into account detailed pneumatic actuation mechanics, e.g. actuation medium pressure-density relation, as well as external disturbances. More recently, Wu *et al.* [113] presented a switching controller based on a model-based (using Constant Curvature kinematics and PVW mechanics) open-loop, and a model-free proportional closed-loop control term, for coarse (large error regions of the task space), and fine (small error regions) system motions, respectively.

C. Data-Driven and Model-Free Control

Although model-based techniques provide insight into the structural and controller design implications of the system parameters, data-driven (with or without an underlying model) techniques can have advantages in accuracy with competitive computational performance for complex systems [141].

Watson *et al.* [116] used real-time position and orientation readings to formulate an online identification problem for updating the robot kinematics model using closed-loop position control via Jacobian corrections. This allowed for autonomous tip localization and position control, but relied on sensing quality and was limited to slowly-moving robots with small external disturbances.

A few studies have looked into model-free methods for controlling growing robots. AlAttar *et al.* [115] approximated the system model with a volatile local linear model based on which a closed-loop controller was evaluated in simulations. Ataka *et al.* [140] presented a deep reinforcement learning framework based on Proximal Policy Optimization that adapted to the increasing length and hence the degrees-of-freedom of a growing robot. This approach illustrated advantages over a Jacobian-based controller in 2D simulations. El-Hussieny *et al.* [133] presented a deep Reinforcement Learning (RL) framework for obstacle-aware control of a growing robot in 2D simulations.

Overall, it can be concluded that data driven techniques can handle modeling uncertainties, but unless the data includes the effects of external disturbances, the unmodeled system dynamics and environmental interactions impact their usability.

D. Teleoperation and Autonomy

Teleoperation allows the user to make decisions and interact with an unknown environment in real-time during the robot navigation. El-Hussieny *et al.* [53] presented a flexible joystick of fixed length, which mapped human input (i.e. its bending) into shapes and movements of the robot. In an adaptation of the design, a camera system was attached to the robot tip [81] to increase situational awareness. However, control interfaces with kinematic dissimilarity to a growing robot (in shape, pose, or degrees-of-freedom) require the human operator to learn the non-trivial mapping between the interface, actuator, and robot degrees-of-freedom to complete tasks. Stroppa *et al.* [123] proposed using a motion tracking system with tactile and haptic feedback to help the operator. Transparent teleoperation is the first step towards the creation of semi or fully autonomous systems.

Autonomous self-growth is considered an emerging solution for navigating, interacting with, and exploring real-world unstructured environments [17]. However, autonomous control depends on the quality of information given by the sensors, where poor quality can distort the system. Autonomous systems can use tip-mount sensors (see Section IV) to provide feedback and enable directional growth, also drawing inspiration from the chemically-guided growth of plants [14]. Closed-loop strategies can update a model based on the sensor information [116]. Combining this with tip localization methods, fully autonomous position control schemes can be implemented without requiring a line of sight of the robot body. Similarly, incorporating measurement systems that collect and process data can allow robots to autonomously configure their shape and adapt to changes in measurements [142]. Fully autonomous systems, however, heavily rely on the algorithmic interpretation of acquired sensing signals.

Semi-autonomous schemes balance the limitations of human-centered teleoperated systems and the reliance on algorithmic perception. Such schemes allow the human to take over during the difficult-to-automate tasks, while reducing their cognitive load [123], e.g. by controlling only a subset of the robot degrees-of-freedom.

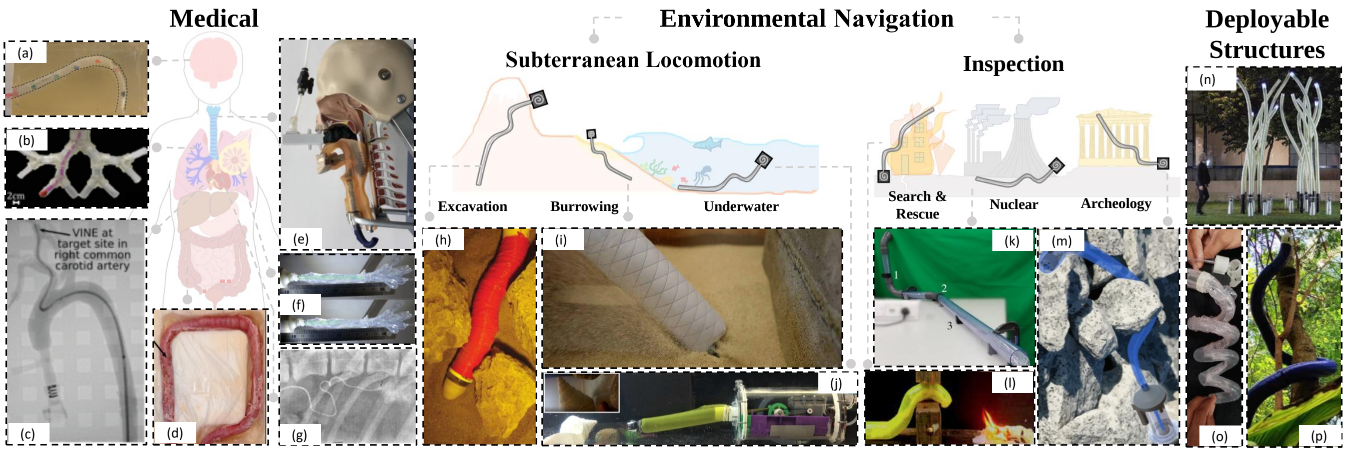

Figure 8. Growing robots are observed under three main application categories. *1.* Medical applications: **(a)** soft catheter for neuro-interventional surgery [66], **(b)** navigating through the respiratory system [31], **(c)** VINE robot for endovascular surgery [62], **(d)** colonoscopy robot [55], **(e)** emergency airway device [143], **(f)** MAMMOBOT to detect early-stage breast cancer [27] and **(g)** intraluminal navigation through blood vessels in a dog [144]. *2.* Environmental navigation, including subterranean locomotion e.g. burrowing, as in **(h)** [16] and **(i)** [114], or **(j)** underwater robots to explore coral reefs [30], or inspection, such as **(k)** radiation monitoring [145], **(l)** detecting and extinguishing a fire [11] and **(m)** navigating through rubble [86]. *3.* Deployable structures, e.g. **(n)** architectural structures [37], **(o)** wearable haptics [24] and **(p)** climbing and twining robot via additive manufacturing [17].

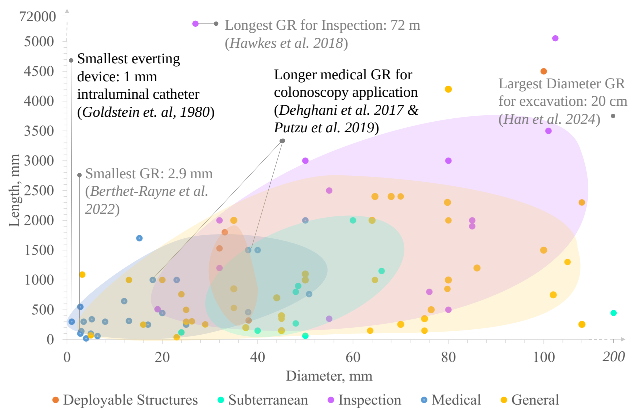

Figure 9. Dimension trends considered in Growing Robots (GR) for the applications: deployable structures, subterranean navigation, inspection, medical, and general.

VII. Applications

The inherent material properties and method of growth from the tip make such robots appropriate for deployment in torturous, constrained environments. They can be used to reach subterranean levels or search-and-rescue victims, navigate complex human anatomies in minimally invasive surgical contexts, and create deployable structures, such as antennas and architectural structures. Fig. 8 summarises the different applications of growing robots, and Fig. 9 highlights how the robot dimensions heavily depend on the intended application.

A. Environmental Navigation

- Search-and-Rescue and Industrial Inspection: The earliest eversion robot concepts were aimed towards inspection applications, when Mishima *et al.* [9] realized their desirable low external friction and flexibility for navigating torturous terrain and rubble. Tsukagoshi *et al.* [10] proposed steering such a robot using two parallel tubes integrated inside the growing robot to navigate through rubble. Further development has led to growing robots for archaeological exploration [81], for reaching trapped victims [146], and for navigating, sensing and decontaminating nuclear environments [64], [145].

As indicated in Fig. 9, inspection robots typically have the largest dimensions, with lengths extending up to 72 m [11]. Hence, they are predominantly elongated based on eversion, as the deployment additive manufacturing-based growing robots is limited by the 3D printer's capabilities.

- Subterranean: Burrowing robots take inspiration from the ability of plant roots and certain animals to penetrate soil by reducing the drag forces they exert. Some examples combine tip eversion with complementary techniques, such as granular fluidization and an asymmetric tip shape to enable successful burrowing [114], [135]. As discussed, the Plantoid [12], growing through additive manufacturing, was also intended for subterranean applications, exploited the viscoelastic properties of PLA to improve interactions with obstacles [16]. Another subterranean application is excavation, first presented in the RootBot [39]. Similar to early patented trenchless piping eversion tubes, the RootBot comprised two everting tubes connected to an excavation module to enhance their steering and retraction capabilities while enabling directional excavation. The system also incorporated a discharge module to prevent excavated soils from accumulating.

Finally, everting growing robots have been proposed for underwater applications, for instance, for navigation through coral reefs. In [147], it was indicated that the tip growth velocity increases with the water flow rate, but is inversely proportional to the depth. An added requirement to underwater eversion robots is buoyancy, which would allow them to float and extend to great lengths without buckling. In [30], saltwater, the same fluid as the surrounding environment, was used as the working fluid to make it neutrally buoyant. Conversely, Kaleel *et al.* [122] suggested the use of helium as the pressurisation medium to develop a buoyancy control model for a floating eversion robot in air, and later make use of the concept in underwater systems.

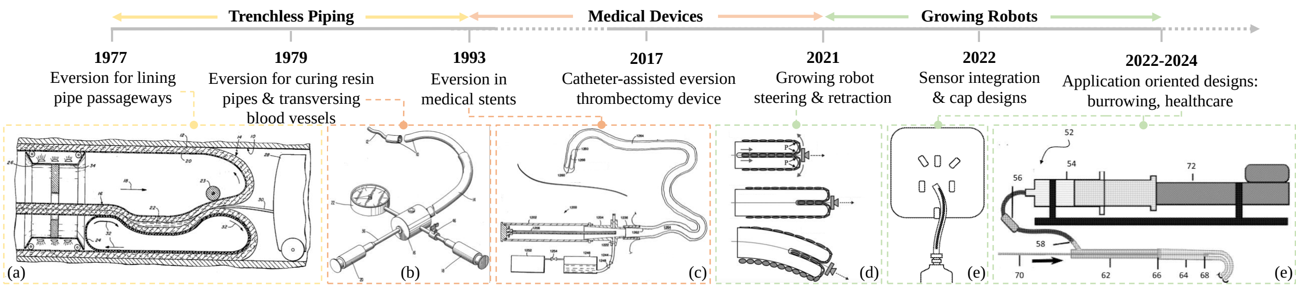

Figure 10. Timeline of patents demonstrating eversion mechanisms, first introduced by Wood *et al.* in 1977 for lining pipe passageways, as in **(a)** [4]. The eversion mechanism was then embedded into minimally invasive surgery devices, such as endoscopy and thrombectomy, from 1993 onwards, as in **(b)** [148]. Eversion in growing robots was first patented in 2021, showcasing robot growth (**(c)** [149]) and retraction (**(d)** [150]). This was further developed by integrating sensors into the system in 2022. Application-oriented patents, such as (e) duty-cycle controller for deployment in the mammary duct [151] and (f) the VINE catheter [152], were demonstrated from 2021-2024.

B. Medical

The use of soft growing robots in minimally invasive surgery has the potential to increase patient safety and minimize tissue damage. Medical growing robots have so far only utilized eversion concepts due to scaling constraints and safety considerations. Medical robots are commonly miniaturised, with an average diameter of 19.9 mm (see Fig. 9), to enable them to fit through small anatomical openings.

Such factors make eversion robots particularly attractive in applications such as endoscopy [55], [153]–[155], wherein a high level of clinical expertise is required to address pain and perforation potentially caused by the high friction between the device and the organ wall. Shike *et al.* [156] integrated an everting sleeve onto traditional colonoscopes, propelling the colonoscope as it grows to reduce shear forces. In [55], the growing robot acted as the colonoscope itself, whereby a latex tube was inflated to enable tip eversion and navigation through the colon, extending to lengths up to 1.5 m (average length of the colon). The robot conformed to the complex colon path more easily than conventional colonoscopy tools, but it still required high level of manipulation expertise. This was later resolved by Saxena *et al.* [154], who automated the steering of a colonoscopy robot to reduce the skill level and time required for the procedure. While both designs demonstrated successful insertion and navigation through the colon, retraction and tool passing were not possible. In [28], a tip-scrunching mechanism was integrated into a colonoscopy robot to enable the passage of instruments through the working channel at any point during robot deployment.

Similarly, growing robots have been used for airway access [83], [157], [158]. Hwee *et al.* [158] designed a multi-element emergency airway system based on a dual-balloon eversion robot. One balloon sealed either airway (trachea or oesophagus) and the other balloon provided pulmonary ventilation to the alternative airway via a tube passing through the robot. This functioned in a similar way to endotracheal tube cuffs, but without the associated insertion and frictional forces.

Growing robots can also be used to address challenges relating to manual-steering catheters during neuro-interventions [66], endovascular [62] surgery, and to navigate small, branching cavities within the body such as the breast [27], [42], [113] and lungs [83]. The growing catheter is pre-formed or steered via tendon-driven or magnetic mechanisms. Benchtop navigation tests indicated that growing catheters have the potential to lead to safer, more efficient procedures than conventional catheters [62]. Moreover, growing catheters showed the capability of achieving sharper bends, enabling them to navigate through complex pathways such as the brain ventricles [66], aorta [62] and ductal tree branches [27].

C. Deployable Structures

Growing robot deployable structures are based on bio-inspired or origami-inspired designs that unfold and transport packages into open space. They are reconfigurable and can adapt their shape based on environmental needs.

For example, physical shape change and reconfiguration can significantly enhance the performance of antennas. The eversion growing antenna design in [33], [75] geometrically reconfigured itself based on operational frequency feedback, enabling shape and angle change without requiring structural support. Fuentes *et al.* [94] proposed creating deployable structures by permanently stiffening the robot at arbitrary points to create shape change and increase the payload capabilities. Deployable eversion structures can also be utilized for haptic interfaces, for instance using an array of soft growing pins [138], or wearable haptics [24].

Additive manufacturing growing robots can often self-sustain and support the weight of their bodies, allowing for the development of structures via interwoven fiberglass [37] or PLA deposition [17]. As such, they have been utilized for large architectural structures, e.g. bridges and walls in [37], and plant-like climbing in unstructured environments in [17].

D. Industrial Adoption & Commercial Translation

With the increasing demand for trenchless piping methods in 1970s, which allowed for the renewal and repair of pipelines with minimal excavation, Wood *et al.* [4] proposed a method to insert a flattened tubular lining into a passageway through eversion. This concept was further developed to evert tubes into passageways by fluid pressure for resin curing [4], [159]–[161] and to place lining pipes into passageways [162], [163]. Similar works were developed to internally line conduits [164]–[166] and to line existing pipelines by inflating and everting a bladder along them [167]–[170].

Introduction of eversion mechanisms for trenchless piping and medical devices eventually led to the research and patents,

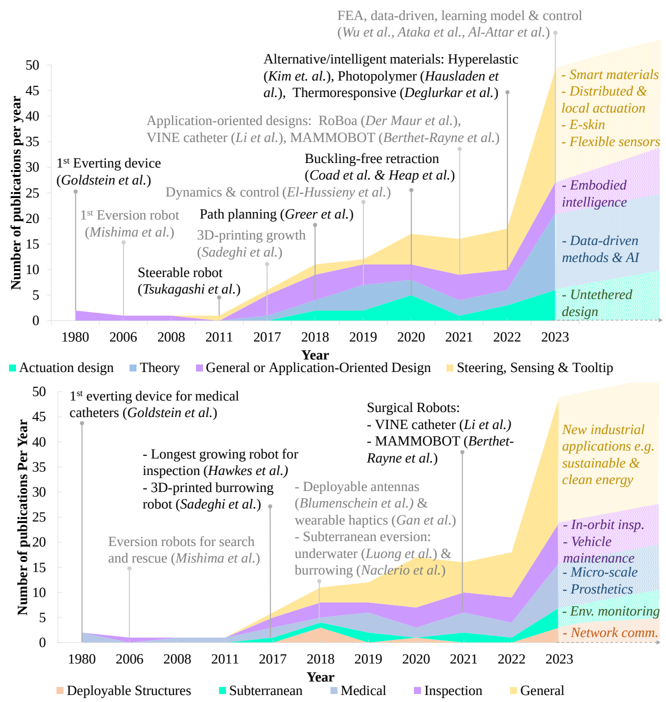

Figure 11. Number of publications on growing robot-related research by year, categorised by publication **(top)** type and **(bottom)** application.

mostly on sensor integration and cap design, for eversion-based growing robots in the past decade [149]–[151], [171]–[175]. An industrial interest is also starting to emerge, particularly within surgical technologies, such as the "BreathFirst" everting emergency airway device (Vine Devices Inc.[1]) [157]. Fig. 10 showcases the development of the eversion mechanism in research and industry, through patents, in trenching, medical technologies and growing robots.

VIII. Discussions and Future Directions

Growing robot research has exponentially increased since its re-establishment in 2017, showcasing over 130 papers and over 15 patents (see Fig. 11). A sharp increase in the number of publications has been observed since 2022, highlighting a wave of new researchers being attracted to this field. In the early years, research was application oriented, developing thus a foundation for growing robot design. This focus shifted towards steering, sensing, and theoretical investigations, further advancing understanding of growing robots. Nevertheless, the research topic remains at its infancy, and there remain many open directions for future work.

A. Working Principle and Fabrication

While a versatile range of materials have been used to fabricate growing robots, thermoplastic LDPE and ripstop nylon fabric remain the dominant materials of choice due to their ease of manufacturing and durability, respectively. The shift towards self-healing polymers and smart materials, capable of responding to their environments, shows promise in more easily combining multiple functionalities, such as sensing and steering, into the body of the robot. While different fabrication methods have been explored, there remains a need for more automated processes to ensure both robustness and repeatability. Recent work on fabrication via laser and ultrasonic welding are steps towards exploring automated fabrication methods, which are generally unexplored.

The realization of pressure-driven eversion and additive manufacturing as actuation mechanisms have distinguished growing robots from other soft continuum robots. However, it is these very features that have also presented significant challenges. Growing robots are tethered to their base, requiring a large volume of material to travel long distances, making the material length (or volume) a limiting factor. This challenge is exacerbated in eversion growing robots, as the path and travel distance is also limited by their dependence on pressure. Investigating designs for growing robots that can recycle their own material, in a similar way to everting toroidal robots, or alternatively utilize material from their external environment to support their elongation, could yield attractive solutions.

B. Steering, State Change and Retraction

Steering of growing robots has been a large topic of interest in the field, with various passive and active methods being incorporated into the design. Passive steering methods have largely focused on pre-defined morphologies for eversion robots and contact-based steering for additive manufacturing robots, which show high efficacy, but are limited to certain environments (e.g. pre-forming requires known pathways, contact-based steering cannot be deployed in open environments). Coupling these passive steering approaches with smart materials and improved fabrication methods, as discussed above, can enhance the passive steering performance of growing robots. Similarly, active distributed steering is limited to certain applications, as the mechanism is integrated directly into the robot body, occupying space and preventing miniaturisation. Alternative mechanisms such as tendon-driven steering were explored at miniaturised scales, but are yet to be optimised to ensure that tendon motion does not affect the eversion performance. This is extended to active local steering, which apart from the latches mechanism [11], always encompassed the integration of a rigid element (e.g. internal-device, magnetic valves, FDM-printer) into the robot body, limiting its compliance and scalability.

While the inherent compliance of eversion robots does not pose limitations in a 2D environment, in a 3D environment the suspension of the robot body makes it mechanically self-load, potentially causing it to collapse under its own weight. Additive manufacturing-based growing robots on the other hand are less compliant but should still grow via architectures and materials that can support an increasing robot weight. Variable stiffness and shape-locking mechanisms can help provide stronger mechanical support where needed by locking the configuration or transitioning to a rigid state, while preserving their compliance at desired points. Most state-of-the-art state-changing eversion robots require additional hardware or material to be incorporated into the robot's body, which adversely affects their eversion performance and poses scaling limitations. Recent work has attempted to tackle this

[1] https://www.wardenchem.com/vine

challenge by functionalizing the working fluid to serve as both the stiffening and pressurisation medium. However, in such cases, tip growth is limited to the compliant state. Further advancement in achieving state change in eversion robots is needed, exploring other approaches such as shape memory alloys and granular jamming, or alternative mechanisms that utilize simple hardware without occupying space along the body.

Finally, while there has been significant work on retracting growing robots, the focus was on eversion growing robots. As a result, 3D-printed growing robots still lack a retraction mechanism, and as such have been confined to open environments where retraction is not required.

C. Sensing and Perception

A major challenge in growing robot research is sensor integration, both as local tip-sensing and distributed sensing. Tip-mount sensor integration approaches are typically rigid, adding weight to the tip and limiting the aperture size the robot can grow through. While novel designs aimed to find alternative approaches, other limitations relating to buckling and friction are still present. Moreover, the challenges associated with distributed sensing have hindered progress with proprioceptive sensing, such as shape and curvature tracking. Recently, distributed sensing was achieved by integrating strain sensors into steering pockets or pouches, reducing the friction issues of placing sensors externally to the robot. In the coming years, the development and advancement of flexible sensors that are compliant enough to evert with the robot body, and the support of AI-based shape sensing, will likely propel this research subdomain. Improvements in sensing can also lead to a shift towards embodied intelligence in growing robots, which was recently touched upon, to enhance steering and navigation control.

D. Modeling, Control, & Autonomy

The complexity of the underlying actuation, steering, and state change mechanisms for growing robots as well as the growing motion in realistic scenarios with environmental interactions necessiate high-fidelity, scalable and computationally efficient models. Future directions on modeling and control of growing robots can be inspired by recent relevant developments within the Soft Robotics community [176] on reduced-order [177], model-based [178], and learning-based [141] control frameworks as well as high fidelity Finite Element techniques. Further development of open-source simulation toolboxes for growing robots, such as the ones presented in [27], [115], [117], [118], will also facilitate the utilization of advanced dynamic modeling and control techniques for growing robots autonomy, and the creation of reliable benchmarks to compare the variety of developed techniques.

E. Applications

Inspection tasks have been the primary application of growing robots. Designing deployable structures, such as antennas, could enable the use of growing robots in wireless network applications. Attention is also drawn to maintenance and inspection of tighter spaces, such as vehicle inspection and in-orbit applications, as well as architecture applications.

Subterranean robots have incorporated novel techniques to overcome resistive forces and achieve burrowing and excavation. Subterranean robots were also shown to support sustainability and address climate change challenges, both underground by monitoring soil conditions, and underwater by exploring the conditions needed for sustaining coral reefs. Overcoming resistive forces while navigating through soil, sand or water, however, remain challenging. As suggested in [60], further bioinspiration from plant root growth can advance the performance of subterranean growing robots by implementing features such as circumnutation and radial expansion to better penetrate soil. Similarly, achieving controllable buoyancy in underwater robots is a challenge to be solved.

At a smaller scale, medical growing robots promise to reduce patient discomfort and increase safety. However, miniaturisation remains a challenge, restricting the anatomies they can be deployed in. Current prototypes have diameters on the order of 3 mm with relatively short lengths. Achieving higher aspect ratios is limited by the fabrication techniques used to form the robot body. In eversion robots, reducing the size of the main body results in an increase in the required pressure to grow, potentially leading to everting membrane bursting. The key focus within medical growing robots is currently minimally invasive surgery, however, with the realization of grasping in [104] as a possible function of growing robots, and leveraging their capability to grow and retract, they show potential for use within limb prosthetics as well.

IX. Conclusion

Growing robots navigate complex and constrained environments via pressure-driven eversion or additive manufacturing. They deposit new material at the tip, allowing them to extend to greater lengths than traditional continuum robots. Their inherent compliance, use of entirely soft materials, and unique locomotion strategies make them well-suited for highly versatile environments. In this review, we highlighted the design, steering, sensing, and control strategies used in growing robots, as well as their main application areas to date. The features and limitations of existing robot designs and models are provided, with the expectation of seeking new approaches to tackle such challenges.

Growing robots enjoy a renewed interest in the field of soft robotics, leveraging features from early research since the 1980s in the piping and medical industries, and taking bioinspiration from plants in the surrounding environment. Thanks to their unique properties and presented challenges, they represent a promising area for future research.

By building on the knowledge and foundation for new growing robot technologies that has been laid by research to date, there is strong potential for the real-world deployment of these robots. With further investigation in the upcoming years, the research community can help solve the unanswered questions and key challenges currently hindering progress in order to increase the impact of soft growing robots in society.

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