A Tip-Extending Soft Robot Enables Reconfigurable and Deployable Antennas

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***Abstract*—Antennas are essential in wireless communications and powering systems. Applications, such as search and rescue and space exploration would greatly benefit from antenna reconfigurability, as well as antenna deployment from a compact and easy-to-transport form. We present the design and analysis of a reconfigurable and deployable antenna that uses a growing soft robot to form the three-dimensional antenna structure. Our approach is based on a pneumatic tip-extending robot instrumented with a conducting element. The robot increases its length to enable antenna deployment and changes shape to enable antenna reconfiguration. As a model system, we demonstrate a monopole antenna design that uses conducting elements formed from a copper strip that is mechanically disconnected at the leading edge of growth to change the length of the antenna and, as a result, change the resonant frequency. To achieve desired operating frequencies, return loss data from the antenna was used as feedback in a closed-loop system to control the antenna configuration. Our monopole supports a frequency tuning range that spans from 0.4 to 2 GHz and can tune between two target frequencies in approximately one second. We also show that the addition of branching and integrated actuators can be used to generate more complex and diverse antenna shapes. Branching is implemented in a model Yagi-Uda antenna and we explore the integration of pull cable actuators and pneumatic actuators with a model helical antenna.**

***Index Terms*—Soft material robotics, mechanism design.**

I. Introduction

ANTENNAS are critical components in wireless applications relevant to the Internet of Things (IoT), search and rescue, communications, and power delivery, to name a few.

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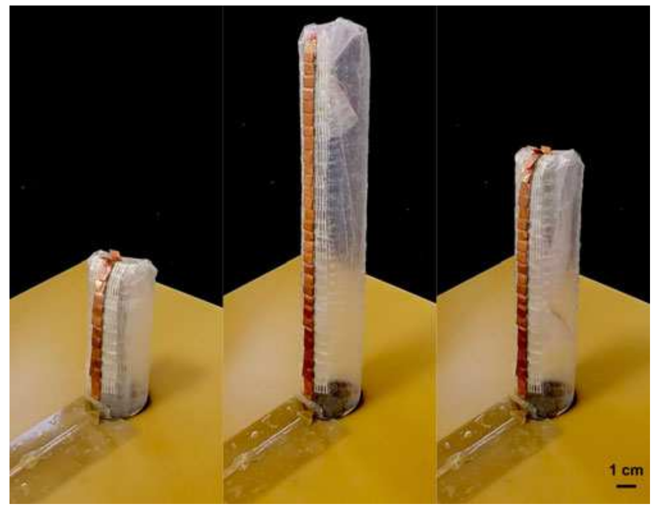


Fig. 1. A soft tip-extending robot is used to deploy and reconfigure a monopole antenna by lengthening and retracting.

These devices consist of metal structures that convert time-varying current to electromagnetic radiation, and their characteristics are strongly dependent on the physical configuration of the metal [1]. By bending, twisting, and changing the geometry of an antenna, its performance can be dramatically controlled and tuned. The ability to deliberately and reversibly alter the fundamental operating characteristics of antennas, such as resonant frequency, radiation pattern, or polarization, will become a salient feature of modern radio frequency (RF) systems that is difficult to achieve within the confines of traditional RF device design.

Dynamically changing the operating modes of antennas is a challenge that has been widely explored through various electronic, optical, and material tuning mechanisms. Some common examples involve the use of RF microelectromechanical system (RF-MEMS) switches [2], varactor diodes [3], and microfluidics [4]. These mechanisms are often restricted by degraded efficiencies, complex biasing circuitry, high voltage requirements, complicated fabrication processes, and high cost, which preclude them from use in many practical applications [5].

Mechanical actuation schemes for antenna tuning have been less widely investigated. Mechanical techniques can bypass many of the issues that face the aforementioned reconfiguration methods, but have been limited by the range of achievable physical shape change and the complexity of the mechanisms required to change shape [6]. Previous designs have repositioned a parasitic plate relative to the antenna [7], changed the bend angle of a microstrip antenna [8], and moved an antenna into or out of the ground plane [9]. These designs are limited to simple mechanical degrees of freedom, i.e., linear translations and pin joint rotations. To realize antennas with increasingly complex reconfigurations using traditional mechanical designs, a significant and often impractical increase in the number of actuators is required.

An alternative to traditional mechanical design exists in the emerging field of soft robotics. Soft robots have continuous, deformable bodies with infinite degrees of freedom that allow them to bend and twist with high curvatures to adapt to their surroundings [10]. Clever variation of material properties in a soft body can result in complex motions such as curling, twisting, extending, or otherwise changing shape, while using only a single actuator [11].

Tip-extending robots are a new class of pneumatically-driven soft robots that lengthen (effectively, grow) and can configure themselves into three-dimensional (3D) shapes in a controlled and reversible manner [12]. The pressure requirement to extend and change the shape of the robot starts out low and slowly increases as a function of robot length [13]. Additionally, the robots are cheap, lightweight, and portable due to the thin-walled, inflatable structure.

In this letter, we combine simulations and experiments to demonstrate that soft robots can be used to construct reconfigurable and deployable electromagnetic structures capable of effectively controlling operating frequency. Integrating soft robots with long-established electromagnetic devices, like antennas, offers a novel, low-cost solution for creating 3D RF devices that are reconfigured mechanically. Tip-extending robots can grow to many times their initial size, allowing frequency selectivity over many orders of magnitude. The tip-extending robot is highly affordable, and the use of relatively lossless dielectric support material and high quality conductive materials results in antennas with high performance. Additionally, these soft robots offer a lightweight, deployable solution for creating the structure of transportable antenna systems. Deployable systems offer many advantages for search and rescue applications or long duration explorations where delivery weight and volume must be minimized [14]. Exploiting the desirable properties of soft robots to easily and rapidly fabricate and tune RF devices has not previously been explored.

This letter is organized as follows. First, we present a study of the design and fabrication of a monopole antenna that makes use of the unique growth feature of tip-extending robots through a novel tip-breaking mechanism that changes the length of the antenna. Next, we establish the frequency modulation capabilities of the antenna experimentally. We demonstrate a closed-loop control scheme for the robot to tune the resonant frequency. Lastly, we design and construct various complex 3D forms, such as helical and Yagi-Uda type antennas.

II. Active Monopole Antenna Design

A. Monopole Antenna Characteristics

As a proof of concept, we design and study in detail a quarter-wave monopole antenna (Fig. 1). The structure consists of a single straight conductor, and its simplicity allows us to easily interpret the relationship between tip-extending robot growth and reconfiguration of the antenna properties. The length of a monopole largely determines the operating characteristics, such that changes in length result in frequency selectivity. Designs have previously been proposed to use monopole length to change frequency [9], but have not been fully implemented. The ability to tune the antenna's operating frequency could be used to change operating bands for spread spectrum communication, filter out interference, or tune the antenna to account for a new environment.

A monopole typically resonates at a wavelength, λ, which is four times the antenna length. The resonant frequency, ν, of an ideal monopole is inversely proportional to the wavelength, though the resonance may vary in non-ideal electromagnetic environments.

$$\nu = c\lambda^{-1} \tag{1}$$

To operate the antenna at a lower frequency, the antenna can be lengthened to a height equal to a quarter of a wavelength corresponding to the lower frequency. Conversely, to operate the antenna at a higher frequency, the antenna can be shortened. The length of the antenna, and its operating frequency, is changed by adding or removing part of the conductor through a tip-breaking mechanism described in a subsequent section.

B. Tip-Extending Robot

The tip-extending robot is used as the support and deployment mechanism for the monopole antenna. The robot consists of a pressurized thin-walled polyethylene tube, with a diameter of 32 mm and a wall thickness of 76 μm. This tube is inverted back into and through itself, where it can be stored in a compacted form like on a spool (Fig. 2). When the internal pressure is raised sufficiently in the robot body, the tube is forced to evert back out at the tip, effectively lengthening the body (Fig. 1). In this way, the robot can quickly deploy to a desired specification in the field, forming structures ranging from millimeter length scales to meters or longer given sufficient support. The self-supporting rigidity of the antenna is dominated by the internal pressure in the robot body. In some real world environments where the stiffness provided by pressure is insufficient, the unique growth ability of the tip-extending robots can allow a robot to grow around or against stable external structures to further support the antenna in tough conditions. The rate of lengthening is controlled by a brushed DC gearmotor with an encoder (Faulhaber) attached to the inverted material. This motor is also used to retract and re-invert the tube in order to shorten the body. The motor produces 100 mNm of torque continuously, capable of retracting the robot while pressurized. In this implementation, pressure is supplied by a high pressure reservoir, but could easily be supplied by a compressor for a portable design. The pressure is kept high enough to extend the robot, around 14 kPa, and held constant so that the control of lengthening and retracting is accomplished through inputs to the motor alone.

C. Tip-Breaking Conductor

The goal of the design is to produce an antenna that follows the shape of the tip-extending robot and adds or removes part

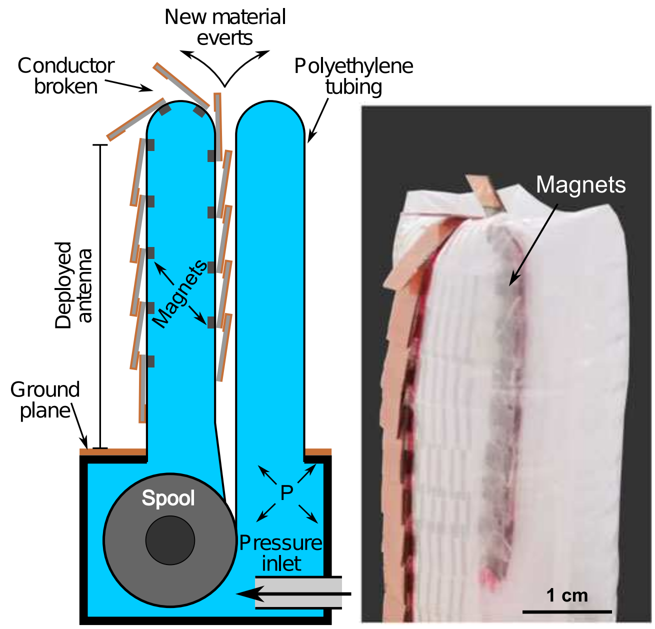


Fig. 2. Schematic of the robotic monopole antenna design with tip-breaking conductor (left). Conductor segments are attached to the exterior of the inflated surface at a single end so that they become disconnected as they evert around the tip. Connection on the surface is ensured by magnets at the points of overlap. Additional material is stored on a spool within a base station, which also provides a ground plane and a location to feed the signal to the soft robotic antenna. The base station is pressurized to cause new material to evert. The image shows a close up of the tip-breaking design as implemented on the physical system (right).

of the conducting element as it grows or retracts, changing the antenna's operating parameters. In order for the antenna to take the same shape as the robot, we affix the conducting elements onto the outer surface of the robot. Since the robot body material is flexible but not stretchable, the conductor does not need to stretch in order to match the shape. This allows us to use cheap, high conductivity strips of copper, rather than more complex stretchable designs [15], which suffer from absorption. Other materials used in flexible devices, such as liquid metals, carbon nanotubes, and conductive polymers suffer from decreased efficiency and increased power loss due to poor conductivity, especially when used in RF applications [16]. The naive approach of attaching a solid and unbroken conducting strip along the whole length of the robot, including the section that is inverted, does not lead to the desired variation in antenna properties.

We design a method to create a break in the conductor at the tip of the robot that leaves the metal strips on the exterior surface of the robot fully connected, but mechanically and electrically disconnected from the conducting elements on the interior (Fig. 2). This is accomplished by subdividing the conductor into overlapping segments that are attached to the robot body at a single end. As these conductor segments come over the leading edge of growth, they remain tangent to the surface and disconnect from the segments on the exterior. Once the next segment comes around the tip, it is connected to the existing antenna with interior magnets. Placing the magnets internally to the tube ensures they will not be part of the conductive path, and while the magnets do not provide much in the way of structural support, they ensure that the copper segments are electrically connected when the path curvature is relatively low. This unique tip-breaking conductor mechanism allows us to create a high performing device using copper segments.

The conducting segments are made of two layers joined by a non-conducting adhesive: a steel backbone to provide the stiffness needed to break contact at the tip, as well as provide ferromagnetic material to attract the magnets, and copper foil that creates the conducting path. To ensure that the poor conductivity of the steel plates does not impact antenna performance, we exploit the skin effect in the design of the segments. At radio frequencies, current travels only on the surface of a conductor, with a penetration depth described by the skin depth, δ. The skin depth of copper can be calculated by Equation 2, where f is the frequency (Hz), ρ is the resistivity (Ωm), and μ is the permeability (H/m).

$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu}} \tag{2}$$

The skin depth at 500 MHz in copper is about 3 μm and decreases with increasing frequency. Therefore, since the copper foil is approximately 36 μm thick, current flows almost entirely at the surface of the copper and does not interact with the poorly conducting steel layer.

For the active monopole prototype, the conductor elements are 10 to 11 mm in length and 6 mm wide. The width is scaled with the size of the tube to allow for growth and retraction. Another important factor in selecting the conductor width is impedance matching to the electrical feed. The copper foil covers the outer surface of the steel backbone, and is folded over to provide a covered conductive surface between successive elements. Spacing for the distal ends of the conductive elements is marked on the thin-walled tube every 6 mm, allowing 4 to 5 mm of overlap. This overlap matches the diameter of the selected magnets, to ensure connection. A piece of soft, double-sided, viscoelastic adhesive (TrueTape LLC) 6 mm long is used to attach the conductor piece to the polyethylene tube. Only 3 mm of the adhesive is attached to the element, allowing the unattached length to create the desired tip-break while enlarging the adhesive contact area to the tube. To scale to different length steps, the element length and overlap can be adjusted. The magnets are attached after the conductive elements with the polarities aligned to stop the magnets from self-attracting.

D. Closed-Loop System

Antenna frequency control is achieved through closed-loop tuning of the antenna based on feedback-controlled robot growth and retraction. A user specifies a desired operating frequency as the reference input. The return loss is measured by the VNA and imported into Matlab at 100 Hz over TCP/IP, where the data is processed to find the resonant frequency of the antenna. The desired and measured frequency values were transmitted to an Arduino Due. The Due uses the frequency error to calculate a desired motor velocity to change the length of the antenna. Velocity control of the motor was implemented using proportional-integral control based on velocity estimates from an encoder at a

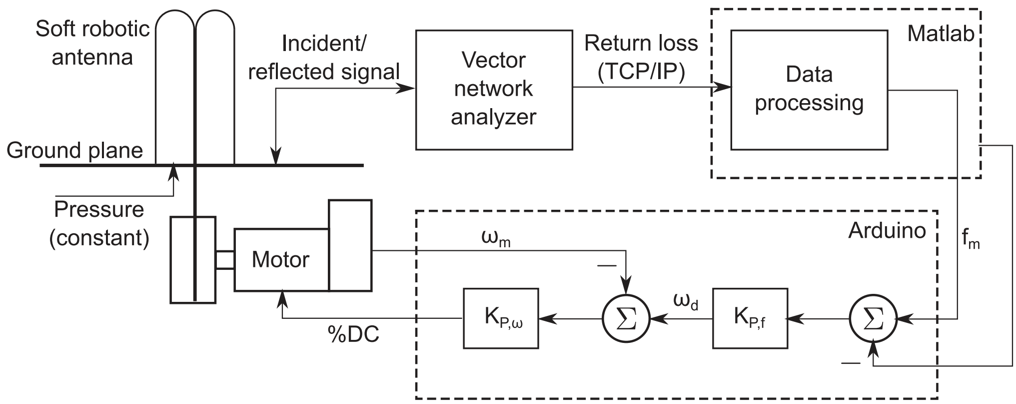


Fig. 3. Block diagram for closed-loop frequency tuning of the growing monopole antenna. Antenna on the surface of the growing robot is fed and measured by the vector network analyzer, which then provides return loss data to Matlab over TCP/IP. The measured resonant frequency, f_m , is found and sent with the desired frequency, f_d, to an Arduino Due microcontroller. Frequency error is used to calculate a desired motor speed, ω_d, which is compared to the encoder estimated motor speed, ω_m , and input to a motor velocity control loop. Pressure supplied to lengthen the soft robot is held constant, making the motor the only controlled input to the system.

loop rate of 5 kHz (Fig 3). The extension of the robotic antenna was rate controlled instead of position controlled because the constant pressure input to the system causes a bias towards extending the robot. To counteract this bias in a position controller, a large derivative term may be needed, which is structurally similar to a rate control loop.

III. Active Monopole Antenna Results

A. Frequency Modulation

We gather return loss measurements from the antenna to characterize the operating frequency and validate our designs. The data is collected through microwave scattering analysis using a vector network analyzer (VNA) (Rohde & Schwarz ZNB20). 1-port scattering analysis was used to measure the input port return loss, Γ. The VNA transmits an incident electromagnetic signal, V_1^+, to the antenna and measures the reflected signal, V_1^-, that is rejected by the antenna as a function of frequency, thus determining the return loss, defined as:

$$\Gamma\ (\mathrm{dB}) = 20 \log \left| \frac{V_1^-}{V_1^+} \right| \tag{3}$$

Return loss indicates how much energy is delivered to an antenna and its potential for radiation. At the resonant frequency, the majority of the incident power is radiated with little reflected power, producing a local minimum in return loss.

The simulated return loss measurements for a monopole of set length were calculated to compare to the experimentally obtained measurements. The simulation was performed in COMSOL Multiphysics with the known conductor strip width and material. Fig. 4 shows the comparison study for an antenna with lengths 40 mm, 52 mm, and 148 mm. The shape of the return loss and resonant frequency match well to that expected based on simulation. There are some artifacts present in the experimental results not seen in the simulations, which may be attributed to the disconnected conductor interior to the robot body, presence of other dielectric structures near the antenna, and the limited size of the ground plane.

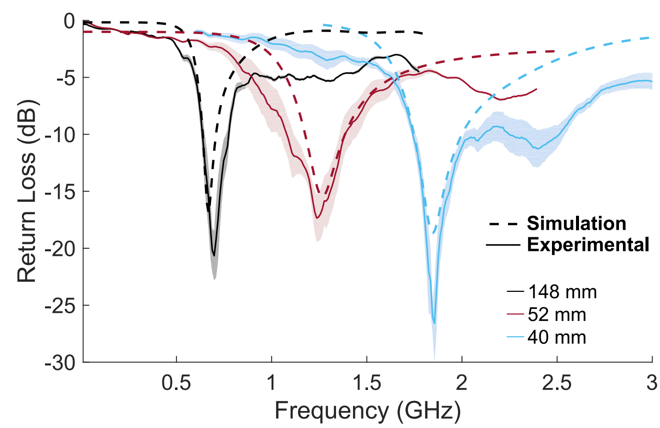
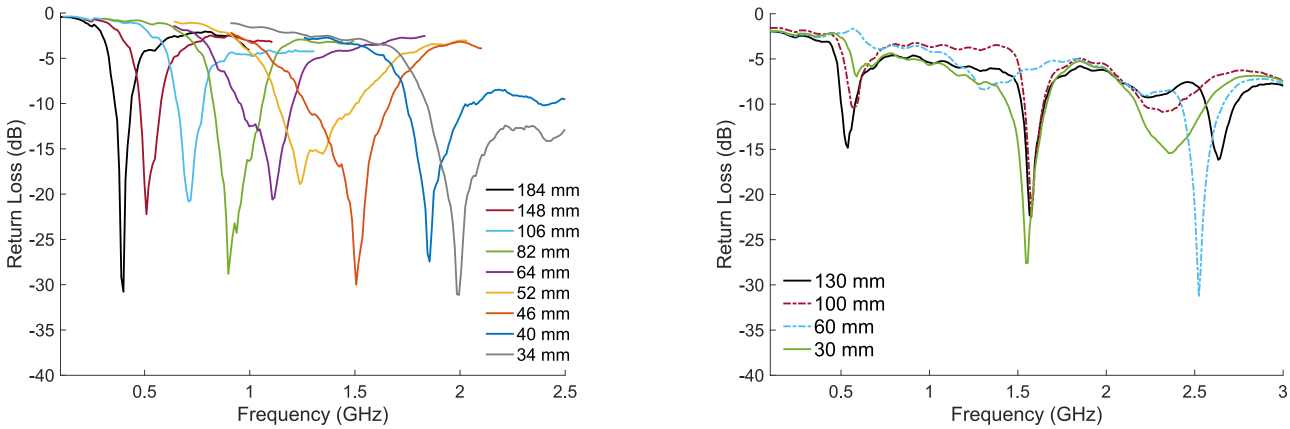


Fig. 4. Comparison of frequency characteristics for simulated and experimentally measured monopole antenna. The results provide evidence of the agreement between simulated and experimental resonant frequency. Ten measurements were taken, with the mean and standard deviations shown.

Fig. 5(a) shows the change in resonant frequency over a wide range of discrete frequencies. The step size achieved in the current prototype is 6 mm, or 30 steps between 10 mm to 184 mm. Only 10 of these are shown in Fig. 5(a). When the length of the antenna decreases, the resonant frequency increases. The antenna is demonstrated to have a tuning range including, but not limited to, 400 MHz to 2 GHz. Other platforms that display comparable tuning ranges include stretchable microfluidic antennas. These systems are mechanically elongated through stretching and are fundamentally restricted by strain limits, hysteresis, and poorer conductivity of liquid metals [17]. Our antenna design avoids these problems by mechanically elongating through growth and using high conductivity copper as the radiator.

B. Tip-Breaking Conductor Comparison

The results of the tip-breaking conductor design are compared to a baseline case with the same robot structure but an unbroken conductor measured in the same way as described above (compare Fig. 5(a) and (b)). This was done to show the



(a) (b)

Fig. 5. (a) Frequency tuning for various monopole lengths using the tip-breaking conductor. (b) Return loss of a growing monopole with an unbroken conductor. Monopole is grown over the same range as the tip-breaking design, but while the relative magnitudes of the peaks change, their frequencies do not shift.

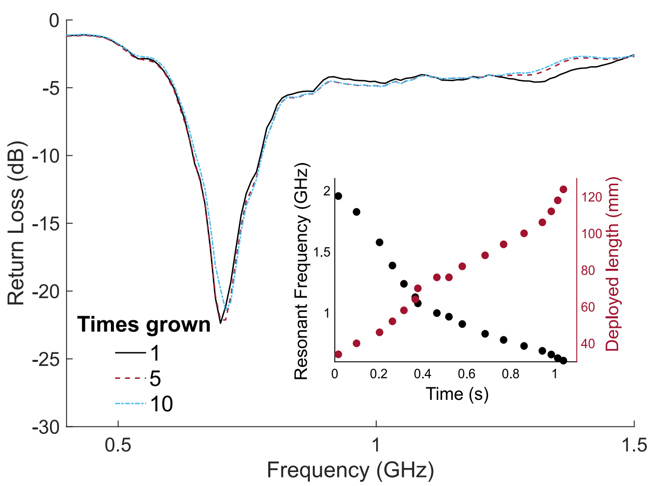


Fig. 6. Return loss is maintained for feedback-controlled monopole grown over many cycles. Frequency reconfiguration from 2 GHz to 600 MHz is achieved in one second, demonstrating the effectiveness of feedback control based on frequency measurement.

lack of clear relationship between antenna length and resonance characteristics when the conductor is unbroken at the tip and runs along the total length of the robot body. As expected, the unbroken conductor antenna retains essentially the same resonant peaks throughout the full range of lengths. The length does have some effect on the relative power, but this is not equivalent to a true frequency reconfiguration. This confirms the benefit of the tip-breaking design in allowing reconfiguration as well as deployment.

C. Closed-Loop Frequency Control

This system stably controls the antenna length in order to give the desired resonance characteristics throughout the full range of producible antennas. The antenna robot is able to go through multiple growth and retraction cycles without damaging the conductor and still maintain frequency selectivity (Fig. 6). The frequency is modulated from 2 GHz to 600 MHz in approximately one second (Fig. 6 inset). This speed was limited by the pressure in the system and the torque-speed capabilities of the DC motor.

IV. Shape Controlled Antenna Design

The monopole antenna design only takes advantage of the linear growth and retraction capabilities of tip-extending robots in order to achieve simultaneous frequency reconfiguration and straight-line deployment. It is possible to deploy more complicated shapes by pre-shaping the robot. While the monopole only achieves frequency reconfiguration, in general it is possible to dynamically alter other antenna properties, such as radiation pattern or polarization, by changing the shape and geometry of the antenna using mechanisms distinct from the robot growth and retraction abilities. To realize reconfiguration and deployment for other standard antenna designs, additional mechanisms are needed, such as branching and integrated turning actuators. We implement these mechanisms in two more advanced antenna models: a Yagi-Uda antenna, which consists of many linear dipole elements in a parallel array, and a helical antenna, where the conductor is wound in a helix shape.

A. Branching

The monopole antenna consists of a singular continuous conductor path. However, antennas are often made up of multiple conductors in an array. In order to realize this using the soft robot, we create parallel deployable paths by branching off of the main robot body. The branches evert to lengthen like the main body, and the length of each branch can be controlled in a similar manner to the monopole, by a reel located in the base (Fig. 7(a)). While the branching locations are permanent after manufacturing, different branch lengths or number of branches can be selected during each deployment.

We implement branching with a model Yagi-Uda antenna with three dipole elements (Fig. 7(b)). Yagi-Uda antennas are extensively utilized, commonly as television antennas [18]. Unlike the monopole that radiates energy omnidirectionally, this antenna is directive, in that radiation is directed away from the

Fig. 7. Tip-extending soft robotic Yagi-Uda antenna. (a) Schematic showing the deployment of branched material and the method to control branch extension through cables attached to the tip of the branch internally. (b) The robotic Yagi-Uda antenna model is sequentially deployed allowing reconfiguration of antenna characteristics as additional dipoles are extended. The center dipole is initially kept from extending, then allowed to extend showing reconfiguration possibilities.

tip of the antenna. Using pairs of branches at right angles to the main body, we are able to achieve this antenna form.

Configuring the number and length of branches is useful for changing the operating characteristics of Yagi-Uda antennas. Increasing the number of dipoles, or branches, and changing the length of the dipoles can change the directivity of the antenna, or how concentrated the radiation is in a single direction, or the operating frequency. By adding more dipole structures, the antenna's radiation pattern is dynamically modified. In the model antenna, the number of dipoles can be increased through growth by deploying more branches off the main body. Partially extending branches using the cables to control extension allows for length selectivity.

B. Integrated Turning Actuators

Turning mechanisms used to shape the growth path of tip-extending robots, described in detail in [12], can be used to actively design the shape of an antenna as it is deployed. While this method allows for active change in shape, it results in the shape of the antenna being fixed after deployment. To create deployable shapes that can also be reversibly reconfigured, we integrate soft reversible actuators into the body of the robot. In general, these actuators shorten or lengthen along a single path, which is achieved by tensioning a pull cable or changing the pressure in a pneumatically actuated muscle [19], [20]. The routing of the actuator on the body will determine the possible shapes that can be made.

We prototyped two soft shape-changing robots that can be used to deploy a reconfigurable helical antenna. Helical antennas are also one of the most utilized antennas, commonly seen in satellite communications [18]. These antennas provide directivity by radiating in a direction away from the antenna along the axis of the helix. Using (1) a single pull cable (Fig. 8) or (2) an inverse pneumatically actuated muscle (IPAM) (Fig. 9) spiraled around a straight robot body, a helix can be formed. The shape of the helix is dependent on the difference in length between the path of the straight body and the shortened path after actuation. The IPAM-actuated helix can be continuously deformed between a straight length and a tight spiral, whereas the pull cable helix can create only a single shape per cable, but

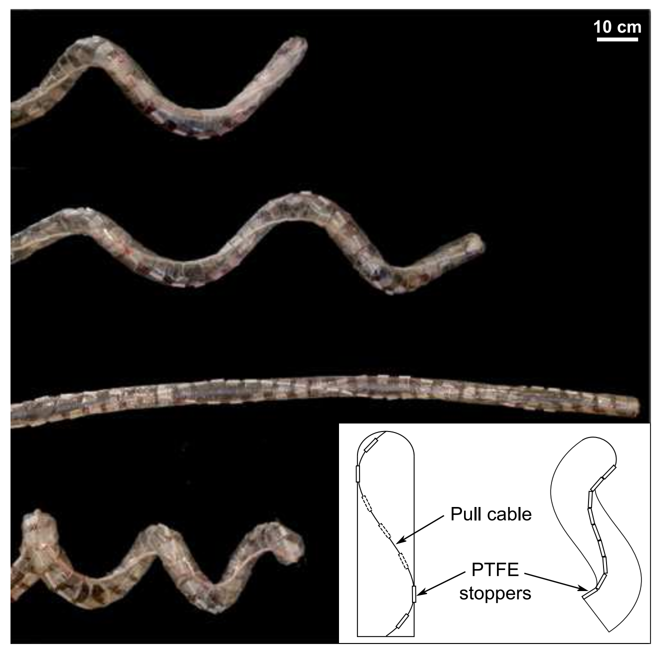


Fig. 8. Tip-extending soft robotic helix antenna reconfigured by a pull cable. Helix shape is held by a cable and PTFE stoppers on surface of the antenna robot body (inset). Extending from the tip changes the number of turns and tensioning the pull cable changes the diameter and pitch angle. Different helical shapes are formed by actuating different pull cables on the surface of the body.

with high uniformity due to the PTFE stoppers. The robot can be reversibly reconfigured from a straight body into a helical shape using these actuators. Growth and retraction are decoupled from the reconfiguration mechanism. When the robot is configured in its straight form, retraction is possible using the same mechanism as the monopole.

Geometric reconfiguration alters important properties of the helical antenna. Changing the number of turns or the pitch angle of the helix modifies the antenna's directivity and tuning the diameter changes the optimal operating frequency. The number of turns can be increased by extending the length of the robot. Modifying the actuator length changes both the diameter and pitch angle of the helix, as seen in Figs. 8 and 9. We will investigate the theoretical and experimental properties of these shape-changing antennas in future studies.

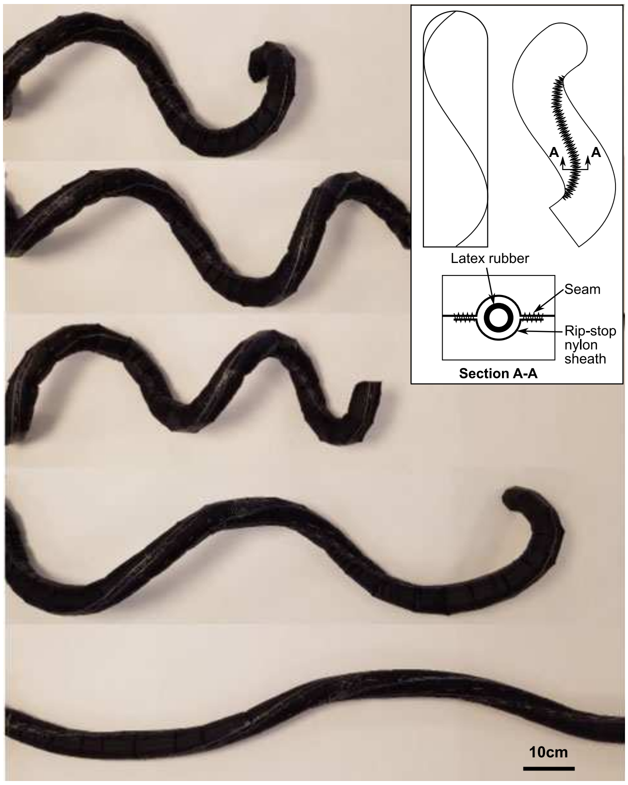


Fig. 9. Tip-extending soft robotic helix antenna reconfigured by an IPAM. Helix shape is held by an IPAM on surface of the antenna robot body, which is lengthened by increasing the pressure within the latex rubber tube (inset). Extending from the tip changes the number of turns and changing the pressure changes the diameter and pitch angle. The helical shape can be continuously reconfigured between the tightest helix and the straight body by changing the pressure in the IPAM.

V. Discussion

The tip-extending robot-deployed monopole antenna exhibited frequency reconfiguration that matches simulations. It accomplishes this using a single tip-breaking mechanism over a wide range of discrete resonant frequencies. Adding branching and actuation capabilities to the robot extends our range of fabricable RF devices to more complex shape-changing antenna structures. These developments in antenna design have implications for reconfiguration, deployment, and prototyping.

Tip-extending robots are unlike most other reconfiguration methods in that they can produce 3D mechanical reconfigurations, though at slower speeds than many other reconfigurable antennas. Systems that involve the use of mechanisms like RF-MEMS switches are often limited to 2D planar antennas with small form factors, such as microstrip or patch antennas. While the monopole only lengthens in a single direction in space, in general the robot body can be formed into an arbitrary desired shape before growing, which we displayed through the model Yagi-Uda. In addition, active shape-change can be achieved through the integration of actuators along the robot body, demonstrated through both helical antenna prototypes. Moreover, these structures can grow to lengths over many orders of magnitude.

The tip-extending robot antenna also provides a novel addition to the realm of deployable antennas. Previous examples for deployable antennas involve unrolling metallic tape-springs [21], moving the ground plane relative to the antenna [9], or using origami techniques [22]. The main disadvantages of these methods are that the intermediate stages of deployment do not necessarily provide good antenna properties, and it is not always obvious how to feed a signal into these structures. The single mechanism for reconfiguration and deployment provides a functional antenna at every stage of deployment. Even for other designs where antenna properties are not necessarily affected by length change, this is still advantageous, as antennas can be deployed to fit an available space or navigate around obstacles in the environment. Since the antenna grows only from the tip, this additionally leads to a stable and stationary feeding point at the base, where signal is fed to the antenna.

Lastly, tip-extending robots provide a prototyping platform capable of producing antennas without any sheet-metal processing or chemical etching, which are the most common methods to construct commercial antennas [17]. The thin-walled polyethylene body of the robot has excellent dielectric properties ($\epsilon_r = 2.25$) comparable to polytetrafluoroethylene (PTFE), making it well-suited for RF applications [23]. Moreover, the robot is mostly air, resulting in minimal interaction between the backbone of the robot body and the active RF device. The customization of these robots enables the rapid construction of 3D structures. Though not displayed here, we believe the ease of changing the robot shape can be used to rapidly test and design new antenna shapes. Moreover, while variation between manufactured devices could exist, the closed-loop control of frequency tuning aims to compensate for device-to-device variation.

There are some limitations and challenges faced by the tip-extending robot design methods. We are presently limited to shapes where the surface curvature is not too high so that the conductor segments in the tip-breaking design do not lose electrical connectivity. During growth, buildup of friction can be problematic as new material must be physically transported from the base through the existing body. Large numbers of densely packed branches and long or high curvature shapes can cause friction to increase above the ability of the pressure to extend the robot. This could be compensated for by increasing the diameter of the main body, but may not always be practical. As well, while the monopole and helical antennas show reversible reconfigurations, retracting the dipole branches of the Yagi-Uda antenna is more difficult. The current Yagi-Uda model is capable of one-way shape change without retraction. For the monopole and helix structures, a reel re-inverts and retracts the tube by applying a force along the direction of growth. Branches are difficult to retract because the force exerted at the base of the tube is at a right angle to the direction of branch growth and causes the tube to buckle instead of retract. Similar buckling may also occur at longer length scales. We expect that improvements such as more flexible and lower friction materials, geometric optimization, and further turning actuator development will expand the range of possible antenna designs.

VI. Conclusion

In summary, we have demonstrated a novel approach for fabricating reconfigurable and deployable antennas integrated with robotic growth. Construction of the antenna in this manner allows for a simple, lightweight, and transportable device that can expand to specifications in the field and adapt to evolving conditions. The resulting antenna's resonant frequency is tunable over a wide range of distinct and discrete frequencies by mechanical modulation and controlled by a closed-loop system. With this manufacturing approach, antennas can be rapidly adapted to new specifications, including other operating frequencies or device sizes. The design of a passive tip-breaking conductor allows for high quality conductive materials to be used in the antenna, while yielding a large reconfiguration. Results taken from a monopole design show good agreement with simulated models. In addition, we demonstrated the possibility for a diverse array of pre-shaped and actively designed RF devices created using tip-extending robots, including more interesting antennas like Yagi-Uda and helical antennas.

By using the tip-extending robot to form useful 3D electromagnetic structures, we exploited robotic growth as a paradigm for a previously unexplored application. We envisioned and presented soft robots as a promising candidate for enabling antennas for applications in which deployment, reconfigurability, and low cost are desired. Incorporating variable length conductor segments can customize antennas to specific applications. Combining these concepts with smart materials, such as thermo-reactive materials, could further enhance the performance of the system by adjusting the flexibility and reconfiguration speed of the system. These design concepts can also be extended to non-antenna applications such as waveguides and transmission lines. Future work includes characterization in an anechoic chamber to determine the actual radiated power transmitted from the antenna, its efficiency, and radiation pattern. Such measurements are needed to fully demonstrate the benefits of the shape-changing antennas. In the future, we envision creating well-characterized electromagnetic structures using high performance functional materials that can be controlled to track and maximize received signal power.

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