A Tip Mount for Carrying Payloads using Soft Growing Robots

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Abstract—Pneumatically operated soft growing robots that lengthen through tip eversion can be used for inspection and manipulation tasks in confined spaces such as caves, animal habitats, or disaster environments. Because new material is continually emitted from the robot tip, it is challenging to mount sensors, grippers, or other useful payloads at the tip of the robot. Here, we present a tip mount for soft growing robots that can be reliably used and remain attached to the tip during growing, retraction, and steering, while carrying a variety of payloads, including active devices. Our tip mount enables two new soft growing robot capabilities: retracting without buckling while carrying a payload at the tip, and exerting a significant tensile load on the environment during inversion. In this paper, we review previous research on soft growing robot tip mounts, and we discuss the important features of a successful tip mount. We present the design of our tip mount and results for the minimum pressure to grow and the maximum payload in tension. We also demonstrate a soft growing robot equipped with our tip mount retrieving an object and delivering it to a different location.

I. INTRODUCTION

Many continuum robots require transport of cameras and other sensors for exploration and inspection tasks. Some of these robots must also carry payloads for manipulation of the environment, object delivery, and object acquisition. For example, a camera-equipped snake robot \cite{1} was recently deployed within a collapsed building for search and rescue after the 2017 Mexico City earthquake. Additionally, a gripper-equipped snake-like mobile robot \cite{2} has recently been demonstrated for grasping and retrieving objects and turning a valve in a mock disaster scenario.

Another type of continuum robot that is also well-suited for exploration and manipulation tasks in confined spaces is a pneumatically driven soft growing robot \cite{3}, \cite{4}. Unlike typical snake-like robots, this type of robot "grows" from a fixed base through the transport of new material through its body and eversion of that material at the tip, driven by internal air pressure.

Mounting of a payload at the tip of a soft growing robot is challenging because material at the tip of the soft robot body changes as the robot grows or retracts. Thus, there must be relative movement between the tip mount and the soft robot body material on which it is mounted. This challenge is also shared by other types of tip-growing robots \cite{5}, \cite{6} and everting toroidal robots \cite{7}, \cite{8}. A successful soft growing robot tip mount must stay on the robot tip for all desired movement and environmental interaction of the robot. Such a mount could be used to carry sensors or tools to physically interact with the environment (Figure 1).

Several designs for tip mounts for soft growing robots have previously been demonstrated \cite{3}, \cite{4}, \cite{9}, \cite{10}, \cite{11}, \cite{12}, but none of them fully meets the desired characteristics of a successful tip mount. Soft growing robots are particularly strong in tension, since their strength is limited only by the tensile strength of their body material. This important feature cannot be exploited using previous tip mount designs, due to separation of the tip mount from the soft robot body tip during application of high tensile loads.

An additional consideration for the functionality of soft growing robots is their tendency to buckle rather than invert their body material during retraction. Buckling during retraction leads to lack of control of the robot’s motion, and...
recent work [13] has shown that placement of a “retraction device” at the tip of the soft robot body prevents buckling and restores control over the robot. In order to extend the dexterity and functionality of our soft growing robot system, we aim to integrate a retraction device and a tip mount capable of withstanding high tensile loads into a single unit.

In this paper, we present a tip mount capable of carrying a variety of payloads and devices while remaining attached to the tip of a soft growing robot during growing, retracting, and steering. Our tip mount enables two new soft growing robot capabilities: retracting without buckling while carrying a payload at the tip, and exerting a significant tensile load on the environment during inversion. Section II presents an analysis of the advantages and disadvantages of various previous tip mount designs, and Section III explains the principles behind our tip mount design. Section IV presents details of our device design and control. Section V characterizes what effect our device has on soft robotic growth, as well as the maximum payload of the device, and Section VI presents a demonstration of the tip mount being used to grab an object and deliver it in a mock disaster environment.

II. ANALYSIS OF PREVIOUS TIP MOUNT DESIGNS

Here we discuss and analyze previous designs of tip mount devices used with soft growing robots. The function of each previous design is shown in Figure 2 and the benefits and drawbacks of each design are shown in Table I in comparison with our current design.

A. String Mount

One method of mounting a camera at the tip of the robot was presented in [4], [9]. In this method, the camera wire is placed in the space inside the tail of the robot, and the camera rests at the tip of the robot, being pushed forward as it grows. However, as you apply pressure to the inside of the robot, this pressure squeezes the tail material, applying a normal force to anything internal to the tail. Since the material of the tail moves twice as fast as the tip of the robot moves (Figure 2(a)), the wire and camera will naturally be ejected and fall off as the robot grows, and the camera will be engulfed as the robot retracts. In [4], [9], this problem was solved by adding airflow through the interior of the tail and pulling back on the wire from the base as the robot grows. One benefit of this method is that there is no contact between the tip mount and the environment. Also, the tip mount can be as small as the payload it is carrying, so it does not restrict the deformation of the soft robot body while squeezing through gaps. Additionally, the robot tail provides a conduit for the camera wire that keeps it from snagging on the environment. However, the technique that allows this tip mount to work in [4], [9] means that the robot material cannot be stored on a spool in the base. This limits the length change using this method: the soft robot body can only grow up to twice the initial robot length. If the robot body material is stored on a spool, as diagrammed in Figure 2(a), a sensor attached to the tip of the robot will not remain at the tip as the robot grows.

B. Outer Cap Mount

Another method of mounting a sensor at the robot tip was presented in [11] and is diagrammed in Figure 2(b). This mounting mechanism uses a rigid cap that fits over the outside of the robot tip and is pushed forward by the soft robot’s growing force. This design benefits from its simplicity and from some ability to withstand side-loads at the tip. Unlike the string mount design, the speed difference between the growing robot’s tail and the wall does not affect the cap’s ability to stay on during growth. However, when the robot is retracted, the cap falls away from the body because the robot applies no forces to hold the mount on when it inverts. Additionally, this mechanism has no pieces internal to the robot, so to add electrical connections for a camera, sensor, or gripper mounted on the cap, the wiring needs to be run external to the robot. This leads to the potential for snags in cluttered environments, so previous use of this design in [11] involved a self-sealing external wire management scheme.

C. Outer Cap with Reel Mount

A third method of mounting a sensor at the robot tip was presented in [3] and is diagrammed in Figure 2(c). This mechanism combines features of the string mount and the outer cap mount, with a wire internal to the tail for electrical connection and cap attachment like in the string mount, as well as an outer cap at the tip. This mechanism overcomes the primary disadvantage of the string mount by adding a motor and spool inside the outer cap that is attached to the wire. This allows this cap design to work with a spooled robot base, since the motor can actively wind up the wire as it is ejected from the end of the robot, keeping the cap attached to the tip. Though not demonstrated in [3], the cap motor could also be used to unwind the wire as the robot retracts, allowing this design to work both in growth and retraction. However, this method of dealing with the internal cable means that, as the length of the robot increases, the size of the spool inside the mount needs to grow as well. This therefore limits the length of the robot based on the size of the tip mount. In addition, the only force keeping the tip mount attached to the end during retraction and growth is the force of the motor inside the mount holding onto the wire. This means that the motor needs to be actively controlled to ensure the robot can grow and retract without the cap falling off, and the motor torque can additionally limit the amount of force the robot can lift when a gripper is attached to the cap.

D. Magnetic Rings Mount

The final method of mounting a payload at the robot tip previously demonstrated in the literature was presented in [10], [12] and is diagrammed in Figure 2(d). The design consists of two pieces which are held together by magnetic force. This tip mount design places part of the cap internal to the robot body for the first time, as opposed to internal to the tail, and the other piece of the tip mount rests external to the robot at the tip. Since no part of the cap is inside
the tail, this design is not affected by the velocity of the robot tail during growth or retraction. The external part of the cap is pushed forward by the growing force as the tip moves forward, while the internal piece and magnetic roller keep the outer piece from falling off the end, while limiting the friction at the interface. The primary benefit of this tip mount design is that, like the string mount, there can be very little contact between the mount and the environment, limiting the additional friction force from sliding. As well, the design can stay at the robot tip during retraction, instead of being engulfed, as long as the external piece is about as large in diameter as the robot body. However, the design can only resist external loads (both lateral and axial) up to the magnetic holding force. Lateral loads especially can be a problem because the rolling magnets may allow the pieces to be pushed apart easily.

E. Previous Design Summary

A summary of the past designs and their capabilities can be found in Table I. These previous tip mount designs identified a number of distinct strategies for staying attached to a moving point. The designs demonstrate a large range of potential mounting locations, including within the tail, external to the robot, and within the robot body. As well, many or all the designs share some features in common, including a surface at the tip to be pushed forward as the robot grows. While none of these designs completely meets the goal of staying mounted during any potential robot actuation or external force, the designs overall give a guide to a fully successful tip mount. However, none of the designs incorporates a way to mitigate buckling of the soft robot body during retraction. Another important feature missing from the existing designs, with the potential exception of the string mount, is the ability to resist tension loads, which will open up the applications of soft growing robots with tip mounts to include more manipulation tasks.

III. DESIGN CONCEPT

In this section, we present the principles behind our current design for a soft growing robot tip mount.

A. Design Principles for Tip Mount

A successful tip mount must carry a payload and remain at the tip of the soft growing robot during all desired movements and environmental interactions. From the previous designs in Section II, the main failure modes of tip mounts are falling off the robot tip as it grows or retracts and being engulfed inside the tail of the robot when retracted. The tip mount must also not interfere with steering of the soft robot body. In addition, to leverage the robot’s strength under tension, the cap should be able to withstand high tension forces. Finally, the design of the tip mount should integrate the function of previous devices which allow the robot to be retracted without buckling [13]. Taken together, we can identify the following key design requirements: (1) a part outside of the pressurized area of the robot body that can be used to mount payloads and remains at the tip during growth, retraction, steering, and external force application, (2) a part that can apply the force to retract the robot body between the tail and the robot tip, to allow retraction without buckling, and (3) a connection between the outside part and the retraction part to hold them together and allow them to move as a single unit.

B. Current Design

Building on previous research and design principles, we propose a design that combines an outer cap with a retraction device. The design includes a hooking mechanism that prevents the outer cap from falling off during retraction and also allows the tip mount to bear high tension loads. Our concept is shown in Figure 2(e) and our design implementation is

|                         | (a) String Mount Design | (b) Outer Cap Mount | (c) Outer Cap with Reel Mount | (d) Magnetic Rings Mount | (e) Current Design |
|-------------------------|-------------------------|---------------------|-------------------------------|-------------------------|-------------------|
| Stopped                 |                         |                     |                               |                         |                   |
| Growing                 |                         |                     |                               |                         |                   |
| Retracting              |                         |                     |                               |                         |                   |
|                         | ![Diagram](a.png)       | ![Diagram](b.png)   | ![Diagram](c.png)             | ![Diagram](d.png)       | ![Diagram](e.png) |

Fig. 2. Function of various previous designs and our current design: (a) string mount [4], [9], (b) outer cap mount [11], (c) outer cap with reel mount [3], (d) magnetic rings mount [10], [12], and (e) current design.

### TABLE I

**Comparison of Tip Mount Designs**

|                                   | String [4], [9] | Outer Cap [11] | Outer Cap with Reel [3] | Magnetic Rings [10], [12] | Current Design |
|-----------------------------------|----------------|---------------|-------------------------|---------------------------|----------------|
| Avoids being ejected during growth? | No             | Yes           | Yes                     | Yes                       | Yes            |
| Avoids falling off during retraction? | Yes            | No            | Yes                     | Yes                       | Yes            |
| Avoids being engulfed during retraction? | No             | Yes           | Yes                     | Yes                       | Yes            |
| Can support high tension forces?   | Yes            | No            | No                      | No                        | Yes            |
| Incorporates retraction without buckling? | No             | No            | No                      | No                        | Yes            |
Fig. 3. (a) Tip mount design, CAD rendering and image. (b) The tip mount consists of three parts: (c) interchangeable outer cap to mount (left) a sensor or (right) a gripper, (d) retraction device including (top) rollers to decrease friction with the robot tip and (bottom) motor parts to grow or retract the material of the soft growing robot, and (e) a hooking mechanism using (left) magnets and (right) bearings to prevent separation of the inner and outer parts.

shown in Figure 3. This design solves the limitations of the other designs as shown in Table I.

IV. Design and Implementation

In this section, we describe the implementation of our tip mount’s mechanical design and control.

A. Mechanical Design

The mechanical design is shown in Figure 3 and incorporates three main components: (1) the interchangeable cap for mounting of sensors or a gripper, (2) the retraction device to allow retraction without buckling, and (3) a hooking mechanism to stably attach the cap and retraction device together.

a) Interchangeable Cap: This part (Figure 3(c)) is designed for easy replacement of the tool attached to the mount. The cap can carry a camera for exploration of unknown environments or a gripper to grab or move objects. In addition, this part is designed with three empty spaces so that it does not impede the function of the three series pouch motor steering actuators [11] attached around the robot. This part incorporates a platform to be pushed forward by the robot material when the robot grows at the tip.

b) Retraction Part: To enable retracting without buckling, this part (Figure 3(d)) contains two motors (3485, Pololu Corporation, Las Vegas, NV) that can pull the tail material while the passive rollers on the top apply a reaction force on tip of the robot. The rollers attached to the motors are covered with high friction material (Non-Slip Reel, Dycem Corporation, Bristol, UK) to avoid slipping relative to the tail. Because the wire that supplies power to the motor is connected through the space inside the robot, power can be supplied to the motors during growth and retraction regardless of the external environment. The rollers at the top of this part serve to reduce friction with the material of the tip during retraction. In order to reduce friction between this part and the wall of the soft robot body, the outer edges of the top rollers and the outer edges of the bearings in the attaching parts are aligned with each other. Aside from the high friction material coating the rollers, all other parts are designed to reduce unnecessary friction.

c) Attaching Part: This part helps to unite the interchangeable cap and the retraction part by connecting them at their bases. This structure holds the mount at the tip even with disturbance forces applied horizontally and vertically and provides structural restraints so that the cap does not fall away from the tip during retraction. This part is designed so that only the bearing parts, made of three pairs of hooks placed circumferentially around the base of the mount, come into contact with the wall material, which must pass through these rollers to grow or retract the robot. A pair of magnets surrounds each bearing to prevent relative tilting or rotation of the cap and the retraction part. Like the bearings, the magnets are attached diagonally to restrain movement in any direction.

B. Control

To control the motion of the soft robot body, we used the base, the joystick, and the steering control algorithm presented in [11] for steering of the soft robot body by coordinating pressures in three series pouch motor actuators placed circumferentially around the body of the robot. Additionally, we developed a method of coordinating the voltages sent to the base motor and the tip motor to allow growth and retraction without building up slack in the tail and to allow retraction of the soft robot body without buckling. For simplicity, we used open-loop voltage control of the motors with no encoders.

a) Growth: During growth, the desired operation was that the pressure in the soft robot body would be set to a pressure higher than that needed to grow at the desired
speed, the motor in the base would be backdriven to let out the tail material without building up slack in the tail, and the motors at the tip (which are not as backdrivable) would be controlled to release the material at the desired speed. To achieve this, we set the voltage of the motor in the robot base to the highest voltage in the growth direction before the motor began spinning with no load applied, and we set the voltage of the motor in the retraction device based on the joystick input to be between the highest voltage in the growth direction before the motor began spinning with no load applied and the highest allowable voltage. Using this control method, the soft robot body with our tip mount attached is able to grow at a maximum speed of 5 cm/s.

b) Retraction: During retraction, the desired operation was that the pressure in the soft robot body would be set low enough to require minimal retraction forces applied on the robot tail but high enough to pressurize the robot body enough to allow easy sliding of the robot body material between the magnets in the hooking mechanism. The motor in the base would be run at high enough voltage to take in the slack in the tail but not so high that buckling occurred during retraction, and the motors at the tip would provide the rest of the necessary forces to retract. To achieve this, we set the voltage of the motor in the robot base to the highest voltage in the retraction direction before the straight robot body began to buckle at the pressure we used for retraction, and we set the voltage of the motor in the retraction device based on the joystick input to be between the highest voltage in the retraction direction before the motor began spinning with no load applied and the highest allowable voltage. Using this control method, the soft robot body with our tip mount attached is able to retract at a maximum speed of 5 cm/s.

V. Characterization

We conducted a set of experiments to characterize the capabilities of the soft growing robot when equipped with our tip mount. These experiments help quantify how much weight can be pushed during growth or pulled during retraction, as well as how improving the performance of different portions of the device would affect the robot’s capabilities.

A. Pressure Required to Grow

An important factor for the function of the soft growing robot is the minimum pressure required to grow. The internal pressure can be set higher than the minimum pressure required to grow, and if the robot body material is not restrained by a motor or friction, the additional pressure will either make the soft robot grow faster [14] or apply more force at its tip [15], up to the buckling load of the soft growing robot body. The internal pressure is limited on the upper end by the burst pressure of the soft robot body material. Adding our device at the robot tip adds friction between the soft robot body material and the device, as well as between the device and the environment, which increases the minimum pressure required to grow. Increasing the minimum pressure required to grow decreases the maximum growth speed or the payload that can be pushed before bursting the soft robot body.

To understand the effect of our device on the minimum pressure to grow (and thus the speed and payload capability of the robot), we conducted a series of growth tests with different parts of our tip mount installed. Throughout this paper, we used a low-density polyethylene (LDPE) plastic tube with inflated diameter 8.5 cm and wall thickness 0.06 mm, and for this experiment, we grew the robot horizontally on a foam board floor. We slowly increased the pressure in the chamber. At each pressure, we loosened the spool in the base and observed whether the robot started growing. We recorded the minimum pressure at which growth was observed for each scenario.

The results are shown in Figure 4. The soft robot body without any tip mount (Figure 4(a)) needs 2 kPa to begin growing, due to the forces required to turn the soft robot body inside out at its tip. The addition of the outer part (Figure 4(b)) increases the required pressure to 3.4 kPa. This increase is due to the friction where the wall and the tip of the soft robot body contact the outer cap, as well as where the outer cap is in contact with the floor. Adding the inner part without the motors and rollers (Figure 4(c)) increases the pressure to 6.8 kPa. This increase is due to the friction that occurs at the point of contact between the retraction part and the outer cap, since there is some sliding between the magnets and the wall material. Finally, with the addition of the motors and rollers inside the inner part (Figure 4(d)), the robot still requires 6.8 kPa to grow, since the rollers roll rather than slide on the tail.

These results indicate that the most important location to decrease friction in the device is in the bearings and magnets interface between the outer cap and the inner retraction part. An additional location that would have a smaller impact on decreasing the minimum growth pressure is between the outer cap and the environment, as well as between the outer cap and the wall. The experimentally determined burst pressure of the soft robot body is 22.0 kPa, so the additional friction of this device decreases the available range of pressure above the minimum growth pressure by only 24% (from 20.0 kPa to 15.2 kPa).

B. Maximum Payload During Retraction

We also conducted experiments to characterize the maximum payload the soft growing robot with our tip mount was capable of retracting, so as to understand how to fully exploit the high tensile strength of soft growing robots. This experiment was performed by attaching weights to a passive gripper (hook) mounted on the interchangeable tip mount. The growing robot was oriented vertically, so the force of the weight acted in tension on the robot and mount, and the robot tried to retract the weight (Figure 5(a)).

The most important factors to consider for how much load the robot can lift are the frictional force the retraction rollers can transmit, the maximum torque of the retraction motors, the breaking strength of the cap material, and the yielding strength of the robot body material. We calculated...
or measured the limits of how much the tip mount could lift based on each of these factors and experimentally verified the lowest of these limits as the lifting capacity of the robot (Figure 5(b)).

a) Rollers Slipping on Tail: One determining factor for the maximum payload that can be pulled by the robot is the friction between the motor-driven rollers and the tail. The force applied by the retraction device on the tail of the robot must be transmitted through this connection point. With our current device implementation, the maximum force that can be applied by the rollers on the tail before the slip occurs is 5 kg. Due to frictional losses in the device and the need for the motors to counteract the internal pressure of the soft robot body as well as the weight of the tip mount itself (0.5 kg), the maximum weight that our device can lift is 2.5 kg. In our device, this slipping of the rollers on the tail ended up being the limiting factor in the maximum payload that the device can pull, but other designs in which the rollers are able to apply higher forces on the tail before slipping (either by using a higher friction material or by enforcing a higher normal force between the tail and the rollers) could increase the weight limit.

b) Motor Torque Limit: The maximum motor torque also limits the payload that can be actively pulled in tension by the soft robot body. The motors used in this device have a gearbox torque limit of 5 kg-cm, so the maximum torque that the two motors can withstand is 10 kg-cm. To convert this torque to a weight for the payload, we divide by the roller radius (3 cm), resulting in a calculated 3.3 kg for motor torque weight limit. However, due to frictional losses in the device and the need for the motors to counteract the internal pressure of the soft robot body and to lift the weight of the device, the actual maximum weight that could be lifted with these motors is lower than this value, but it could not be experimentally determined, because the rollers began slipping on the tail before the motors reached their limit. Use of stronger motors could improve the weight limit due to this factor.

c) Device Yielding: The tip mount hooking mechanism between the inner and outer parts was developed to withstand tilting, unhooking, or breaking. In order to measure the effect of this interface on the weight limit, we mounted the tip mount device at the end of the robot and applied an increasing load until the inner and outer parts broke apart. When a load of 7 kg was applied, the outer part flexed and broke and became separated from the inner part. This factor’s weight limit could be improved by switching to a stronger material and reinforcing the design.

d) Material Yielding: As expected, the highest force limit for lifting under tension comes from the yielding of the soft robot body material. Considering this factor, the weight that can be lifted depends on how much force the material can withstand in tension. First, we experimentally determined the yield stress of the material by increasing the pressure until the robot body burst, which happened at \( P = 22.0 \) kPa. Then, we used the equation for hoop stress in a thin-walled cylinder to calculate the yield stress of the material:

\[
\sigma = \frac{Pr}{t},
\]

where \( P \) is the pressure inside the robot, \( r \) is the tube radius (\( r = 4.25 \) cm), \( t \) is the material thickness (\( t = 0.06 \) mm) and \( \sigma \) is the hoop stress at yield, which was calculated to be 15.6 MPa. To calculate the maximum tension load that can be supported by the soft robot body before material yielding, we multiplied by the cross-sectional area of the wall, giving a value of 25.5 kg for the maximum payload. The weight limit of this factor could be improved by switching to a material with a higher yield stress, a larger radius, or a higher thickness, although increasing the radius would also decrease the burst pressure, and increasing the thickness would likely increase the minimum pressure required to grow.

VI. Demonstration

The tip mount presented here allows us to mount sensors, grippers, or other devices at the tip of a soft growing robot while still allowing the robot to perform the motions of...
Trapped Victim
Water bottle
Fig. 6. Demonstration of a new capability of object retrieval and delivery made possible by our tip mount. (a) In a mock disaster scenario, the soft growing robot (b) grows and steers to pick up a water bottle, (c) retracts with the water bottle, (d) grows and steers and places the object in the trapped victim’s hand.

VII. CONCLUSION AND FUTURE WORK

In this paper, we presented a tip mount for soft growing robots that can carry a variety of payloads and uses mechanical constraints to stay at the robot tip. We summarized and analyzed past tip mount designs, showing the different methods for attaching to the moving material of the tip and explaining the pros and cons of each method. The new tip mount design takes inspiration from these past designs while adding a more secure attachment without sacrificing the function of the growing robot. The tip mount is able to lift a significant amount of weight in tension, highlighting the growing robot’s strength in tension. With the addition of a retraction device, the new tip mount demonstrated retracting without buckling while transporting a payload. This device aids in development of soft growing robots as applied to tasks that might be seen in disaster situations.

Future work will increase the tip mount’s ability to deform and leverage the tip placement of sensors like cameras. One of the biggest advantages of soft growing robots is that they are fully deformable and primarily composed of air, which allows them to squeeze into and pass through narrow gaps. However, with this rigid tip mount device, the soft robot would not be able to pass through gaps that are narrower than the diameter of the robot. In addition, since this cap gives a reliable way of keeping a camera at the tip of the robot for any potential actuation, a next step will be to investigate more fully the use of a tip mounted camera. We will investigate ways to give visual feedback to a user to help them control the robot, as well as potentially allow shared or full autonomy of the soft growing robot. These developments will bring the robot closer to being useful in real-world exploration or manipulation scenarios.

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