SlipStream: A Modular Soft Robotic System for Constrained Navigation in Complex Environments

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***Abstract*—This work describes the design, development, and validation of a modular soft robotic system capable of navigating confined environments with an inner diameter as small as 5 cm. The system employs a flexible, tread-based locomotion mechanism and a compliant structural design, enabling it to traverse complex terrains including loose debris, deformable boundaries, and inclined surfaces with sharp turns. Through iterative prototyping, the robot was optimized for maneuverability, adaptability, and structural integrity across a variety of challenging environments. The current configuration successfully completed an obstacle course simulating real-world conditions; however, the design is inherently modular and can be scaled or adapted to suit different diameters, tasks, and sensing payloads. This platform demonstrates the utility of soft robotics for a wide range of applications, including but not limited to inspection, environmental monitoring, maintenance in constrained spaces, and disaster response scenarios.**

***Index Terms*—Soft robotics, modular design, confined navigation, tread locomotion, search and rescue, cable installation.**

I. Introduction

A. Background and Motivation

The installation of electrical and communication cables in existing environments remains a labor-intensive and costly challenge. Traditional cable installation methods often require extensive trenching, wall modification, and complex routing that disturbs infrastructure and demands pre-planning to accommodate future needs.

In industrial contexts, laying fiber optic cables underground can cost between $5,000 and $20,000 per mile, depending on terrain complexity and permitting requirements [1]. In residential settings, the cost of wiring a typical home ranges from $4 to $9 per square foot, adding up to as much as $22,500 for a 2,500 ft^2 house [2]. Retrofitting older buildings increases costs further due to limited access and the invasive nature of the modifications [3].

A critical limitation in current practices is the inflexibility of traditional cable installation tools. Most conventional systems are not designed to handle variable pipe diameters, sharp 90° and 180° bends, or deformable and irregular environments. This is especially problematic when working in retrofitted buildings or complex conduit networks. Existing equipment often imposes strict bend radius constraints, increasing the risk of mechanical damage to cables when those limits are exceeded [4]. Additionally, high sidewall pressure in conduits—exacerbated by tight bends or transitions—can lead to cable deformation or failure [5]. Many tools currently in use were built for older, lower-density cable types and are ill-suited to handle modern high-fiber-count cables, which require more careful handling and routing [6]. These shortcomings necessitate detailed planning during initial construction to anticipate future cable needs, a practice that is often impractical and rarely followed [7]. As a result, cable retrofitting becomes costly, invasive, and error-prone, calling for adaptable solutions like modular soft robotic systems. As shown in Fig. 1, automated cable-laying at construction sites highlights the growing demand for robotic systems that can operate efficiently in confined, irregular environments [3].

Fig. 1. Automated cable-laying in a construction environment. Such scenarios illustrate the need for adaptable robotic systems capable of navigating confined, complex spaces to reduce labor and installation costs [3].

To address these challenges, we propose a modular soft robotic system capable of navigating pipe-like environments as narrow as 5 cm in diameter. The robot utilizes flexible materials and tread-based locomotion to traverse rubble, deformable boundaries, vertical inclines, and tight turns. Its modular design allows adaptation to different diameters, payloads, and tasks.

While the system was initially developed for the RoboSoft Competition, its form factor and adaptability make it a strong candidate for practical applications in:

- **Cable Installation in Industrial Settings**: Reducing trenching and labor costs for underground conduits.
- **Home Wiring and Retrofitting**: Navigating pre-existing pipe networks in homes for smart home integration, sensor deployment, or rewiring.
- **Infrastructure Inspection and Maintenance**: Offering access to aging, complex, or inaccessible conduit networks.

Beyond these, the technology has potential in areas such as environmental monitoring, disaster response, agricultural automation, and minimally invasive deployment of sensors or micro-devices. By leveraging soft robotic principles, the system presents a scalable and minimally invasive solution to diverse challenges in confined-space navigation and deployment.

II. Methodology

A. Requirements and Specifications

To address the challenges identified in current cable installation and infrastructure access methods, this work outlines the development of a modular soft robotic platform designed for traversal through confined and variable environments. While the system was validated using a standardized obstacle course, the design specifications extend far beyond competition constraints and are motivated by practical, real-world deployment.

A central requirement is the robot's ability to navigate within cylindrical conduits as narrow as 5 cm in diameter. This necessitates a compact, low-profile design that is both compressible and flexible, enabling traversal through tight, curved, or irregularly shaped pathways. The robot must maintain functionality under conditions involving restricted clearance, shifting terrain, and non-linear pipe geometries. To achieve this, soft and compliant materials—such as silicone, elastomers, or flexible polymers—are used in conjunction with adaptable mechanical linkages and low-profile actuation systems.

The locomotion mechanism must support forward and reverse motion, while also enabling precise directional changes, including 90° and 180° turns. These capabilities are essential not only for structured test environments but also for navigating real-world infrastructure such as sewer lines, utility conduits, or buried electrical pathways that frequently feature bends, joints, and material transitions. The robot is designed to maintain traction on varied surfaces such as rubble, soil, and deformable substrates, and it must be capable of ascending and descending inclines.

Beyond physical traversal, the system must support modularity for scalability and adaptability. This includes the ability to add or remove sensing, cabling, or manipulation payloads based on the task. For example, cable-laying modules, inspection cameras, or environmental sensors can be integrated without reengineering the entire system.

While validated under controlled conditions, the underlying design choices are applicable to a wide range of operational domains including—but not limited to—cable deployment in new or existing buildings, search and rescue in debris-laden areas, minimally invasive pipeline maintenance, and exploratory missions in hazardous or inaccessible environments.

The performance specifications guiding development include:

- Minimum operational inner diameter: **5 cm**
- Capable of 90° and 180° turns
- Robust traversal over rubble, soft walls, and slopes
- Modular payload support for application-specific functionality

These criteria informed the selection of materials, structural layout, actuation design, and system integration approach throughout the development process.

III. Design Overview

The final robot is designed to navigate pipe systems with internal diameters as small as 5 cm, using a compliant angled wheel configuration that allows for maximum surface contact and improved traction on curved surfaces. This balances flexibility and structure, integrating compliant drive elements with a compact actuation system.

A key feature of the system is the compliant linkage system, which provides high traction by conforming to the pipe surface. Fig. 2 shows the fabricated elastomer wheel, while Fig. 3 presents its CAD model, highlighting the compliant geometry.

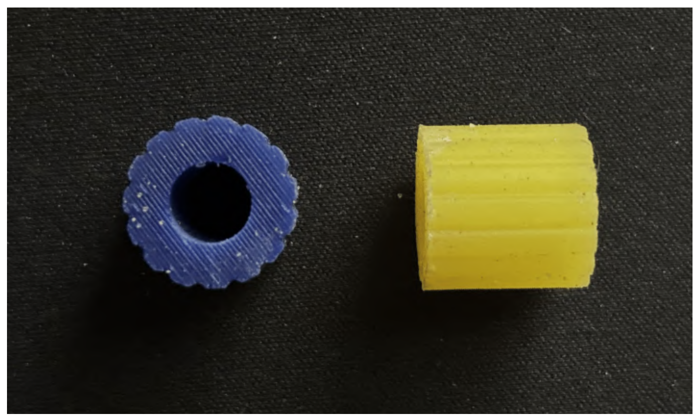

Fig. 2. Fabricated elastomeric wheel for high-traction interface.

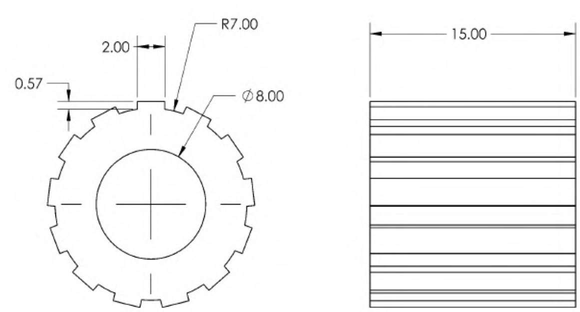

Fig. 3. CAD model of elastomeric wheel showing compliant design features.

To complement the soft wheels, precision resin wheels were used to provide rigid structure and accurate alignment. Fig. 4 displays the printed precision resin wheel, while Fig. 5 shows its CAD counterpart.

Each drive wheel is powered by a compact Pololu motor housed within a custom-designed hub. The hub integrates motor mounting, cable routing, and alignment features in a

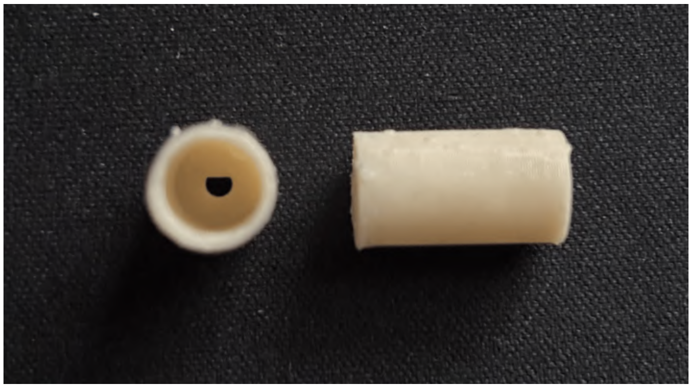

Fig. 4. Precision resin wheel fabricated as structural support for the elastomer wheels.

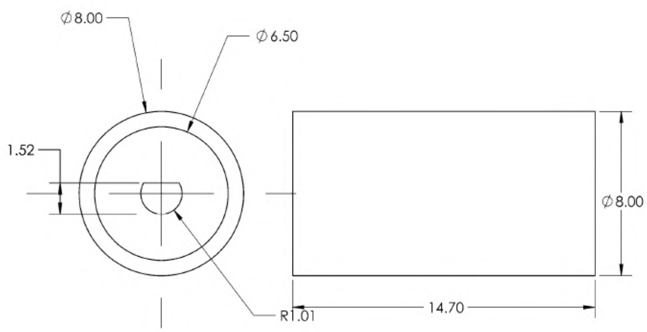

Fig. 5. CAD rendering of precision resin wheel with hollow inside geometry.

single resin-printed body. Fig. 6 shows the assembled physical hub, while Fig. 7 presents the CAD model.

Fig. 6. Resin hub with cavities for the motor and wire routing.

The complete robot incorporates two of these drive assemblies connected via a dual four-bar linkage, allowing independent articulation on either side. A spring system underneath ensures equal wall contact without ceiling interference. Fig. 8 shows the full assembled robot, and Fig. 9 illustrates its CAD representation, highlighting the tread orientation and linkage structure.

This integrated design delivers the performance necessary for pipe traversal, while offering a modular base for future enhancements including autonomous navigation, cable-laying modules, or onboard sensing capabilities.

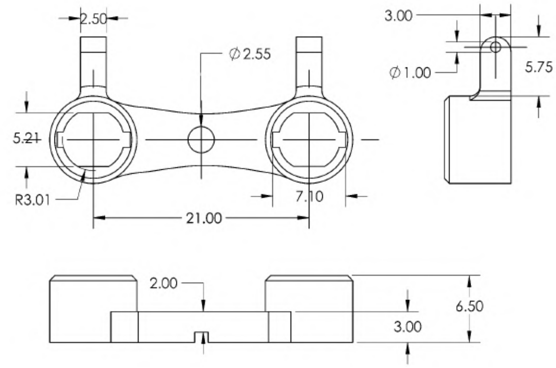

Fig. 7. CAD Drawings of the wheel hub showing motor slot and routing guides.

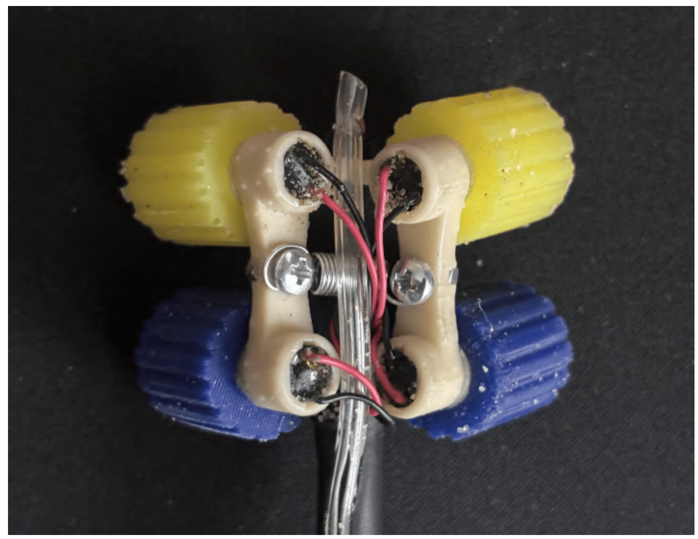

Fig. 8. Fully assembled robot with angled wheel configuration and compact frame.

IV. Materials and Component Selection

A. Electronics and Mechanical Components

All components were chosen to meet strict spatial and functional constraints, optimizing for speed, compactness, and modularity. The robot uses four **Pololu 136:1 Sub-Micro Plastic Planetary Gearmotors** [8], each offering a compact 6 mm body with a 19 mm length, ideal for confined applications. At 500 RPM, this motor provides sufficient speed for timed traversal while preserving low profile requirements. Alternate configurations can leverage higher-torque, lower-RPM versions for tasks such as payload transport or cable deployment.

Table I summarizes the bill of materials for a single robot unit, excluding interchangeable or optional variants.

Depending on application needs, alternate motor gear ratios (e.g., 100 RPM or 210 RPM) can be substituted to adjust the torque-speed tradeoff without altering the chassis or wheel mounts.

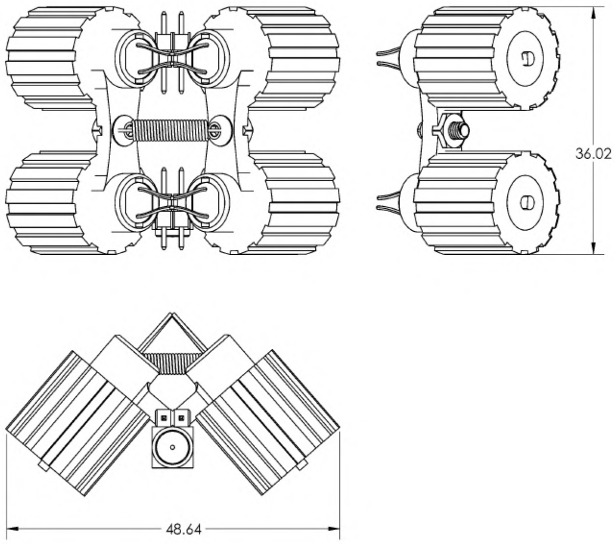

Fig. 9. CAD model of final robot showing wheel layout and compliant spring attachment.

TABLE I
BILL OF MATERIALS FOR ONE ROBOT UNIT

Item	Qty	Unit Cost	Total
Pololu 136:1 Sub-Micro Plastic Planetary Gearmotor 6Dx19L mm [8]	4	\$15.95	\$63.80
DRV8835 Dual Motor Driver Carrier [9]	1	\$4.95	\$4.95
Seeed Studio XIAO nRF52840 MCU [10]	1	\$9.90	\$9.90
JST RCY Plug with Leads, Female [11]	2	\$1.49	\$2.98
JST RCY Plug with Leads, Male [12]	2	\$1.49	\$2.98
0.625" Spring (Pack of 5; 1 used) [13]	1	\$12.60	\$2.52
Fray-Resistant Sleeving 1/8" ID, Black, 10 ft [14]	1	\$2.99	\$2.99
Total Cost (1 Robot)	–	–	**\$90.14**

B. Material Evolution and Selection

The robot's structural components underwent several rounds of material transitions to meet the competing demands of strength, precision, and tolerancing.

We began with **Bambu PLA Basic**, which offered fast printability and low warping, but its mechanical strength and dimensional precision were inadequate for critical load-bearing and press-fit parts. According to manufacturer data, it has a tensile strength of 35 ± 4 MPa [15].

To improve structural rigidity, we transitioned to **Bambu PPA-CF**, a carbon-fiber reinforced nylon filament with exceptional tensile strength of 168 ± 4 MPa [16]. While this material offered superior strength and layer adhesion, the limitations of FDM printing introduced dimensional inaccuracies and rough tolerances—especially problematic for motor fits and tread channels.

Ultimately, we adopted **Precision Resin** (e.g., Formlabs Precision Model Resin), which balanced moderate strength (50 MPa) with extremely high print accuracy—achieving tolerances of up to 0.01 mm [17]. This enabled precision press-fits, cleaner axle alignments, and smoother tread tracking in the final build.

TABLE II
TENSILE STRENGTH AND DIMENSIONAL PRECISION OF SELECTED MATERIALS

Material	Tensile Strength (MPa)	Dimensional Precision
PLA [15]	35 ± 4	0.15 mm
PPA-CF [16]	168 ± 4	0.10 mm
Precision Resin [17]	50	0.01 mm

C. Fabrication Process

Fabrication of the robot begins with the two primary hubs, which are 3D printed in Precision Resin using a **Formlabs SLA resin printer**. SLA printers include a layer resolution of **25–100 μm** and a dimensional precision of up to **±0.01 mm** in x, y, and z axes. These tolerances are critical for achieving consistent motor fits and clean, interference-free wheel alignments.

Once printed, the hubs undergo an alcohol rinse followed by **ultrasonic cleaning** to remove residual resin from intricate features. After cleaning, the parts are **UV-cured** in a post-processing station to finalize the mechanical and thermal properties of the resin.

Each hub is designed to press-fit two **Pololu 136:1 500 RPM Sub-Micro Plastic Gearmotors** [8]. A total of four motors are used per robot. The precision of the Formlabs resin print allows us to design press-fit cavities within a **±0.01 mm** margin, ensuring secure motor installation without the need for adhesives or fasteners.

Following motor installation, four **hollow wheels** are printed in the same Precision Resin, each featuring a D-shaped cutout to align with the motor shaft. These wheels are then mounted directly onto the motor shafts, completing the rotational drivetrain. Their tolerances mirror the hub's precision, ensuring a smooth and concentric fit on the shaft.

All motor wires are routed internally through a **fray-resistant sleeve** [14] that exits toward the robot's central control box, reducing the chance of snagging during pipe navigation.

The two hubs are mechanically linked using **two 2-pin male headers** [18], which serve as the flexible pivot point and ensure structural continuity across the robot body while enabling torsional flexion.

To increase traction, the robot uses a soft outer wheel layer cast from **Ecoflex 00-50**, a platinum-cure silicone elastomer. For this process, a PLA mold was designed to match the wheel contour and serve as a base. The Ecoflex base and curing agent are mixed in a 1:1 ratio by weight, and pigment is added for visual contrast. Once cured, the elastomer treads are peeled from the mold and **glued** directly onto the precision resin wheels. This rigid–compliant bonding ensures consistent traction while maintaining wheel geometry.

V. Results and Discussion

A. Competitions

The final version of the robot—featuring a four-motor drive, precision resin hubs, and a bottom-mounted spring compliance mechanism—was evaluated in multiple competitive settings and consistently delivered outstanding performance. The system demonstrated reliable traction, stability during turns, and smooth traversal across variable terrain without requiring physical intervention.

During the 2025 IEEE 8th International Conference on Soft Robotics (RoboSoft), the robot secured **2nd place overall** and recorded the **fastest completion time** across all teams in its category. The competition consisted of a multi-segment course including straight segments, angled turns, rubble, flexible walls, and inclined slopes.

In a separate inter-university soft robotics competition featuring teams from the University of Michigan, Yale, WPI, and ASU, SlipStream earned **perfect scores on all obstacles** and the **fastest overall time**, validating its performance against diverse academic teams.

Table III summarizes the robot's competition performance. Each obstacle was completed on the first try (**I**) and received a "Good" rating, the highest possible score.

TABLE III
Performance Results of Final Design Across All Obstacles

Task	**Score**	**Attempt**
Straight Segment	Good	I
90° Turn	Good	I
Straight Segment	Good	I
Rubble Segment	Good	I
Straight Segment	Good	I
Flexible Segment	Good	I
180° Turn	Good	I
Straight Segment	Good	I
Downward Slope	Good	I
Upward Slope	Good	I
Straight Segment	Good	I

B. Discussion

The success of SlipStream demonstrates the viability of soft robotics in constrained and dynamic environments where traditional rigid-body systems often fail. Its deformable structure, compliant suspension, and modular architecture enabled it to adapt in real-time to varying pipe geometries and surface conditions.

Importantly, the robot's performance was not only a result of iterative mechanical tuning, but also careful material selection and precision manufacturing. The combination of soft elastomer treads and rigid, high-tolerance resin hubs allowed for a compliant-yet-controlled drive system, while the four-motor layout ensured balanced torque distribution.

SlipStream's performance strongly supports its potential for real-world implementation in domains such as infrastructure inspection, in-pipe cable routing, medical catheter locomotion, and search-and-rescue operations in debris-filled or collapsed environments. With minimal design modifications, the platform is scalable and modular, making it suitable for both industrial and biomedical applications requiring navigation through complex, narrow spaces.

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