Development Process of an Isoperimetric Robot

Nathan Usevitch, Zachary Hammond
Allison Okamura, Sean Follmer
Department of Mechanical Engineering
Stanford University

Mac Schwager
Department of Aeronautics
and Astornautics
Stanford University

Elliot Hawkes
Department of Mechanical Engineering
University of California at Santa Barbara

I. Introduction

This extended abstract discusses the the development process of an isoperimetric truss robot, first presented in [1]. The robot and its general principle of operation is shown in Fig. 1. This robot builds on past work done in both the design of truss robots, soft robotics, and modular robotics, while overcoming some of the limitations of these respective approaches. This architecture has led to the creation of a human-scale untethered robot capable of shape change, locomotion, and manipulation tasks. The robot is capable of compliant interaction like soft robots but without an air supply, shape change like truss robots but without brittle rigid components, and can be manually reconfigured like other reconfigurable robots, but where each subcomponent is relatively simple (capable of motion in only one degree of freedom).

The robot consists of a set of robotic roller modules and a set of inflated fabric tubes. The roller modules pinch the tubes between cylindrical rollers, inducing a region of low bending stiffness that acts as an effective joint, but still allowing airflow between adjacent segments of the tube. The tubes are routed such that each tube makes up several of the edges in the final robotic truss structure. The robot changes shape when the roller modules are driven along the inflated beam, lengthening one edge of the robot and shortening another, while conserving the total length of the tube. The fact that the total edge length of the robot is conserved leads us to call this robot an ”isoperimetric” robot, meaning that the perimeter of the robot remains constant. The constant perimeter means the total volume within the tubes of the robot remains constant, removing the need for an active source of compressed air.

In this abstract we first describe the work that inspired us to begin development on an truss robot composed of soft pneumatic actuators. After several prototypes, we recognized some of the limitations created by using an onboard pressure source, and discovered a new constant-volume configuration that removed the need for a pressure source but created new mechanical design challenges. The prototype development process is then illustrated and discussed.

II. Inspiration

Robotic trusses, or networks of linear actuators connected by universal joint capable undergoing shape change, have been proposed by many researchers. These robots could use their high number of degrees of freedom to adapt to many tasks or to locomote over varied terrain. Work on this concept has been done as part of development of variable geometry trusses [2], tetrahedral robots [3],the NASA Ants project [4], and many others. More recent work has focused on tensegrity robots [5], [6] and variable topology truss robots [7]. In many of the past implementations, a significant challenge has been building a device where each edge of the structure has a large extension ratio, the structure can support sufficient load, and be compliant and resilient to impacts. Our initial inspiration was to create a truss robot where the edges consisted of pneumatic actuators. These pneumatic actuators could be lightweight, inherently compliant and designed to have an extremely large extension ratio.

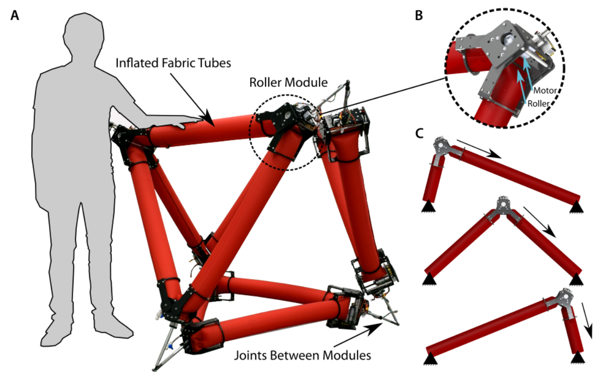

Fig. 1. Overview of the isoperimetric robot.

III. Early Development and Key Realization

Initially, we developed new types of soft actuators, including the pneumatic reel actuator [8], and antagonistic pneumatic artificial muscle [9], and sought to integrate them into truss robots. These actuators showed some promise when tethered to an external pressure source and valves. However, moving the control valves and pneumatic source onto the robot itself proved challenging in that the added mass of these components frequently caused the robot to collapse, or the limited flow rate of lightweight pumps made actuation extremely slow. With these limitations in mind, we began looking for ways to remove the dependence on slow and inefficient microcompressors. Our key realization was to to switch from using using a pneumatic source to pump air into and out of the system, and instead use a fixed volume of air within inflated tubes that acted as a structural element. From other work with inflated actuators, we were aware that when a high bending moment

Fig. 2. Development of prototypes from the earliest proposed robotic roller (top left), to two triangles connected together into a PVC frame (bottom right).

was applied to a thin-walled inflated beam, it tended to buckle in a relatively small area, forming a region of low bending stiffness while the rest of the beam maintained its strength. We leveraged this fact by building roller modules that induced and controlled the position of these buckle points. This key realization led to the concept of the isoperimetric robot.

IV. Prototyping Process

With the concept of the isoperimeric robot, we began a prototyping process to determine how a robotic roller module could control and move the location of buckle points in an inflated beam. The evolution of a our prototypes is shown in Fig. 2. Our first robotic rollers consisted of PVC tubes and rubber bands that were placed on inflated low density polyethylene (LDPE) tubes. We made several realizations throughout the prototyping process. One realization was the need to use a tube material that would not plastically deform or stretch, leading us to switch from LDPE tubes to fabric tubes. We also realized the importance of mechanical rings that ensured that the tube remained routed through the centerpoint of the cylindrical rollers. We realized the need to remove additional degrees of freedom introduced into the system by the physical offsets between adjacent rollers. We experimented with a variety of different sizes of tubes to ensure that the structure had the necessary strength to support its own weight and the weight of external loads during operation. We experimented with different materials to ensure sufficient friction between rollers and the fabric tube, eventually deciding to to coat the robotic rollers with a high-friction material. During operation, we also had to develop a procedure to ensure that the radios used for communication would reboot if exposed to a static discharge due to buildup static charge caused by the rollers rolling along the fabric tubes.

V. Conclusion

This abstract has described some of the development process behind the isoperimetric robot. In general, a high-level goal of capable truss robots led to early exploration of soft pneumatic actuators for robotic trusses. However, hands-on prototyping of these robots made it clear that the dependence on heavy pneumatic control and pressure-generation hardware was a significant limitation. This led to the development of a new concept- the isoperimetric robot that maintained the overall volume of air and the perimeter of the structure, but changed the location of the joints. Extensive prototyping and hardware experimentation enabled this concept to be translated into a functional robotic system. While the isoperimetric robot does introduce new constraints into the operation of truss robots, it has led to a capable human-scale untethered truss robot capable of locomotion, manipulation, and interaction in the real world.

References

[1] N. S. Usevitch, Z. M. Hammond, M. Schwager, A. M. Okamura, E. W. Hawkes, and S. Follmer, "An untethered isoperimetric soft robot," *Science Robotics*, vol. 5, no. 40, 2020.

[2] F. Naccarato and P. Hughes, "An inverse kinematics algorithm for a highly redundant variable-geometry-truss manipulator," 1989.

[3] G. J. Hamlin and A. C. Sanderson, "Tetrobot modular robotics: Prototype and experiments," *in Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 390–395, 1996.

[4] S. Curtis, M. Brandt, G. Bowers, G. Brown, C. Cheung, C. Cooperider, M. Desch, N. Desch, J. Dorband, K. Gregory, K. Lee, A. Lunsford, F. Minetto, W. Truszkowski, R. Wesenber, J. Vranish, M. Abrahantes, P. Clark, T. Capon, W. Michael, R. Watson, P. Olivier, and M. L. Rilee, "Tetrahedral robotics for space exploration," *IEEE Aerospace and Electronic Systems Magazine*, vol. 22, no. 6, pp. 22–30, 2007.

[5] J. Bruce, A. P. Sabelhaus, Y. Chen, D. Lu, K. Morse, S. Milam, K. Caluwaerts, A. M. Agogino, and V. SunSpiral, "Superball: Exploring tensegrities for planetary probes," in *12th International Symposium on Artificial Intelligence, Robotics, and Automation in Space*, 2014.

[6] M. Vespignani, C. Ercolani, J. Friesen, and J. Bruce, "Steerable locomotion controller for six-strut icosahedral tensegrity robots," *in Proc. IEEE International Conference on Intelligent Robots and Systems*, pp. 2886–2892, 2018.

[7] A. Spinos, D. Carroll, T. Kientz, and M. Yim, "Variable topology truss: Design and analysis," *in IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2717–2722, 2017.

[8] Z. Hammond, N. Usevitch, E. Hawkes, and S. Follmer, "Pneumatic reel actuator: Design, modeling, and implementation," *IEEE International Conference on Robotics and Automation*, pp. 883–888, 2017.

[9] N. S. Usevitch, A. M. Okamura, and E. W. Hawkes, "Apam: antagonistic pneumatic artificial muscle," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2018, pp. 1539–1546.