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DOCTORAL THESIS

Fabrication and Untethered Actuation of Soft Robotics with Miniature Piezoelectric Pump System

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Abstract

Soft robotics provide great possibilities to break the gap between robots and humans. It is believed to work with humans or even in the human bodies thus the demand of portability, safety, and autonomy of soft actuators need to be fulfilled. Fluid elastomer actuators (FEAs), which are driven pneumatically or hydraulically, have demonstrated huge promise for these specific applications. However, the requirement of a miniature actuation system is still insufficient. The large and cumbersome power source trouble the development and the lack of a lightweight and high-output miniature pump has limited the usefulness of soft robotics driven by FEAs. Besides the actuation functions, the processing of micro FEAs is still in its infancy. With the limitation of technical resolutions, the size of the "micro" FEAs is still in the size of millimeters. This research focused on providing solutions to both the two problems to push this area forward.

The first work in this dissertation is to provide a miniature untethered actuation solution for soft robotics. Based on the literature review, it still lacks a miniature pump with a large flow rate and pressure output although the size and the rigidity have been priorly focused on. So comparing the existed solutions, I designed and fabricated a miniature pump based on the piezoelectric effect to solve this problem. After that, the flow rate and pressure output were measured to optimize the design. The power output and the pumping behavior were then also analyzed to detailly describe the pump. And finally, I used the pump to drive a pneunet design FEA to prove the availability. In this study, I present a compact-size (2 cm^3), lightweight (4.2 g), and high-output piezoelectric pump with Bluetooth connectivity. The pump can generate a maximum flow rate of 28.8 mL/min or maximum pressure of 100 kPa with a low power consumption of 63.5 mW. The design parameters are optimized to achieve the maximum flow rate and pressure outputs. The stability and repeatability of our pump enable open-loop control for the actuation of FEAs. A wireless gripper and an inchworm-like soft crawler are fabricated by integrating miniature pumps with pneunet bending actuators. These applications demonstrate the versatility of the

pumps in the untethered actuation of FEAs for autonomous soft robotics.

Another work of this research provides a massive product fabrication process of the micro FEAs. Although the traditional molding and demolding technique shows great advantages to fabricate FEAs in the scale of centimeters. The resolution and bonding rupture make it challenging to fabricate micro FEAs with same technique. Also soft lithography and additive manufacturing process have performed as possible solutions, the dimension of the actuators is still normally on the scale of millimeters. So in this study, I used direct photolithography process to fabricate the FEAs with a critical dimension of tens of micrometers which is in the range of the smallest FEAs. This process based on a photolithographic sacrificial layer allows a micro FEA in a dimension of $150\times150\times2100\ \mu m^3$ with a critical chamber width of 50 μm. The bending behavior is measured in response to the applied pressure. The actuators were also evaluated with different membrane thickness, materials, and chamber geometries to optimize the performance. And the potential applications are also demonstrated with some integrated grippers which were fabricated directly without any other bonding process.