An Ultra-Compact Precision Liquid Drug Delivery System Based on Cascading MEMS Membrane Pumps

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Ultra-compact liquid drug delivery devices are useful for the treatment of chronical diseases such as diabetes and growth hormone disorders. Current portable insulin pumps are based on linear actuators driving by motors, which are relatively bulky and expensive. There are miniature devices exploiting current-driven phase change of shape memory alloys as the actuation mechanism, however, the delivery accuracy of these devices has a lot of room for improvement.

Miniature piezoelectric membrane pump (Fig. 1(a)) of a chip size fabricated by MEMS technology has the potential for an ultra-compact liquid drug delivery device. However, the fluid delivery accuracy is affected by device components such as membrane fatigue and piezoelectric actuator degradation, and external factors such as the variations in temperature, back pressure and actuation voltages. In this work, we developed a novel two-stage pumping scheme by cascading two membrane pumps in tandem to address the accuracy issue (Fig. 1(b)). The first-stage pump is driven by a piezoelectric thin film actuator and its output is used as the actuation force to drive the second-stage pump. The second-stage high-precision pump has a fixed volume (δV) that is much smaller than the first-stage pump. During operation, the output from the first-stage pump will completely displace the liquid in the main body of the second-stage pump, thus delivering an accurate volume of liquid (δV) with every actuation event. Since the volume of the first-stage pump is much larger, variations in its output due to aforementioned factors will result in the same output (δV) from the second-stage pump. This yields a highly accurate fluid pump operating in a "digital" mode, in which the delivery of a volume ΔV is accomplished by actuating the second-stage pump by a number of times equal to $\Delta V/\ \delta V$.

The two-stage miniature pump is integrated with a drug reservoir, a lithium-ion soft pack battery, and a PCB driving circuit to form a ultra-compact and high-precision liquid drug delivery system (Fig. 1(c)). Using the digital delivery mode, the system has an accuracy error of ~4% in a single shot of dosage, and the deviation improves to ~1% after averaging over ten shots (Fig. 2). The two-stage pumping design also comes with other benefits. The second-stage pump is completely made of biocompatible materials and the drug only flows through the second-stage pump to ensure biosafety. The system is also capable of delivery drugs at the presence of a large back pressure because the first-stage pump can output a high pressure to actuate the second-stage pump. The design, fabrication, and characterization of the high-precision miniature liquid drug delivery system will be discussed in detail. In addition to the drug delivery application, the miniature MEMS pump system can also be used as pressure sources for lab-on-chip devices to fully enable a compact system for POCT diagnosis, organ-on-chip, cell culture automation, and other microfluidics applications.

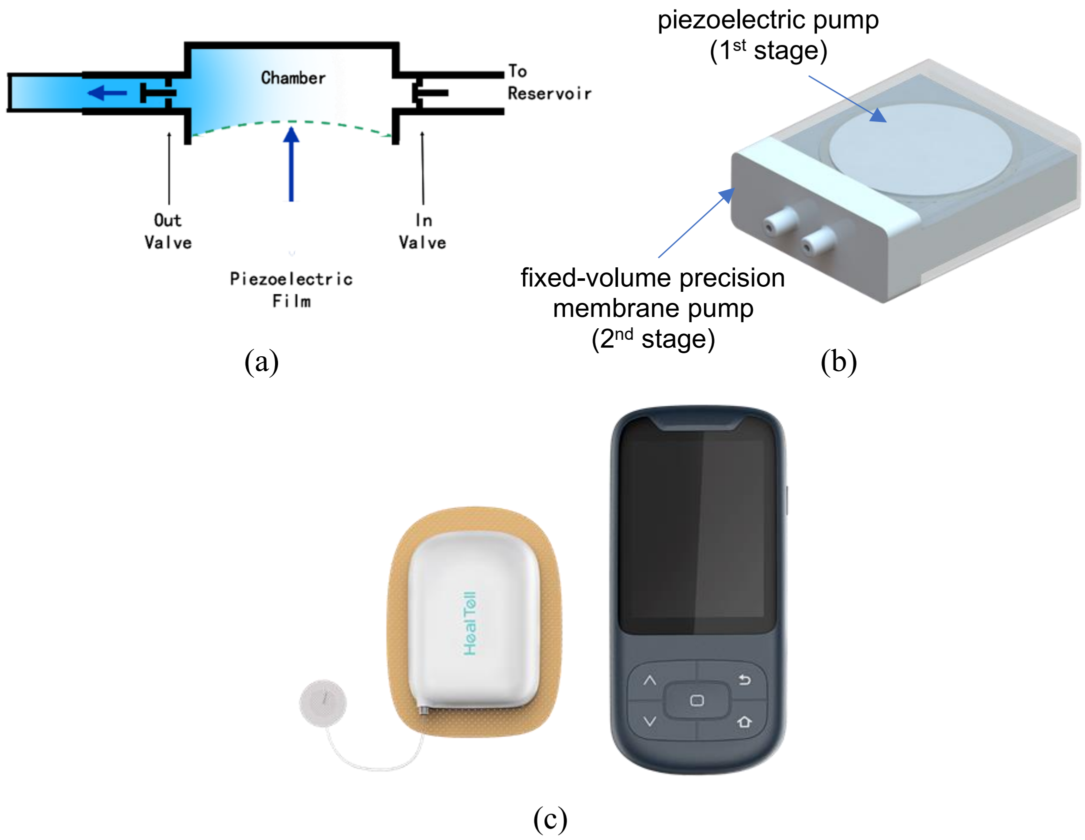

Figure 1. (a) A schematic of the principle of a membrane pump with two check valves; (b) a schematic of a two-stage MEMS pump chip with cascading membrane pumps; (c) an image of the complete drug delivery system, including the pump chip, drug reservoir, battery, circuitry, and a bluetooth remote controller. The pump chip, drug reservoir, battery and circuitry are assembled in a compact unit as shown in the middle of part (c).

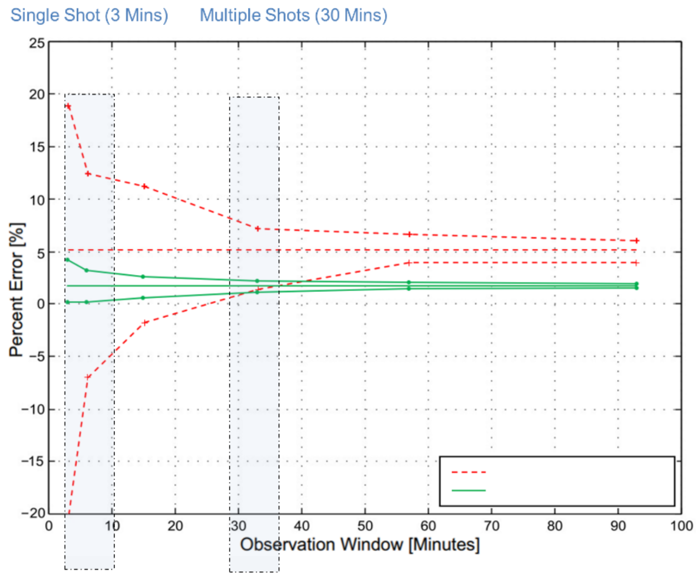

Figure 2. Trumpet graphs comparing the accuracies of a leading commercial insulin pump (red curve) and the drug delivery system developed in this work (green curve). Current system can achieve a volume error of ~4% in a single shot of dosage; the volume error improves to ~1% after averaging over 10 shots.