Wearable Soft Pneumatic Ring with Multi-Mode Controlling for Rich Haptic Effects

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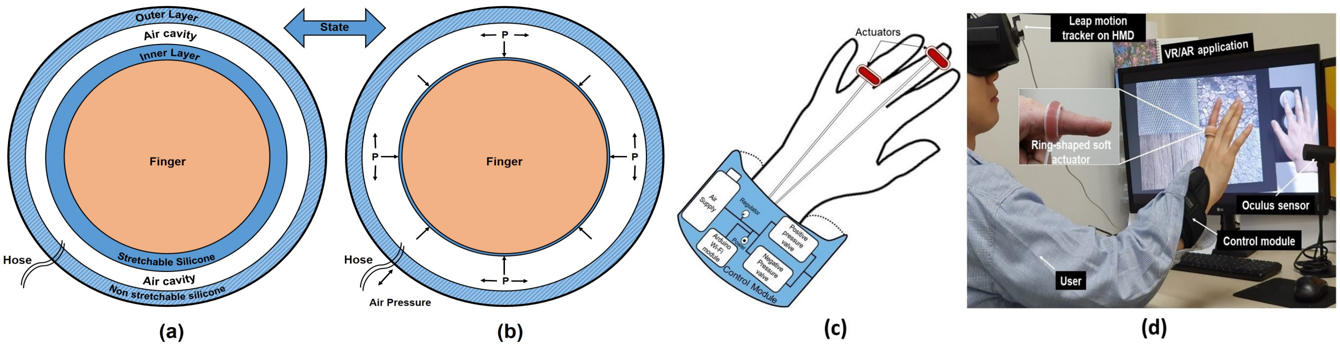

Figure 1: Illustrated concept and use-case of our soft haptic ring: (a) a cut section view of the multi-layer membranes of the ring in a normal state, (b) pressurized state, (c) pressure control module and examples of actuator's positions of finger mounting, (d) illustrative scenario of VR/AR application: exploring the virtual textures and perceiving its haptic feedback.

KEYWORDS

Haptic, Actuator, Pneumatic, Vibrotactile, Multi-mode, Soft-haptics, Augmented reality, Haptic interface.

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1 INTRODUCTION

Common mechanical actuators for haptic feedback are generally dedicated to creating single kind of feedback, e.g., vibrotactile only, the pressure only, or shear force only, [Choi and Kuchenbecker 2013; Girard et al. 2016; Pacchierotti et al. 2017]. This is against the fact that highly realistic fully immersive VR/AR sometimes requires rather complete and rich multi-mode haptic feedback. For instance, when rubbing your finger on a wooden desk, the fingertip simultaneously senses both the high-frequency vibration due to the roughness of the surface texture and the quasi-static pressure due to pushing force, and your brain combines them to feel it as a wooden desk. The lack of any of the involved physical signal may seriously deteriorate the realism. This may be one of the reasons why current haptic interface technology for VR/AR environments is not at the same level as visual interfaces.

Using multiple actuators having different covering bandwidth can be one of the solutions. However, making different mechanical end-effectors from multiple actuators share the same contact area on a finger skin is not a trivial task. Besides, multiple hardware inherently makes the system bulky, decreasing the usability, especially when wearability is one of the important requirements.

This paper presents our new haptic interface that partially overcomes the issues. The interface is a soft silicone bladder and wearable, i.e., small and light enough to wear, to the finger as a ring. It is capable of providing various haptic feedback including high pressure, high-frequency vibration (up to 250 Hz), and an impact to the finger simultaneously through a single end-effector. Through our empirically formulated controlling algorithm, the rendered pressure, the frequency of the vibration, and the amplitude of the vibration can be precisely controlled.

2 OUR APPROACH

We choose to use pneumatic actuation to a soft bladder due to the following reasons. First, pneumatic actuation is small and lightweight (if combined with miniaturized valves and compressed air tanks) but powerful, so is optimum when considering portability. Our device, for instance, can generate up to 2.2 g acceleration and up to 7.6 N force with the hardware weight only 250 gram. Secondly, the membrane of the ring-shaped bladder used as an end-effector is very thin and flexible, so it can be not only used as a static pressure contactor but also moves rapidly to convey vibration. More importantly, combined with a high-pressure air source, the bladder can generate very fast changing pressure, which can be perceived as an impact. As a result, the design of this bladder is one of the essential

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parts to realize multi-mode feedback. To our knowledge, vibrotactile feedback using a pneumatic bladder has not been researched anywhere. The followings detail our approach.

2.1 Soft Ring

The core part of our implementation is the soft ring end-effector. It consists of three layers: an inner layer of stretchable material, an air cavity where compressed air enters from a hose connected to the valves and air source, and an outer layer of the non-stretchable material (refer to fig. 1(a) and (b)). When air pressure blows to the cavity, the stretchable material inflates inward and push the skin of the user, while the non-stretchable material maintains the size and shape of the ring.

The multi-layer ring was cast using the Ecoflex 00-30 (Smooth-on Inc.). Original silicone is stretchable, but we embedded a non-stretchable fabric during standard silicone curing procedure when manufacturing the non-stretchable membrane.

To achieve precise control of the ring, two solenoid valves are connected to the hose: a positive valve for inflating the bladder and a negative valve to release the air to deflate the bladder.

2.2 Controlling

The feedback mode changes according to the control of the valves on the hose. If the positive valve is just opened for a certain duration and closed, static pressure can be generated to the skin. If both valves are periodically opened and closed, vibrotactile feedback is generated. By using the negative valve synchronously with the positive valve, we can control the amplitude of the vibration independently from the frequency.

The precise control of the feedback is achieved through proper control of the valve opening duration. To this end, we experimentally identified the relationship between the duration and the actual feedback. Below are some examples of experimental results.

Fig. 2 (a) shows an example the measured acceleration (using an accelerometer, ADXL335-Analog Devices) at the surface of the haptic ring against the various frequencies with two preset internal air pressures, i.e., 5 and 10 psi. The ring generates the most substantial magnitude of $\tilde{2}.2$ g (g= 9.8 m/s^2) by ten psi air source, followed by the magnitude of $\tilde{1}.8$ g with five psi internal air pressure. The notable characteristic observed here is that the magnitude of the vibration increases with decreasing in frequency.

Fig. 2 (b) illustrated the measured force (by FlexiForce) against the frequency (Hz). Since internal air pressure is prefixed, the ring generates the strongest force of approximately $\tilde{7}.60$ N at ten psi and $\tilde{4}.25$ N at five psi. Another notable characteristic is that the inverse relationship is observed between the force feedback and generated frequency. In order to use the experimental results, we fitted the data with a 3rd-order polynomial as shown in Fig 3.

3 DISCUSSION AND CONCLUSION

Pneumatic actuation techniques have the potential to produce not only pressure but also vibrotactile feedback. We presented a pneumatic actuated soft actuator with various rendering modes; the device provides not only static pressure $\tilde{7}.6$ N, and acceleration $\tilde{2}.2$ g to the skin, but also generates high-frequency vibrotactile feedback up to 250 Hz based on fast controlling of valves. This current setup is a lightweight, small, and includes soft end-effector, altogether generates significantly rich haptic feedback when compared to common mechanical haptic actuators. The various rhythmic pattern can be created by introducing a change in the time interval.

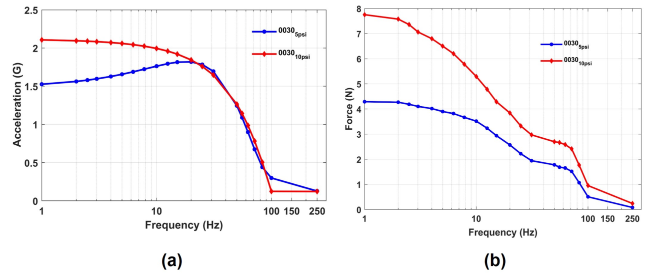

Figure 2: Illustration of (a) frequency response and (b) force response of the ring in various frequency (Hz).

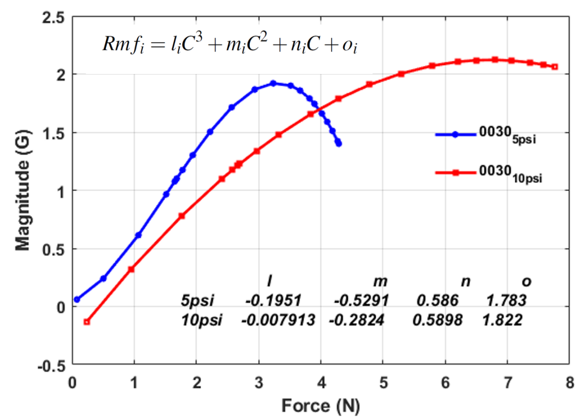

Figure 3: The relationship between magnitude and force of the developed actuator against frequency (Hz), where i is the corresponding frequency, $\mathrm{Rmf_i}$ is the magnitude of the vibration, and l, m, n, and o are the polynomial coefficients.

Several potential applications of the actuator are including spatial orientation, guidance, assertive alert, and sensory substitution. We illustrated the one of application of our set-up is combined with the VR/AR application (see Fig. 1 (c) and (d)). We also formulated the relation between valve opening, frequency, force, and magnitude characteristics of our setup to ensure the accurate rendering. Future work is to evaluate the extensive user perception study of this multi-mode haptic actuator for VR/AR applications.

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