Pneumatactor Arrays for High Frequency Vibrotactile Feedback

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***Abstract*— Soft and conformable pneumatic tactile interfaces have the potential to complement traditional rigid systems by offering more natural and subtle feedback. This presents the need for economical, scalable miniaturized systems adept in providing high-frequency vibrotactile stimuli. We present the development of a novel silicone-based pneumatic vibrotactor (pneumatactor) array controlled by a sequence of high-frequency air valves engineered to deliver vibrotactile feedback.**

I. INTRODUCTION

Traditional vibrotactile haptic displays in common industrial and research applications are built upon largely rigid substrates, and therefore are limited in their abilities to render realistic experiences in a variety of form factors [1]. Pneumatic haptic displays present a promising solution to the limitations of traditional tactile interfaces. Pneumatic bladders, designed to inflate and deflate, can be manufactured in any shape and size, effectively mimicking natural environments. Their adjustable stiffness, which closely resembles human skin, enables the creation of softer, more authentic haptic feedback. Such capabilities hold promise for applications in virtual reality, prosthetics, and beyond. Despite the evident potential, these systems face challenges in bulkiness, cost efficiency, and noise control, which necessitate further development.

High-frequency pneumatic actuation methods have previously been explored. Sonar et al. were pioneers in this field, successfully implementing closed-loop control for solenoid-gated pneumatic actuators for frequencies upto 100Hz [2]. Subsequently, van Beek et al. validated the effectiveness of soft Pneumatic Unit Cells [3] with similar frequency characteristics against rigid vibrotactors, utilizing both quantitative and qualitative assessments [4]. However, despite the successful transmission of vibrational data, the resulting devices were notably bulky and costly. In this context, we introduce a novel methodology of producing an arrays of pneumatic vibrotactors (pneumatactors) capable of maintaining frequencies up to 90Hz, while reducing costs by approximately 50% and weight by about 75%.

II. IMPLEMENTATION

The proposed pneumatic tactile haptic device has two intended goals: (1) to rapidly actuate pneumatactors at a range of frequencies controllable through an external trigger, and (2) to generate independent tactile patterns for the users to feel.

Six cylindrical pneumatactors are fabricated using stereolithography 3D printing with a silicone-based resin. The tactors further undergo a cleaning and curing process for structural hardening. Through an iterative process, the tactors achieve optimized dimensions with an 17mm inner diameter, a 0.4mm diaphragm, a 3mm wall thickness, a 4mm bottom thickness, and a 2mm inlet diameter.

Three sets of pneumatactors are operated by three 3-Way Air Valves. Each valve assembly includes one solenoid connected to a 2.5 l/min 4.5V Air Pump, while the remaining solenoids are interconnected in a parallel arrangement with the first. A unified PWM signal drives three SPDT Relays, which drive the actuation of these valves. At any given instance, airflow within the three valves is directed towards one of the two paired pneumatactors, resulting in a $180°$out-of-phase actuation. Since the pump is unidirectionally pumping air out, the valve connection configuration allows the deflation of the other pneumatactor via the third port on the valve, which is open to atmosphere. This deflation is driven by the excess pressure inside the tactor. This setup is depicted in Figure 1 (a) with purple (or labelled ”High”) and green (or labelled ”Low”) arrows highlighting directional flow. The system is controlled by lightweight and stackless multithreads on an Arduino Uno, capable of actuating the three ports with three independent PWM waves.

III. PRELIMINARY ANALYSIS

An inflated pneumatactor is modeled as a spherical cap to estimate the maximum mechanical frequency range possible on the device. The increase in volume $V_\uparrow$ is given by Equation 1:

$$V_\uparrow = \frac{\pi \times h_\uparrow}{6} \times (3a^2 + h_\uparrow^2) \tag{1}$$

where $h_\uparrow$ is the height of the spherical cap or effective indentation of the skin, and a is the inner radius of the pneumatactor. Using this working volume and the known flow rate, optimization curves are drawn to aid design choices. This method method relies on two key assumptions: 1) the minimum skin indentation sensitivity at higher velocities is approximately 1.5mm for the forearm [5], and 2) the pneumatactor's maximum deflation time is equal to the inflation time t (constant for given bladder dimensions and material) [6]. Building upon this, Equation 2 determines the pneumatactor's maximum operational frequency. This corresponds to different skin indent depths at a specified pump flow rate, as depicted in Figure 2.

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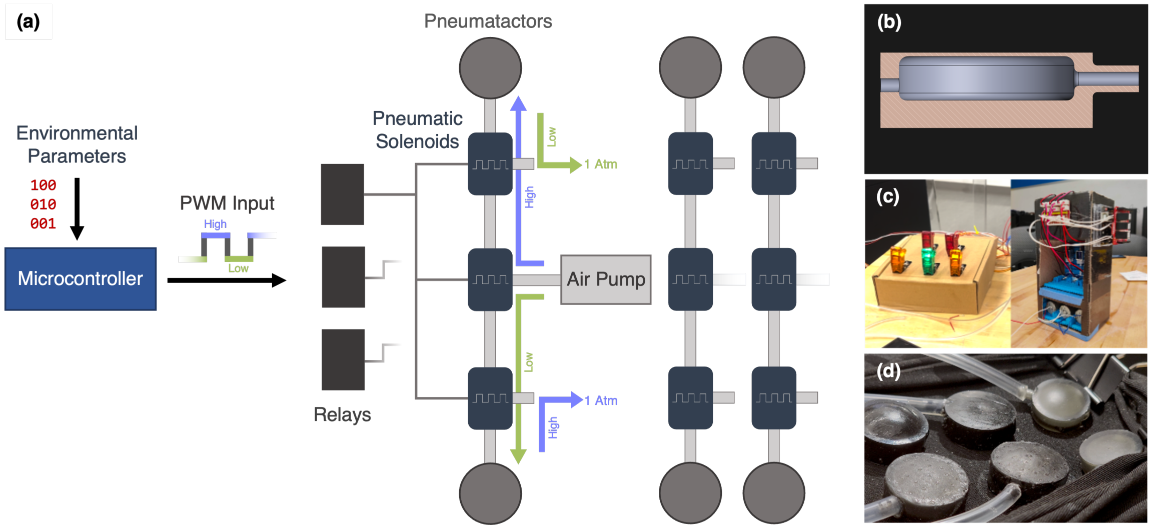

Fig. 1. (a) Representation of pneumatactor actuation setup, (b) pneumatactor cross-section; (c) constructed actuator prototype; (d) array placement.

$$f_{max} = \frac{1}{2 \times \frac{V_{\uparrow}}{Flow\ Rate}} \quad (2)$$

The device is designed to create skin indentations of 2mm at 90Hz, resulting in an inner radius of 8.5mm based on Equation 2. The indent depth is chosen based on existing literature demonstrating the effectiveness of touch at different levels [5]. These estimated parameters have been validated through the attachment of a piezoelectric disk to the pneumatactor's diaphragm and high-speed photography.

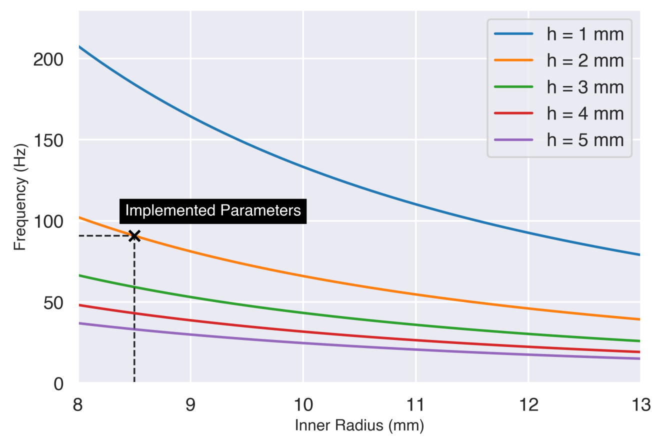

Fig. 2. Frequency-inner radius relationship and the chosen parameters.

IV. Future Directions

Ongoing efforts are concentrated on quantifying the scalability and resolution of the array. The inverse relationship between frequency and radius in pneumatactors offers exciting prospects for further development. Reducing the size of individual units in an array leads to higher achievable frequencies, although this progression is currently hindered by the actuation speeds of valves and relay circuits.

Implementing closed-loop pressure control will allow the pneumatactors to be inflated to a specific pressure and be actuated at specific frequencies centered around it, allowing for both mechanotactile and vibrotactile feedback at the same site. Further reduction in hardware size is also crucial for creating compact, portable systems. Additionally, future perceptual studies with the pneumatactors and comparing the outcomes to those from rigid vibrotactile displays will offer significant insights into the effectiveness of the device.

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