A Multichannel Pneumatic Analog Control System for Haptic Displays

Multichannel Pneumatic Analog Control System (MPACS)

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ABSTRACT

Soft robotics use in haptic devices continues to grow, with pneumatic control being a common actuation source. Typical control systems used, however, rely on a digital on/off control allowing only inflation/deflation at a set rate. This limits the degrees of freedom available when designing haptic experiences. We present an alternative system to allow the use of analog control of the pneumatic waveform profiles to design and experiment with haptic devices, and to determine the optimum wave profile for the desired experience. Using a combination of off-the-shelf components and a user interface, our system allows for rapid experimentation with various pressure levels, and the ability to control waveform profiles in a common format such as attack-sustain-release. In this paper, we demonstrate that by altering the attack and release profiles we can create a more pleasant pulsing sensation on the wrist, and a more continuous sensation for communicating movement around the wrist.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI); Haptic devices**;

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1 INTRODUCTION

Soft robotics is a rapidly expanding field, providing compliant mechanisms that are adaptable, flexible and safe for use within human-robot interaction. This is particularly true in the broader area of haptics and wearable systems where low encumbrance and high safety are of crucial importance [21]. One common method of driving soft robotic systems is through pneumatic systems, which have been used in applications such as rehabilitations [13] and providing haptic information [9, 14, 19]. Pneumatic systems are particularly valuable thanks to their intrinsic compliance, which increases safety when interacting with humans.

Typically, pneumatic devices are connected to a constant/regulated pressure source and controlled through a system of valves. This allows for limited control, only either allowing more pressure in, or allowing pressure to release. Often this only provides two different states, pressurized or unpressurized, comparable to an on-off system; herein referred to as *digital control*. Some literature incorporates a pressure sensor to allow the device to stop at a lower pressure state [4]. However, the inflation speed is therefore only dependent upon the mechanical characteristics of the system and is unable to be altered. Alternatively, by using electronically controlled pressure regulators, we can control not only the desired pressure level, but the speed and the path to get there; herein referred to as *analog control*.

Due to the increase of degrees of freedom that the analog control enables when building the waveform, it is crucial to maintain the ease of use of the system by designing an intuitive user interface. Such an interface should allow to efficiently draw any type of waveform, handle multiple channels, and quickly test the waveform on any combination of channels. Previous research has proposed user interfaces and authoring tools for single- and multi-channel haptic displays; where users can tune a waveform and its parameters for single-channel haptic devices [2, 5] or vary multiple timeline tracks to manipulate spatiotemporal behaviors of haptic patterns rendered on multi-channel haptic devices [11, 15, 16]. Similar to these tools, we designed a graphical user interface (GUI) that allows users to create and tune haptic patterns in order to construct a variety of multichannel haptic effects, play them on a pneumatic haptic device, and save them for later use.

Therefore, in this paper, we present a desktop based Multichannel Pneumatic Analog Control System (MPACS), built from off-the-shelf components, which enables for experimentation of the impacts of analog control. In addition, we illustrate a sample user interface that allows quick development, customization, and rapid testing of various waveforms for a multi-channel pneumatic haptic display. Unlike the rough sine wave demonstrated in [4] using a closed loop control of solenoid valves, our setup produces smooth analog pressure waveforms, which may have the potential to transfer wider and better distinguishable expressions to the users. Further, we demonstrate two impacts of analog control on the haptic experience: increasing pleasantness in a pulsing sensation and increasing perceived continuality in tactile apparent movement.

The organization of the paper is as follows: we first present the hardware and GUI design, including a performance verification of

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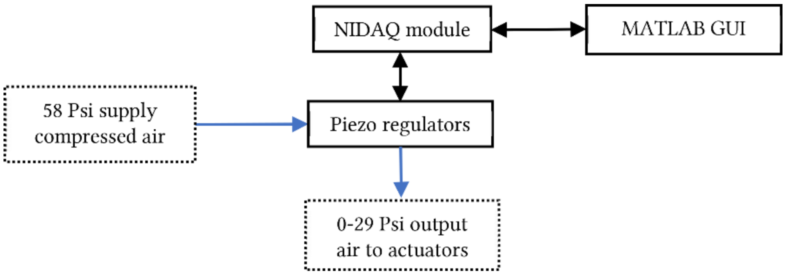


Figure 1: – Hardware arrangement

the hardware, and a design rational for the GUI to enable flexibility and quick prototyping. We then present two demonstration user studies which highlight examples of the impact on user experience resulting from the extra flexibility of the analog control. Finally, we conclude the paper with a general discussion and identify the focus of future work.

2 MULTICHANNEL PNEUMATIC ANALOG CONTROL SYSTEM

MPACS has two main components: one is the hardware setup and the other is the GUI. These components along with the hardware performance is describe in this section.

2.1 Hardware

The hardware arrangement is shown in Figure 1. The electronic controlled piezo regulators (VEAB-B-26-D2-F-V1-1R1, Festo, Germany) were chosen due to their high speed and relatively quiet operation. These piezo regulators are capable of outputting 0 – 29 Psi and are controlled through a 0 – 10 V signal, with a linear relationship between input voltage and output pressure. These piezo regulators also return a 0 – 10 V signal reading the actual pressure recorded by the pressure regulator. Initial testing showed that increasing the supply air pressure increases its speed of response, therefore the compressed air supply was regulated to its maximum input pressure of 58 Psi.

To control the electronic piezo regulators, a National Instruments Data Acquisition (NIDAQ) module (National Instruments, USA) was used. This was composed of a cDAQ chassis (cDAQ-9174), an analog voltage output module (NI 9264), and an analog voltage input module (NI 9205). The output module was used to send pressure commands to the regulators, and the input module was used to record both the sent pressure commands and the recorded pressure commands simultaneously. The type of recorded signal can be seen in Figure 3b.

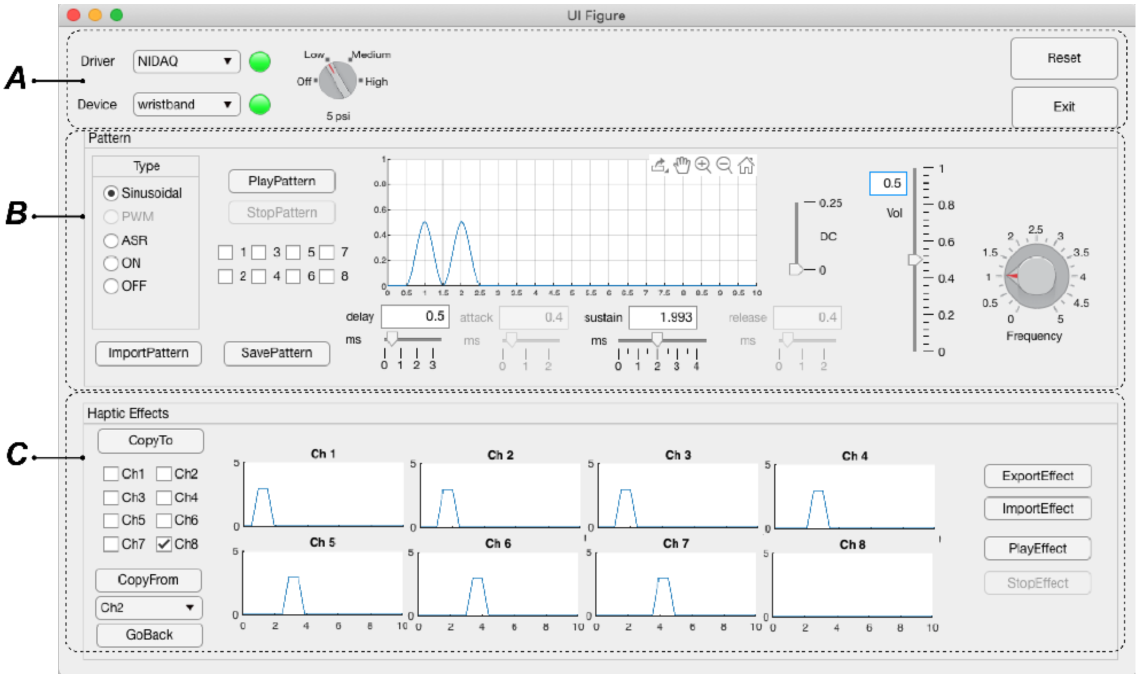
2.2 Graphical User Interface

We designed a GUI to enable the design of various haptic patterns and test them on multichannel pneumatic haptic displays. The GUI provides users — such as engineers, designers, scientists and students — with the flexibility to vary various signal parameters, play them through diverse combinations of channels, store them for future use, and characterize the "feel" of feedback rendered on the haptic device. Here, we describe a GUI developed in MATLAB's App Designer tool. The tool is accessible for non-programmers and allows quick prototyping with various UI elements. In addition, the large library of MATLAB toolboxes can be accessed, including the data acquisition toolbox, which is used to read and write multiple analog input-output channels in the NIDAQ module at a 1 kHz sample rate. The GUI is designed by focusing on three aspects i.e., the graphical user interface 1) is intuitive to logically flows between various operations, 2) provides flexible control of multiple channels, and 3) scales to various hardware devices and user applications. Figure 2 shows the GUI and highlights three panels. These panels are described in the following subsections.

2.2.1 Driver and Device selection panel. First, a user selects the suitable driver and the haptic device from those available (Figure 2A). Once both the driver and the device are uploaded, the status LEDs turn to green and the "Pattern" and "Haptic Effect" panels are enabled. The user then set the maximum allowable pressure in the session using a discrete knob. Currently, we have built drivers for NIDAQ and USB serial modules. However, the GUI will accommodate audio based custom drivers in future revisions. In this paper, we will focus our implementation with the wristband haptic device.

2.2.2 Pattern panel. The Pattern panel allows the user to pick a waveform type from a list or directly load a pre-stored pattern, adjust its parameters, and play the pattern through selected channels of the haptic device (Figure 2B). Once the user is satisfied with the pattern, they can save the pattern, and/or copy it to the Haptic Effect panel (see subsection 2.2.3) in order to construct multichannel haptic effects. The Pattern panel also includes a dynamic graphical visualization of the waveform as various control parameters are adjusted. This provides users with real time feedback and helps them to fine tune haptic pattern. The graphical visualization in Figure 2B shows a two second long 1 Hz sinusoidal waveform at half the full pressure (i.e. 2.5 Psi). In the current implementation, we have implemented Sinusoidal and ASR (attack-sustain-release) patterns, however, additional patterns and their parameters can be added to the 'Type' list in future revisions.

2.2.3 Haptic Effect panel. The Haptic Effect panel shows time series plots of each of the eight channels of the haptic device (Figure 2C). The user can copy a pattern from the Pattern panel to each time series plot in order to construct a spatiotemporal haptic effect. This effect can be played through the haptic device or exported as an ascii csv format for use in other applications. This panel is useful for creating haptic effects to evaluate the feel of a device, to



Driver NIDAQ

Device wristband

● Sinusoidal

delay 0.5 ms

attack 0.4 ms

sustain 1.993 ms

release 0.4 ms

Vol 0.5

☐ Ch1 ☐ Ch2

☐ Ch3 ☐ Ch4

☐ Ch5 ☐ Ch6

☐ Ch7 ☑ Ch8

CopyFrom Ch2

Figure 2: – A graphical user interface to author and control haptic effects for a haptic device. (A) Driver and device selection panel, (B) the Pattern panel to create, edit, play, load and save haptic patterns, and (C) the Haptic Effect panel to construct expressive haptic effects and play them on the multichannel pneumatic haptic device.

run engineering and psychophysical testing, to form a library of haptic effects that can be shared to other users and used in another application, and many more. Users can also construct new effects in a different tool and import them in the GUI and play them on the haptic device. The waveform time series showed in Figure 2C displays a haptic effect used to render continuous pleasant sensation around the wrist, similar to the effect used in our pilot study (Section 3.2).

2.3 Hardware Performance

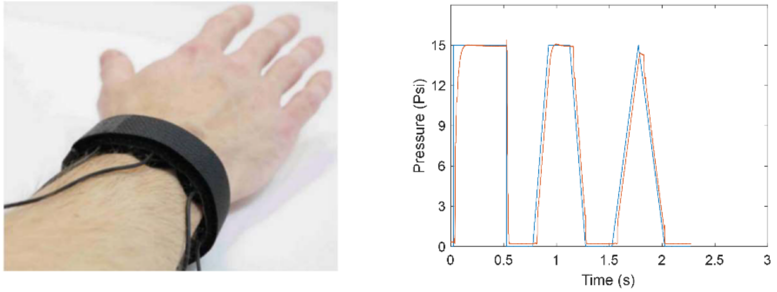
For our demonstration of interfacing with a multi-channel pneumatic haptic display, we use the Bellowband pneumatic wristband developed by Young et al. [20], shown in Figure 3a. This is a lightweight wristband, with 8 Bellowband actuators made from thermoplastic polyurethane (TPU) layers that can render pressure and vibration cues to the user. In the demonstration user studies, outlined in section 3, we use ASR pulses to vary the shape of a square waveform. To demonstrate the response time of the pressure regulators, we ran three pulses to a single Bellowband actuator: a 500 ms long square pulse (ASR profile of 0ms - 500ms - 0ms), a pulse with an ASR profile of 150 ms - 200ms - 150 ms, and a 500 ms triangle pulse (ASR profile of 250 ms - 0 ms - 250 ms). The recorded command pressure and actual pressure at the output of the pressure regulator are shown in Figure 3b. Haptic delays can start to increase errors in task performance for delays above 25 ms, but are not perceivable by the user until delays reach 50 ms or higher [8]. However, in simple tasks such as a button press, the reduction in performance is not significant until delays reach towards 200 ms [7]. The square wave (first pulse) has a 13 ms delay from receiving the control signal to when the regulator detects an increase in air pressure. For the second and third pulses, the measured pressure had a 24 ms and 23 ms delay behind the control signal at 50% up the attack section (7.5 Psi), respectively, and delays of 20 ms and 17 ms behind the control signal at 50 Psi down the release section. These performances are therefore below the suggested perceptual and performance limits of haptic latency [7, 8]. As a side note, the delay at the top of the pulse, particularly noticeable in the square wave, is largely due to the capacitive nature of filling the actuators and occurs independently of the type (digital vs analog) of actuation. It is also worth noting that part of the capacitive nature of the recorded response is due the pressure sensor being embedded in the regulator rather than the actuator, however, this enabled us use only off-the-shelf components.

3 EXPERIENCE PILOT STUDY

3.1 Background

With this pilot study, we verify the potential impact of the analog control on waveform perception using two different type of tactile feedback: squeeze and tactile apparent motion.

Pneumatic based haptic displays have been used to apply pressure [10] and squeeze [12] haptic cues on the wrist, and have the ability to render cues ranging from a subtle to a strong sensation. We hypothesize that by altering the attack and release profile of the pulse during the compression/squeeze sensation, it will change the pleasantness of the sensation.



(a) (b)

Figure 3: – (a) Bellowband pneumatic wristband [20], (b) Response time of system connected to Bellowband

Tactile apparent motion is the illusion of continuous movement sensation from discrete actuators through the use of overlapping stimulations [1]. This has been demonstrated with the use of rigid vibration motors [17] and voice coil actuators [3, 6]. This effect has also been previously shown on pneumatic actuators [18], but when using limited control variables with digital pneumatic control. Through the use of our analog control system, in addition to the Interstimulus Onset Interval (ISOI) — the delay between subsequent overlapping actuations— that is traditionally implemented, we are able to control the inflation/deflation time of the pneumatic actuator, which we hypothesize will increase the impact of the illusion of apparent motion.

3.2 Method

To test the capacity for discernment between a purely on-off signal and an analog signal with an ASR profile, a pilot study was conducted with six participants (three females, age 37.0±4.6; mean±std). More specifically, the difference in pleasantness (study 1) and signal continuity (study 2) were assessed. The setup for both studies was the same, the participants were wearing the Bellowband haptic display on their right wrist, and noise cancelling headphones playing pink noise. They were also instructed to keep their eyes closed during the experiment to concentrate on the haptic sensations.

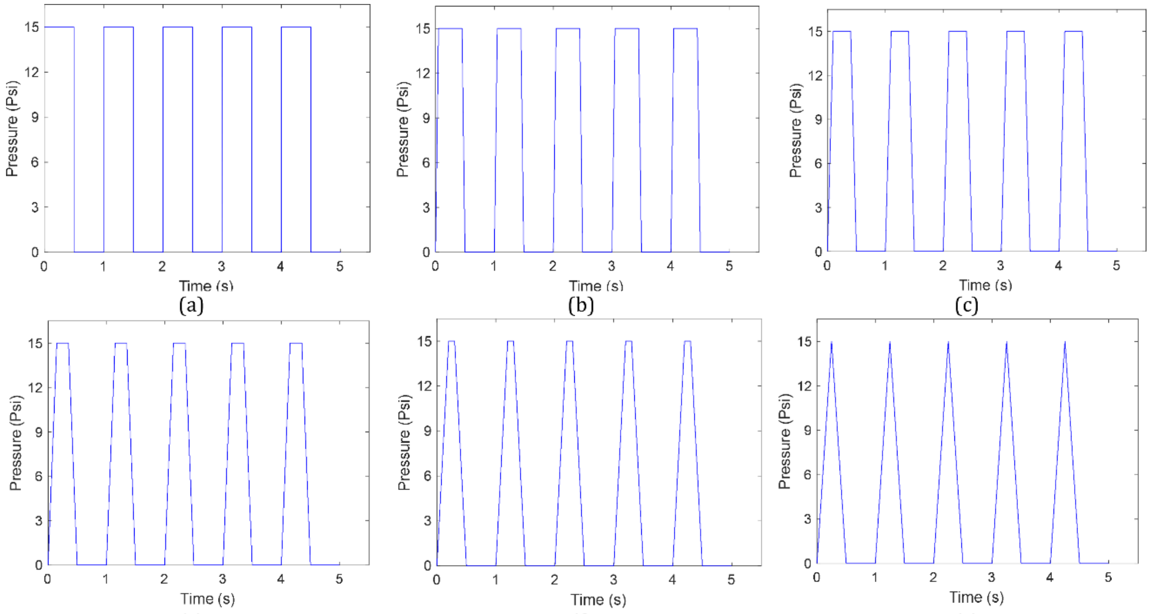
To test the pleasantness (study 1), the six different waveforms shown in Figure 4, were presented to the participants. They were composed of five pulses of an amplitude of 15 Psi, a duration of 500 ms, and played at 1 Hz. The attack and release durations of the waveform were the varying parameter; they changed in a mirror manner from 0 ms (square waveform) to 250 ms (triangle waveform) in 50 ms increments. The sustain duration was reduced each time proportionally to ensure the total waveform lasted 500ms. All eight actuators of the Bellowband were activated at the same time. At the beginning of the study, the six waveforms were presented once to the participant to familiarize themselves with the haptic sensations. Each of the six waveforms was then presented randomly five times to the participants (30 trials per participant). For each trial, the participants had to verbally rate the pleasantness of the waveform on a hedonic scale from 1 being “Not pleasant at all” to 5 being “Very pleasant”.

To test the continuity of the signal (study 2), the same six different waveforms as in study 1 were presented to the participants, but this time, each of the eight Bellowband actuators were triggered with an ISOI of 50 ms, which represents a 150 ms of superimposition of the waveforms. This represents the sensation of a signal running around the wrist (clockwise for the participant). Again, the attack and release durations of each pulse were the varying parameters, with the six waveform patterns shown in Figure 5. The waveform was played three times with a 600ms delay between the repetitions. Each of the six waveforms was then presented randomly five times to the participants (30 trials per participants). Participants had to rate the signal continuity verbally from 1 being “Not continuous at all” to 5 being “Very continuous”.

3.3 Results

Figure 6 shows the results for the pleasantness. The graph in Figure 6a represents the average for each participant, and the average for all participants (with standard deviation bars) is shown in Figure 6b. In both these graphs the waveforms along x-axis correspond to the increase in attack and release durations of the waveforms, and the y-axis is the participants pleasantness rating (integer from 1 to 5). We can see a visual correlation between the increase of the attack and release duration and the rating of sensation of pleasantness. This appears to plateau, with only a minimal rated difference between waveforms 5 and 6. However, there is a clear trend across all participants, that by changing these attack and release profiles it provides an extra dimension to control the perception of pleasantness. The large standard deviations in the collated results are from a combination of: six waveforms with only five ratings, participants limited to whole number responses, and no normalization undertaken between participants. This was intentional so that the participants were not focused on identifying the six waveforms (i.e. matching them 1-6), but instead on their rating. One participant noted how enjoyable they found the larger attack-release profiles which was found similar to a massage sensation, and how when it went it back down towards the shorter attack-release profiles it was particularly unpleasant.

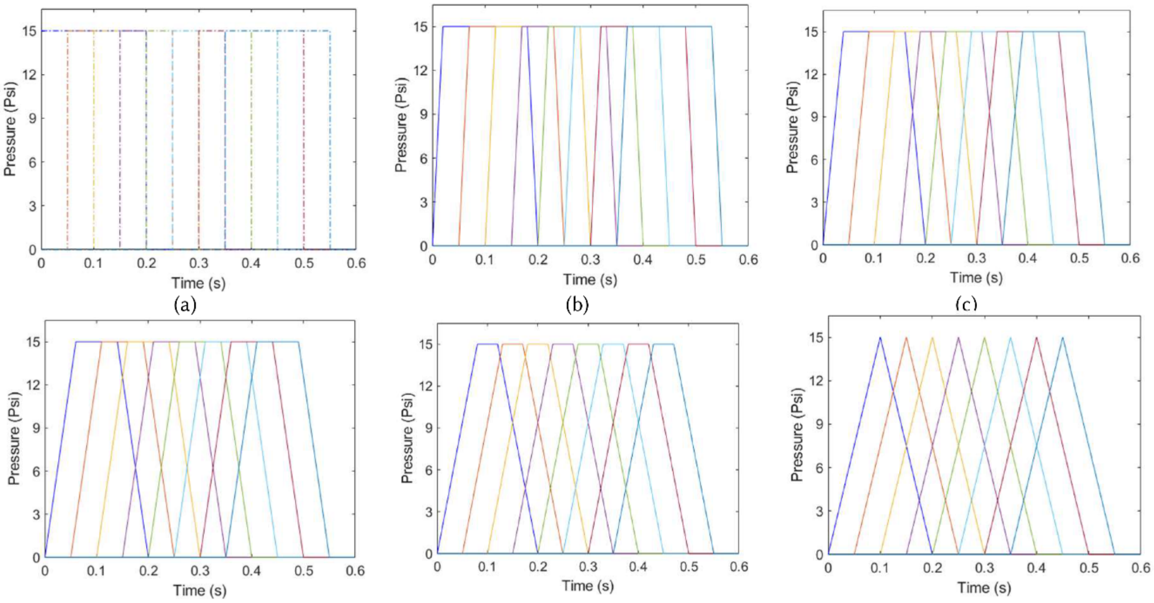
Figure 7 displays the results for the sensation of continuity, with Figure 7a showing the average for each participant, and Figure 7b presenting the average for all participants (with standard deviation bars). Again, in both these graphs the waveforms along x-axis correspond to the increase in attack and release durations of the waveforms, and the y-axis is the rating of continuality (integer from 1 to 5). There is a visual correlation between the increase in attack and release durations and the rating of signal continuity.



(a) (b) (c)

(e) (f) (g)

Figure 4: -Pleasantness pulses



(a) (b) (c)

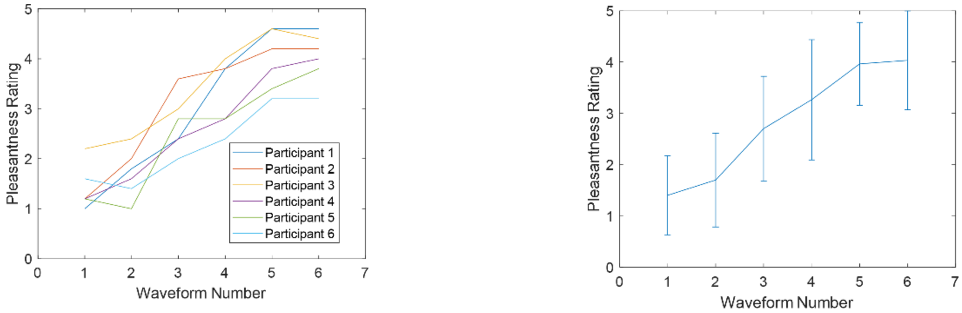
(e) (f) (g)

Figure 5: – ISOI Wave – showing single pulse only

However, this appears to plateau at waveform 4 onwards, with some participants peaking at waveform 4. One participant made the comment that although waveform 1 still felt continuous, they could feel the pulsing from the individual bubbles. Again, there is large standard deviation from rating 6 profiles with only 5 whole number ratings and no normalization.

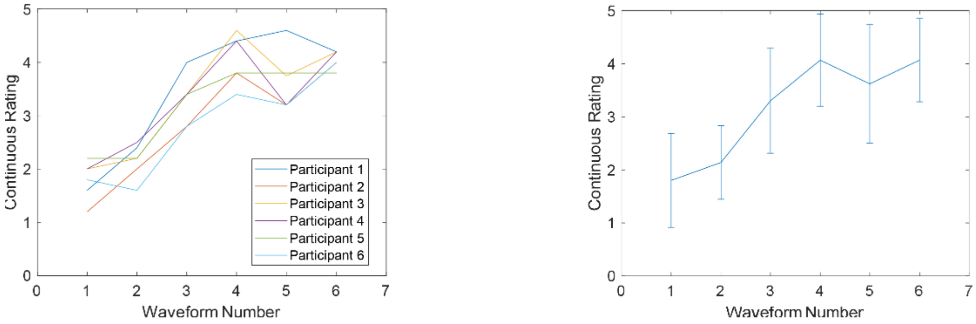
4 CONCLUDING REMARKS AND FUTURE WORK

We have presented an off-the-shelf system that allows haptic designers and engineers to quickly experiment with analog control pneumatic systems and we demonstrated that its performance delays are below the perceptual and performance limits. In addition,



(a) (b)

Figure 6: - Participants pleasantness rating (1-5) for each of the six different waveforms: (a) Individual participant average, (b) Collated group average with standard deviation per trial



(a) (b)

Figure 7: – Participants's Continuous rating (1-5) for each of the six different waveforms: (a) Individual participant average, (b) Collated group average with standard deviation per trial

we described an example user interface to quickly modify multiple waveform parameters for rapid prototyping and experimentation. The results of our pilot study not only show that the change in attacks and release parameters of waveforms are perceivable, but they lead to changes in the experience by increasing the pleasantness of a pulse sensation and continuality of the movement sensation.

There are a wide variety of applications and needs for haptic displays, and due to these differences in desired experience there is no universal optimal haptic waveform profile. For the pulse sensation presented here, some applications will require the square waveform to produce a more urgent and attention-grabbing notification, some will desire the pleasant triangle waveform, whilst others somewhere in between. However, using this system increases the degrees of freedom available to designers to prototype and experiment the best waveform possible for their application.

In this study, we presented a benchtop system for evaluating different waveform parameters. At the moment, we applied our system only to one style of wristband actuator, and solely examined the impact of varying the attack and release profiles for squeeze and apparent motion. In our future work, we will examine a variety of different waveform profiles and pressure levels to a greater extend of pneumatic haptic displays to examine the impact on the type of experience we create.

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