pneuCNTRL: a Pneumatic Control System for User Studies on Dynamic, Haptic Inflatables

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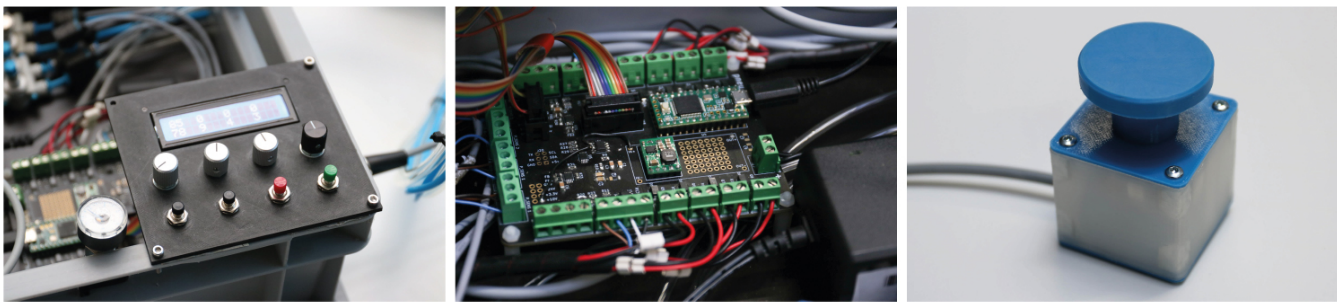

Figure 1: Overview of the *pneuCNTRL* hardware. From left to right: experimenter's interface, electronic control unit, participant's interface.

ABSTRACT

We present *pneuCNTRL*, a system providing a programmable, precise air pressure control in a multi-channel setup with interactive actuated, soft and malleable inflatables which we used for studies on data physicalization. *pneuCNTRL* is a compact, easy-to-use, and affordable solution that allows researchers to quickly and accurately control shape and haptic properties of inflatable structures in HCI experimental studies. We describe its design and functionality, and summarize our experiences with its use in research and teaching. We also discuss potential benefits of *pneuCNTRL*, such as its ability to support a wide range of experimental designs and the exploration of novel research questions.

CCS CONCEPTS

• **Hardware** → **Emerging interfaces**; • **Human-centered computing** → Human computer interaction (HCI); Visualization systems and tools.

KEYWORDS

inflatables, soft robotics, haptics, haptic interaction, surface texture, fluidic interfaces

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TEI '24, February 11–14, 2024, Cork, Ireland
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ACM ISBN 979-8-4007-0402-4/24/02.
https://doi.org/10.1145/3623509.3635263

ACM Reference Format:
Hannes Waldschütz, Rosa van Koningsbruggen, and Eva Hornecker. 2024. *pneuCNTRL*: a Pneumatic Control System for User Studies on Dynamic, Haptic Inflatables. In *Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '24), February 11–14, 2024, Cork, Ireland*. ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3623509.3635263

1 INTRODUCTION

Shape-changing inflatable textile structures (short: inflatables) are a promising approach in human-computer interaction (HCI) for lightweight, non-rigid interactions [12, 15, 22]. Instead of using rigid mechanisms for shape-creation and actuation, the underlying principle to obtain such pliable structures and mechanically compliant actuators leverages fluidic pressure. Inflatables are mainly discussed as actuators in the field of soft robotics, where ongoing developments combine pneumatic actuation techniques with pliable actuators, to construct robotic grippers, pneumatic-muscles, or locomotion systems [9, 20], but have also been explored in HCI contexts [15, 22]. Some of the advantages of inflatables are that they are inherently mechanically compliant, thus adjusting to the users' bodies, and that force can be distributed over extended distances without requiring rigid connections or heavy components at the end location. Therefore, inflatables are often used in wearables to provide haptic feedback or to emulate the pressure sensation of human touch [3, 7, 14, 16], for haptic feedback in VR [5], but have also been utilized to provide dynamic haptic feedback, for instance creating a variable physical button layout for virtual keyboards [6].

In our own research, we explore the potential of inflatables to create shape-changing artifacts that dynamically represent data in the physical realm, called *data physicalizations* [10], which represent data through material and geometric properties. Previous research shows that physicalizations support collaboration, reduce cognitive load, and seem to elicit more emotional responses [10, 21]. The latter is especially the case for the haptic modality [8]. Despite this potential, most physicalizations focus on visual output, possibly because haptics are often 'given' property of the used materials. If a physicalization is made of wood, it is difficult to dynamically change its weight or texture. Here we see a potential for inflatables, which based on pressure, can change their shape, stiffness, and surface texture among others—something we explored in a case study summarized in Section 4. For this, we utilize airtight membrane materials such as coated textiles, as these allow for a wide variety of shapes.

However, due to the complexity of the technology, and the lack of affordable and versatile control systems, the application of inflatables in data physicalization and user studies towards this has been limited. Especially for haptics, only subtle changes in shape and/or texture are needed to be perceivable, which requires precise and fast sub-Bar pressure control. Although initial work (e.g., [17, 18]) has created pneumatic control systems in an HCI context, no prior work has created a dedicated and fine-grained system that could easily be used for studies on haptic interaction with inflatables of varying material and size.

Therefore, we introduce *pneuCNTRL*, a control system to drive the haptic properties of inflatable objects made of coated textiles, silicone, or other materials. We developed *pneuCNTRL* to support our own research on haptics in inflatable physicalization. However, it can be used in other contexts as well (e.g., for simulating haptic experience in VR applications, for haptic feedback through a wearable). *PneuCNTRL* consists of a programmable, precise, and multi-channel air pressure control for the actuation of inflatables with three different modes of operation. A *manual mode* allows for direct manipulation of the connected inflatables, a *sequencer mode* lets the user cycle through predefined pressure levels on all channels, and a *remote mode* enables external control from a connected computer. The entire control system is self-built, open source[1], and low-cost, so we consider our contribution a building block that others can use to build upon when aiming for user research with inflatables.

PneuCNTRL was utilized in a lab-study with twelve participants, with the aim to validate whether people can distinguish the haptic feedback from 3 different inflatable physicalizations and interact with them (Figure 4) as well as in an interdisciplinary student project on inflatables for data physicalization and tangible interaction for the duration of one semester.

2 RELATED WORK

Previous work in HCI explored the design space of inflatables [22], introduced new fabrication approaches (cf. [15], and has started to research the haptics of inflatables. For example, *milliMorph*[12] and *VenousMaterials*[13] explore the design space and fabrication of micro-fluidic structures for haptic interaction. *MCPACS* is a pneumatic control system that offers analog manipulation of pneumatic wave forms, enabling the creation of pleasant, seemingly continuous, and fine-grained pulses to be felt at the wrist. *Pneumatibles* was used to create a pressure sensitive button that provides different types of haptic feedback through *"sequential reductions of air pressure"* [4]. Facilitating shape change, the *MorpheesPlug* [11] toolkit allows users to create 6 widgets that can be used for 7 types of shape change (e.g., fold or spiral). Lastly, *FlowIO* extended the idea of a toolkit to a development platform for inflatables [17].

Although these works give insights in (1) how to design and fabricate inflatables, (2) build a control system for inflatables, and (3) how to generate subtle changes which can be used for haptic feedback, our work contributes in making haptic inflatables easily applicable for a user research context—which requires precise control over timing and pressure values, easy and comfortable interaction on the user/controller side, and reliable function for repetitive tasks (e.g., repeating the same sequence of shape and pressure changes various times each for numerous study participants), in combination with high requirements regarding safety of use.

3 THE SYSTEM

For *pneuCNTRL* we set the following requirements: (1) ability to control fine-grained state changes of the inflatables at 0.01 bar/step (preliminary experiments showed this resolution to be appropriate for rich haptic feedback); (2) constant pressure at set point, compensating for any unwanted pressure loss; (3) a multi-channel setup for controlling multiple artifacts simultaneously; (4) ability to store and recall pressure levels; (5) ability to step/cycle through a predefined data set; (6) support of customized user input devices such as push buttons; and (7) safety measures to prevent inflatables from exploding, as our early exploration made us realize that these could accidentally explode when pressurized too much (just like a balloon). Thus, to ensure participant safety, the control system needs to prevent over-pressurizing the inflatables.

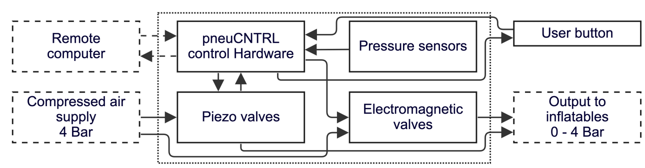

Figure 2: System layout. Dotted frame indicates physically included units, dashed frames show connected external entities.

As Fig. 2 shows, the resulting system is designed as a closed loop pressure regulation (required for maintaining pressure levels), implemented for 8 separate channels for pneumatic control with additional input capabilities for interaction. Four Channels are capable of controlling pressure up to 4 bar (58 psi), where the other 4 channels control up to 2 bar (29 psi). This split of valve technology was implemented to reflect different needs for a wide range of inflatables: electromechanical valves withstand higher pressure ranges, offer faster air flow, but require external pressure sensing, while piezo valves are easier to use, offer integrated closed loop control and CV[2] feedback, which comes at the cost of slower air flow and limited pressure ranges. Preliminary testing showed that all channels operate with an accuracy of +/- 0.02 Bar.

PneuCNTRL combines off-the-shelf parts, such as industry standard pneumatic valves with custom developed control circuitry

[1]https://github.com/hnnswldschtz/pneuCNTRL2

[2]control voltage

(Fig. 5). The control electronics drive four electromechanical valves and four piezo-electrical valves, and read out their individual output pressure states, with pressure sensors applied on all channels. Thus, air-pressure is monitored at all times for a closed-loop control of the pneumatic channels. Safety measures are implemented in the hardware, such as pressure regulators and relief valves, as well as in the control software, to avoid over-pressurizing the artifacts (a threshold that needs to be carefully set for each new inflatable).

The operator can choose between three modes of operation: (1) *Manual mode:* to set each channel to a chosen pressure value through the integrated interface, built from knobs, switches, and an LCD display. This mode of operation enables a highly intuitive and straight forward way to precisely set the individual channels for experimenting; (2) *Sequencer mode:* to cycle through stored data points of a predefined data set. This is especially useful for user study scenarios. Data for playback can be uploaded as .csv[3]; and (3) *Remote mode:* to control the pneumatic outputs in real time from a remote machine through a USB connection. This allows for further integration into existing systems.

At all times, the channel states can be observed on an integrated LCD display. In parallel to the device's operation through the screen and interface, *pneuCNTRL* features a customizable and programmable input channel with which one can navigate through a stored data set. In its current version, a simple physical button was chosen to facilitate navigation through the data set. Bi-directional communication allows driving, e.g., RGB LEDs inside the button from the control system. Having an integrated basic display functionality for visual feedback proved useful when deployed in a user-study. For instance, in our study, a fading light illustrated the transition between pressure levels: the light went out when the inflatables had achieved constant pressure, informing the participant that it was ready to be explored.

3.1 Electronics

The PneuCNTRL control electronics hardware is a custom designed, printed circuit board (PCB), implementing the following logical blocks: logic control unit, electromagnetic valves driver stage, piezo valves driver stage, pressure sense input stage, power management. The logic control is based on a teensy3.2 microcontroller board [19], connecting all system units via I^2C, SPI, UART and digital signal lines. Since two types of valves are installed, two types of valve controlling units are implemented. The electromechanical valves are switched through a mosfet diver stage. Proportional valves are controlled on four channels with a digital-to-analog conversion fed into an op-amp amplification stage. The pressure sensor's control voltages are scaled and converted in the input stage on eight channels via voltage dividers, followed by an analog-to-digital conversion. Power conversion (from +24V) is done by an off the shelf stepdown module for +5V and an additional voltage regulator circuit for +3V. Finally, there is a small prototyping area for user add-ons. This hardware is released as open hardware, licensed under CERN-OHL-W v2[2].

[3] comma separated values

3.2 Pneumatics

Taking into account the need for multi-channel operation, eight pneumatic channels are implemented in the device. To cover a wide range of output pressure and applications, two types of valves are used to control inflation and deflation of the attached actuators. Four *SMC* 5/3 electromechanical valves can switch up to 8 bar, four *Festo* proportional piezo-electronic valves can regulate up to 1 bar. Both types of valves are suited for different needs: while the former are great for stronger pneumatic actuators or rigid actuators, the latter are better suited for soft actuators with smaller volume and less pressure. Electromechanical valves provide larger airflow, pressure, and strength, but lack the ability to control flow rate and pressure (beyond binary switching). Piezo-electronic valves allow direct manipulation of airflow and pressure setpoint at the cost of limited pressure and airflow. Pressure sensors are implemented on all channels, either as a plugin parallel to the airflow of electromechanical valves or as a feature of the proportional valves. Each electromechanical valve is connected in series with two flow regulators, to manually set the channels fill- and release slope characteristics. Pneumatic connections utilize industry standard pneumatic hoses and connectors. Input pressure (4 bar/ 59 psi) must be provided by an external air compressor (e.g., jun-air 6-25).

3.3 Software

The firmware is written with the *Arduino* programming language [1], running on a *Teensy3.2* board which features an *ARM Cortex-M4* microcontroller[19]. Its functionality centers mainly around the implementation of a closed loop control of the air pressure on each pneumatic channel, which is crucial to maintain precise pressure levels and safety. Therefore, constant polling of the analog-to-digital converters (for pressure reading) and driving the valves through the respective circuits is of highest priority. Apart from that, we tried to facilitate the addition and manipulation of user-defined content, e.g. adding new inflatable objects to the software, defining their properties and assigning them to a channel is done through a standardized interface.

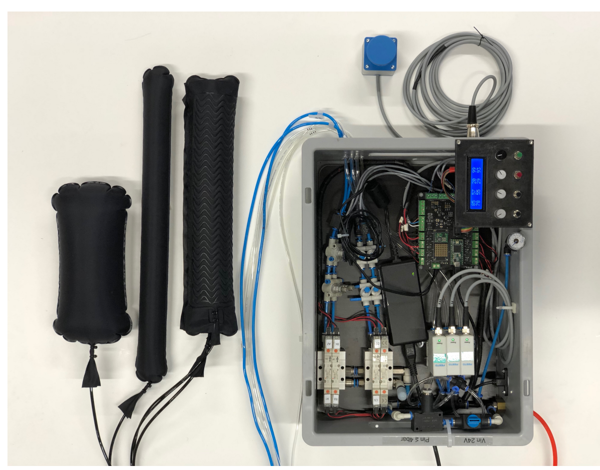

Figure 3: *pneuCNTRL* with attached inflatable objects for user testing.

Figure 4: The three inflatable prototypes controlled with *pneuCNTRL*. Each represents the data through a different haptic feedback: Bend (low pressure values are easy and high values difficult to bend); Squeeze represents data through the resistance felt when squeezing the artifact; for Surface Texture, a texture can be felt at higher pressure values, but it disappears at low values.

While initial parameters of the connected inflatables (e.g., pressure limits) need to be present in the source at compile time, new data sets for the *sequencer mode* can be uploaded and stored in the device at run-time. See online repository for source code, further documentation and dependencies. The software is released under GPL-3.0-or-later.

3.4 Data import

To facilitate the setup of a new project and its parameters, new data sets can be uploaded through a simple comma separated list, representing the state of all channels (thus the connected inflatables) for any given point in time in rows and columns (e.g., 3 rows represent three data points, 6 columns carry the data points for 6 actuated channels). The above described *sequencer mode* allows straight forward 'playback' of the given data.

4 EXPERIENCES WITH USING pneuCNTRL

4.1 Lab Study

PneuCNTRL was deployed in a lab user study with twelve participants. For the experiment, three inflatable objects (physicalizations), (Figure 4) were created from airtight TPU coated Nylon textiles. These were designed to represent data haptically through subtle changes of their internal pressure. We focused on interactions that can be performed with inflatables, which result in distinct haptic feelings: bending, squeezing, and feeling a surface texture. Based on the internal pressure, the ease with which the user can bend or squeeze the object or perceive the texture, changes. The aim of the experiment was to gain insight in how people perceive the different inflatable states.

The three objects were controlled with *pneuCNTRL*, changing pressure levels according to a small data set[4]. Since participants would be exploring this data set on their own, changes to the inflatables needed to happen quick and in the background. *pneuCNTRL* was triggered via a button push from participants to change the internal pressure, so participants could loop through the data set as often as they wanted to and re-experience a state, without intervention of the researchers. As our study involved only a small data set (six data points), one button sufficed. For larger data sets, *pneuCNTRL* can be connected to other input devices, such as a keypad or a dial. Moreover, here *pneuCNTRL* controlled the inflatables synchronously, meaning that all three physicalizations represented the same state. However, the system can also be used for asynchronous control of multiple inflatables. PneuCNTRL simplified the experimental setup and worked reliably throughout the experiments (>=8hrs), allowing us to focus on observing and interviewing, while the system automated the control. Although the study was not conducted to evaluate the performance of pneuCNTRL, but pneuCNTRL was used to run the study, we could observe its performance and gain valuable insight regarding overall reliability, accuracy and consistency of pressure levels.

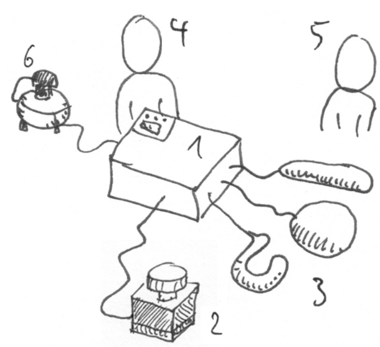

Figure 5: System overview, with 1-*pneuCNTRL*, 2-input device, 3-inflatables, 4-experimenter, 5-participant, 6-air compressor

4.2 Student Project

pneuCNTRL was also utilized in a 1-semester interdisciplinary student project on 'inflatables for data physicalization'. The groups' aim was to research, design, and to prototype inflatables by following the question how data can be conveyed with dynamic physical objects and how to design multimodal approaches of representing data. *pneuCNTRL* played a crucial role to enable the students to focus on the overall general concept and design, while they could rely on the existing implementation of a closed loop pneumatic control system to run their ideas and projects with, not having to

[4] the data points in their original order: 30%, 60%, 100%, 20%, 10%, 0%

deal with these technical details. The results included a table with pneumatically actuated legs (that extend individually) to display the balance of a given meal through the angling of its surface (the plate would slide off when the meal is unbalanced), an interactive storytelling installation with inflatable props and a 'hugging machine'. All of these were built using textile sheet inflatables for actuation and controlled by *pneuCNTRL*. We observed that after a short (1h max.) introduction to the operation of *pneuCNTRL*, the students were capable of independently operating and programming the device according to their needs, based on fundamental knowledge of Arduino programming and pneumatics (additional help was still available and provided). The groups used *pneuCNTRL* for their demos for approx. 8 hrs in total.

5 CONCLUSION

We presented *pneuCNTRL* a versatile, reliable and accessible control system for the actuation of inflatable objects from air-tight membrane materials such as coated textiles, silicone, or other materials. The device combines intuitive hands-on settings for experimenting with the ability to predefine entire sequences for playback, with high repeatable precision. Preliminary tests regarding the precision of pneuCNTRL showed that the system operates with an accuracy of +/- 0.02 Bar, further testing with calibrated equipment needs to be done to assess the system's performance. While our original intention was to develop a control system for our ongoing research on shape-variable data physicalization, this setup could also be used to control further studies focusing on the haptic perception of inflatables in other contexts, e.g., as wearables (such as a wristband, or integrated into a jacket), and to control not just levels, but pressure patterns over time or space (e.g., sections of a jacket getting tighter). The relatively low-threshold entry point into a reliable pneumatic actuation control, while offering precise and repeatable actuation, indicates further potential of our approach for use in research, educational formats and even prototyping scenarios. Early observations made during the user study and teaching sessions support this notion.

ACKNOWLEDGMENTS

This work was supported by a grant from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) -420584617 / HO3901/4-1.

REFERENCES

[1] Arduino. 2023. https://www.arduino.cc/ Last accessed October 18, 2023.
[2] Myriam Ayass, Andrew Katz, and Javier Serrano. 2022. CERN-OHL-W. https://ohwr.org/cern_ohl_w_v2.txt Last accessed September 17, 2023.
[3] Alexandra Delazio, Ken Nakagaki, Roberta L. Klatzky, Scott E. Hudson, Jill Fain Lehman, and Alanson P. Sample. 2018. Force Jacket: Pneumatically-Actuated Jacket for Embodied Haptic Experiences. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173894
[4] Kristian Gohlke, Eva Hornecker, and Wolfgang Sattler. 2016. Pneumatibles: Exploring Soft Robotic Actuators for the Design of User Interfaces with Pneumotactile Feedback. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. Association for Computing Machinery, Eindhoven, Netherlands, 308–315. https://doi.org/10.1145/2839462.2839489
[5] Sebastian Günther, Dominik Schön, Florian Müller, Max Mühlhäuser, and Martin Schmitz. 2020. PneumoVolley: Pressure-Based Haptic Feedback on the Head through Pneumatic Actuation. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3334480.3382916
[6] Chris Harrison and Scott E. Hudson. 2009. Providing Dynamically Changeable Physical Buttons on a Visual Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. Association for Computing Machinery, New York, NY, USA, 299–308. https://doi.org/10.1145/1518701.1518749
[7] Liang He, Cheng Xu, Ding Xu, and Ryan Brill. 2015. PneuHaptic: Delivering Haptic Cues with a Pneumatic Armband. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers (ISWC '15)*. Association for Computing Machinery, New York, NY, USA, 47–48. https://doi.org/10.1145/2802083.2802091
[8] Trevor Hogan, Uta Hinrichs, and Eva Hornecker. 2017. The Visual and Beyond: Characterizing Experiences with Auditory, Haptic and Visual Data Representations. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (Edinburgh, United Kingdom) *(DIS '17)*. Association for Computing Machinery, New York, NY, USA, 797–809. https://doi.org/10.1145/3064663.3064702
[9] Filip Ilievski, Aaron D. Mazzeo, Robert F. Shepherd, Xin Chen, and George M. Whitesides. 2011. Soft Robotics for Chemists. *Angewandte Chemie International Edition* 50, 8 (2011), 1890–1895. https://doi.org/10.1002/anie.201006464 Number: 8 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/anie.201006464.
[10] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3227–3236. https://doi.org/10.1145/2702123.2702180 event-place: Seoul, Republic of Korea.
[11] Hyunyoung Kim, Aluna Everitt, Carlos Tejada, Mengyu Zhong, and Daniel Ashbrook. 2021. MorpheesPlug: A Toolkit for Prototyping Shape-Changing Interfaces. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–13. https://doi.org/10.1145/3411764.3445786
[12] Qiuyu Lu, Jifei Ou, João Wilbert, André Haben, Haipeng Mi, and Hiroshi Ishii. 2019. milliMorph – Fluid-Driven Thin Film Shape-Change Materials for Interaction Design. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New Orleans, LA, USA, 663–672. https://doi.org/10.1145/3332165.3347956
[13] Hila Mor, Tianyu Yu, Ken Nakagaki, Benjamin Harvey Miller, Yichen Jia, and Hiroshi Ishii. 2020. Venous Materials: Towards Interactive Fluidic Mechanisms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, Honolulu, HI, USA, 1–14. https://doi.org/10.1145/3313831.3376129
[14] Florian 'Floyd' Mueller, Frank Vetere, Martin R. Gibbs, Jesper Kjeldskov, Sonja Pedell, and Steve Howard. 2005. Hug over a Distance. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems (CHI EA '05)*. Association for Computing Machinery, New York, NY, USA, 1673–1676. https://doi.org/10.1145/1056808.1056994
[15] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. 2016. aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. Association for Computing Machinery, Tokyo, Japan, 121–132. https://doi.org/10.1145/2984511.2984520
[16] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. 2017. Squeezeback: Pneumatic Compression for Notifications. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 5318–5330. https://doi.org/10.1145/3025453.3025526
[17] Ali Shtarbanov. 2021. FlowIO Development Platform – the Pneumatic "Raspberry Pi" for Soft Robotics. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–6. https://doi.org/10.1145/3411763.3451513
[18] Benjamin Stephens-Fripp, Ali Israr, and Carine Rognon. 2021. A Multichannel Pneumatic Analog Control System for Haptic Displays: Multichannel Pneumatic Analog Control System (MPACS). In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–7. https://doi.org/10.1145/3411763.3451742
[19] Paul Stoffregen. 2020. teensy3.2 reference. https://www.pjrc.com/teensy/teensy31.html Last accessed October 12, 2023.
[20] Hongbo Wang, Massimo Totaro, and Lucia Beccai. 2018. Toward Perceptive Soft Robots: Progress and Challenges. *Advanced Science* 5, 9 (Sept. 2018), 1800541. https://doi.org/10.1002/advs.201800541 Number: 9.
[21] Yun Wang, Adrien Segal, Roberta Klatzky, Daniel F. Keefe, Petra Isenberg, Jorn Hurtienne, Eva Hornecker, Tim Dwyer, and Stephen Barrass. 2019. An Emotional Response to the Value of Visualization. *IEEE Computer Graphics and Applications* 39, 5 (Sept. 2019), 8–17. https://doi.org/10.1109/mcg.2019.2923483
[22] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13)*. Association for Computing Machinery, St. Andrews, Scotland, United Kingdom, 13–22. https://doi.org/10.1145/2501988.2502037