High Spatial Acuity Haptics

PEYTON RAPO and ALEXANDER FERNANDEZ, University of Washington

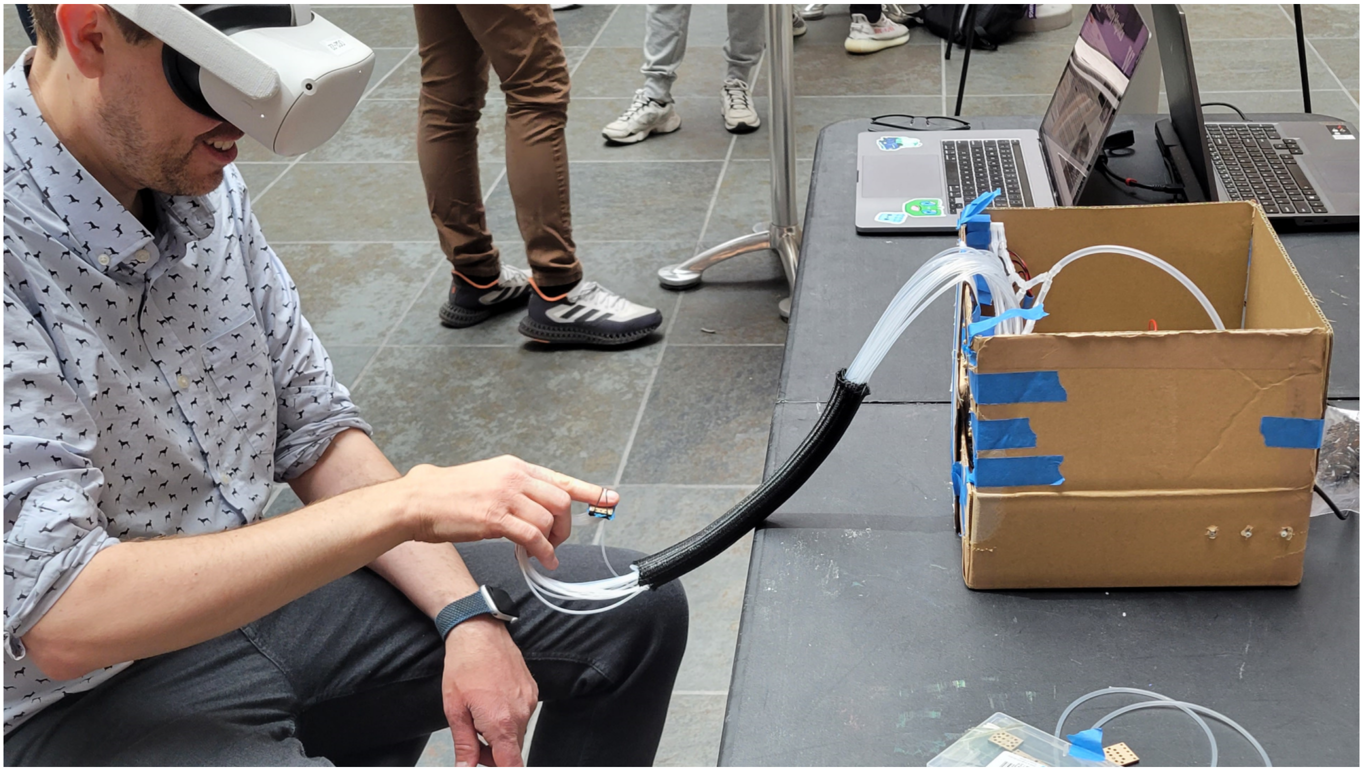

Fig. 1. A small haptic device attached to the index finger of a users. This device is capable of applying pressure at varying locations on the fingerpad via inflating bubbles. When interacting with objects in a virtual environment, this localized pressure can be used to mimic the sensation of real touch.

Traditional VR experiences may have great visual fidelity, but often leave users with a spectral feeling due to the lack of physical feedback in response to their action; to combat this, we have constructed a haptic device which can be attached to a user's finger. The device has a fine grid-like arrangement of 16 latex bubbles which can be pressurized to inflate against the users fingerpad. An external control system is connected to the fingerpad, and allows for each bubble to be individually inflated, giving the user highly localized feedback based on where exactly their finger came in contact with a virtual object. With around 3 mm center-to-center separation between these bubbles, we believe our device's spatial acuity rivals the state of the art from commercially available devices.

1 INTRODUCTION

In most state of the art VR systems, the focus is often on achieving a great visual fidelity in combination with great audio fidelity. However, these VR systems tend to lack a physical feedback system besides sometimes the vibration of controllers. It is possible for users to buy peripherals in order to feel physical feedback, but these devices can cost in the thousands of dollars or can only be rented. In our project, we created a cheaper haptic actuator which achieves as good, if not better, spatial resolution than some commercially available products today.

There are a few approaches that companies take when creating physical feedback through haptic actuators for the finger pads. They broadly fit into 3 categories of whether they use electricity, vibrations, or physically touching the finger. Companies that use electricity will use a special material which the finger rests against to send small shocks. Companies that use vibrations will use varying levels of vibrations to stimulate the finger. Companies that physically touch the finger will have usually have a grid or other partitions that let them put pressure on different areas of the finger.

Our design centers around a system of inflating small 1.9 mm diameter air bubbles arranged in a hexagonal-like grid on a pad that presses against your finger pad. The bubbles are placed around 3 mm apart as this approaches the limit at which our nerves can tell apart two objects. The bubbles are inflated via tubing which connected to a series of three air pumps. The bubbles can be in one of two states, on or off, depending on if the valve, in which the tubing is connected, is opened or closed. We also regulated the pressure in the tubing, using a pressure sensor, as to prevent the

Authors' address: Peyton Rapo, peytor01@cs.washington.edu; Alexander Fernandez, alexfern@cs.washington.edu, University of Washington.

bubbles from popping and to turn off the air pumps when they were not needed.

What we found over the course of this project is that it is not too difficult to set up a haptic actuator with air bubbles, although it can be quite time consuming. We were able to activate any combination of the air bubbles based on what was needed for the scene and the latency was low enough that it could be felt in real time. In the future we hope to be able to achieve varying levels of pressure in each bubble in order to achieve the effect of pressing into objects, not just touching them.

1.1 Contributions

- Built a haptic actuator out of valves, air pumps, and transistors with good spatial acuity
- Implemented software to translate where we touched in VR to what we should activate on the finger pad
- Implemented a duty cycle for activating the air bubbles
- Implemented a self-regulating pressure loop

2 RELATED WORK

There are too many types of ways people have tried to develop haptic feedback for VR whether they be exoskeletons or arm-worn devices to go into detail into all of them, so we will be restricting this section to covering ideas that are similar to ours. These being ones that go on the finger and are for the purpose of feeling shape. Kappassov et. al. [1] goes into depth on the taxonomy of the haptics as a whole.

In that paper, they breakdown finger-worn haptic feedback into a few categories: skin stretch, vibrotactile, and force feedback. Skin stretch is done through having a pad worn under the finger which is pulled up into the finger to add pressure. Vibrotactile is using vibrations to try to stimulate the finger. Force feedback is the most akin to what we are doing in that it is devices that push into the finger.

The device that the paper references is Carpi et. al. [6]. In that paper they describe creating a controllable membrane that the finger sits against which will change height depending on the circumstance. In comparison to our design, they have a better system of control for controlling the height, but have a significantly lower spatial acuity due to the size of the membrane only allowing one surface for the finger to rest against.

A design that is closer to ours in execution and spatial acuity would be the design presented by Caldwell et. al. [4]. In their design they employ a 4 by 4 grid of rods which are mounted onto springs and controlled by a thread running underneath the pad. This design matches our spatial acuity, but the placement of their rods differs slightly than ours as ours was designed to fit the entire finger pad and is longer as a result. The control systems are also very different as theirs uses springs and thread as compared to our use of air.

The closest design to ours that we found comes from HaptX [5]. Their design also uses a series of controllable air bubbles, but they have better control over the height of each air bubble and their finger pad is much thinner. Their design is not entirely better than ours as our does have higher spatial resolution and is significantly cheaper to create.

3 METHOD

Our projected consisted of both creating novel hardware within the desired constraints, as well designing a haptic rendering engine which could control such hardware based on the users actions within a virtual environment.

3.1 Fingerpiece

Haptic feedback is provided by applying pressure at various locations on the fingertip. This pressure is translated via numerous malleable bubbles which can be controllably inflated out of holes in a wearable fingerpiece. This fingerpiece will be affixed to one of the users fingertips (typically the right index finger).

Independent bubble inflation is achieved by supplying pressurized air through numerous control tubes–with one tube attached to each bubble. By making these tubes fairly small, we can obtain a high bubble density and fast response times.

3.2 Control System

At the source of each of the control tubes are valves, which allows for binary `ON/OFF` control of a pressurized airflow heading to each bubble. Three way solenoid valves should be used, with the `ACTIVE` position of each valve connecting a control line to a source of pressurized air, and the `REST` position connecting the control line to a vent. Having an active vent is critical for allowing quick deflation of the bubbles; otherwise, the device would have to rely on slow pressure leaks for the bubbles to eventually deflate.

Pressurized air could be supplied from a large bottled source whose release rate can be electronically controlled, but we thought it would be more practical to simply use small ad-hoc air pumps. Our system was also (originally) designed to use a pressure sensor to control the activation of the pumps, allowing us to dynamically adapt to rate of usage and maintain a consistent pressure. If the pressure is allowed to build up too high, then a bubble may pop if its control valve is activated, or a spontaneous breakage may eventually be created elsewhere in the system due to the pressures rising outside of part or joint tolerances.

A microprocessor (in communication with the haptics engine) sends out control signals to transistors to appropriately active the valves and pumps as required.

3.3 Finger Tracking

In order to accurately provide haptic feedback, it is necessary to track the movement of the users finger with high accuracy. Just half a centimeter of displacement could represent the difference between the user barely above the surface of an object and the finger firmly pressed against it. To model even subtler changes and surface textures, sub-millimeter precision may become required.

Yet the primary goal of our work wasn't to break new ground in motion-tracking, and our valves only have binary control, so we likely only need to meet the former level of precision for an acceptable user experience; to this end, we intend to use optical pose estimation to more easily integrate it with the rest of our design.

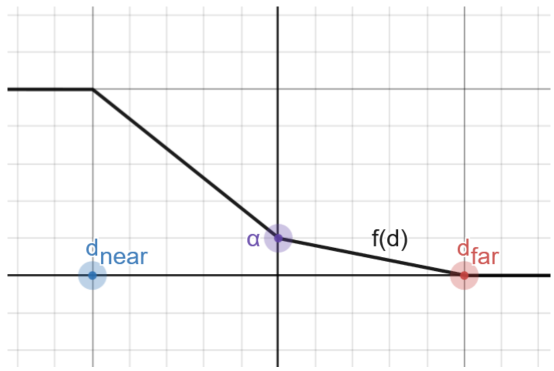

Fig. 2. An example activation function $f(d)$ translating surface distances to how much each bubble should inflate. In this particular case, we parameterize our function by d_{far} (the farthest distance any pressure should be felt), α (the relative pressure to feel when the fingertip is just touching the surface), and d_{near} (how far into the surface the bubble pressure should reach a maximum)

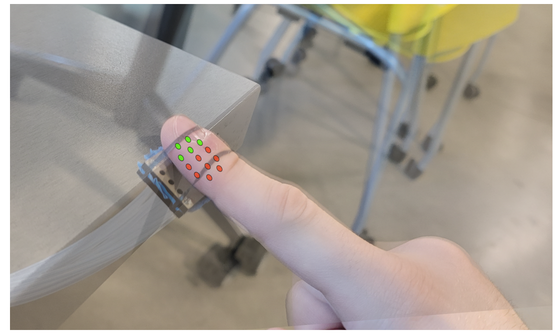

Fig. 3. A simulated view of what actually happens while touching the edge of a table in a virtual environment.

3.4 Haptic Rendering

Using finger positioning and information about the virtual environment, we can then determine what parts of the fingerpad to stimulate. Our algorithm is as follows:

- For each bubble on our haptic device, find the corresponding location on the users finger in virtual space; this may be derived by applying a translation in the local plane of the virtual fingerpad based on each bubbles particular location in the grid.
- At the location of each bubble, determine if it is inside an interactable collider or not.
  - If that location is not inside anything, then raycast from the bubble's location outwards in the direction normal to the users fingerpad, and determine the distance to the nearest interactable object.
  - If instead we are inside an interactable object, then raycast backwards and interpret the distance to the closest surface as a negative value.
- For each bubble, using the (signed) distance to the nearest interactable surface, apply an activation function which translates that into the relative amount of pressure that should be applied at that bubble. The exact function to use is an implementation detail, but one possible example is depicted in Figure 2.

After this first algorithm determines the relative inflation that each bubble should have, that data should be forwarded to the device's micro-controller so that it can appropriately adjust the pneumatic system. The controller's exact behavior behavior is an implementation detail, but we roughly intend for it to:

- Adjust the source pressure relative to the average requested bubble height.
- Apply some threshold to the requested bubble heights, and activate the values for bubbles which are greater than this threshold.

With the appropriate engine handling the virtual environment, and other software tying each of these steps together, the user should be able to feel these bubbles inflate against their finger as it gets close to objects; moreover, the bubbles which inflate should be correlated to what parts of the virtual finger are touching the object. A visualization of the intended effect can be seen in Figure 3.

4 IMPLEMENTATION DETAILS

4.1 Fingerpeice Assembly

Our device's final fingerpiece included 16 bubbles. We used two layers of laser-printed acrylic with cutouts for the bubble grid, plus some extra screw holes. Extremely small 2mm OD Silicone tubing was needed to supply provide pressurized air at the target density (3mm separation per bubble). The upper part of acrylic used 2mm holes, and the lower layer slightly smaller 1.9mm ones, allowing it to clamp onto the tubes so they wouldn't slip out. We expect that these holes need to remain within a 0.1mm tolerance for this technique to work; in particular, we used a computerized laser cutter to precisely cut two halves within these limits.

In-between the two layers is a thin sheet of latex (which was simply cut out from a latex glove). With each of the tubes, we pushed parts of the latex up into the cutouts of the upper acrylic layer. This naturally forms a seal around the tip of the tubes due to the tight tolerances, and when the tube becomes pressurized, the latex at the tip will inflate into a bubble. It was vital during our construction that the tubes and latex were pushed into the upper layer before the layers are clamped together; this is required to have enough hand-room to manipulate the tubes and to allow the latex to have sufficient slack to be pressed into the holes.

Once the tubes were inserted, the two layers could be screwed together, and the entire fingerpiece assembly can be affixed to a user's finger using small rubber bands. The final piece is shown in Figure 4.

4.2 Pumps, Valves, and Tubing

We used three simple (12V) aquarium air pumps connected in parallel. These then branched air using (`3mm ID`) silicone tubing into sixteen different 3-way (12V) micro-solenoid valves. Since both ran

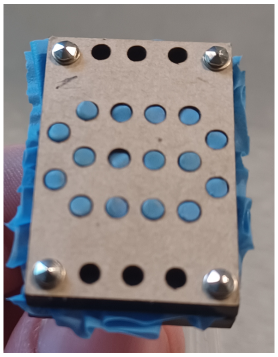

Fig. 4. The assembled fingerpiece. Note that we were unable to get the bubbles to a uniform height.

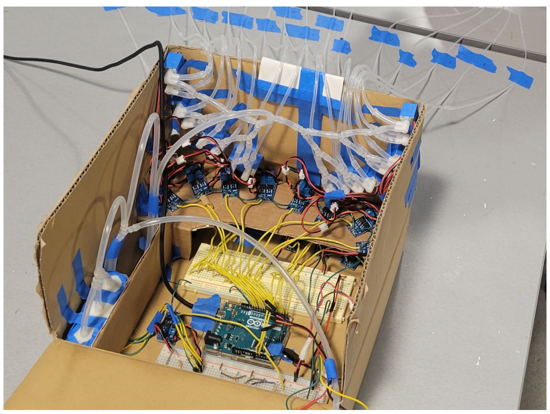

Fig. 5. An inside view of the pneumatic control crate.

off of 12V power, a common battery could be used to power both components.

The output tube of each valve was then slowly downsized from 3mm ID/5mm OD to 1.5mm ID/3mm OD, and then finally to 1mm ID/2mm OD. Although proper connectors could be used for junctions of the largest tube sizes, adaptors for the 2 smaller sizes were prohibitively expensive; instead a combination of tight fits and silicone adhesive were used to seal each adaption-point.

4.3 Microcontroller, Circuits, and Sensor

An Arduino Leonardo was used as the brains of the pneumatics; the board has just enough pins to individually control each of the valves. *Specifically, the pins activate MOSET trigger switches which are attached attached to the valves and the pumps.* Moreover, convenient tools and libraries already exist for interfacing with Arduinos—namely the USB serial communication interface.

A (2SMPP03) pressure sensor was attached to our pressurized air to regulate air pressure. To use the sensor properly, we needed to create a constant current source and output amplification circuit on one of our breadboards as depicted in Figure 6.

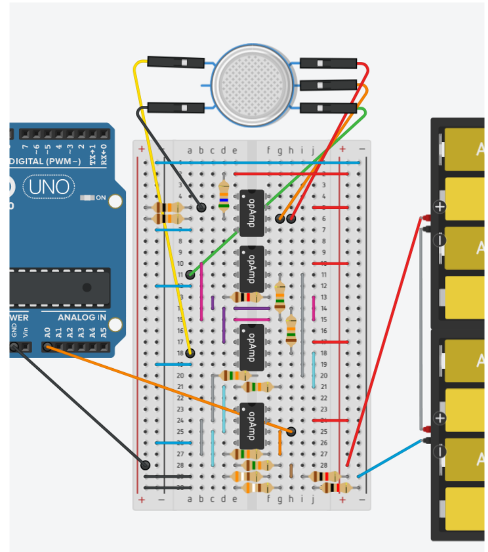

Fig. 6. A circuit consisting of a 100 μA current supplier, and a three-op amp instrumentation amplifiers to make the sensors output more detectable on the Aurdino analog pin.

A target pressure could be specified on the Arduino, which would turn the Pumps on or off whenever the pressure fell below a certain amount below or above the target respectively. *Unfortunately the sensor is quite fragile and broke during development, so it could not be included in the final design.*

4.4 Virtual Environment and Software

We decided to use a Meta Quest 2 for our project; it has both extensive software support in modern game engines, as well as built in hand tracking, which freed up more time for us to focus on constructing our hardware.

Our demo was then built inside of Unity, due to its ease of use. The haptic rendering was then implemented as a script, and functions as described in Section 3.4.

Since Unity will be running on the Quest itself, which is not directly attached to the control crate, the script's output is instead communicated over WiFi. In particular, it sends a Web Request to a NodeJs server running on a local computer which then forwards the information to the Arduino controller over its direct USB connection.

4.5 Extra Feature: Duty Cycles

During development we experimented with opening the valves at a partial rate based on a specified duty cycle to hopefully induce a steady partial inflation of the bubbles. *During testing, this did not work very well because the pressure vented too quickly.*

5 EVALUATION OF RESULTS

Overall our system worked liked we wanted it to and we could render any combination of the 16 bubbles on our finger pad. This would allow users to feel edges and ridges as they are more defined features which are large enough to render. When using the system however, users reported that when touching objects the immediate 0 to full pressure was snappy and caught them off guard. This is due to the lack of a steady increase in pressure. Also when constructing the finger pad, due to the lack of precision in putting the tubes in, not all of the bubbles were the same height giving it an uneven feeling with some bubbles not being felt at all.

6 DISCUSSION OF BENEFITS AND LIMITATIONS

One of the benefits of our system are that the parts to build it were relatively cheap; in total, the components we used costed around $350–and you could probably get everything for closer to $250 by ordering from cheap resellers with longer shipping times. Additionally, the end result is surprisingly light weight, but there is still significant pressure on your finger from the air bubbles.

The main difficulty that followers of our approach may encounter is with creating the fingerpiece as we didn't use stock components. People may need access to specific equipment such as a laser cutter, and some of the steps to assemble it can be quite time consuming such as putting the tubes into the piece. Nonetheless, we expect anyone with sufficient time could probably set up such a device by following our hardware implementation details. *We, the authors, somehow managed despite our lack of shop experience.*

Another limitation would be that, in our current model, the air pumps start to lose potency after a while either due to wear from our pressure sensor breaking or the system draining the batteries over extended period of time. The air bubbles also tended to pop since we weren't regulating our air pressure and the material we were using was stretching more and more over each use.

7 FUTURE WORK

The next steps for this project focus on improving the capabilities of the project we have described. We want to explore better control over the height of the air bubbles we are producing and how much pressure they are pushing into the finger. A way to do this may include splitting the air pumps over multiple channels and activating different numbers of them depending on the amount of pressure we want to deliver or simply setting up a pressure chamber to draw from. Another part of this project we would want to improve on for the future would be how to better condense all of the wires and tubing to make the system less burdensome for the user to use. It may be worth also exploring the possibility of adding even more air bubbles to achieve an even higher spatial resolution.

8 CONCLUSION

The ultimate goal of VR is immersion. To achieve that goal people would need the virtual world to be indistinguishable from the real world. For the current state of the art products out there, it is possible to visually and audibly feel immersed, but there is a lack of immersion of physical senses. While there do exist haptic products that people can buy or rent, these products tend to be at a price point that most people cannot afford. With our project we hope to have shown that it is possible to experience physical feedback while on a much more affordable budget.

ACKNOWLEDGMENTS

We would like to thank Douglas Lanman, for his mentorship and invaluable teaching. Also, as a hardware project, we had many part requirements; as such, we thank John Akers (and by proxy the University) for assistance with funding this ambitious project. We also would like to thank Nicholas Colonnese for his consultation and advice. Moreover, we wish to give some credit to Nick Langhorn, who originally intended to join us on the project, and helped collaborate on our earlier design ideas. Finally, we wish to thank Anh Vo, and various staff members at *The Mill*, who assisted with some of hardware wiring and parts fabrication respectively.

REFERENCES

[1] A. Adilkhanov, M. Rubagotti and Z. Kappassov, "Haptic Devices: Wearability-Based Taxonomy and Literature Review," in IEEE Access, vol. 10, pp. 91923-91947, 2022, doi: 10.1109/ACCESS.2022.3202986.

[2] J. Perret and E. Vander Poorten, "Touching Virtual Reality: A Review of Haptic Gloves," ACTUATOR 2018; 16th International Conference on New Actuators, Bremen, Germany, 2018, pp. 1-5.

[3] V. R. Mercado, M. Marchal and A. Lécuyer, ""Haptics On-Demand": A Survey on Encountered-Type Haptic Displays," in IEEE Transactions on Haptics, vol. 14, no. 3, pp. 449-464, 1 July-Sept. 2021, doi: 10.1109/TOH.2021.3061150.

[4] I. Sarakoglou, N. Garcia-Hernandez, N. G. Tsagarakis and D. G. Caldwell, "A High Performance Tactile Feedback Display and Its Integration in Teleoperation," in IEEE Transactions on Haptics, vol. 5, no. 3, pp. 252-263, Third Quarter 2012, doi: 10.1109/TOH.2012.20.

[5] Haptic gloves G1 - gloves for virtual reality and Robotics. HaptX. (2023, May 16). https://haptx.com/

[6] Frediani G, Mazzei D, De Rossi DE, Carpi F. Wearable wireless tactile display for virtual interactions with soft bodies. Front Bioeng Biotechnol. 2014 Sep 1;2:31. doi: 10.3389/fbioe.2014.00031. PMID: 25225636; PMCID: PMC4150388.