Soft Interfaces

Softinterfaces.com

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Preface

This thesis began with a vision of soft shape-changing interfaces, developed over the past two years and shared through the platform softinterfaces.com. It explores how technology can be expressed through form and integrated into the materials that shape our surroundings. Through experiments with magnetics, textiles, fluidics and pneumatics, I investigated ways for interfaces to communicate not only through sight and sound but through motion, deformation and touch. Reciprocity is the core of soft interaction; sensing and actuation must be designed as one, so the interface can feel and move in a single continuous conversation. In doing so, I became aware of how material dictates experience. The stickiness of silicone, the noise of air, and the bulk of tubing aren't just technical frictions they influence how people engage with the interfaces, what they expect from it, and how it fits into everyday life.

With the earlier soft interfaces I kept running into the same limitations: noise, rigidity, leakage, bulk and heavy power consumption. They were difficult to miniaturise, impractical to embed and still fell short of the subtle softness and interaction I envisioned. Creating thin, silent and high resolution actuation that disappears into surfaces demanded a different approach, which led me to electroosmotic pumps (EOPs), a scalable fluidic technology with no moving parts that supports both actuation and embedded sensing.

Rather than outsource the technical development or rely on speculative prototypes, I chose to build these pumps myself. As a designer, I believe knowledge comes through making, not just imagining how something could work, but physically engaging with materials, circuits, and failures. Throughout this process, I interviewed experts from BMW, Disney Research, Accenture, and research groups to position EOPs within a wider design and industry context. Rather than validating a novel actuator, this thesis explores how designers can actively shape its expression and use. It demonstrates how designers can engage directly with emerging technologies through physical prototyping, positioning design as a bridge between early-stage technological development and applied contexts in sectors such as soft robotics, automotive and entertainment.

Abstract

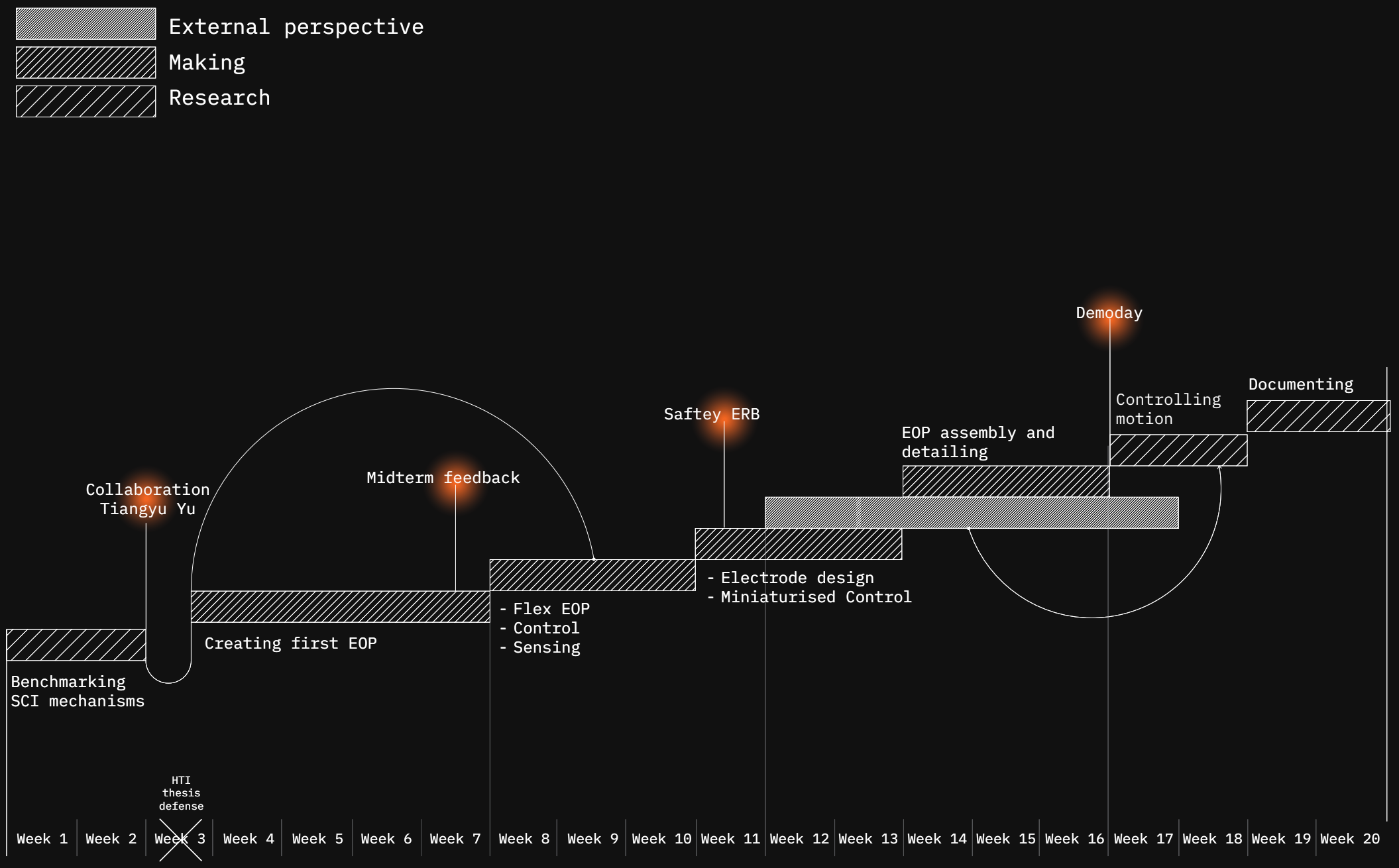
Soft interfaces powered by electroosmotic pumps (EOPs) enable interaction through silent, fluid-driven motion. These thin, flexible, and energy-efficient systems produce surfaces that rise, ripple, or pulse in response to electrical input, guiding attention or conveying affective states such as calm or urgency. With integrated pressure sensing, they support real-time, reciprocal interaction and can be embed- ded into curved or layered contexts. Despite their promise, the role of design in shaping how such systems are experienced and applied remains underexplored. Prior work has focused on technical validation, with limited attention to human–system interaction or application framing. This thesis uses a Research-through-Design approach to develop and evaluate EOP-based prototypes, integrating microfluidic actuation, soft fabrication, and sensing. Expert interviews with BMW, Disney Research, and Accenture situate the work in real-world contexts. The research contributes novel interaction scenarios and design insights, positioning design as a bridge between early-stage technology and expressive, applied use.

https://softinterfaces.com/EOP.html

AI use statement

AI tools have been utilized throughout this thesis, particularly in coding tasks such as Python scripts and high-voltage control code. Given the specialized nature of the project, the role of AI was relatively limited for these codes. For the creation of application images, ChatGPT's generative AI was employed to quickly visualize potential future directions. Additionally, AI was leveraged during the writing process to condense and summarize text in order to adhere to the word limit.

Design process



Introduction

Smart objects have quietly embedded themselves into daily life. Voice assistants manage calendars before we wake, watches flag irregular heart rhythms in real time, autonomous cars hold their lane through fog, and thermostats trim energy bills by learning our routines. Yet the ways we physically interact with these systems remain largely unchanged. Despite increasing intelligence, most devices are still encased in static forms: mechanical buttons, flat capacitive screens, and vibration motors dominate the interaction landscape [23, 10, 29]. Their bodies remain inert, offering no expression to match their growing intelligence.

This one-sidedness in interaction, where systems sense richly but respond in fixed, limited ways, creates a growing gap. As Bruns et al. argue, current technologies lack artefact expressivity: the capacity to convey intent, emotion, or responsiveness through physical form [5]. Interaction is constrained by the limited material vocabulary of our devices. While screens glow and voices speak, their physical form stays silent.

Shape-changing interfaces (SCIs) offer a potential shift. Rather than relying on sound or visual cues, SCIs communicate through temporal form, shape changes that unfold over time [31]. They allow devices to pulse, yield, stretch, or retract, suggesting curiosity, resistance, urgency, or calm [6, 24, 4]. By engaging physical movement as a communicative medium, SCIs promise interfaces that feel more embodied, more reciprocal. In embodied interaction, meaning emerges through bodily engagement with technology. SCIs use movement, resistance, and form as part of the interaction itself, something felt, not just observed. They also support reciprocal interaction, where the system responds in physically expressive ways, creating a continuous dialogue with the user [5]. This turns interfaces from passive tools into active, responsive participants.

Yet despite decades of research, most shape-changing interfaces remain embedded in academic and lab-based contexts, with limited translation into industry or everyday use. The inFORM system [8] and MilliMorph [15] exemplify influential SCIs that demonstrate expressive potential, but have not seen widespread deployment beyond research. The Grand Challenges in Shape-Changing Interfaces paper identifies five persistent barriers: actuation, artifact integration, sensing and control, design tools, and user experience [1]. Among these, actuation remains the most technically limiting. Common technologies like pneumatics, shape-memory alloys (SMAs), and dielectric elastomers are often bulky, noisy, power consuming, or hard to integrate into small or complex products [13, 30, 1].

Soft interfaces require the integration of both sensing and actuation to support intelligent, reciprocal interaction. Yet much of HCI and soft robotics research continues to treat them separately, advancing either expressive actuation or novel sensing techniques, but rarely both within a unified system. Work from the Morphing Matter Lab [19] has explored actuation through programmable materials and dynamic structures. However, for the kinds of responsive, relational forms envisioned in this work, actuation alone is not enough. Without sensing, shape change becomes a one-way gesture rather than an interactive exchange. Projects like Kobakant [14] have focused on soft, textile-based sensing, but these capabilities often remain isolated. The Grand Challenges paper emphasizes the need to “tightly couple shape-change actuation and sensing,” enabling systems that can perceive and adapt in real time [1].

Wang et al. demonstrate that embedding sensing directly into actuating materials enables localized, real-time feedback, enriching temporal control and expressive interaction [32]. Few systems, however, pursue this as a true sensing–actuation composite: a material that both moves and feels. McEvoy and Correll’s concept of robotic materials offers an emerging model for such integration, where sensing, actuation, computation, and communication are embedded within a single substrate [17].

Soft materials play a critical role in enabling expressive, responsive interfaces. They bend, compress, and disappear into their environments. They feel natural to touch, support peripheral interaction, and conform to complex shapes [27]. In HCI’s material turn, materials are no longer seen as passive enclosures but as active participants in interaction [31, 25]. Winters et al. describe how gradual, temporal shape change through principles of tension and release can evoke expressive, relational qualities in dynamic materials [33].

This thesis explores electroosmotic pumps (EOPs) as a new approach for soft, expressive, shape-changing interfaces. EOPs are a class of microfluidic actuators that operate without moving mechanical parts, using silent, bidirectional fluid flow to create deformation. Unlike conventional actuators such as motors or pneumatics, EOPs are compact (less than 5mm thick), lightweight , and capable of producing high resolution shape change with low voltage and fast

response times (under one second) [36, 28, 29]. Previous work has embedded EOPs into miniature haptic and shape-changing displays [36, 28, 29], but their potential as fully flexible, materially integrated interfaces remains underexplored. This thesis moves beyond grid-based output and technical benchmarks, investigating EOPs as part of a sensor-actuator composite designed for embodied, reciprocal interaction in HCI contexts.

This thesis employs a Research-through-Design approach [39] to explore how electroosmotic pumps (EOPs) can enable expressive and reciprocal interfaces. It integrates microfluidic EOP actuation, pressure sensing, and soft material fabrication into a unified system, developed and critically examined through designerly practice. These material, technical, and experiential investigations come together as an inquiry into the design potential of EOP interfaces. The resulting prototypes and interpretive insights serve as both the method and the core contribution of this RtD process. Insights from industry experts in automotive design, smart products, and soft robotics help contextualize potential applications and challenges beyond the lab, demonstrating how a design-led approach can accelerate technology transfer by identifying meaningful use cases, articulating human–system interaction possibilities.

Contributions

1. **A sensing–actuation composite:** *EOP interfaces that detect pressure while generating dynamic form.*
2. **A designerly fabrication workflow:** *documenting and reflecting on materials, methods, and iterations from a design-led perspective.*
3. **Expert interviews:** *insights from automotive, smart products, and soft robotics domains on real-world needs and potential.*

In doing so, this work demonstrates how designers can contribute to emerging technologies by devel- oping integrated prototypes, documenting material practices, and connecting technical exploration with real-world perspectives.

I became interested in electroosmotic pumps (EOPs) while searching for alternatives to the limitations I kept encountering in earlier soft interface prototypes: noise, bulk, rigidity, and lack of integration. In that process, I reached out to Tiangyu Yu, author of the FlexEOP paper, who introduced me to their potential as thin, silent actuators for soft, materially embedded interfaces. Rather than treating them as black-box components, I chose to build the pumps myself, applying my background in design, proto- typing, and electronics to engage directly with their underlying mechanisms. This was both a risk and a creative opportunity: to bring my design knowledge into a space typically reserved for engineering, and to tailor the actuator's behavior and form to support new modes of tactile and embedded

Technical Background

To work meaningfully with electroosmotic pumps, I first had to understand how they move. This section outlines the principles behind their operation as a foundation for building, testing, and tuning them.

Electro Osmotic Pumps

Electro-osmotic pumps (EOPs) are fluidic actuators that move liquid through porous media by applying an electric field, no motors, or moving parts involved. Instead, flow emerges from surface-level charge interactions: when a polar fluid (e.g. distilled water) meets a solid like glass, surface groups (such as silanol, Si–OH) release protons, leaving behind a negative surface charge (Si–O–). This at- tracts a layer of positive ions from the fluid, forming a mobile region of charge near the surface. Go to Appendix G1 for a more detailed explanation.

Applying a voltage across the porous medium causes these ions to move. As they move, they drag surrounding fluid molecules along, producing a directional flow through the membrane. This phenomenon is called electro-osmotic flow (EOF), and it forms the core operating principle of EOPs. The fluid velocity u can be described by the Helmholtz–Smoluchowski equation:

$$u = \frac{\varepsilon \zeta}{\eta} E$$

where:

- ε is the fluid's permittivity,
- ζ is the surface potential (related to surface charge density),
- η is the dynamic viscosity of the fluid,
- E is the applied electric field.

This equation shows that EOF is linear, reversible, and directly controlled by the applied field. Choosing a fluid with high permittivity and low viscosity, paired with a membrane that generates strong surface charge, allows for faster flow and greater actuation. Which is why Propelene Carbonate is chosen as the working fluid.

In this work, the pumps are built as layered stacks, with fluid moving vertically through a glass fiber membrane. Each pump includes a patterned electrode on either side of the membrane. These electrodes are perforated with circular vias, 0.15 mm in diameter and a pitch of 0.55 mm . This geometry ensures the electric field penetrates evenly across the pumping surface, avoiding dead zones or uneven actuation. Uniform electric field distribution is essential: not just for efficiency, but for reliable, repeatable deformation across arrays of pumps.

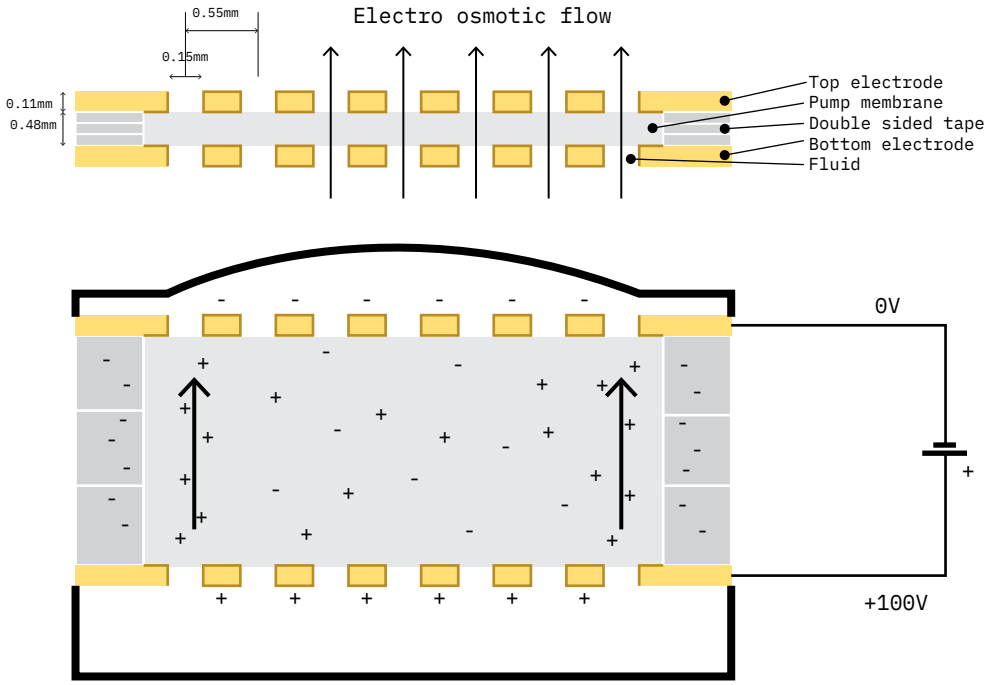
Because the electrodes are porous and aligned with the membrane, fluid moves directly from the reservoir through the pump and into a sealed upper chamber. This chamber sits beneath a flexible silicone layer, which inflates as fluid fills the space, producing a tactile, visible shape change. This design enables actuation that is not only thin and silent, but can also allow for complex movements and shapes pulling liquid from one reservoir.

EOPs in HCI

This thesis builds on recent HCI research exploring electro-osmotic pumps (EOPs) as thin, silent actuators for shape-changing and haptic interfaces. Shultz and Harrison [29] were the first to demonstrate how EOPs could be embedded directly into the surface of a shape-changing display, introducing the concept of embedded electroosmotic pumps for scalable haptic output. The follow-up work, Fluid Reality [28], showed how miniaturized EEOPs could be arranged into fingertip-scale haptic arrays. More recently, FlexEOP [36] introduced flexible PCB substrates to fully soften the pump stack, eliminating rigid elements for improved conformability.
However, the focus across these works remains primarily on engineering metrics such as actuation pressure, response speed, and array resolution. The shape outputs largely replicate conventional interface elements like pop-up buttons, sliders, icons, or VR feedback cues, staying close to established UI paradigms. While experimental work on internal pressure sensing has emerged, sensing remains underdeveloped and underexplored.

Actuation for Shape Change

A variety of actuation methods have been explored (Appendix G2) for shape-changing interfaces, each with tradeoffs in force, form factor, and integration. Mechanical systems such as motors and solenoids provide high force and fast response [8, 11, 7], but require bulky hardware and produce audible noise. Magnetically actuated arrays like PotMag [38] reduce wiring but



still rely on rigid infrastructure. Pneumatic systems are standard in soft robotics [22, 16], offering large, smooth deformation, but depend on compressors and valves, limiting compactness and adding operational noise. Hydraulic and fluidic systems [18, 21] can be compact but face challenges in sealing, leakage, and complexity. Microfluidic approaches [15, 37] allow dense, silent actuation in thin films but suffer from low force and fabrica- tion difficulties. Smart materials like dielectric elastomers and SMAs offer silent, thin actuation [26], but often lack speed, control, or robustness. Speaker-based systems such as HaptiCoil [35] provide compact, fast feedback but use rigid components and have limited displacement.

EOPs offer a distinct alternative: silent, thin, and soft actuation using fluid flow through porous membranes. They support multi-channel control, are easily integrated into deformable surfaces, and are well suited for distributed, expressive shape change.

Emerging Applications

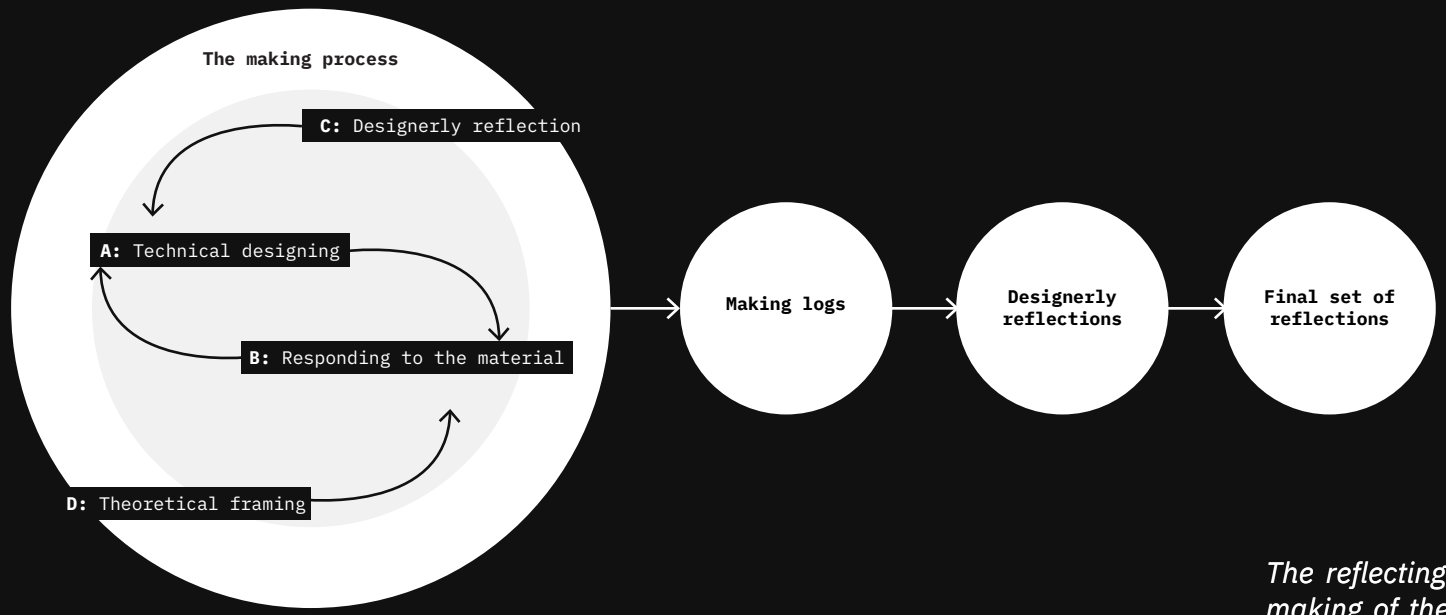
While soft interfaces mainly stay in research, Motorskins has demonstrated textile-based actuation for wearables and automotive interiors [20]. EOP applications show their promise for embedded, responsive systems. The Kjus HydroBot ski jacket uses EOPs to regulate moisture through soft textile layers [2]. Fluid Reality and explore gloves for VR feedback [28]. These examples remain early-stage, but suggest growing interest in these interfaces.

Actuation Method	Resolution	Integration	Scale	Force	Low Power	Speed	Low Noise	Manufacturability
Mechanical	+	o	++	++	- -	++	-	+
Pneumatics	o	-	+	+	-	+	- -	o
Fluidics	o	-	o	+	-	o	o	o
Microfluidics	+	++	-	-	+	+	++	-
Electroosmotic Pumps	++	++	o	o	++	+	++	- -
Dielectric	+	++	o	o	o	++	++	-
Shape Memory Alloys	o	+	+	+	-	-	++	o
Thermal-Responsive	o	+	o	- -	++	-	++	o
Moisture-Responsive	-	+	-	- -	++	- -	++	o
Magnetic	++	o	o	-	-	+	++	o
Speaker-Based	+	++	-	-	++	+	++	-

Method

This research adopts a Research-through-Design (RtD) approach, grounded in material exploration and iterative prototyping [39], and informed by Material-Driven Design (MDD) principles that foreground the expressive potential of emerging materials in shaping both form and interaction [12]. Through the lens of a designer embedded in material engineering within HCI [34], the project inves- tigates the expressive potential of electroosmotic pumps (EOPs) as actuators for shape-changing interfaces. Rather than evaluating a predetermined system, the research generates knowledge through designing, where making, reflection, and situated interaction are central to inquiry. The process began with hands-on fabrication of EOP actuators, adapting and extending methods from prior work [29, 36, 28].

This phase involved experimenting with electrode configurations, membrane architectures, gluing strategies, and transitioning from rigid to flexible circuit substrates. Each iteration was documented in a design logbook, inspired by Gaver et al.'s annotated portfolio approach [9]. The logbook served as a reflective tool to capture technical challenges, tactile responses, and emerging interaction qualities. Building on these material explorations, a sensing layer was integrated using custom pressure sensors to enable reciprocal interaction between user and interface. A control system, built around a high-voltage driver chip, supported coordinated actuation of up to 32 electrodes resulting in 16 pumps. Motion behaviors were refined manually through tactile feedback, investigating how timing, rhythm, and spatial variation influence the expressive quality of deformation. To situate the work within both applied and speculative domains, seven semi-structured interviews were conducted with experts from academia and industry, including representatives from **BMW Group, Disney Research, Motorskins, Car Design Research, Morphing Matter Lab, Materiability and Accenture.** Experts were selected for their expertise in designing or applying emerging physical interfaces. Interviews were recorded, transcribed, and analyzed using open coding and thematic analysis [3]. Key themes included: The soft advantage, from lab to market, applications. Reflections from all phases were synthesized to clarify the design potential and expressive range of EOP-based interaction systems. Together, these material, technical, and experiential design phases form a holistic inquiry into the potential of EOP-based systems. The resulting prototypes and interpretive insights constitute both the method and the contribution of this RtD process.



The reflecting process visualized, the left shows the actual making of the EOPS, which was analyzed in two steps. The whole process informas the final set of reflections

Making

The making process was captured in three phases. First, I kept handwritten fabrication logs using Gaver's annotated-portfolio method. Next, I added designer reflections in orange ink to those same pages. Finally, while drafting this report, I reviewed the logs a third time to integrate both the technical notes and the reflections.

Design-Process Framework

While developing the soft-EOP interface I saw four kinds of reflection taking place at once:

A. Technical Designing – scripting PCB layouts, drawing electrode shapes, planning the layer stack, exporting KiCad Gerbers.

B. Responding to the Material – fixing leaks, cracks, chemical stains or silicone deformation as they appeared.

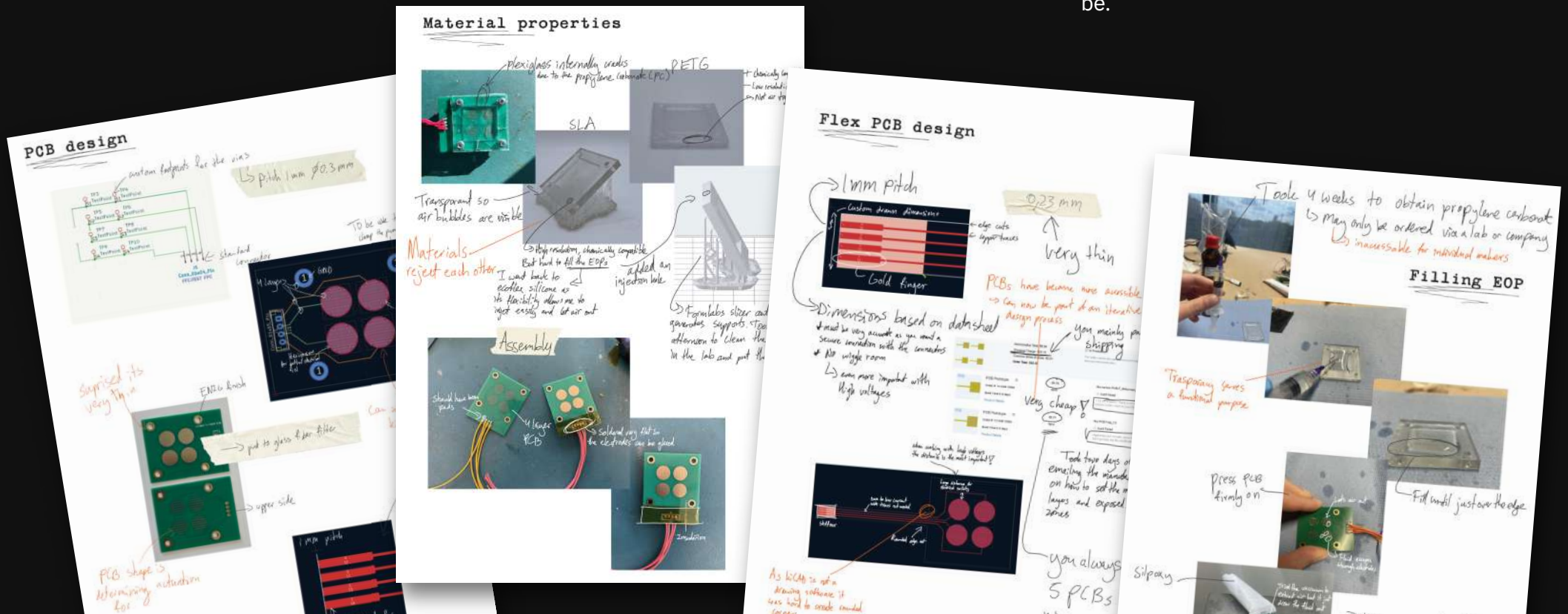
C. Designer Reflection – notes on the tension between design goals and engineering work, plus comments on material qualities, affordances and visual feel (written in orange).

D. Theoretical Framing – Points where theory helped me frame what was happening.

These four activities were not linear phases but part of a continuous, overlapping loop of reflection.

Replication EOP

I began by replicating an electro-osmotic pump (EOP) presented in the flat-panel-haptics literature [20]. Because the publications omit key fabrication details, Tiangyu Yu of FlexEOPs [28] was consulted on material selection, bonding protocols, and filling techniques. The reference design employed a rigid 0.6 mm FR-4 board with four circular electrode zones, 0.3 mm vias on a 1 mm pitch, and an ENIG finish. Procuring laboratory-grade propylene carbonate, glass-fibre filters, and a custom PCB took about six weeks, highlighting the limited accessibility and replicability of current EOP technology. I tested acrylic, PETG, and SLA-printed resin for the reservoir. Acrylic cracked on contact with propylene carbonate, while PETG was chemically stable but leaked. SLA resin offered high resolution and compatibility but was hard to fill without air pockets. Vacuum filling also removed the fluid. Despite these issues, one stack actuated successfully at 150 V and 1.2 mA, producing silent inflation. This actually felt magical like some invisible force moving. As this thesis aims to create fully soft integratable interfaces I went on to explore how thin, silent, and tactile this could be.



Towards soft interfaces

To make the interfaces thinner, more integrated, and capable of sensing, I created custom flex PCBs for both actuation and sensing, following the approach in [28]. This included designing flexible gold- finger connectors. For the top actuation layer, I used Ecoflex 30 mixed with carbon black pigment and cast it between acrylic sheets spaced 0.4–0.5 mm apart. This produced a consistent membrane, though thickness could still vary by up to 1 mm. Baby powder reduced surface stickiness. The softness allowed the full actuator body to respond visibly to electro-osmotic flow. Filling was also easier, air could be drawn out and the injection hole sealed with Silpoxy. This resulted in the first working actuator–sensor composite. To communicate the outcome and involve stakeholders, a video was produced (https://softinterfaces.com/EOP.html).

Controlling Movement

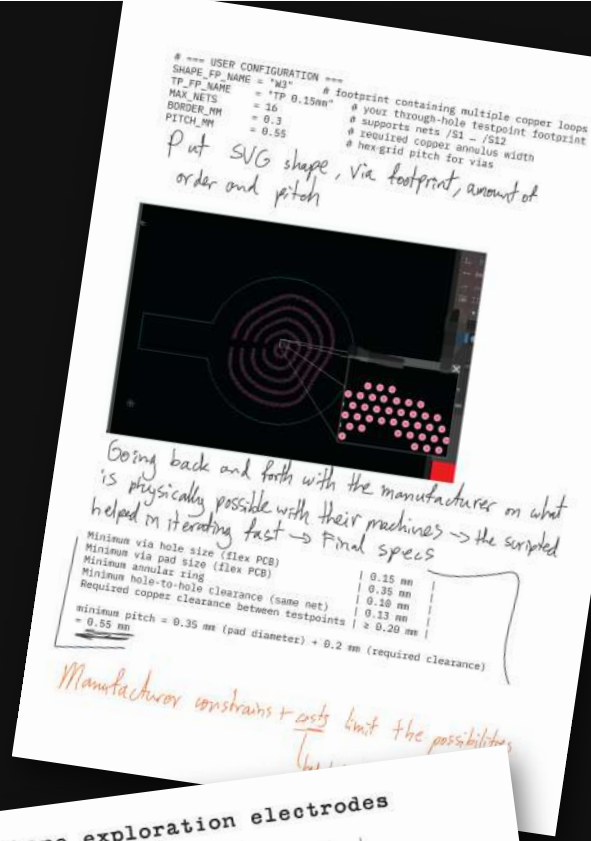
The first control setup used HV relays, a 12 V boost converter, and a microcontroller. While bulky and noisy, it allowed quick, low-fidelity prototyping with safe 200 V switching. Here I got the first change to control movement in my designs. I put on several different frequencies and acutated the four dots one by one to create patterns.

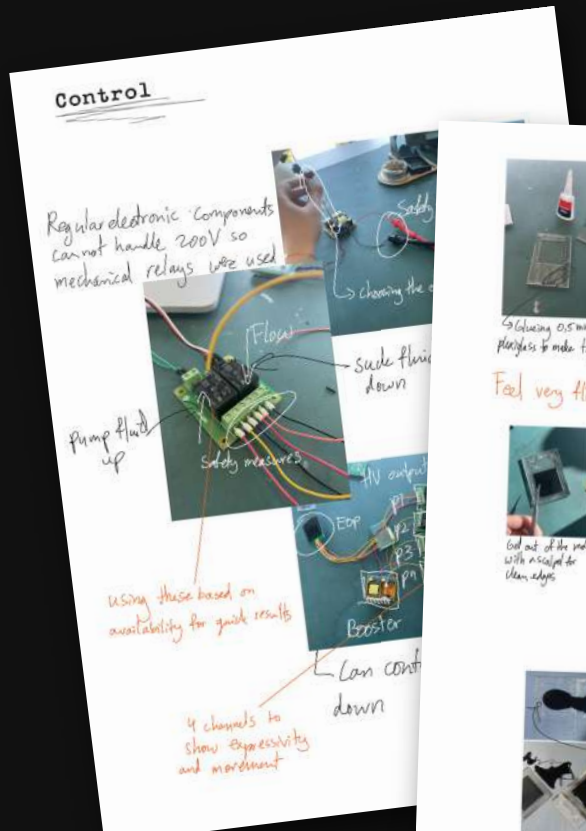
Form Exploration

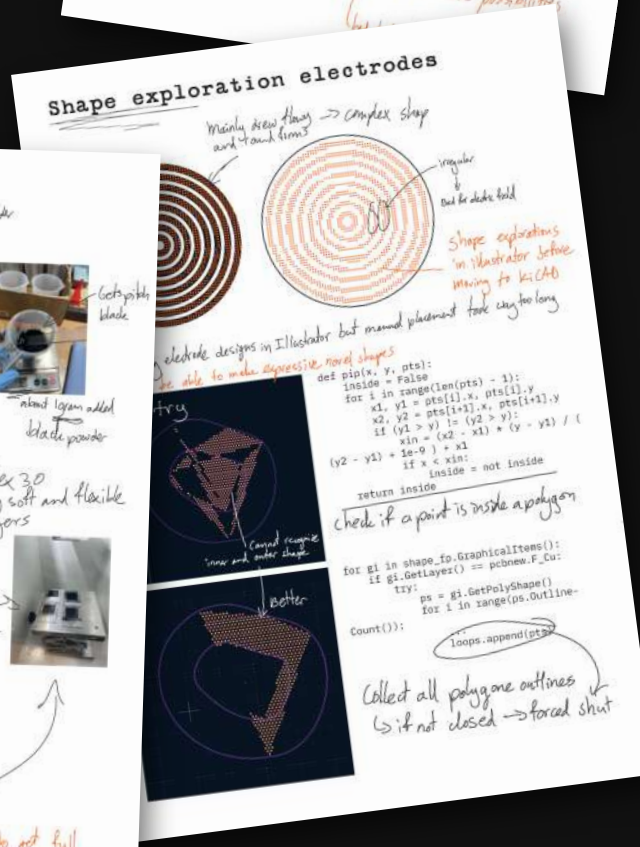
The electrode shape defines how the actuator deforms. I wanted to move beyond standard geometries like grids or rectangles toward forms that suggested motion or expression. I started drawing spirals and asymmetrical fields in Illustrator but quickly ran into limits; placing thousands of vias by hand was not feasible. To solve this, I wrote a Python script (shared on Github) that loads SVG shapes, places vias on a 0.55 mm hex grid, skips points closer than 0.3 mm to the edge, and as- signs net names (/S1–/S5). This allowed for complex electrodes with 2,500–4,000 vias while staying within manufacturer specs: 0.15 mm via holes, 0.35 mm pads, 0.2 mm clearance. Working closely with the fab, we pushed pitch and hole sizes to their limits for better flow. Five final electrode designs were made using more abstract organic shapes. Tiangyu Yu, who had previously used only simple shapes, now uses this script to generate more complex layouts. As a strong supporter of open source, I was glad to share it back with him.

Controls for Expressive Movement

To control expressive movement, I needed to drive many electrodes at high voltage. I chose the







HV507 chip, which supports up to 64 outputs, and used 32 channels to control 16 pumps. How- ever, documentation for high-voltage electronics was limited, making PCB design difficult. Through this process, I had to learn about decoupling capacitors, star grounding, ground planes, and other hardware practices. There was a constant tension: I wanted to focus on designing motion and shape change, but had to invest significant time in engineering just to make that possible. PCBs are designed with regards to safety as tehy use high voltage, more info in Appendix G4.

Fabrication

Layer stack and materials. The final electro-osmotic pump consists of the following layers:

1. Flex PCB – 0.11 mm
2. Glass-fibre filter Grade F 0.67mm thick
3. 3M 468 adhesive – 0.16 mm
4. Silicone reservoir wall – 1.0 mm
5. Ecoflex top membrane – 0.3–0.5 mm

The working fluid is propylene carbonate. Each pump holds approximately 10 mL when filled.

Gluing methods

Silpoxy is the only adhesive that bonds silicone, but it begins to cure after just 5 minutes. I tested multiple Gluing methods:

- Extruded top layer – Adding a ridge to the silicone for clearer lines.
- Squeeze bottle – inconsistent and prone to clogging
- Toothpick dabs – precise but hard to do within 5 minutes with complex shapes

Black pigmentation. Black SilcPig dye was added to Ecoflex to make the membrane opaque and highlight surface movement. Although the thin top layer still revealed some electrode detail: useful for debugging and visual feedback. But in a finished product, a fully black surface would be preferred to allow the interface to appear and disappear on demand.

Laser cutting

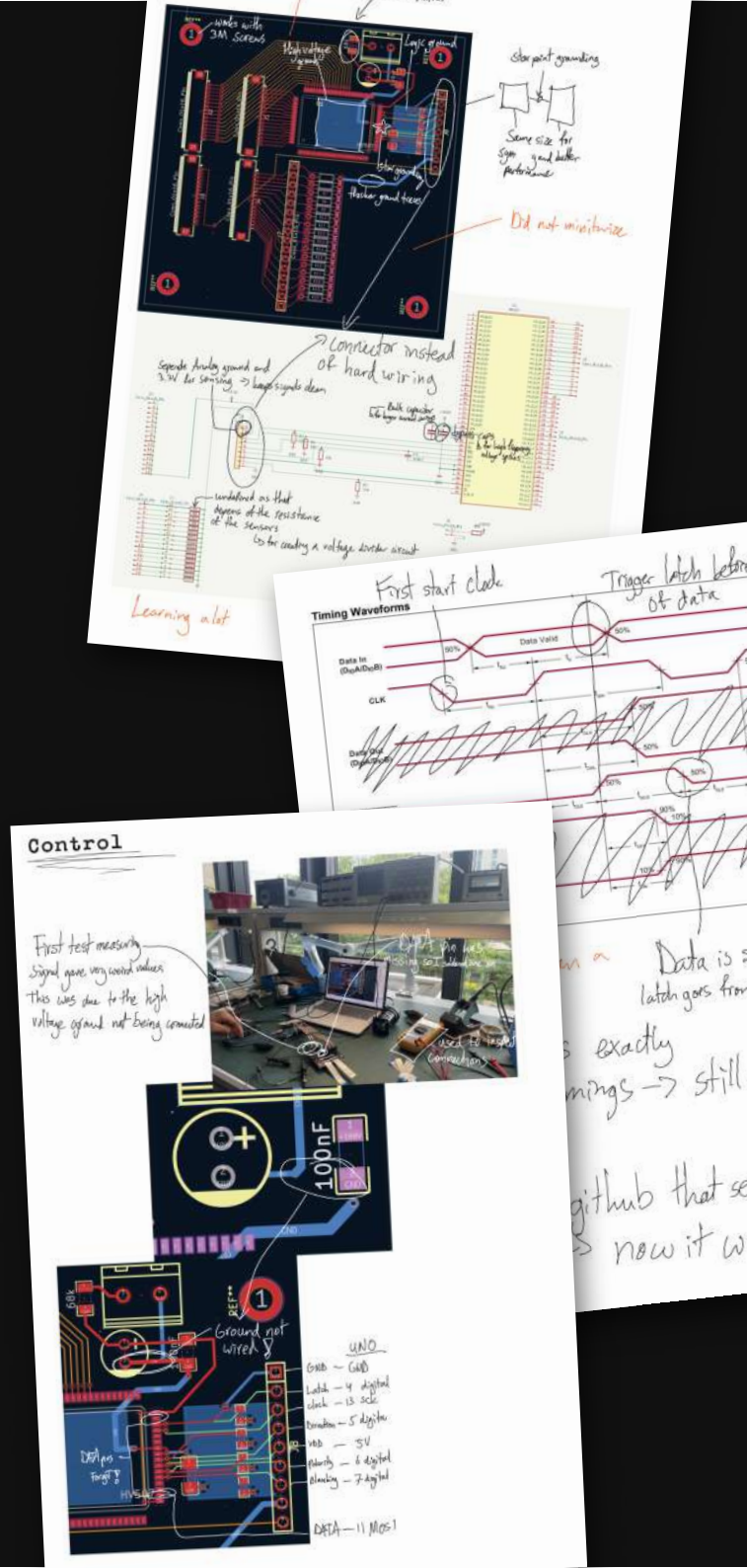
Glass-fiber filters are extremely fragile and were cut at low power with the ventilation turned off. They were handled with tweezers to avoid damage. All adhesive layers were also lasercut for precision.

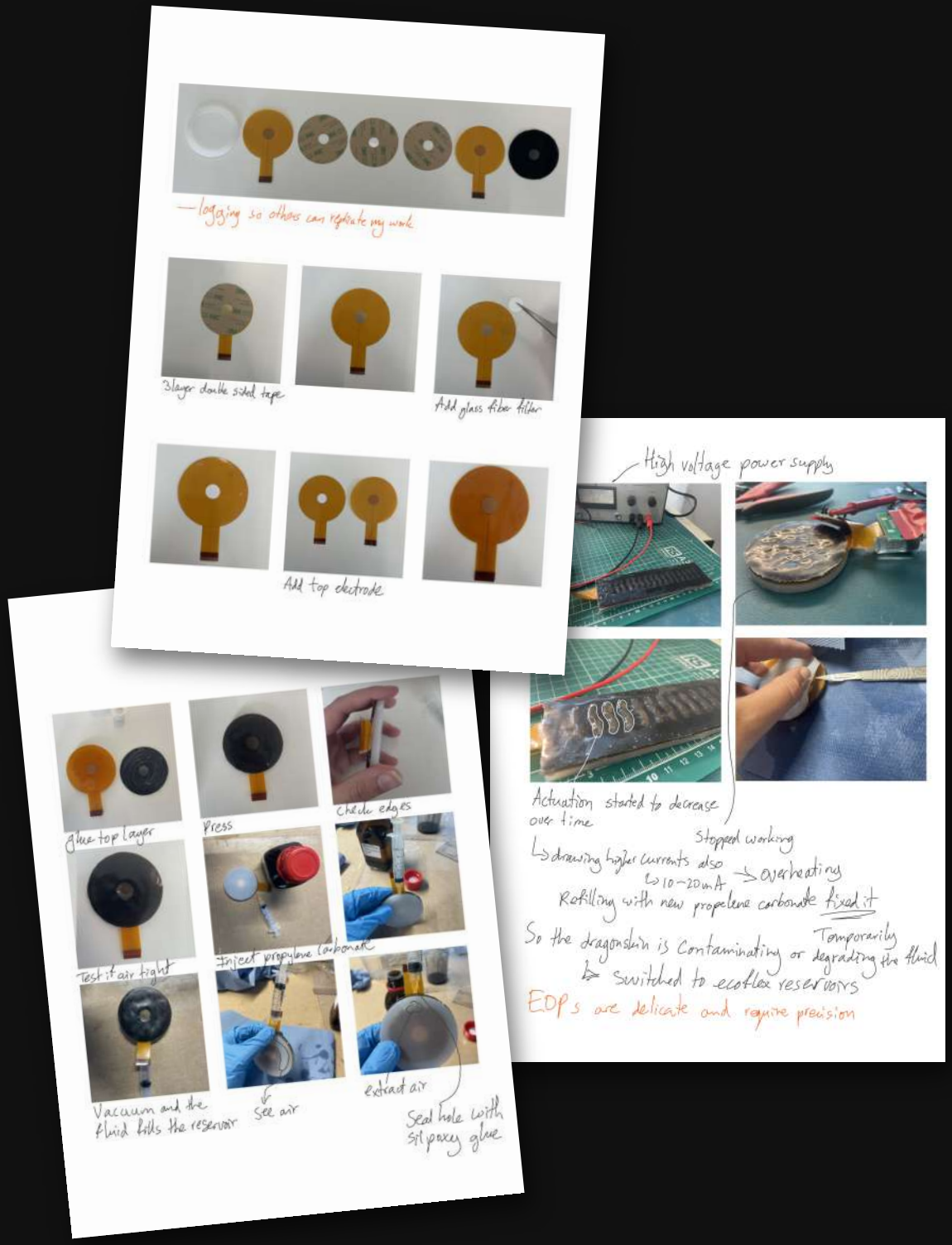
Debugging

Establishing communication with the HV507 was difficult due to limited documentation. I spent five days aligning timing diagrams resulting in a big time investment. The result is a high- fidelity control board capable of driving 16 pumps. It also created the opportunity to integrate sensing, making a fully responsive EOP system possible.

Fragility

Over time, the pumps became less efficient: actuation weakened and current draw rose to 10–20 mA, suggesting fluid degradation. Refilling with fresh propylene carbonate helped briefly, but the problem kept returning. Dragonskin silicone was the issue and contaminated the propylene carbonate. All pumps were reassembled using Ecoflex for the reservoir, which restored stability and efficiency. This shows how sensitive the EOP effect is. Small material choices had significant impact, and maintaining function depended on careful control at every layer.





Reflections

Making in this project meant navigating between design, engineering, and material practice. Designing custom PCBs became part of the iterative process, made possible by low-cost fabrication and fast shipping (2 weeks from China). This shifted electronics from something fixed that comes at the end of a design process to something iterative: a material that could evolve alongside the design.

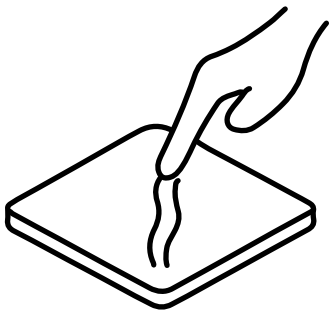
At the same time, building electro-osmotic systems remained slow, expensive, and fragile. Materials were difficult to source and often failed from small mistakes. This demanded careful iteration and shaped the way progress happened: through cautious testing.

Documenting the process was not just for tracking progress, but to support replication. Each material choice, failure point, and workaround was logged with the aim of making the process accessible to others.

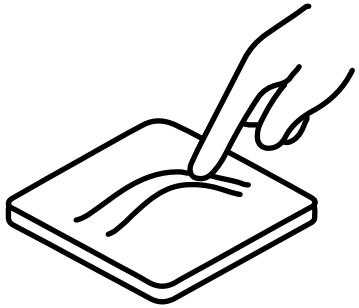
To create complex electrode layouts, I moved between drawing, scripting, and manufacturing constraints. KiCad wasn't designed for expressive forms, but scripting via placement opened up new spatial possibilities that linked shape to behavior. Electrode design became a way to design motion.

Throughout the making, there was a constant tension between wanting to focus on interaction and having to build the infrastructure to make it possible. Shifting between writing code, debugging hard- ware, and sealing silicone was part of the process. Making, in this context, was where form, function, and expression came together.

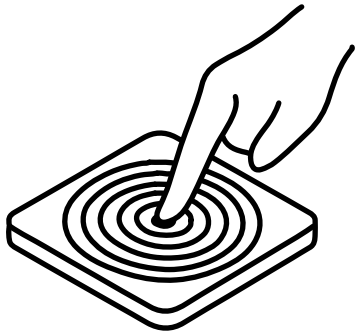
Midterm Interaction explorations



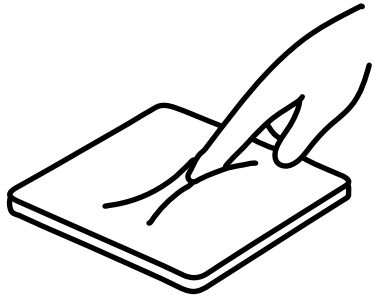
Guiding touch



Asking attention



Ripples



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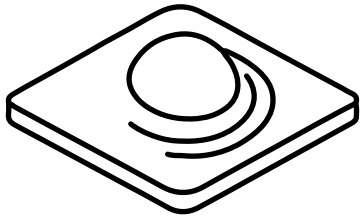
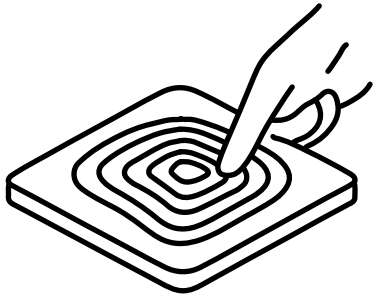
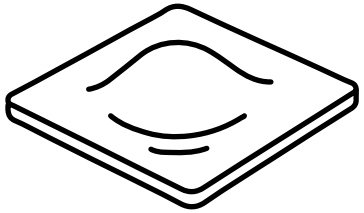


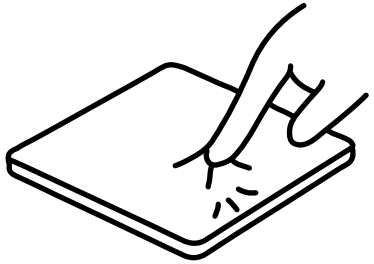
Moving



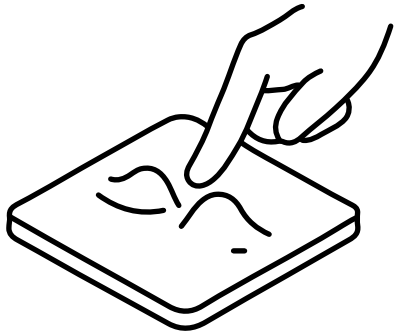
Fluid forms



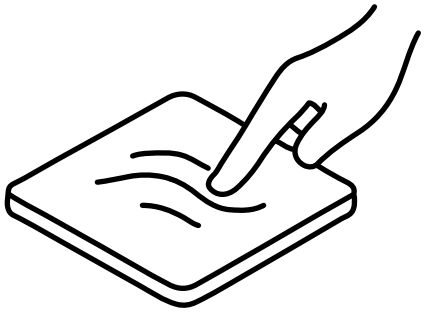
Slow swell



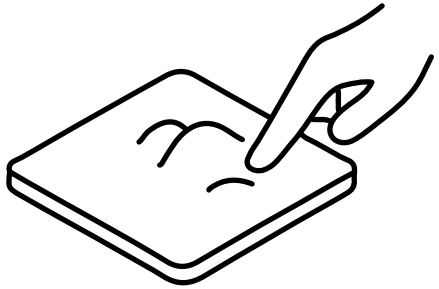
Pulsing



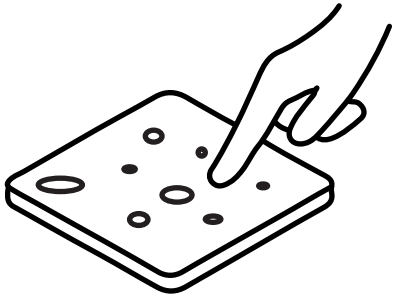
Pinch & release



Soothing



Force feedback



Excitement

Expert interviews

Accenture

Eric van Dorst is Design Director at Accenture Industry X and contributed strategic insight. Together with Wouter van der Woude and Geert Roumen: design engineers based in Eindhoven, their input focused on early-stage prototyping, making emerging materials like EOPs practically deployable across mobility, healthcare, and consumer tech.

Consumer market | Manufacturing | strategy

Materiability

Virginia Binsch is the Co-Director of the Materiability Research Group, which bridges material science and architecture through digital fabrication and responsive matter. Her perspective emphasizes emotional tactility and potential of emerging materials.

Emotional design | Soft robotics | Material science

Motorskins

Facundo Gutierrez is the co-founder and Managing Director of MotorSkins, a Berlin-based startup developing soft, textile-based actuation systems inspired by biological motion. With applications in both wearables and in-car interaction, Gutierrez advocates for distributed actuation that is silent, soft, and embedded directly into surfaces.

Soft robotics | Fluidics | Manufacturing

Morphing matter lab

Tiangyu yu is a PhD researcher at the Morphing Matter Lab (UC Berkeley), working on electro osmotic pumps. His work explores the intersection of programmable materials and interaction design, with a particular focus on haptics and flexible electronics.

EOPs | Flexible electronics

BMW

Mohsen Kaboli is a senior researcher in robotics and haptic interaction at BMW Group. His work explores how tactile feedback and sensor fusion can be applied to intelligent vehicles, particularly in enhancing comfort, safety, and telepresence inside future car interiors.

Automotive | Tactile sensing | Integration

Disney Research

Guirec Maloisel is a senior researcher at Disney Research Zürich, working on novel actuators, expressive materials, and character performance. His work centers on simulating and controlling movement into surfaces: especially in entertainment robotics and ambient environments.

Soft robotics | Control

Car Design Research

Sam livingstone is Director of Car Design Research, a UK-based consultancy advising major automotive manufacturers on design strategy, UX, and future mobility. He offers insights into trends, brand identity, and the evolving expectations around human-machine interfaces in automotive contexts.

Automotive | Trends | Manufacturing

Qualitative Analysis

To ground this work in real-world contexts, seven semi-structured interviews (Appendix D) were conducted with experts from Motorskins, BMW Group, Accenture Industry X, Disney Research, Car Design Research, Carnegie Mellon's Morphing Matter Lab, and the Materiability research group. The goal was to understand how electroosmotic pumps (EOPs) are perceived across different domains, and what constraints or opportunities they present for shape-changing, haptic, and embedded interfaces.

The transcripts (Appendix E) were analysed using an inductive, open coding process in NVivo [3]. In total, 18 distinct codes were created, covering topics like noise, interaction vocabulary, integration, Trends, and market potential. The coding was iterative: new labels were added as fresh concepts came up, rather than forcing data into earlier categories.
After coding, all excerpts were moved into Figma (Appendix F) for clustering and visual analysis. Codes that dealt with similar concerns were grouped and compared until broader patterns started to take shape. For example, haptic interaction, shape-change prototypes, and expressive movement were merged into the theme Shape-Change as Language.Through this process themes emerged:

(1) The Soft Advantage
(2) Control & Quiet Engineering
(3) From Lab to Market
(4) Shape-Change as Language
(5) Shy Tech
(6) Applications (Displayed visually)

Shape-Change as Language
One of the richest discussions across the interviews was the idea that shape-change, especially when made programmable through EOPs, could become a new channel of communication. Unlike traditional haptics, which rely on vibration or single-point cues, participants described how motion, timing, and direction could convey meaning in more subtle, embodied ways.
Sam Livingstone suggested that even a simple directional signal could feel radically different from current feedback styles:

"Maybe it has a directional pulse or something that moves in a certain direction to signal something specific. That alone gives it a completely different feel from existing haptic experiences."

Virginia Binsch pointed to the lack of existing conventions for interpreting haptic feedback:

"In color it's like this color stands for this this is not really there for sounds or haptics."

Together, these comments highlight the need for a richer interaction vocabulary for shape-changing interfaces. A leftward pulse might indicate turning; a slow bulge might suggest escalation. The meaning comes not from a single gesture, but from pattern and feel. Virginia's research into inflatable textiles supports this. She found that fast, twitchy pulses were often interpreted as urgent or annoying, while slow, symmetrical inflations felt calming or organic. These emotional differences emerged purely from shape change, no lights, sounds, or labels.

Later in his interview, Sam reflected on the expressive potential of motion itself:

"It's not just a single notification, it's the way it moves, the speed, the degree to which it notifies you. That gives you a set of maybe five, six types. Not infinite, but still rich."

The Soft Advantage
Softness was described by nearly all participants not simply as an aesthetic quality, but as a functional affordance. For automotive experts in particular, softness meant access: the ability to fit into irregular, high-curvature geometries without interfering with surface finishes or comfort. Facundo Gutierrez (Motorskins) described how his team was able to prototype a deformable interface inside a steering wheel for Lotus:

"They (the client) were first like, there's no way we can put anything in the steering wheel because there is just no technical space, and it's a double curvature surface and it needs to be super tight. And we could, because it's really soft and it will shape."

Tiangyu described it as the only viable option for on-skin feel:

"Also people find the haptic feedback nicer than motors or vibration. Not just noise, it's how it feels."

Experts highlighted the expressivity of soft motion, how slow deformations and shapes could suggest emotion or intent. Virginia Binsch described how soft inflations could evoke calm, anticipation, or even hesitation, depending on timing and geometry.Mohsen Kaboli (BMW) added another dimension, framing softness as a kind of embodied intelligence. In his view, materials that deform and respond to their environment aren't just more comfortable, they're also safer, more adaptive, and better suited to interaction.

Control and Quiet Engineering

This comment from Facundo Gutierrez (Motorskins) captures a common frustration: even large, well- resourced brands struggle to integrate soft actuation cleanly. Despite the appeal of softness, current systems often rely on bulky compressors and awkward workarounds: making them hard to scale beyond prototypes.

"But we're surprised to discover that some of the major and brands in Germany, we thought they'd have better parts. But what we found, when we opened it, sometimes they have like the same noisy pump you'll find online inside of a leather case with a lot of foam to try to make it silent."

For Motorskins, the way forward is smarter towards more embedded control. Rather than increasing hardware, they focus on reducing complexity. But even with embedded logic, limits remain. The team deliberately keeps systems simple:

"There is a fair amount of research that puts logic gates within the material itself... so to control more output with fewer pumps."

"We were keeping it relatively simple, so controlling no more than five circuits at the time."

This shows the tension between what soft robotics promises and what's feasible in practice. More channels mean more tubing, more failure points, and more bulk, especially hard to manage in wear-ables or vehicle interiors. Tiangyu from the Morping Matter lab noted that his EOPs struggled with reliability and safety:

"We do still have safety concerns. Mainly sharp objects are tricky, we only interact with it carefully in the lab."

Shy Tech

BMW describes "shy tech" as interaction that stays hidden until needed: technology that doesn't advertise itself, but appears when context calls for it. Mohsen Kaboli explained:

"You don't see it, because in BMW it's called shy tech. You don't see the technology, but we call it function-on-demand. If you need it, then it comes, it pops up."

This concept of invisibility can enhance aesthetics. BMW described how haptic interfaces can integrate into surfaces without disrupting form. By embedding functionality and sensing into soft surfaces, the interface becomes ambient and context- aware. There are no buttons or lights until interaction is initiated. This makes haptics uniquely suited for environments where space is limited and distraction is costly, such as in vehicles.

Several experts connected this to a desire for private communication in shared spaces. Sam Livingstone described how subtle haptic cues could deliver selective signals:

"Because what you've actually got there is also a very private kind of notification. If you've got multiple users in the car, this could be a signal or message that only one person is aware of."

Rather than demanding attention, shy tech remains in the background, surfacing only when needed, and only for those it's meant to reach.

From Lab to Market

Across interviews, experts shared a vision of where interaction is headed within their domains: away from screens and voice control toward more ambient, embedded forms of feedback. BMW explained:

"Actually, now the new ones (cars) don't have any screen anymore. Screen is old."

While these changes are still emerging, many saw integrated haptics as a potential way to move beyond screens without increasing cognitive load or visual clutter. Silent, embedded feedback was seen as a natural evolution. However, Sam Livingstone cautioned against designing only to match current trends:

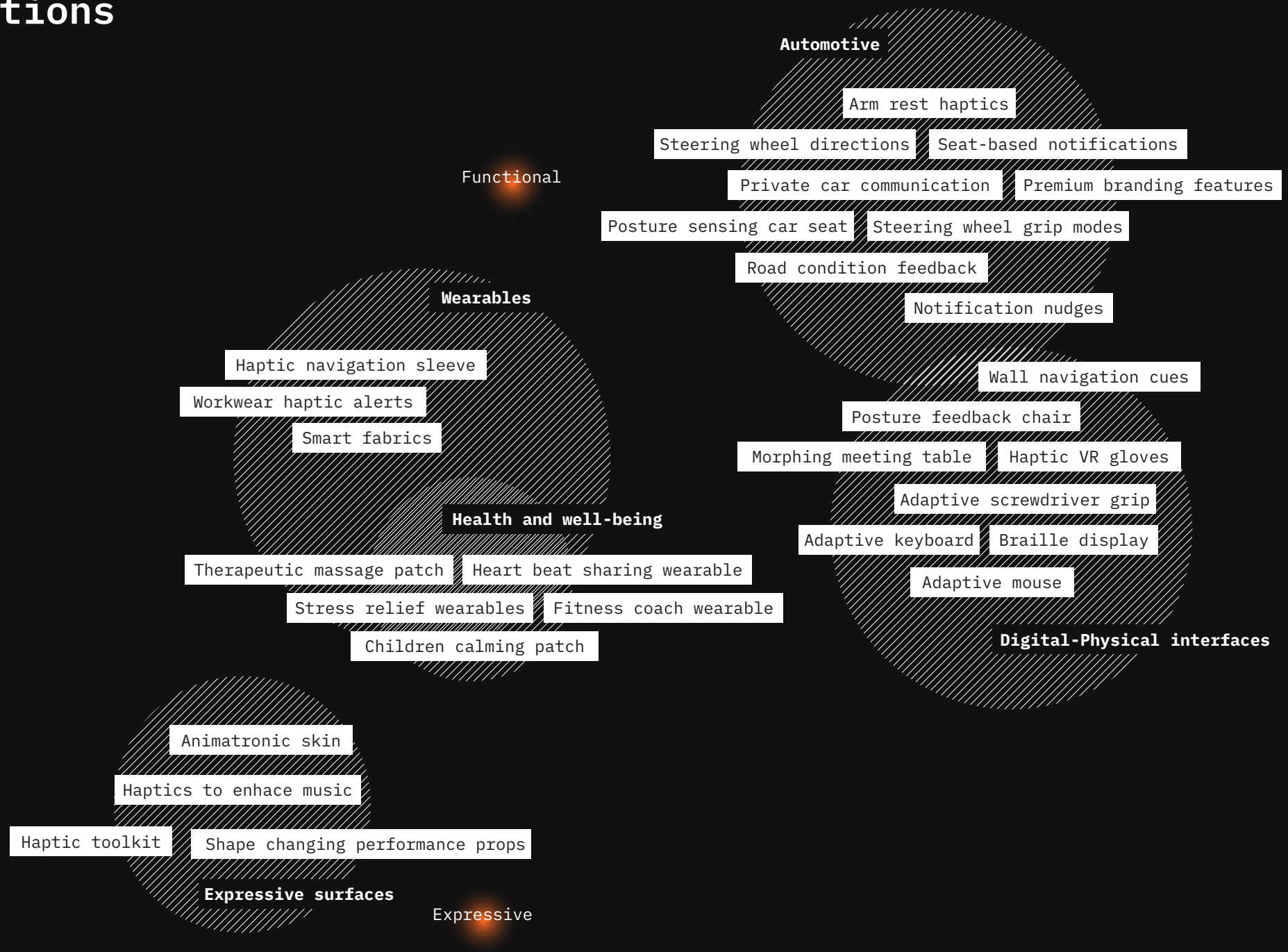
"To some degree, I don't think you should only be looking to establish whether what you've got might align or fit with trends when it's potentially something which is innovating or pioneering, and therefore in a position to potentially affect changes and trends."

That said, translating soft interaction into market-ready products comes with clear hurdles: especially around manufacturing, cost, and scale. Automotive, even in the luxury segment, remains extremely cost-sensitive. A technology may be elegant and promising, but if it adds weight or expense without a clearly felt benefit, it risks being sidelined:

"Even if you're in the luxury segment, it's very tight and very competitive. They try to save a lot."

Several experts suggested starting with niche applications where the value of soft, expressive haptics is more immediately visible. These might include healthcare, high-end consumer tech, or in-car experiences. From there, building toward scalable production would require engaging suppliers early and designing for manufacturability.

Applications



Navigation wearable: A wearable gives directional tactile cues (e.g. turn left/right) via shape change on the shoulders.

Music Enhancer: A wearable device provides subtle tactile feedback that sync with the music, enhancing the auditory experience and adding a physical dimension to the sound.

Calming wearable: Consistent haptic breathing feedback helps regulate anxiety or stress

Adaptive screwdriver: Shape-changing grip gives feedback or guides usage in complex repair tasks.

Animatronic skin: Soft animatronic skin that adds extra motion making it feel more lifelike and emotionally expressive during interaction.

Navigation wearable: Deformable surface presents braille for visually impaired users..

Arm rest signals: Private interaction in car interiors. A gentle shape change can signal turns, posture shifts, or guide the driver quietly.

Haptic VR gloves: Soft haptic gloves provide tactile feedback for virtual environments or games.

Adaptive grip: Wheel grip morphs when switching between driving modes (comfort/sport).

** AI generated images - find prompts here:*
https://chatgpt.com/share/685dba9e-a390-8000-a281-6c8aeee46210

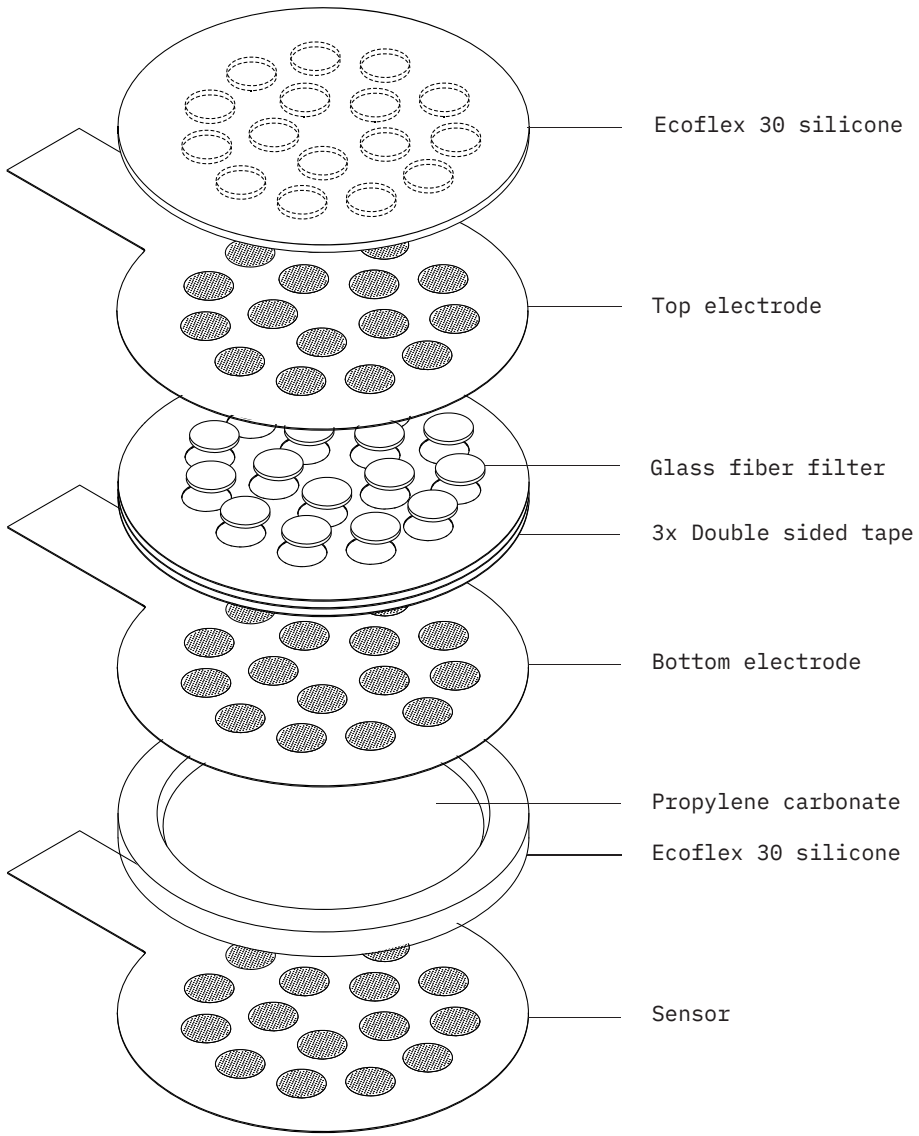
Electrodes close-ups

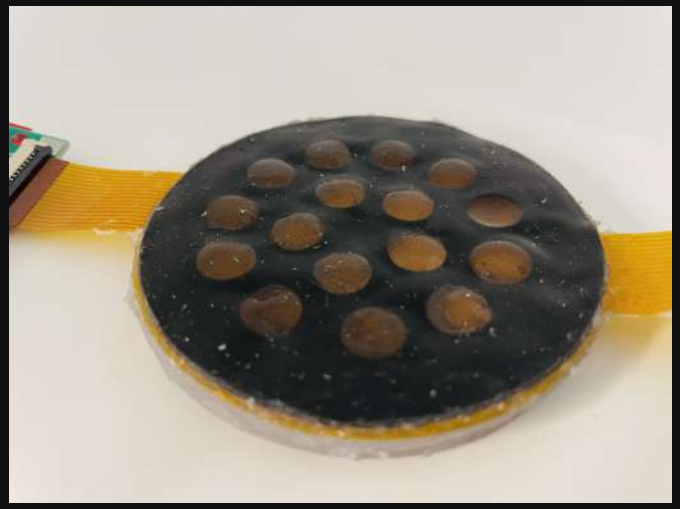
Final design

The final EOPs consist of several layers. The top and bottom layers are made of Ecoflex 30, chosen for its flexibility and chemical compatibility with the working fluid, Propylene Carbonate. This fluid is injected via a syringe. When a positive voltage is applied to the bottom electrode, the fluid flows upward toward the top actuation layer, inflating the dots. Reversing the polarity causes the fluid to return to the reservoir, creating visible indents in the interface. A glass fiber filter is used to enable the EOPs to function effectively. Sil-Poxy glue is used to bond the silicone to the flexPCBs. Double-sided TPE is used to build the pump without adding bulk.

These interfaces operate at approximately 100V and 2–3 mA, resulting in low power consumption. They are about 6 mm thick and fully flexible. A custom pressure sensor is placed underneath. The EOPs are controlled using the HV507 chip, which can drive up to 32 electrodes, allowing individual control of 16 pumps. This setup enables expressive shape change at higher resolutions. A voltage booster is used to generate the required high voltage and an Arduino UNO is used to control the system, chosen for its 5V switching compatibility.

Electro Osmotic Pump (EOP)



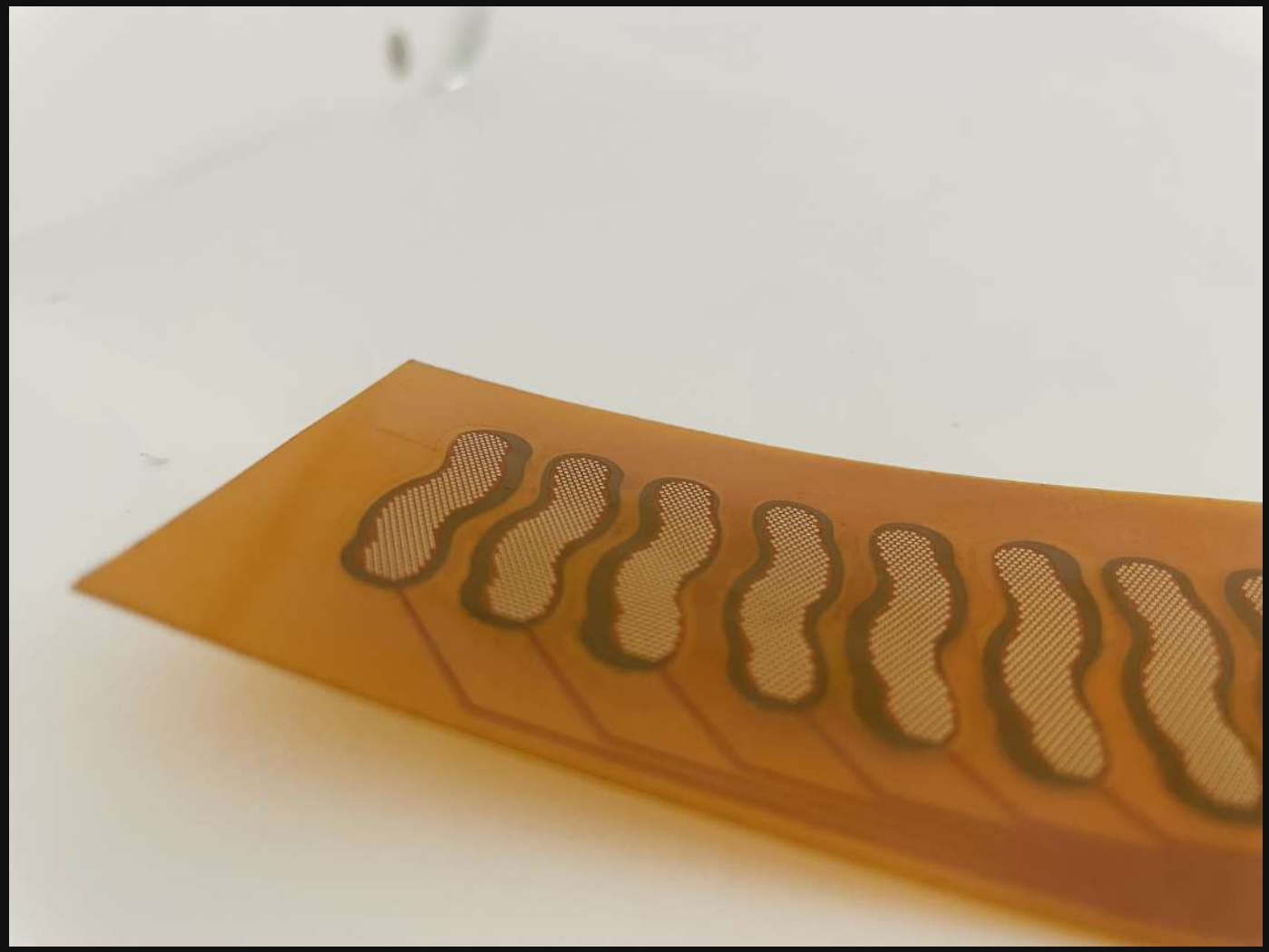


Actuation

Applying 70 Volts 2mA over the electrodes allows the top surface to deform. By switching the polarity of the electrodes we can reverse the shape change.

Sensing

Custom pressure sensors are made to support reciprocal interaction. Below you can see the black velostat through the electrode. The sensors can sense multitouch and pressure sensing through the EOPs.

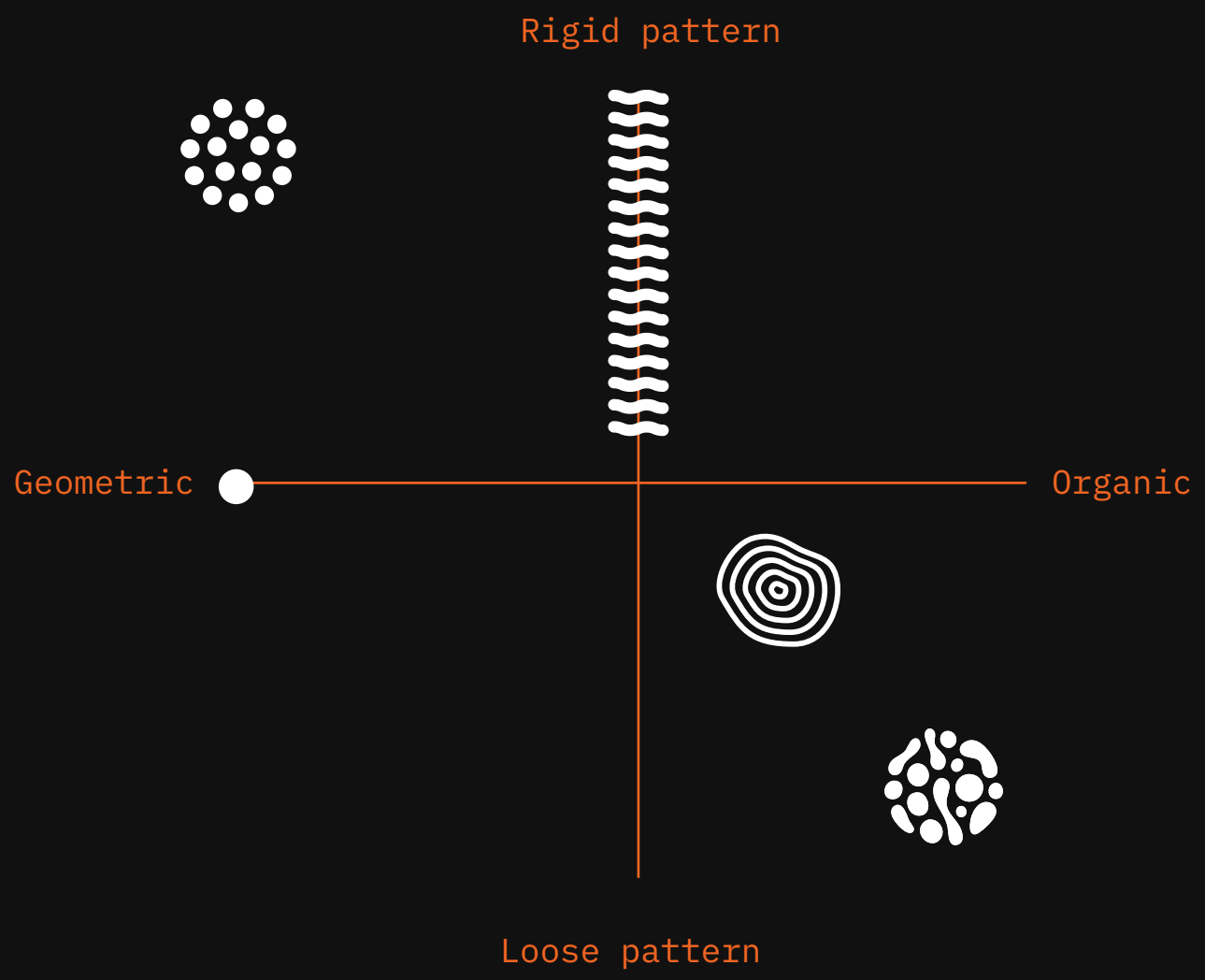


Final electrode designs

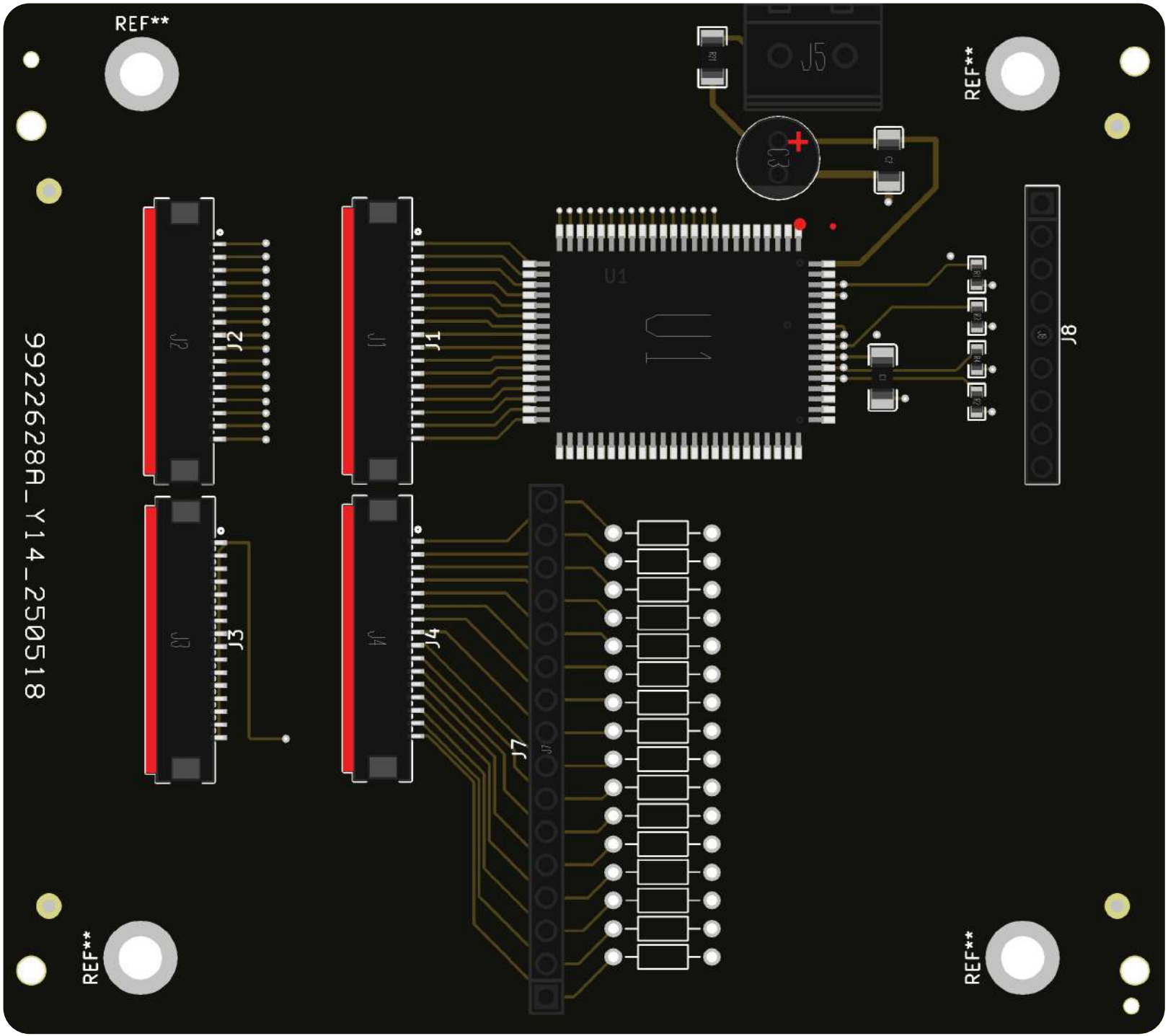
Electrode shapes

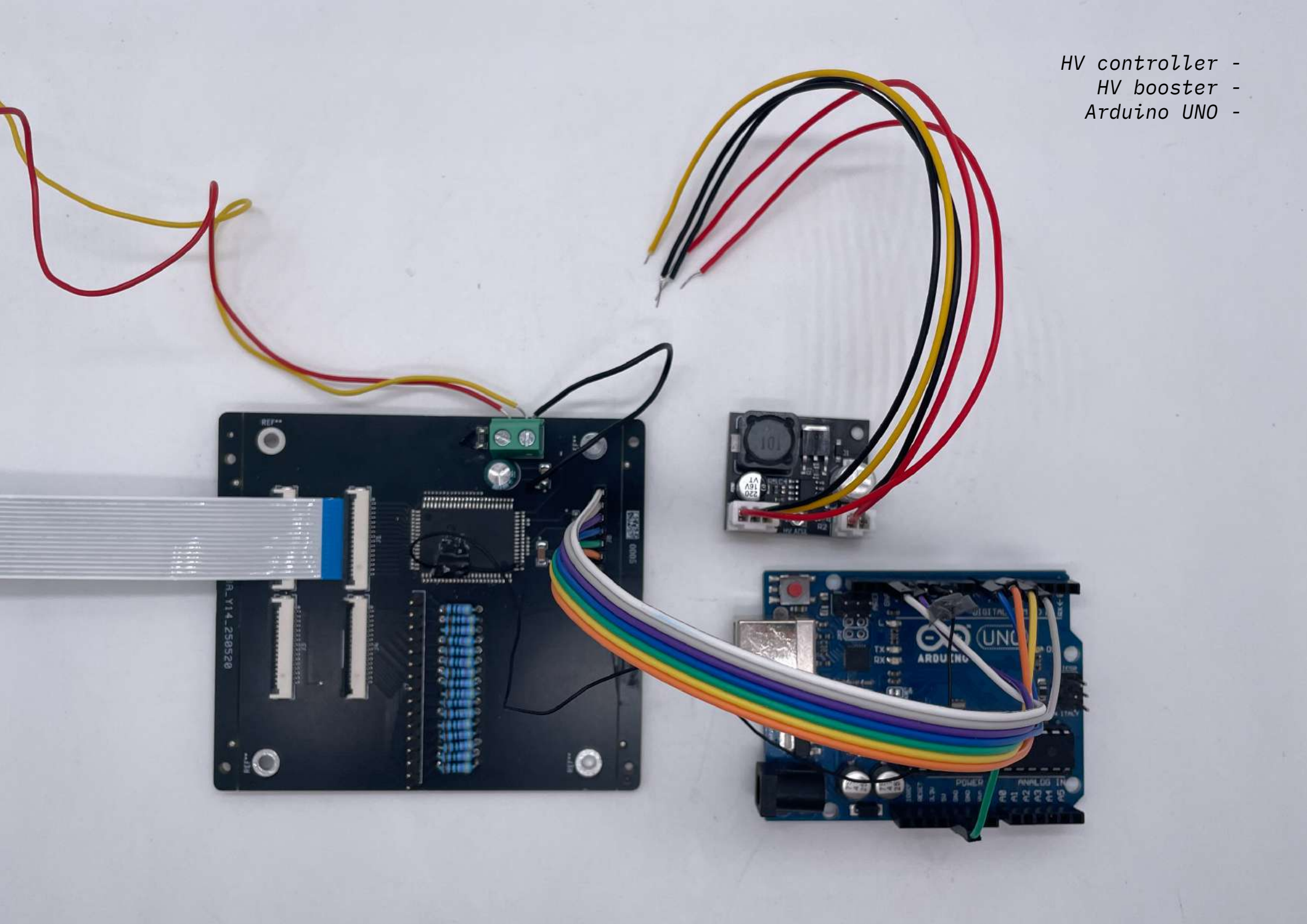
The shapes used in this soft interface were intentionally selected based on user-centered findings from Brocker et al.'s [40] study on soft robotic design. Their research showed that users strongly associate certain forms and motion types with familiar objects, emotional cues, or affordances. For example, more organic and loose shapes often reminded users of marine life or soft materials, and were seen as comforting, gentle, or expressive. Thus, ideal for wearable, therapeutic, or emotionally responsive interfaces. On the other end, geometric and rigid forms were linked to tools, mechanical parts, or predictable actions, making them better suited for structured, controlled interactions. Placing shapes across these two axes (geometric to organic, rigid to loose grid) allowed us to cover a wide spectrum of user expectations and interpretations. Abstract shapeswere chosen so the movement mainly dictates the meaning of the shape change.

This approach is also supported by the paper's core design insights. Simpler, more abstract forms with recognizable motion patterns were seen as more intuitive, while overly detailed or ambiguous shapes were less effective. By using this variety, we can cover a wide range of expressive shape change.



Custom HV controller




HV controller -
HV booster -
Arduino UNO -

Discussion

Shape-Change as Language
This thesis set out to explore how electroosmotic pumps (EOPs), typically grounded in engineering contexts, could be reimagined for expressive, reciprocal interaction. Using a Research-through-Design approach, EOPs were not merely validated as actuators but embedded within materially integrated interfaces—highlighting how design can shape both technical function and experiential quality.

The results show that EOPs offer distinct advantages for soft interface design: silent operation, compact form, and high-resolution control. Yet, their practical use remains limited by fabrication complexity, material sensitivity, and fragility. This reveals a key tension: while EOPs enable nuanced, embodied interaction, they require a deep technical understanding to realize that potential. Here, the designer's role becomes central: not just to refine aesthetics or usability, but to actively translate technical systems into responsive, tactile expressions.

Building the pumps from scratch demanded significant engineering fluency. Hardware design, material sourcing, and high-voltage electronics became core parts of the design process. This shift emphasizes that designing with emerging technologies often means engaging with the infrastructure itself, not just outcomes, but the controls that make interaction possible.

A core contribution of this work is the realization of a sensing–actuation composite: a system where deformation and feedback occur within the same material structure. This integration allows for real-time, reciprocal interaction: opening space for shape-change to function as a subtle language, where motion, rhythm, and form convey meaning.

While formal user testing was beyond scope, expert interviews across automotive, soft robotics, and entertainment sectors confirmed the growing interest in soft, embedded interfaces. Participants described a future in which shape-change could complement or even replace conventional outputs, especially in environments where screens, buttons, or audio cues are intrusive. They emphasized softness not only as a tactile quality but as a way to more intuitive, ambient interaction.

By documenting my making and sharing all code via GitHub, the work invites others to replicate and build upon it.

Future work
While the system successfully supports independent control of 16 pumps, its expressive potential remains underexplored. Future work should investigate how movement across surfaces can be choreographed to evoke specific meanings or emotions. Workshops or participatory studies could also provide insight into how people interpret and engage with these motion-based cues. Workshop set up can be found in Appendix G3.

On a technical level, improving reliability is a critical next step. The pumps remain sensitive to fluid degradation, contamination, and material inconsistencies. Long-term testing and environmental stress would help identify failure points and inform design for durability.

Power requirements remain a key limitation. Although EOPs operate at lower voltages than many electrohydraulic systems, the current 150V range still imposes strict safety and hardware constraints. Future research should aim to reduce the required driving voltage below 50 . I have had one that worked on 70V showing it should be possible. Promising strategies include modifying membrane surface properties, optimizing fluid-channel geometry, or decreasing electrode spacing to maintain effective electric field strength with lower applied voltage.

Outlook
BMW has asked me to continue the development of EOPs, exploring ways to integrate actuation into their advanced soft sensors. They have also proposed the possibility of patenting this technology and invited me to consider continuing my work at their lab. Sam Livingstone has offered to connect me with manufacturers and suppliers, should I decide to move forward with production. Furthermore, he invited me to showcase the project at the Munich car show. Virginia Binsch suggested the idea of hosting a workshop to allow designers to experience the material firsthand. These opportunities reflect the potential directions this project could take.

Conclusion

This thesis explored electroosmotic pumps (EOPs) as a new approach to soft, materially embedded interfaces. By building custom EOPs and integrating sensing and actuation into a unified composite, it demonstrates how these technologies can support subtle, reciprocal interactions. A designerly fabrication workflow was developed to navigate the technical and material challenges, offering practical insights for others working at this intersection.

Expert interviews provided real-world perspectives from automotive, wearable, and interactive product domains. While the prototypes remain early-stage, the conversations affirmed interest in soft, silent, and integrated forms of feedback. Rather than presenting a finished solution, this work shows how designers can meaningfully engage with emerging technologies, not just by imagining future applications, but by shaping them through hands-on experimentation and reflection.

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Appendix

A. Reflection
B. Links
    1. Video
    2. Github (code and PCBs)
C. Making logs
D. Interview questions
E. Interview transcripts
F. Qualitative analysis
G.
    1. EOP explained
    2. SCI actuation benchmark
    3. Workshop
    4. Safety
H. Consent form & ERB

Appendix A

Reflection

eflectionI have a clear vision around soft interfaces and wanted to take a step closer to realizing that future. Looking back, I did make that step.

One of my goals was to learn how to create electronics that aren't just working in a demo but robust and safe enough for real use. I'd been designing soft interfaces for a while, using Eagle and hand-soldered circuits, but they often broke, like in my VENTI M1.2 project, where the wires came loose so often I lost count. I wanted to move beyond that and make something that could survive outside a lab or exhibition space.

That led me to custom PCB design, high-voltage systems, and working in KiCad. I had to learn about custom footprints, clearances, and safety standards, things I never really had to think about before. Because D.search didn't have much experience with high voltage either, I had to figure out a lot on my own. Thankfully, I could rely on Geert van den Boomen and Lou Feijs for guidance. It allowed me to develop my engineering skills.

In the end, I do feel that creating these EOPs in three months was too ambitious, leading to results that are not as refined as I had hoped. There was almost no fabrication documentation, and most papers left out important details. I contacted several authors, and only Tiangyu Yu responded, but that one conversation gave me enough confidence to try. Getting the materials took six weeks, which meant I had one shot at making it work. Luckily, the first design functioned. From there, I improved it and integrated it into a system. I was constantly torn between focusing on getting the electronics to work and pivoting to start mimicking the motions I wanted to create. For weeks, I felt more like an engineer than a designer. This allowed me to grow but also caused a lack of me as a designer in this thesis. It's sad that I didn't have time to explore the expressive potential of the EOPs or run a workshop on interactions.

Amy's advice to "build your brand" stuck with me. I ended up buying softinterfaces.com and using it to document and share my projects. It's not just a portfolio. It's a space for positioning, reflection, and outreach. During this project, it helped a lot. I didn't have time to publish formally, but the website gave me a way to share the work, and that felt right. I often like to help students with their projects and want to inspire others about the possibilities of soft robotics. The website also helped in contacting experts. Normally, I'd wait until a project felt finished before reaching out. This time, I shared a short video at midterm, posted it on the site, and contacted people directly. It worked. Almost everyone said yes. I had conversations with BMW, Accenture (previously VanBerlo), Disney Research, Motorskins, TNO, and Materiability. Some even offered jobs or potential collaborations.

That reminded me I don't have to wait until everything's perfect. Sharing early helped me reflect on the work, see it through others' eyes, and get meaningful feedback while I was still making. That gave me more confidence and helped sharpen the project's direction.

Designer vs Engineer
One of the biggest struggles in this thesis was trying to balance doing and thinking. There's a constant tension between being hands-on and having time to step back and consider meaning or impact. I spent weeks sourcing materials, fixing circuits, documenting, and positioning, and sometimes I wondered: is this still design? Or am I just trying to keep things from breaking?

At times I felt more like an engineer than a designer. I didn't always have the space to explore the interaction side as deeply as I'd hoped. That's something I want to do differently next time, to create space for user experience, expression, and interpretation, not just technical functionality. Because in the end, that's what drew me to design in the first place.

This project made me rethink the kind of designer I want to be. I want to keep bridging engineering with design. I believe this crossover is powerful and leads to innovation. I want to keep inspiring others, whether through documentation, seminars, exhibitions, or hands-on collaborations. I see myself continuing in design engineer roles in innovative contexts like the BMW interaction group or innovation at Accenture.

Appendix B

Links

www.softinterfaces.com

https://github.com/Tessavana/Soft-interfaces-files.git

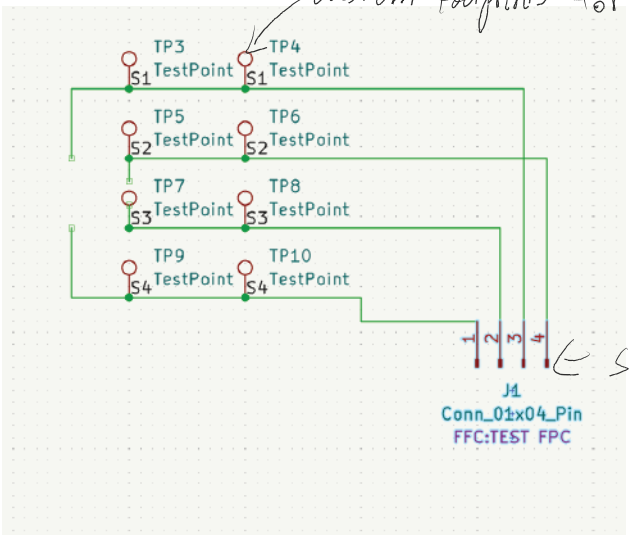
Appendix C

Making logs

PCB design

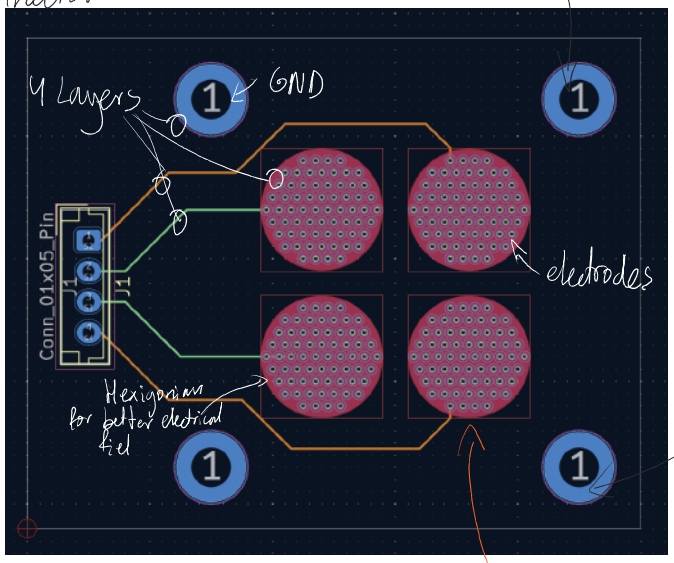
custom footprints for the vias

↳ pitch 1mm ⌀0.3mm



standard connector

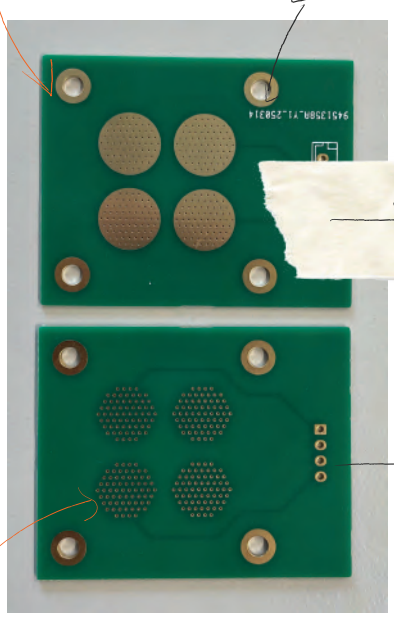
To be able to clamp the pump



Can we automate? KiCAD API?

Suprised its very thin

ENIG finish

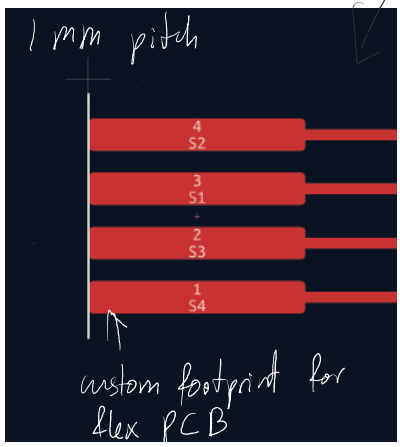


→ put to glass fiber filter

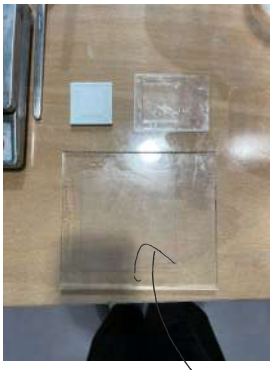
→ upper side

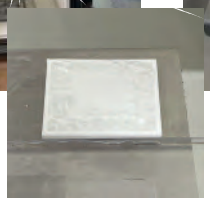
PCB shape is determining actuation for

flex can only be 2 Layers



custom footprint for flex PCB

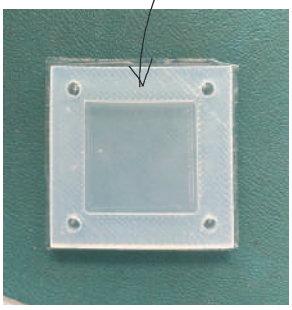


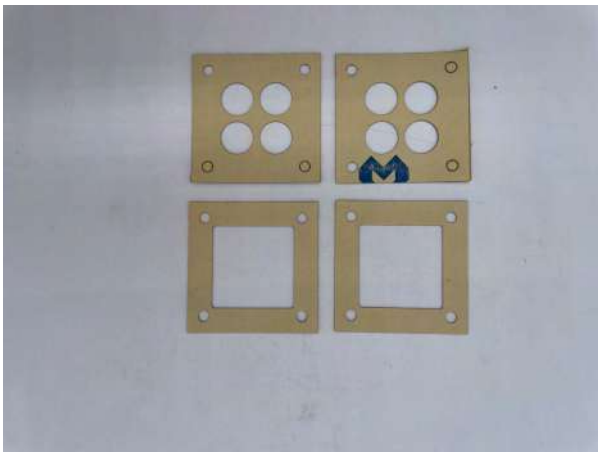


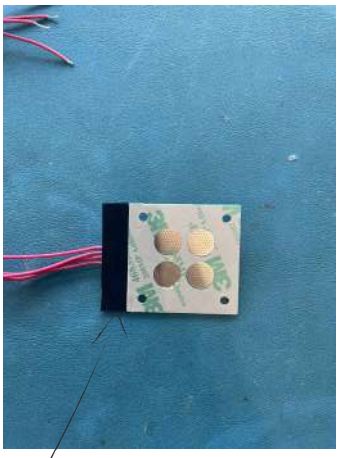
Thicker materials
more air bubbles

0,2 mm
↓
Too thin

Silicone reservoir



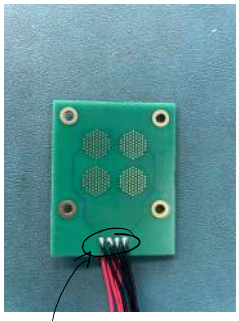


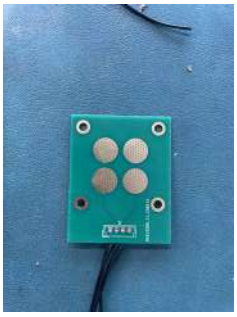


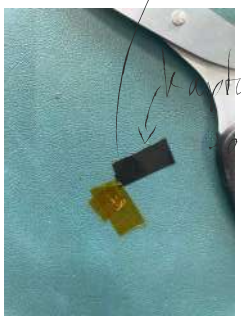
Laser cut

used tweezers

tape as adhesive & spacer

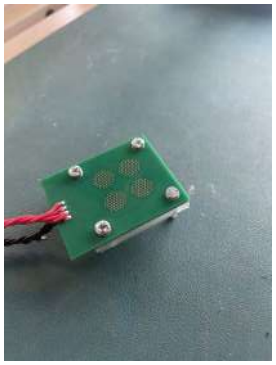




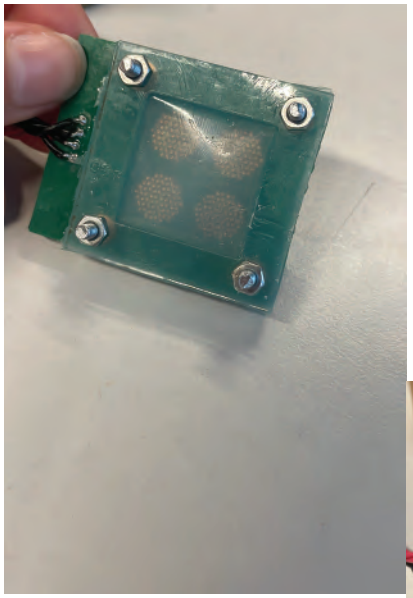


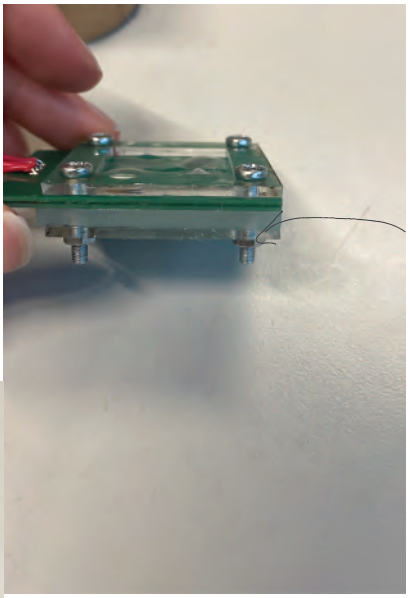
cotton and insulating tape
to put between the two PCBs

GND and V very
close to each other
→ use pads
for PCB 2

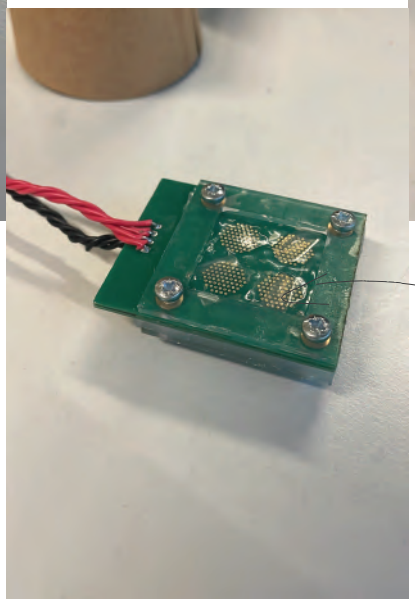


Version 1

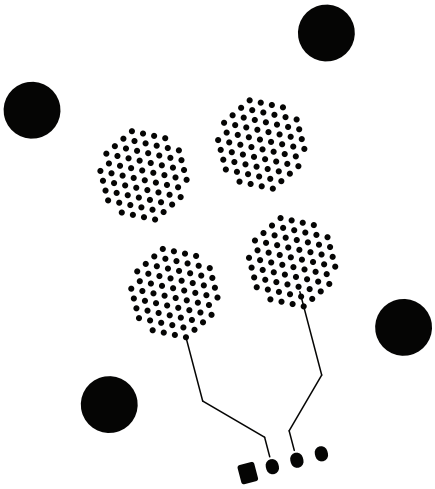


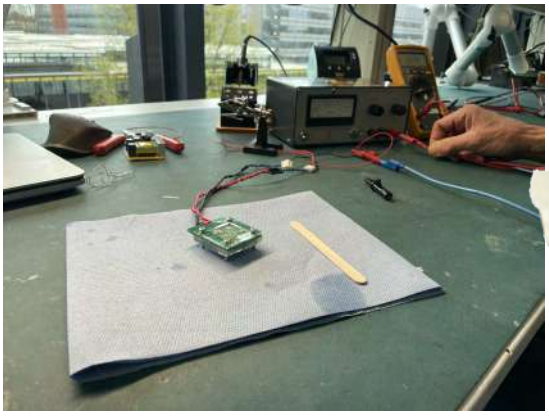


clamping adds height

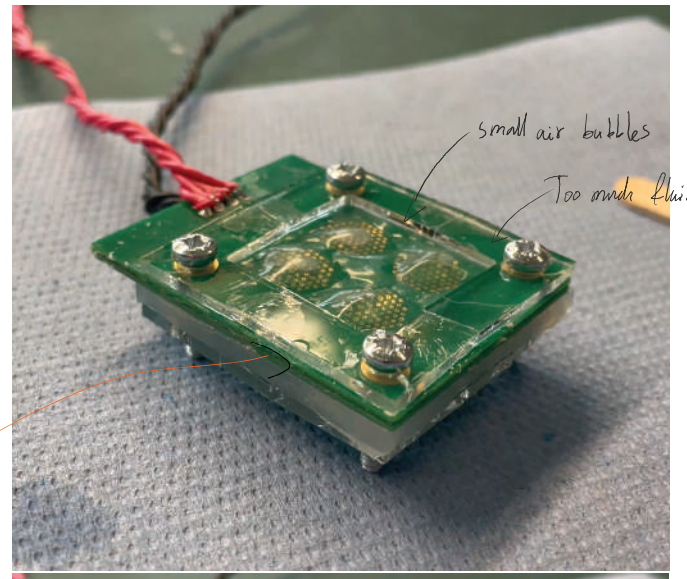


filled up too much

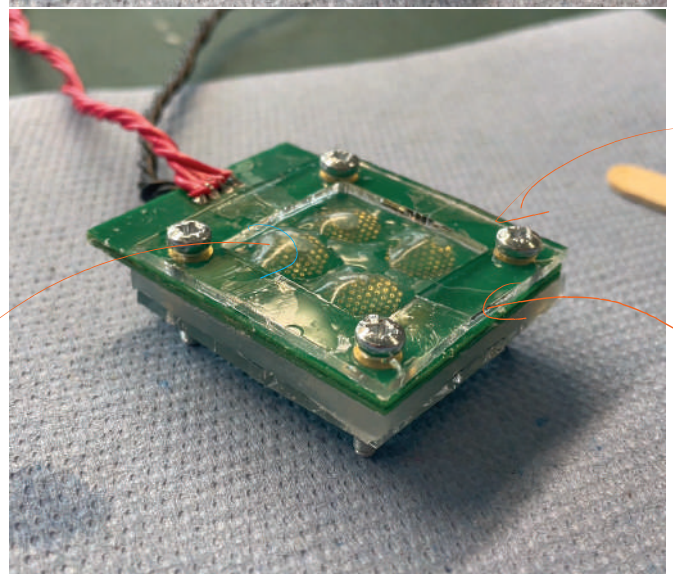




150 V
1.2 mA
↓
180 mW



Some Leaking

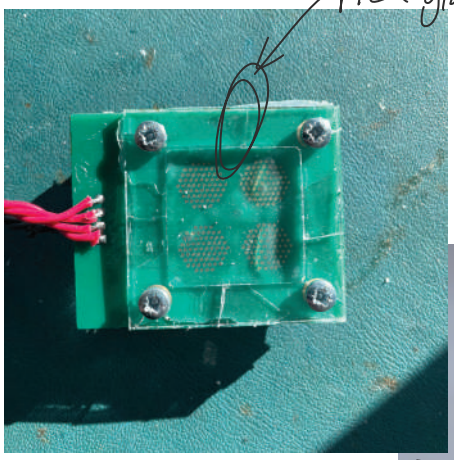


Relatively quick

Satisfaction

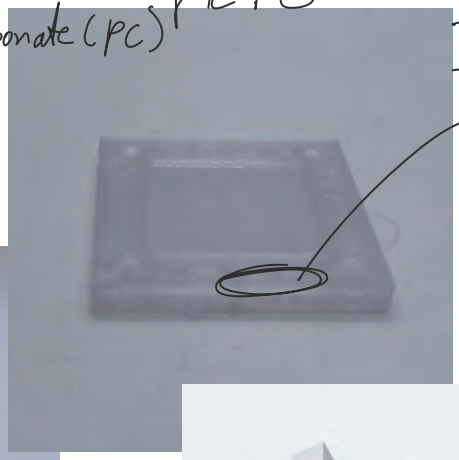
no noise or heat

Material properties



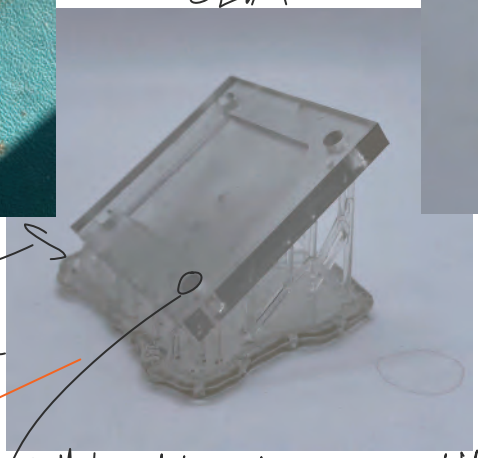
plexiglass internally cracks due to the propylene carbonate (PC)

PETG



+ chemically compatible
− Low resolution
→ Not air tight

SLA



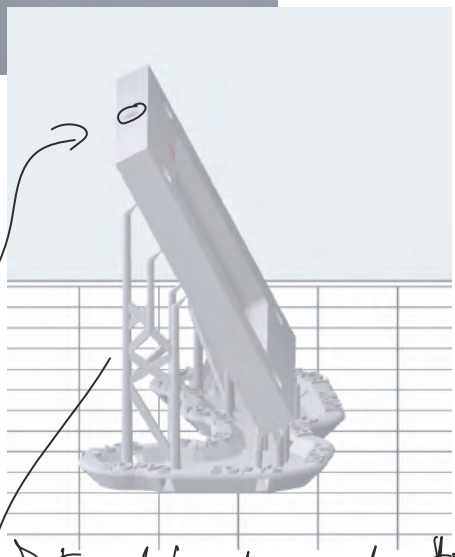
Transparant so air bubbles are visible

Materials reject each other

→ High resolution, chemically compatible
But hard to fill the EOPs

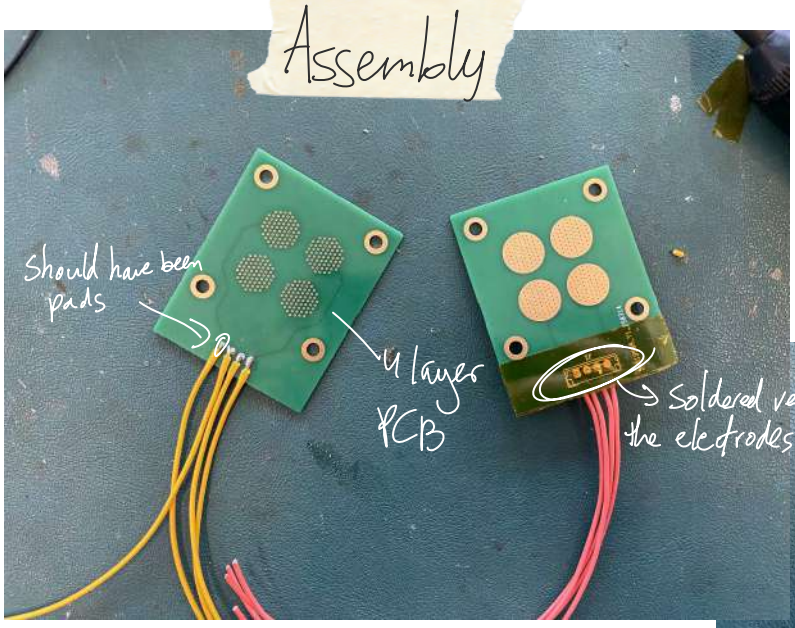
I went back to ecoflex silicone as its flexibility allows me to inject easily and let air out

added an injection hole



→ Formlabs slicer automatically generates supports. Took an afternoon to clean the formlabs in the lab and put the print on

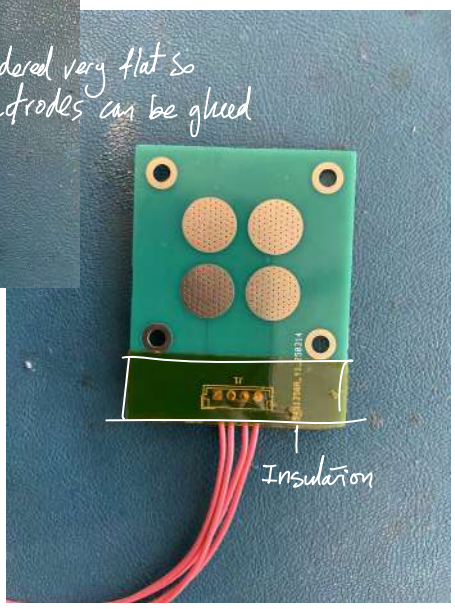
Assembly



Should have been pads

4 layer PCB

Soldered very flat so the electrodes can be glued



Insulation

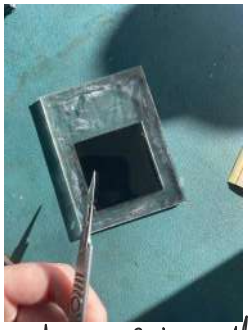
↳ Glueing 0,5 mm perspex on plexiglass to make thin membranes
↳ 0,4 – 0,5 mm thick

Adding carbon black powder to the Usilicone.

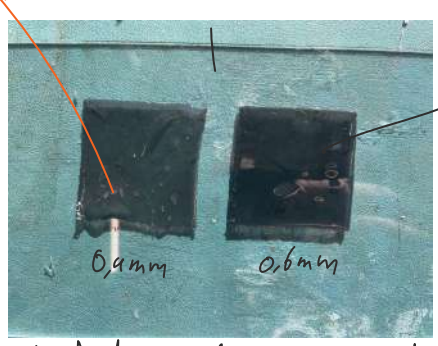
Gets pitch black

about 1 gram added black powder

Feel very flimsy and sticky



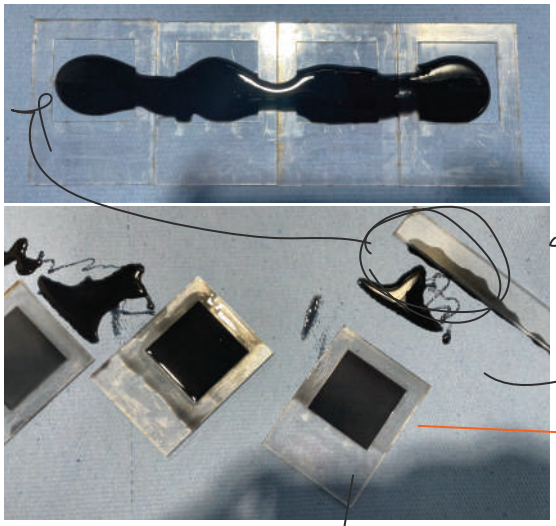
Get out of the mold with a scalpel for clean edges



Ecoflex 30 for very soft and flexible top layers

* thickness changes to "blackness"
↳ can never achieve pitch black as its so thin

One air bubble is fatal so a vacuum chamber is used



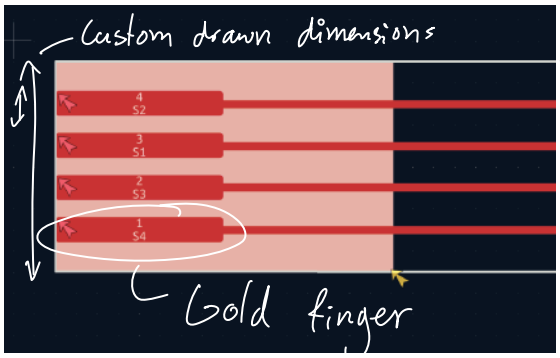
Swipe excess off

Very hard to get full control over material thickness

↳ Cures in about 2 hours

Flex PCB design

1mm pitch



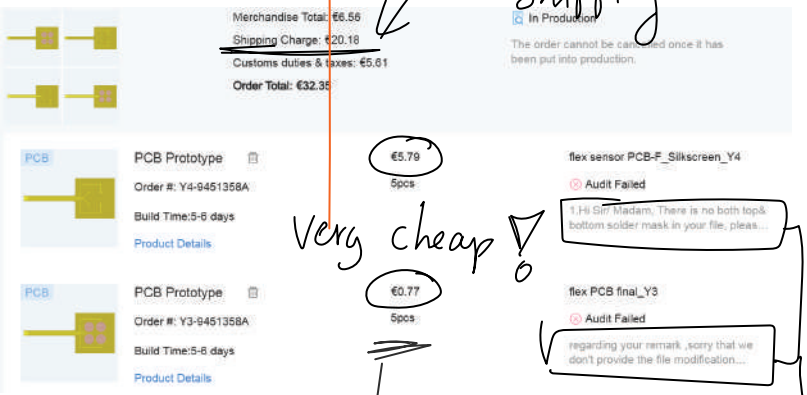
0,23 mm

very thin

PCBs have become more accessible
→ Can now be part of an iterative design process

Dimensions based on datasheet
* must be very accurate as you want a secure connection with the connectors
* No wiggle room
↳ even more important with High voltages

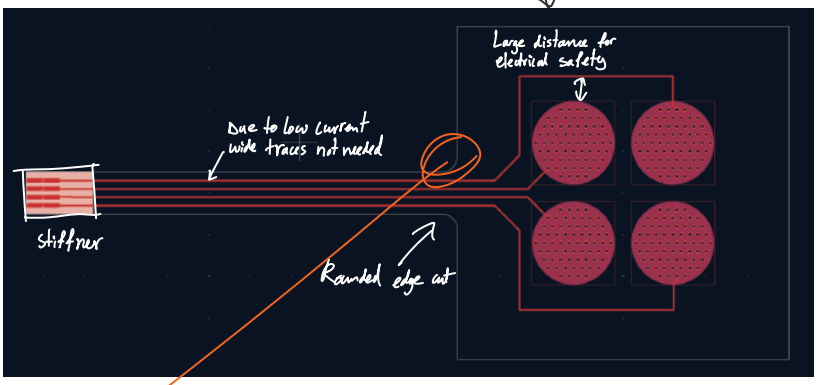
You mainly pay for shipping



Very cheap!

Took two days of emailing the manufacturer on how to set the masking layers and exposed copper zones

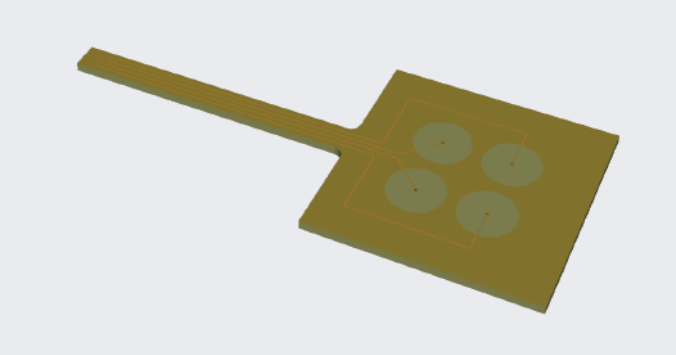
when working with high voltages the distance is the most important!



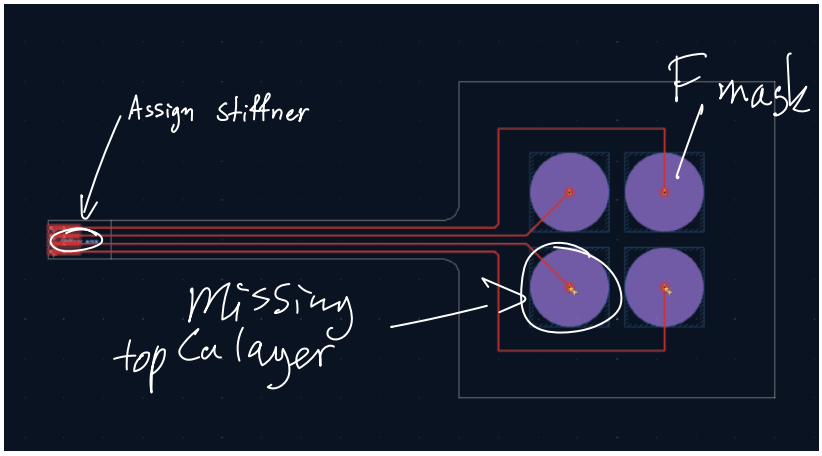
As KiCAD is not a drawing software it was hard to create rounded corners

you always order 5 PCBs as minimum

Sensing



3D gerber viewer



Wrong masking layers

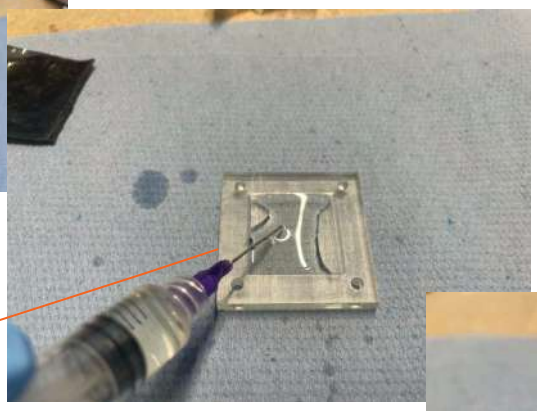
Mistakes happen

Led to failed sensing PCB

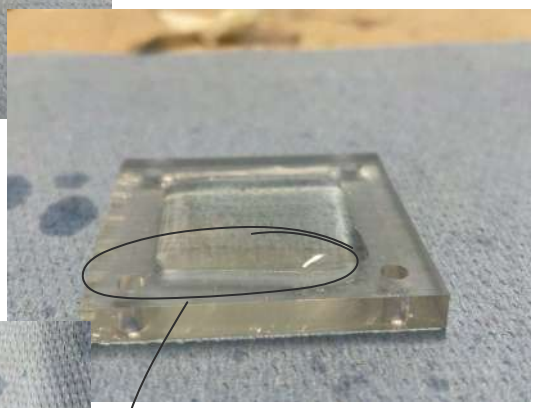
Enough exposed copper to be used as a sensor → you get 5 PCBs so you can use 2 for the pump and 2 for sensing

Took 4 weeks to obtain propylene carbonate
↳ May only be ordered via a lab or company
↳ inaccessable for individual makers

Filling EOP

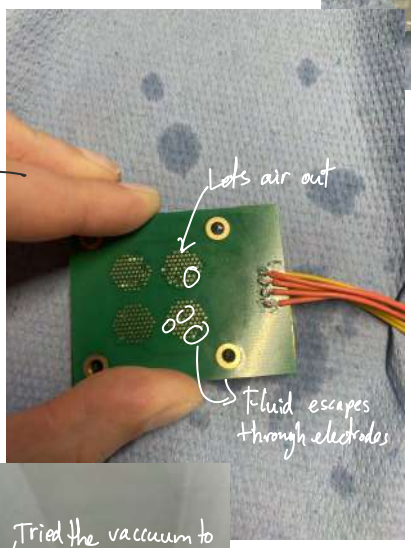


Trasparacy serves a functional purpose

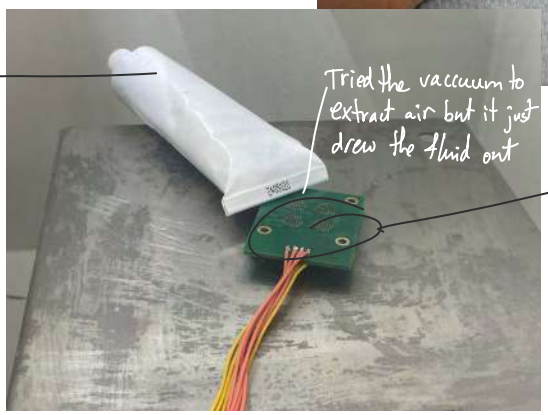


Fill until just over the edge

Press PCB firmly on



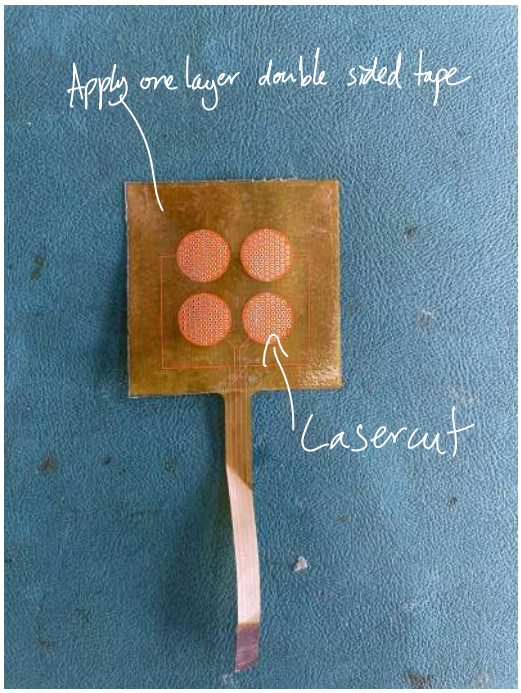
Silpoxy

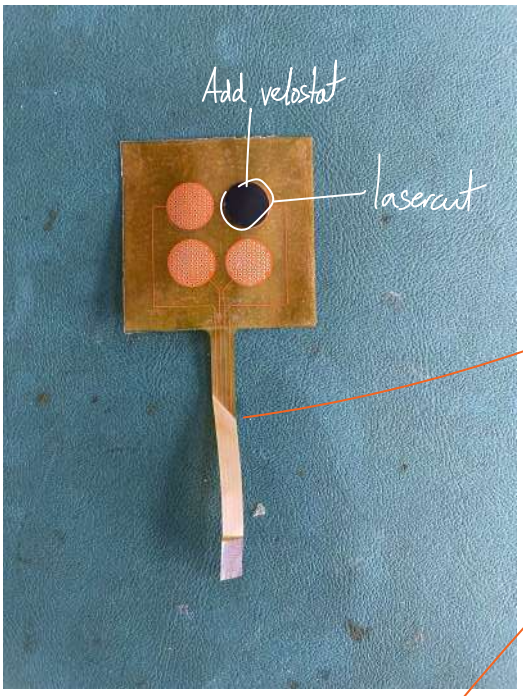


→ Very messy assembly method
Top part gets wet → hard to glue
lots of air gets in while glueing

↳ now use silicone reservoirs
- easy to inject
- keep air out

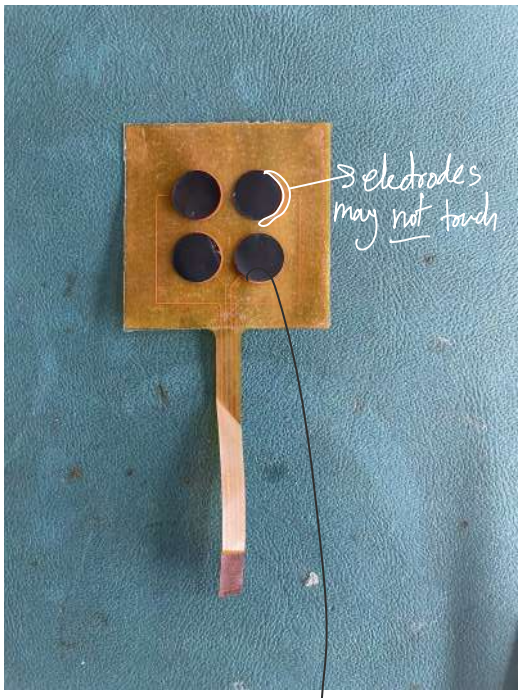
Sensing

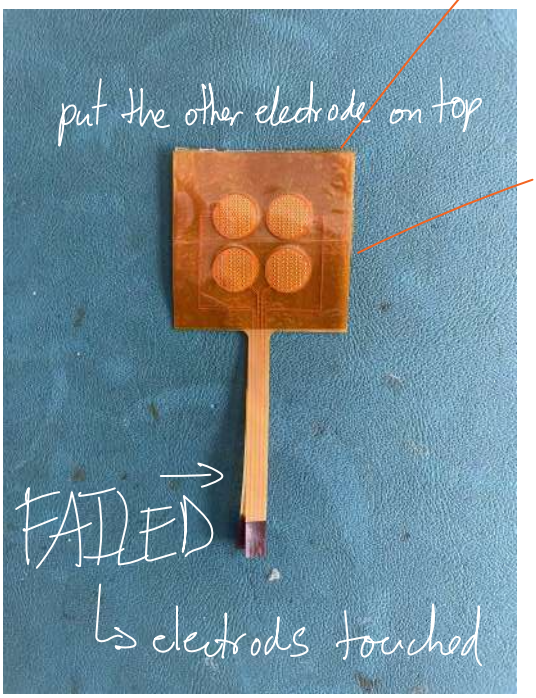




Irreversible denting from manufacturer

Enabling embodied reciprocal interaction





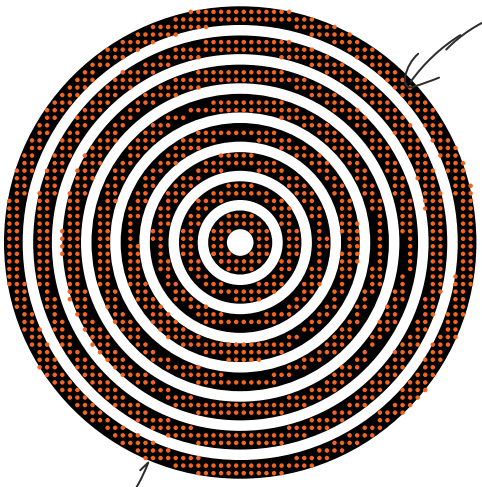
kapton layers give orange effect

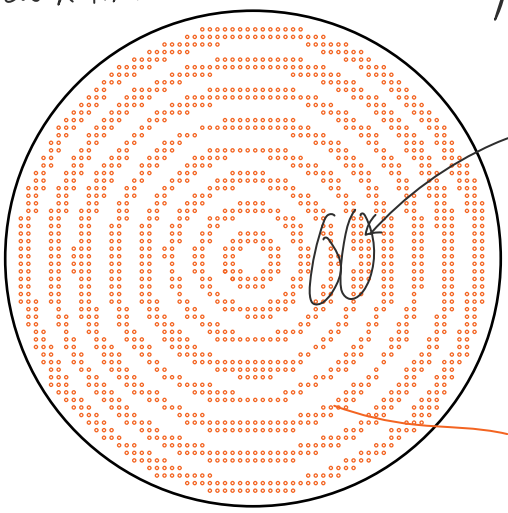
larger velostat would have been better

↳ lasercut tape was the issue
2nd try used Z-axis conductive connecting tape
↳ no 4 holes just one sheet

Shape exploration electrodes

Mainly drew flowy and round forms → complex shap



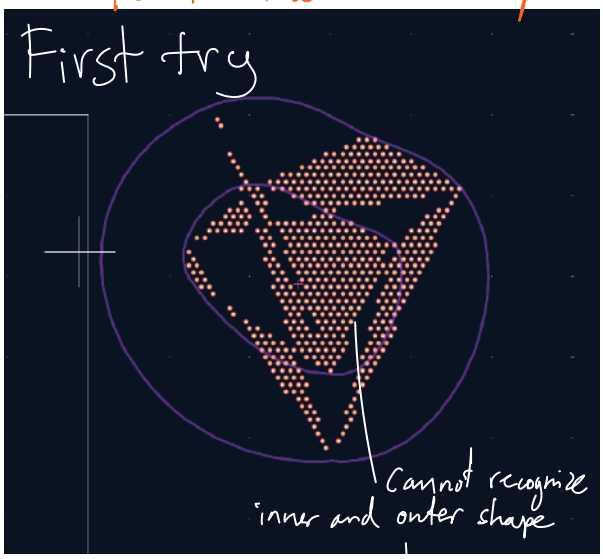


irregular
↓
Bad for electric field

Shape explorations in illustrator before moving to KiCAD

Drawing electrode designs in Illustrator but manual placement took way too long

— To be able to make expressive novel shapes




```
def pip(x, y, pts):
    inside = False
    for i in range(len(pts) - 1):
        x1, y1 = pts[i].x, pts[i].y
        x2, y2 = pts[i+1].x, pts[i+1].y
        if (y1 > y) != (y2 > y):
            xin = (x2 - x1) * (y - y1) / (
(y2 - y1) + 1e-9 ) + x1
            if x < xin:
                inside = not inside
    return inside
```

check if a point is inside a polygon

```
for gi in shape_fp.GraphicalItems():
    if gi.GetLayer() == pcbnew.F_Cu:
        try:
            ps = gi.GetPolyShape()
            for i in range(ps.Outline-
Count()):
                ...
                loops.append(pts)
```

Collect all polygone outlines
↳ if not closed → forced shut

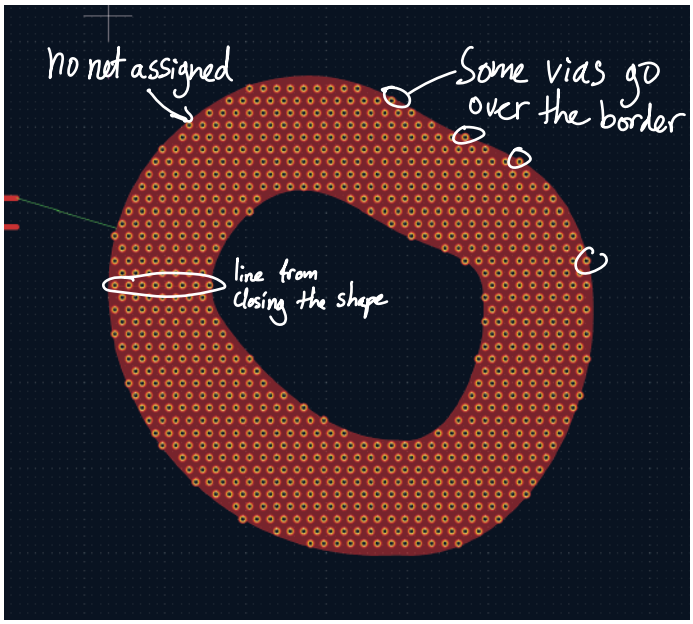
```
def seg_dist(x, y, x1, y1, x2, y2):
    dx, dy = x2 - x1, y2 - y1
    if dx == 0 and dy == 0:
        return math.hypot(x - x1, y - y1)
    t = ((x - x1)*dx + (y - y1)*dy) /
(dx*dx + dy*dy)
    t = max(0, min(1, t))
    px, py = x1 + t*dx, y1 + t*dy
    return math.hypot(x - px, y - py)
```

Calculate shortest distance from a point to a polygon edge
↳ to create a copper border

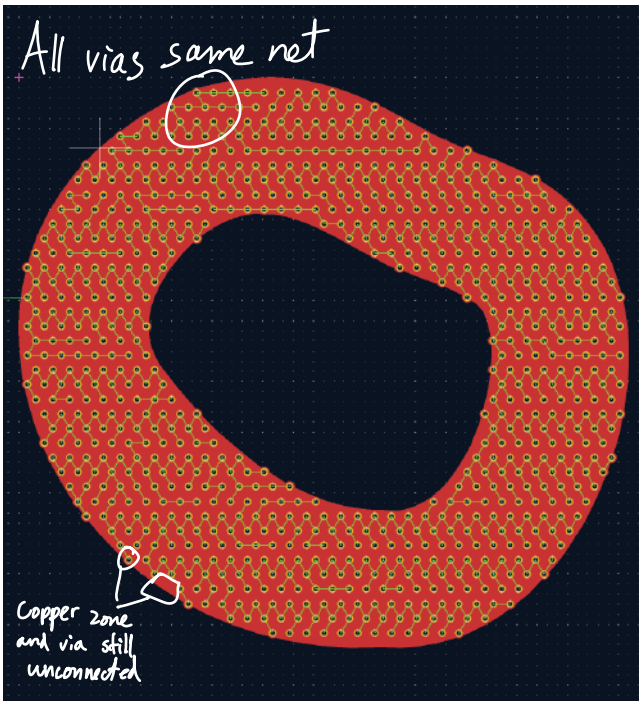
```
# 2a) Place vias (must be ≥border from any edge)
        placed = 0
        y = ymin; row = 0
        while y <= ymax:
            xoff = 0 if (row % 2) == 0 else pitch/2
            x = xmin + xoff
            while x <= xmax:
                if pip(x, y, pts):
                    dmin = min(
                        seg_dist(x, y, pts[i].x, pts[i].y, pts[i+1].x, pts[i+1].y)
                        for i in range(len(pts)-1)
                    )
                    if dmin >= border:
                        via = tp_tpl.Duplicate()
                        via.SetPosition(pcbnew.VECTOR2I(int(x), int(y)))
                        # **Only** override net; leave pad layer set alone!
                        for pad in via.Pads():
                            pad.SetNetCode(netcode)
                        board.Add(via)
                        placed += 1
                        total_vias += 1
                x += pitch
            y += dy; row += 1

        print(f"• Loop {idx+1}→{netname}: placed {placed} vias")
```

makes hexigonial grid

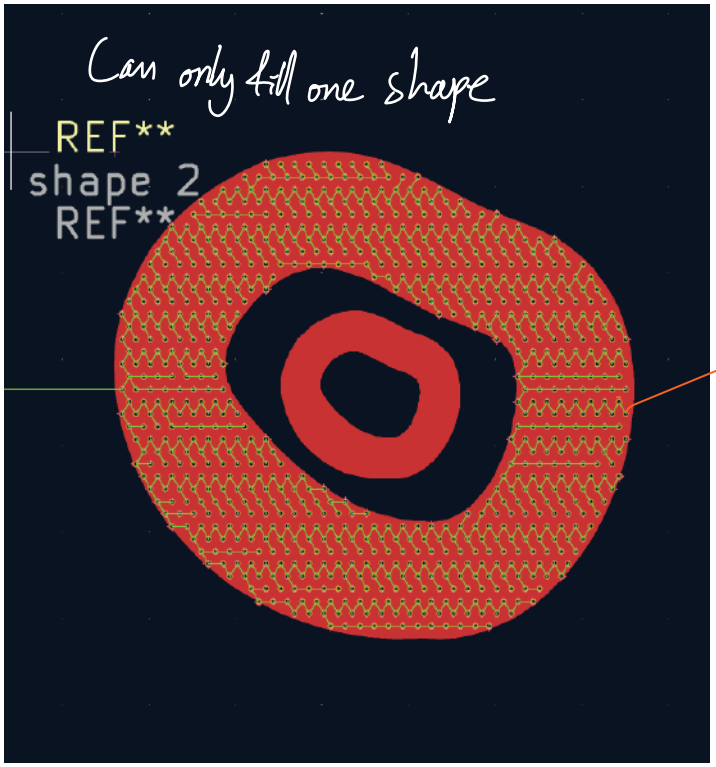
only place via if not too close to the edge



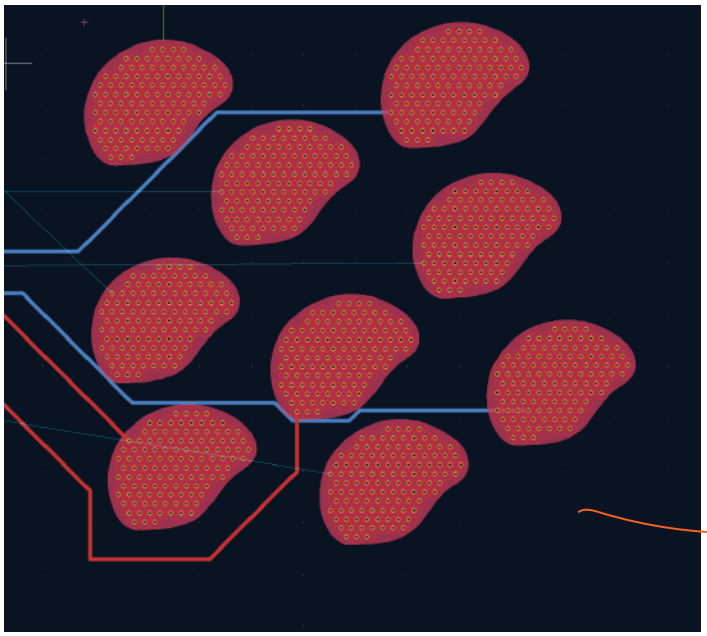
```
  # 2b) Create the F.Cu zone (outline
only; you'll press B to fill)
        zone = pcbnew.ZONE(board)
        zone.SetLayer(pcbnew.F_Cu)
        zone.SetNetCode(netcode)
        zone.SetIsFilled(True)
        zone.SetPadConnection(pcbnew.-
ZONE_CONNECTION_FULL)
        zone.SetLocalClearance(0)

        chain = pcb-
new.SHAPE_LINE_CHAIN()
        for p in pts:
            chain.Append(p)
        zone.Outline().AddOut-
line(chain)
        board.Add(zone)
```



Coding improves reproducability of the work



AI tools have democratized coding → allowing also designers to code more advanced



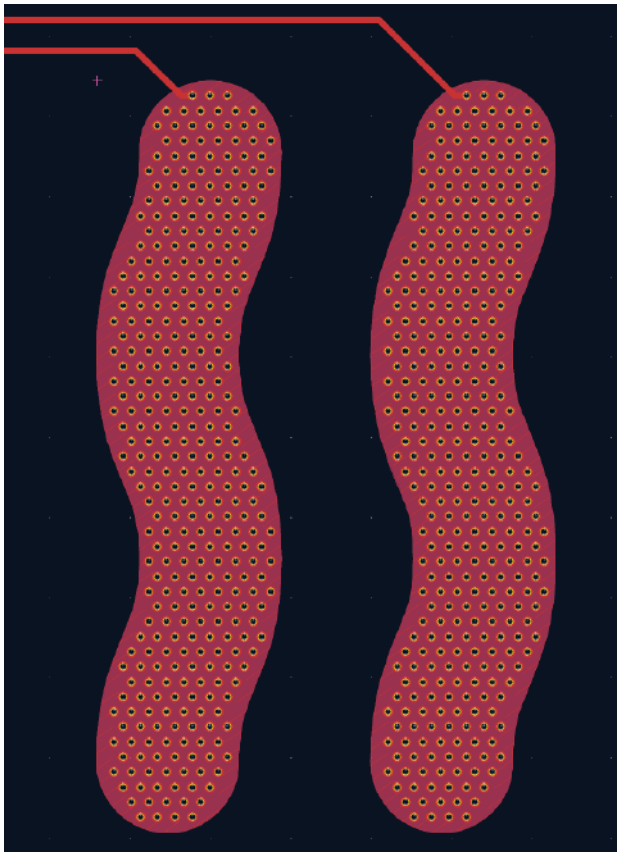
Give each shape an automatic different net

```
# Build list of net names:
["/S1","/S2",…]
NET_NAMES = [f"/S{i+1}" for i in
range(MAX_NETS)]
```

Automation -> improves manufacturability

```
exec(open(r'C:\Users\tessa\OneDrive\Documents\ID thesis\first
PCB\Scripts\script.py').read())
• Loop 1→/S1: placed 1015 vias
• Loop 2→/S2: placed 792 vias
• Loop 3→/S3: placed 548 vias
• Loop 4→/S4: placed 329 vias
• Loop 5→/S5: placed 130 vias

□ Done. 2814 vias placed; zones created—press B to fill.
```

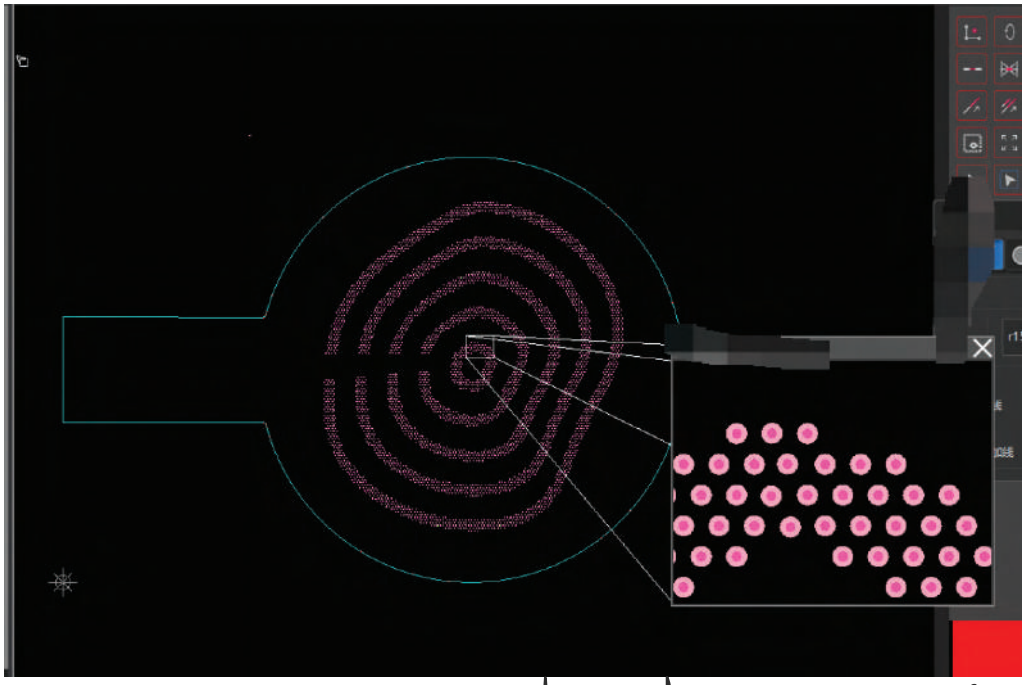
output gives how many vias placed



Defining a new copper zone based on the input SVG finally allowed me to connect the vias to the zone with correct masking for exposed electrode designs.

```
# === USER CONFIGURATION ===
SHAPE_FP_NAME = "W3"      # footprint containing multiple copper loops
TP_FP_NAME    = "TP 0.15mm"   # your through-hole testpoint footprint
MAX_NETS      = 16            # supports nets /S1 … /S12
BORDER_MM     = 0.3           # required copper annulus width
PITCH_MM      = 0.55          # hex-grid pitch for vias
```

Put SVG shape, via footprint, amount of order and pitch



Going back and forth with the manufacturer on what is physically possible with their machines → the scripted helped in iterating fast → Final specs

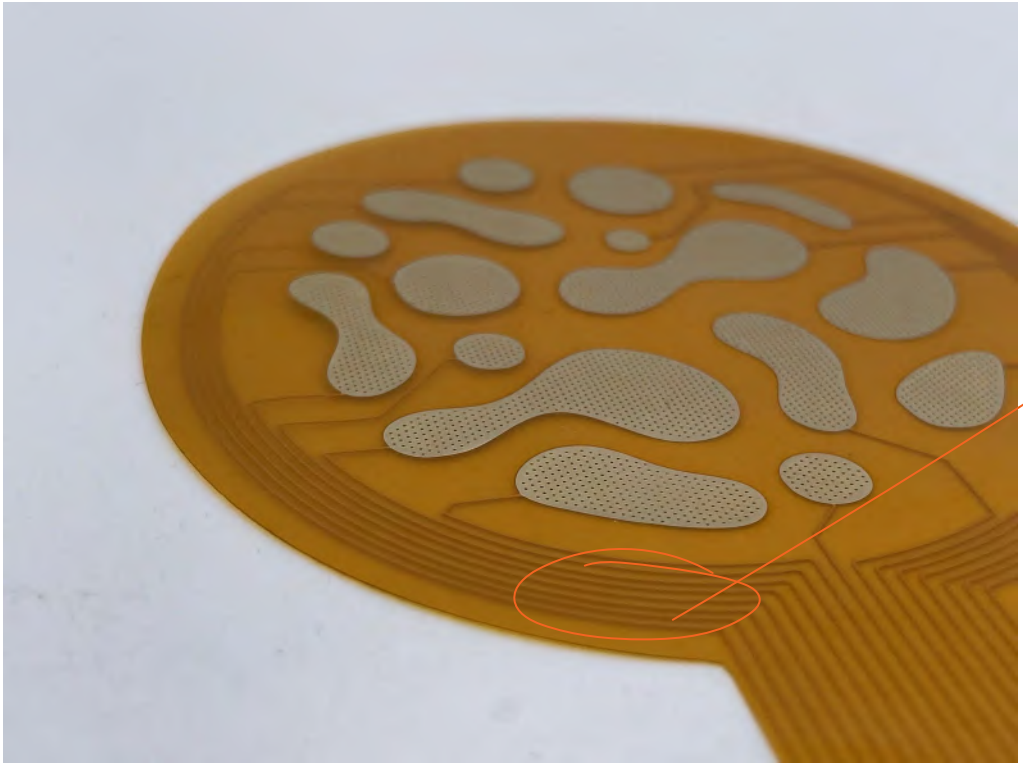
Minimum via hole size (flex PCB)	0.15 mm
Minimum via pad size (flex PCB)	0.35 mm
Minimum annular ring	0.10 mm
Minimum hole-to-hole clearance (same net)	0.13 mm
Required copper clearance between testpoints	≥ 0.20 mm

minimum pitch = 0.35 mm (pad diameter) + 0.2 mm (required clearance)
= 0.55 mm

Manufacturer constrains + costs limit the possibilities

had to keep it within 10×10 cm

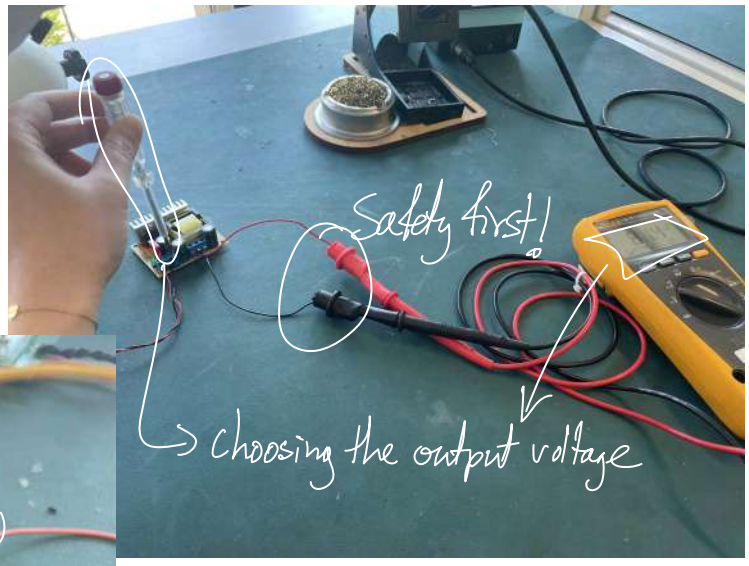
The final electrodes

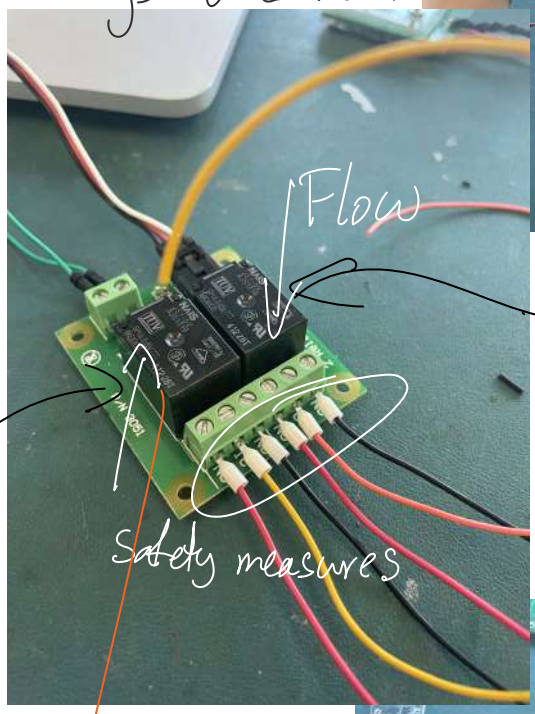


As kicad is not drawing software these traces took 2 days to make → was needed for aesthetic and safety purposes

Control

Regular electronic components cannot handle 200V so mechanical relays were used

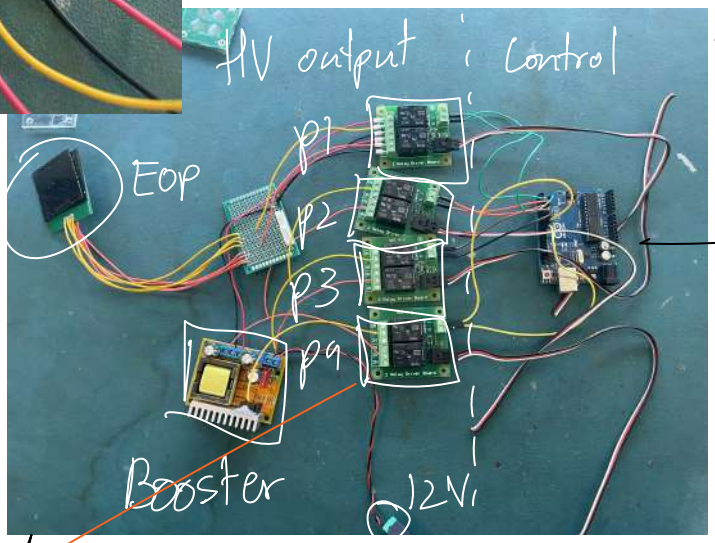




suck fluid down

pump fluid up

using these based on availability for quick results

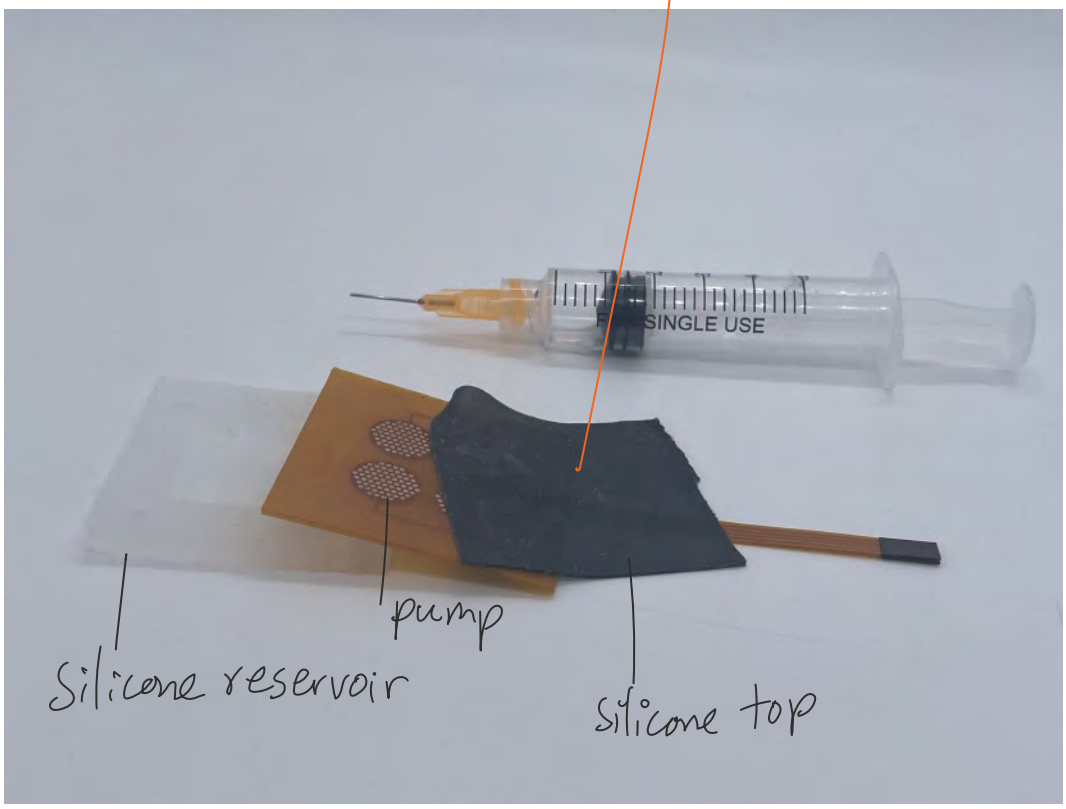


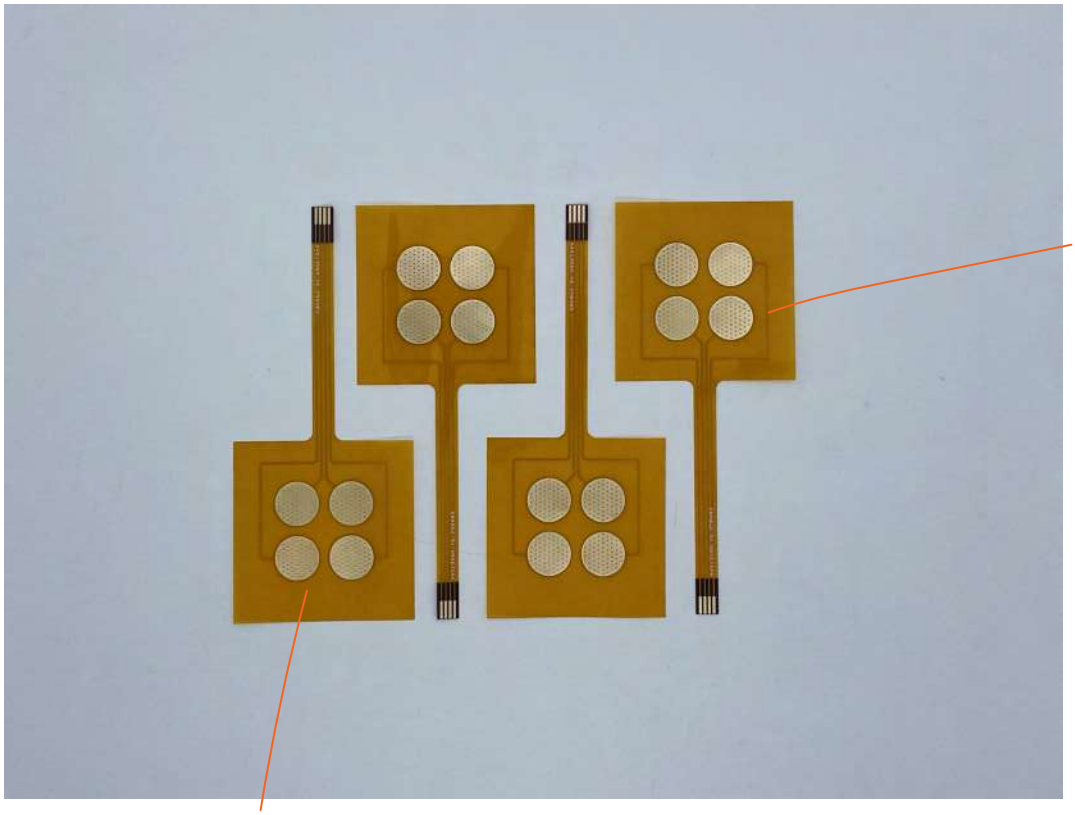
5V switching signals

Can control 4 pumps up and down

4 channels to show expressivity and movement

baby powder to resolve the sticky feel

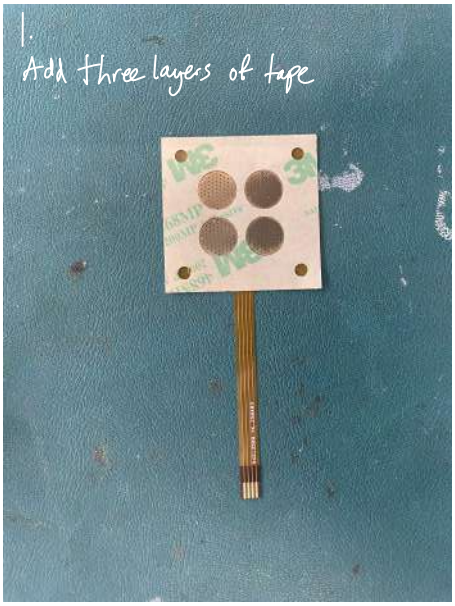


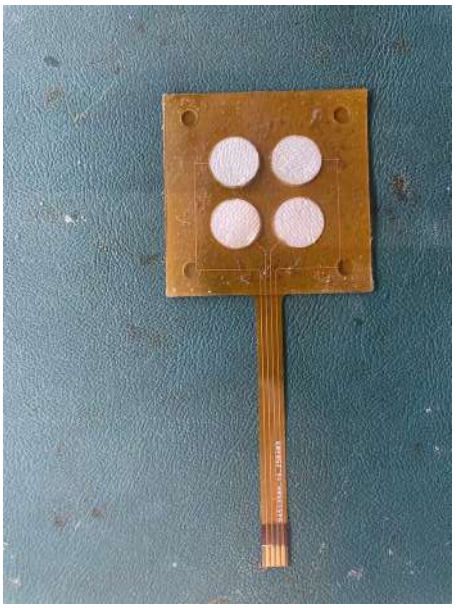


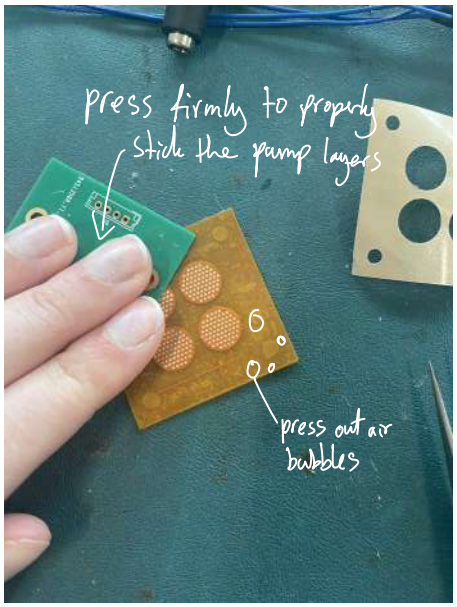
Transparency in design

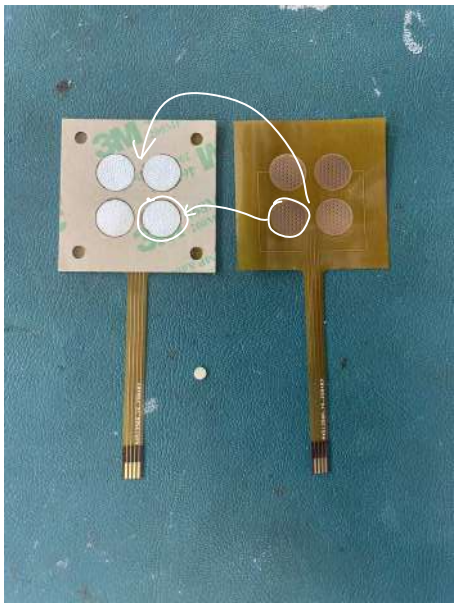
The kapton and gold give aesthetic qualities

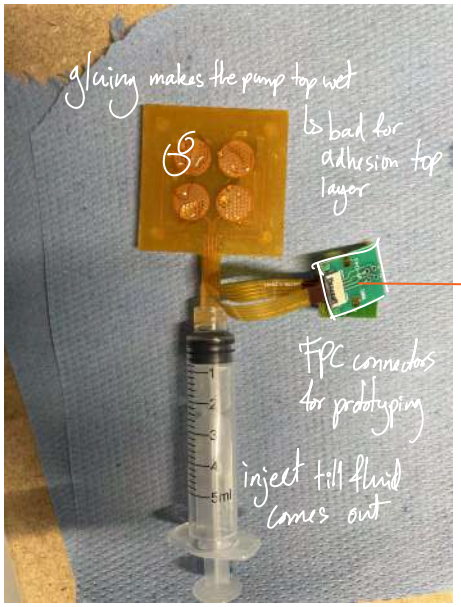
Flex EOP assembly

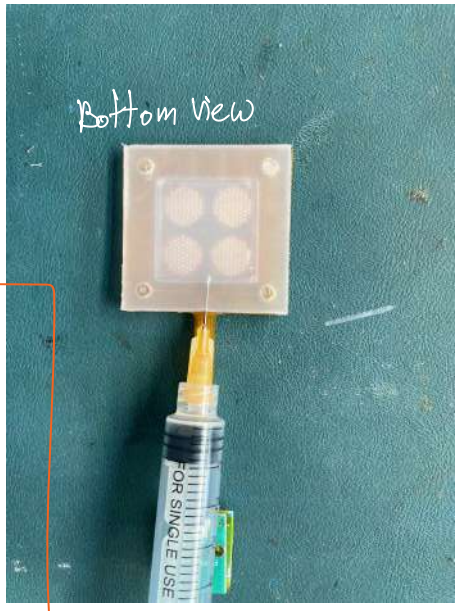








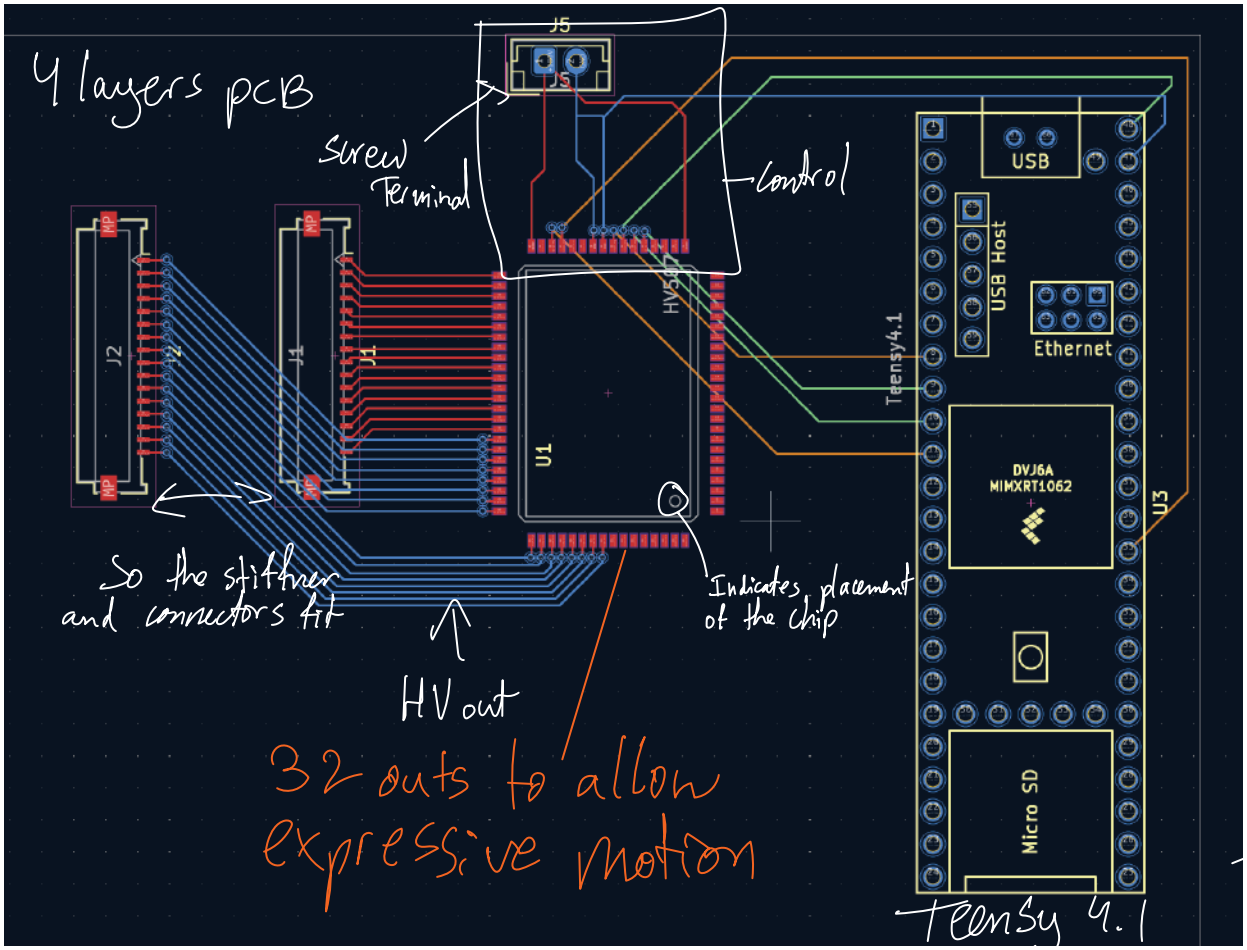


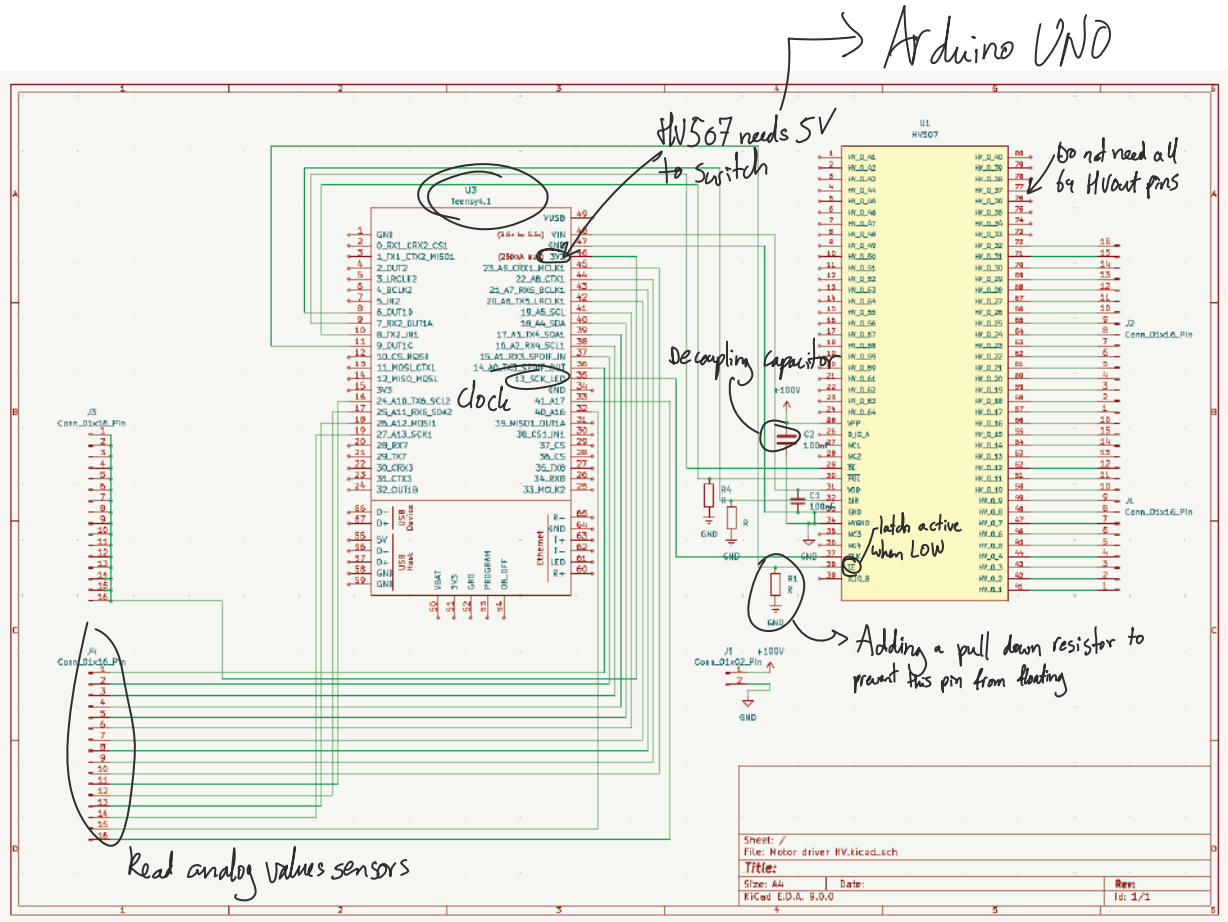


Full assembly takes about an hour

low vs high fidelity electronics are needed per design phase

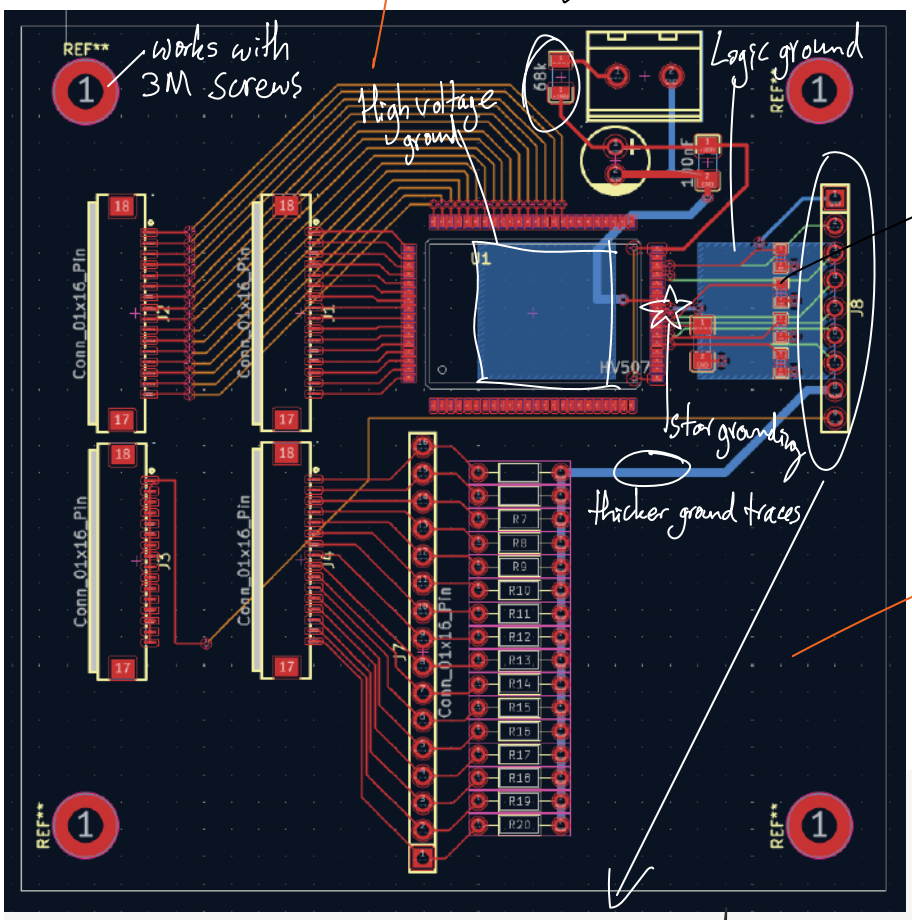
PCB design

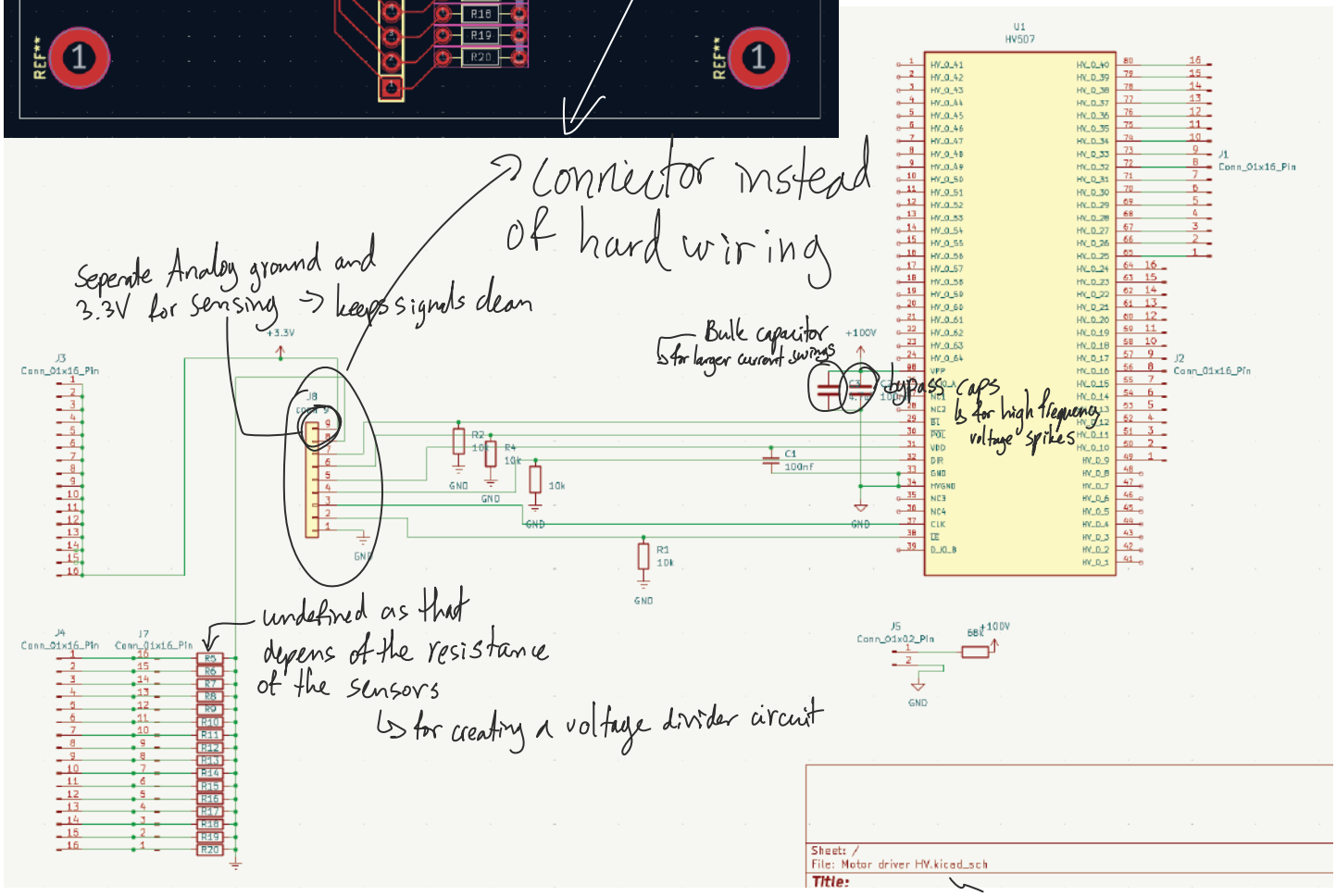




Familiarizing with the HV chip

put functionality above aesthetics for routing

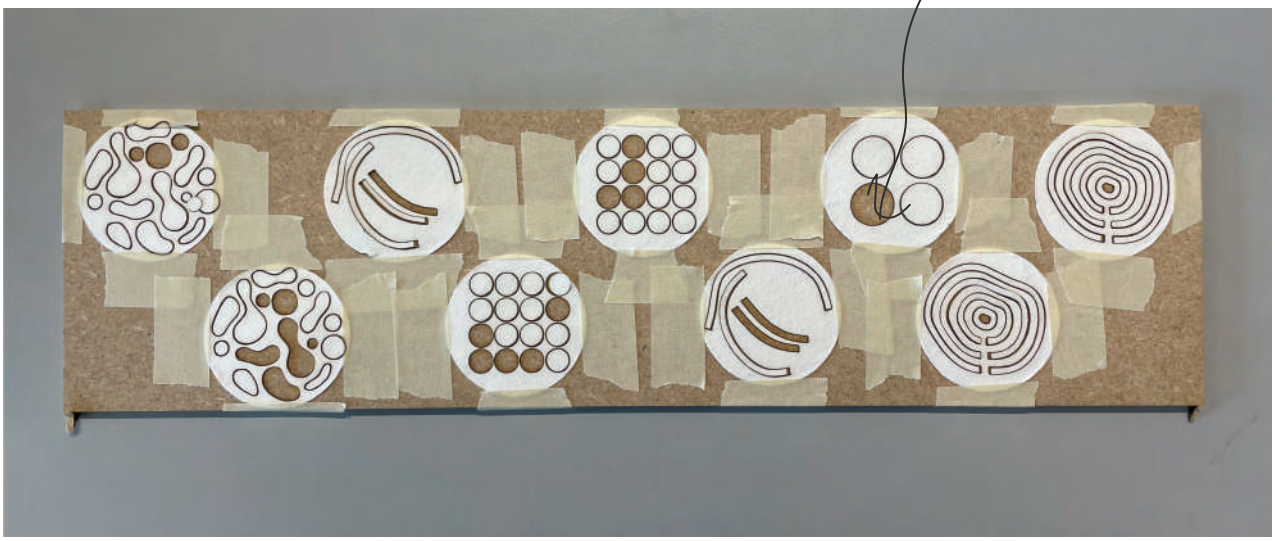


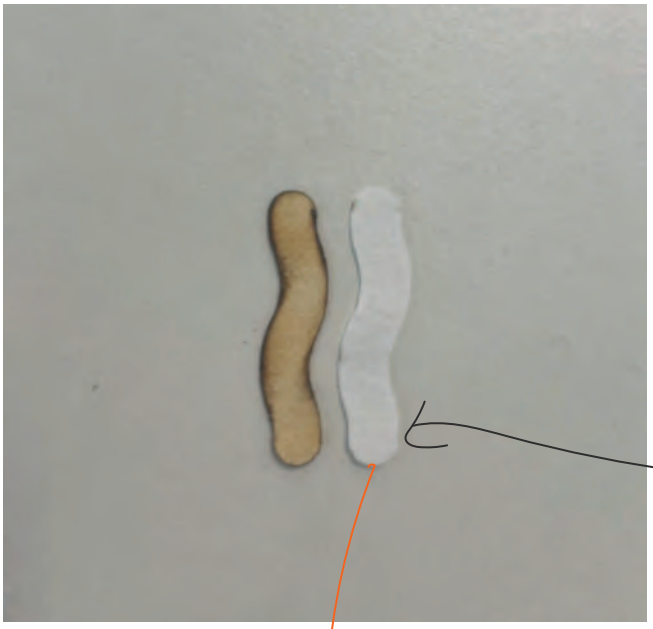


Learning a lot

Fabrication

Ventilation causes some to fly away





Tweaking lasercutter settings so the delicate glass fiber filter does not burn

picked up with tweazers as its so delicate

Very fragile and delicate

Dragonskin 20
→less flexible than ecoflex

extruded to get cleaner gluing results

As it's so thin hard to get properly black

↳ Tried old silicone dye to get the top layer more black → DID not cure anymore

↳ switching to silc pig black dye worked well

Learned by doing

Apply thick layer of silpoxy

Used a toothpick to neatly glue around the pumps

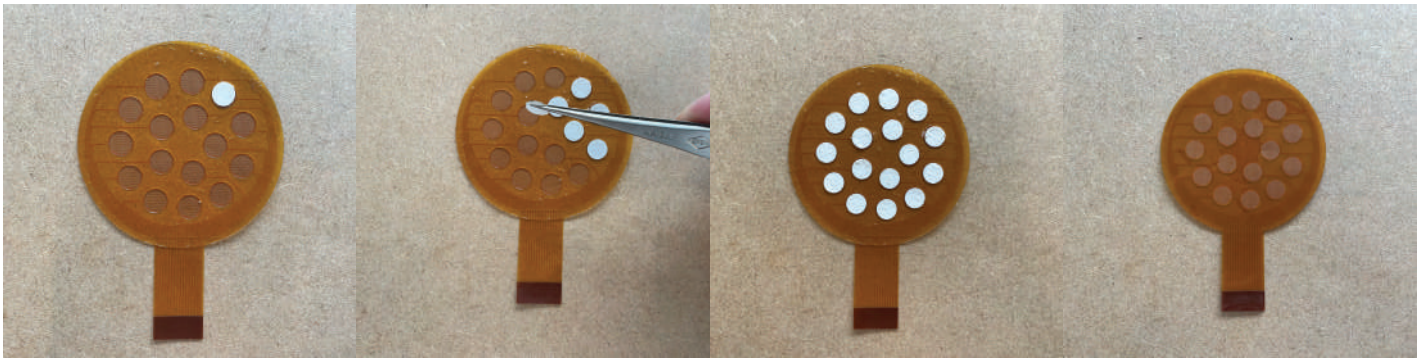
Tried this to apply glue precisely

dried too soon

Did not want to come out

Scalpel to clean up the edges

Assembly



Making of the pump layer

First assembly failed so I pulled it apart.

Too thick to actuate, cannot measure the thickness

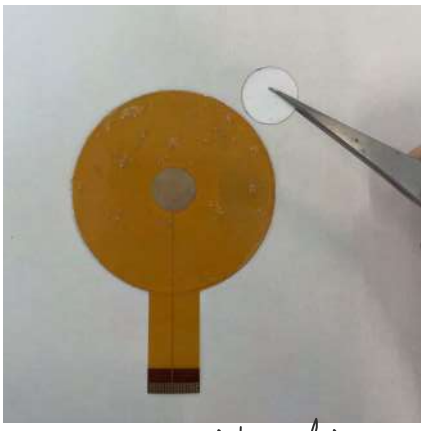
Testing without top layer

liquid coming up at 50 V already so it is working!

Testing, Trying, Testing → Learning

— logging so others can replicate my work

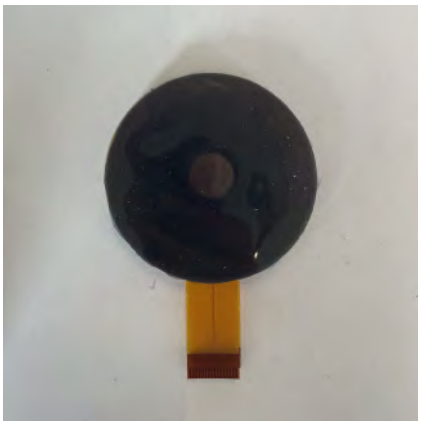
3layer double sided tape



Add glass fiber filter

Add top electrode

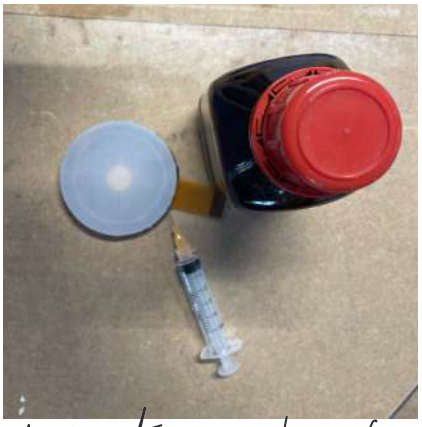
glue top layer



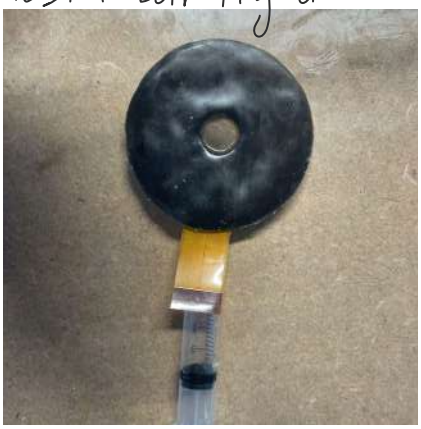
Press

Check edges

Test if air tight

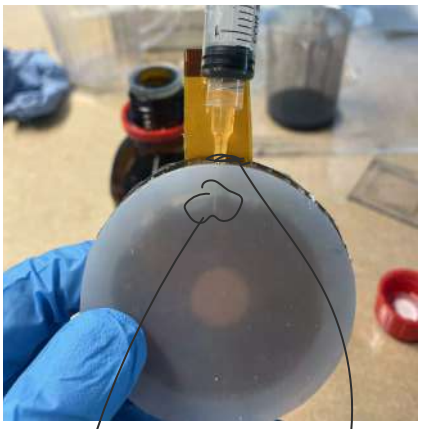


Inject propylene carbonate



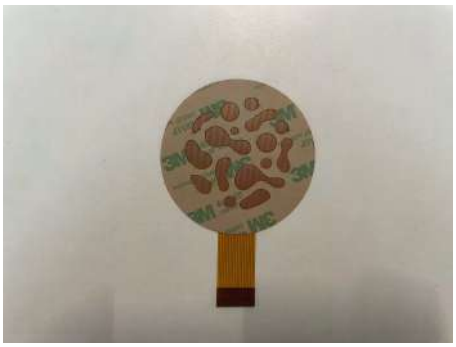
Vaccuum and the fluid fills the reservoir

See air



extract air

Seal hole with Silpoxy glue

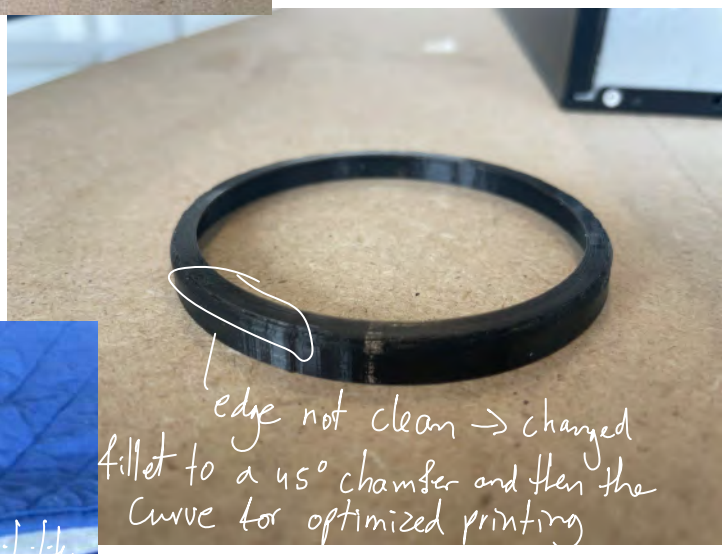


this was very hard to glue cleanly

Did work out nicely

Making mistakes is costly with EOPs

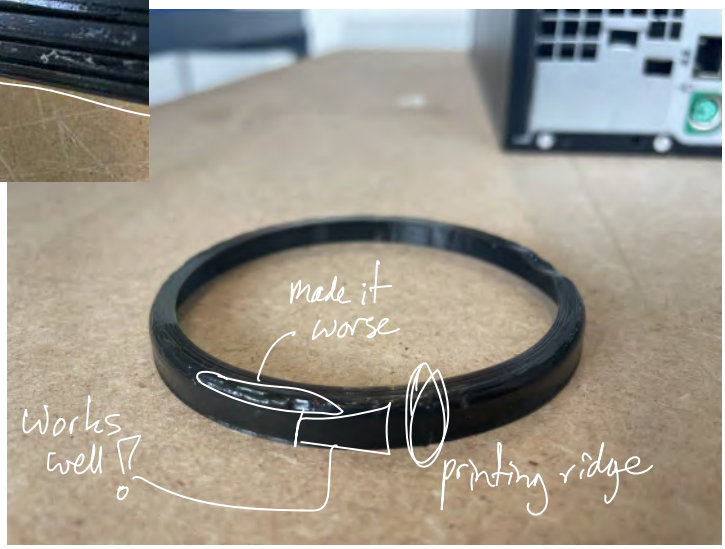
TPU cover to keep flexibility but covers up the edges



edge not clean → changed fillet to a 45° chamfer and then the curve for optimized printing

To reduce layer visibility

For a cleaner look



make it worse

works well

printing ridge

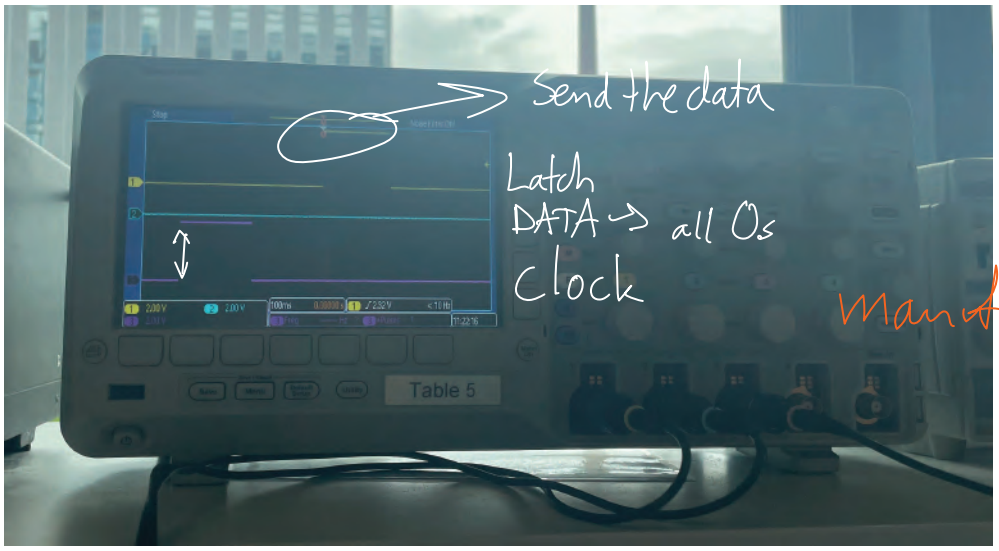
Demoday

Using "keukenpanelen" to make a black pillar o
30x30 cm

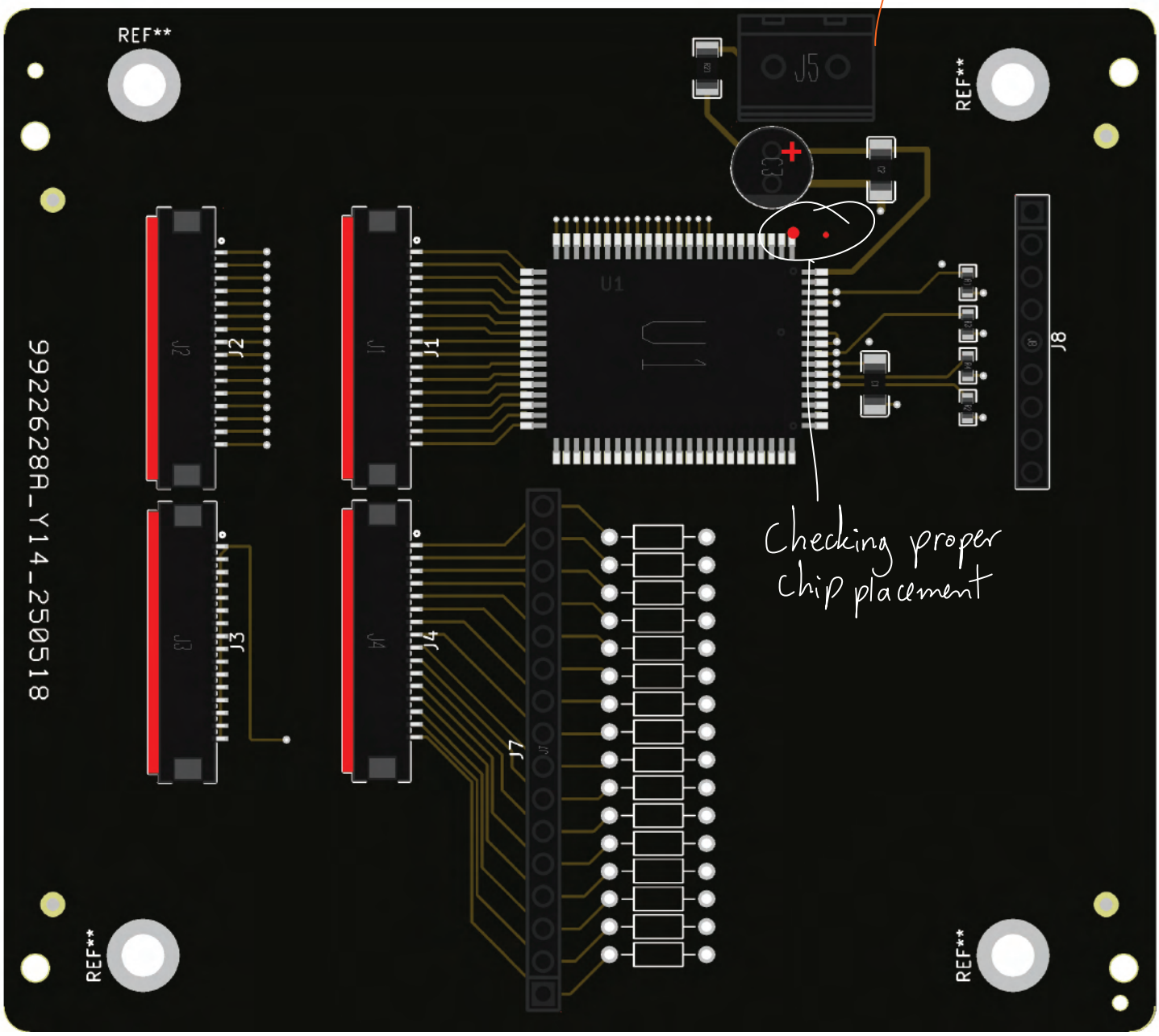
EOPs put into the display box

Simple explanation of electro osmotic flow was easily understood

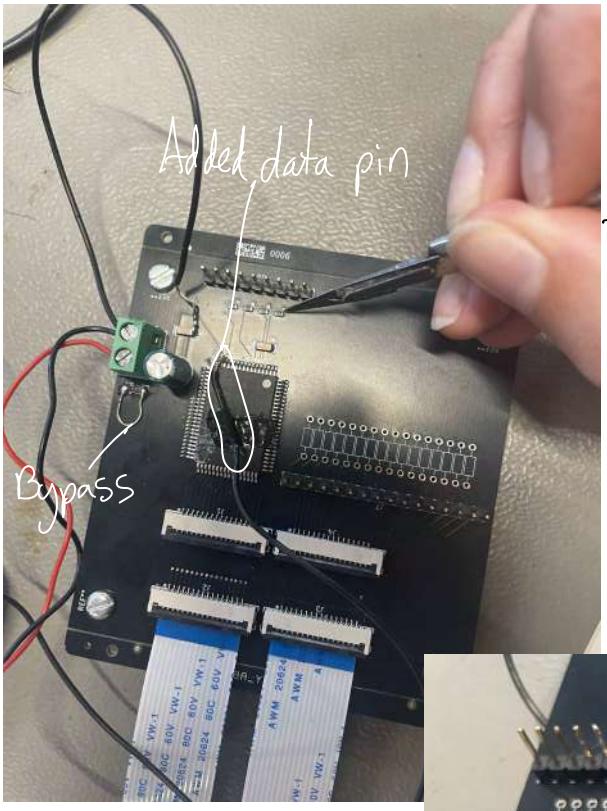
Showed its potential



Visuals for manufacturer communication

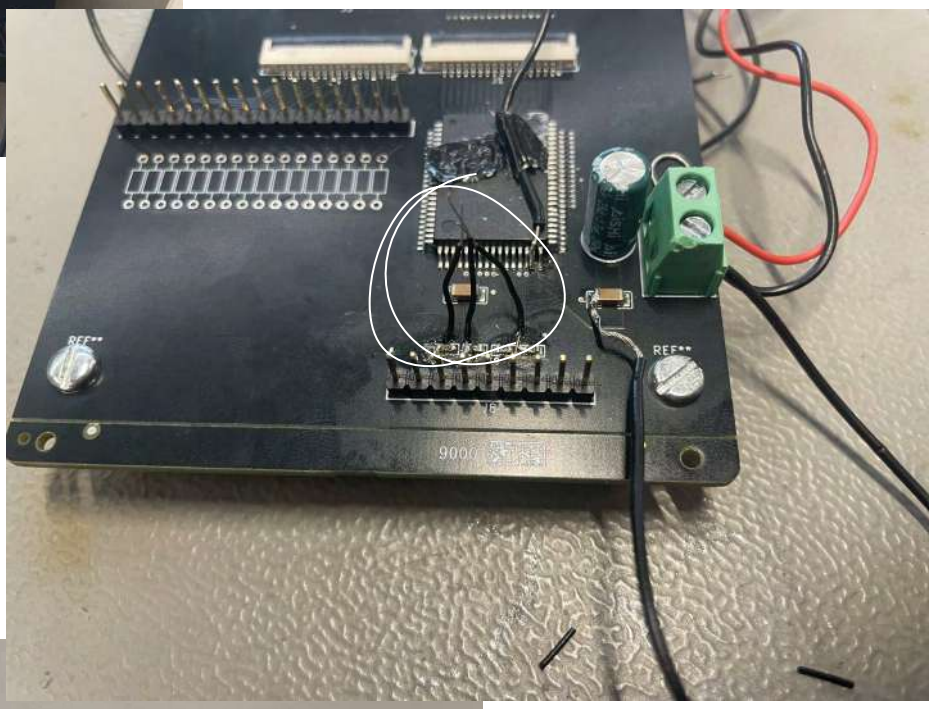


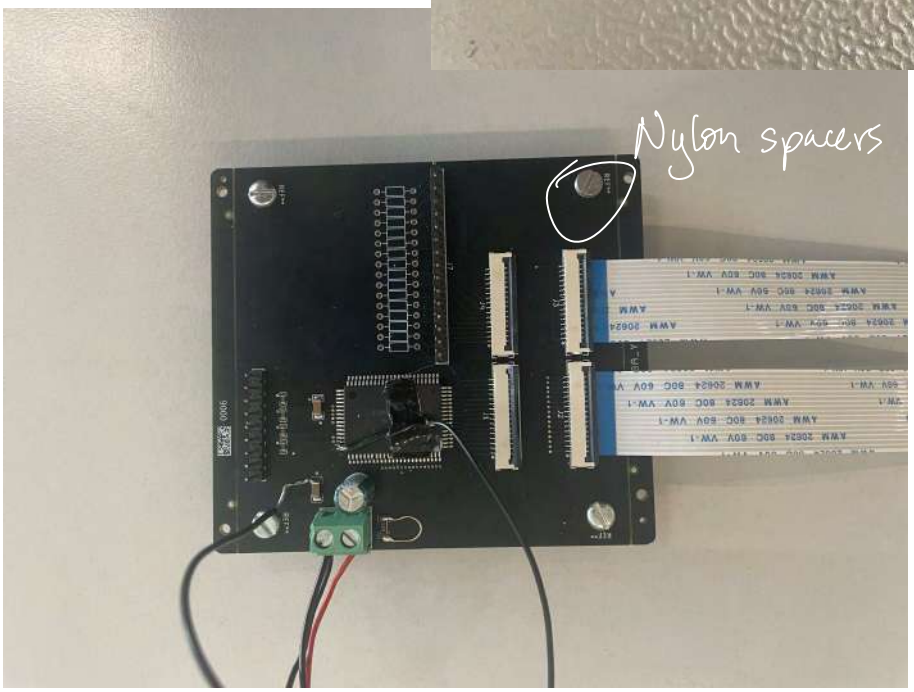
Checking proper chip placement



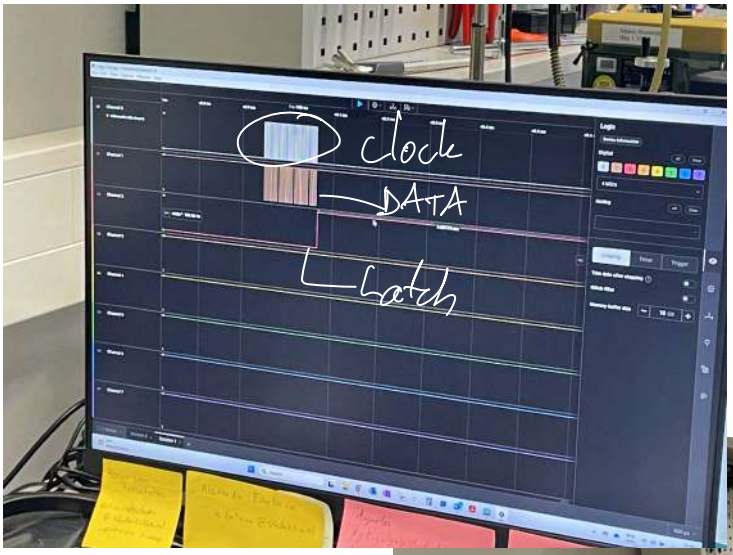
scratch out pull down resistors and make them pull up

↳ did not solve our issues

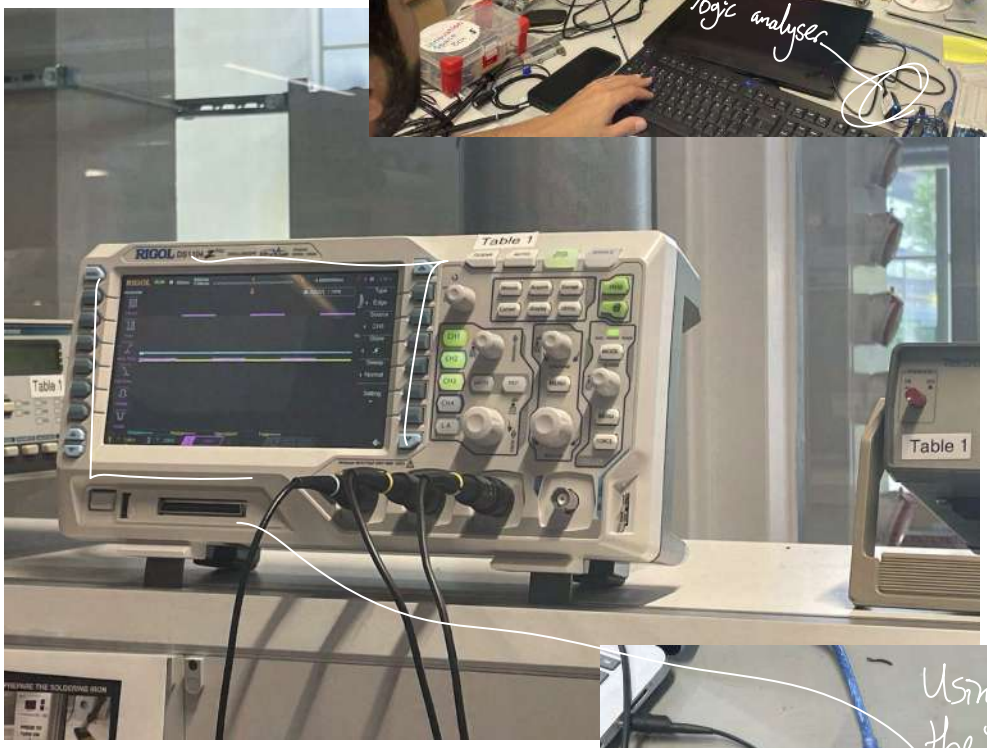


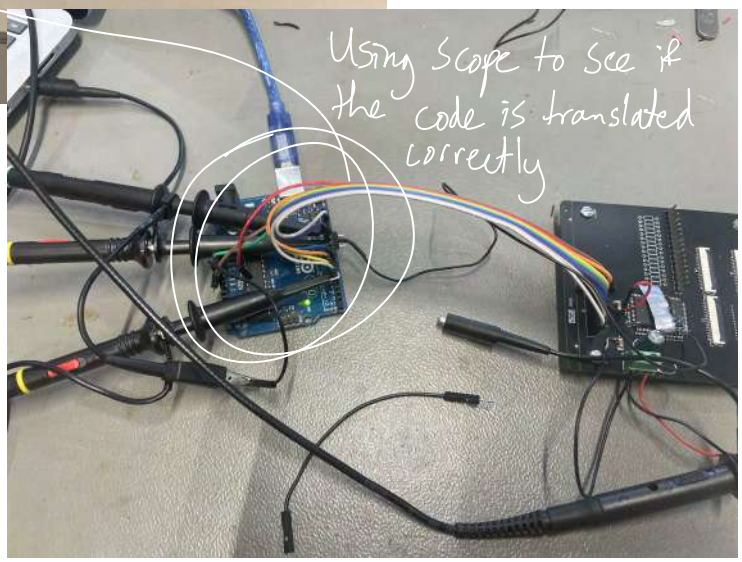


Issue must be in the software then!



Documentation on High Voltage chips is very minimal as they are not often used
↳ caused a lot of struggle
↳ there were no example codes or schematics

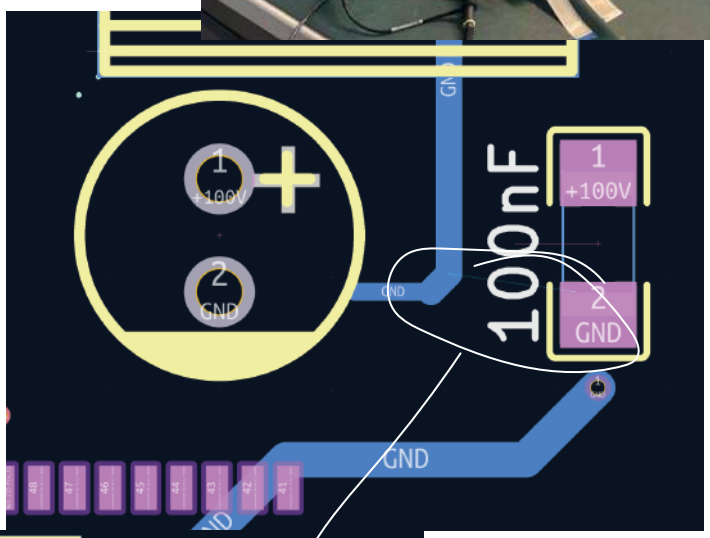


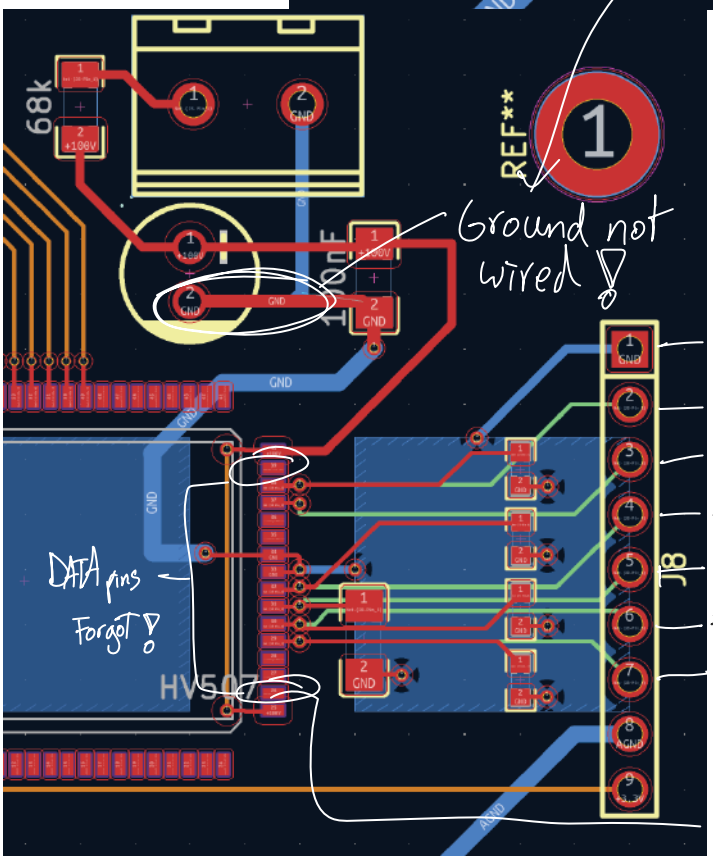


Very frustating process
↳ I just want to design motion

Control

First test measuring signal gave very weird values
This was due to the high voltage ground not being connected





UNO

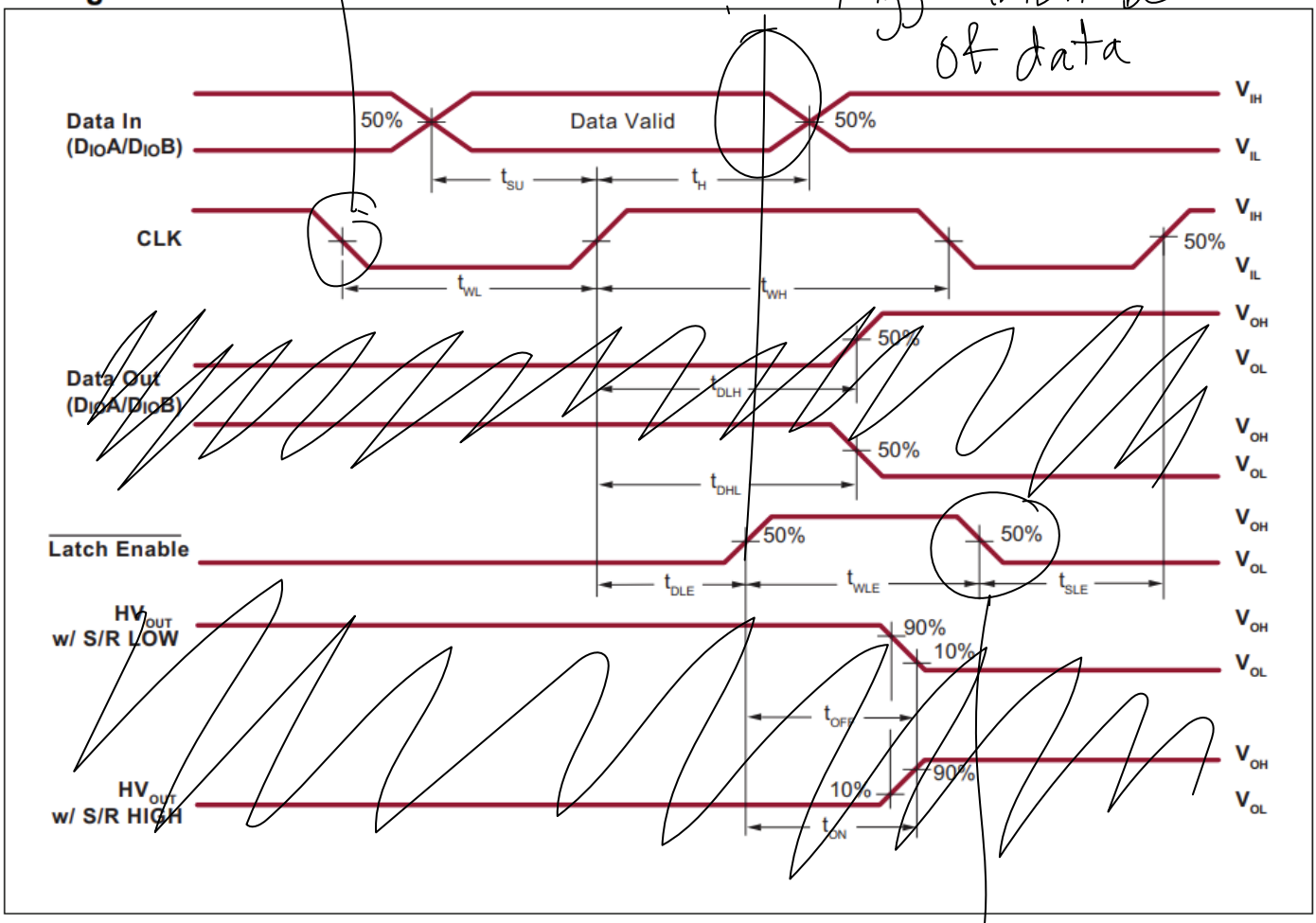
GND — GND
Latch — 4 digital
clock — 13 sck
Direction — 5 digital
VDD — 5V
Polarity — 6 digital
Blanking — 7 digital

DATA — 11 MOSI

First start clock

Trigger latch before end of data

Timing Waveforms



Felt more engineer than a designer

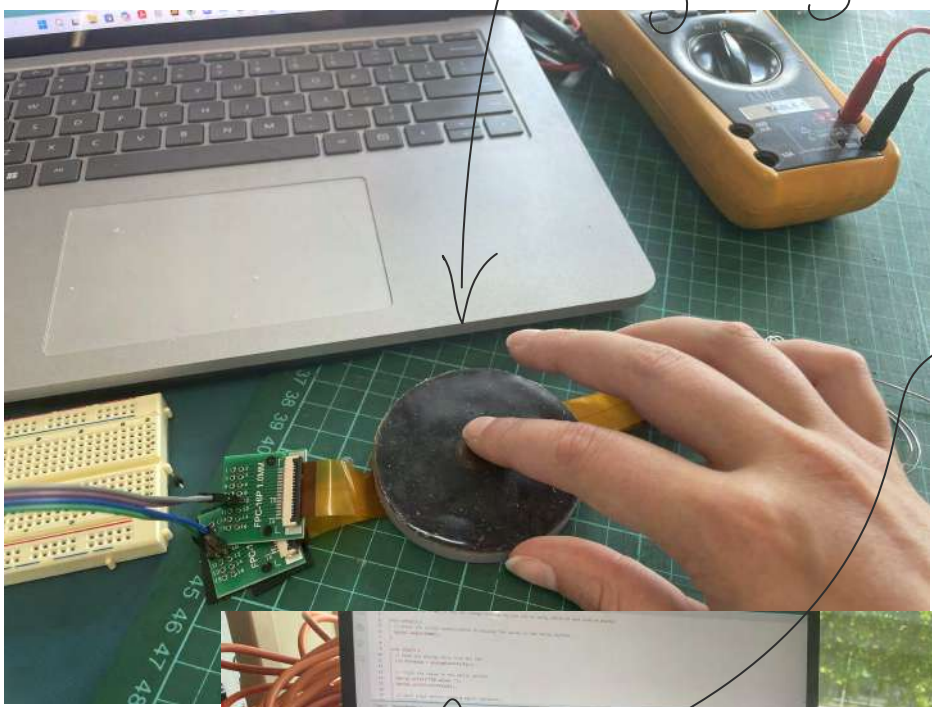
Data is stored when latch goes from high to low

Spend two days exactly matching these timings → still did not work!

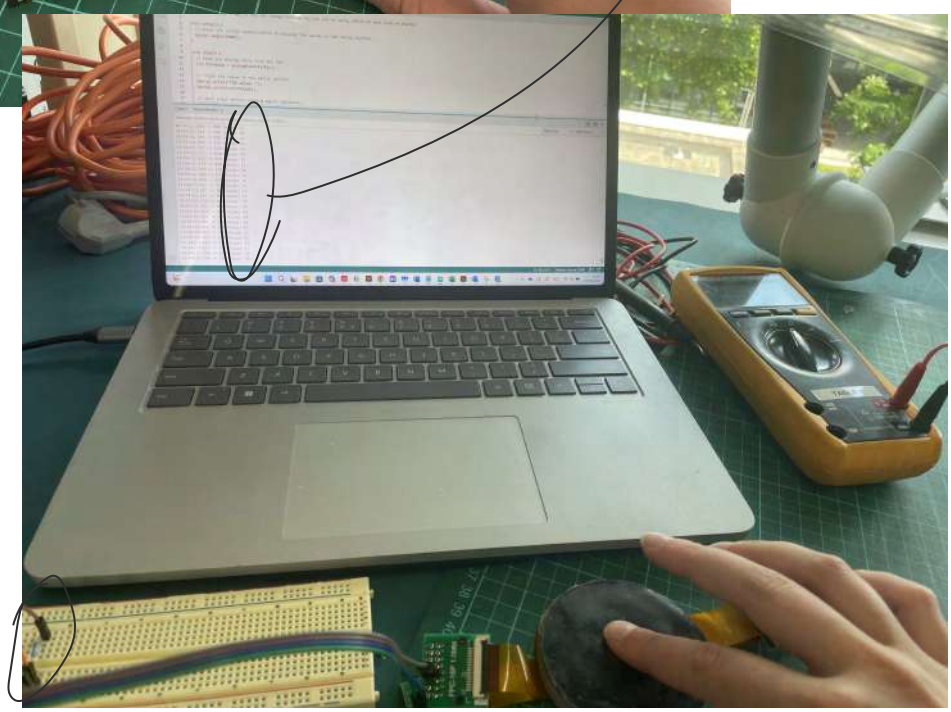
↳ found a github that set blanking to High → now it worked

Sensing

Testing sensing through the pump layer

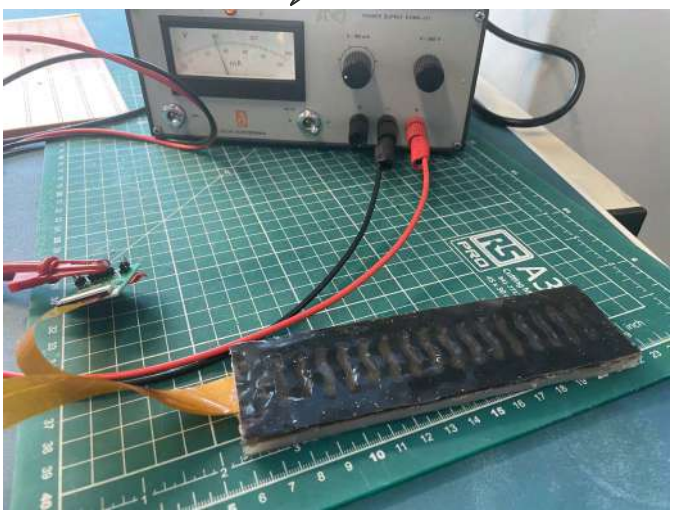


Works well



Simple voltage divider, the sensor has a resistance of $\approx 250\Omega$
so a 250Ω resistor was used

High voltage power supply



Actuation started to decrease over time

↳ drawing higher currents also

↳ 10–20 mA → overheating

Stopped working

Refilling with new propelene carbonate fixed it

So the dragonskin is contaminating or degrading the fluid

Temporarily

↳ Switched to ecoflex reservoirs

EOPs are delicate and require precision

Appendix F

qualitative analysis

Qualitative analysis

Control and quite engineering

maar je hebt een 200 V. Ik weet niet of dat een probleem is, maar mijn intuïtie zegt dat het wel moet probleem is, maar je hebt ook gewoon de low voltage directive en die moeten we volgen. En als je het vanuit daar kan redeneren moet het kunnen.

-: Limitations fluidics

But Without the electronics, but bulky again. So I like, also, the area of smartness, like, not trying to immune to, to mimic the binary system with fluidics, but just making use of the The nature of the flow on how you can control it for the specific action. You you want to perform. So using like a Walking Rollers they're like a lot of clever solution that I don't know. The name is bending a certain angle, there it won't flow because it's throttling itself and then after another angle it opens and that kind of like solutions that things the best the tradeoff is that everything is hard coded, so you don't have the opportunity

-: Control

So it's in a continuous problems and not so much.
Discrete design choices.

Abkoude, Tessa van 11:04
Yeah.

Maloisel, Guirec 11:06
So I'm not sure if it really fits in that case or like how.
What would be the kind of continuous variables that can address? I guess the voltage maybe is one. But in terms of the design, I guess.
You can't really change much continuously or you have.
To.

-: Control

How you can move it then we develop these sensors, you know these are the fabric based sensors or this type of sensors. This is a resistive and capacitive something like this.

-: Sensing

The pump are an issue. We found there like available in the market and Silent and micro pumps and They are like still fairly expensive but for this stage of prototyping, and it's it's good.

-: Noise

But we're surprised to discover that some of the major and brands in Germany, they have like for all four because for example in the city already have integrated pumps, you know for the lower back so important and this kind of thing. So probably see. I know that Yes. Okay.
Facundo Gutierrez: they have thought they have better parts. But what we found when we open it sometimes they have like the same noisy pump you'll find online inside of a leather back with a lot of fun to try to make it silent. But but definitely in

-: Noise

the pneumatics keep giving issues.

-: Prototype shape change

We do still hasve safety concerns. Mainly sharp objects are tricky. We do not have a solution for safety concerns and they are definitely still there. We only interact with it carefully in the lab.

-: Limitations fluidics

Safety concerns

Noisy mechanics

We draw the PCBs manually. It's a lot of work actually. Sharing the script would be very nice

-: Prototype shape change

There is like a fur amount of research that more like Logic gate within the material itself to try to control more outputs with less pumps. So to put some of the smartness, on the material itself, mmm, things like a series of Problems of course. But if you nail that one it will help you. Yeah, to, I mean, we had always this talk like an area Cool research. You're gonna see like an awesome prototype on the soft road. It's super lightweight, a little in a lot of stuff. And then there is a tube that goes to a compressor.

-: Control

That's what it wasn't so far, we were keeping in like relatively. Simple, controlling no more than five circuit. Let's say at the time,

-: Control

We have different types of sensors.
For example, is like a capacitive sensor.
Resistive sensors

-: Sensing

Camera means vision camera can see upper body in the car because camera is not low.
But Kiara, for example covered.

-: Sensing

High control resolution

Material embedded computation

And then the challenge was that typically what what you get will not be physically possible because with these tools selected tool is that where the physics of the robot. So it's gonna introduce some. I don't know sharing or local compression or something that's not not very intuitive.

-: Prototype shape change

table. And and as we started working many with wearables. Always been aware that that's The elephant in the room. Let's say that. Yeah, you can do. and otherwise that is super lightweight and low profile and then you need like a gigantic backpack and then Into the idea. So I am. Yeah, I think the solution is coming from embedding more smartness, in the control in the Material system itself with textiles and silicon or whatever.

-: Control

We have different, basically vital signals and if you realize, oh, you need to move, you will get rehabilitation exercise with a tactile and seat means you move your body right.

-: Sensing

It it's a worry especially because that once we explore more on the medical, so And to know what happen if it breaks if it is safe. And in that case, we're working with water. So, but if it is safe for the skin and things like that. Mmm, but but the, the reason for using like liquids and for us what more
You: Yeah.
Facundo Gutierrez: relatively, I mean, a non-compressible fluid. So, to reduce the volume because that was a closer with let's say where you're just like moving, The liquid from A to B, instead of like having an external pump with an input.

-: Limitations fluidics

No, this seat is was half a million.
It we built this one, the seat itself is very good. There is is amazing seat. There is no noise, is very good.

-: Noise

I mean, like anything, do sculpts and mesh like I think we use Maya I think, but it also blender.

-: Prototype shape change

A lot of with Liquids. So in that one, if you have a leak it's a big problem. But then if you have an open system and with a pump, let's take an error. Then what we learn is that leaks, as long as they're under control, it's like and Sometimes they are not. There and deal breaker, but it really depends on the application.

-: Limitations fluidics

Sensing possibilities

Because this is a completely story by 2029. You can to track the body and to detect out of posse detection. Because of the safety because they know where are you, you know where is your post in the seat.

-: Sensing

But if there will be a sense of touch here, you know. Even if you grasp the object, the object object cannot move. Sorry, cannot be destroyed and object is transferred and vision cannot work here. Or for example, this is the robot.

-: Sensing

Sustainability

Prototyping shape change is hard

Yeah. So I mean for that we use mostly like Maya or any animation software to deform the mesh kind of manually as an artist would do.

-: Prototype shape change

there are always going to chase you with sustainability and

-: Limitations fluidics

Is it pressure sensors with some machine learning algorithms? We do the hand gesture recognition. You know you can have like a tapping pad in different types because you can.

-: Sensing

Yeah. And there are ways to to do. Oscillating. Rings, for example, or encoding sequences of inflation. Depending on how you define design. The resistors, let's say between the channels and things like that. so,

-: Control

but that we're working. Not a microfluidics but I'm really fluidics. And I think that I've seen what you want to use mainly for Microfluidics, because I mean, in the automotive, those were our smallest circuits in a way because if you inflate one button, but if you think something like a bigger surface, like the if you want to see the whole, then you have a problem with with flow rate

-: Limitations fluidics

An animator defined a kind of expressions that he would like to have in a new would optimize for the shape.
Actually of the electrodes.

-: Prototype shape change

Over time we do see some gas forming on the ECG and also they have less fluid in them some how. I also do not know how that happens. However after filling them up a bit they do still work even after 4 months.

-: Limitations fluidics

Durability issues

And because I think it's, it's or at least for a while, it's gonna be tricky to make it. Cost efficient, so it's going to be slightly bulky and slightly expensive. So we
You: Yeah.
Facundo Gutierrez: need to be for for an application. That requires that rather than starting with and must consumption of product, but

-: Limitations fluidics

Dat ik ook weer weer weer aan context van Van het product, maar Als je dat over over Wearables wat ik een vrij logisch logisch implementatie vindt. Ja door het door het stiekem hele ruwe omgeving dus, zeg maar. Mensen zweten een beetje het beweegt het buigt altijd, stof gaat alle kanten op. Voor elektronica een best weel nare omgeving. Het moet wel een jaar of 2 heel blijven, dat is best wel veel.

-: Limitations fluidics

It's this for HML Yes. And it's just like we we measure the internal pressure

-: Sensing

Is pressure sensors with some machine learning algorithms? We do the hand gesture recognition. You know you can have like a tapping pad in different types because you can.

-: Sensing

From lab to market

the majority of interfaces has migrated to the screen and a lot of voice control as well. In China and Western markets in the US, Europe will follow and are indeed following, although. It's likely they will never go quite that far, and China may come back slightly because there's been a rear guard action which I expect you aware of

-: Trends

A scalable and it is skeleton. So, for us, something key was to And that was also one of the best strategic decision of why we decide to go with textile based. So, robot was to,
You: Yeah. Okay that makes sense. Like here we I know we just have a modified 3D
Facundo Gutierrez: To be able to produce role to roll. Essentially, what we admission, and the pilot land. It's just like, you have like different roles and you're like, Melting them together and then you have a soft robot in the end of the night. And

-: Market potential

En klanten zullen ook zeggen, wat kost dat dan?

-: Market potential

En nu moet via klanten alles geïnd worden en daardoor wordt het wel echt de vraag wat is de gebruikers winst, hoe kunnen we dit aan laten sluiten.

-: Market potential

Costs?

Ook, hoe ziet het internet eruit door zo'n interface? Ja, dat zijn interessante vragen, dat kan Natuurlijk geluid en dit gebruik wel nog invallen. Maar hoe? Hoe ziet dat eruit en hoe kun je dan navigeren? Want dat we nu allemaal op een glazen plaat aan wrijven zijn is nou niet het meest logische.

-: Trends

Mooie brug tussen pure technische innovatie en industrial design. Hoe kunnen we nou met deze technologie een gaaf product ontwikkelen door deze technologie te gebruiken op een manier waar deze onderzoekers nog nooit aan gedacht hadden.

-: Market potential

Ik kan het in professionele sectoren wel voor me zien. sommige dingen zijn nou eenmaal niet aan de consumenten markt besteed. As je dit kan gebruiken om op een hele andere manier kan voelen.

-: Market potential

Visualize its potential

Look outside consumer market

To some degree, I don't think you should only be looking to establish whether what you've got might align or fit with trends when it's potentially something which is innovating or pioneering, and therefore in a position to potentially Dr. and effect changes and trends.

-: Trends

So, does it fit within automotive? Broadly speaking, yes, it does. I wouldn't say it's strictly on trend, but it aligns with the growing emergence of haptic technologies. To some extent, you could say it taps into that. But more importantly, I think it's highly relevant, especially when used in conjunction with voice and other forms of input or feedback.

-: Trends

Ook met bijvoorbeeld een cursor op een scherm bewegen is eigenlijk heel raar dat je niet voelt aanraken je het aan de objecten van het scherm zit. Ik geloof, je bent misschien al soort van je, een soort platte wereld

-: Trends

If it's something which actually is more controllable, and then if it doesn't make sense for us to include in a design trend report and instead if you have a small. Video clip of it that would also be appropriate. So yeah, just keep me posted because I'm curious to know how this goes. I do think that what you've got there as a sort of. Offer really does have validity.

-: Market potential

You need to work out that and I suppose related to that you also just as an individual and professionally need to work out what if you like the own as your competency, you know what you can do which nobody else can do because of reasons XYZ. And yeah, sure, that might be a bit harder to find, but I think somehow you need to make yourself a valuable commodity, not just in terms of describing what you can do so they can understand that and take it. But in terms of how you describe what you can do to. Take what you've got further

-: Market potential

would imagine you ought to get to successfully engage with them to gain some feedback like I'm doing with you, but also to some extent, you might be giving away your idea. And or your. Equity, it's always a challenge. I think in your situation as is as a consultant sometimes. So maybe you also need to be fairly clear at the outset what you're seeking to gain from them potentially in terms of a position or a placement or some form of contract to again to be able to work with them or maybe some sort of research sponsorship to to progress what you've got.

-: Market potential

Haptic dimension to displays

Client adoption

Client adoption

This artificial muscles inside the spikot type of project.
I mean it.
It remained a more like a blue Sky research project. In the end I didn't.
Yeah, so far we haven't really explored concretely how to use that parameter, because I mean, there's still a whole question of where.
To route and meet the.
The muscles in like the inlet and outlet.
And also the noise that you can make.
So I mean that from that point of view that that could be promising.

-: Trends

So novel it could set a trend

Ja, Als je kijkt naar naar onze projecten dan, want zijn onze klanten niet zo heel tech savy zegmaar. Ze hebben een probleem en willen een oplossing, dat doen wij voor ze. Een aantal jaar geleden werkten we met een 60 milli wave sensor waar je mensen mee in de ruimte kunt zien, of dat vinden ze echt tofl! Maar dat is ook heel erg de engineering mindset en waren zij een stuk minder enthousiast. Dat is prima want wij zijn de technevt.

-: Market potential

that being said, normally it could start from a design department or sometimes from Kind of portfolio growth kind of manager. So someone that was actually not really expert on product development, but they they saw the opportunity to do something new and most of the time, it was sort of curiosity driven. And then you need to see there which ones
You: Yeah.
Facundo Gutierrez: have potential to go to the market and which ones the brands are just interesting enough. So case, that's gonna look cool for me, making some waves. But then And not really applying to push it forward.

-: Market potential

en als iemand in Amerika dan jouw paper leest over 5 jaar denkt dat is tof doordat ook die use cases erin staan, ja dan be je koning.

-: Market potential

Obviously, I think the challenge with the project you've got is that it's inherently quite slight or small. So the, the, the magic of it is only really going to be known when you've actually got it in a fairly fully realised production capacit

-: Market potential

not sure that what you've got should necessarily align to trends, because then you are passively following something when actually your technology might be central to leading something. I'm not saying your specific projects. Have to reinvent the wheel for the car industry, but.

-: Trends

Actually, now the new ones doesn't have any screen anymore.
Screen is old.

-: Trends

No screen or voice control

Sector where you have a small nudge to draw your attention to what something is, and then that thing is identified through a spoken word or sound rather and or visual. So in other words, the product that you have works as in in a way to effectively augment the performance of other interfaces

-: Multimodal

there's not a lot in real world applications but it's in the market and one of the things that we cost, so automotive, even if you're in the lecture luxury segment is very it's very tight so it's very competitive. So they try to save a lot and so, Wait, is an issue of course, but cost is another one.

-: Market potential

Applications

the 4th thought application would be music. So to augment the sound that you get to sort of fundamentally if you like, if you think about how you might hear a piece of music in your in your your.
Speaker
Oh, OK.
Speaker 1
Yeah.
Speaker 2
Your foot is tapping the floor because involuntarily, you're sort of, you know, so actually to have some subtle sort of movement that augments things like music could be, I think, not necessarily useful and maybe not everybody wants it, but I still like that could be a thing.

-: Applications

Feedback naar een gebruiker toe is is is best een best complex ding omdat er gewoon niet zo veel id. we hebben beeldschermen audio en ledjes. maar eigenlijk is die connectie met techniek nooit echt seamless. als ik toegang wil tot mijn telefoon, moet ik mijn telefoon pakken. als we het over VR hebben heb je weer een bril nodig die je eerst op moet doen. Wat dat betreft is haptics een hele subtiele manier van output van een digitaal systeem.

-: Applications

..Let's say that's a tool for remote operation, like for surgery or or even fixing something, or aerospace, this kind of things. And because I think it's, it's or at least for a while, it's gonna be tricky to make it. Cost efficient, so it's going to be slightly bulky and slightly expensive. So we
You: Yeah.
Facundo Gutierrez: need to be for for an application. That requires that rather than starting with and must consumption of product, but

-: Applications

De schroevendraaier van een toekomst zeg maar, Misschien kunnen we wel de diameter van het handvat veranderen en kunnen we daarmee de torque varieren.

-: Applications

Als je gewoon kijkt naar pixels op je scherm kun je dat natuurlijk ook in je hardware iets laten doen, dan kun je gewoon in after effects iets in 2d tekenen en dan kijk je of die 2d map en map je die naar de electrodes op dat ding.

-: Applications

zeg een toetsenbord van je laptop dat dat dat dat dat dynamisch toetsen kan kan kan maken,

-: Applications

Dynamische vliegtuigvleugels, dus aerodynamische vlakken , dat je hollingen kan verander.

-: Applications

Maybe to feel another persons heartbeat. she even used human like materials as it really fit the context. maybe kombucha? gets very skin like?

-: Applications

I don't remember the company, but they have like these haptic gloves and they have a team up to 20 texts per finger, which is something that different technology will be
You: Yeah.
Facundo Gutierrez: impossible to achieve

-: Applications

Maybe its even impossible to design for a certain emotion. different sensual surfaces.

-: Applications

in materiability have may project with the concept breathe.

-: Applications

Het eerste waar ik aan denk is, stel je hebt een t shirt waar dit in verwerkt zit, dan is dat een subtiele manier van ontvangen van feedback. En daarnaast ontvang jij het alleen. Met beeldschermen of ledjes is dat nooit echt individueel.

-: Applications

It will be amazing if you could make it a tutorial. Yes It is very nice and was hard to maintain.

-: Applications

It could possibly even layer these and have different patterns of electrodes and. Combining these have more larger range of Faucets that you can realize.
I don't know if it's something considered at all.

-: Applications

It super high transfer potential for any product or surface you interact with that wants to communicate data and information. Haptically communicating the senses. wall or a phone.

-: Applications

Bij microsoft Research hadden we zo een programmeer.
Tool gemaakt voor blinde kinderen. Dat is Misschien ook wel waar waar dit interessant is, Omdat je dan ja, Dat was allemaal met draaien en kabels. De wind en soort van op een tafel. Maar dat ja, ik kan me voorstellen dat dit soort actuators.
Voor Mensen die niet kunnen zien, dan kunnen helpen

-: Applications

And you deform the skin to where it shapes basically.
But you could potentially get more subtle.
Expressions by directly creating the skin basically.

-: Applications

In a vehicle, though, there's the opportunity for much more. For example, imagine it was running along your leg although that might not be the best idea, just for the sake of argument. It could actually deliver a sequence of movements

-: Applications

maybe in the medical fields, calming the nervous systems, or a patch for children. soft massage. like a braille canvas. Like a kindle with this technology.

-: Applications

We see most potential in haptic technologies for EDPs as the resolution is very high and would be able to provide good haptic feedback. We are looking at VR and cars mainly. but also putting it on body.

-: Applications

Maybe for animatronic, especially for the skin or like because we so typically how these are actuated?
Is that you have?
Rigid linkages inside the head, and then there's a silicone skin on top that's attached. So points and it's so it's a bit like puppeteering in a way.

-: Applications

So the way you get notification on on, on a watch or something like that on your phone, which just gives you a little bump to inform me that notifications happen. It seems like an obvious opportunity for that to be, if you like that.

-: Applications

Words filming it early in the morning, but a low a background notification form and and therefore the way that that would work is exclusively in conjunction with a visual or audio alert as well. And I think that would actually in my view be a very effective interface which has not really happened in the auto.

-: Applications

Also, be in a seat or some other area where the steering where the where the where the driver is in constant constant contact with it such that that notification is something which reliably reaches them. So that strikes me as like the most obvious opportunity space and something which is quite cool albeit.

-: Applications

Ja en meerder dimensies zou inderdaad heel interessant zijn. waar we nu naar een twee dimensionaal scherm kijken en er zit een derde dimensie in die je kan beinvloeden met je muis. en Als je ecth andere dimensies zou kunnen voelen in je scherm. En er zijn waarschijnlijk beroepen waarbij ditt heel belangrijk is

-: Applications

That same potential applies to the steering wheel too. You don't know exactly where the driver's hands will be, and different people use their hands differently. So, maybe it has a directional pulse something that moves in a certain direction to signal something specific. That alone gives it a completely different feel from existing haptic experiences and opens up new kinds of communication

-: Applications

Ik zat ook te denken dat als je gewoon een touchpad hiermee maakt dat het ook wel best wel nice is om te laten zien wat het concept is.

-: Applications

The soft advantage

Shape change as language

You know, for example, when you see you know and then you can feel also. Or we call it even teleoperation you know there there are many use cases, for example, for the Tele operation, for even, for the telemedicine. You can use it for the Tele operation means if you want to have a robot. You know, the robot wants to grasp something, and then you see, and the robot is grasping. But you need to feel it by what the robot can feel as well.

-: Haptic interaction

We have a tactile, you know, and then it you can interact basically with the armrest is a kind of an armrest, but it's a like a skin on your body.

-: Haptic interaction

That alone gives it a completely different feel from existing haptic experiences and opens up new kinds of communication

-: Haptic interaction

Abkoude, Tessa van 20:11
The haptic feedback or what type is it?

Kaboli Mohsen, ZI-212 20:13
Actually we we use just the the motors of the the robot even we didn't use it because the motor.

Abkoude, Tessa van 20:20
Ah, OK.

Kaboli Mohsen, ZI-212 20:22
It gives some because the we we we intentionally tried to.
Use whatever seat has you know.

-: Shape change

We have also the Raiders and when you are in a seat, even with the pressures even I know how you are sitting and the seat can change your body pose you know in order to have a UU pressure on the seat and not to feel pain and.

-: Shape change

So basically we are working on multimodal perception.
For interiors of the car, you know, for example, having a tactile haptics vision, you know, Raiders and so on.

-: Multimodal

Feedback naar een gebruiker toe is is is best een best complex ding omdat er gewoon niet zo veel id. we hebben beeldschermen audio en ledjes. maar eigenlijk is die connectie met techniek nooit echt seamless. als ik toegang wil tot mijn telefoon, moet ik mijn telefoon pakken. als we het over VR hebben heb je weer een bril nodig die je eerst op moet doen. Wat dat betreft is haptics een hele subtiele manier van output van een digitaal systeem.

-: Bridge digital with physical

Subtle nudging

Expressive haptics for digital layers (AI IoT etc)

New feel of communication

So the way you get notification on on, on a watch or something like that on your phone, which just gives you a little bump to inform me that notifications happen. It seems like an obvious opportunity for that to be, if you like that

-: Haptic interaction

We have different like rufuni, nufonian, caepaus or I don't know pachini and so on here and in one I mean the finger tip we have 200 receptors here in in actually in a human. If you put your finger like this two fingers and put it on your.
Back you you feel there is only one point.

-: Haptic interaction

If you have now VR, Glasses. Then you can see.
And the robot can see this one.
And then can learn. But what you feel the robot cannot feel and vice versa?

-: Haptic interaction

This is the thing. Then we could have a multimodal interaction, you know. For example, if you're gonna have like a teams in the car and you have this armrest, we could feel each other, you know, you know, we could, you know, two cars you know.

-: Responsive surfaces

Multimodal

We, we and we mean: everyone sees its own stuff and you can interact basically by the armrest here.

-: Haptic interaction

Exactly. You don't see. Even you don't see just you touch it and then you can control. Basically everything is like is my body, you know is my body.

-: Haptic interaction

Complex shapes

Higher resolution is very important.
Because, you know, in human.

-: Haptic interaction

In terms of shapes we have not really explored anything. We are still sticking to squares and regular grids.

-: Interaction vocabulary

Communicate through movement and speed

And then it's a question of talking about how the nature of your technology then actually provides of trying to paint the picture more in terms of actually how it then feels and somehow knock up that whether it's the steering wheel, the seat, whether you it's progression, the speed of it, the variance and and the opportunity for you to be able to provide not just a sort of the single here we are that's the notification, but through movement and speed. And with the. The degree to which it notifies you to articulate, I'm going to say four or five, maybe six or seven, I don't know, but it won't be endless different ways that one sort of set embedded whenever these called can actually do it.

-: Interaction vocabulary

Color is like this color stands for this
not really for sounds or haptics.

-: Interaction vocabulary

Trying out shape change

we start with syringes and pumps hand held so direct and fluent and fast. Then we smaller pump control station with an Arduino. for defined pretesting. three rotary knobs, air in air out, venting, volume amplitude.
pump not strong enough for bigger than 25 cm. the fluid was not as fluid as I hoped for because of the gradient was not so smooth.

-: Prototype shape change

Now with this why you want you mainly pair it with like a voice or a visual interface that you have them combined right to provide more information about the.

-: Multimodal

Words filming it early in the morning, but a low a background notification form and and therefore the way that that would work is exclusively in conjunction with a visual or audio alert as well. And I think that would actually in my view be a very effective interface which has not really happened in the auto.

-: Multimodal

Let the material speak

We find a material super open and explorative, what does the material allow you to do it. or you could do top down, design for an application and make the material do what you want to do.

-: Prototype shape change

Als je gewoon kijkt naar pixels op je scherm kun je dat natuurlijk ook in je hardware iets laten doen, dan kun je gewoon in after effects iets in 2d tekenen en dan kijk je of die 2d map en map je die naar de electrodes op dat ding.

-: Interaction vocabulary

I was always searching someone to help me in that idea is called tactile. Is a tactile Internet, is vehicle to vehicle communication. Look now we can see each other and we can hear each other, but we cannot feel each other. If we will have this this we will have this.

Abkoude, Tessa van 37:43
Yeah.
Yeah.

Kaboli Mohsen, ZI-212 37:49
Sensors, you know, I'm when I'm touching. Then you will be touched.
There, you know, because you will get.

-: Responsive surfaces

Shy tech

If you touch anywhere. You know, then you can control because it's that area is we call it sensitive areas. You don't see because in BMW it's called shy tech. This you don't see the technology, but if the we call it function in demand if you need it pop. it comes it pop.

-: Integration

pop up on demand

These are.
This is just for our to control something.
This is not doesn't exist and this goes inside and we have something even.
This is the basically the the.
The glass, you know, like a rear glass

-: Integration

Or for the armrest. If you have an armrest, you know we have this sensor and you have it here, then we could even feel, you know or with a seat you could feel this one was the idea.

-: Integration

Integration

Here in the car and exactly and then this part will be can be transferred. A non transparent and everything can be projected, but for the interaction look the sensors is here.

-: Integration

And you know, is flexible and even foldable everything and is a capacitive, you know

-: Integration

And the idea is there is no button anything. How you can move it then we develop these sensors, you know these are the fabric based sensors or this type of sensors.
This is a resistive and capacitive something like this.

-: Integration

mple, it will be on a seat and also the armrest for example. You know I can show you even.

-: Integration

Up and then you interact. Then it will basically fade out.

-: Shy Tech

This is the thing we we call it private communication.

-: Shy Tech

Private communication

Het eerste waar ik aan denk is, stel je hebt een t shirt waar dit in verwerkt zit, dan is dat een subtiele manier van ontvangen van feedback. En daarnaast ontvang jij het alleen. Met beeldschermen of ledjes is dat nooit echt individueel.

-: Shy Tech

But if you you are using the finger you know touch because the touch is the.

Abkoude, Tessa van 49:47
Yeah.

Kaboli Mohsen, ZI-212 49:54
Is a private communication and people they prefer to use silent communication and brings a privacy.

-: Shy Tech

This you don't see the technology, but if the we call it function in demand if you need it then it comes it pop.

-: Shy Tech

The main thing, I think, is just talking about the way it communicates, and how that has a certain value compared to other ways people might be informed. Because what you've actually got there is also a very private kind of notification. If you've got multiple users in the car, this could be a signal or message that only one person is aware of.

-: Shy Tech

Privacy

And the other thing is we call it a, we call it privacy because if there will be a sound or a vision based on the basically the vision, everyone can.
Get to know those messages.
But if you want to have it private.
You know, then the car can use kind of the haptic for us is bringa a privacy.

-: Shy Tech

They might be different, you know, because it's silicone silicone or for example, as I said, I was trying to bring like a textile based stuff, you know.
And when it comes to the actuators.
Of course.
But silicone.
I don't know.
I don't know this this kind of thing, but.
I we have a neighbour department.
They are working on materials.
That's for the interiors.

-: Integrated in fabrics

Integration in fabrics

to have exactly the material that is perfectly fit to aim what to accomplish with it. So interesting and so hard at the same time. where to start with choosing a metrial, textile would be amazing, but silicone its parameters n aptic experiences are limited. certain types of interactions you would like to encrouages you with is

-: Integrated in fabrics

We can die. Any materials to be the the sensor and I can. And if you ask me why, for example, here, as I said, we have a multi modal sensor. We are measuring the biosignals body temperature, heat, everything.

-: Integrated in fabrics

Integration

for example, with lots of something that pop out and and they were quite happy that we say we can put it in the steering wheel and they were like first, like there's no way we can put anything in the steering wheel because there is just no Technical space and it's a double curvature surface and the need to be super tight and and we could because it's really a stick and it will shape.

-: Integration

For example, your clothes. What? You have it.

Abkoude, Tessa van 15:09
Yeah.

Kaboli Mohsen, ZI-212 15:10
This can be a sensor.
We have it.
We have this as soft as this.

-: Integrated in fabrics

Subtle haptic feedback

Will be soft means you can have will be adaptive and bring to safety because for the human robot interaction.

-: Soft

Adaptivity

Working on a tactile and haptic as well and this for example one of the application will be an armrest

-: Responsive surfaces

Sensing

Even for example, I'm moving you can see. And then even we can detect the size of the. Basically the person here and only the area you are in contact will be warmed up.

Abkoude, Tessa van 18:44
Yeah.

Kaboli Mohsen, ZI-212 18:52
You know or cool down. And this is like interactive surfaces

-: Responsive surfaces

It is because we can then integrate it and deform around difficult shapes. Also people find the haptic feedback nicer than motors or vibration. soft is an very obvious choice I think. Also with the flex PCBs we were able to go even thinner. We are now lookin into stretchable PCBs to be able to make them even more soft and flexible.

-: Soft

Well in that we're gonna I think we've always been quite lucky because most of the time the clients found us another way around. So they were not We didn't have to sell on why soft. It's

-: Soft

Robot can feel, you know, you need to be soft everything because.
Then then we we call it embodied intelligence.
Because the future robotics will not be hard.

-: Soft

Appendix G

1. EOP explained
2. SCI actuation benchmark
3. Workshop
4. Safety

A

Electro osmotic pumps

Electro-osmotic pumps (EOPs) form the core actuation technology in this haptic interface. Unlike conventional pumps, they operate entirely without mechanical movement. Fluid is drawn through a porous membrane by applying a low voltage across two patterned electrodes. This approach enables thin, silent, and scalable actuation in soft, sealed microchambers.

Fundamental Principle of Electro-Osmotic Flow

Electro-osmotic flow (EOF) refers to the motion of liquid through narrow pores under the influence of an electric field. The process relies on a subtle but important surface-level interaction: when a polar fluid (e.g. distilled water) contacts a solid surface like glass, chemical groups on the surface (specifically silanol groups, Si–OH) can release hydrogen ions (H^+), leaving behind a net negative charge in the form of siloxide ions ($Si–O^-$). This negatively charged surface attracts positive ions (counterions) from the fluid, forming a mobile layer of charge near the surface.

When an electric field is applied across this charged porous material, the positive ions begin to flow toward the negatively charged electrode (the cathode). Because these ions are surrounded by solvent molecules they drag fluid with them as they move. This interaction results in a smooth, net flow of fluid in the direction of the ion drift.

The resulting fluid velocity u can be described by the Helmholtz–Smoluchowski equation:

$$u = \frac{\varepsilon \zeta}{\eta} E$$

where:

- ε: the fluid's permittivity (its ability to allow electric fields to pass through),
- ζ: the surface potential of the porous membrane (related to the strength of the surface charge),
- η: the viscosity of the fluid (how easily it flows),
- E: the applied electric field (voltage divided by the thickness of the membrane).

This formula shows that to maximize flow, the system should use a high-permittivity fluid, low-viscosity liquid, and materials with a strong surface charge. The flow is directly proportional to the applied field, making EOPs controllable and reversible via simple electrical signals.

System Architecture: Layered Pump Stack

The physical layout of the pump closely follows the flat panel haptics [20] design. The device consists of a vertically stacked architecture, from bottom to top:

- **Fluid reservoir**: The base layer holds a supply of pumping fluid—propylene carbonate with a small amount of dissolved salt.

- **Bottom electrode**: A gold-coated PCB with vertical through-holes, aligned with each pumping unit. It provides the lower electrical contact and allows fluid access into the membrane above.
- **Glass fiber filter membrane**: A laser-cut disc of porous borosilicate glass. This is the active pumping medium.
- **Top electrode**: Identical in layout and material to the bottom electrode. It completes the electric field path and enables upward fluid motion.
- **Fluid chamber**: A small, sealed pocket above each filter captures pumped fluid.
- **Flexible membrane**: The top layer is a deformable silicone sheet that inflates locally when fluid fills the chamber beneath it, producing a tangible bump.

When voltage is applied with the bottom electrode made positive and the top electrode negative, positive ions in the fluid begin to migrate upward through the filter. This electrokinetic motion drags fluid from the reservoir, through the membrane, and into the top chamber—causing the silicone membrane to bulge outward.

Electrode Design and Perforation Geometry

Electrode patterning is critical to the efficiency of the pump. Both the top and bottom electrodes are made from thin PCB layers coated with gold for chemical stability. Each electrode includes an array of vertical through-holes (typically 200–250 µm in diameter, with 1 mm spacing). These holes serve two purposes: they allow the electric field to penetrate the membrane, and they allow the fluid to physically move upward.

The ratio of hole size to spacing is tuned to ensure a homogeneous electric field across the full area of each pump. Too few holes lead to field gradients and uneven pumping; too many reduce structural stability or interfere with electrode function. In flat panel haptics, the geometry is chosen to balance field uniformity, fluid throughput, and mechanical strength. The circular layout and via alignment with the filter ensures vertical flow without turbulence or dead zones.

The electrodes are placed directly against the filter membrane, ensuring close proximity and minimizing the required voltage. Because both electrodes are porous, fluid can pass from the reservoir, through the membrane, and into the upper chamber without obstruction.

Glass Fiber Filter: Molecular-Level Function

The glass fiber filter is a porous disc made from borosilicate glass, typically with pore sizes of 0.7–1.2 µm. At the molecular scale, its function is driven by the chemistry of the glass surface. Silanol (Si–OH) groups on the silica structure lose protons when in contact with a polar solvent, leaving Si–O□ groups behind. These create a net negative charge throughout the internal surface of the filter.

When the fluid (propylene carbonate with dissolved salt) enters the membrane, the positive ions from the salt are drawn to these negative sites. The largest of these are tetrabutylammonium ions (TBA□), which loosely associate with the charged pore walls.

When voltage is applied, TBA□ ions migrate toward the cathode, dragging surrounding solvent molecules with them through the complex network of pores. This generates bulk flow, even though the actual surface charge is distributed in many random directions along the internal walls. Because the filter is shaped as a thin disc, and the voltage is applied vertically, the net result is consistent upward flow.

At the macro scale, the glass fiber filter behaves like a spongy, ion-sensitive pump. It contains no valves, no pistons, and no moving components—just a passive network of microchannels that activate when voltage is applied.

Pumping Fluid Choice: Why Propylene Carbonate?

In conventional electro-osmotic systems, water is often used due to its high permittivity and ion-carrying capacity. However, water brings significant downsides for sealed, solid-state devices:

- **Electrolysis**: Water splits into hydrogen and oxygen under moderate voltage, forming gas bubbles that disrupt the flow.

- **Evaporation**: Even in sealed cavities, water loss over time is a reliability risk.
- **pH drift**: Electrochemical reactions change the fluid's acidity, altering performance and degrading materials.

Propylene carbonate (PC) solves these problems. It is a polar aprotic solvent, meaning it carries electric charge well but does not easily undergo electrolysis. Its dielectric constant is high ($\varepsilon \approx 65$), supporting ion separation. Its viscosity is low, enabling fast flow, and its volatility is minimal—so it stays stable in a closed device over months or years. Crucially, it interacts favorably with glass surfaces, allowing the formation of a stable negative surface charge.

To create the ion-carrying environment needed for pumping, a salt such as tetrabutylammonium perchlorate is added to the fluid. The large TBA□ ions are effective charge carriers, remain stable in PC, and do not easily adhere to surfaces or clog pores. Together, this combination provides a long-lived, efficient electro-osmotic pumping fluid.

Controlling Flow: Voltage Polarity and Performance

The flow direction is entirely controlled by the voltage polarity. When the bottom electrode is made positive and the top electrode negative, TBA□ ions and the fluid move upward. Reversing the voltage reverses the flow. This bidirectional capability is a unique strength of EOPs—allowing both inflation and deflation of the flexible membrane under full electrical control.

The amount of flow depends on:

- The strength of the electric field (i.e., voltage across the membrane)
- The permittivity and viscosity of the fluid
- The surface charge of the membrane
- The electrode coverage and geometry

In flat panel haptics, pumps typically operate at a few tens of volts and achieve up to ±50 kPa of pressure. Each actuation cycle fills or empties the upper chamber in roughly one second, resulting in tactile feedback that is fast, repeatable, and energy-efficient.

Conclusion

Electro-osmotic pumps enable a radically different approach to haptic actuation: one based on fluid physics and solid-state control, not mechanical motion. By carefully engineering each part of the system—from electrode geometry to surface chemistry to fluid properties—it's possible to build thin, durable, and high-performance devices. The glass fiber filter provides the charged microstructure. The PC-based fluid enables stable operation. And the electrode design ensures effective field penetration and fluid flow.

Together, these choices make EOPs uniquely suited to applications like shape-changing displays, wearable haptics, and next-generation human–computer interaction.

B

Benchmarking mechanisms

Nowadays, we interact with technology more closely than ever before. As products become more embedded into daily life, there is an opportunity, and a need, to rethink how they communicate and respond. Many current interfaces feel rigid and detached from the way we naturally interact with the world. In contrast, soft interfaces offer a more intuitive, expressive, and human approach. Inspired by soft robotics, they use soft materials and shape change to create interactions that adapt to us; physically, quietly, and responsively.

This shift aligns with a broader challenge in the field: how can we create shape-changing interfaces that are not only expressive, but also thin, scalable, quiet, and energy-efficient? As outlined in Rasmussen et al.'s *Grand Challenges in Shape-Changing Interfaces* [1], no single actuator technology meets all design goals. Early pioneering work, such as Iwata et al.'s *Project FEELEX* [9] and Follmer et al.'s *inFORM* [7], demonstrated the feasibility of using arrays of motorized pins to generate haptic relief and spatial feedback. Mechanical and pneumatic systems offer strong forces but add bulk and noise. Meanwhile, emerging actuators like dielectric elastomers and electroosmotic pumps (EOPs) show great promise for high-resolution, silent, and integrated shape change.

This thesis focuses on the creation of soft interfaces and explores EOPs as a particularly suitable actuation method. Through a detailed comparison of available technologies, I identify where EOPs stand out and how they can enable interfaces that are not only functional, but feel natural and expressive. This review surveys these diverse actuation methods in detail, examining their operational principles, performance parameters, integration challenges, and suitability for various applications. Emphasis is placed on key metrics such as spatial resolution, integration/form factor, scale of operation, force output, power consumption, actuation speed, noise levels, and manufacturability.

Mechanical

Pin - based displays employ arrays of actuated pins to render dynamic, tactile surfaces. Early work such as *inFORM* [7] used hundreds of motorized push-rods to create 3D forms, while Iwata et al.'s *Project FEELEX* [9] introduced haptic feedback for graphical output. More recent approaches like MorphMatrix [4] have reduced hardware complexity by driving 64 pins with only two motors via a camshaft mechanism. Although such systems offer high spatial resolution, each pin serving as a discrete "pixel", they are often limited by bulky wiring, high power draw, and scalability issues.

Motorized actuation utilizes electromagnetic motors (DC motors, servos, linear actuators, or steppers) and mechanical linkages to produce shape change. These systems deliver significant force and stroke, enabling even a small servo to bend plastic or lift several hundred grams, making them well-suited for supporting user interaction forces or fast actuation. For instance, ShapeClip [8] provided a low-cost kit where servo-driven rods could be attached to furniture to form dynamic interfaces, while larger installations like Relief and TRANSFORM employ grids of motor-driven pins to create 3D surfaces. More recent designs, such as those in MorphMatrix [4], offer flexible frameworks with linear actuators and customizable linkages for prototyping widgets like buttons and sliders. The key advantages of

motorized systems lie in their precise control and rapid response, often achieving millisecond-scale actuation, and their ease of integration with standard electronic control (e.g., microcontrollers and drivers). However, traditional motors (especially linear actuators with lead-screws or gearboxes) tend to be bulky and heavy, making them unsuitable for wearable or mobile devices. Furthermore, scaling up (e.g., a 10×10 array) increases system complexity, power consumption, and noise, which can detract from the desired subtle or ambient interaction. Although actuator multiplexing and other smart mechanisms can mitigate these issues, the grand challenge remains: achieving comparable force and speed in much smaller, lighter packages or designing mechanisms that significantly reduce the number of motors required for a given shape resolution.

Fluidic Shape-Changing Interfaces

Pneumatics

Pneumatic actuation uses compressed air or vacuum to inflate, deflate, or otherwise deform soft structures. It is one of the earliest and most popular approaches in shape-changing interface research. Pneumatics excel at producing smooth, continuous deformations and soft, safe interactions. They can achieve relatively large shape changes using lightweight components such as flexible membranes and air. Many interfaces leverage this principle, from flexible displays that bulge under touch to wearable devices that tighten or loosen. In terms of performance, pneumatics offer moderate speed (inflation typically occurs in a second or two, depending on pump strength) and can generate substantial force/-pressure (e.g., enough to lift objects or provide haptic force). However, they require external hardware such as pumps, compressors, and valve controllers, which can impact integration into mobile devices. Efforts like Sustainfatable [14] explore using ambient energy (e.g., solar-heated air) to drive pneumatics, reducing tethering and power needs. Overall, pneumatic actuation provides highly deformable, soft, and scalable shape change, but faces challenges including sustaining pressure (leaks or material creep), system bulk (from air supplies), and noise (from pumps and valves). Designers mitigate these issues by employing quiet pumps, passive check-valves to maintain shape without continuous power, or by relocating the air source away from the user. Notable examples include Ou et al.'s aeroMorph [17], which developed a software and CNC heat-sealing system to quickly fabricate custom inflatable hinges in paper and plastic.Despite delivering smooth, continuous deformations and high force output, pneumatics add bulk through external tubing, pumps, and valves, and typically produce audible noise.

Fluidics

Fluidic systems use liquids to drive motion. In shape-changing interfaces, liquids enable precise control and decent force output, with one-way valves often used to hold positions[15]. While hydraulics are attractive for applications demanding rigidity or load-bearing support, they introduce bulk from reservoirs and pose leakage risks, factors that make them less suitable for wearable or ultra-thin designs. Moreover, fluid-based actuators can leverage properties such as viscosity or inertia to create damping or resistance when a user deforms a fluid-filled interface. In wearable contexts, researchers have explored fluidic fibers and textiles, such as OmniFiber [10], which integrate narrow fluidic channels in fibers that bend when air or liquid is pumped, allowing fabrics to "move" and provide gentle forces for assistive clothing. Other examples include phase-change hydraulics, where Narumi et al.[16] developed Liquid Pouch Motors: flat actuators containing a small amount of liquid that vaporizes when heated, expanding the pouch like a piston (fabricated via laser welding for rapid prototyping). Although fluidic actuation demonstrates robust force capabilities as seen in robotics (where hydraulics power heavy machinery), these systems share challenges with pneumatics: they require pumps and valves, are complex to assemble, and raise safety or usability concerns (e.g., potential leaks that could damage electronics or cause discomfort). Hence, despite promising advances like self-contained fluid circuits in soft robots, fluidic actuation remains primarily in the context of research prototypes.

Microfluidics

Microfluidic Actuation

Microfluidic actuation embeds networks of small channels and chambers into thin films to achieve high-resolution, localized shape change. The milliMorph project [13] demonstrates that a thin, flexible film with millimeter-scale "actuator pixels" can produce intricate surface deformations. By using networks of microchannels, chambers, and often MEMS-scale pumps or valves, microfluidics bring fluid-based shape change down to the millimeter or sub-millimeter scale. The HCI community has been actively exploring microfluidics as a way to achieve high-resolution shape outputs in thin, flexible form factors. For example, milliMorph showcased a thin-film material with embedded millimeter-scale fluidic chambers and channels that can be selectively inflated. Lu et al. detailed design and fabrication techniques for these tiny fluid networks, effectively creating programmable deformation pixels on a sheet. Because each chamber is small, the material can bend or bulge at many closely spaced points, producing rich shape details that larger pneumatic bladders cannot achieve. Although each micro-actuator typically generates only a few newtons of force (suitable for tactile feedback), microfluidics enable extremely high integration since actuators can be built directly into layers of an interface (such as films or textiles). They are also largely silent, given that fluid motion at the micro-scale produces negligible noise, and many microfluidic pumps have no moving parts. Furthermore, the speed is high; small volumes of fluid can be moved in fractions of a second, so microfluidic elements often respond almost instantaneously. Despite these advantages, microfluidic shape-changing interfaces are technically challenging, requiring specialized fabrication techniques (cleanroom micromachining, laser cutting, or novel printing techniques) and careful sealing of minute volumes. Researchers have begun developing design tools, such as MilliWare [29], to assist in parametric modeling and simulation of millifluidic interfaces. While microfluidic actuators are ideal for small, detailed interfaces (e.g., wearable pads or tactile displays), scaling them up by tiling many micro-chambers presents challenges in wiring and control.

Electroosmotic Pumps (EOPs)

Electroosmotic pumps (EOPs) use high electric fields to drive fluid through microchannels without any moving parts. In the Flat Panel Haptics project [20] and FlexEOP [28], arrays of Embedded Electroosmotic Pumps (EEOPs) are integrated into actuator layers only 1–2 mm thick. Operating at high voltages (typically 100–300 V) but drawing very low current (in the µA–mA range), they achieve rapid response (around 1 s per stroke) and enable high-resolution, silent shape-changing surfaces, though their force output is modest (approximately 1 N per cell). An EOP uses an electric field to drive ions in a fluid through tiny channels or porous media, effectively pumping the fluid on a microscale without traditional moving parts. Shultz and Harrison's Flat Panel Haptics demonstrated this concept by achieving a shape-changing display that is only a few millimeters thick; each EEOP unit moves its entire fluid volume in about 1 second, generating up to 50 kPa of pressure; enough to lift a 5 mm bump capable of resisting a typical finger press. Notably, the system remains under 5 mm in total thickness (including fluid and a flexible top layer), making it suitable for integration behind OLED screens in tablets or phones. EOP-based actuators are quiet and low-power compared to electromagnetic or SMA actuators, and they offer fine resolution since pump pixels can be made as small as needed. On the downside, EOPs require high voltage, which adds circuit complexity, and the fluid and pump materials must be carefully chosen to avoid issues like drying, bubble formation, or electrochemical degradation. Although currently experimental and fabricated in controlled lab settings, their reliance on microfluidic and PCB-printing techniques suggests a viable path to mass production.

Smart Material Actuators

Dielectric (Electroactive) Actuators

Dielectric elastomer actuators (DEAs) are based on thin, rubbery membranes with compliant electrodes that expand or contract when subjected to high electric fields (typically 1–5 kV). One notable example is HASEL actuators [19], which use liquid-filled pouches to achieve lifelike, muscle-like movements in ultra-thin packages. Schultz et al. [20] further discuss the potential of electroactive polymers for achieving high-resolution, silent actuation. Although DEAs offer extremely fast response (in the millisecond range) and excellent integration (down to micron thickness), their force output is

limited for load-bearing tasks and the high-voltage drive circuitry requires careful design. In HCI, dielectric actuators are emerging as a means to embed actuation directly into surfaces. For instance, researchers such as Leithinger et al. have suggested that electro-actuated materials could eventually replace bulky mechanical actuators, enabling interfaces that appear to "breathe" or pulse naturally. The strengths of dielectric actuators include their slim form factor, high bandwidth, and silent operation; however, challenges remain in terms of manufacturing uniform thin films with reliable electrodes and encapsulation for longevity.

Shape Memory Alloys (SMAs)

Shape memory alloys (SMAs), such as Nitinol, contract when heated and return to their original shape upon cooling, effectively acting as artificial muscles. In applications like Tahouni et al.'s NURBS-forms [23], SMA wires are embedded in flexible modules to actively bend surfaces. SMAs typically operate at low DC voltages (around 5–12 V) with current draws near 1 A for rapid heating, providing a high force-to-weight ratio where even a thin wire can produce tens of newtons. They have been widely used in early explorations of organic device forms due to their compact size and silent operation. However, SMAs suffer from relatively slow cycle times (0.5–2 s or more), high power consumption due to Joule heating, and potential fatigue over many cycles, limiting their suitability for rapid or frequent shape changes. Methods such as using thinner wires, active cooling, or antagonistic SMA pairs have been explored to improve responsiveness. Despite these drawbacks, SMAs enable elegant, compact mechanisms in prototypes ranging from shape-changing phone sleeves to kinetic art installations, though their use is typically reserved for applications where gradual change is acceptable.

Thermal-Responsive Actuators

Thermal-responsive materials encompass shape memory polymers (SMPs), liquid crystal elastomers (LCEs), bimetals, and phase-change materials (e.g., wax composites). While SMPs require complex programming to temporarily "memorize" shapes, LCEs offer a more direct route to reversible actuation through controlled molecular alignment. By pre-aligning the liquid crystalline domains prior to cross-linking, LCEs can be programmed so that heating triggers a predictable deformation and cooling returns the material to its original state. For example, recent work by Winters et al.[24] demonstrates that thermo-responsive LCE fibers can be engineered to achieve programmable and reversible shape changes with high spatial resolution and low-voltage activation. In parallel, dynamic robotic fibers developed by Kolvenbag et al. [11] have shown that such LCE-based actuators can produce rapid, tunable movements ideal for soft robotics and interactive textiles. Although these systems typically require active heating, which may involve considerable power during transitions, they possess the unique ability to latch into a new configuration with minimal energy input once cooled. Thus, despite response times ranging from several seconds to minutes, thermal-responsive LCE actuators are particularly well suited for ambient, deployable applications such as adaptive displays, soft haptic interfaces, and responsive architectural elements.

Moisture-Responsive Actuators

Moisture-responsive, or hygromorphic, actuators leverage materials that swell or contract in response to changes in humidity. In Yao et al.'s *bioLogic* [25], bacterial spores printed on textiles cause ventilation flaps to open as the wearer sweats, and similar behavior is documented in hygromorphic composites in a Smithsonian article [21]. More recently, Den Teuling et al. demonstrated chitosan biofilm actuators that harness ambient moisture to produce controlled, reversible deformations, offering a sustainable and energy-autonomous solution for adaptive interaction design [5]. In parallel, moisture-responsive hydrogels have been explored as soft actuators, where water uptake induces significant volumetric expansion or contraction, enabling gradual shape change. Although their low force output and slow response limit their use to adaptive textiles or ambient interfaces, moisture-responsive actuators are appealing for sustainable, energy-autonomous designs. They are well-suited to applications where the actuator can naturally get in a changed state and where environmental conditions drive shape change.

Magnetic Actuation

Magnetic actuation leverages magnets or electromagnets to induce shape change without direct mechanical contact. Yasu's *MagneShape* [26] demonstrates a pin-based display where embedded magnets are repositioned by a single moving magnet carriage, enabling high-resolution tactile output with fewer actuators. Additionally, Lee et al. [12] explore using magnetic fields to actuate soft, flexible interfaces, showing rapid response and low power consumption when using permanent magnets. Magnetic systems benefit from near-instantaneous field changes and silent operation; however, achieving high spatial resolution may require complex magnet arrangements, and strong magnetic forces can lead to increased size and power requirements.

Speaker-Based Actuation

Speaker-based actuation repurposes conventional audio drivers to create vibrations or small deformations in flexible membranes. The HaptiCoil [27] system, for example, presents a method for prototyping low-cost, compact, and customizable soft haptic buttons using waterproof planar micro-speakers adapted with a novel hydraulic coupling mechanism. These devices can sense force input via self-inductance and provide tactile output in a single package, offering a wider perceptual range of haptic stimuli while maintaining low power consumption (typically under 40 mW). They have demonstrated how audio drivers can modulate surface textures in interactive installations, suggesting that speaker-based actuation could offer a cost-effective means of integrating widely available components into shape-changing systems.

Comprehensive Comparison Table

The following table compares all actuator types across key performance metrics:

Comparing

Actuation Method	Resolution	Integration	Scale	Force	Low Power	Speed	Low Noise	Manufacturability
Mechanical	+	o	++	++	- -	++	-	+
Pneumatics	o	-	+	+	-	+	- -	o
Fluidics	o	-	o	+	-	o	o	o
Microfluidics	+	++	-	-	+	+	++	-
Electroosmotic Pumps	++	++	o	o	++	+	++	- -
Dielectric	+	++	o	o	o	++	++	-
Shape Memory Alloys	o	+	+	+	-	-	++	o
Thermal-Responsive	o	+	o	- -	++	-	++	o
Moisture-Responsive	-	+	-	- -	++	- -	++	o
Magnetic	++	o	o	-	-	+	++	o
Speaker-Based	+	++	-	-	++	+	++	-

Table B.1: Comparison of Actuation Methods using Symbolic Ratings.

The diverse range of actuation mechanisms each offers distinct advantages, yet all come with trade-offs that must be carefully balanced against the intended application:

- **Resolution versus Force:** Systems such as microfluidic actuators, electroosmotic pumps, dielectric actuators, and speaker-based methods excel at achieving very high resolutions and ultra-thin integrations. These are ideal for wearable devices or interfaces requiring fine control, yet they often produce lower force outputs compared to the robust mechanical, pneumatic, or hydraulic systems.
- **Integration:** The emerging technologies:dielectric actuators, microfluidics, and speaker-based systems are naturally suited for integration into compact, conformal devices. In contrast, mechanical, and pneumatic, actuators require significant space and tend to be bulkier, making them more suitable for large-scale installations rather than for personal or wearable devices.
- **Speed and Energy Consumption:** Speaker-based and dielectric actuators can achieve rapid responses on the order of milliseconds with minimal power, which is critical for interactive applications. Conversely, thermal-responsive and moisture-responsive actuators operate much

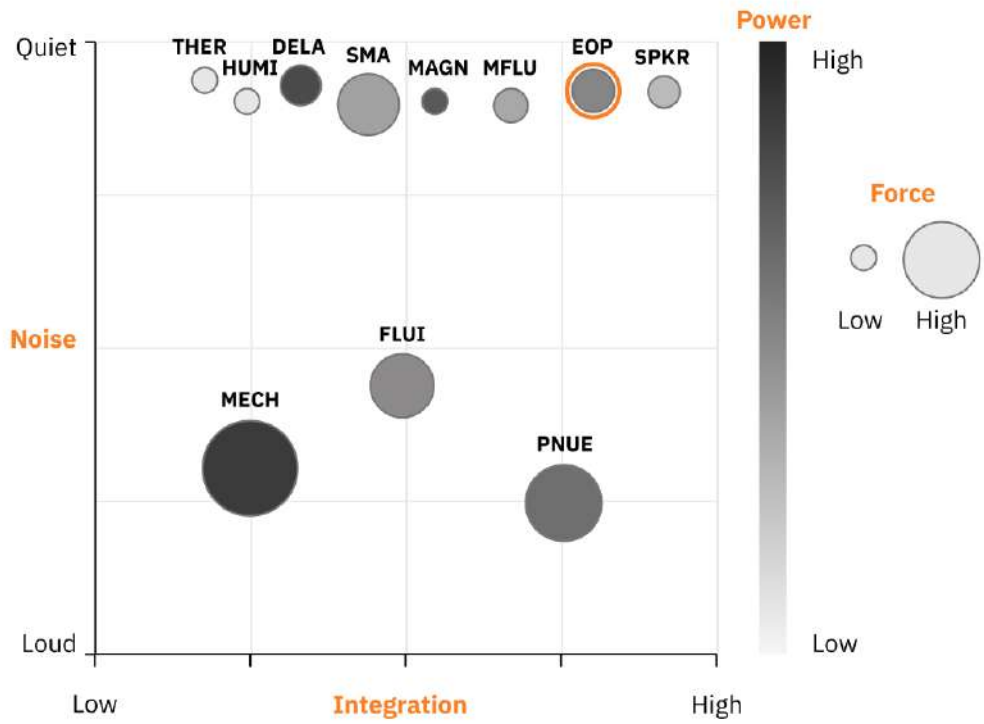


Figure B.1: Visualization of the compared metrics

slower, typically requiring seconds or even minutes to effect shape change, though they can often maintain their state with little or no continuous power.

- **Manufacturability and Scalability:** Well-established methods such as mechanical pin arrays and pneumatic systems benefit from mature manufacturing processes. However, as design trends push toward miniaturization and wearable formats, newer approaches like electroosmotic pumps and microfluidic systems face significant challenges in fabrication and scaling.
- **Noise and User Experience:** Noise is a critical consideration in many applications. Mechanical and pneumatic systems can produce substantial auditory feedback due to motor and pump operation, whereas speaker-based, dielectric, and magnetic actuation methods operate almost silently.

Visualizing

This visualization compares shape-changing actuation mechanisms across five key performance dimensions: integration, noise, force output, power efficiency, and resolution. These metrics were selected based on their relevance to the development of soft interfaces that could be integrated in a real world context.

The **integration** axis reflects how easily actuators can be embedded into products or materials. Technologies like electro-osmotic pumps (EOPs) and microfluidics score high due to their thin, flexible form factors, while pneumatic and motorized systems are limited by bulky hardware.

The **noise** axis indicates sound during actuation, quiet operation is ideal for real-world and wearable use. Mechanical and pneumatic systems tend to be loud, while EOPs, dielectric actuators, and SMAs are nearly silent.

Circle **size** shows output **force**. Motorized and pneumatic actuators offer high force, whereas microfluidics and passive materials (e.g., thermal or moisture-responsive) produce less.

Circle **color** represents **power efficiency**. Light tones mark low-power or passive systems (e.g., mi-

crofluidics, moisture-responsive), while darker tones indicate high-power needs due to heating or high-voltage requirements (e.g., SMAs, pneumatics).

Why EOP?

Motivated by the aforementioned fndings and arising needs, this workshop specifcally focuses on exploring the haptic potential for EAMs. Built from lightweight and soft materials, EAMs show shared characteristics with the potential to overcome longstanding challenges of traditional electromechanical haptic actuators, as they are silent, compact, responsive, and customizable. However, due to limited commercial availability, HCI researchers, designers, and practitioners face interdisciplinary challenges when approaching these materials. EAMs require specialized fabrication processes and non-conventional, high-voltage (0.1-10kV) control electronics, inhibiting rapid prototyping workfows when designing interactive systems. Additional considerations include the reliability, longevity, safety, performance, and haptic qualities of each approach. To explore these questions, our workshop brings together researchers in the feld, aiming to facilitate knowledge exchange within the UIST community.

As we move toward embedding soft interfaces into everyday products and objects around us, key requirements include seamless integration, minimal noise, high resolution, safety, and energy efficiency. Our comparative analysis of shape-changing actuators shows that while mechanical and pneumatic systems offer strong forces and rapid response, they often fall short in form factor, quiet operation, and scalability—critical factors for wearable devices or home applications. On the other hand, emerging smart materials and microfluidics provide high-resolution, ultra-thin integration but may not yet deliver sufficient force or ease of control.

Electroosmotic pumps (EOPs) offer a compelling middle ground for real-world deployment. Their advantages include:

- **High Resolution and Fine Control:** EOPs can achieve densely packed “pump pixels” that enable nuanced, high-definition shape changes—ideal for detailed tactile feedback and visual expressivity.
- **Ultra-Thin Integration:** With actuator layers as thin as 1–2 mm, EOPs are well-suited for integration into modern consumer devices, such as adaptive displays or wearable interfaces.
- **Silent and Low-Power Operation:** Operating at high voltages (100–300 V) but drawing minimal current, EOPs ensure quiet functionality and energy efficiency, crucial for devices intended for daily use in quiet environments.

However, EOPs are not without limitations. Their modest force output (approximately 1 N per cell) may limit their applicability in high-load scenarios, and the high-voltage circuitry required introduces design complexity and safety challenges that must be carefully managed. Additionally, material selection remains critical to prevent issues like drying or bubble formation. While further work is needed to enhance their force output and robustness, their potential for safe, subtle, and adaptable soft interfaces makes them a strong candidate for the next generation of interactive devices.

C

Workshop

This workshop investigates the expressive and communicative potential of soft robotic actuators, specifically Embedded Electroosmotic Pumps (EOPs), by facilitating reciprocal embodied interaction. Drawing on a broad base of theoretical and methodological work in Human-Computer Interaction (HCI), shape-changing interface (SCI) research, and embodied design, this session invites participants to engage with an EOP-based soft interface through structured observation, bodily interaction, open coding, and speculative design. The workshop focuses on developing a practical, grounded vocabulary for how soft shape-changing interfaces behave and communicate.

Rationale

Soft robotic interfaces offer the potential to move beyond rigid input-output modalities, creating nuanced, physical communication channels between user and system. The expressive dimension of shape change — and particularly, the relational or reciprocal engagement it can afford — remains under-explored [20, 3]. The use of Embedded Electroosmotic Pumps (EOPs) offers a unique opportunity to further this investigation. EOPs operate silently, are thin, use low-energy, and allow both sensing and actuation within a soft material[20]. Their characteristics open up interaction possibilities.

Following Rasmussen et al.'s [18] framework of expressive parameters — including orientation, form, spatiality, texture, viscosity, and temporal dynamics — this workshop positions movement not simply as mechanical change but as expressive behavior. In tandem, Bruns et al.'s [3] framework categorizes expressivity through sensory-motor activity, dynamic form, social activity, and value, offering a layered lens through which both actuator and user responses can be understood. We ground this session in a reciprocal loop that values timing, ambiguity, pacing, and interpretation over simple stimulus-response mechanics.

Objectives

The workshop is designed to:

- Investigate how users perceive and interpret shape change from EOP-based actuators.
- Examine how reciprocal, embodied interaction emerges in real-time with shape-changing systems.
- Identify expressive behavioral patterns through thematic analysis of interaction footage and notes.
- Build a language of actuator behavior grounded in affective, embodied, and contextual meanings.
- Speculate on situated interaction scenarios where such soft, expressive systems can play communicative roles.

Schedule

This workshop is divided into five phases, combining observational study, embodied interaction, group analysis, and design speculation.

15 min: Introduction and Framing

The facilitator introduces the research context:

- Capabilities of EOPs and rationale for their use [20].
- Show videos
- Framing from Rasmussen's expressive parameters [18] and Bruns et al.'s interactional expressivity [3].

The goal of the workshop is framed as investigating the question: *How can we read, interpret, and respond to soft actuator behaviors as expressive forms of communication?*

15 min: Passive Observation and Semantic Mapping

Participants observe a predefined series of EOP behaviors, e.g. : slow rise, rapid contraction, pulsation, wavering, and hold-release cycles. These behaviors are designed to represent a range of movement parameters, including temporal variation (e.g., rhythm, pacing), deformation type (e.g., elongation, undulation), and spatial reach.

Participants engage in a think-aloud protocol [6] as they document initial impressions. They use semantic differential scales adapted from Strohmeier et al. [22] to describe each movement using dimensions such as calm–tense, hesitant–assertive, mechanical–organic, and inviting–repelling.

Participants also sketch movement profiles and note potential associations or metaphors (e.g., "breathing," "retreating," "hovering") and how those might be interpreted.

25 minutes: Reciprocal Embodied Interaction

Turn-taking interaction between participant and actuator, informed by somaesthetic and performative interaction methods [3].

Each participant takes turns engaging with the EOP in a seated interaction station. The actuator initiates movement (either via scripted sequence or sensor-based trigger), and the participant responds using bodily motion (gesture, posture, touch). The actuator, in turn, responds via a second scripted or sensor-mediated behavior.

This loop emphasizes timing, proximity, intensity, and attention to how users pace their engagement. Some participants are prompted to respond with mirroring or contrastive gestures; others are free to improvise. All interactions are video-recorded.

20 minutes: Group Debrief and Thematic Coding

Method: Open coding in group format [2].

Participants are grouped into 3–4 person teams. Each group:

- Shares their experiences, movement sketches, and notes.
- Identifies recurring themes or behavioral metaphors (e.g., "hesitation," "assertion," "invitation," "withdrawal").
- Maps actuator behaviors to interpretive terms, discussing divergences or shared perceptions.

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15 min: Speculative Application Scenarios

Each group selects one or two expressive actuator behaviors from the prior phases and imagines how such behaviors could be used in their context/profession. Groups sketch these scenarios and describe how turn-taking or responsiveness would work in situated use. The session closes with short presentations.

C.1. Data Collection and Analysis

The following materials will be collected:

- Video/audio recordings of interaction sessions.
- Semantic maps and sketches from observation phase.
- Movement-behavior vocabularies from group coding.
- Scenario sketches and rationales from speculative phase.

Analysis will proceed through inductive thematic analysis [2], examining the qualities attributed to actuator behaviors, timing and pacing of user responses, and the types of metaphors used to interpret movement. Particular attention will be paid to expressivity in interaction as relational, multimodal, and situated.

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