Tangible Explorations of Sonolithography

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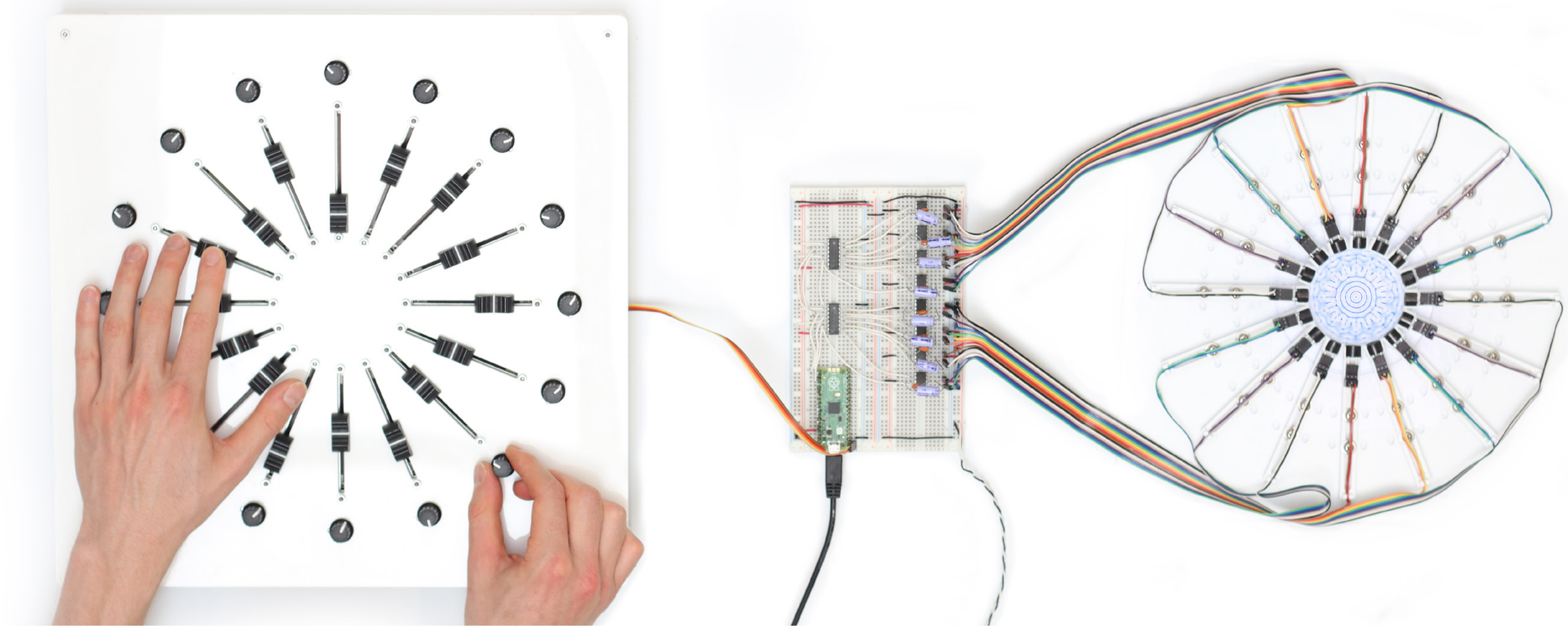

Fig. 1: The sonolithography setup, hands-on interactions with the Orbograph (left) allow for exploration of patterning within the transducer array (right).

ABSTRACT

Sonolithography is the process of directed patterning of airborne particles through the exertion of acoustic radiation forces in ultrasound fields. In this work we present a novel way to explore and gain intuition about the process through tangible interaction. We demonstrate the design and use of a physical instrument for the creation of sonolithographs. The design includes the "Orbograph", a tangible controller that embodies key acoustic parameters through direct tactile interactions; a low-cost and open-source driving circuit; and a configurable transducer array. We demonstrate its capabilities by presenting sonolithographs made with the tool that contain linear patterns, grids, circular and more complex shapes. By using different dyes and active materials, we demonstrate sonolithography's creative application as well as suggest its potential in the fabrication of interactive devices. Through this work we encourage a playful artistic exploration of the domain to motivate future research in sonolithography for tangible material interactions.

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CSS Concepts

- Human-centered computing

INTRODUCTION

The boundary between art and science has historically been blurred by those in the pursuit of visualising acoustic fields. As well as revealing previously hidden acoustic fields, complex and visually appealing patterns were created that encouraged further artistic exploration. The figures presented by Ernst Chladni [25] explored the visual effects of the modal vibrations of a resonating plate as sand would accumulate to the lines of minimum vibrational amplitude. This work inspired both scientific experimental methods such as Kundt's demonstration of the speed of sound in his eponymous tube [15] and further artistic exploration in the field of Cymatics [12] and its implementations [9,15,23].

In a similar way to the movement of particles on the surface of Chladni's plate and in Kundt's tube at low frequencies, the use of inaudible ultrasonic frequencies have been shown to directly exert forces on particles in air and other fluid media. Particles present inside an acoustic field experience acoustic radiation forces, a non-linear effect that arises due to the scattering of the wave by the particle in a medium. The theory of acoustic radiation forces exerted on particles in acoustic fields has been well studied [2,8,13,29] and has led to a number of applications.

Acoustic radiation forces in ultrasound fields have been of particular interest to Human Computer Interaction (HCI) researchers ever since their application to mid-air haptics was shown [10]. Low-cost transducers and digital controllers have enabled an explosion of applications of ultrasonic phased arrays in further mid-air haptic work [4], acoustic levitation projects for particle based displays [19,22,26], wireless power transfer [20], and personal fabrication [7]. This research has underpinned commercial ventures [4,21] and open-source designs [29–31] that have had massive uptake by wider community due to their ease of fabrication at home, or in Makerspace and FabLab environments. These approaches however, centre around the use of algorithms that enable single or multi-point configurations for focusing, rather than exploring the natural patterning characteristics of the whole acoustic field.

The use of acoustic radiation forces for particle patterning has been an active field of research within the scientific community as a contact-free manipulation technology, and is being investigated by well-equipped laboratories for a number of applications. These include acoustofluidics and lab-on-a-chip technology [32,35], bioprinting and cell patterning [1,6], and in material science [5,23,28].

The work in acoustic particle patterning has been limited within science research due to specialised and expensive equipment requirements. Sonolithography [27] proposes particle patterning with more accessible equipment, and for patterning with air as the medium. This allows for lower control frequencies to be used to get similar resolutions to liquid based approaches due to the slower speed of sound in air. Sonolithography also makes use of much the same technology that has already been developed by the HCI community for ultrasonic single and multi-point focusing systems.

To gain a better understanding of the behaviour of ultrasound fields in patterning, and specifically to uncover potential applications acoustic particle patterning technology, we must form clearer intuitions around these inherently obscure phenomena. By designing a system for direct tangible control of the yet unexplored parameters of sonolithography, we seek to both develop our own understandings of this behaviour as well as invite more participants to benefit from exploring the domain as a both scientific and creative project.

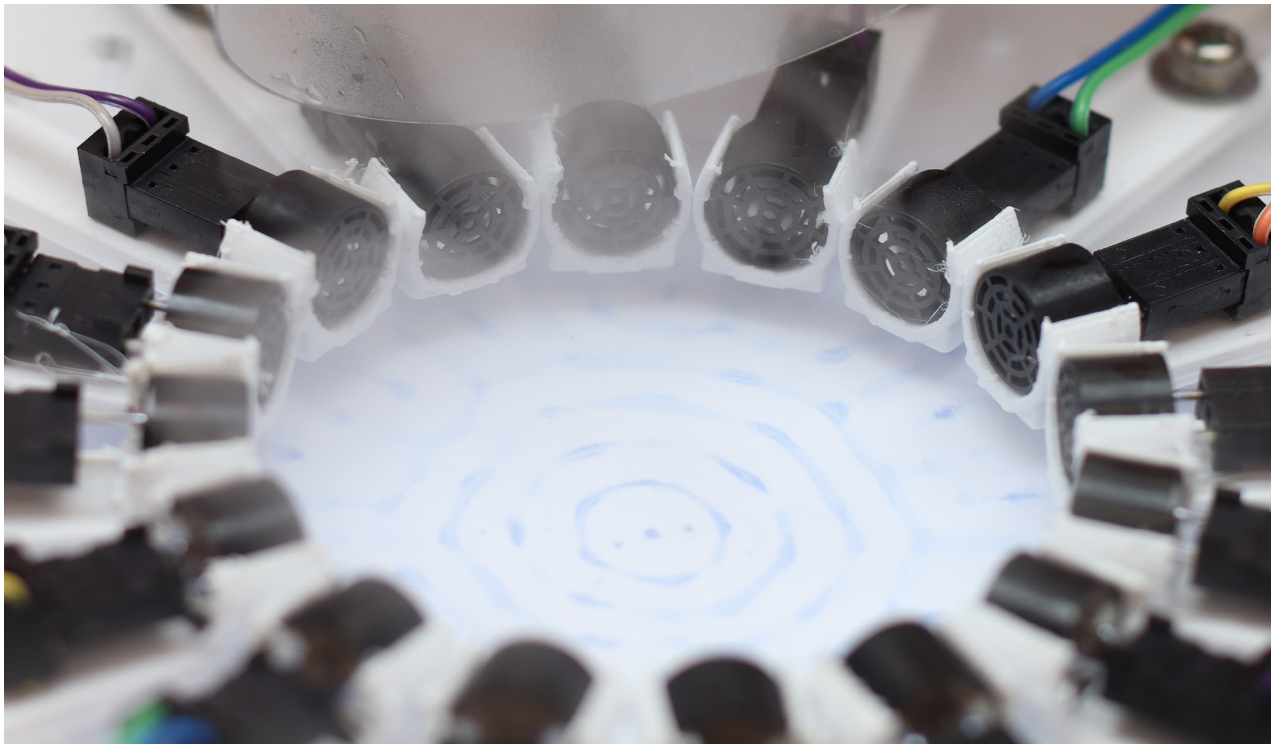


Fig 2: Sonolithography in action: particle patterning ink droplets using ultrasound fields.

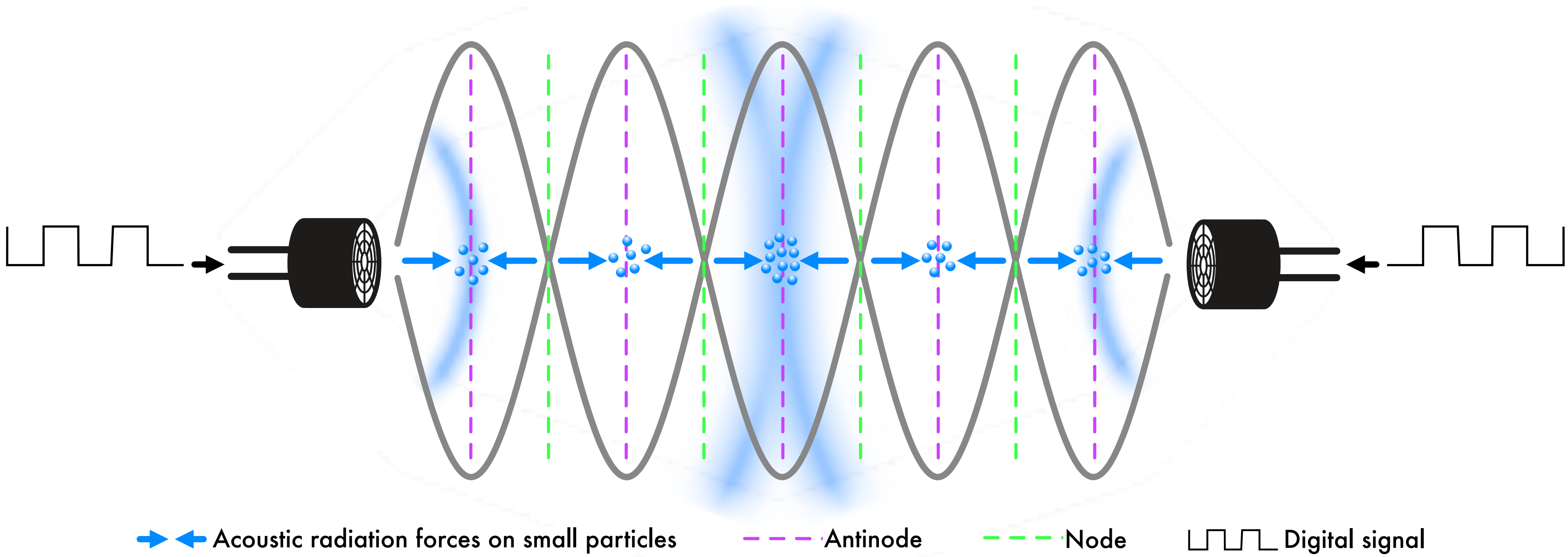


Fig 3: Graphical representation of acoustic field between a pair of transducers.

Ishii et al's vision of radical atoms [11] couples malleable and reconfigurable physical particles with real-time digital models. While the wavelengths provided by sonolithography can't manipulate swarms of particles at the atomic scale, it nonetheless provides an interesting way of mediating between models and particles at the microscale, significantly smaller than has been possible with conventional actuation approaches.

OVERVIEW OF SONOLITHOGRAPHY

Sonolithography [fig. 2] utilises acoustic radiation forces to pattern aerosolised media onto different substrates. First introduced by Shapiro et al. in 2020 [19], where the technology was presented as a tool for indirect and direct cell patterning in fixed acoustic fields. The authors also suggest the potential application of dynamic phased arrays for control of the resulting patterns, and exploration of novel materials for patterning.

In sonolithography observed patterns result from acoustic pressure fields formed from the output of multiple ultrasonic transducers. Each transducer is a small speaker optimised to produce a fixed frequency sinusoidal pressure wave through the resonance of a ceramic piezoelectric element. Figure 3 shows how the transducer can be excited by a driving signal to create a set pressure amplitude (magnitude of the wave produced) and relative phase shift (position along the waveform where it starts relative to the others). Propagating waves with the same frequency traveling in opposing directions interfere to create standing waves. Points along the standing wave vibrate as a function of time, yet their amplitude distribution does not vary in any spatial dimension. Positions at which the amplitude is zero are called *nodes*, whereas positions where the amplitude is highest are called *antinodes*. When acoustic pressure waves radiate out from multiple transducers, the shape of the acoustic field can be controlled.

The properties of the particles and the medium within which they are suspended dictate the radiation force magnitude and direction. For larger incompressible particles like millimetre sized polystyrene spheres suspended in air, that are often used in acoustic levitation applications, the radiation force is in the direction of the nodes, as is observed in acoustic tweezer experiments [17] . In sonolithography, the aerosol droplets used are mostly small, on the order of micrometres and these experience forces towards antinodes [13], so when they settle they mark out the lines of maximum acoustic pressure.

Sonolithography lends itself well as a personal fabrication technology given the potential to pattern a wide range of materials including cells, conductors, and organic semiconductors to create thin-film devices. Unlike traditional digital tools for printing and plotting, sonolithography pairs a unique combination of order and an organic quality that bridges between the digital and physical. This encourages creative applications that could extend existing paper-based circuit sketching and computation [3,18].

TANGIBLE SONOLITHOGRAPHY

The phenomena that underpin sonolithography are inherently difficult to form clear intuitions about. The relatively small invisible forces that result from inaudible frequencies are what make sonolithography attractive, however, they also pose challenges in comprehending these phenomena at a fundamental level. Naturally forming layers of abstraction and computation on top of the technology mean we can build intuitive models around it, but effort is still required to model and control some of the more complex interactions of small particles in acoustic fields. Therefore, we are introducing a tangible system with a high degree of direct control. The system helps users understand how the changes they make to the acoustic field through the control of field geometry, phase, and amplitude change final patterns. These variables have traditionally been fixed in sonolithography systems [27] where the focus has primarily been on the materials and deposition technique.

Our tangible sonolithography system presented here comprises of three main components: The patterning system which is a configurable array of 40kHz transducer elements along with an fluid atomizer; An open-source driving circuit; and the Orbograph, a tangible interface to control the phase shifts and amplitudes of transducers laid out in a radial pattern.

Configurable Transducer Array

The acoustic wave field is formed within the transducer array, and is where the patterning occurs. Each transducer is held in place on an arm screwed through a slot into a laser-cut acrylic base plate with geometrically spaced holes. This allows for reconfigurability and flexibility along with constraints that guide the user to natural orientations and spacings. Multiple mounting geometries have been designed to accommodate different configurations and symmetries [fig. 4 a-c]: square, hexagonal, and hexadecagonal (16-sided). The 16-sided array provides the most flexibility when selecting which transducers to use and highest magnitude of acoustic radiation force given the greater number of transducers. A round cut-out in the centre of the plate allows the user to place a sheet of paper or other substrate below the field to be patterned upon.

Above the deposition surface, an atomizer is held with a

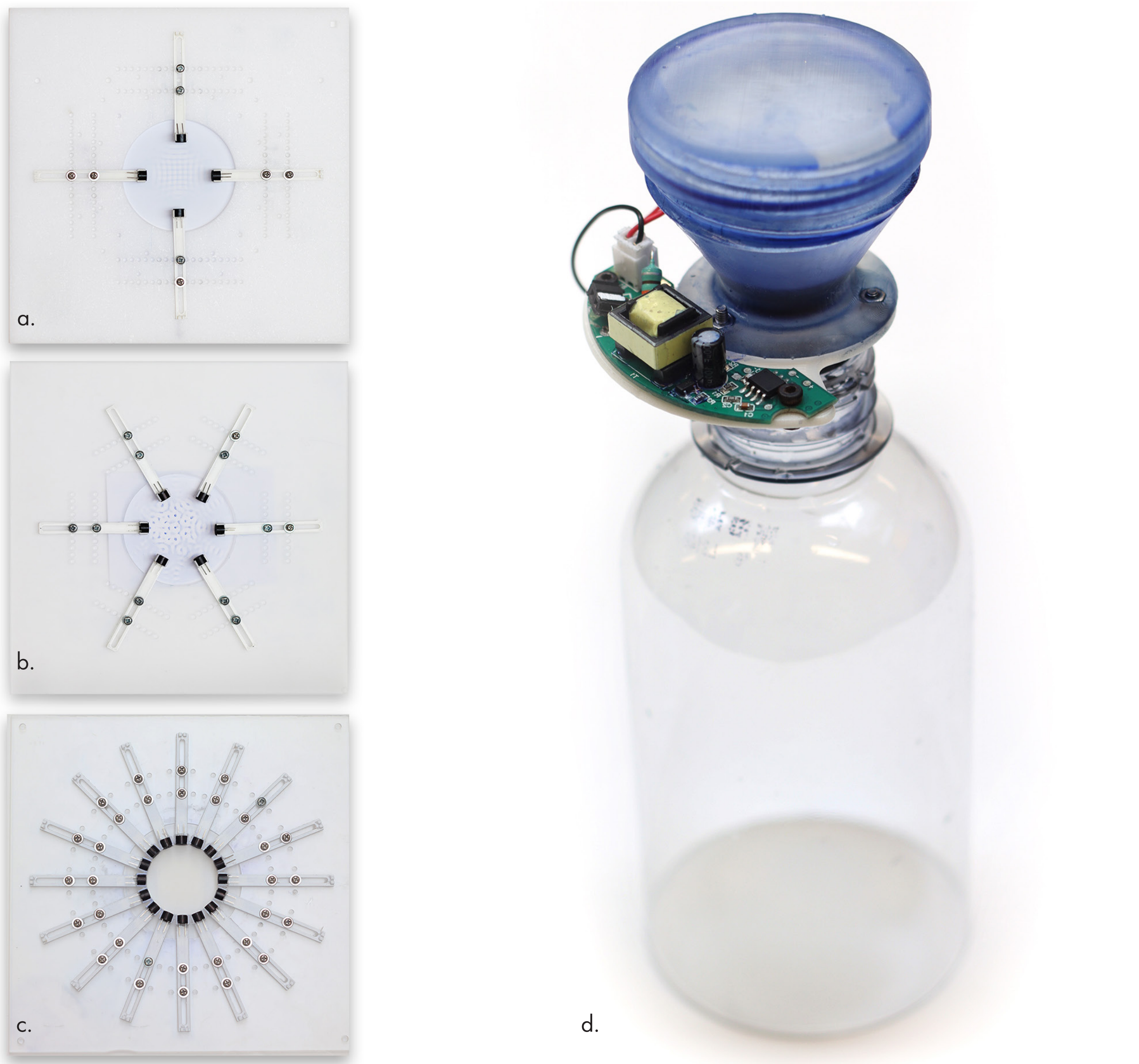


Fig 4: a-c: square, hexagonal, and 16-sided transducer array plates with 3D printed transducer mounts. d: The atomiser assembly to be held above the transducer array for creating fine mists of ink droplets.

reservoir of dilute ink solution [fig. 4 d] that produces a fine mist that under gravity falls onto the surface. The acoustic forces above the surface direct the fine mist into their final pattern. The atomiser assembly is comprised of a driver circuit, a piezoelectric mesh nebuliser disk, a 3D-printed reservoir, and the top end of a plastic bottle that both confines the aerosol as well as decelerating the flow of droplets for them to pattern more evenly. Different materials with low viscosity can be passed through the atomiser. The replaceable piezoelectric mesh nebuliser disk is a low cost part that can be replaced if the system becomes clogged.

Open-Source Driving Circuit

The array of transducers is connected through a ribbon cable to a simple circuit [fig. 5] composed of a number of gate drivers that amplify up logic-level signals to 0-18V pulses. The logic-level signals contain the wave information and are generated by a Raspberry Pi Pico. The Pico microcontroller can create signals with up-to π/16 phase resolution, and a range of 16 amplitude levels. To minimize the usage of pins and accommodate for future expansion of the system, the waveforms are serialized on the Pico to be sent into a pair of shift registers to control all 16 transducers.

The generation of control signals and serialization of wave forms for the shift registers all happens using the Programmable Input Output (PIO) of the Pico. This liberates the main cores of the Pico to process incoming phase and amplitude data.

All the components on this signal pipeline are low cost and designed to be simple and easy to reproduce on a breadboard. Replicating the devices and software requires limited effort for a technically competent designer or end user, and instructions for replicating the system and producing resulting sonolithographs can be found at oliverchild.com/sonolithography.

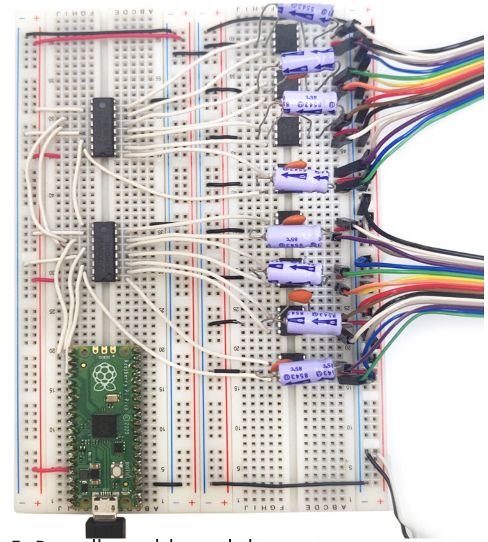


Fig. 5: Breadboard-based driver circuit.

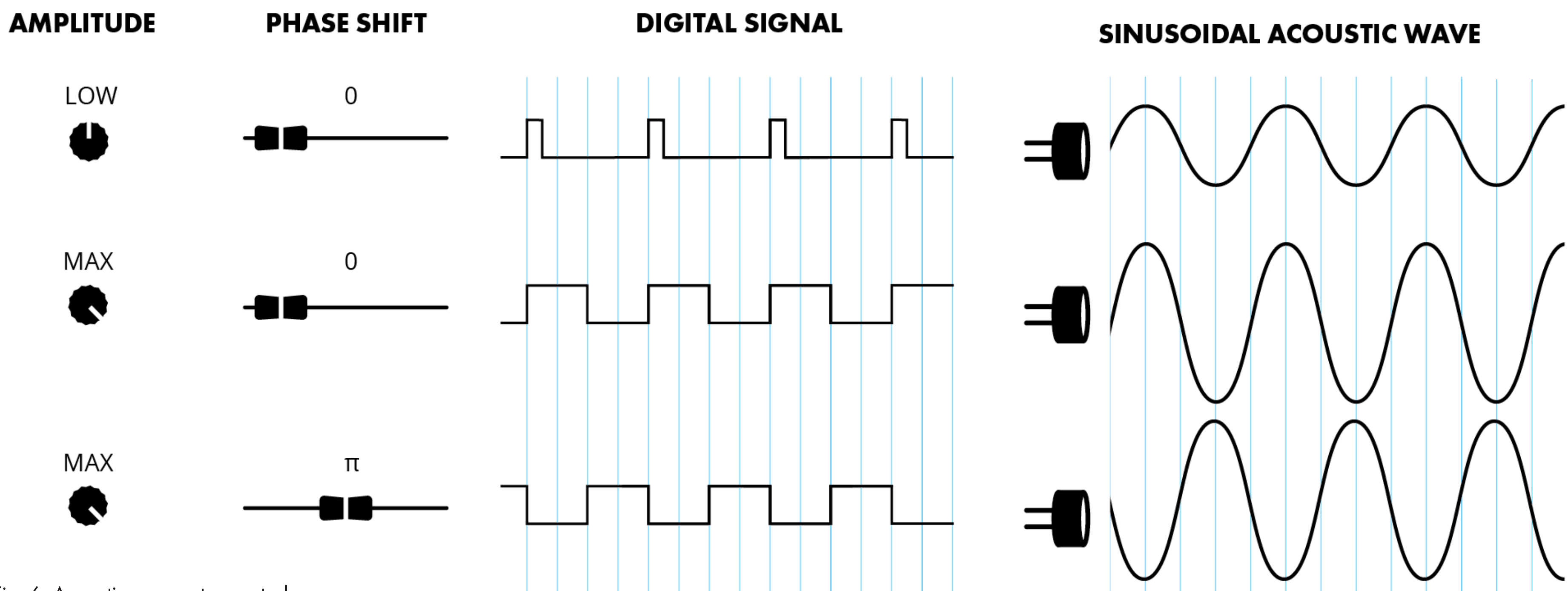


Fig. 6: Acoustic parameter control.

Fig. 7: The Orbograph interface provides tangible control of acoustic parameters.

Orbograph, a Radial Tangible Controller for Sono-lithography

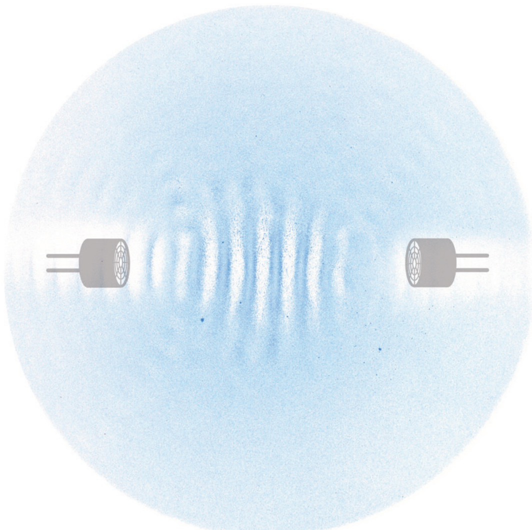
The user interacts with the device through the Orbograph [fig. 7], a tangible mixer-like interface with sliding and rotational potentiometers placed in a radial pattern. The maintenance of clear state in the position of the physical input provides user feedback that wouldn't be received from inaudible ultrasound or from patterns which can be relatively slow to emerge.

Figure 6 shows how the sliders control the relative phase of each transducer, and the rotational potentiometers control the amplitude. The positioning of each of the potentiometers is such that it mirrors the positions of the transducers when in a radial 16-transducer array. The location of each of the inputs gives the user visual feedback and helps understand the state of the device. Sliding potentiometers were used for the phase shift control to give the user the feeling of pushing the wave back and forth. The transducer settings are polled from the potentiometers by a second microcontroller and sent over to the main Pico over a serial connection.

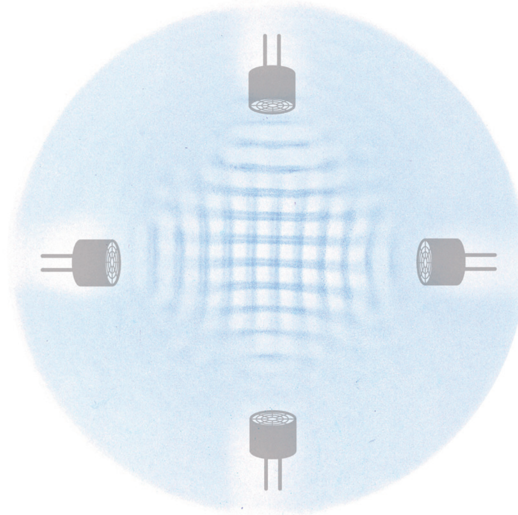
The Orbograph's fixed shape doesn't mean it can't be used with arrays other than those that contain 16 transducers. The mapping is less clear, but as all configurations have a radial ordering, it is possible to make slider/knob pairs inactive and still use the controller. The mapping is less intuitive and could be replaced by a screen-based digital controller. However, when considering the trade-off between configurability and maintenance of state and physical control, the Orbograph was still considered a superior solution.

REPLICATING SONOLITHOGRAPHY

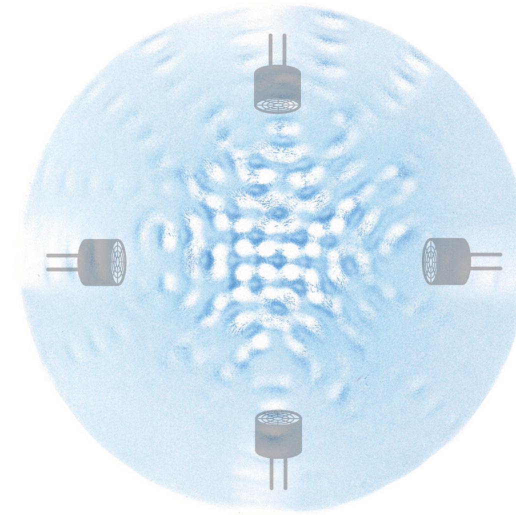
The main design considerations for the device were to ensure it was as easily understandable and accessible to a wide audience without sacrificing configurability and flexibility. By opting for off-the-shelf components and not consolidating each of the elements into a manufactured circuit design, we hope to encourage others to try the technology for themselves, or take elements from our design and incorporate them in other systems. All the components of the design can be fabricated by an individual with some technical experience with the tools available in an equipped Makerspace or FabLab.



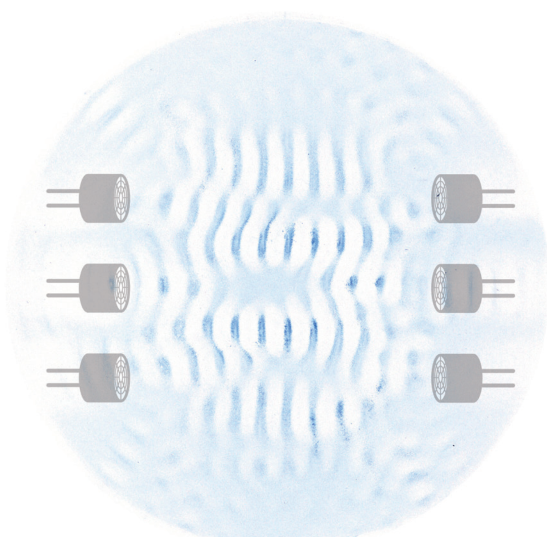
[A] Opposing transducers at maximum amplitude create a linear standing wave pattern between them with half-wavelength (4.3 mm) spacing.



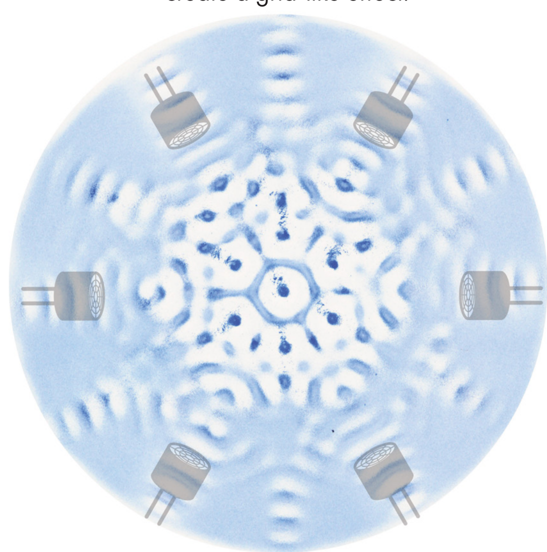
[B] Patterning can be repeated and overlaid between two orthogonal pairs of transducers to create a grid-like effect.



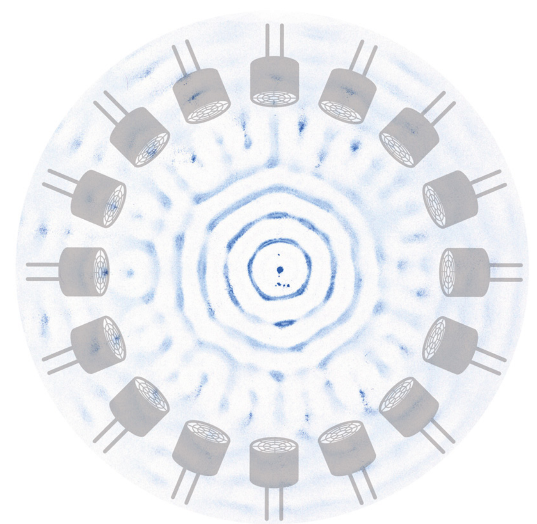
[C] When 4 inward-pointing transducers are all in phase and with equal amplitude a grid of spots immerges.



[D] Interference between adjacent transducers in a 2x3 opposing setup introduces wobble rather than making a stronger version of [A].



[E] 6 inward-facing transducers produce snowflake like patterns when all transducers are on and at equal phase.



[F] The 16-transducer setup creates increasingly sharp and darker concentric rings.

EXPERIMENTATION AND EXPLORATION

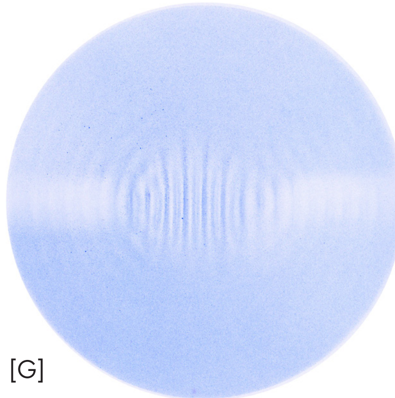
The reconfigurability of the system allows for rapid testing of different control regimes. In particular, the positioning, phase, and amplitude of each transducer can be varied resulting in many different patterns. Rapid testing and intuitive control results in a tight feedback loop between the user and the device which helps develop intuition for the technology's behaviour, constraints and possibilities.

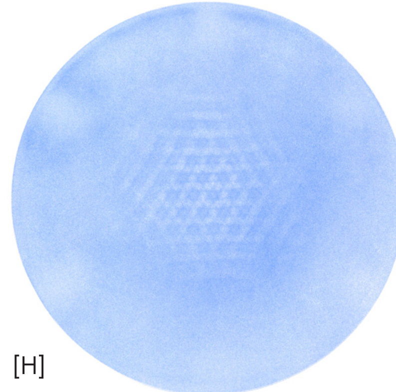
Simple transducer setups with only a couple emitters such as [A], resulted in predictable results with lines matching the half wavelength spacing of the standing wave. By changing the relative phase of one of the transducers, the position of the lines could be varied. This is demonstrated in sonolithograph [G] where a second patterning step was made but with a pi phase shift applied to one transducer, resulting in a doubling of the pitch of the final pattern.

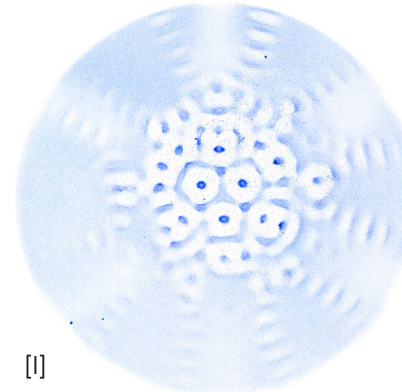
These basic regimes can also be combined in more complex transducer layouts. In sonolithographs [B] and [H] the same single pair transducer wave field is created, but it is repeated across multiple pairs to create square and hexagonal grids respectively.

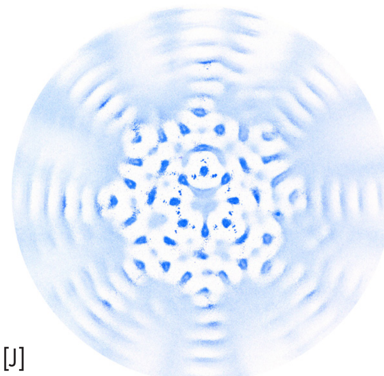
When more transducers are used, the patterns are harder to predict and produce more intriguing results. When a line of opposing transducers are laid out linearly, interference occurs between not only between opposing transducers, but also adjacent ones as demonstrated in sonolithograph [D]. Focal points also become more prominent as shown in patterns [C], [E], [F] and other setups, where the acoustic radiation forces all point towards a particular point within a certain locality.

With simple and symmetric parameters across transducers, these setups form structured patterns. Sonolithograph [I] is related to [E] in that it is the exact same configuration except that [I] has opposing phase shifts between adjacent transducers resulting in focal points surrounding the centre rather than on the centre. Both however embody the same snowflake-like characteristics from the symmetry of the settings, and the shape of the array. When the symmetry in the transducers and settings is broken, the resulting patterns very quickly become more chaotic in nature as represented by [K]. Simple cases like [O] where the transducers are


[G]


[H]


[I]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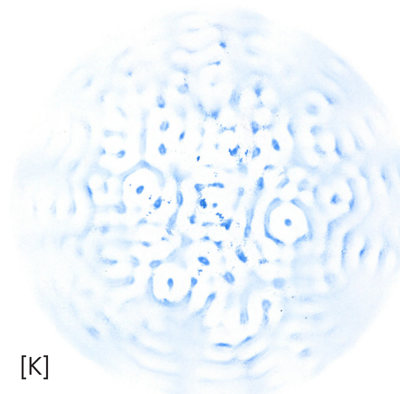
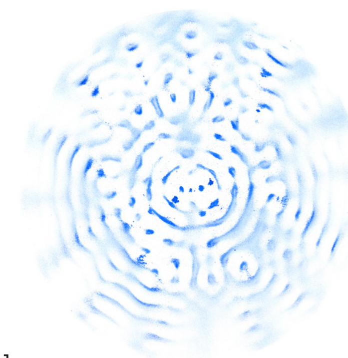
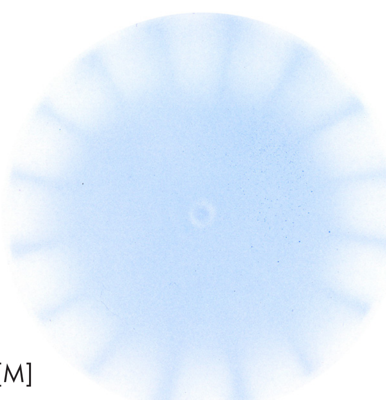
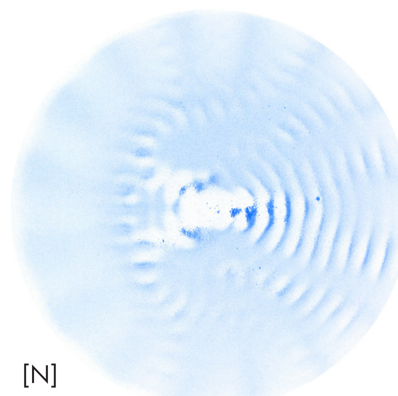
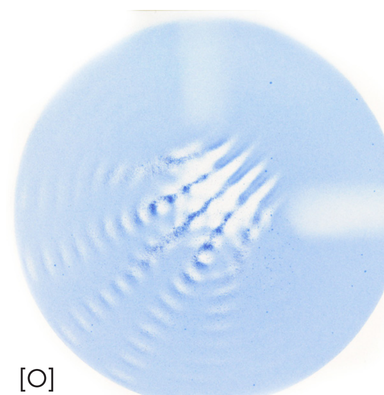

[K]


[L]


[M]


[N]


[O]

placed orthogonally and don't have opposing matching transducers, still show some order.

Reflections also play an important role as can be seen in [N] where the 5 right-most transducers in the 16-transducer ring were active. This creates a focal point, but then a secondary interference pattern can be observed on the left where waves reflect off the transducers on the other side of the array and produce their own patterns.

The amplitude control also has an effect on the resulting fields and final images. By reducing the amplitude of the transducers significantly, less clear lines can be observed and only more central activity is clear. This is represented in pattern [M] where all transducers in the 16-transducer array are active with the same phase shift, but with minimum amplitude.

Use of Colour

While most patterns were made using a dilute solution of fountain pen ink, it is possible to make patterns in other colours by using different materials, seen in figure 11. In a number of examples we used a range of diluted food dyes instead to show the range of possibilities. Combining colours in the same sonolithograph can help demonstrate how changing the acoustic parameters during the patterning is done to achieve different patterns. In figure 8, we demonstrate how a grid pattern is made by first patterning in blue while one pair of opposing transducers is active, then patterning once more in orange while the other orthogonal pair of transducers are active, overlaying the same pattern but with a 90 degree rotation.

Observed Phenomena

When droplets coalesce in air, larger droplets experience a force towards the nodes of the acoustic field as opposed to the antinodes. In the images, this can be sometimes observed as darker dots in between patterned regions, where the larger droplets have formed shown in figure 9.

Within antinodes there is a clear gradient of colour. This phenomena is not very well explored, but we believe it is the accumulation of droplets at a barrier that is formed by droplets that have already been deposited. Existing drafts and turbulences in the air created by the atomisation process, direct how and where droplet density gradient occurs as seen in figure 10.

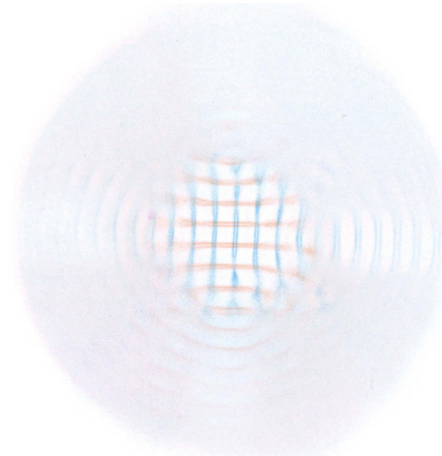


Fig. 8: Sonolithograph with two overlaid colours.

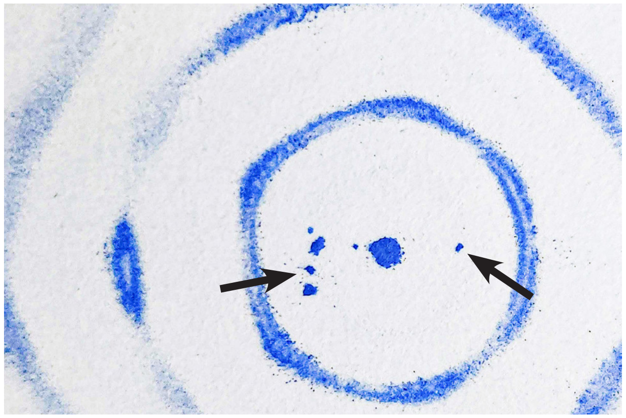


Fig. 9: Spots form at nodes where droplets coalesce.

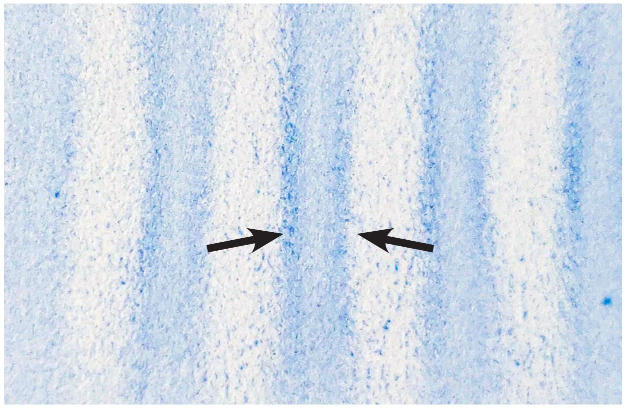


Fig. 10: Darker edges on antinodes.

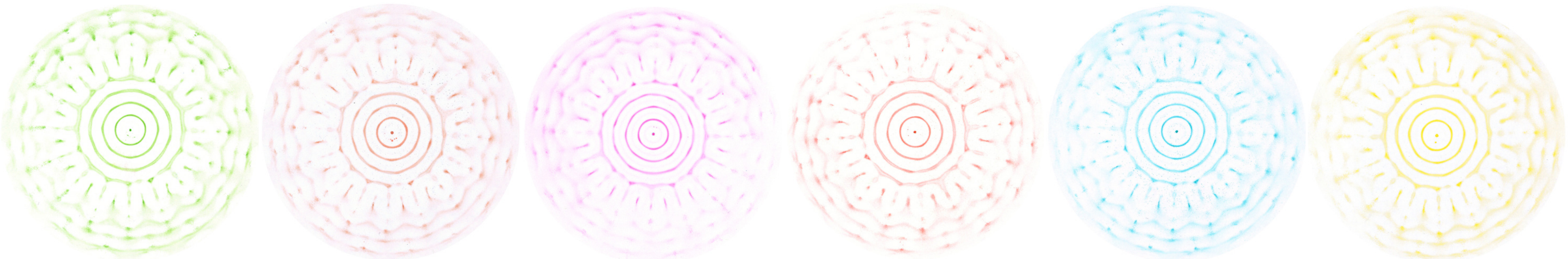


Fig. 11: Sonolithographs created with different food dyes.

CREATIVE APPLICATIONS

Sonolithographs lend themselves to creative expression as well as scientific exploration. The inherent symmetries paired with the organic and chaotic nature mean that they can be used to create generative and natural looking pieces. Through user intervention during the patterning process, by varying the acoustic parameters, and adding other features to the patterns, a number of creative examples were produced:

- Figure 12: Using the setup as a stamp to create repeated images.
- Figure 13: A dandelion using smaller masked regions of the sonolithographs for the head, with a stem and leaves painted on with a brush afterwards using the same ink.
- Figure 14: A streaked pattern that was implemented by pulling the paper that was being printed onto while patterning process was happening.

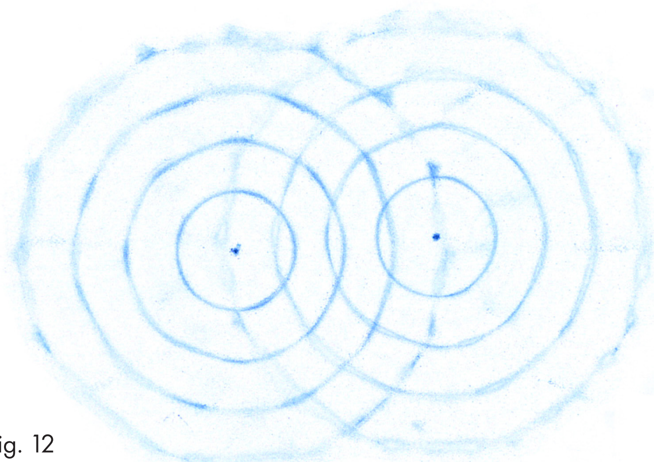


Fig. 12

Fig. 13

Fig. 14

PATTERNING ACTIVE MATERIALS

Sonolithography is not only confined to patterning inks and dyes; any material that can be aerosolised can theoretically be patterned. In figure 15 we show that PEDOT:PSS, a conductive organic polymer in water solution can be used in the sonolithography system and utilised as the top layer of an electroluminescent device. By following the method introduced by Wessely et al. in Sprayable User Interfaces [33], we demonstrate it is possible to deposit active materials from *Lumilor* [36] to create displays that can be used in interactive applications. In the example, a copper backplane is covered with a layer of white paint then electroluminescent material. The PEDOT:PSS is patterned above this and a painted on copper stalk acts as a top electrode. This is the first ever application of ultrasound to create displays in this way and opens the possibility of digitally addressable masking.

DISCUSSION

Through our design and exploration of the sonolithography system we have increased our understanding in two main areas: discovering new possibilities within the space of patterning regimes, and gaining insight into the interaction mechanisms with the system. Both present avenues for future work.

The tangible and reconfigurable nature of the system provided rapid feedback to changes and encouraged exploration of potential patterns. We discovered several configurations that produced aesthetically pleasing images, whereas many of the configurations would produce “noisy” fields that resulted in blotchy patterns with little order. The amount of control offered to the user provides a large search space, but only a small subset of acoustic parameter configurations were considered interesting or useful. Added complexity of more transducers and different amplitude and phase shifts without symmetry would almost invariably be considered too complex and chaotic to find interesting. Reflections of the acoustic waves and other environmental effects may have played a role in these results too. In future work it would be interesting to explore how the search space could be constrained computationally to still provide the user with a richness of results without reducing the feeling of control. The increased intuition and discoveries brought by this device could help guide this process, in particular, the discovery of various basic foundational transducer arrangements which

Fig. 15: Sonolithographs made with active materials in off and on states.

used symmetrical control features could be combined to form more complex ones.

The tangibility of the controller did add a level of feedback that is otherwise missing in the process due to only other signal that represents change in the system being the changes seen in the final image. This worked especially well for the most used configuration with 16 transducers in a ring setup. However, when using the controller with different array shapes, this usually required a certain amount of un-intuitive mapping between controls and transducers. It still provided rapid control, but wasn't as seamless. A screen-based approach may have been better for reconfigurability, but would have had to sacrifice the physicality of the system which provided it with its novelty and aesthetic charm.

The analogue control interface also meant it was difficult to set exact values for each of the acoustic parameters. When trying to match the phase or amplitude of different transducers, or ensure the phase was the inverse of another, there were only the relative positions to use as a reference. The inaccuracy of control of the process is comparable to the manufacturing variation between transducers. This wasn't so much of an issue in this explorative system, but still reduced the level of perceived control the user experienced.

CONCLUSION

Ultrasonic acoustic forces in HCI research have experienced huge interest due to their non-invasive nature and applicability to ubiquitous computing. This is continuing to be a promising and rich research space especially in acoustic patterning which has applications in personal fabrication and beyond. In this work we have presented a novel system for the artistic and playful exploration of Sonolithography, as well as demonstrated some of the possibilities and limitations of the technology. Sonolithography can facilitate low-cost thin-film printing in a broad range of materials. By focusing on the design of a tangible, low-cost, and extendible solution, we encourage others who may not traditionally be involved, to creatively explore the space. It is the mentality of widespread access without tethering to large-scale investment which makes these techniques truly exciting for researchers and end users. We believe sonolithography has an important part to play in the future of HCI and is a step towards the realisation of dynamic material interaction.

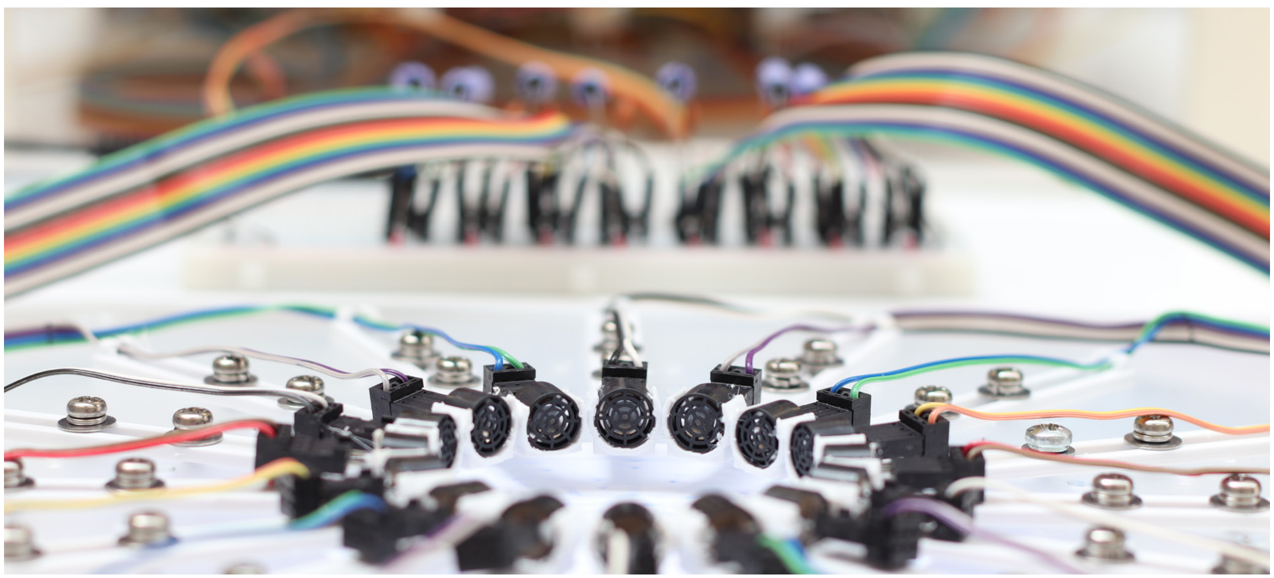


Fig. 16: Transducer array and driving circuit.

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