2024

RESEARCH & INSIGHTS IN APPLICATION OF ACOUSTIC LEVITATION

To identify and analyze the key market trends and development in holographic display technology over the last five years.

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Table of Contents

As I start planning about on my future career paths, I've come to understand that it's crucial to -

1. Choose an industry that is on the rise, one that offers lots of opportunities for growth, good pay, and significant room for growth and advancement.
2. Focus on developing a strong set of core skills that will set me apart from others in the field and increase my value in the job market.
3. Be strategic about the organizations I choose to work with, seeking out companies with strong reputations, great leaders, or the potential for me to build something truly outstanding.

By keeping these three elements - industry, skills, and organization - at the forefront of my career decisions, I believe I can create a clear path for long-term career and fulfillment after graduation of this MSc IoT degree.

Current Development

The primary strength of acoustic levitation lies in its ability to manipulate objects without physical contact, eliminating contamination risks and allowing for precise control over sensitive materials and in mid-air.

Possible Applications

- **Contactless manufacturing and manipulation**: Acoustic levitation can be used to move, separate, and purify sensitive materials, such as droplets, living cells or electronic components, in a contactless manner, reducing the risk of contamination or breakage [1, 2, 3].
- **Holographic displays**: The technology can be used to create new kinds of holographic displays [1, 4, 5].
- **Mid-air haptics**: Mid-air haptic feedback can enhance touchless interfaces by providing tactile sensations to the user, making the interaction more engaging and intuitive. There is also the potential of Incorporating mid-air haptics in VR and AR applications can greatly enhance the sense of immersion by providing realistic tactile feedback to the user. [8]
- **Tissue engineering and cell culturing**: 3D cultures exhibit better biomimetic properties compared to 2D cultures. These properties are important for in-vitro modeling systems, as well as for in-vivo cell therapies and tissue engineering approaches. [10].
- **Specimen Holding and Non-contact analysis**: The ability to control tiny objects without touching them could enable researchers to study the dynamic properties of biological materials, such as insect wings or termite legs, without causing damage or disruption [1, 2].
- **Experiment Automation for studying chemical reactions and biological processes**: The development of optimized reflective metamaterials allows for more precise control over the acoustic field, enabling the levitation of multiple particles at arbitrary distances [2]. By merging two levitated droplets in midair, experiments can be performed without the use of containers, thereby automating the process and minimizing contamination [1, 7]. Experimental automation with a multi-axis CAL was demonstrated by [6].

Limitations and Challenges

- The inherent properties of acoustic waves present challenges in their control and manipulation.
- The limited force generated by acoustic waves restricts the levitation of larger or heavier objects.
- Sensitivity to external factors like air currents and background noise affects the stability and precision of the levitation process.

- Findings from Asier Marzo's Work, as in the supplementary tables [9]:
  - Development of an acoustic hologram optimizer for Particle Acoustic Levitation Systems (PALs).
  - Data shows that linear spring constants along the Z-axis for various setups range from 0.06 mN/m (Vortex Trap, Hemisphere Array) to 14.90 mN/m (Standing Wave, 2 Opposed Arrays).
  - These small vertical trapping forces limit the weight of levitable objects.
  - For instance, a spring constant of 0.28 mN/m (Twin Trap, Flat Array) generates a restoring force of only 0.784 μN for an object displaced by 2.8 mm from the center.
  - This restricts applications to lightweight materials, limiting potential uses of acoustic levitation technology.

- In the conclusion of Fushimi and Ochiai's book chapter [1], it highlights the need for improved transducer specifications, wider bandwidth and frequency ranges, and better temporal control. It's worth noticing that as the power of the acoustic field increases, it becomes more difficult to maintain stable levitation and control the position of the levitated objects. High-power acoustic waves can generate air currents and turbulence that disrupt the levitation stability.

✷ Challenges for Holographic Displays

- Limited size and resolution
- Interference from external noise sources and air currents
- Use of pulsed or duty-cycled acoustic waves has inherent instability, as the levitation force is not constantly maintained
- Scalability issues

✷ Challenges for Contactless Manufacturing

- Limited object size and weight capacity
- Precise control and stability issues
- Complex acoustic field setup and calibration
- Environmental disturbances
- Scalability for industrial applications
- Material compatibility with acoustic forces

✷ Challenges for Mid-air haptics

- Limited tactile resolution
- Effectiveness in noisy environments or in motion
- Limited transducer range and integration challenges with MR systems
- Spatial resolution limitations
- PAL and Wearable device compatibility

✷ Challenges for 3D Cell Culturing

- Precise control over levitated cells/tissue samples
- Risk of liquid droplet evaporation affecting cell culture
- Complexity and cost of integrating with automated setups
- Limited scale and throughput
- Possible Contamination issues

Acoustic Hologram Optimization

- Acoustic hologram optimization is a critical process for achieving accurate reconstruction of acoustic fields in various applications, such as medicine, biology, and engineering[1]. The levitation of Mie-regime objects (whose size is comparable to or larger than the wavelength of the incident sound waves) using acoustic vortices was first demonstrated in 2018 [12]. Initially, scattering calculations via the boundary element method were necessary. [13] However, recent advances in analytical solutions for acoustic radiation forces have enabled more efficient approaches. Gor'kov potential is unsuitable for single-sided acoustic levitators with strong traveling wave modes. Various formulations can calculate acoustic radiation force. The Gor'kov method is less appropriate for phased array transducers (PATs) in traveling wave configurations (i.e., single-sided). Instead, a spherical harmonic approach is more suitable for single-sided transducer arrays, as it can calculate forces for Mie-regime targets and arrays. [14]

- Fushimi and Ochiai discussed several optimization approaches in their book chapter [1], including the Gerchberg-Saxton (GS) method, gradient descent algorithms, and direct approaches, as compared in the table below.

#	Approach	Advantages	Disadvantages
1.	Gerchberg-Saxton	Simple to implement and great at maximizing amplitudes	Less accurate
2.	Eigensolver approach	Moderate accuracy	Inflexible with change in targets
3.	Gradient descent	Achieves higher accuracy and scales well compared to conventional methods like Eigensolver	Inefficient when optimized with finite differences
4.	Direct approach	Accurate generation of holograms and flexible objective functions	slow and computationally intensive for large-scale problems
5.	Deep learning	Fast execution time and no iteration	Currently limited to fixed elements

- For example, The Diff-PAT platform, which utilizes automatic differentiation, is highlighted as an effective method for optimizing acoustic holograms [11]. Diff-PAT has demonstrated superior performance compared to conventional algorithms, even when only controlling the phase of the acoustic wave. This optimization platform is suitable for a wide range of phased array transducer (PAT) applications without introducing additional complexity. Moreover, the application of Diff-PAT to phase plates has resulted in a significant increase of over 8 dB in the peak noise-to-signal ratio of the acoustic field. The flexibility and computational efficiency of Diff-PAT make it a promising tool for improving the performance of acoustic holograms in various fields [11].

Industry Trend

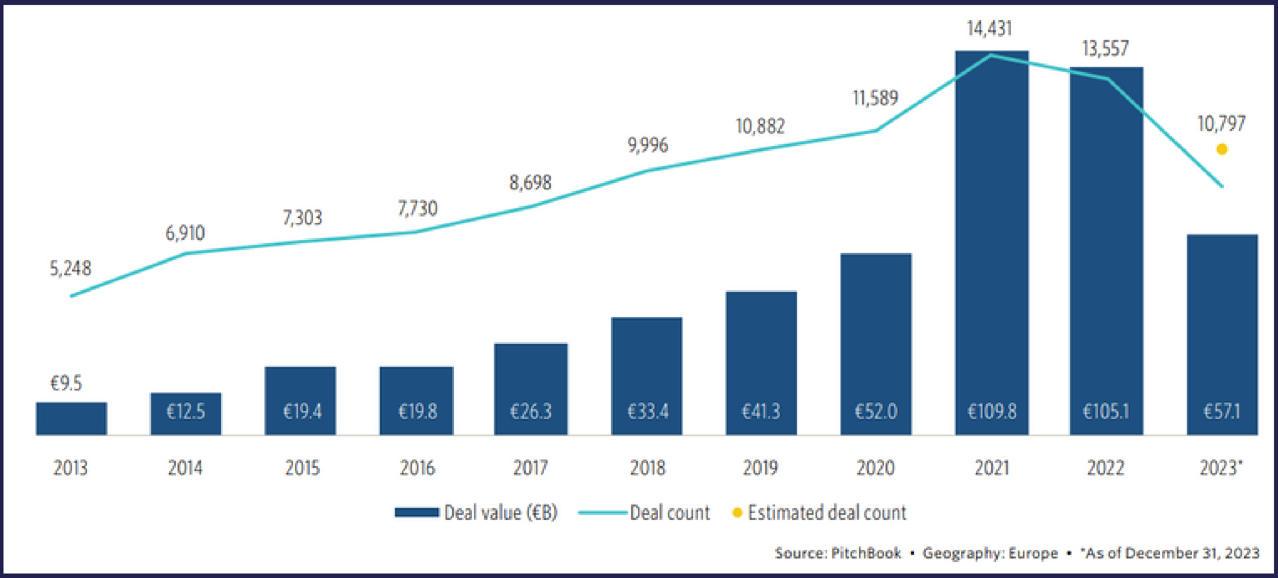
By aligning product ideation with industry growth potential, companies can better position themselves for long-term success.

From a product lifecycle management perspective, choosing a rapidly-growing industry during the product design stage is crucial for several reasons.

- First, it ensures that there is a strong market demand for the product, which can lead to higher sales and revenue growth.
- Second, rapidly-growing industries often have more opportunities for innovation and differentiation, allowing companies to create unique value propositions and gain a competitive edge.
- Third, these industries typically attract more investment capital, providing resources for product development, marketing, and expansion.

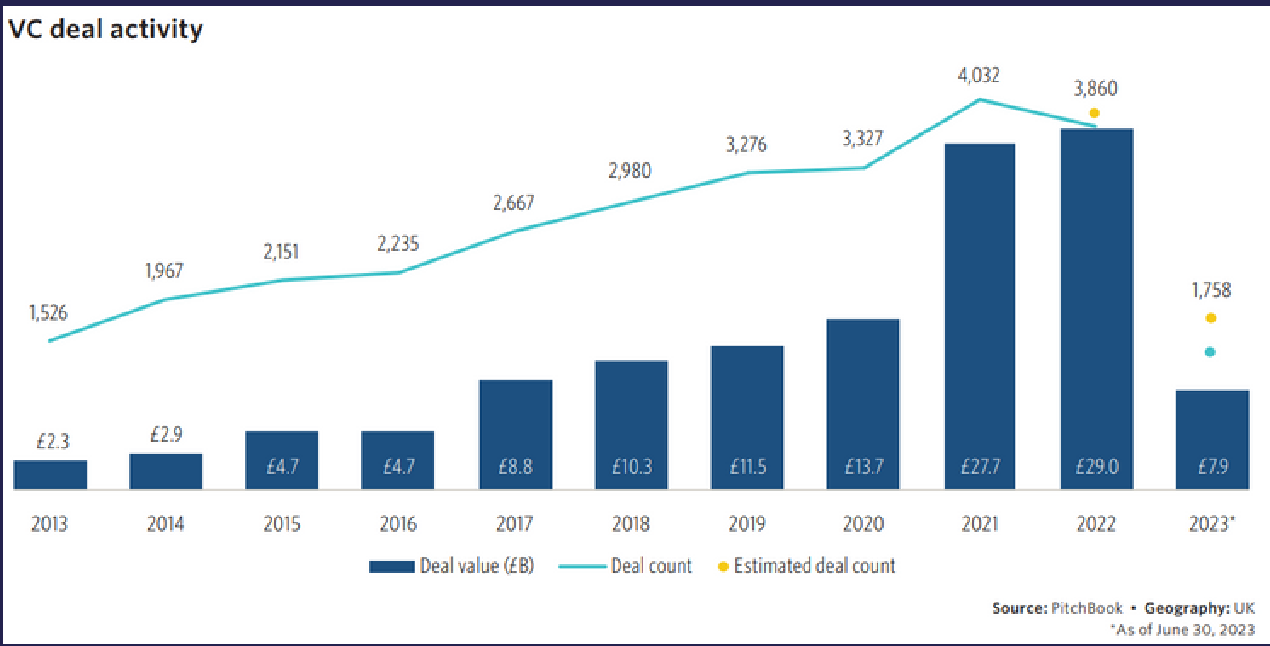
PEVC Activity in Europe

Based on the 2023 Annual European Venture Report [16] and 2023 UK Private Capital Breakdown [17] by the Pitchbook, private equity and venture capital funding in Europe and the UK has shown mixed trends in 2023. While overall deal activity has declined, there have been some notable bright spots. In the EU, the European VC deal value declined by 45.6% in 2023, with cleantech attracting top deals. France & Benelux emerged as the winner of regional trends, while biotech & pharma showed the most resilience by sector. In the UK, private equity deal value increased by 13.2% quarter-over-quarter in Q2 2023, driven by smaller deals in the £100-500 million range. Take-privates and carveouts remain popular due to market timing and structural issues.



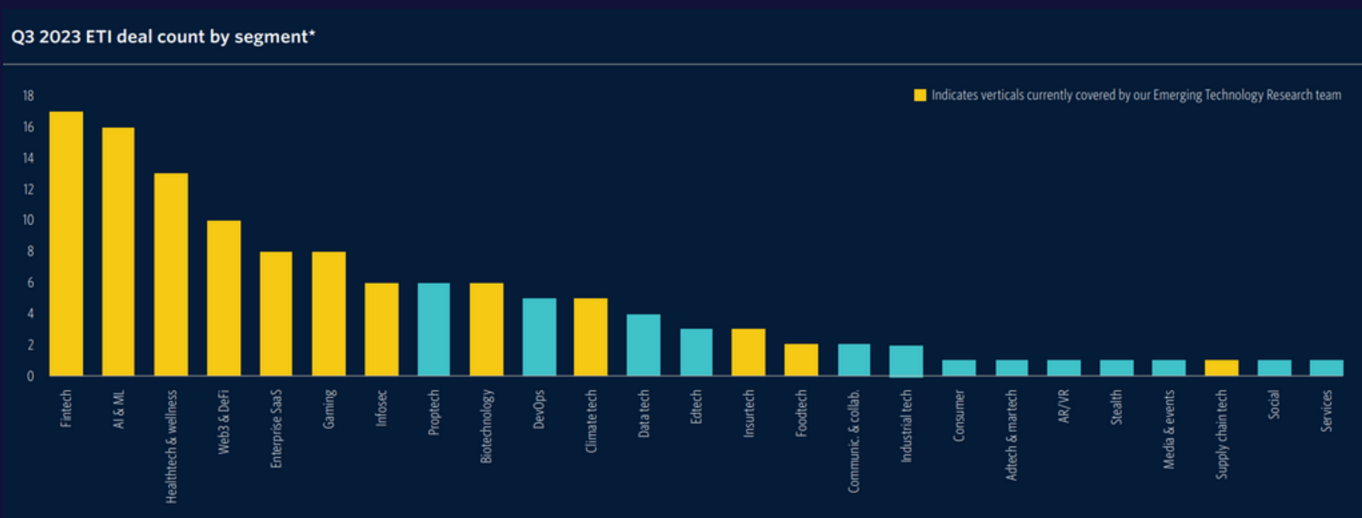
VC Activity in the UK

UK venture capital deal value fell by 57.7% in H1 2023 compared to the previous year, although it increased sequentially in Q2. The macroeconomic landscape remains challenging, with high inflation and interest rates. However, the healthcare sector has shown resilience, with deal values in healthcare services & systems and healthcare devices & supplies remaining relatively stable.



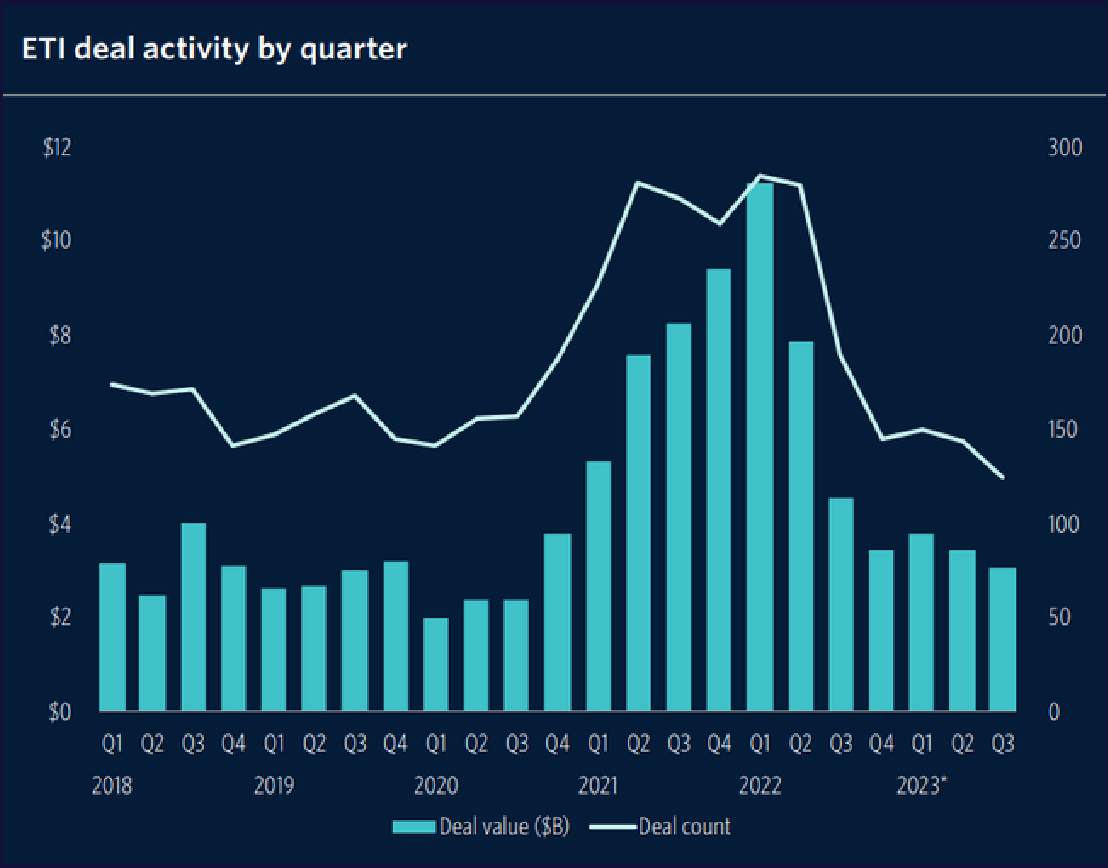
Trending by Sectors

The Emerging Tech Indicator report [15] highlights several key trends in global venture capital funding. AI & ML and biotechnology continue to dominate, capturing the largest shares of capital. Other notable sectors include healthtech & wellness, fintech, and climate tech. Within AI & ML, investments focused on machine learning operations, data management, and tools for AI deployment. In biotechnology, companies leveraging AI for drug discovery and development attracted significant funding.



Choosing the right industry and product category is essential for rapid growth, and the PEVC funding trends provide valuable insights. The strong interest in AI & ML and biotechnology suggests that products leveraging these technologies could have significant growth potential. Similarly, the resilience of the healthcare sector in the UK indicates that healthcare-related products may be well-positioned for success.

However, it is important to consider the specific market dynamics and competitive landscape within each industry and product category. While overall funding trends can provide guidance, companies must also assess the unique value proposition and differentiation of their products. By aligning product design with both industry growth potential and a clear understanding of customer needs and preferences, companies can position themselves for rapid growth and long-term success.



source: [15]

Moreover, the decline in overall PEVC deal activity highlights the need for companies to be strategic in their funding approaches. Those that can demonstrate a compelling value proposition, strong market demand, and a clear path to profitability may be better positioned to attract investment in a more challenging funding environment. By carefully considering industry trends, product differentiation, and funding strategies, companies can maximize their chances of success in rapidly-growing markets.

Insights to the Holographic Displays and Mixed Reality Industries

Demand Side

- Users highly value the immersive and interactive experience brought by holographic displays and MR. Compared to traditional 2D displays, holographic displays and MR can create a more realistic and immersive experience, making users feel as if they are within the virtual scene. Secondly, image quality and low distortion are also key concerns for users. Only high-resolution, high-contrast, and vibrant images can provide the ultimate visual enjoyment. Furthermore, users expect simple operation and lightweight devices, allowing them to immerse themselves in the virtual world anytime, anywhere, without being limited by the scene or hardware. In summary, immersion, interactivity, image quality, and portability constitute the core demands of users for holographic displays and MR. [18]

Hardware Side

- Currently, the industry is making efforts from multiple aspects to meet users' demands for holographic displays and MR. On one hand, major manufacturers are continuously breaking through the bottlenecks of optical technology, developing new optical waveguides, diffractive optical elements, and other core components to significantly improve key indicators such as image brightness, field of view, and color saturation [18] . On the other hand, the industry is actively exploring cutting-edge display technologies such as light field reconstruction, computer holography, and digital light processing, aiming to bring revolutionary enhancements to the user experience [19] [20]. At the same time, mainstream MR devices are being optimized in terms of volume, weight, and wearing comfort, allowing users to immerse themselves in the virtual world more easily [18].

Software Side

- On the software side, holographic displays and MR are becoming increasingly intelligent through the introduction of multi-modal interaction technologies such as gesture recognition, voice interaction, and eye tracking, greatly reducing the learning curve and usage threshold for users. Meanwhile, numerous content providers are actively deploying rich 3D volumetric content, offering users a vast array of games, videos, educational resources, and more, thus expanding the application boundaries of holographic displays and MR. As technology continues to evolve and the ecosystem becomes more robust, it is foreseeable that holographic displays and MR will bring unprecedented new interactive experiences to users

Competition Side

- Looking at the holographic display and MR track, a batch of representative players have emerged both domestically and internationally, and the competition is exceptionally fierce. Faced with common user demands, companies are taking different paths to reach the same goal, but they are exhibiting differentiated characteristics in their specific implementation approaches.

- For example, international giants such as Microsoft and Magic Leap, with their strong technological accumulation and financial strength, are conducting comprehensive layouts in optical systems, display technology, interaction methods, and more, aiming to seize the high ground of the industry through "integrated hardware and software" solutions [19]

- In contrast, smaller startups such as Light Field Lab and Lingxi Microlight are focusing more on vertical industry scenarios, providing customized industry solutions for medical, education, industrial, and other niche fields through a "customized software + hardware selection" model [18].

- Overall, companies around the world are making joint efforts across multiple dimensions such as hardware performance, software ecosystem, interactive experience, and industry applications, striving to better meet users' personalized needs through differentiated advantages and gain a foothold in the holographic display and MR track

Application Case Studies

------ Acoustic Haptics

1. Mouth Haptics

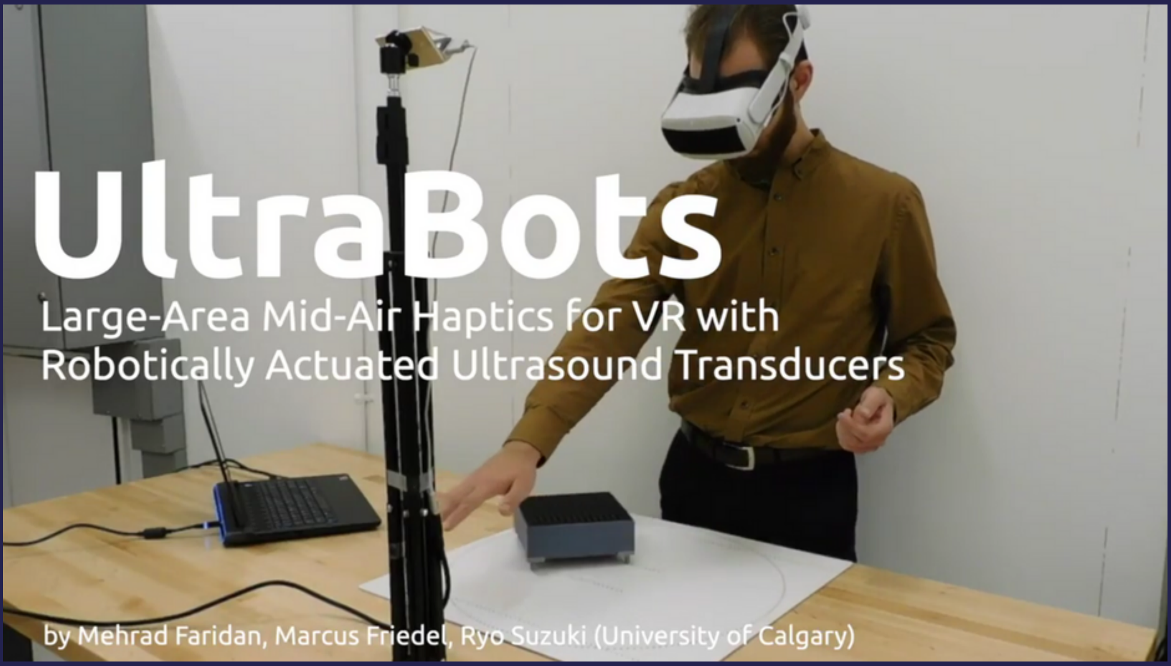
Shen et al. [22] introduced an innovative approach to enhancing virtual reality (VR) experiences by providing tactile feedback to the mouth. They utilized an ultrasound phased array integrated into a VR headset to generate focused points of haptic feedback on and within the user's mouth. By strategically manipulating the phase and amplitude of the ultrasound waves, the system can create localized sensations on the lips, teeth, and tongue, simulating the feeling of objects and textures in the virtual environment. The results indicate that users can distinguish between different virtual objects and textures based on the mouth haptics feedback, leading to a more engaging and believable VR experience.

By providing tactile feedback to the mouth, it addresses a previously overlooked aspect of haptic feedback, setting it apart from other haptic solutions that focus primarily on the hands and body. Moreover, the potential applications of this technology extend beyond entertainment, with valuable use cases in fields such as medical and dental training, speech therapy, and accessibility for individuals with sensory impairments.

2. UltraBots

UltraBots [21] is an innovative system that enables large-area mid-air haptics for VR using robotically actuated ultrasound transducers. This cutting-edge technology allows users to experience tactile sensations in VR without the need for physical contact or wearable devices. By employing an array of ultrasound transducers mounted on robotic arms, UltraBots can dynamically position and orient the transducers to create haptic feedback over a large interactive area. This approach overcomes the limitations of traditional stationary ultrasound haptic devices, which have a limited range and cannot provide tactile sensations beyond a fixed focal point.

The UltraBots system consists of multiple robotic arms, each equipped with an ultrasound transducer array. These robotic arms can move and rotate the transducers in real-time, allowing for precise control over the location and intensity of the haptic feedback. By coordinating the movements of the robotic arms and modulating the ultrasound waves, UltraBots can generate a wide variety of tactile sensations, such as vibrations, textures, and even the sensation of touching virtual objects. This technology opens up new possibilities for immersive VR experiences, enhancing user engagement and realism.



Competitiveness and Value in VR Industry

UltraBots has the potential to significantly enhance the immersiveness and realism of VR experiences by providing large-area mid-air haptic feedback. This technology offers a competitive advantage over existing haptic solutions, as it eliminates the need for physical contact or wearable devices, allowing for more natural and intuitive interactions in VR. As the demand for immersive VR experiences continues to grow, UltraBots has the potential to become a valuable addition to the VR industry, setting a new standard for mid-air haptic technology.

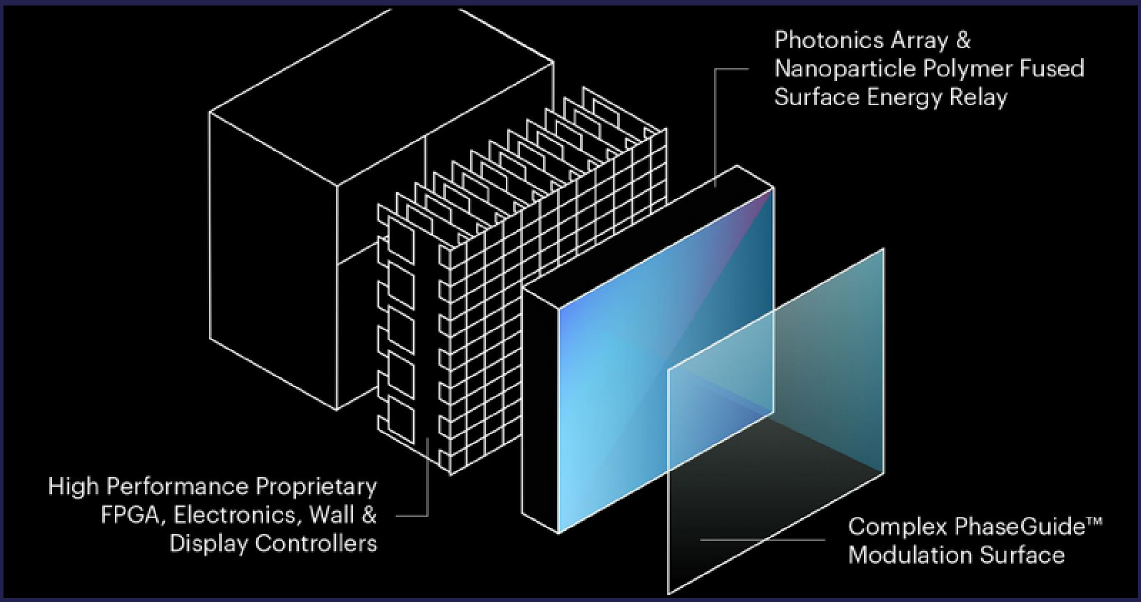
Application Case Studies

------ Holographic Display

3. Light Field Lab

Light Field Lab is a pioneering company in the field of holographic display technology. They are developing a groundbreaking light field display system that aims to revolutionize the way we experience visual content. Unlike traditional displays that emit light in a single direction, Light Field Lab's technology generates a complete light field, creating a true three-dimensional image that can be viewed from multiple angles without the need for special glasses or headgear.

The core of Light Field Lab's technology lies in their proprietary light field display modules. These modules consist of a dense array of tiny, individually controllable light emitters called nano-photonic waveguides. By precisely manipulating the phase, amplitude, and direction of light emitted from each waveguide, the display can reconstruct the complex light field of a 3D scene. The modules can be seamlessly tiled together to create large-scale displays with billions of pixels, enabling immersive and lifelike holographic experiences.

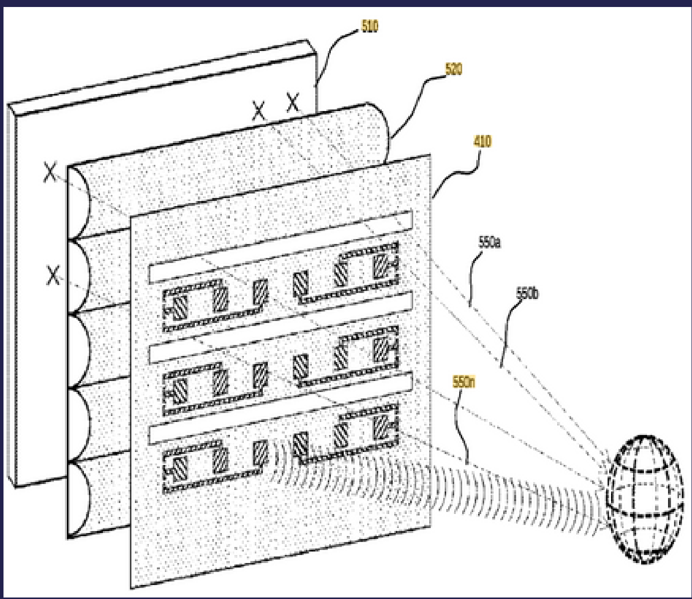


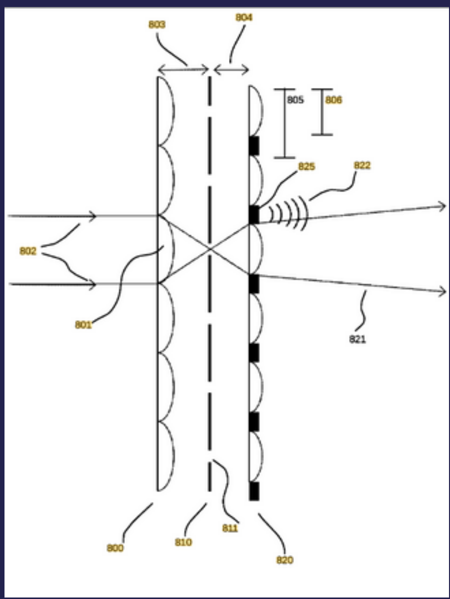
One of the key advantages of Light Field Lab's technology is its ability to generate true volumetric images with accurate depth cues and motion parallax. The technology also supports multiple viewers simultaneously, allowing each person to see the holographic content from their unique perspective without any loss of image quality or resolution.

4. Daniel Smalley's Design to Integrate Flat-Panel 3-D Display with Acoustic Haptics

The Figure in the left depicted Prof. Daniel Smalley's invention [23] which aims to provide a more immersive and scalable multi-sensory experience by integrating a 3-D display with ultrasonic transducers for generating directional audio and tactile feedback, all within a compact, tileable unit. This is achieved by utilizing a slit plane placed in front of the 3-D display, with the ultrasonic transducers mounted on the opposite side of the slit plane facing the user.

1. The invention comprises a 3-D display 510 and a slit plane 410, combined in a preferred embodiment.
2. A lenslet array 520 may be placed between the 3-D display 510 and the slit plane 410. In one embodiment, the lenslet layer 520 focuses the light from the 3-D display 510 vertically through the slit plane 410.
3. Ultrasonic transducers 430a ... n are attached, adhered, connected, or otherwise secured to, or included or manufactured as a part of, the front side of the slit plane 410 (the side opposite to the 3-D display 510).
4. The light from the 3-D display 510 passes through the slits in the slit plane 410 to generate a 3-D image.
5. The ultrasonic transducers 430a ... n on the slit plane 410 generate focused acoustic fields and/or tactile fields.
6. The combined visual components from the 3-D display 510 and the audio and tactile sensations from the ultrasonic transducers 430a ... n create a multi-sense experience for the user.





The Figure in the right shows a lenslet array 800, a slit plane 810, and a third plane 820 with a lenslet array and ultrasonic transducers. The light from the 3-D display passes through the lenslet array 800, then through the slits 811 in the slit plane 810, and finally through the third plane 820 with the lenslet array and ultrasonic transducers. In this alternate embodiment, the ultrasonic field and the 3-D imagery are fully superimposed as they are emitted from the same plane, creating a more seamless multi-sensory experience. [23]

5. Samsung's glasses-free 3D monitor

Samsung showcased an innovative glasses-free 3D monitor concept at CES 2024. This monitor can seamlessly switch between 2D and 3D modes using an active lenticular lens. In 3D mode, it employs two cameras at the top of the display to track the user's head and eye positions in real-time then adjusts the 3D mapping to match the user's eyes, creating a convincing glasses-free 3D effect for that single user.

The core technology seems to be the combination of the active lenticular lens layer on the screen itself along with the eye tracking to adjust the 3D effect in real-time as the user moves.

One advantage of this monitor is that it can seamlessly switch between 2D and 3D modes for different use cases. However, its eye tracking-based 3D is for a single user viewing experience, not a group setting. This makes it best suited for personal gaming, 3D design work, or other single-user applications rather than shared viewing.

6. Other Common Holographic Display Methods

(1) 3D LED fans

It consists of a rapidly spinning fan with LED lights arranged on the fan blades. As the fan rotates at high speeds, the LEDs flash in a precise pattern, creating a persistence of vision effect. This means that the human eye perceives the rapidly flashing lights as a continuous image.

Hologram fans offer a captivating visual experience, making them popular for advertising, product displays, and entertainment purposes. However, the image quality and resolution are limited by the number of LEDs and the fan's size. [26]

6. Other Common Holographic Display Methods

(2) Fog Screen

It has nozzle to generate a fine mist of water droplets, creating a translucent screen suspended in the air. The projectors, positioned either in front of or behind the water curtain, cast images onto the mist. As light hits the water droplets, it scatters, making the image visible to the audience. The result is a seemingly floating, semi-transparent image that appears three-dimensional.
Water mist displays can be large in scale, making them suitable for outdoor events, product launches, and art installations. However, they require a controlled environment with proper water drainage and may be affected by wind or air currents. [24]

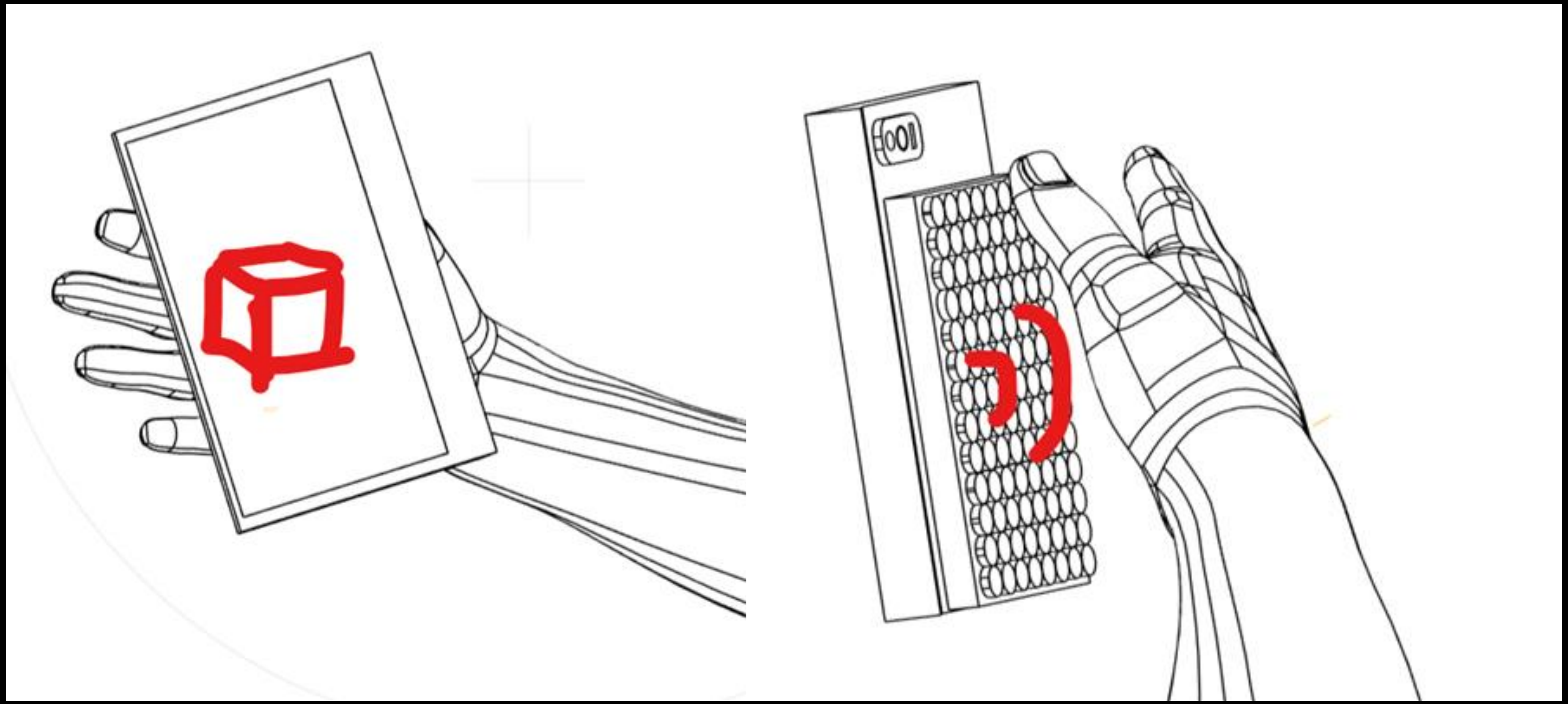
(3) Drone holographic light show

It uses a swarm of synchronized drones equipped with LED lights to create dynamic, 3D displays in the night sky. These shows are choreographed using specialized software that controls the drones' movements and the colors of their LED lights. The drones fly in formation, creating intricate patterns, shapes, and even animated sequences. The software takes into account factors such as wind speed, GPS coordinates, and the drones' relative positions to ensure precise and safe flight paths. They offer a unique and eco-friendly alternative to traditional fireworks displays, as they produce no air or noise pollution and can be reused for multiple performances. However, drone light shows are dependent on weather conditions and require a skilled team to operate and maintain the drones. [25]

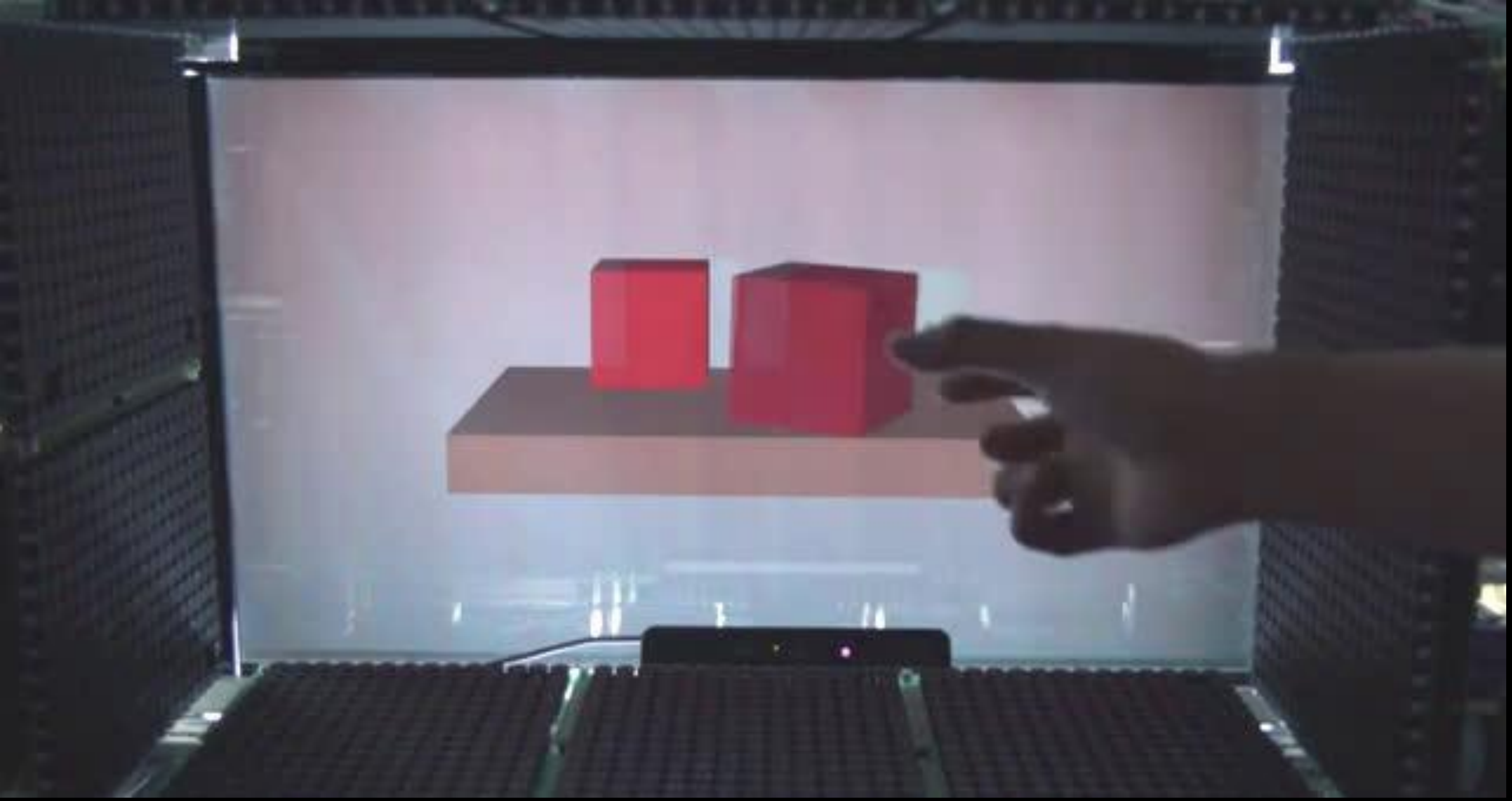
source: [27]

Comparing these three holographic display methods, Hologram fans are compact, affordable, and suitable for indoor use, but they have limited image size and resolution. Water mist displays can create large, immersive experiences, but they require a controlled environment and may be affected by wind. Drone light shows offer the grandest scale and can create stunning aerial displays, but they are dependent on weather conditions and require significant resources to execute.

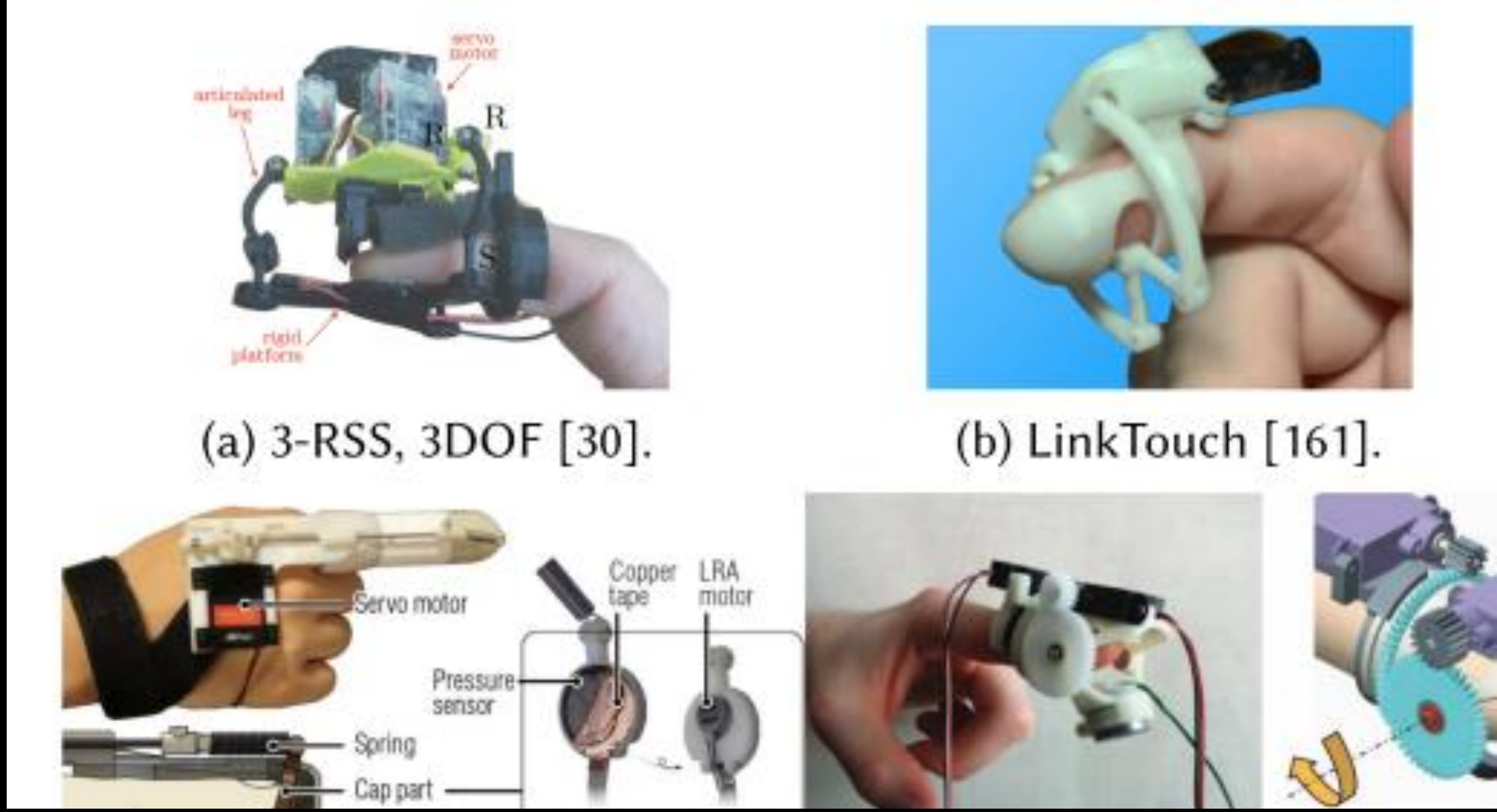
PalmPet: A Handheld Ultrasonic Haptic Accessory to Enhance Mobile AR Experiences



John Chen Supervisor: Ryuji Hirayama



Matsubayashi et al
(2019)



Pacchierotti et al
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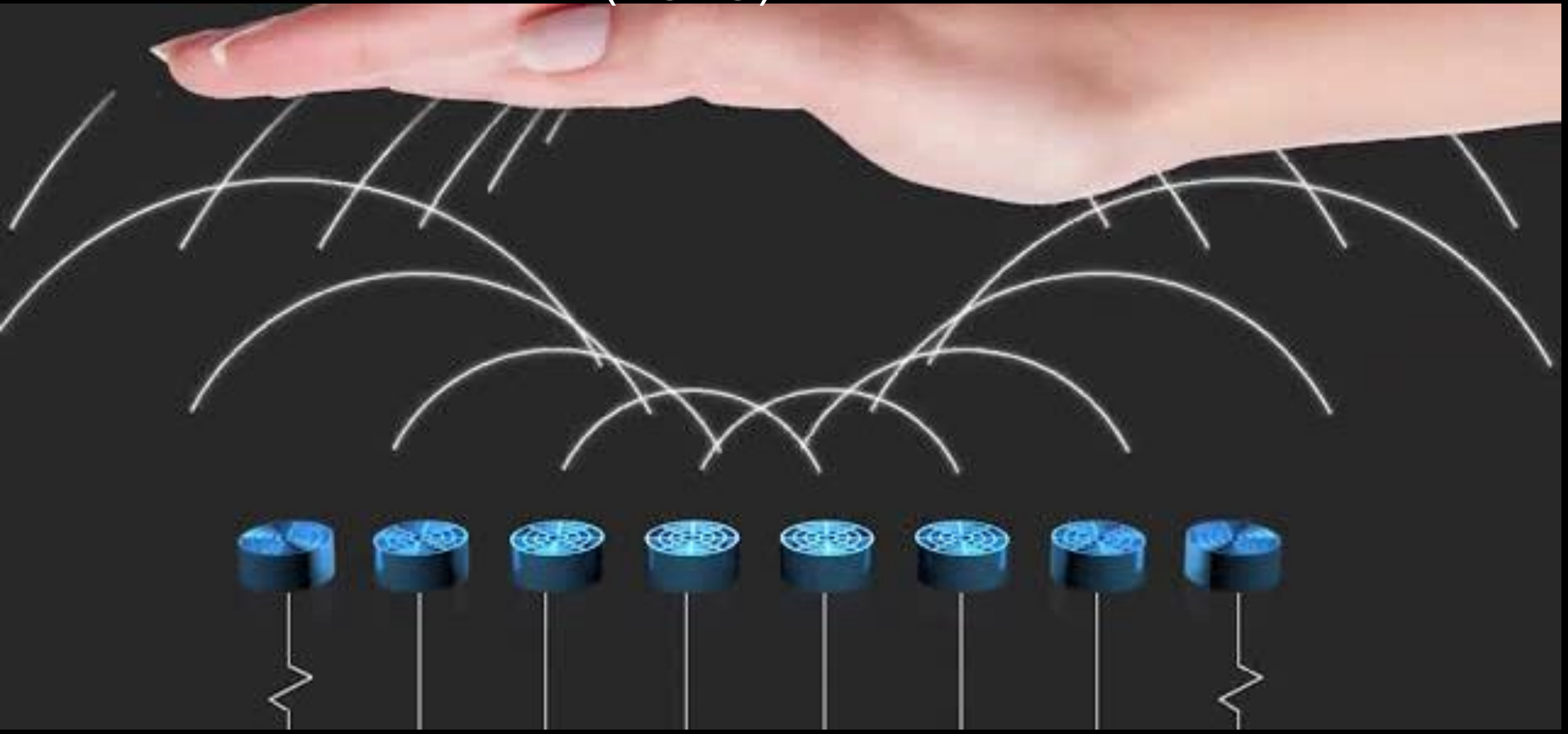

Long et al
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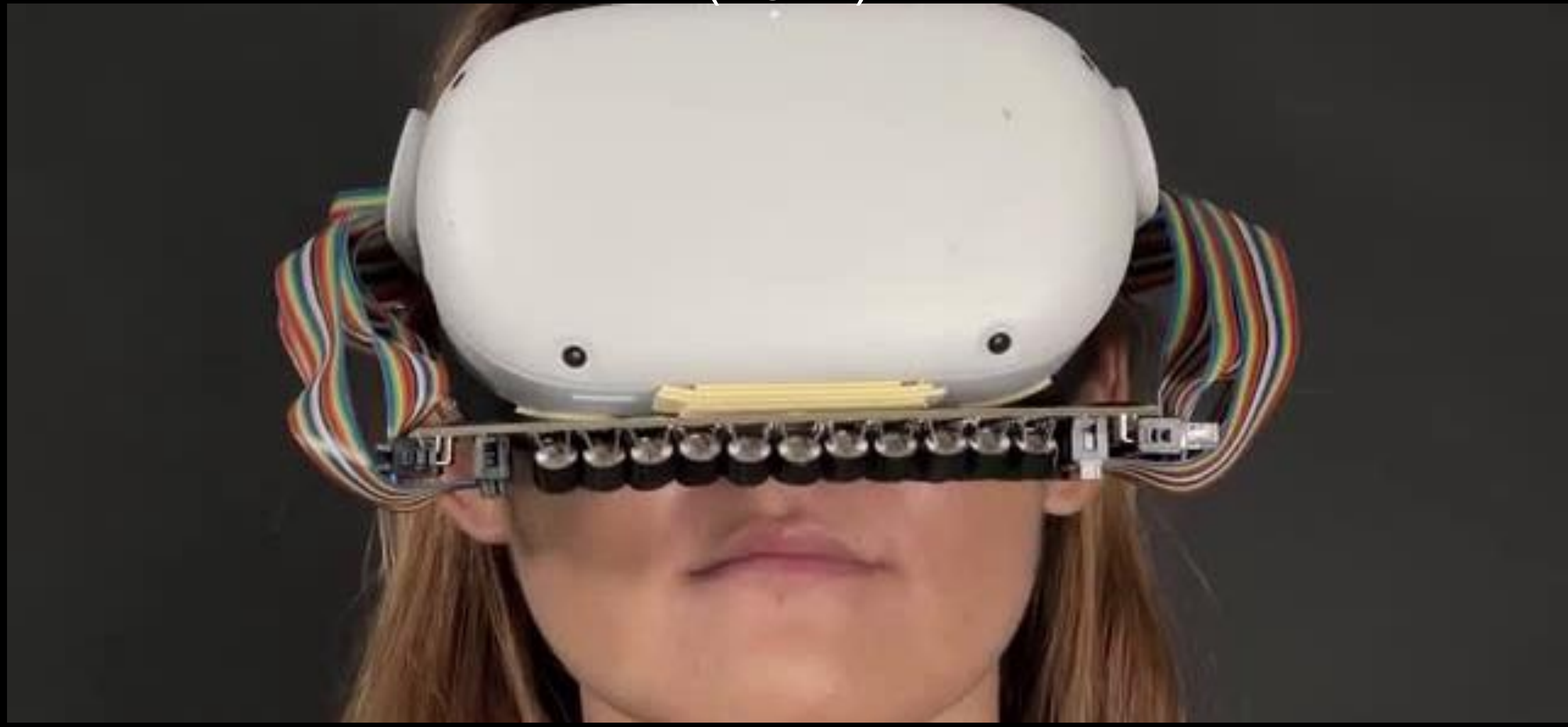


Shen et al. (2022)

The Problem:

Existing haptic systems are often bulky, stationary, and separate from displays. Integrating transducers into VR headsets (Shen 2022) faces challenges like transducer positioning obstructing cameras and reducing haptic effect strength due to narrow emission cones (80°), many transducers could not participate in the beamforming pattern, reducing the haptic effect strength.

My proposed solution:

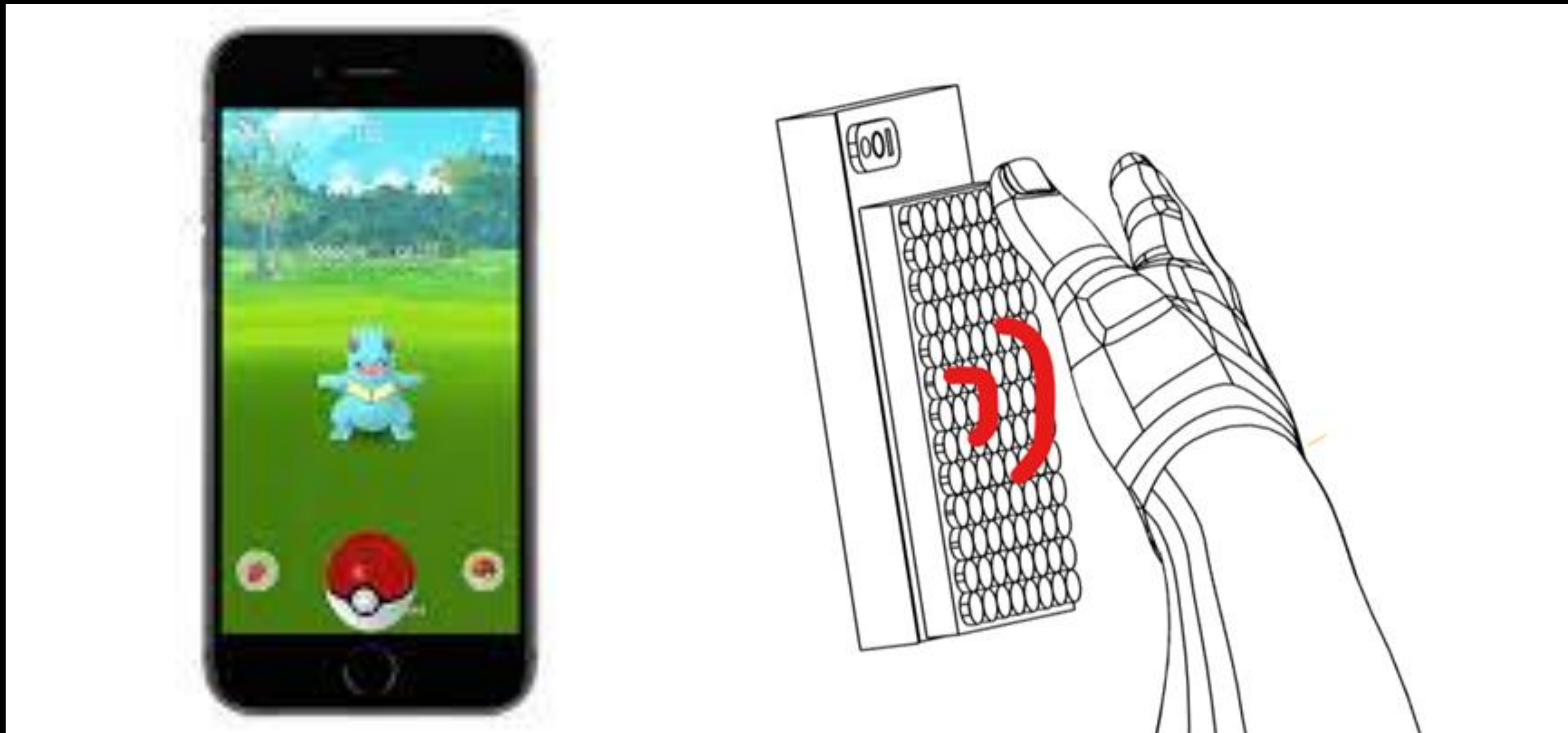
An 8x8 phased array of ultrasonic transducers attachable to the back of a smartphone, directly addresses this gap by providing mobile AR applications with haptic feedback, enhancing user experience without compromising portability and user’s palm always within optimal effective range (6-8 cm) for maximum acoustic radiation.

Methodology:

Mini PAT board -> Computation in Laptop via WiFi / embedded solver / cloud computation -> An AR mobile APP similar to Pokemon Go

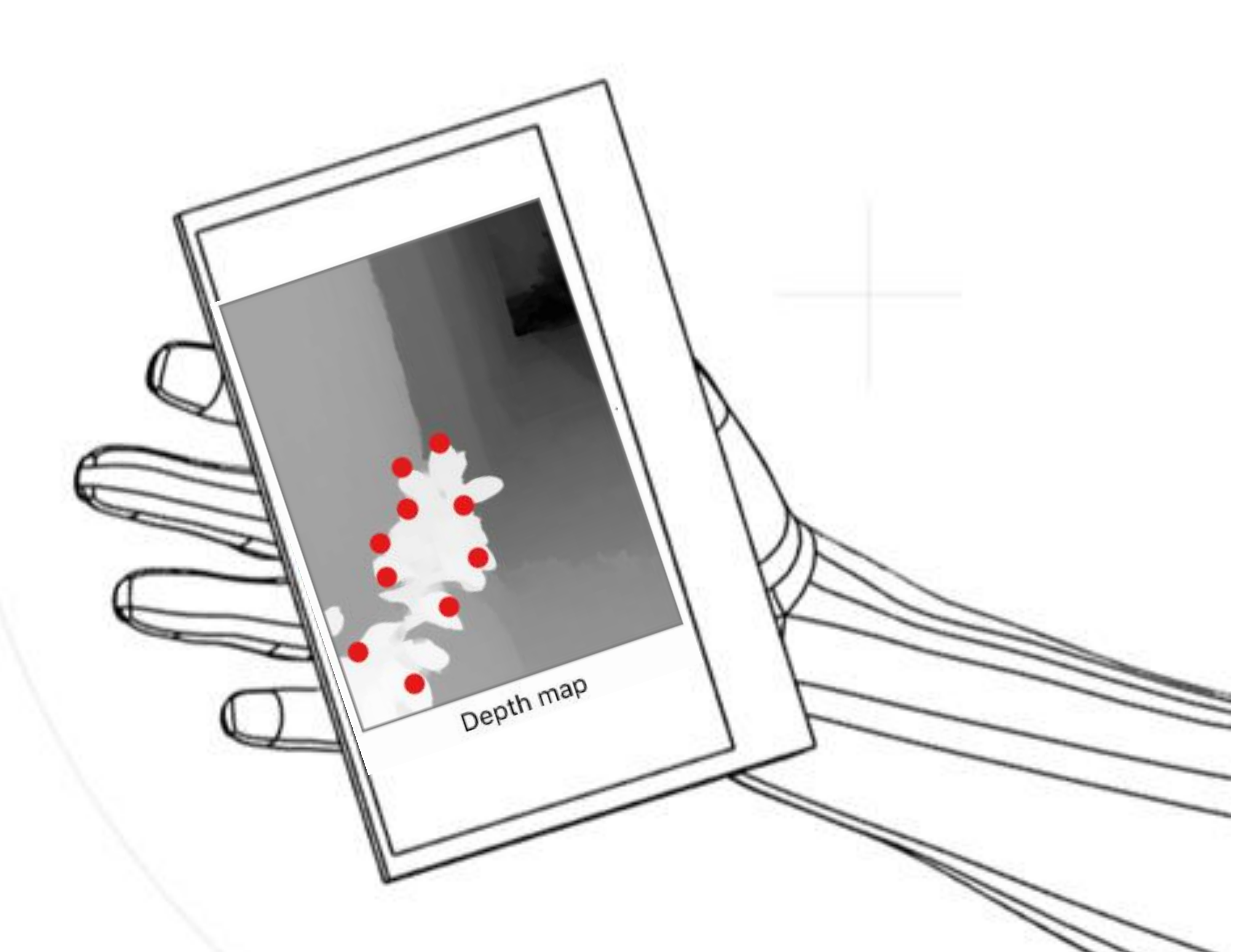
Scenario 1:

Pet movement on the palm -> changing focal point positions

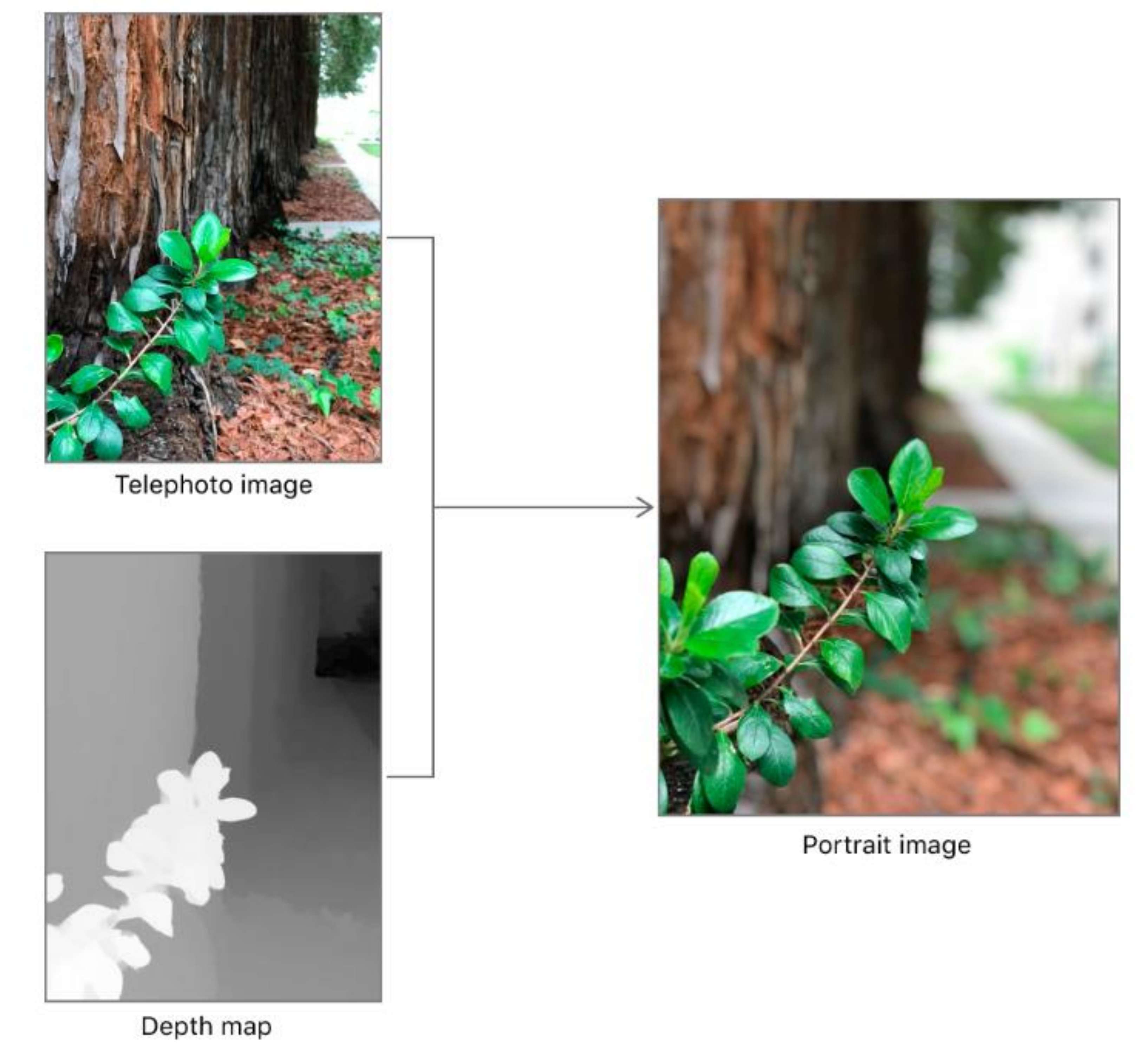


Methodology:

Scenario 2: 2D Depth Object Sensation (see-through the phone and feel the closest object or virtual Pokemon)



Send 10 least dense position in the image to the solver, Update one focal points at 10 frames per second to simulate dynamic haptic feedback.



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