Institution: University of Bristol		
Unit of Assessment: 11) Computer Science and Informatics		
Title of case study: Making the digital world feel more human: using haptic feedback to bring back the sense of touch		
Period when the underpinning research was undertaken: 2011 - 2016		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Sriram Subramanian	Professor of Human Computer Interaction	09/2007 to 07/2015
Bruce Drinkwater	Professor of Ultrasonics	03/1996 to present
Mike Fraser	Professor of Human Computer Interaction	04/2004 to 09/2019
Ben Long	Research Associate	11/2011 to 02/2015
Sue Ann Seah	Research Associate	02/2012 to 01/2015
Period when the claimed impact occurred: 2014 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

University of Bristol research into mid-air haptic feedback technology led to the creation of the highly successful spin-out company Ultraleap (formerly Ultrahaptics). Ultraleap now employs 170 people, has raised GBP65 million in investment, and acquired a US company in 2019 to expand their portfolio of technologies. Sales of over 1,000 development kits have led to the incorporation of their haptic technology into applications and products in the home, automotive, industrial and digital fields with partners including Microsoft, Coca Cola, Bosch and global market leader in digital signage BrightSign. Commercially available products include a vehicle, digital signage and VR gaming technology.

2. Underpinning research

Haptic feedback is to the sense of touch what visual feedback is to sight, and audio feedback is to hearing. The development of touch screens enables digital interaction using a greater range of gestures and motion but, without haptic feedback, the user retains a reliance on visual cues to know whether an action has been completed. The University of Bristol's Interaction and Graphics Research Group have conducted research on advanced user interaction modalities since 2009. Initial research by Subramanian and Fraser, funded by EPSRC [i], focussed on new forms of displays and devices that enhance the way a user interacts with computational devices, showing the limitations of touchless interaction [1].

Working to incorporate haptic feedback into touchless interactions, the team focussed on the use of ultrasound-based air pressure waves to produce tactile sensations in mid-air. Mid-air, touchless haptics bring significant benefits to users, including avoiding having to physically touch an object or surface, with obvious public health benefits, and being able to position a touchless interface right next to a user, with safety and convenience benefits in situations such as in-car interfaces or in interactive signage. Existing techniques had shown that an array of ultrasound transmitters could create tactile sensations in mid-air at a single focal point but had no ability to create multiple focal points simultaneously due to interference issues.

These issues of interference were subsequently solved by Subramanian's team, in collaboration with Drinkwater from Mechanical Engineering, who investigated novel approaches to multi-point and mid-air haptic feedback and introduced a system they called *UltraHaptics* [2]. This research, supported by ERC funding [ii], proposed a solution using a novel waveform synthesis algorithm that provided far greater control over the pressure distribution created by arrays of ultrasound emitters than existing techniques, and was thus capable of creating multiple simultaneous focal points and controlling them individually (Figure 1a).

The hardware was also extremely scalable, comfortably extending from small arrays (4x4 transducers) to setups featuring multiple large arrays (20x20 and beyond). It also scaled from computationally intensive applications requiring a powerful PC down to embedded systems.

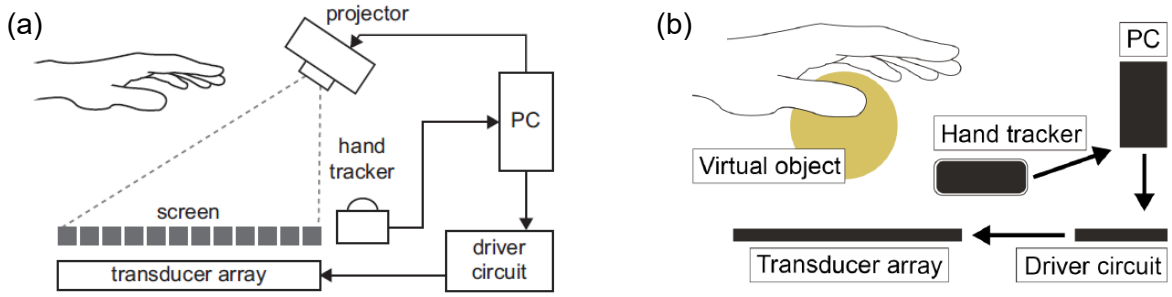

Figure 1 - (a) the UltraHaptics system that employs focused ultrasound to project discrete points of haptic feedback through the display and directly on to users' unadorned hands; (b) system set up for the creation and testing of 3D haptic shapes.

Follow up research considered how to produce convincing sensations of motion, as well as how users perceive a static point. Using the *UltraHaptics* system, the University of Bristol team (funded by EPSRC [iii]), showed the minimum shape size required to perceive a point, the minimum distance to perceive motion [3], and demonstrated the ability of the system to manipulate physical objects in a vertical plane [4]. This research resulted in novel hardware with much greater directionality than conventional emitter arrays, enabling the creation of pressure patterns in a larger volume of air with a smaller array.

To enable a user to feel a three-dimensional object and provide a more realistic experience, the group developed an algorithm that could control the volumetric distribution of the acoustic radiation force field when using a two-dimensional phased ultrasound array [5]. This enabled the production of a volumetric haptic shape in mid-air, but was also capable of running interactively, allowing the creation of real-time haptic sensations and dynamically changing shapes. The capability to create mid-air haptic shapes is advantageous as a user does not need to wear any attachments or be restricted by the use of any tools (Figure 1b).

Development of a working prototype using EPSRC Impact Acceleration funds enabled the physical demonstration of the technology, and the exploration of applications and market segments. Patent applications were filed by the University of Bristol in 2013 and 2014 on the method for producing an acoustic field, the method for providing tactile sensations, and on modulating haptic feedback [6]. These patent applications were licensed (and subsequently assigned) to the newly created company, Ultrahaptics (now Ultraleap), set up by Carter, Subramanian and Long to commercially exploit the results of the research.

3. References to the research

[1] Cauchard JR, **Fraser M,** Han T, **Subramanian S.** (2012). Steerable projection: exploring alignment in interactive mobile displays. *Personal and Ubiquitous Computing,* 16, 27–37. DOI:10.1007/s00779-011-0375-3

[2] Carter T, **Seah SA, Long B, Drinkwater B, Subramanian S.** (2013). Ultrahaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces. In: *Proceedings of the 26th annual ACM symposium on User interface software and technology,* 505-514. DOI:10.1145/2501988.2502018

[3] Wilson G, Carter T, **Subramanian S,** Brewster SA. (2014). Perception of ultrasonic haptic feedback on the hand: Localisation and apparent motion. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems,* New York, USA, 1133–1142. DOI:10.1145/2556288.2557033

[4] **Seah SA, Drinkwater BW,** Carter T, Malkin R, **Subramanian S.** (2014). Correspondence: Dexterous ultrasonic levitation of millimeter-sized objects in air, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 61 (7), 1233-1236. DOI:10.1109/TUFFC.2014.3022

[5] **Long B, Seah SA**, Carter T, **Subramanian S.** (2014). Rendering Volumetric Haptic Shapes in Mid-Air Using Ultrasound. *ACM Transactions on Graphics* (TOG), 33(6), Article 181. DOI:10.1145/2661229.2661257

[6] Carter T, **Long B, Subramanian S**. (2014). Method and apparatus for modulating haptic feedback. GB201415923

Key grants:

[i] **Subramanian S.** Mobile VCE Strategic Partnership: User Interaction, EPSRC, EP/G058334/1, 2009-2012, GBP208,956

[ii] **Subramanian S.** Interactive systems involving multi-Point surfaces, haptics and true 3D displays, ERC, 2011-2016, EUR945,742

[iii] **Subramanian S.** Exploration of Ultrasound based haptic interaction on a multi-touch surface, EPSRC, EP/J004448/1, 2012-2015, GBP335,832

4. Details of the impact

Commercialisation of new technology

Ultrahaptics Limited was formed in November 2013 to commercialise technology that provides mid-air haptic feedback. The technology stemmed directly from research undertaken at the University of Bristol [1-5], which was the basis for patents and other intellectual property rights (including [6]) licensed to Ultrahaptics. The license included know-how related to the patent applications such as algorithms [2, 5], methods for integrating the haptic feedback mechanism into commercial products [3, 6], as well as software developed to control, evaluate and simulate an array of ultrasound transducers. The licensed rights have formed the basis of continued research within the company, being cited in subsequent company patent applications [A].

Ultraleaps' forecast sales revenue for 2020 is GBP4.5 million, chiefly from licenses to AR/VR companies, touchless interfaces, and sales of development kits [A]. Ultraleap now employs 170 people, including 140 in Bristol and 30 in Silicon Valley. Twelve of these employees came from Leap Motion, a Silicon Valley-based company focussed on advanced hand-tracking technology which was acquired by Ultrahaptics in 2019, before rebranding as Ultraleap [B]. The workforce has 27 different nationalities and 35 PhD graduates. The company has raised GBP65 million in investment funding over four investment rounds.

The initial commercial offering was an evaluation kit which was sold to individual users and companies from late 2014. The kit allowed companies to evaluate the technology and develop concepts and prototypes for their own applications, and allowed Ultrahaptics to pursue development agreements with relevant partners. Within two weeks of launch, the team was expanded to handle the demand for kits.

Ultraleap now has two commercially available kits: *STRATOS Explore*, a flexible, scalable high-end haptics development kit, and *STRATOS Inspire*, a complete haptic module. *Explore* allows developers to create immersive and interactive experiences but is not certified for public use, whereas *Inspire* can be used for interactive public installations. More than 1,000 kits have been sold across the world to large industrial companies as well as smaller development companies [A].

STRATOS Explore

STRATOS Inspire

Development and partnerships

Using the evaluation kit as an entry point from 2014, development agreements were reached with companies across a range of sectors, resulting in prototypes, demonstrators, and commercially available products. These are outlined below.

i) Automotive

In 2017, Harman (now owned by Samsung), a long-term BMW partner, incorporated Ultraleap's mid-air haptic technology to create a system of virtual buttons and knobs which can be closer to the driver than physical ones, as well as noiseless feedback warnings for lane departure, forward collision, and blind spot detection [Ci]. Similarly, Bosch presented a conceptual cockpit incorporating haptic feedback technology from Ultraleap [Cii].

Bosch conceptual cockpit

More recently, a partnership between Dimenco, BHTC and Ultraleap resulted in Simulated Reality displays for a fully natural, interactive in-car centre console at the Frankfurt Motor Show. The Head of Technical Marketing & Technology Scouting at BHTC described the benefit of combining knowledge from the three companies *"….in a multimodal approach - to address multiple senses in an HMI* [human machine interface] *- makes traveling safe, comfortable, relaxing and fun. Driving becomes an experience."* [Di]. In 2020, Ultraleap's mid-air haptic and hand-tracking technology was incorporated into DS Automobile's new concept vehicle to "…*eradicate the constraints of touchpads…Through Leap Motion and Ultrahaptics technologies, you make a hand gesture and receive a sensory answer."* [Dii].

ii) Virtual Reality (VR) gaming and visualisation

Ultraleap's mid-air haptic and hand-tracking technology has been integrated into Fallen Planet Studio's technology [Ei] that is licensed by multiple VR arcades, including Inmotion VR [Eii], as well as directly into the VR experience industry such as The Void's Star Wars experience [Eiii]. The CEO of Fallen Planet Studios explained that *"…by implementing Ultrahaptics' mid-air technology we are able to deepen that level of immersion to new levels, without saddling the user with additional hardware for them to navigate. This combines to create a compelling out-of-home experience that really has to be felt to be believed."* [Eii].

Interactive cinema signage

Ultraleap's technology has also been incorporated into interactive displays: a collaboration between Dimenco, Microsoft and Ultraleap led to the demonstration of the world's first interactive 8K 3D display at CES 2020 [F]. This display enables creators to build 3D designs in a fully spatial environment, without the need for headwear or other wearables, delivering a dramatic improvement in possibilities and overall immersive productivity.

iii) Digital signage and kiosks

In 2018, Ultraleap installed two interactive digital signage installations and one static installation in a top-tier cinema complex in Los Angeles in order to quantify the impact of interactivity in digital out-of-home advertising [Gi]. The study showed an increase in attention time, brand awareness, dwell time, and conversion rate for the posters with haptic feedback which was corroborated by a further academic study [H]. This has led to multiple partnerships including with digital signage company BrightSign [Gii], the global market leader in digital signage media players, and with ZeroLight [Giii]. These have resulted in interactive digital exploration experiences at trade shows and in public spaces.

More companies have moved to self-serve kiosks to reduce customer wait time and staff requirements, but concerns have been raised about the hygiene implications of a multi-user touch screen, especially in light of the pandemic. In June 2020, CEN Media Group and Ultraleap signed a deal to install touchless technology incorporating haptic feedback at kiosks in their cinema network, starting with ten US city locations: "…*the installations will include Ultraleap's hand tracking and mid-air haptics which will limit the spread of germs and…provide safe and natural interaction with content*..." [I].

In October 2020 Ultraleap launched an application that can be used to rapidly retrofit kiosks and touchscreens to become touchless devices using hand tracking technology [Ji]. Ultraleap has signed a deal with Cortina Productions to roll the technology out across museums and exhibitions and complements their existing collaboration on mid-air haptics. The Principal and Director of Development at Cortina Productions, said: *"Over the last few months we've seen a drastic spike in requests from clients for touchless solutions for their interactive exhibits. Our clients rely on us to be at the forefront of new technology and to deliver experiences that are engaging and innovative. Ultraleap's technology not only helps us to provide the 'wow factor', it is completely touchless, making it the perfect solution to our clients' requests."* [Jii].

5. Sources to corroborate the impact

[A] Ultraleap (2020). Corroborating statement – CTO & Co-founder

[B] Design News (2019). Together Ultrahaptics and Leap Motion Could Transform How We Interact with Devices

[C] (i) ExtremeTech (2017). Harman, Ultrahaptics team up for mid-air haptic feedback
(ii) Wired (2017). Bosch wants to bring haptics to cars to let you control your entire dashboard with gestures

[D] (i) BHTC (2019). BHTC and Dimenco demonstrate the latest development in Simulated Reality display visualization at the Frankfurt Motor Show (IAA)
(ii) DS Automobiles (2020). DS Aero Sport Lounge: The Art of Travel

[E] (i) Fallen Planet Studios (2018). News: Feel The Power
(ii) VR Focus (2019). News: ImmotionVR's Cabot Circus Branch Now Features Mid-Air Haptic Feedback On AFFECTED: The Visit
(iii) Road to VR (2019). Ultrahaptics Relaunches as 'Ultraleap' After Leap Motion Acquisition

[F] Dimenco (2020). World's first 8K 3D display for the creator market at CES 2020

[G] (i) Ultraleap (2019). Interactivity Adds Measurable Value in DOOH [Study]
(ii) BrightSign (2020). BrightSign Approved Partners
(iii) AV Magazine (2018). Porsche ad displays react to bare-handed gestures

[H] Limerick *et al.* (2019). User engagement for mid-air haptic interactions with digital signage, *Proc. 8th ACM International Symposium on Pervasive Displays* DOI:10.1145/3321335.3324944

[I] Kiosk Marketplace (2020). CEN Media Group teams with Ultraleap on touchless DOOH

[J] (i) Ultraleap (2020). Ultraleap launches application to turn public touchscreens touchless
(ii) Cortina Productions (2020). Cortina Productions and Ultraleap sign deal as touchless tech demand soars in museums and exhibitions