Using and Validating Airborne Ultrasound as a Tactile Interface within Medical Training Simulators

Gary M.Y. Hung[1], Nigel W. John[1,*], Chris Hancock[1], and Takayuki Hoshi[2]

[1] Bangor University, Bangor, UK
{g.m.y.hung,n.w.john,c.hancock}@bangor.ac.uk
[2] Nagoya Institute of Technology, Japan
hoshi.takayuki@nitech.ac.jp

Abstract. We have developed a system called UltraSendo that creates a force field in space using an array of ultrasonic transducers cooperatively emitting ultrasonic waves to a focal point. UltraSendo is the first application of this technology in the context of medical training simulators. A face validation study was carried out at a Catheter Laboratory in a major regional hospital.

Keywords: Airborne Ultrasound, Acoustic Radiation Pressure, Tactile, Medical Simulation, Palpation, Augmented Reality.

1 Introduction

Medical trainees typically gain experience by performing procedures on real patients whilst supervised by an expert. Porta [1] recently evaluated the willingness of patients to have a trainee performing a surgical procedure and found that they are more reluctant to allow a trainee to perform the operation in comparison to a senior clinician. This makes gaining consistent, frequent access to a significant number of patients for training purposes difficult. Medical simulators are one solution and offer a platform on which the trainee can practice for long periods without the worry of making mistakes on a real patient. Virtually created patients are computer generated and use different display technologies (often stereoscopic) to provide a visual representation. Unlike mannequins, virtual patients typically have no physical presence. However, most commonly performed procedures, such as a palpation, involves the clinician interacting with the patient using their hands or fingertips to conduct diagnosis or treatment. Therefore, it is important to simulate and stimulate the physical sense of touch when presenting a virtual patient to make the training session of sufficient fidelity to be beneficial.

A physical phenomena known as Acoustic Radiation Pressure (ARP) [2] is generated by focusing multiple ultrasonic transducers to create a force field. The force can be concentrated at a particular point in three-dimensional space and the width of the focal point can be as small as 5 mm in the transmission medium of air. This paper demonstrates the feasibility of using ARP from focussed airborne ultrasound to

* Corresponding author.

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simulate common tactile sensations found on the body of a patient. We expand on out initial results [3] that focussed only on simulating a pulse like sensation, and provide the results of an evaluation of the system that was conducted at a major regional hospital.

2 Background and Related Work

Palpation is a common and necessary skill that all clinicians should be able to do. They may use their fingertips to feel a pulse, which is caused by the motion of the artery wall as the heart beats to circulate blood around the body. Some common palpable arteries are the carotid (neck), radial (wrist) and femoral (thigh). Examples of implementing a pulse in medical simulators include using a hydraulic pump to inflate a rubber tube embedded in a tray of silicone [4], or using a commercial force feedback joystick with a modified end effector [5].

A heart murmur is a condition where the valves of the heart show abnormal pulsations. A thrill sensation is also palpable and can be felt with the palm of the hand. The sensation is similar to a vibration but has a larger region of effect in comparison to an arterial pulse felt with the fingertips. An auscultation simulator [6] used a mannequin with embedded speakers to replicate the audible sounds of the heart. However, it is mainly designed to be used with a stethoscope and does not present a palpable thrill.

Other technologies have been used to provide tactile feedback. Shape memory alloys are typically used to achieve linear actuation of pin arrays [7, 8] but are known to suffer from slow response times, not sufficient to simulate a pulse rhythm. A pneumatic balloon array [9, 10] is an alternative to pin arrays but cannot achieve the same height as pins. Air tubes can also be used to create pressure on the pad of the finger [11] but requires the finger to be fully compressed against the valves to build up significant pressure, whereas if solenoids are used [12, 13] the devices tend to be too big. Finally, electrocutaneous stimulation could be achieved with electrodes [14] but requires a more complex control mechanism to display a desired sensation and may cause pain to the user.

2.1 Airborne Ultrasound

ARP is the acoustic pressure from a sound wave. From linear momentum, it can be explained as air particles pushing against the surface of an object (Fig.1). There will be many particles hitting against the surface and so the total force is an accumulation of the particles. The equation for radiation pressure on a surface [15] is given as:

$$P = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where p is total sound pressure from all ultrasonic transducers [Pa], α is the constant of reflection coefficient, ρ is the density of the transmission medium [kg/m^3] and c is the speed of sound in the transmission medium [m/s]. Equation (1) suggests it is possible to control the radiation pressure (P) as it is exponentially proportional to the sound pressure from the total number of ultrasonic transducers (p).

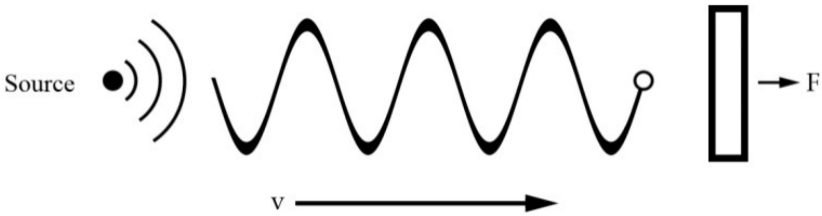

Fig. 1. The momentum of a particle transfers energy to the surface it hits. An accumulation of particles generates a sufficient amount of force that can be felt on the palm of a hand.

There are a few exemplar applications using airborne ultrasound for tactile feedback but this emerging technology has not yet been used in medical simulators. The first demonstration of using ARP was to co-locate a haptics sensation with the visual output from a holographic display giving the effect of making holograms touchable [16]. Later examples include a musical instrument with tactile feedback [17], allowing aerial input to a computer [18], adding tactile feedback to a handheld device for watching and feeling television content [19] and establishing a link between digital content and the physical world via an interactive table [20].

We believe that airborne ultrasound also offers the potential to simulate a tactile sensation such as a pulse or thrill sensation, and be able to simulate patients with different pulse rates or varying levels of strength in their pulse sensation due to age or body fat. Also a patient may exhibit arrhythmia, an abnormal condition featuring irregular pulse patterns, rate and rhythm. Airborne ultrasound offers greater controllability as modulating the amplitude of the control signals will directly influence the strength of the displayed sensation. A second benefit is airborne ultrasound's greater spatial resolution, which provides more control over where the sensation can be displayed i.e. the displayed sensation is not permanently fixed in one location. This will allow other scenarios to be simulated and provide more flexibility.

3 UltraSendo Configuration

A schematic of the UltraSendo hardware components is shown in Fig. 2. The PC contains the software for an Altera Field-Programmable-Gate-Array (FPGA) circuit board, the software runs indefinitely until switched off. The FPGA circuit board acts as the controller for UltraSendo and generates 40 kHz square wave signals driving the ultrasonic transducers. The pulsation or thrill effect is achieved by modulating the global duty cycle of this square wave. This technique is similar to pulse-width modulation by which we superimpose a periodic ON and OFF interval to the original 40 kHz wave. This technique allows us to simulate different pulse rates to represent different patients, different anatomical pulses or even irregular rhythms. The FPGA is connected to an intermediary distribution board that sends copies of the signal to each amplifier. Since there is only one signal pattern in the current implementation, it is not yet possible to re-position the focal point. If such capability is desired, however, the system design allows for a cost-effective upgrade by replacing the distribution board with another that feeds unique signals to the amplifiers.

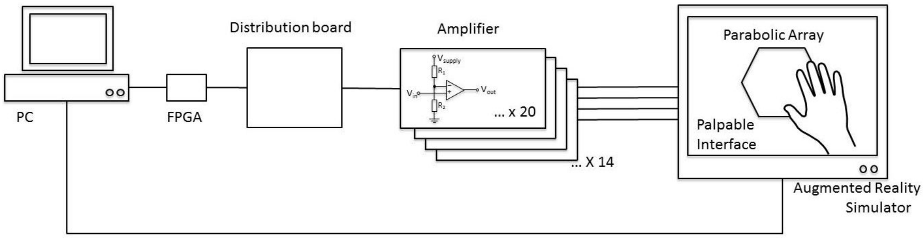

Fig. 2. Schematic of UltraSendo

Fourteen amplifier boards have been used, each consisting of twenty LM301AN operational amplifiers, providing one dedicated amplifying channel for each transducer. The boards are positioned in two stacks to save space. By making separate amplifier boards hosting small sets of twenty op-amps, it is possible to expand the system to a higher number of channels as required and thus increase the number of transducers when higher output is needed. The amplification circuit is a comparator that switches output from +15V to -15V. This polarity swing ensures the maximum displacement of the transducers diaphragm. Since the intermediate values in the digital signal are unnecessary for maximum output, they can be discarded. However, this also means it is not possible to modulate the intensity of the emitted beam by changing the amplitude of the original square wave signal.

A flat planar array of transducers would require phase shifts in the control signal to compensate for the different distances that the ultrasonic beams from each transducer have to travel to reach the focal point. UltraSendo uses a parabolic array so that the distance from each transducer to the focal point is the same (Fig 3). Thus the array can be driven with just one control signal that is copied and distributed to each transducer. Since all transducers are orthogonal to the focal point there is little power loss from beam divergence allowing a larger force to be achieved compared with using a flat array. The transducers in the parabolic array are arranged in the shape of a hexagon to fit as many transducers as possible into a given space. Combined with the use of smaller transducers (10 mm wide), UltraSendo is able to make use of more transducers than other implementations, e.g. Ciglar's parabloic array [17]. The resulting force output of UltraSendo was measured to be around 2.08 gf (gram-force) which surpasses the force output reported in [21] of 1.6 gf.

Existing airborne ultrasound devices are contact free and display the sensation as is i.e. feeling the raw acoustic waves. However, this sensation of touching air does not closely resemble that of touching the skin of a patient. The construction of UltraSendo has therefore taken a hybrid approach. For improved face validity, we use a simple membrane patch to represent the skin. This patch is structurally suspended horizontally above the parabolic array allowing the ultrasound to focus directly underneath the membrane. A flat membrane has been used to approximate the palpation and thrill sites. Although there will be some curvature on the surface of a real patient, the skin is flattened as the clinician applies force with their hand and fingers. Due to limitations in the maximum output force of airborne ultrasound, the selection of the membrane material needed consideration. The material cannot be too thick otherwise it will mask the pressure from the focal point. The material must also be non-porous

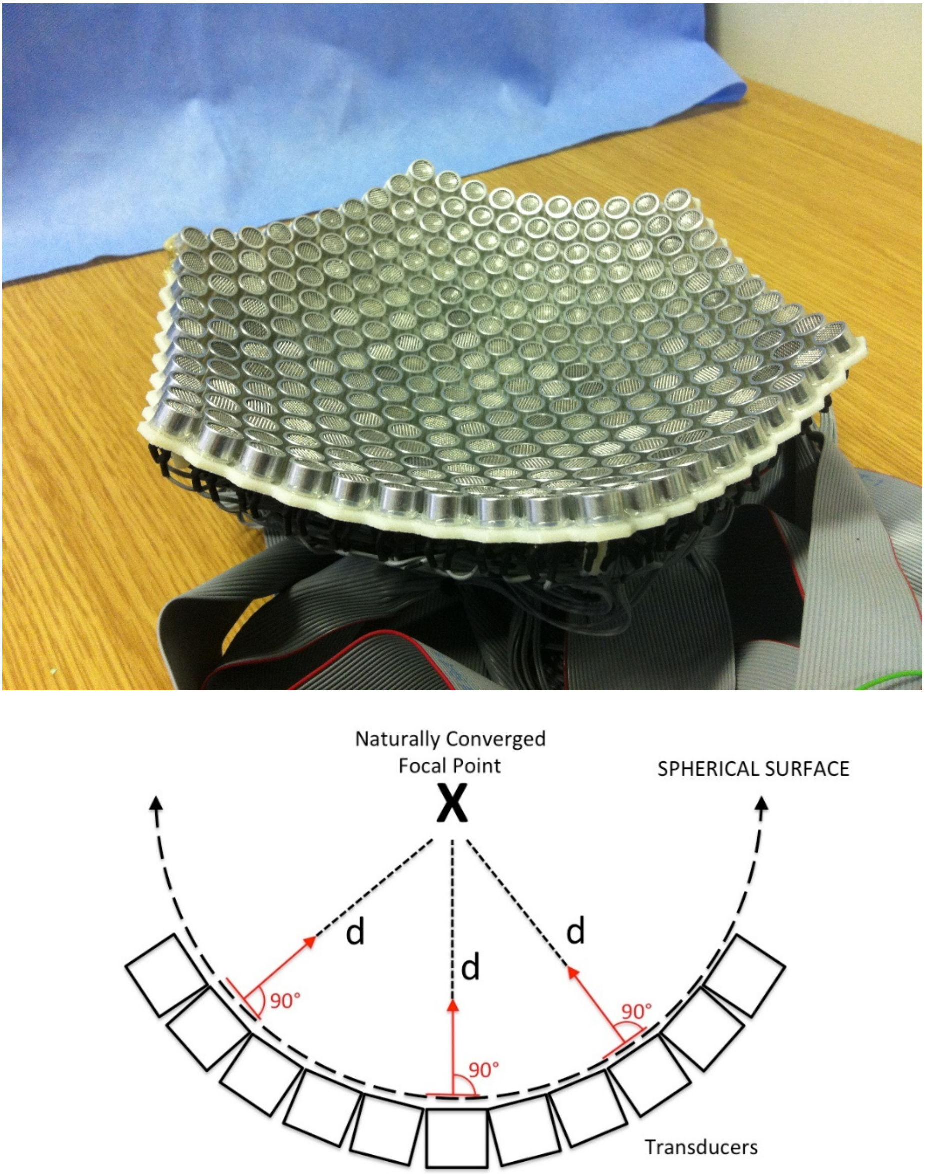

Fig. 3. Hexagonal parabolic array consisting of 271 ultrasonic transducers. All the ultrasonic beams will travel a distance of d to reach the focal point.

otherwise the focal point will not push against the surface and air particles by the ultrasound beam will bypass the surface through micro pores. The initial material that we are testing is polythene, a widely available thermoplastic polymer consisting of long hydrocarbon chains (commonly used for shopping bags). It is light and non-porous.

Finally UltraSendo was integrated into an augmented reality simulator (Fig.4). We used an approach pioneered in our PalpSim simulator [4], which uses chroma-key techniques to allow the trainees own hands to be superimposed onto the computer graphics rendering of the patient. UltraSendo's hardware components are therefore covered in blue cloth so that they can be masked out of the scene rendered on the computer monitor. A webcam is positioned underneath the monitor to provide a video feed of the trainees' hands. The trainee looks down at the monitor as if he/she is looking down at a patient.

Fig. 4. One of the clinicians from Glan Clwyd Hospital evaluating UltraSendo. He can see his own hand placed on the palpable surface in the virtual patient displayed on the horizontally mounted monitor.

4 Face Validity Study

UltraSendo was taken to the Catheter Laboratory at the Ysbyty Glan Clwyd hospital in North Wales to collect expert user feedback. The laboratory is a major facility in the region for the treatment of patients with heart and chest conditions. Eleven clinicians made up of seven males and four females participated in this session. The majority of the participants specialised in Cardiology. They were asked to explore UltraSendo's palpable interface with their fingertips to search and feel for a pulse sensation. Then they were asked to explore the same palpable interface with their palm to feel for a thrill sensation (Fig.4). The strength of the force output was adjusted according to these different sensations, and to compensate for the distance to the skin of the anatomy that is causing the pulse or thrill (the heart is deeper inside the body, for example). After this interactive session, they completed a short questionnaire to rate how realistic they believed the sensation was as a pulse and thrill.

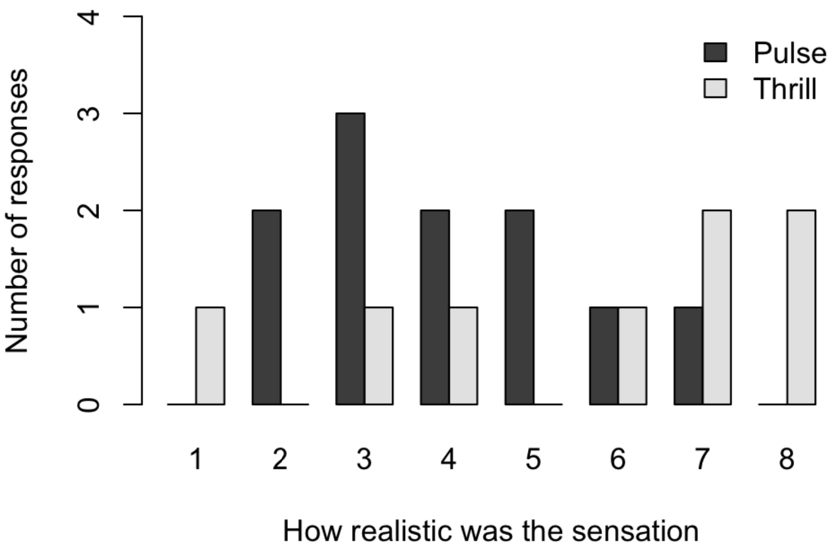

Fig. 5. Ratings for each interpretation of the displayed sensation as an arterial pulse and a thrill sensation

Referring to the bar plot (Fig.5) the distribution of responses for both the thrill and pulse sensation is shown. For the pulse sensation, UltraSendo received a mixed review with the feedback spanning the whole range of ratings. The majority of the responses are towards the middle left of the rating scale meaning that the sensation felt was not satisfactorily realistic enough. This is in contrast to the positive results that we obtained with the hydraulic system that we reported in [4]. For the thrill sensation, there is also a mixed review but responses do reside closer to the "very realistic" rating. Certainly the thrill sensation was received as more realistic than the pulse.

The clinicians were asked to indicate their years of experience in their specialty from the following options: 1-5, 5-10, 10-15 and +15 years and how often they palpate patients on a monthly basis. These parameters are plotted as a 3D graph (Fig.6). Whereas the sample size is too small to make any definite conclusions, some potential trends can be observed. A best fit regression plane is drawn for this plot to show the relationship between the parameters. The plane declines from left to right as years of experience and frequency of palpation increases. The junior clinicians are rating the fidelity of UltraSendo higher possibly because they have less experience of the sensation of a real palpation with which to compare against. The senior clinicians have been exposed to a wider range of forces and tactile sensations and thus could suggest the force generated by UltraSendo is apparently weaker than the real sensation.

Several comments from the participants were also noted. Some suggested that the force of the sensation needed to be increased to closer simulate the pulse sensation that the participant expects to find when palpating a real patient. A further observation made whilst watching the participants palpate UltraSendo was that almost all the participants initially depressed the membrane patch with substantial amount of force. The cardboard structure used for the UltraSendo prototype was not strong enough on occasions and could buckle. This is probably the reason why the participants could not

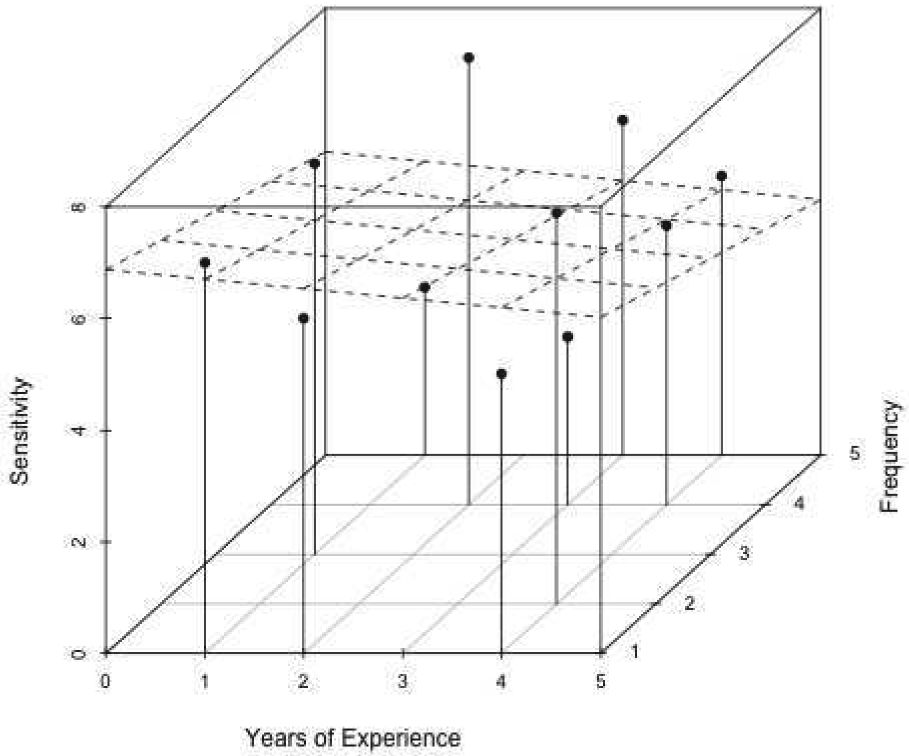

Fig. 6. 3D plot to show the relationship between the ability to detect the sensation against the participants' experience in their field

palpate with more strength. Another participant suggested the palpable surface could be improved by presenting a surface that felt like human skin to increase the realism of the simulator. The palpable surface is currently covered by the blue drapes to integrate the device into the augmented reality simulator and thus may not feel like touching the skin of a human.

5 Conclusions and Future Work

UltraSendo has enabled a tactile sensation to be achieved in a medical simulator for the first time using ARP. Our goal has been to provide a programmable tactile interface using an actuator that has no moving parts. The face validity is not yet sufficient to be able to deploy a production version of this technology and other tactile solutions will currently perform better. However, constructive feedback from participants in the face validation study highlighted the areas that need to be improved. In particular, the force from UltraSendo is weaker compared to palpating a real patient. This could be due to the small output force of the transducer array or the sturdiness of the physical infrastructure. For example, the palpable surface is particularly fragile as the volume underneath this surface is hollow. Thus the amount of force a user can apply to this surface is limited. Replacing the transmission medium of air with a denser medium such as water or gel can provide the physical support that the palpable surface requires in order to tolerate a higher amount of applied force. The propagation of ultrasound through mediums other than air have also been shown to generate a greater force magnitude. The textural sensation can also be improved by using a material that feels closer to human skin, such as elastomer, which can tolerate higher degrees of elastic deformation and thus is more resilient to damage compared to a thin sheet of polythene. This material can also be molded to represent the contours of a real patient – the focal point of the transmitted ultrasound can be adjusted for both curved and flat surfaces. The next phase of this research will therefore explore alternative ultrasound transmission mediums.

Currently UltraSendo displays the pulse/thrill sensation at a fixed focal point. This is because all 271 transducers are driven by the same control signal. To have the ability to relocate the focal point of airborne ultrasound, each transducer must have its own control signal. By replacing the Distribution board that the amplifier port is connected to, with another printed circuit that makes unique connections from the amplifier to the FPGA component, each transducer can be driven individually. This allows phase differences (delays in the signal) to be introduced and so the ability to change the location of the tactile effect anywhere within the region above the array of transducers. It would also be feasible to design a motion platform onto which the transducer array can be mounted and so change the location of the tactile effect by physically moving the array. This does, however, introduce more moving parts into the hardware and so introduce more reliability and robustness issues.

Changing the parameters such as the strength, location and the rhythm of the tactile sensation can simulate different patient profiles. For example a weak pulse suggests the patient may be elderly or has high body fat percentage. An irregular pulse rhythm could also indicate arrhythmia, a difficult condition to train the detection of as accessibility to real patients with this condition is limited. UltraSendo already supports the ability to present abnormal pulse rates and beat patterns. The next validation study will therefore also gather user feedback on how realistically UltraSendo can simulate different patient conditions.

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