35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

UltraPulse – Simulating a Human Arterial Pulse with Focussed Airborne Ultrasound

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***Abstract*— Medical simulators provide a risk-free environment for trainee doctors to practice and improve their skills. UltraPulse is a new tactile system designed to utilise focussed airborne ultrasound to mimic a pulsation effect such as that of a human arterial pulse. In this paper, we focus on the construction of the haptics component, which can later be integrated into a variety of medical procedure training simulators.**

I. Introduction and Background

Medical simulators often use haptics devices to offer the doctor a training session to practice and improve their skills without exposing the patient to undue risk [1]. Haptics refers to both force feedback and tactile feedback but there are very few medical simulators that currently utilise the latter. One simple clinical skill is the detection of an access site to the patient's arteries by palpation. Using their fingers, the doctor feels for a pulsing sensation on the body of the patient indicating the presence of an artery. It is important that a simulator for this procedure includes realistic tactile feedback for the training session to have any significant value.

A. Acoustic Radiation Pressure

UltraPulse attempts to realistically simulate an authentic human pulse with focussed airborne ultrasound as the driving technology. By combining many ultrasonic transducers, it is possible to generate a focussed point of pressure in mid-air. This phenomenon is known as acoustic radiation pressure [2], [3].

In order to selectively create a pressure focal point in a given 3D workspace, the ultrasonic beams from all transducers must be synchronized. For a planar arrangement of transducers, this synchronisation can be achieved by using driving signals with adjusted phases, with each transducer having its own dedicated driving signal. A parabolic arrangement, however, requires only one signal pattern to drive all its transducers as the main lobes of the transducers can be physically aligned towards a single point in mid-air.

Focussed ultrasound has several beneficial properties in the context of a medical simulator. Ultrasound is considered to be non-contact feedback i.e. the user does not need to use or wear any peripherals. Its frequency range overlaps the 1kHz bandwidth of human tactile perception. This means it is possible to generate a full range of perceivable vibrations using such a device. The spatial resolution of the stress field (the size of the focal point) can be as small as 1cm.

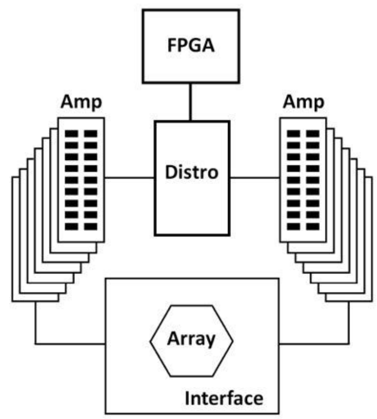

Fig. 1. UltraPulse system diagram

B. Related Work

There are only a few other devices that utilise focussed airborne ultrasound as a tactile interface, and none in the context of a medical simulator. The earliest airborne tactile device was Iwamoto's hexagonal array of transducers [2]. This device had a fixed focal point as the transducers on a concentric circle were driven by an identical driving signal. A later version by co-author, Hoshi, expanded the system's capabilities to be able to re-locate this focal point anywhere in a given workspace [3]. This technology has subsequently been adapted for applications such as mobile haptic feedback [4], digital control of tangible objects [5] and musical creation [6].

II. System Hardware

The UltraPulse system is based on a parabolic hexagonal array of 271 ultrasound transducers and consists of the five major components described below, and shown in Fig.1. The total cost of the components used is £2,550 (US$ 4,100).

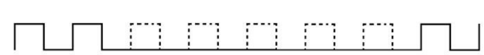

Fig. 2. 40kHz square wave modulated with on and off intervals

A. Driver System

A Field-programmable gate array (FPGA) controller generates a single 40kHz square wave signal pattern to drive all 271 ultrasonic transducers. The pulsation effect is achieved by modulating the global duty cycle of this pattern as shown in Fig.2. This technique is similar to pulse-width modulation by which we superimpose a periodic ON and OFF interval to the original 40kHz wave (dashed lines in Fig.2 represent off state). This technique allows us to simulate different pulse rates to represent different patients or different anatomical pulses.

B. Distro Board

The FPGA is connected to an intermediary component, a printed circuit board (PCB) that distributes copies of the signal to each amplifier. Since there is only one signal pattern, it is not possible to re-position the focal point. If such capability is desired however, our system design allows for a cost-effective expansion by replacing the distribution board with another PCB that feeds 271 unique signals to the amplifiers.

C. Amplifiers

There are 14 amplifier PCBs each consisting of 20 LM301AN operational amplifers, providing one dedicated amplifying channel for each transducer. The boards are positioned in two stacks to save space (Fig.3). By making separate amplifier boards hosting small sets of 20 op-amps, it is possible to expand the system to a higher number of channels as required and thus increase the number of transducers needed for higher output.

The amplification circuit is a comparator that switches output from +15V to -15V. The polarity swing ensures the maximum displacement of the transducer's 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.

D. Parabolic transducer array

The amplifiers are connected to the parabolic hexagonal array of transducers (Fig.4). Each transducer (Prowave 400ST100) has a 10mm diaphragm and has a Sound Pressure Level rating (abbreviated as "SPL", measured in dB units) of 112dB specified in the transducer's datasheet. A hexagon is the most economical shape to fit as many transducers into a given area as possible. The parabolic arrangement focusses the main lobe of each transducer towards a single point.

There are several advantages to this approach. Firstly, we can use a minimal control system as there is only one driving signal to manage. A parabolic dish naturally converges all of the transducer beams hence no phase-control is necessary. Second, all transducers have a main beam (Fig.5), diverging from this main beam results in a loss of intensity. In planar arrangements the focal point is artificially created by adjusting the phase of the individual signals but the parabolic dish physically aligns the transducers main emission lobe towards the focal point reducing loss of intensity.

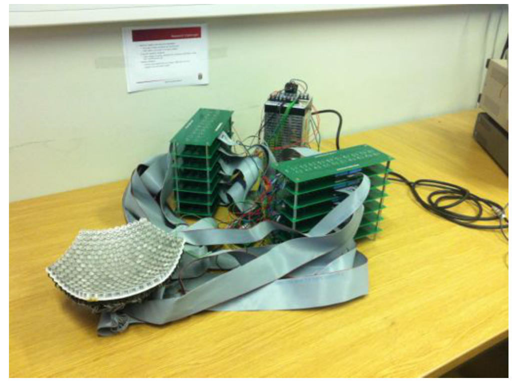

Fig. 3. UltraPulse without user interface

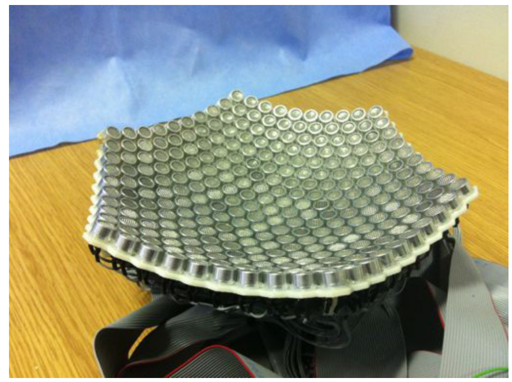

Fig. 4. Parabolic hexagonal transducer array

Increasing the number of transducers in the hexagonal array, by adding more rings to the array, increases the maximum output. However, this increase is not linear. Fig.6 plots the sum of contributions obtained from equation (1) for different numbers of hexagonal rings of transducers in a hypothetical array. We roughly estimate the sum of contribution with the following equation:

$$C \equiv \sum_{i=1}^{N} \cos^2(\theta_i) \tag{1}$$

where C is the sum of contribution, N is the number of transducers, and θ is the angle of incidence. The graph reaches a point where adding more transducers will have little effect on the maximum output. This is because the angle of incidence increases as more transducers are added to the concave hexagon array. A transducer with an angle of 90° will have zero contribution towards the force vector facing the user's leveled hand. An alternative method would be to use transducers with a much higher SPL rating but such transducers are difficult to procure commercially.

E. Membrane Interface

Making direct contact with the focal point provides a sensation similar to touching blowing air. A patient's body

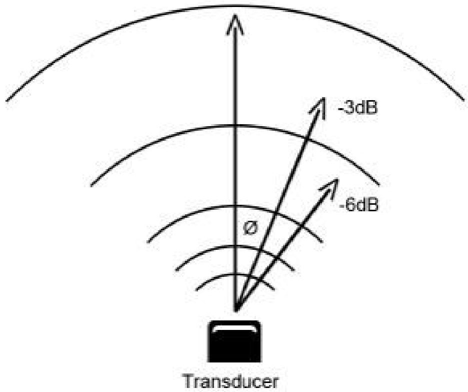

Fig. 5. Ultrasonic beam pattern and attenuation from beam divergence [7]

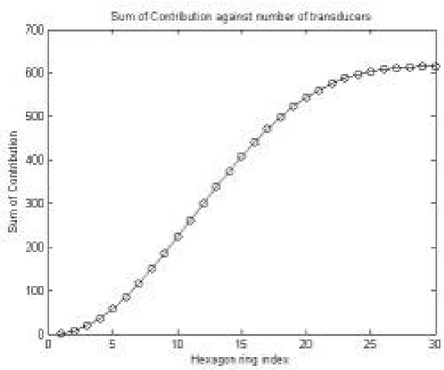

Fig. 6. Contribution effectiveness towards output when increasing number of transducers in hypothetical hexagon concave array

however is solid. For face validity, we have therefore constructed a simple membrane interface out of a thin layer of polythene. The user places their fingers on this membrane patch when palpating and searching for the pulse (Fig.7). A rough indication of the force output is measured with a digital scale. The force was estimated to be around 2.08gf (gram-force). Due to limitations in the output force of this technology, the selection of the membrane material needs consideration.

In consideration of the force output limit, the material cannot be too thick otherwise it will overpower the pressure from the focal point. The material must also be non-porous 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 (most commonly used for shopping carrier bags). It is light and also non-porous.

III. Results

UltraPulse presents a tangible arterial pulse to the user. The polythene membrane provides a medium for which the user can interact, removing the sensation of blowing air.

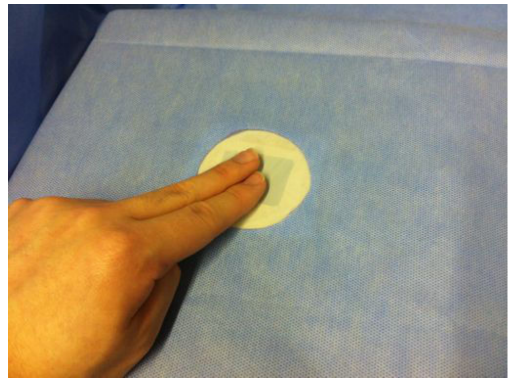

Fig. 7. Interface with blue cloth dressing

Fig. 8. PalpSim hydraulic pulse system

A. User feedback

Initial feedback from our clinical collaborators is promising. When performing a palpation on the simulator, the tactile effect from UltraPulse is quickly located by an operator and with a realistic level of tactile force. A range of acoustic pressure effects have been demonstrated to represent different patient types, for example, the pulse appears weaker and is far more difficult to locate on a large patient. The use of the polythene membrane is effective enough, but does not closely resemble the "feel" of skin.

The implementation of UltraPulse is being refined as a result of the initial user feedback. A more extensive validation study is currently being planned, which will expose a range of clinical end users to the simulator including nurses and medical students.

IV. Conclusion

We have built UltraPulse, a novel tactile system that simulates the tactile pulsation effect of a human pulse, aimed at training palpation skill. UltraPulse provides a tunable tactile sensation that appears, to an experienced clinical observer, to be consistent with periodic arterial wall motion. This novel technology could form a core component of a range of simulations that emulate vascular access procedures that are guided by the palpation of an arterial pulse.

A. Comparison with previous work

We have previously built a simulator for femoral palpation and needle insertion (PalpSim [8]) which offers a convenient platform for initial testing of UltraPulse. PalpSim uses a custom built hydraulic interface to provide a pulse like tactile effect - see Fig.8. This consists of a silicone filled tray with a thin tube running through it, sealed at one end and connected to a hydraulic pump at the other. A piston drives water through the tube in a controlled fashion to simulate a pulsing flow. This tactile component can be replaced by UltraPulse with the remainder of PalpSim being unaffected.

An augmented reality environment is used by PalpSim with a blue chroma-key mask to hide the physical interfaces and allow computer graphics models to be superimposed onto the environment. UltraPulse has therefore been draped in blue cloth so that it can be used seamlessly within the PalpSim environment.

B. Future Work

Switching to different patient types with different pulse rates is currently achieved by replacing the program uploaded to the FPGA with one containing the new parameter values. The next step would be to include a software interface allowing the parameters to be changed more readily.

The strength of the pulse cannot be modified as easily with the comparator approach but it is possible to expand the system to include a component that controls the maximum voltage swing of the amplifier, which in effect determines the sound pressure level output of each transducer. Alternatively, a control circuit could be created to decide how many transducers are to be operational, which determines the overall force output. Fig.6 suggests it is still effective to add more transducers to our 10 ring hexagon array but alternatively the maximum strength of the focal point can also be increased by using transducers with an SPL rating higher than 112dB.

The UltraPulse hardware can be expanded to include the ability to re-position the focal point facilitating the notion of presenting different body parts, where the arterial pulse may be positioned elsewhere in the workspace. Vessel palpation is a particular case as it needs a linear distribution of tactile force along the line of the vessel. With an updated system, we can, and intend to develop this type of output for vessel palpation.

The current beta interface will be further improved to physically mimic the contours of a human body combined with a 3D stereoscopic display to present a virtual patient to adhere to face validity. The virtual patient can be modified to present different parts of the body. This study currently use polythene as the membrane interface but other material may be more suitable and will be investigated.

References

[1] T. R. Coles, D. Meglan, and N. W. John, "The Role of Haptics in Medical Training Simulators: A Survey of the State-of-the-art", *IEEE Transactions on Haptics*, vol. 4, no. 1, pp. 51-66, Jan-Mar. 2011

[2] T. Iwamoto, M. Tatezono, and H. Shinoda, "Non-contact Method for Producing Tactile Sensation Using Airborne Ultrasound," *EuroHaptics 2008, pp. 504-513, 2008.*

[3] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda, "Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound," *IEEE Transactions on Haptics*, vol. 3, no. 3, pp. 155-165, Jul. 2010.

[4] J. Alexander, M. T. Marshall, and S. Subramanian, "Adding Haptic Feedback to Mobile TV," *ACM Conference of Human Factors* (CHI 2011), 2011.

[5] M.T Marshall, T. Carter, J. Alexander, S. Subramanian, "Ultra-Tangibles: Creating Movable Tangible Objects on Interactive Tables", *Proceedings of the 30th International Conference on Human Factors in Computing Systems.* (CHI 2012). May 2012

[6] M. Ciglar, "An Ultrasound Based Instrument Generating Audible and Tactile Sound", *New Interfaces for Musical Expression*, 2010, pp. 19-22.

[7] Application notes Ultrasonic Ceramic Transducers. SensComp. *http://www.senscomp.com/pdfs/using-piezo-sensors.pdf*

[8] T.R. Coles, N.W. John, D.A. Gould and D.G. Caldwell, "Integrating Haptics with Augmented Reality in a Femoral Palpation and Needle Insertion Training Simulation" *IEEE Transactions on Haptics: Special Issue on Haptics in Medicine and Clinical Skill Acquisition*, vol. 4., no. 3, pp 199-209, May-Jun 2011