The Development of a Robotic Approach to Therapeutic Ultrasound

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Abstract. Despite the recent wealth of research into therapy with high intensity focused ultrasound (HIFU), its clinical application still has limitations. These relate to the accuracy of the HIFU beam, the ability to visualize the target volume, and the understanding of the beam interaction with tissue. In the work reported in this paper, the output characteristics of a single channel HIFU transducer have been investigated in detail with the aid of a six-axis robot. Results show that by altering the drive parameters of the transducer clearly defined thermal or mechanical damage can be produced. The nature and patterns of damage produced by pre-programmed treatment volumes are now being investigated in tissue.

1. Introduction

To reduce suffering from traditional open surgery, in terms of trauma to the body, blood loss, long-term recovery, postoperative pain, and the risk of infection, minimally- and even non-invasive techniques are an alternative to the traditional route in the treatment of localized malignancy for most patients. Currently, regional chemotherapy and radiotherapy are regarded as the main cancer treatments. However, both of them have major side effects. Compared to these two techniques, another truly non-invasive modality, high intensity focused ultrasound (HIFU) is potentially significant as it can destroy deep-seated tumors without damaging normal tissue surrounding the tumor [1, 2], and without increasing the risk of distant metastases [3].

Just as sunlight is focused down to a spot using a magnifying glass to increase thermal intensity, HIFU is focused on to the tumour within the human body and the ultrasonic energy is converted to heat due to absorption. When the rate of heating is much greater than the rate of cooling, the temperature in the focal area can rise above a threshold of 56 °C in 1-2 s, approach 80 °C rapidly [4], which will consequently cause cell death through coagulative necrosis while the surrounding or overlying normal tissue is spared. And the tissue denaturation and coagulation occurs irreversibly [5 - 7].

Typically, the lesion caused by HIFU exposure tends to be ellipsoidal in shape, with a length of 1 - 2 cm along the beam axis and a diameter of 1 – 3 mm [8]. Compared to the whole target volume, it
is required that the focal zone of HIFU beam should be scanned throughout the entire tumour, that is to say lesions are generally placed side by side and layered from the most distant part of the tumour to the nearest until the required volume has been covered. During scanning, localisation, repeatability and the accuracy of lesion placement are very important parameters which may result in unpredictable damage to normal tissue. Therefore, a robotic manipulator may be employed as a precise and accurate targeting mechanism [9, 10].

The first robot-assisted surgical application, the PUMA 560, was used in the 1980s to place a needle and obtain a stereotactic brain biopsy under CT guidance [11]. Subsequently, robotic technology has been applied in a variety of different surgical fields, such as cardiothoracic surgery, neurosurgery, radio surgery, urology and gastrointestinal surgery.

This paper reports on research into issues relating to the design, development and testing of a reliable HIFU treatment system, particularly addressing the challenge of improving the treatment accuracy. The system under investigation is intended to be deployed by an industrial robotic manipulator to allow the focus to be positioned rigidly and precisely, and to make the tool reconfigurable to meet the needs of the particular location or procedure through its reprogrammable property. It is not envisioned that the complete system could be used in the operating room but that it will provide indications of the usefulness of robotic techniques for implementation with equipment directly compatible with the operating room.

A graphical user interface written in the LabVIEW programming language (National Instruments, Newbury, England) serves as the control centre to define HIFU treatments, making it possible to control experimental parameters from one computer. This interface sets up the communication network of the HIFU system to connect each element together, including the robotic manipulator. It can be used to change and control the HIFU parameters which contribute to the lesion formation during experimental procedures, and to acquire, analyze, display and then store related data.

2. The Robot Assisted HIFU System

This paper describes the development of the robot assisted HIFU system. The RX 90 robotic manipulator applied in this system is produced by STÄUBLI Ltd, Switzerland. It is a modified industrial robot with six degrees of freedom (X, Y, Z, yaw, pitch, and roll) [12, 13]. Although not a clinical system, this manipulator is very stable, programmable and flexible. Its end effector can be placed in any orientation within the work envelope, which is almost a sphere, and an inner counting system is used to return the absolute position of the end effector of the robot. The default speed of this manipulator on boot up is 150 mms$^{-1}$, and the acceleration/deceleration is 90 mms$^{-2}$, with ±0.02 mm repeatability at constant temperature. Figure 1 illustrates the configuration of the HIFU system [14-17].

![Figure 1 The configuration of the HIFU system](image)

The HIFU treatment system comprises four co-operating modules:
1. **HIFU-generator module**: Composed of signal generator (Agilent 33220A Function / Arbitrary Waveform Generator, maximum frequency 20 MHz), power amplifier (ENI 3100LA broadband power amplifier, Gain 55 dB) and single HIFU transducer (Precision Acoustics Ltd, fixed ideal focal length 72 mm, operating frequency 1.09 MHz).

2. **Monitoring and measuring module**: Includes oscilloscope (Tektronix TDS 2024B, Serial digital oscilloscope, 200 MHz bandwidth, 2.0 GSa/s), temperature-measurement unit and ultrasound imaging unit (Sonosite 180).

3. **Robotic control module**: A STÄUBLI RX90 robot with CS7 robotic controller. The motion of this robotic manipulator is controlled by code in the V+ programming language.

4. **System control module**: A graphical user interface written in NI LabVIEW programming language to serve as the computer control centre.

For safety, a 20 dB attenuator was connected between the signal generator and power amplifier to reduce the ±10 V maximum output of the signal generator to below the 1 V rms maximum input amplitude of the power amplifier. The HIFU transducer was attached to the robot with a specific holder which was designed to replace the conventional robot gripper. The movement of HIFU beam was controlled with the robotic arm by running robot programs, using the V+ language.

Serial communication between the robot and a laptop computer, which serves as the system control centre to communicate with individual components, was established by an RS232 link. The signal generator, oscilloscope and the temperature-measurement unit were also connected to the same laptop via its USB 2.0 port. The key HIFU parameters such as the exposure duration were controlled by a LabVIEW program. Measurement data were collected by a special I/O functional node in LabVIEW, and then processed, displayed, and stored.

A polyacrylamide (PAA) gel phantom was made as an experimental sample for HIFU treatment to visualize the effects of the temperature rise in the focal area and the formation of a lesion. As a thermally sensitive indicator, liquid fresh egg white separated from egg yolk shortly before phantom preparation was added to the phantom material [18]. The optically transparent PAA gel phantom has similar acoustic properties to those of soft tissue, including speed of sound, density, and attenuation coefficient. The solution was mixed with 44.5% volume in volume (v/v) degassed water; 30% (v/v) egg white; 24.8% (v/v) 40% w/v acrylamide (SIGMA A4058); 0.5% (v/v) of 10% ammonium peroxydisulfate (SIGMA 215589); and 0.2% (v/v) of TEMED (VWR, 110-18-9) [19, 20]. Degassed water was used as the coupling medium as it transmits HIFU without spatial distortion.

The characterization of the focused field establishes a set of parameters of great importance to HIFU treatment. The beam profile and the focal length can be estimated through measuring the ultrasonic field [21]. The temperature rise, the key feature of HIFU exposure [22], can be recorded by medical thermography, here using an ALTAIR workstation provided by Cedip Ltd., a JADE MWIR camera, an FG9800 digital PCI frame grabber, and ALTAIR software for image acquisition and processing.

### 3. Acoustic Field Measurements

The measurement system was set up as shown in Figure 2(a). The HIFU transducer was fixed vertically on the end effector of the robot and a custom-made ultrasonic receiving transducer, with a diameter of 3.3 mm and a resonant operating frequency of 30 MHz, was placed at the bottom of water tank to measure the acoustic energy. The signal was amplified through the receive amplifier of a pulser/receiver (DPR 300, JSR Ultrasonics, New York, USA).

The robot was controlled by V+ program code to follow a step-by-step procedure which was a meander line in one x-y plane. Then the transducer was moved to the next plane, 1 mm higher in the +z direction, and the same motion was repeated. That is to say the robotic motion contributed a 3D matrix to measure the acoustic field. The robot stopped at each step and sent a signal to the computer to trigger the LabVIEW program, and then started recording the peak-to-peak voltage value measured.
by the receiver. Four data points were collected at each step and their average value was treated as the final value and stored in a Microsoft Excel file.

![Diagram of ultrasonic field measurement system](attachment:image.png)

(a)

![Beamplot of focal zone](attachment:image.png)

(b)

Figure 2  (a) The system used to measure the ultrasonic field. (b) Contour map of the focal zone in ultrasonic field along the axial direction

![Snapshot frames of isosurface amplitudes](attachment:image.png)

Figure 3  Snapshot frames of isosurface amplitudes within the focal zone.
In this paper, the robotic motion formed a 7 x 7 x 36 point matrix in space. There were 7 steps in the x and y directions respectively and 36 steps in z direction, with each step of 1 mm. The distance between the surface of the HIFU transducer and the receiving transducer was changed from 50 mm to 85 mm. Figure 2(b) shows the contour map of the focal zone along the axial direction, from which the maximum amplitude i.e. the focal point was obtained as at a distance of 67 mm from the HIFU transducer. Confirming the value of the experimental measurement, the ultrasonic field did not have as compact a focal zone as expected.

These data were later processed by an IDL7.0 program. Some snapshot frames are shown in Figure 3 indicating the focal zone of the acoustic field. Snapshots 1 - 6 show the isosurface amplitudes from the inside of the focused beam to the outside respectively.

Figure 4  (a) The system to measure the temperature changes during HIFU exposure;  (b) Temperature vs. time graph of 30 s exposure with an additional 30 s cooling time; (c) Medical thermography at the focal point at 2, 10, 20, and 30 s respectively.

4. Temperature Measurement
Being distinct from the main configuration of the HIFU system, the temperature measurement system is shown in Figure 4(a). The transducer was immersed in degassed water, and placed 67 mm below the upper surface of the gel phantom where the transducer focal point was acquire from just below the sample surface. The thermal camera was placed above the gel phantom with an air path to its upper surface. The temperature changes at the phantom surface were measured every 50 ms for 30 s exposure time with an additional 30 s cooling time. The power input to the HIFU transducer was
approximately 70 W. Figure 4(b) is the temperature vs. time graph during the total 60 s procedure, the temperature reached 56 °C in about 4 seconds from an initial gel temperature of 24°C, and reached 66.49 °C in about 5.7 seconds. That is in broad agreement with the study by ter Haar (2001) showed that the temperature will exceed 56 °C in 1-2 seconds at an intensity of 1 kW.cm⁻². Figure 4 (c) displays the images captured at 2 s, 10 s, 20 s and 30 s during this 30 s exposure time. The temperature scale is in Celsius.

5. Experiments and Results

Ex vivo experiments were carried out in the gel phantom by varying three main experimental parameters, the exposure time (ranging from 5 s to 55 s), transducer input power (30 W and 70 W) and the distances between the transducer and the phantom (ranging from 65 to 80 mm). The robotic arm holding the HIFU transducer was controlled by V+ codes to move along a specific path in space, to place lesions step-by-step and to vary the distance between the transducer and phantom. A LabVIEW program was used to set up communications within this system and to control other trial parameters. Using the HIFU system assisted by both the robot and LabVIEW, multiple series of lesions were created in one procedure, under various experimental conditions.

Figure 5 shows one series of deep-seated lesions created within phantom material by using different exposure durations ranging from 5 to 55 s. The phantom was imaged using a Sonosite 180 medical ultrasound machine. Figure 6(a), (b) and (c) are the same series of lesions from an overhead view. As can be seen, the lesions have been generated in a straight line with a measured separation of 7 mm.

Figure 5 Ultrasound image of a series of deep-seated lesions generated with different exposure times.

(a) (b) (c)

Figure 6 Lesions in overhead view with the measured distance between adjacent lesions
A further pre-programmed treatment was investigated to demonstrate both the flexibility of this robot assisted HIFU system and the ability to produce complex patterns. A smiling face was “drawn” on the surface of a HIFU phantom, as shown in Figure 7. The robotic arm carrying the HIFU transducer was driven to move to specific locations pre-planned in V+ code. The duration of exposure was controlled by enabling and disabling automatically the output of the signal generator providing the input to the power amplifier using LabVIEW.

![Figure 7 The smiling face lesion in PAA-egg white phantom caused by HIFU exposure](image)

6. Conclusion
In this paper, a HIFU treatment system assisted by a modified industrial robot (STÄUBLI RX 90) and computer control was first described. Based on this system, HIFU beam profile and temperature increases were investigated to fully understand the principles of HIFU treatment through thermal ablation. Experiments were carried out with PAA gel phantom material to test not only the effects of HIFU treatment but also the flexibility of the robotic system and the feasibility to produce lesions in complex patterns. The main conclusion of this investigation is that HIFU thermal ablation can be successfully applied with the assistance of the robot and other hardware under computer control.

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