“Mechanical Scanning Focused Ultrasound Therapy Device for integration with Microwave Thermal Imaging System (MTIS)”

Submitted to:

Mariela Koenig
National Instruments

by
Timothy Raynolds
Lincoln Potwin

Thayer School of Engineering

Dartmouth College

Timothy Raynolds
timothy.raynolds@dartmouth.edu
(603) 738-4459

Lincoln Potwin
lincoln.a.potwin@dartmouth.com
(617) 448-9699

Abstract

The "Mechanical Scanning Focused Ultrasound Therapy Device for integration with Microwave Thermal Imaging System (MTIS)" includes the development of a simple apparatus for manipulating the location of a beam geometrically focused ultrasound transducer to be used in conjunction with a Microwave Thermal Imaging System for breast hyperthermia treatment. Previous inventions were cumbersome and expensive and did not include noninvasive monitoring.

Description

Hyperthermia is a means to treat malignant tumors with heat and has been shown to significantly improve treatment success rates when combined with radiation and chemotherapy. Previous designs to deliver heat during hyperthermia treatment using focused ultrasound have not incorporated a noninvasive means of monitoring heat delivery. They comprised primitive scanning capabilities accomplished with expensive and cumbersome devices, which had to operate while submerged in a liquid tank.

Our design affords repeatable three-dimensional manipulation of the focused ultrasound beam with precision accuracy through simple vertical manipulation of three support rods, while integrating it with the noninvasive MTIS. (Previous feasibility of noninvasive thermal monitoring using microwave imaging was demonstrated in Meaney et al. 2003.) All mechanical manipulation is provided by three computer-controlled motors residing below the liquid tank with the movable support rods passing through hydraulic seals in the tank base.

Our device integrates focused ultrasound (for hyperthermia treatment) for a relatively small target area (i.e. the breast) with thermal monitoring capability using the MTIS. The temperature feedback data is intended to provide the missing technology necessary for clinical implementation of hyperthermia as a treatment for (breast) cancer. It eliminates most patient safety concerns by configuring all electrical components outside of the tank. Its design is simple and cost effective, allowing for heating of tumor volumes anywhere within a breast.

Description of How it works.

The team developed a method of mechanically manipulating a focused ultrasound transducer by adjusting the positions of three vertical support rods. The rods are connected to linear actuators controlled by a micro-controller. Due to the design constraints for integration with the noninvasive liquid-coupled MTIS, the three rods could only be moved vertically through hydraulic seals in the base of the MTIS illumination tank. The three vertical rods are then attached to the transducer inside the illumination tank. The vertically manipulated coordinated motion of the three rods will facilitate uniform heating over an entire tumor target region through the ability to scan the focused beam in an arbitrary pattern. The MTIS will provide essential location and temperature monitoring feedback data.

Matlab was used to simulate the motion of the bowl transducer with mechanical linkages. A prototype based on the Matlab simulation was constructed with the Matlab algorithm providing input data to the Labview software interface.

Benefits

Our device will facilitate the possibility of a noninvasive hyperthermia treatment for breast cancer. The system design is robust and cost-effective.

Discussion of differences between this device and prior technology

The Lele patent discloses a mechanically scanned line-focus ultrasound hyperthermia system that "generates a line focus beam of ultrasound that can be mechanically scanned across a treatment volume of tissue."(U.S. Pat. No. 4,938,216, Lele). This patent addresses one form of delivery and scanning of ultrasound for hyperthermia. Numerous other patents disclose various ways of delivering hyperthermia in various patterns and with various other methods (U.S. Pat. No. 4,441,486, Pounds, U.S. Pat. No. 4,549,533, Cain et al, U.S. Pat. No. 4,586,512, Do-Huu, U.S. Pat. No. 4,622,972, Giebler Jr.). While scanning the beam to heat a region was proposed, it was not reduced to practice.

Hynynen, K. (1987) This system implemented a cumbersome and expensive mechanism for scanned ultrasound heating. It did not include a noninvasive thermometry device. There are some safety issues because the large electrical device resides within the tank. Our system addresses all of these concerns.

Numerical simulations were reported in several papers to model the heating of a scanned focused ultrasound treatment. The scanning was generally considered for annular geometries because scanning in a path other than a circle imposed significant complexities on the mechanical design. Our system is capable of scanning in arbitrary geometrical patterns.

Objectives

There were three areas of concentration in order to create the necessary software and hardware to execute our plan:

1. A simulation of the manipulation of the geometric bowl-shaped ultrasound transducer using Matlab to produce a three-dimensional mock-up of the transducer and its pressure field.
2. Construction of the prototype that employs a geometrically focused ultrasound transducer and manipulator capable of delivering the ultrasound beam to an arbitrary point. This included the construction of the apparatus to hold the linear actuators with a mock-up of the bowl transducer with focus. The three-dimensional movement of the transducer required significant attention to the configuration of the linkages and actuators to produce a reliable and repeatable system.
3. The last portion will integrate the design and Matlab routines with the Labview motion control software and provide remote access by a personal computer.

Simulation of Motion Control (objective 1):

A pyramid figure was used (in Matlab) to simulate the ultrasound field created by a focused bowl transducer. In order to create this pyramid in Matlab a 3D Matrix was used (see Figure 1).

$$t1=\begin{bmatrix} 0 & AE & AB & 0 & AE & AE & AB & AE & 0 \\ 0 & EC & 0 & 0 & ED & EC & 0 & ED & 0 \\ 0 & 0 & 0 & 0 & H & 0 & 0 & H & 0 \end{bmatrix}$$

The matrix of the pyramid is then multiplied by a 3D rotational matrix. For rotation about the y-axis (angle A), the pyramid, t1, is multiplied by:

$$R_y(\theta)=\begin{bmatrix} \cos(A*pi/180) & 0 & -\sin(A*pi/180) \\ 0 & 1 & 0 \\ \sin(A*pi/180) & 0 & \cos(A*pi/180) \end{bmatrix}$$

When rotating about the x-axis (angle A), t1 is multiplied by:

$$R_x(\theta)=\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(A*pi/180) & -\sin(A*pi/180) \\ 0 & \sin(A*pi/180) & \cos(A*pi/180) \end{bmatrix}$$

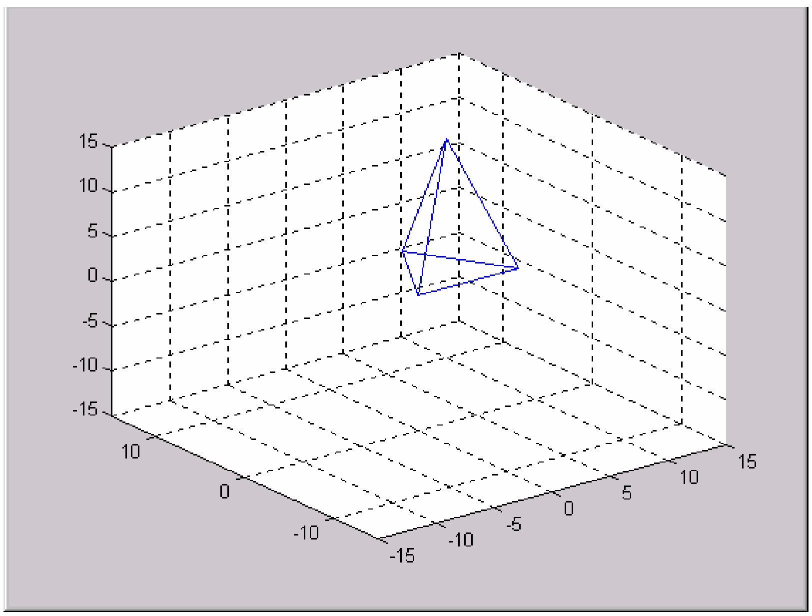

Figure 1. 3D representation of pyramid

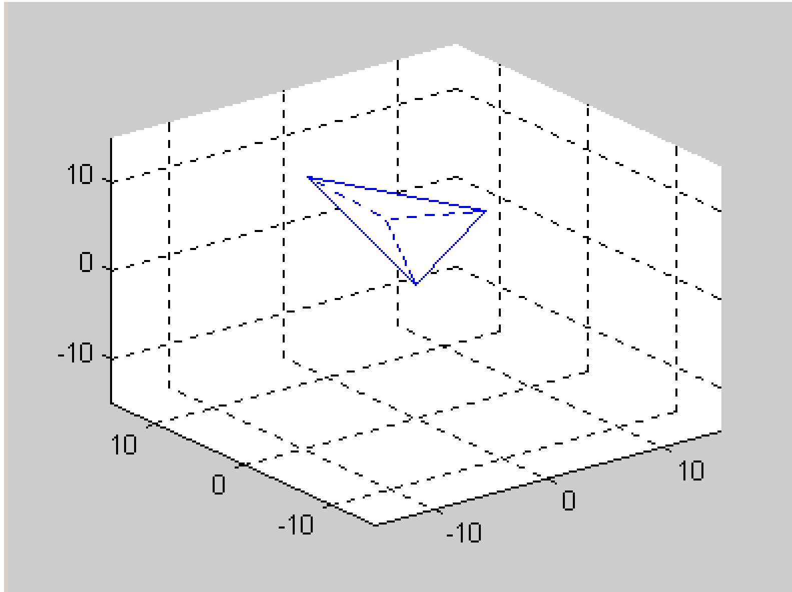

Figure 2. 3D Pyramid rotated 45° about y-axis

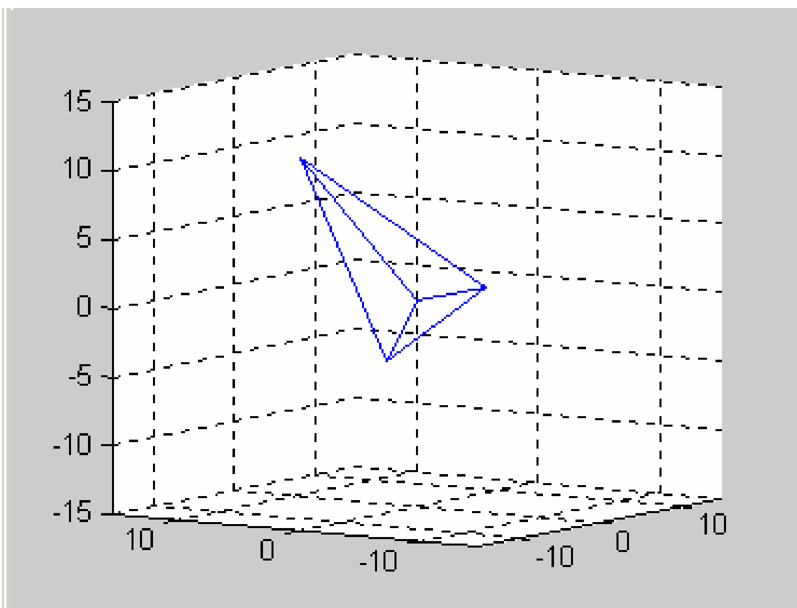

Figure 3. 3D Pyramid rotated 45° about x-axis

The next step required the ability to translate the focal point of the 3D pyramid in a horizontal plane. A subroutine was created to calculate the angles for given locations and direct the focal point of the transducer to these points. This enables the simulation to move the focal point to a user-defined location.

The simulation shown in Figure 4 illustrates spiral manipulation of the transducer to deposit energy in the entire area of interest. (Note that the physical focus is not a point as depicted in this figure, but rather a vertically oriented "cigar-shaped" zone such that scanning the center-point in a spiral corresponds to heat deposited in a cylindrical volume.) The final stage involves attaching linkages to the three corners of the base of the pyramid that would be present in the physical implementation.

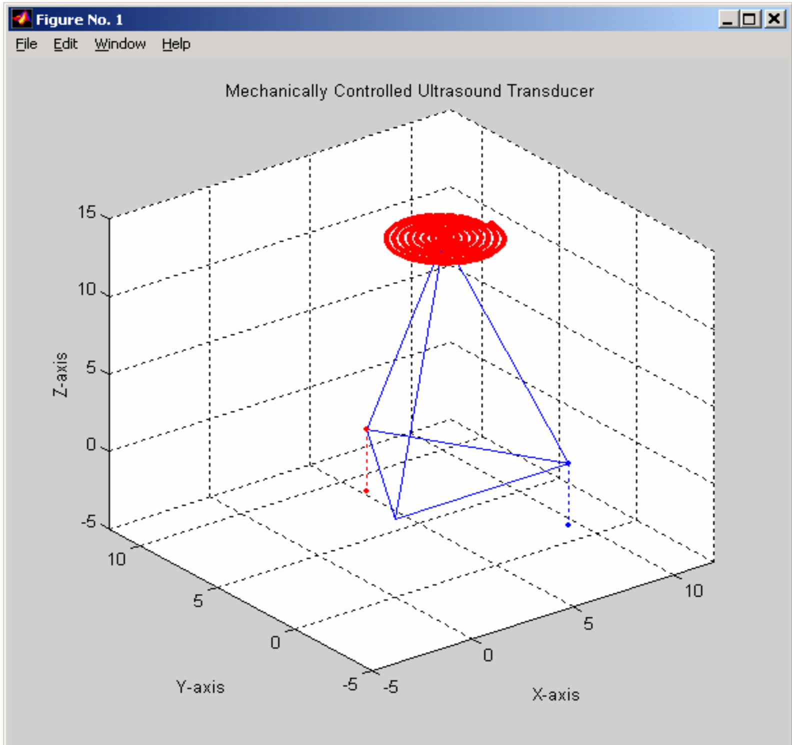

Figure 4. Matlab simulation of 3D pyramid with linkages attached and heating zone

System Design (objective 2):

The first step of this implementation included selection of a set of linkages that would allow this motion to occur but still maintain their structural stability. The linkages chosen allowed only one degree of freedom at the first of the three pivot points with two and three degrees of freedom at the second and third points, respectively. This was accomplished by using a ball socket device at each location to limit motion to one degree of freedom. Point A was designed with just a ball socket joint (see Figure 5). Point B consisted of a ball socket device with a clevis pin joint oriented such that it would constrain movement to just the Z and X directions.

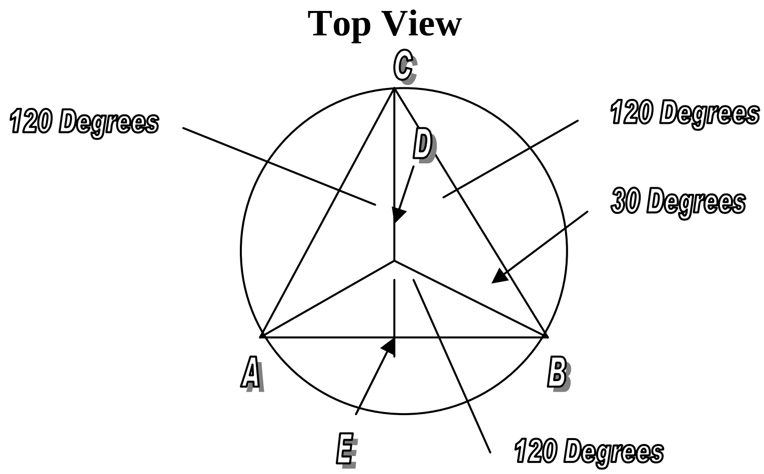

Figure 5. Top view of pyramid showing linkage connection points A,B,C and focal point D

Point C employed two ball socket devices connected to each other allowing freedom to move in all three (X, Y, Z) directions.

The invention includes a Matlab simulation to assist in the design process. Fabrication of a prototype capable of performing these tasks was then developed.

Integration of Labview, Matlab, for remote access (objective 3):

Labview software provides a VI (virtual instrument) that will execute and utilize Matlab variables for input to a micro-controller, which allows us to reproduce the simulated motion in real time. Other software used to execute this interface includes Viewpoint 6K Motion Library and Motion Planner for the 6K4 Parker Hannifin micro-controller. Hardware included THK KR mini-actuators with servo-encoded motors with dedicated Yaskawa servo-pacs.

Conclusion

All that remains to be developed is a design alteration for integration with the next generation prototype of the MTIS. This will require a repositioning of the linear slides to fit within the five-inch diameter space allotment at the center of the new prototype design. Preliminary drawings show that this is possible if the linear slides are rotated 180 degrees and mounted on a central pillar. The new prototype of the MTIS locates its vertical movement actuators external to the footprint of the illumination tank therefore reserving space for the “Mechanical Scanning Focused Ultrasound Device” in the center of the base of the illumination tank.