FUSBOTs: Image-guided Robotic Systems for FUS (Focused Ultrasound Surgery)

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Abstract:

Minimally invasive and non-invasive surgical techniques remained a prime research focus in bio-medical arena in the past over two decades due to their numerous advantages over conventional surgery methods. Remote ablation of deep-seated abnormalities by various modalities such as the use of focused high intensity ultrasound can provide completely non-invasive procedures if the energy in the beam is carefully targeted. Tissue ablation due to High Intensity Focused Ultrasound (HIFU), alternatively known as Focal Ultrasound Surgery (FUS), is primarily effected by conversion of mechanical energy of an ultrasound wave into heat energy at its focal point. A temperature range of 60-80°C is achieved and the thermal effect could lead to immediate coagulative necrosis within focal zone.

In this paper, the potential of mechatronic/robotic assistance in the operating room and system overview of various robotic systems, named FUSBOTs for non-invasive ablative procedures are described. The operation of the ablative/surgery system requires appropriate positioning of HIFU transducer(s) in a pre-arranged spatial configuration. For FUSBOTs, the robotic manipulator design and thus kinematics and dynamics of mechanical configuration are based on various specific applications. The common features include: the use of image guided, interactive and supervisory control by the surgeon. The dimensions and range of motions of our robotic systems correspond to human anthropomorphic data.

Keywords: *Focused Ultrasound Surgery, Medical Robots, Image-guided Surgery, High Intensity Focused Ultrasound*

1. Introduction

The use of robotic principles in surgical assistance, particularly in the area of minimally invasive surgery (MIS), provides several advantages. These include higher accuracy, precision and repeatability in positioning surgical tools and maneuvering controlled trajectories. Minimally invasive and non-invasive surgical techniques remained a prime research focus in bio-medical arena in the past over two decades due to their numerous advantages over conventional surgery methods.

In minimally invasive applications such as endoscopic surgery, it is required to design devices that can be inserted through small access holes with good dexterity and intuitive control while the surgeon views the operative filed through the video images reproduced at the surgeon's console. Other systems include minimally invasive repetitive orthopaedic tasks, percutaneous needle puncture soft tissue biopsy and surgery as well as non-invasive radiosurgery. The representative example of these include master-slave robotic systems, such as the Da Vinci system (Intuitive Surgical, Inc. USA), ROBODOC (Integrated Surgical Systems, Inc. USA), CASPAR (ortoMAQUET GmbH, Germany), and Cyberknife (Accuray Inc. USA). Thanks to the availability of noninvasive imaging techniques, such as computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography, fluoroscopy etc., which provide digitized images for precise location of diseased areas. Advanced manipulation and computational tools can be used in pre-planning, registration, and navigation of surgical devices based on the image data so as to spare the surrounding and intervening healthy tissue. Most of the surgical robotic systems work in interactive, semi-autonomous or, assistive modes under supervisory control of the surgeon.

Remote ablation of deep-seated abnormalities by various modalities such as the use of focused high intensity ultrasound can provide completely non-invasive procedures if the energy in the beam is carefully targeted. Tissue ablation due to High Intensity Focused Ultrasound (HIFU), alternatively known as Focal Ultrasound Surgery (FUS), is primarily effected by conversion of mechanical energy of an ultrasound wave into heat energy at its focal point. A temperature range of 60-80°C is achieved and the thermal effect could lead to immediate coagulative necrosis within focal zone. This modality has shown promising clinical evidence, particularly in the field of urology and oncology and as the technique and instrumentation is evolving, the application base is further broadening.

In this paper, the potential of mechatronic/robotic assistance in the operating room and system-overview of various robotic systems, named FUSBOTs for non-invasive ablative procedures are described.

2. System Overview: FUSBOTs (**F**ocal **U**ltrasound **S**urgery Ro**bots**)

An overview of representative applications of a series of robotic systems dedicated to FUS devised by our research group is described in the following. The operation of any ablative/surgery system requires appropriate positioning of HIFU transducer(s) in a pre-arranged spatial configuration with respect to the target site. For FUSBOTs, the design of various robotic manipulators and thus their associated kinematics and dynamics are based on various specific applications. Their common features include: the use of image guided, interactive and supervisory control by the surgeon. The dimensions and range of motions of FUSBOTs correspond to human anthropomorphic data.

Once the surgical protocol is decided in the pre-planning phase, the robot accurately positions all the transducers at specified locations such that the focus (or, the con-focal region in case of multiple probes) is coincident with the planned lesion position on a given 2D image. During the procedure, a real-time lesion positioning and tracking algorithm updates the formation of lesions in the desired target with a predictive temperature map processed from on-line imaging data. The information that is managed by the control module includes not only surgical planning data such as protocol settings, thermal dosage calculations and image data, but also robot dynamic coordinates, safety control information etc.

2.1 FUSBOT^{BS} – Breast Surgery System

In this application, a custom designed 5-DOF (3 for positioning, 1 orientation of end-effector and 1 for imaging) robot for FUS application of breast, FUSBOT^{BS} (superscript BS=> Breast Surgery), for guiding an end-effector through a pre-determined and image-guided trajectory is developed and tested (figure 1). The end-effector comprises a purpose built jig for mounting the HIFU transducer(s) and it operates in a degassed water tank. HIFU probes are positioned such that the focal zone (of single probe) or, joint focus (of multiple probes) overlaps within the affected target area. Fragmentation of energy into multiple low energy beams help in minimizing hot spots in overlying structures.

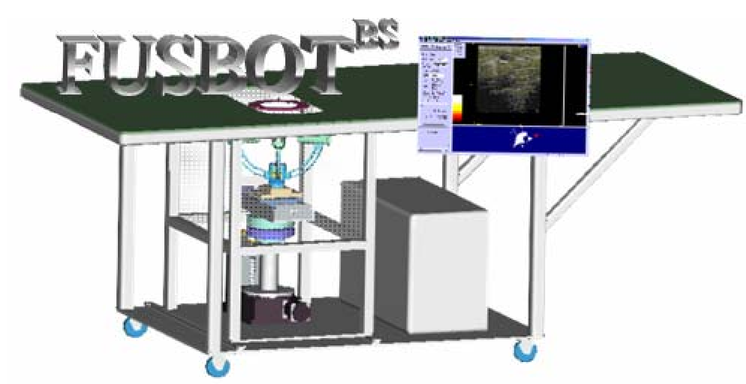

Figure 1: The FUSBOT^{BS}

For a target tumor area larger in size than the focal zone of the beam, the HIFU probe(s) need to sweep the entire volume of the lesion in 3D. The probe manipulation modules and robotic work-envelope encompass the human torso region and thus are capable in reaching and treating cancers/tumors other than the breast, such as through acoustic windows in trans-abdominal and supra-pubic routes. The specific area of interest can be reached by using a sliding window opening at the top of the water-tank. At present the end-point accuracy of this system is tested to be within 0.5 mm. Various laboratory trials in tissue *in vitro* and *ex vivo* using the system validate its excellent precision and repeatability.

2.2 FUSBOT^{US} – Urological Surgery System

The changeable end-effectors in FUSBOT^{BS} system (as described in the previous section) allow surgery through trans-abdominal route to reach urological organs. The purpose of contriving the FUSBOT^{US} system (superscript US=> Urological Surgery), however, was to enhance the flexibility to deliver multi-probe, multi-route access to remote and disparate organs for two main reasons: 1. to produce adequate dosage in the selective overlapping focal zone while keeping low dosage exposure in individual beam paths 2. in order to gain better access to areas which may not be reached by any one route alone due either to deterioration of beam convergence along a long path or, due to inhibited (bone/air) access window. A modular approach is adopted for safety reasons. The main components of the system include: Probe Manipulation Modules (PMM) each equipped with 3-degrees of freedom; Base Harness (BH) registered to the operating table, Graphical User Interface (GUI) and image control. HIFU dosage delivery is controlled separately so as to avoid any interference with the manipulation system. Similar to the previous system, the treatment is planned using image guided (diagnostic ultrasound) interface, which employs image coordinate transfer to the robotic manipulator with respect to the patient coordinates for a selective dosage delivery (figure 2).

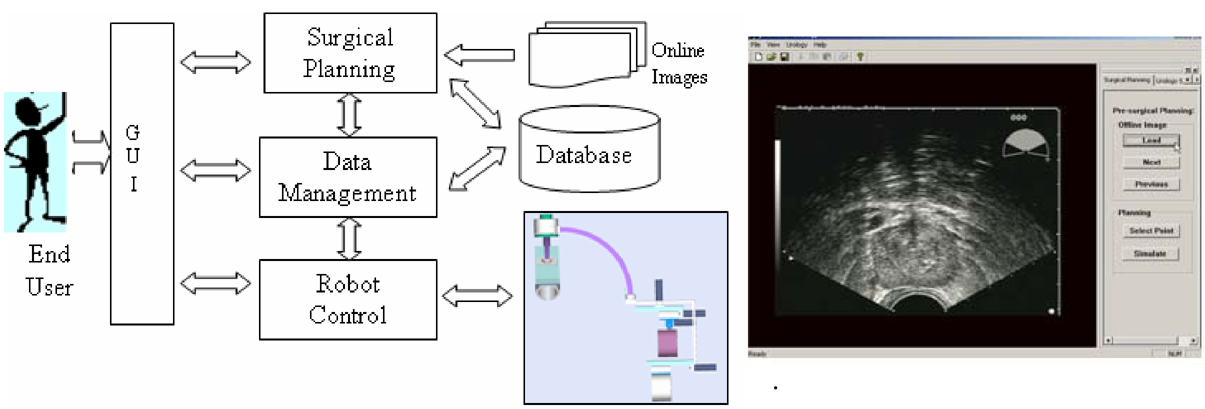

Figure 2. Software structure of control module; Graphical User Interface

2.3 FUSBOT^{NS} –NeuroSurgery System

The present version of neuro-surgical system is developed for a single/multi probe *in situ* approach for surgery of deep-seated targets of the brain through a precise craniotomy. The desired craniotomy is performed using Neurobot system with an integrated precision Hexapod system (a Skull base drilling system developed at MAE under our previous project, led by Prof. Teo MY). The accuracy of this system is within ± 0.1 mm. An optical tracking system, OPTOTRAK®, tracks the displacements of infrared markers placed both on the hexapod mobile platform and on the patient. A detailed atlas of the brain can be developed using pre-operative MRI scans to help the neurosurgeons in precisely calculating 3D volume of the region of interest during pre-planning phase.

In the ablative approach using HIFU, the target site is registered to an extended end-effector, called HIFU-effector, at the Neurobot system through an appropriate couplant bellow to the *dura mater* with a provision for attaching changeable end-effectors for a surgical drill unit (as used for creating craniotomy). This module is rigidly coupled on the Hexapod and is actuated with the 7th DOF of the robot, thus maintaining the original accuracy and registration (figure 3).

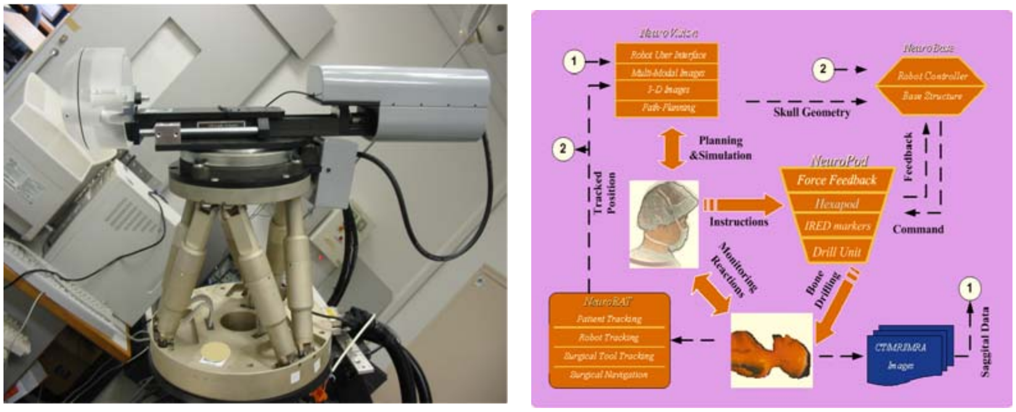

Figure 3: The Neurobot base mounted with a HIFU-effector (a), various modules of Neurobot (b).

Conclusive Remarks

A brief overview of a series of novel surgical robotic systems dedicated to FUS applications of various parts/organs of the human body was discussed in this paper. The range of benefits reaped in other medical procedures by the use of robotic technology should be extended to non-invasive ablative procedures, which share extended problems of image guidance, precise targeting and control.

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