Image Guided Robotic Systems for Focal Ultrasound Based Surgical Applications

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1. Introduction

Surgical resection remains the mainstay for conventional treatment of cancers/tumors. Normally, a margin area surrounding the cancer is removed to minimize relapse. However, due to the need for large access wounds for excising deep-seated abnormalities, traditional open surgery is associated with several operative and post-operative complications resulting into high morbidity and mortality rates. Many patients are not good candidates for resection. Minimally Invasive Surgery (MIS), though introduced in the earlier part of the 20th century, started to gain wide clinical acceptance during the 1980s. In MIS, also known as key-hole surgery, the affected area is laparoscopically or, endoscopically resected under visual guidance. In these applications, specialized tools and devices are used that can be inserted through constrained access holes while the surgeon views the operative filed through the video images reproduced at the surgeon's console. Hand-eye coordination using indirect means (2D imaging) presents a challenge to the clinical users for precise visual and tactile feedback and thus involves a steep learning curve. Minimally invasive procedures offer several advantages over open, conventional surgery, notably shorter length of stay, decreased analgesic requirements, shorter recovery time, decreased post-operative complications, and in some cases a lower morbidity rate as well. Surgery, either in an open or key-hole mode, is usually followed by adjuvant and non-invasive procedures, such as radiotherapy and chemotherapy, particularly when the neoplastic growth is stage-II and beyond.

Minimally invasive and non-invasive ablation procedures (thermal-ablation/cryoablation/ chamical ablation) in the management of cancers for deep-seated abnormalities are available using various modalities, for instance, radio-frequency, ultrasound, microwaves etc. (Giovannini and Seitz 1994; Crews et al 1997; Kennedy et al 2003). In thermo-therapeutic techniques, heat diffusion to sites adjacent to the target is common due to extended periods of exposure and convection by blood perfusion (Lang et al 1999). Achieving temperature control at desired levels is very difficult. Therapeutic techniques such as radiation therapy, chemotherapy, hyperthermia may be effective only in early stages. Such therapies are given either alone or in appropriate combination (Ando et al 2003; Soo et al 2005). For instance, cellular membrane permeability (and thus the efficiency) of chemotherapy is increased if hyperthermia is induced prior to or, along with drug infusion. For completely non-invasive interventions, the use of High Intensity Focused Ultrasound (HIFU), alternatively known as

Focal Ultrasound Surgery (FUS), is gaining importance in the recent years (Madersbacher et al 1993; Hynynen et al 2001; Chauhan et al 2001; Uchida et al 2002; Kennedy et al 2003). 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.

Advanced manipulation by the use of robotic technology and computational tools can be used in pre-planning, registration, and navigation of surgical devices based on the image data. Thanks to the availability of noninvasive imaging techniques, such as computed tomography (CT), magnetic resonance imaging (MRI) and functional MRI, positron emitted tomograpgy (PET) ultrasonography etc., which can provide digitized images for precise location and function of diseased areas. Robotic assistance provides several benefits such as higher accuracy, precision and repeatability in positioning surgical tools and maneuvering controlled trajectories (Ballantyne 2002; Davies et al 1999, Cleary and Nguyen 2002; Mack 2001). Other systems include minimally invasive repetitive orthopaedic tasks, percutaneous needle puncture, soft tissue biopsy and surgery as well as non-invasive radiosurgery. The representative examples include master-slave robotic system - Da Vinci system (Intuitive Surgical, Inc. USA), orthopaedic surgery systems - ROBODOC (Integrated Surgical Systems, Inc. USA), CASPAR (ortoMAQUET GmbH, Germany), Active constraint robotic devices (Acrobot Company Ltd, UK) and radiosurgery system - Cyberknife (Accuray Inc. USA) (Bodner et al 2004; Davies et al 2005; Taylor and Stoianovici 2003).

In this chapter, system overview and salient features of a range of image-guided robotic systems for non-invasive applications using FUS, devised by the Biomechatronics group, Robotics Research Center at our University, are described. These robotic systems, named FUSBOTs (acronym for **F**ocal **U**ltrasound **S**urgery ro**BOT**s) are developed for several clinical applications such as breast surgery (superscript BS: FUSBOT[-BS]), urological surgery (FUSBOT[US]) and neuro-surgery (FUSBOT[NS]). The chapter is organised into four main sections: introduction, methods and means, system overview followed by discussions/conclusions.

2. Methods and Means

2.1 The modality: HIFU

HIFU is emerging as a potential non-invasive modality for thermally induced ablation of deep-seated abnormalities because of its unique ability in non-invasively targeting deep-seated tissue volumes. Focused ultrasound surgery prevents the risk of ionization as prevalent in other non-invasive modalities such as LASER, microwave and X-ray – based ablations. Ultrasound waves are mechanical waves that can propagate through biological tissues and can be brought to a tight focus. The physical mechanisms responsible for therapeutic effects of ultrasound are both thermal and mechanical stress. Tissue ablation due to HIFU 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 the focal zone (an irreversible damage due to protein denaturation, protein synthesis inhibition, chemical bond disintegration in DNA /RNA molecules and other associated mechanisms). The temperature elevation produced in the focal region of the targeted beam produces immediate cytotoxity with a very sharp boundary between dead and live cells at its contour; the damaged region is called a *lesion*.

The targeted beam shape in FUS can be evaluated by modelling the ultrasonic field in front of the transducers (Porges 1972; Kinsler and Fry 1982). When ultrasound energy propagates through a biological medium, a part of it is absorbed and gets converted into heat. For a plane wave of intensity I_0, travelling in a medium with amplitude absorption-coefficient, α, the rate at which heat is generated Q, is given by:

$$Q = 2.\alpha.I_0 \tag{1}$$

This heat energy is responsible for various reversible or irreversible biological changes depending upon the irradiation parameters. For precise computation of temperature, the following Bio-heat equation is used to determine the spatial distribution of temperature in the tissues (Pennes 1948)-

$$\rho.c.\frac{\partial T}{\partial t} = \nabla.k\nabla T + q - Q_p + Q_m \tag{2}$$

where, ρ is the density (kg/m³), c is the specific heat (J/Kg·K), k is the thermal conductivity (W/m·K), T is the temperature (°C), q is the heat source (W/m³), Q_p is the perfusion heat loss (W/m³), and Q_m is the metabolic heat generation (W/m³). The exposure duration is kept very small (on the order of 1-10s) as compared to hyperthermia (10-40 min). The problems posed by heat diffusion due to blood perfusion are, therefore, less significant.

2.2 Prevalent HIFU Applicators

The common types of HIFU applicators include spherically focused transducers (also called focused bowls) and electronic phased arrays. Either type can be used in various modes: extracorporeal, intracavitary or, directly placed near the target site using minimally invasive techniques. Ultrasound frequencies on the order of 1-4 MHz and transducers with apertures upto 10 cm in diameter are reported in the literature. The dosage and treatment planning require the ability to model the system to predict exposure outcomes. The calculations for modeling the acoustic field of a spherical radiator at a single frequency have been suggested by many researchers, who derived a two-dimensional field model based upon the Huygen's principle and the Fresnel-Kirchhoff diffraction theory (Goodman 1968). The acoustic intensity, I, at any arbitrary point P in the field at a distance r from the source and time t is given by the following relation:

$$I = (A/\rho cm^2)\left\langle \sum_m \sqrt{\frac{2\lambda}{\pi r}}.e^{i(wt-kr)} \right\rangle^2 \tag{4}$$

where, λ is the wavelength of acoustic waves, ω is the angular frequency, k is the wave number, ρ is the density and c is the velocity of acoustic waves in the medium, m represents the number of probes and A is an arbitrary constant. However, fixed focus, large aperture bowl shaped transducers present several limitations such as reduced flexibility in beam positioning, ineffective coupling, large treatment duration and presence of off-focal hot-spots in the intervening tissue while scanning the beam to cover the target region. In order to obviate some of these problems, the use of multiple transducers have been proposed (Chauhan et al, 2001; Davies et al 1999; Haecker et al 2005), which are positioned to form a confocal region. The participating probes being smaller than the conventional HIFU probes

have lower energy in the off-focal areas. The spatial configurations of these probes with respect to each other and with respect to the target tissue were studied by developing 2-D and 3-D numerical models and verified in *in vitro* and *ex vivo* tests. The selected beam-characteristics for a trio of HIFU probes (aperture 25.4 mm; Frequency 2 MHz) are reproduced in table 1 (Chauhan et al 2001).

Probe configuration	Axial spread (mm)	Axial intensity (I_f/I_o)	Radial spread (mm)	Radial intensity (I_f/I_o)
C0($\theta = 0°$)	38.0	490	2.0	485
C1($\theta = 23°$)	7.0	1150	1.5	820
C2($\theta = 32°$)	13.0	825	3.0	945
C3($\theta = 45°$)	23.0	750	2.5	780
C4($\theta = 60°$)	20.0	704	3.5	780
C5($\theta = 75°$)	25.0	490	2.0	670
C6($\theta = 90°$)	Not well defined	650	Not well defined	585

Table 1. Selected beam characteristics for various spatial configurations of multiple probes

The computer simulations help in treatment planning for dosage levels and optimum range of inter-probe distances and angles of orientation (defining size and shape and intensity in the superimposed foci) as suited to a specific application. The 3-D model, by analogy with optical field theory, uses the Fresnel-Kirchoff's diffraction theory to evaluate the pressure amplitude at any location in front of the transducer by taking a double integral over the entire surface of the source:

$$p = \frac{i\rho c k}{2\pi} U_o \int_0^a R \left(\int_0^{2\pi} \frac{e^{i(\omega t - kr)}}{r} d\phi \right) dR \tag{5}$$

where, U_0 is the peak amplitude at the transducer face, a is the radius of the transducer, R is the radial location on the transducer face, ϕ is the angular location on the transducer face and other symbols have their usual meanings as described earlier.

Phased array transducers use the same basic acoustic principles as acoustic lenses that focus a sound beam. Variable delays are applied across the transducer aperture. The delays are electronically controlled and can be changed instantaneously to focus the beam in different regions. Phased arrays can be used for electronically steering the beam over the area of interest without mechanically moving the transducer, and thus provide more flexibility in the shape and size of the resulting lesions and various focal patterns can be planned. However, the inherent disadvantages include increased complexity of scanning electronics (particularly for large arrays), higher cost of transducers and scanners, formation of interference zones which may produce pseudo foci beyond the actual focal regions, large number of elements and hence greater complexity in treatment control. With improvement in array technology, both linear and 2-D arrays are now available which can provide high-quality HIFU applicators.

In the past over a decade, various HIFU devices and systems were made commercially available. A FUS device called Sonablate 200™ (Focal Surgery Inc. of Indianapolis Milpitas, CA) was developed for the treatment of Benign Prostatic Hyperplasia (BPH) and prostate cancers. Other systems targeted for BPH and cancer treatment are Ablatherm™ and Ablatherm[R] (Technomed International, France; EDAP TMS S.A., France). Magnetic Resonance Image (MRI) guided HIFU surgery system ExAblate® 2000 (Insightec Ltd., Israel) is FDA approved for the treatment of uterine fibroids. It utilizes MRI to visualize treatment

planning and monitoring in real time. Model JC Haifu focused ultrasound based tumor therapeutic System by Chonqing Haifu technology company, China, is used for clinical ablation of solid tumors.

3. An Overview of Robotic FUS Systems

As mentioned earlier, we devised a series of robotic systems called FUSBOTs (Focused Ultrasound Surgery Robots) in our laboratory for facilitating automated image-guided focal ultrasound procedures to treat cancers/tumors in various parts of the human body (Chauhan 2002; Chauhan et al 2004; Chauhan et al 2007). The operation of the ablative system requires appropriate positioning of HIFU transducer(s) in a pre-arranged spatial configuration. Single as well as multiple probe approaches are used for deploying HIFU energy in the specified targets. The lesion created by a single exposure in HIFU based ablation is often smaller than the desired target region. The confocal region of the probes is thus required to be mechanically scanned over the region of interest. For FUSBOTs, the robotic manipulator design, and thus kinematics and dynamics of mechanical configuration, are based on specific application. The common features include: image guidance using diagnostic ultrasound, surgical feedback and interactive & supervisory control by the surgeon. Once the surgical protocol is decided in the pre-planning phase, the robots accurately position the HIFU transducer(s) 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. Before proceeding for the overview of individual systems, first some common features of FUSBOTs are discussed.

3.1 Image Guided Robotic Surgery

Various radiological techniques such as CT, MRI, PET, ultrasound etc. are available today to study the anatomy and functionality of human body for either diagnostic purposes and/or surgical update during a procedure. In systems involving image guided surgery (IGS), the operative procedure is planned and effected by continuous acquisition and update of real-time images. These images are registered to the operative field or, region of interest (ROI) and are presented to the surgeon on a monitor/display which can help in guiding and manupulating the surgical tools in intended position (Weese et al 1997; Ballantyne et al 2002; Cleary and Nguyen 2002; Chauhan 2002). IGS systems are a leading indication, for instance, in locating tumours/cancers while planning for surgical resection or biopsy. To track patient's position, intra-operative position sensing and tracking devices are often used in Computer Assisted Surgery (CAS). Such devices are useful for precisely localizing (position and orientation) surgical tools with either external or, impregnated markers or, rigid anatomical structures proximal to the ROI. The principle of information acquisition is governed by the type of sensor(s) used in the intervention. In certain cases, where pre-operative imaging modality differs from the real-time imaging modality, multi-modality registration is required to locate abnormalities. The use of augmented reality, by superimposing graphical overlays of internal anatomy on a surgeon's view of the patient helps in guiding through a surgical intervention.

IGS is vastly adopted in robotic surgery wherein the robot coordinates are mapped to the on-line images and end-effectors are geometrically linked to surgical work-space. For image guided surgical robots, the target and surgical protocol is pre-defined by the surgeon based

on pre-operative and/or interventional data. The correlation of data along with coordinate transformation helps in guiding surgical tools through specified trajectories to the target. The imaging data is usually integrated in a graphical user display (GUI). Through visual localization, GUI allows interactive planning and coordination of user-guided and/or automated surgical tools in the target site. Since most of the imaging modalities provide images in digitized format, it is accurate and efficient to register the medical image to the patient using robots for subsequent manipulation. Robotic/mechatronic assistance and imaging guidance yields higher accuracy, precision, reliability and repeatability in manipulating surgical instruments in desired locations.

3.2 Image Guided, Surgical Feedback Sub-system

In order to make FUS clinically acceptable as a treatment modality, the availability of lesion positioning and feedback during HIFU exposure are crucial. It is highly desirable that some means should be devised for measurement and control of thermal dosage in order to adjudge the efficacy of FUS systems. Clinical evidence supports that MRI can provide reliable, on-line temperature feedback during HIFU exposure (Hynynen et al 2001; Kopelman et al 2006). However, the energy application system integrated with MRI, besides bringing high costs to the treatment procedure, also involve compatibility of the ultrasound source with high magnetic fields and restricted scanning to reach intended targets.
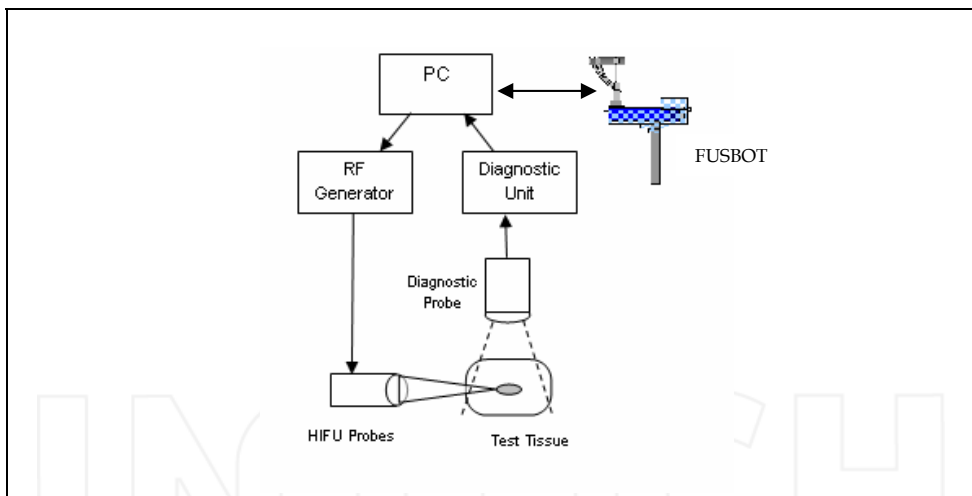

Figure 1. System schematic diagram - experimental set-up

Precise monitoring of variations in physical parameters of the tissue interacting with the incident modality, such as velocity of propagation, absorption and attenuation properties of the external energy etc., can provide vital information in discerning overall success of the treatment (Chauhan et al 1990; Chauhan et al 2007). We developed image guided surgical feedback sub-system with the goal of tracking the lesion position and monitoring the ablation procedure by recording thermal map on-line. Both of these crucial parameters are correlated and fused with the real-time ultrasound imaging. A sensory sub-system integrates robotic sensors for proximity and reach with diagnostic ultrasound through a

central processor as shown in figure 1. A temperature dependent parameter, such as velocity of the incident beam (amplitude and phase-shift of the echo) is recorded before and after the exposure for building a thermal map. Temperature data is experimentally calibrated with the help of bead thermistors impregnated at the target sites. The control software for system operation is written in Visual C++. Probe positioning mechanisms and scanning of the focal region in the desired target is done using dedicated manipulator systems as will be presented in the following sub-sections. The dimensions and range of motions of FUSBOTs correspond to human anthropomorphic data.

3.3 FUSBOT[BS]: The Breast Surgery Robotic FUS System

The robotic system, FUSBOT[BS] was developed in order to mechanically scan and ablate a specified target in human breast. The lastest version of custom designed robotic system for this application has 5-DOFs (3 for positioning, 1 orientation of end-effector and 1 for imaging) in order to guide an end-effector through a pre-determined and image-guided trajectory (figure 2). 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) overlap within the affected target area. Fragmentation of energy into multiple low energy beams help in minimizing hot spots in overlying structures.

Figure 2. FUSBOT system for Breast Surgery and trans-abdominal route applications

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 ± 0.2 mm. Various laboratory trials in tissue *in vitro* and *ex vivo* using the system validate its excellent precision and repeatability.

3.4 FUSBOT^{US}: The Urological Surgery Robotic FUS System

The changeable end-effectors in FUSBOT[BS] system (as described in the previous section) can 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. The system schematics and GUI layout are shown in figure 3.
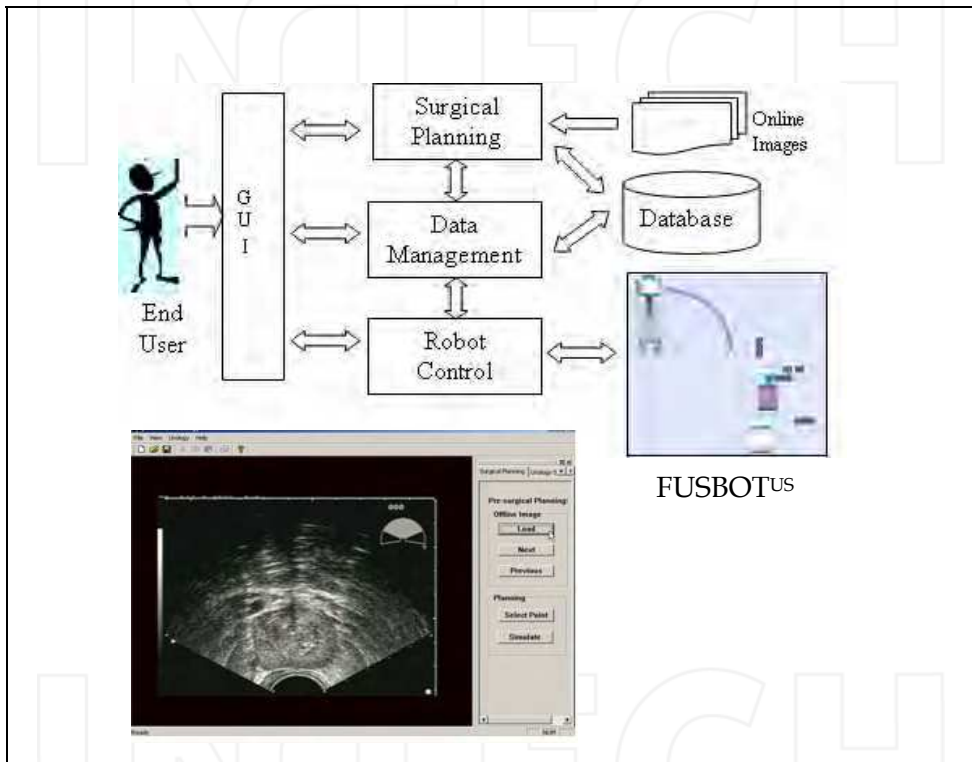

Figure 3. FUSBOT [US]: Urological Surgery System - Software structure of control module; Graphical User Interface

A modular approach is adopted for safety reasons. The main components of the system include: Probe manipulation modules each of which are equipped with 3-degrees of freedom; a base harness registered to the operating table, Graphical User Interface 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 .

3.5 FUSBOT[NS]: The Neuro-Surgery Robotic FUS System

The present version of neuro-surgical system is developed for both single and 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 4).
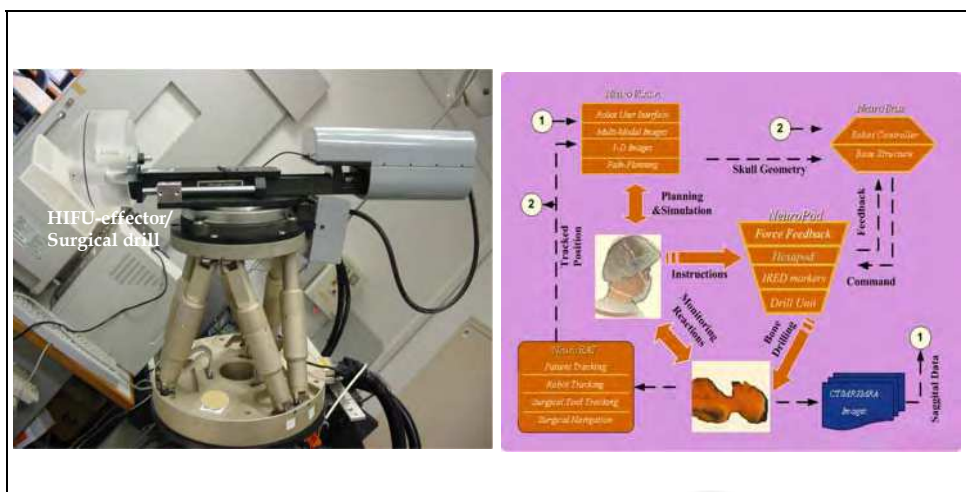

Figure 4. The Neurobot base mounted with a HIFU-effector; various planning modules of Neurobot

4. 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. Besides automated scanning using multi-probe HIFU technique, control algorithms for on-line feedback information such as lesion tracking and temperature mapping using diagnostic ultrasound are implemented in FUSBOTs. The power levels sufficient for creating a lesion result in a change in tissue reflective characteristics and affect echo amplitude. Our preliminary test results in excised porcine

adipose tissue establish the feasibility of this technique under varying dosage protocols. In these tests, a lesion detected by the algorithms correlated well within the macroscopic position as found after resection. The maximum positioning error was found to be within 0.5mm in the lateral dimension. Future work would include integration of HIFU dosage control sub-system with the image/data fusion in order to update computed dosage on-line. Further tests would also be desirable in tissue *in vivo*.

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophogeal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently "medical roboticists" or not.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

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