Image Acquisition and Data Fusion for Planning and Feedback during Image Guided Surgery

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Abstract – This paper presents fusion of real-time images and data from various sensors for on-line surgical planning as integrated in a non-invasive surgical robotic system. High Intensity Focused Ultrasound (HIFU) is used as a treatment modality while on-line images are acquired using diagnostic ultrasound and registered with the proprioceptive sensors of a customized robotic system for ablative procedures. As temperature is a crux parameter in thermotherapy and ablative systems, thermal data is captured using external sensors and fused with real-time images for the purpose of dosage planning and surgical monitoring. A lesion tracking algorithm is developed to track the position of lesions. This position is registered with therma-map superimposed on intra-operative images. The methodologies of lesion tracking and thermal mapping are described.

Keywords: Tracking, Non-invasive Sensing, Image Guided Surgery, Image registration.

1 Introduction

In image-guided surgical systems, the operative procedure is planned and facilitated by augmentation of real time images registered to the operative field or, region of interest (ROI) and linked to a monitor display. The display of imaging data is usually integrated in a graphical user interface (GUI), which controls surgical tools either operated manually or, positioned by a robotic system. The images are processed and updated continuously on the GUI for visual localization and interactive planning for coordination of user-guided and/or automated surgical tools in the ROI. Image Guided Surgery (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 field [1-3]. In certain cases, where pre-operative imaging modality differs from the real-time imaging modality, multi-modality registration is required to locate and register abnormalities in the image and patient coordinates for planning.

IGS systems are vastly adopted, for instance, in locating tumours/cancers while planning for biopsy or surgical resection during minimally invasive interventions. To track patient’s position, intra-operative position sensing and tracking devices are often used in Computer Assisted/Integrated Surgery (CAS/CIS). Such devices are useful for precisely localizing (position and orientation) surgical tools with respect to fiducial markers (either external or, impregnated proximal to treatment site) or, rigid anatomical structures in the vicinity of ROI and overlapping real-time images. The markers could be passive or, active (such as position sensors based on optical, mechanical, acoustic, magnetic mechanisms) for intraoperative localization of ROI in the images relative to the surgical tools. The principle of information acquisition and processing is pertinent to the type of sensor(s) used in the intervention. Certain procedures require building-up a volumetric 3-D data-set of the specific part of anatomy that includes the target area both in order to accurately register pre-surgical and intra-surgical data sets, and also to compute surgical/dosage parameters. In certain procedures, the use of augmented reality, by superimposing graphical overlays of internal anatomy on a surgeon’s view of the patient may help in guiding through a surgical intervention.

1.1 IGS and Robotic Surgery

Surgical robots and minimally invasive surgical systems are gaining popularity in clinical practice. The surgical potential of these devices have been recognized in many specialties, wherein the advantages include accurate registration to medical images and the patient’s anatomy, precise positioning of surgical tools, excellent repeatability, manipulation ability to expand surgeons’ dexterity in minimally invasive procedures through complex trajectories [1-5]. For image guided surgery the target and surgical protocols are predefined by the surgeon based on pre-operative and/or interventional data. The correlation of these data, followed by coordinate transformation between image and operative domain helps in guiding surgical tools through specified trajectories to the target, thus precisely reaching the target defined by the surgeon. Since most of the computer based imaging modalities provide images in digitized format, it is accurate and efficient to map the medical image to the patient coordinates and using robots for subsequent
manipulation. The fusion of pre-operative and interventional images and sensor data can be used to improve pre-operative planning and decision on surgical protocols as well as real-time control of surgical instruments deployed by robotic systems. In this paper, we present data fusion strategies for surgical planning and monitoring as applied to a surgical robotic system developed in our lab, named FUSBOT_BS (acronym for Focal Ultrasound Surgical Robot for Breast Surgery), for non-invasive ablation of breast cancers using HIFU [2,6].

1.2 Focal Ultrasound Surgery

In the recent years, HIFU has emerged as a potential non-invasive modality for cancer treatment [7-11]. Focused Ultrasound Surgery (FUS) using HIFU prevents the risks of ionization. High-intensity ultrasound beam is brought to a tight focus within the target tissue volume using focused ultrasound transducer(s). Due to absorption of energy during its propagation through the medium, temperature elevation on the order of 20-40 °C is observed in the focal region (depending upon the incident intensity in the beam). This sudden rise in temperature produces immediate necrosis and protein denaturation leading to cell death in the exposed region. The boundary between dead and live cells is sharply demarcated, thus producing highly localized damage in selected targets. In certain configurations of HIFU transducers such as large single spherical bowls and phased arrays, there is a likelihood of off-focal hot-spots due either to formation of standing waves, beam overlap during scanning or, grating lobes. These undesirable hot-spots can be eliminated by controlling the power in the beam by selective configuration of transducers and appropriate ablation protocols, thereby inducing completely “trackless” lesions in deep-seated targets.

In order to make FUS a clinically acceptable treatment modality, the availability of lesion positioning and feedback during HIFU exposure are crucial. In thermo-therapeutic and surgical procedures such as hyperthermia and FUS, temperature is a parameter of utmost importance governing the efficacy of the procedure. Thus, it is highly desirable that some means should be devised for its on-line measurement and control during the exposure. Diffusion and relaxation time weighted MRI, can provide reliable, on-line temperature feedback during FUS [9]. However, the main issues involved in using interventional MRI are high treatment costs and devising a compatible ultrasound source and other sensors to work within high magnetic fields. Also, due to the size of the MRI suite, the flexibility in scanning of beam to reach intended targets is jeopardized. Precise monitoring of variations in physical parameters of the tissue interacting with the incident radiation/modality, such as velocity of propagation, absorption and attenuation properties of the external energy etc., can provide vital information in judging the overall success of the treatment. In this paper, an integrated diagnostic ultrasound guided system for lesion positioning and on-line estimation of thermal behavior is presented.

2 Methods and Means

2.1 System Overview

A single exposure during FUS creates an ablative region (called s lesion) of limited dimensions, which is often smaller than the desired target region. We devised a robotic manipulating system, FUSBOT_BS, for precisely scanning and ablating a specified target, in 3-D, over the entire volume of interest. FUSBOT_BS is a 4-DOF system comprising of three positioning and one orientation axes as shown in figure 1. It is used to deploy either a single or multi-probe HIFU end-effector in a defined, constrained work-envelope to target user-specified areas using on-line image guidance. The robot works partially in an integrated water tank (coupled to the part/organ of interest) for effective energy transfer to the target tissue. A schematic diagram for on-line surgical planning is shown in figure 2.

Figure 1. FUSBOT_BS axes and work envelope

Figure 2. Surgical Planning schematics.

The treatment is carried out by means of suitable exposure duration of the HIFU beam targeted at a user-defined spot (marked with a light pen on a touch screen or, mouse click on the image display), following a scanning motion of the probe(s) and subsequent exposure, thus covering the entire volume of the tumour/cancer region in a three-dimensional manner. In the first version of FUSBOT, the planning and operational control of the lesioning process...
was in open-loop. The dosage parameters were computed based on numerical modelling and simulation of the interactive ultrasound field, and tuning through empirical results. For further details on the system and on-line registration of image-robot-patient coordinates, please refer to [3,6,10]. The present work attempts to map the temperature rise in the target for monitoring the ablation process on-line.

2.2 Image and sensor Data Fusion

This sub-system was devised for lesion position tracking and thermal monitoring during ablation. Both of these crucial parameters are correlated and fused with the real-time imaging information. A sensory sub-system integrates robotic proprioceptive sensors for proximity and reach (for precise target positioning) with diagnostic ultrasound through a central processor as shown in figure 3. The main system counterparts are the mechanical manipulator carrying a set of HIFU probes in a selective configuration and an imaging ultrasound probe at its central shaft integrated with the end-effector gantry (known coordinates), a PC-based controller, a RF Generator and a signal processing circuitry integrated with the central processor and sensor suite. HIFU probes used in this research were procured from Imasonic Inc., France (focal length 80mm, operating at a central frequency of 1.75 MHz). HIFU parameters such as exposure time, dead-time, power in the beam, number of probe channels etc., are controlled remotely through an RS-232 connection. Robot and HIFU dosage control are de-linked for safety reasons. The diagnostic images from the diagnostic ultrasound unit are continuously updated on the GUI using an image grabber card controlled by Galil controller.

Data processing and sensor fusion: Data from various sensors (positioning, imaging and thermometry) is simultaneously acquired prior and after an exposure. A temperature dependent parameter, such as velocity of the incident beam (measured amplitude and phase-shift of the echo) is recorded. Temperature data is pre-calibrated, empirically with the help of small impregnated bead thermistors at the target site. The acquired data is synchronized and digitized prior to sending to the central processor. The echo amplitude and position is processed (peak/edge detection) and registered for gray level and phase-shift at the target site, weighted and mapped to the calibrated temperature. At the same time, on-line diagnostic images are processed (normalized thresholding followed by Mean and Gaussian filters) and scanned in the ROI selected by the user (instead of processing the whole image) in the on-line image correlated both with the target and end-effector position. The user-selected ROI is scanned using a small scanning window (optimized to 5x5 pixels) and an average of 4 nearest neighbors is computed for tracking lesion position (by deducing the largest gray scale gradient). Figures 4 and 5 show flow-charts for sequential steps involved in lesion positioning and phase-shift measurement respectively.

3 Results and Discussions

Several signal attributes involved in dosage computation (such as exposure time, power in the beam, central frequency) and resulting lesion position and lesion extent (dimensions, intensity distribution) effect a change in the image and diagnostic data. Tissue reflective characteristics are affected during ablation and this variation in data in terms of gray level and sound velocity is mapped and used for deducing the position and temperature of the resulting lesions. Test protocols were
conducted in ~200 samples (excised porcine and lamb tissue) with changing power in the incident beam and exposure time. It was found that the echo amplitude was highly variable with change in exposure parameters and tissue types. However, normalized phase-shift and gray scale change resulted in consistent data interpretation in controlled environment (degassed, temperature controlled bath). In these tests, lesions detected by the algorithm correlated well within the macroscopic position as found after resection. Image display resulted by fusion of position and thermal data is shown in figure 6. The maximum positioning error was found to be ± 0.5mm in the lateral dimension. By re-orienting the imaging probe in a direction parallel to the axial dimensions of the lesions, the positioning was dramatically improved. However, it is noted that such an option may not be feasible in practical applications.

4 Conclusions

A method of fusing on-line data on lesion tracking and thermal mapping using diagnostic ultrasound for feedback in FUS applications is described. Our preliminary test results in excised porcine and lamb tissue establish the feasibility of this technique under varying dosage protocols. Future work would include integration of HIFU dosage control with the image/data fusion in order to update dosage to the user on-line. Further tests would also be desirable in tissue in vivo.

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