Framework of US-guided HIFU therapeutic system for renal diseases

Release 1.00

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July 19, 2010

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Abstract

The authors describe a framework for the US-guided therapeutic HIFU system for renal diseases. In particular, the HIFU system is integrated with robotic servoing capability so as to track quasi-periodically moving renal tumors and stones. The system is composed of the US imaging part, software for target detection, robot part for servoing the end-effecter, HIFU irradiation part for destroying stones and tumors, and quality assurance system for planning and maintenance of HIFU irradiations. In this paper we illustrated the overall system configurations and explained the details of each component and their integration.

Contents

1 Introduction

Renal stones and renal tumors are the most representative renal diseases. As a recent non-invasive treatment method for renal stones, extracorporeal shock wave lithotripsy (ESWL) is used with real-time stone monitoring by fluorescence X-ray imaging, however long time exposure can cause secondary damage by radioactivity. In the case of renal tumors, usually resection of the tumor area has been thought to be the most effective treatment method despite its invasiveness.

In contrast to the previous invasive methods for treating renal diseases, ultrasound (US) is a promising modality for non-invasive medicine such as diagnostics and therapeutics. In particular, the integration of US-guided monitoring and high intensity focused ultrasound (HIFU) treatment is a new alternative diagnostic and treatment method for renal diseases by using cavitation-control lithotripsy (CCL) for renal stones and thermal ablation for tumors.

Although the non-invasive and highly precise irradiations are available by HIFU, tracking respiratory motions of renal targets is still quite challenging. In particular, many existing commercial HIFU systems cannot realize an anesthetic HIFU treatment for these moving targets; in other words, surgeons should ask patients' breath-holding in order to locate the end-effectors for every irradiation. This causes time-consuming, inaccurate, low-intensity treatment, and is also a burden for patients as well as surgeons. Therefore, we aim to develop an automatic tracking system for HIFU treatment of renal stones and tumors.

Figure 1 shows the overall system architecture of our theragnostic HIFU system customized to both renal stones and tumors. Indeed, the research for renal stones is already presented in [1] by our group and renal tumor tracking is still being studied with partially different setups. Our HIFU system is composed of three hardware subparts for HIFU irradiations, US imaging, and robot part. Two tracking algorithms have been developed according to the recognition approaches for renal stones (point targets) and tumors (volumetric targets). Each tracking algorithm produces the position of the HIFU irradiation, however we need additional preoperative data for renal tumor recognition, which is a 3-D model of the kidney and tumor. Moreover, a quality assurance system for HIFU irradiation is also equipped to provide the quantified HIFU focal models in the preoperative planning and the maintenance of HIFU irradiation performance.

In this paper, we will explain the roles of each part in detail and the integration of hardware and software subparts.

2 US Imaging part

The ultrasonic imaging system is equipped with two sector type imaging probes. It scans two mutually perpendicular image planes of the two probes in turn. An ultrasonic scanner (EUB-8500, Hitachi , Japan) provides this function with its biplane model. This biplane model is quite useful for a visual recognition of both in-plane and out-of-plane motion of targets.

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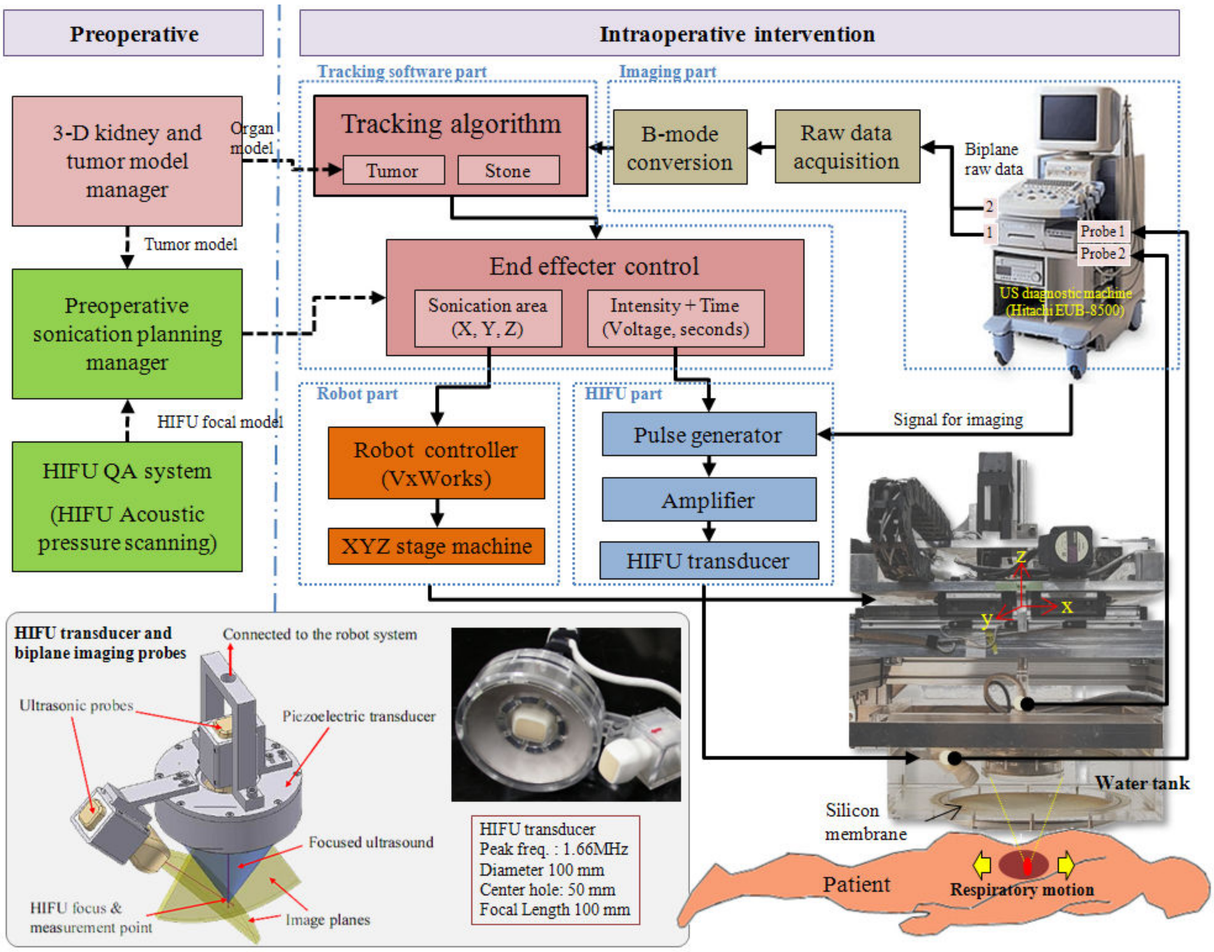

Figure 1: System architecture for prototype theragnostic HIFU system and end-effector design.

In case of ultrasonic imaging, a frame grabber (Matrox Meteor-II Digital) is used for capturing raw data. Figure 2 shows the detail steps for B-mode image restoration from US raw data. Capturing raw data is more beneficial than capturing video output due to the following points. First, an ultrasonic scanner provides 30 Hz frames to external devices through its video output channel. Therefore, when a small target such as a stone should be detected, we can achieve higher frame rates by defining ROI and minimizing FOV. Indeed, about 200 fps at 24.32 deg FOV can be achieved for stone monitoring. Second, capturing video output does not provide full size of both images at maximum FOV (85.02 deg) for detecting kidney boundaries. That is actually, contrary to stone tracking, maximum FOV is required to obtain kidney boundaries which will be an anatomical landmark to know the relative area of the renal tumor. Additionally, we can adjust the pixel intensity conversion, which is usually log compression for an entire image, to emphasize pixel intensities for some local areas such as the target stones or organ boundaries.

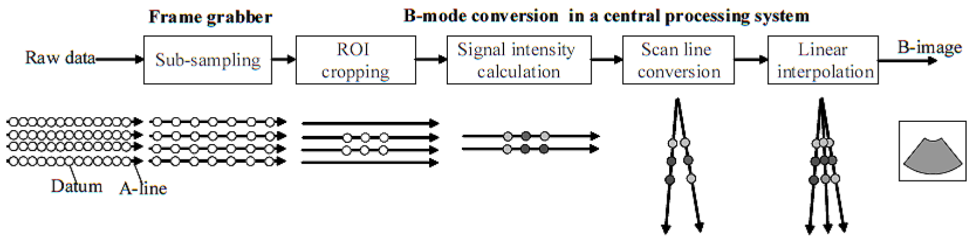

Figure 2: B-mode image conversion from grabbed raw data.

3 Tracking software

Two tracking software were developed for each target as shown in Fig. 3. The key points for both tracking software are automatic and real-time target recognition by detection of anatomical landmarks. In the case of the stone tracking, the targeting stone itself is a landmark: vividly different acoustic impedance of stones makes a relatively clear echo difference from tissues in US images. Therefore, it can be simplified by blob tracking. Moreover acoustic shadows under the stones are the other critical landmark to detect stones. The calculation for a stone recognition is done in about 5 ms. The detailed algorithm and evaluation for stone tracking is presented in [2]. On the other hand, kidney tumors usually have similar acoustic impedance with surrounding normal tissues, so it is very hard to extract the tumor region from an US image. Therefore, other anatomical landmarks should be found. Currently, tumor recognition is still being studied: now, we register biplane US image with 3-D preoperative organ model in order to define the relative tumor area from the registered organ. Thanks to the 2.5-D US model from the biplane US image, the registration with 3-D preoperative model can be accelerated. Now real-time organ pose estimation can be calculated in 14 fps for the phantom kidney. For this work, the brief algorithm evaluation using a phantom kidney model has been reported in [3]. For both targets, a detected irradiation position in the software is transferred to the robot part which will be explained in the next section.

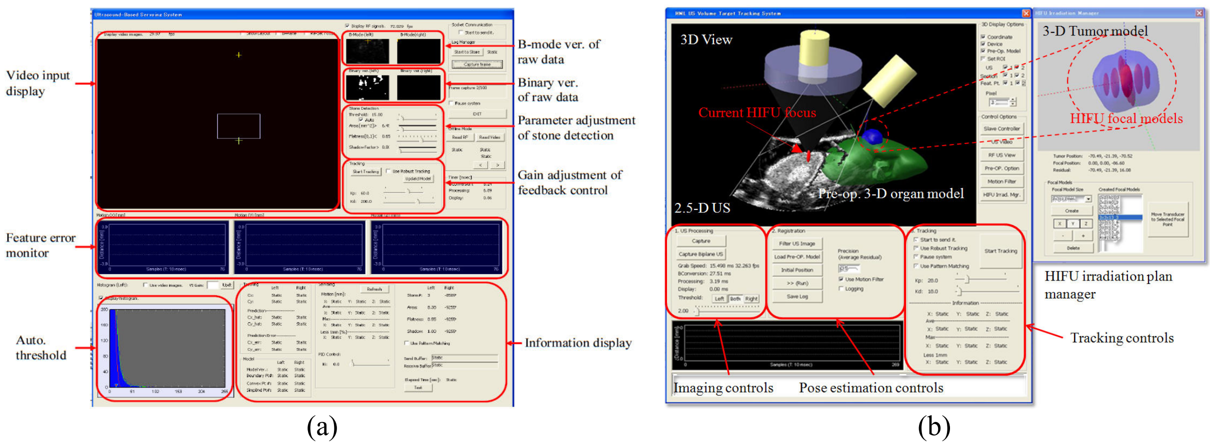

Figure 3: Screenshots of the tracking software for (a) stone and (b) tumor.

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4 Robot part

As shown in Fig. 1, ultrasonic image-based hand-eyed servo control structure is implemented. In other words, two ultrasonic imaging probes and HIFU transducer are attached to the end-effector of the XYZ robot. The end-effector of this system is depicted in left bottom of Fig. 1. This ultrasonic integrated system controls X, Y and Z directional DC stepping motors independently. The robot controller applies a VxWorks (Wind River Systems of Alameda, California, USA) machine on VMEbus (Motorola Inc., USA). The CPU board of the controller is MVME2434 (Motolora Inc., USA).We use VPG-86 (COSMOTECHS, Japan) as a motor controller board. The robot system moves the end-effector according to the distance error between HIFU focus and the irradiation position decided by the tracking software. As the result, the focal point of HIFU synchronizes with the target area.

In addition to the US visual feedback, since the motion of the targets is quasi-periodical, we use a periodic motion model and compensate the tracking delay due to the target detection and robot control by using a feed-forward control structure. For the experiment, the linear actuator was used to simulate a craniocaudal motion of the kidneys. Phantom targets (model stone and silicon kidney) are attached on the tip of the actuator and used to verify that our system can track targets.

5 HIFU irradiation part

The HIFU irradiation part plays a role to transmit HIFU waves to the target. It consists of pulse generators, an amplifier, and a single-element piezoelectric transducer. HIFU waves are transmitted by the piezoelectric transducer according to a RF (Radio Frequency) pulse signal which is formed by pulse generators (WF1946B, NF Corp., Japan). The amplifiers (RITEC RPR-4000, Warwick RI, USA, for stone destruction, 2100L, E&I, USA, for thermal ablation) magnify the intensity of the RF pulse signal. To avoid acoustic interference between HIFU and imaging probes, the pulse generators generate RF pulses interlacing with the scanning signal from the ultrasonic imaging system.

For the renal stone pulverization, locally controlled cavitation induced by HIFU accelerates erosion and minimizes the injury of surrounding tissues. For that, the RF waves consist of 100 cycles of a 1.66 MHz pulse to generate micro-bubbles, and 3 cycles of a 555 kHz pulse to expand and explode micro-bubbles to create an intense cavitation [4]. Maximum acoustic pressure is about 200 MPa at this time. In contrast to the renal stone destruction, about 5~6MPa in peak pressure (~ 1000W) is used with a 1.66MHz pulse and longer irradiation to achieve the temperature evaluation up to 60~70 degrees in a few seconds.

For the acoustic intervention with patients, the HIFU transducer and imaging probes are set in a water tank, which contacts with patients' skin via a silicon membrane. A water circulation system is also required to extract air from the water tank as an additional subsystem for the HIFU irradiation part.

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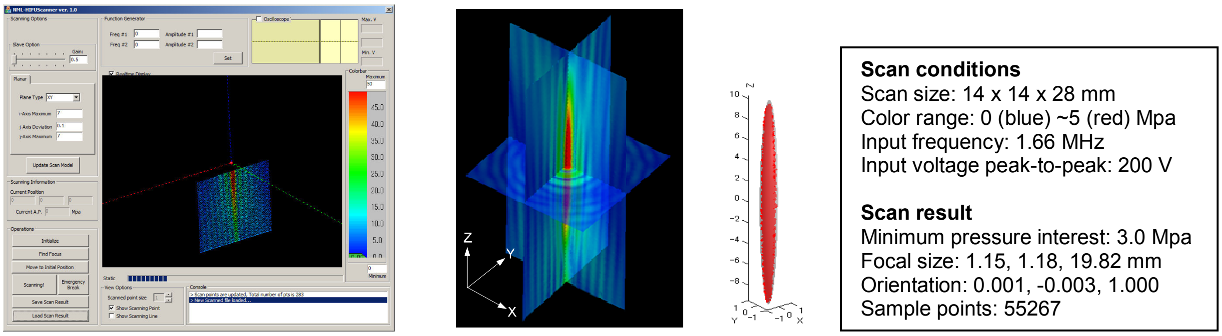
6 HIFU quality assurance system

A HIFU acoustic pressure scanning system is also an important part of our HIFU system. In particular, we developed a customized acoustic pressure scanning system in our robotic HIFU system, which enables fully automatic measurement of three-dimensional acoustic pressure distribution and quantification of focal regions according to the input voltage amplitudes. The scanned focal models are used for maintenance of HIFU irradiations as well as for planning target destruction. Since our HIFU system has a capability of XYZ movements, the additional required hardware for scanning are a sensor (needle hydrophone) and oscilloscope with network capability. The scanning process is monitored in the developed software on the fly, displaying a color-coded sensor response from the oscilloscope. Figure 4 shows the screen shot of the scanning software and its scan result. The detailed system configuration and scanning process is presented in [5].



(a) (b)

Figure 4: (a) Acoustic pressure distribution scanning software and (b) a scanned focal model.

7 Conclusions

In this paper, we presented the framework for an US-guided robotic HIFU system for renal diseases. This system is still a prototype; we do not have clinical experience with this system yet. However, we proposed this visual servoing integrated HIFU system as an alternative system for currently unavailable robotic HIFU treatment for renal diseases. The system includes (1) US imaging part, (2) tracking software, (3) robot part, (4) HIFU irradiation part, and additional QA system for HIFU irradiation.

Specifically, for the tracking by visual feedback, (1) raw US data are grabbed and converted into images, (2) two perpendicularly set US probes and the target detection algorithms provide the three-dimensional target information, (3) robot part synchronizes the HIFU focus on the target area, applying feed-forward control for the robust target motion tracking. (4) For HIFU irradiation in stones and tumors, two different irradiation conditions are also introduced with their QA system.

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Acknowledgements

The authors acknowledge the support of Global Center of Excellence for Mechanical Systems Innovation (GMSI) in the University of Tokyo, Translational Systems Biology and Medicine Initiative (TSBMI), and the MEXT program of the Ministry of Education of Japan.

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