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A Mechanical System Identification Method for Non-Invasive Ultrasound Theragnostic System

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Abstract: In this paper, we propose a mechanical system identification method for the Non-Invasive Ultrasound Theragnostic System (NIUTS). NIUTS tracks and follows the movement in an affected area (kidney stones, in the present study) by irradiating the area with high intensity focused ultrasound (HIFU). Blur noise caused by oscillation of the mechanical systems deteriorates the servoing performance. To enhance the servoing performance, it should be required to identify the mechanical system with mechanical oscillation part.

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1. Introduction

Areas can be selectively diagnosed and treated non-invasively by using high-intensity focused ultrasound (HIFU), based on the same principle as conventional ultrasound. It propagates harmlessly through living tissue. If the ultrasound beam is focused too tightly, however, energy in the focal volume may raise temperature locally [1].

It is thus possible to treat an affected area in the focal volume without damaging surrounding or overlying tissues using high-intensity focused ultrasound (HIFU), which, as a noninvasive technique, is an attractive alternative to current abdominal and endoscopic surgeries (Fig. 1(a)).

![Diagram of HIFU and kidney stone](image_url)

Fig. 1. (a) High Intensity Focused Ultrasound (HIFU). (b) Destruction of a model kidney stone by HIFU.

A number of reports have been made since Lynn, et al. demonstrated the potential medical application of HIFU[1][2]. e.g., the non-invasive destruction of kidney stones (Fig.1 (b)) by collapsing energy of cavitation.
However, during ultrasonic ablation, focus positioning is vital to keep the HIFU (High-Intensity Focused Ultrasound) beam close to the target. One advantage is that debris from such stones is small enough to avoid problems with adjacent organs [3]. HIFU is widely used in clinical practice [4][5]. Some 19 devices in clinical use were used to treat 1650 patients with a variety of tumors [6][7]. Compensation was not made, however, for movement in the affected area, mainly due to respiration. The need to prevent such movement, when irradiating focused ultrasound on the affected area, thus conventionally places a large burden on the physician and patient.

In the proposed non-invasive ultrasound theragnostic system, movement is compensated by tracking and following the affected area through stereo ultrasound imaging, while simultaneously irradiating HIFU onto the affected area. Here, theragnostics is a compound word between therapeutics and diagnostics.

The concept behind our proposal focuses on destroying tumors and stones. Using focused ultrasound directly without damaging healthy tissue while tracking and following the affected area—kidney stones in this case—during movement due, for example to the patient’s respiration.

Pernot et al., Nakamura et al., Thankral et al., and Ginhoux et al. have studied how to compensate for organ movement[8][12]. Pernot et al. proposed 3-dimensional (3D) motion canceling using multiple ultrasound transducers on a spherical surface but servoing performance is insufficient [8].

Nakamura proposed synchronization between organ movement and slave manipulator operation using a 955 fps high-speed CCD camera and robot controlled based on robust control theory[9][10]. Thankral et al. proposed modeling physiological movement based on a Fourier linear combiner (FLC) algorithm [11].

Ginhoux et al. proposed model predictive control (MPC) with an adaptive observer [12], as applied to a living pig, and verified the proposal’s effectiveness. Their system is based on a 500 fps high-speed CCD camera. However, such an optical high-speed CCD camera cannot be used for non-invasive diagnostics and therapeutics, due to the need to avoid damaging healthy tissue.
Abolmaesumi et al., Krupa et al. have studied the motion tracking using image speckle information [13][14]. Abolmaesumi proposed a controller utilizing diagnostic image features for carotid artery [13]. Krupa proposed an estimation and control method to automatically synchronize the 6-DOF motion of an ultrasound probe with a moving 3D ultrasound volume [14].

In this paper, the concept of a non-invasive ultrasound theragnostic system is first described. Second, an overview of the system configuration is presented. Third, we discuss the required servoing precision and the problems and solutions associated with visual motion tracking of target tumors and kidney stones in the body by using ultrasound images. Fourth, we propose a mechanical system identification method to cope with the mechanical oscillation problem.

2. Non-Invasive Ultrasound Theragnostic System

2.1. Concept of NIUTS

Based on recent studies, HIFU is regarded as very promising medical technology for the treatment of renal tumors and stones. However, the respiratory-induced motion of the kidney seriously decreases the efficacy of HIFU treatment.

To overcome this limitation, most treatment using HIFU has required the patient to be awake during the operation to control respiratory excursions in the kidney. As expected, patients and surgeons prefer to perform HIFU therapy under general anesthesia to ensure patient comfort and immobility. Accordingly, it is imperative to develop methods for respiratory motion compensation in the therapeutic HIFU system.

The concept of a non-invasive ultrasound theragnostic system is one that compensates for movement by tracking and following the affected area by stereo ultrasound imaging while irradiating the affected area with HIFU. The proposed system uses focused ultrasound to destroy tumors and stones without damaging healthy tissue. This is achieved by tracking and following the affected area to compensate for movement due to the patient’s respiration, heartbeat, and other causes.

2.2. System configuration

The system configuration of the non-invasive ultrasound theragnostic system is shown in Fig. 2. Stereo ultrasound diagnostic images are acquired using 2 diagnostic probes. Based on stereo ultrasound diagnostic images, 3D positioning data of the affected area, the relative value between the affected area and the focused position of HIFU, is obtained.

In control, the focus tracks and follows the kidney stone by using 3D positioning data. HIFU is irradiated onto the kidney stone using the function generator, amplifier, and transducer. The specification of irradiation of HIFU is detailed in reference [3].

The motor controller is based on a PID controller and outputs control signals according to the received visual feedback error. Since position-based visual servoing (PBVS) is applied [1], the received error is used to define the desired position from the current position of the end-effector. The "sync. data" in the figure avoids the interference between the therapeutic and the diagnostic ultrasound.

3. Problems with visual motion tracking using ultrasound images

In this section, we discuss the required servoing precision and the problems in the visual motion tracking by ultrasound images. First, we discuss the required servoing precision. Desired servoing precision in the presented system is within the margin of the irradiated object as shown in the following relation.

\[ E_d < k_{rt} \Delta r_{av} \]  

where \( k_{rt} \) is a proportionality constant. In the present study, we set \( \Delta r_{av} = 5 \) mm based on the advice of a medical professional (The margin of the current radiation therapy). Therefore, the desired target tracking precision is 2.5 mm (\( k_{rt} = 0.5 \)).
We now discuss the problems and solutions associated with visual motion tracking of the target kidney stone in the body based on ultrasound images (Fig. 3). The servoing error increases when the Image Quality (IQ) for visual servoing of the target is decreased.

The noise factors, which deteriorate the IQ, are classified into the following four factors: (i) acoustic shadows generated by the high acoustic impedance tissues like rib bones, (ii) organ deformation or texture pattern change in the ultrasound image due to organic motion, which is primarily due to motion perpendicular to the ultrasound image plane, (iii) confusing surrounding tissues or bubbles, which are generated by HIFU irradiation, image aliases, etc. (iv) blur noise caused by oscillation of the mechanical systems.

Servoing errors cause the image to change, which in turn increases the servoing error. This negative spiral causes the servoing performance to become increasingly worse. However, if the servoing performance can be improved by some method that results in a positive spiral, the possibility of dramatically enhancing the servoing performance is increased.

In this paper we propose a mechanical system identification method, to cope with the noise factor (iv) blur noise caused by oscillation of the mechanical systems.

4. Mechanical system identification method

4.1. Block diagram of controller for NIUTS

Fig. 4 is a block diagram of the controller for NIUTS. Here, \( r \) : Target position, \( e \) : Servoing error, \( \hat{e}' \) : Referred servoing error (100Hz), \( \hat{e}'' \) : Presumed target position, \( \hat{e}''' \) : Presumed servoing error (1kHz), \( u \) : velocity command value, \( y \) : Focus position of HIFU, \( \hat{y} \) : Presumed focus position of HIFU.

Our system is composed of position acquisition part \( O(s) \) (Ultrasound machine and image processing unit), Controller part \( C(s) \), motor driving part of XYZ stage \( P(s) \), Oscillation part of the hardware mechanism \( M(s) \). The presumed value \( \hat{O}(s) \) for \( O(s) \) (Time delay system from the input of ultrasound probe to the output of the position error information).

In order to enhance the servoing system, which is robust for the oscillation of the mechanical system, we have to identify the oscillation part of the hardware mechanism.

4.2. Mechanical system identification

First, we identify the motor driving part of XYZ stage \( P(s) \). This stage is controlled by the stepping motor and we apply first-order system model to identify the system. In this system, the input is the desired velocity and the output is the HIFU focus position. This system includes the integrator \((1/s)\).
\[
\hat{P}(s) = \frac{K}{s(1 + Ts)}
\]  

(2)

Here, parameters \( K \) and \( T \) should be identified. For identification, we use the desired velocity input data and position output data while tracking and following the artificial kidney stone [15] (The kidney stone moves based on the real human kidney motion data). The data, which is used for the system identification is shown in Fig.5. Here, the controller C is set as a constant. As a result, we identified \( \hat{P}(s) \) as the following equation.

\[
\hat{P}(s) = \frac{1000}{s(s + 1000)}
\]  

(3)

The mechanical part is observed to be oscillating during tracking with a constant controller C. Then, we need to identify the mechanical oscillation part \( \hat{M}(s) \) to cope with this oscillation problem. Mechanical oscillation, which is one of the noise factors, which deteriorates the servoing performance, as mentioned in Section 3.

First, we obtain the oscillation data of the mechanical part. An overview of the oscillation data acquisition system is shown in Fig.6. We utilize a force sensor and an elastic cord to acquire the oscillation position data. The nominal value of the force sensor is 0.5 kgf. Position data is calculated from the value of the force sensor.

Fig. 7 shows the obtained oscillation data. Fig. 7(a) is the servoing error data. In the figure, the blue line is the referred servoing error \( \hat{e} \), which is calculated from the ultrasound image, the red line is the servoing error \( r - \hat{r} \), which don’t include the mechanical oscillation. These two data show that the mechanical part is oscillating. Fig. 7(b) is the oscillation position data, which is obtained by the elastic cord. The oscillation has the resonance frequency around 9 Hz.

Second, we identify the mechanical oscillation part \( \hat{M}(s) \). Although \( \hat{M}(s) \) is supposed to have many oscillation mode, the most dominant oscillation mode, which deteriorate the servoing performance, is around 9 Hz. Then, we estimate \( \hat{M}(s) \) as 1 DOF oscillation system as the following equation.

\[
\hat{M}(s) = \frac{-s^2}{s^2 + 2 \omega_0 s + \omega^2}
\]  

(4)

The input is the position of the XYZ stage. The output is the oscillation data, which is obtained by the abovementioned elastic cord. Fig. 8 shows the obtained frequency response of the mechanical oscillation part. From the figure, the resonance frequency is 8.9 Hz.

Although the gain is 7.2 dB from the figure, the actual peak gain should be higher. This is because, the transformation of force data to the position data is not so accurate and other factors occur, which reduce the oscillation. Then, we rely much on the phase data and identify the mechanical oscillation part as the following equation (\( \zeta = 0.11, \omega = 8.9 \times 2\pi \)).

\[
\hat{M}(s) = \frac{-s^2}{s^2 + 2 \cdot 0.11 \cdot (8.9 \cdot 2\pi) s + (8.9 \cdot 2\pi)^2}
\]  

(5)

In order to reduce the mechanical oscillation, we have to design the oscillation reduction filter such as Notch filter. This is our future work.

**5. Conclusion**

In this paper, the concept of a non-invasive ultrasound theragnostic system is first described at first. Second, an overview of the system configuration is presented. Third, we discuss the required servoing precision and the problems and solutions associated with visual motion tracking of target tumors and kidney stones in the body by using ultrasound images. Fourth, we propose a method to identify the mechanical oscillation part of the system. In order to reduce the effect of the mechanical oscillation, we have to design the oscillation reduction filter, such as Notch filter, which is our future work.

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