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Technical note

Ultrasound-guided three-dimensional needle steering in biological tissue with curved surfaces

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ABSTRACT

In this paper, we present a system capable of automatically steering a bevel-tipped flexible needle under ultrasound guidance toward a physical target while avoiding a physical obstacle embedded in gelatin phantoms and biological tissue with curved surfaces. An ultrasound pre-operative scan is performed for three-dimensional (3D) target localization and shape reconstruction. A controller based on implicit force control is developed to align the transducer with curved surfaces to assure the maximum contact area, and thus obtain an image of sufficient quality. We experimentally investigate the effect of needle insertion system parameters such as insertion speed, needle diameter and bevel angle on target motion to adjust the parameters that minimize the target motion during insertion. A fast sampling-based path planner is used to compute and periodically update a feasible path to the target that avoids obstacles. We present experimental results for target reconstruction and needle insertion procedures in gelatin-based phantoms and biological tissue. Mean targeting errors of 1.46 ± 0.37 mm, 1.29 ± 0.29 mm and 1.82 ± 0.58 mm are obtained for phantoms with inclined, curved and combined (inclined and curved) surfaces, respectively, for insertion distance of 86–103 mm. The achieved targeting errors suggest that our approach is sufficient for targeting lesions of 3 mm radius that can be detected using clinical ultrasound imaging systems.

1. Introduction

Needle insertion into soft-tissue is a minimally invasive procedure used for diagnostic and therapeutic purposes such as biopsy and brachytherapy, respectively. In the current study, we present an image-guided robotic system that scans the soft-tissue phantom with a curved surface to localize the target and reconstruct its shape, pre-operatively. The image-guided robotic system then steers the needle to reach the localized target position while avoiding obstacles (Fig. 1). Two-dimensional (2D) and three-dimensional (3D) ultrasound imaging were used to localize the target and the needle during needle insertion [1]. The ultrasound transducer used for visualization of the needle and target needs to be controlled in order to scan the curved surface of the soft-tissue phantom. An algorithm based on implicit force control is proposed to move a transducer over a curved surface to maximize contact surface area for improved needle and target visualization.

The effect of system parameters on needle deflect and target movement during biopsy were investigated in several studies [2–5]. These parameters include needle diameter, insertion speed and bevel angle. Prior to needle insertion, these parameters can be set to minimize the target movement during insertion and consequently, improve the targeting accuracy.

1.1. Related work

In previous studies, robotic systems have been used to control the ultrasound transducer for scanning [6–9]. An example of an early study that explores the advantage of robotic ultrasound

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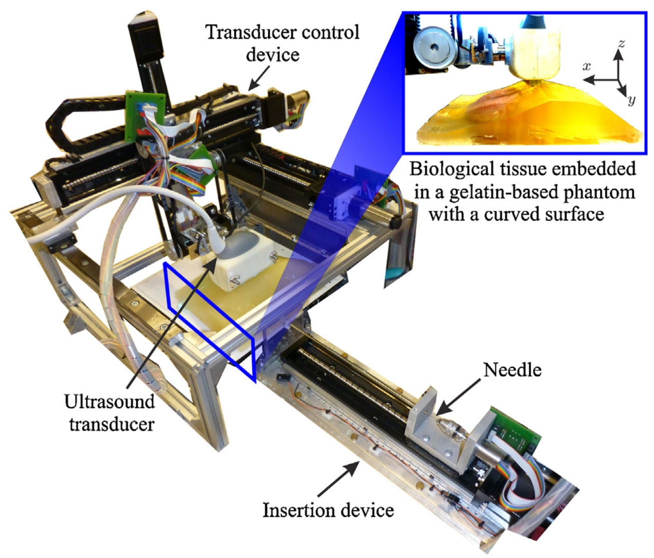

Fig. 1. The experimental setup used for needle insertion into a soft-tissue phantom that includes biological tissue (chicken breast tissue) with a curved surface. The inset shows an ultrasound transducer moving over a curved surface.

systems for scanning curved surfaces is the development of *Hippocrate*, a robot arm for medical applications with force feedback [10]. One of the applications of *Hippocrate* is the manipulation of an ultrasound transducer on a patient's skin in an automatic manner while maintaining a constant exerted force. The ultrasound images are used to reconstruct the 3D profile of arteries. The same robot has been used in studies of Krupa et al. that investigated an ultrasound-based visual servoing system [11,12]. Abolmaesumi et al. developed a tele-operated ultrasound system that allows the radiologist to view and manipulate the ultrasound transducer at remote site, while being assisted by force and image servo controllers [13]. Javier et al. developed an ultrasound system to 3D reconstruct the shape of *in-vitro* stenoses using an industrial robotic arm with force feedback [14]. Nadeau et al. presented a hybrid visual/force control to automatically align the transducer and keep the ultrasound image static even in the presence of physiological motion disturbances [15]. Besides proper contact force, the alignment/orientation of the ultrasound transducer is important to maintain the image quality. This alignment can be achieved by visual servoing [11] and also by force/torque control. However, the presented scanning systems require a pre-determined transducer path. This means that any deformation or change in the path causes scanning inaccuracies and consequently, errors in needle steering.

Flexible needles are used to steer around sensitive and hard tissue such as blood vessels and bones, respectively [16–18]. Such needles are fabricated with an asymmetric tip (bevel tip) that naturally deflect during insertion into soft-tissue [19]. The needle deflection due to its tip-asymmetry is used to steer the needle toward a certain target position [20,17]. In previous studies, control algorithms were developed for needle steering in 2D space. DiMaio and Salcudean presented a path planning and control algorithm that related the needle motion at the base (outside the soft-tissue phantom) to the tip motion inside the tissue [21]. Abayazid et al. presented a 2D ultrasound image-guided steering algorithm, and a 3D steering algorithm where they used Fiber Bragg Grating sensors for feedback [22,23]. Several 3D path planning algorithms have been introduced that are based on rapidly exploring random trees (RRTs) [24,25]. Our approach integrates the algorithm presented by Patil et al. to quickly compute feasible, collision-free paths in 3D-space [25].

1.2. Contributions

In the current study, we introduce a complete system where we scan a curved (breast-like) soft-tissue phantom to localize the target and obstacle positions, and also reconstruct the target shape. In previous studies, the ultrasound-guided steering experiments were performed on soft-tissue phantoms with flat surfaces but this is not the case in many needle insertion procedures such as breast biopsy [26,27]. In the current study, a robot is used to control the ultrasound transducer to keep contact between the transducer and the curved surface of the soft-tissue phantom using force feedback. We then integrate 3D tracking, path planning and control algorithms to steer a bevel-tipped flexible needle in a curved phantom to reach the localized target in 3D-space while avoiding a physical obstacle. Before conducting the insertion experiments, we investigate experimentally the effect of system parameters on target movement in biological tissue. The parameters include the needle insertion speed, bevel angle, needle diameter, skin thickness, target distance and target size. The results of this study is used to select the system parameters that reduce the target motion to minimize the targeting error while steering the needle. The algorithms are validated by conducting insertion experiments into a soft-tissue phantom and biological tissue (*ex vivo* chicken breast tissue) while avoiding a physical obstacle. To the best of our knowledge, the use of 3D ultrasound tracking combined with 3D path planning for needle steering toward a target and avoiding physical obstacles in a curved phantom has not been demonstrated.

2. Ultrasound scanning over curved surfaces

In this section, we present a method for ultrasound scanning of phantoms with curved surfaces. The scan is performed in steps using an ultrasound transducer. The target location is estimated using the ultrasound images that are captured at the end of each scanning step. Proper contact between the ultrasound transducer and the phantom surface is crucial for generating ultrasound images. A five degrees-of-freedom (DOF) device is designed in order to properly scan curved surfaces using a 2D ultrasound transducer. The system is an extension of the 3DOF Cartesian transducer positioning device presented by Vrooijink et al. [28]. In this study, a rotational mechanism is attached to the previous device in order to include two more DOF (Fig. 2).

2.1. Mechanical design

The ultrasound positioning device is augmented with a 2-DOF rotational mechanism. The mechanism design allows the transducer to roll and pitch using differential gears (Fig. 2). The midpoint of the transducer contact surface is assumed to be the end-effector of the system. The rotational mechanism is actuated by two ECMax22 motors with GP22 gear head (Maxon Motor, Sachseln, Switzerland), which are controlled by Elmo Whistle 2.5/60 motor controller (Elmo Motion Control Ltd, Petach-Tikva, Israel). The system has a force/torque sensor (ATI Nano-17, Industrial Automation, USA) to measure the contact forces applied to the transducer. The force measurements are used to align the transducer contact surface with the curved phantom surface.

2.2. Alignment control algorithm

A controller based on implicit force control [29], is developed to align the transducer with the phantom surface. The alignment control is important to assure the maximum contact area between the transducer and the phantom. The alignment control is done in three steps as described in Algorithm 1, where f_{ref-c} is the reference contact force, f_c is the exerted contact force, $\boldsymbol{f}_{ref}$ is the vector

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