Published in final edited form as:

IEEE Trans Ultrason Ferroelectr Freq Control. 2009 July ; 56(7): 1301–1303. doi:10.1109/TUFFC.2009.1185.

3-D Ultrasound Guidance of Autonomous Robot for Location of Ferrous Shrapnel

Albert J. Rogers, Edward D. Light, and Stephen W. Smith

Duke University, Biomedical Engineering Department, Durham, NC

Albert J. Rogers ; Edward D. Light ; Stephen W. Smith: stephen.w.smith@duke.edu

Abstract

Vibrations can be induced in ferromagnetic shrapnel by a variable electromagnet. Real time 3-D color Doppler ultrasound located the induced motion in a needle fragment and determined its 3-D position in the scanner coordinates. This information was used to guide a robot which moved a probe to touch the shrapnel fragment.

I. Introduction

The location of foreign bodies, such as shrapnel, within tissue is a requirement for many emergency procedures. To treat wounded patients, the foreign bodies must be distinguished from the surrounding tissue by an imaging system. Fluoroscopy or CT scans are effective ways of locating metal objects inside the body but are limited in the emergency context by their size and ionizing radiation. Previously, we have shown the ability to guide a surgical robot to high contrast targets such as a needle tip or cyst using a real-time 3-D (RT3D) laparoscopic ultrasound probe as a guide [1]. In a subsequent study we used image thresholding to fully automate the detection and robot guidance process [2].

Metal fragments of uneven geometry or small size often produce a weak echo or are obscured by other biological echogenic structures so that a simple thresholding algorithm will not enable target detection. McAleavey *et al.* previously described the use of a time variable magnetic field to detect ferrous brachytherapy seeds using 2-D color Doppler ultrasound [3]. In this study, we used such a variable electromagnet and 3-D color flow Doppler ultrasound to increase the contrast of ferrous needle fragments and improve the performance of an image-guided autonomous robot for a simulated interventional procedure.

II. Materials and Methods

As described previously by Pua *et al.* [1] and Whitman *et al.* [2] the *z*-axis of a 3-degree-of-freedom Cartesian Robot Linear Motion System (Model H26T55-MAC200SD, Techno, Inc., New Hyde Park, NY) was carefully aligned with the axis of a 2.5-MHz matrix array transducer (2-D array of piezo elements, see [4]) of the Model 1 3-D scanner (Volumetrics Medical Imaging, Durham, NC). With the transducer aligned in the robot's coordinate system, an aluminum probe needle was attached to the robot's arm and directed at a fiducial cross-hair on the transducer. A 2-mm long fragment of a steel needle 0.7 mm in diameter was suspended in a water bath at a depth of 4 to 7 cm to simulate shrapnel.

A 38.1-mm diameter solid iron core electro-magnet with 450 turns of wire was attached to the transducer so that the magnetic field was approximately collinear with the transducer axis (Fig. 1). The magnetic field was produced with a 4 A, 60 Hz alternating current from a variable ac generator (Variac) to produce a vibration in the length of the needle fragment. A 60-Hz Variac was used because it is able to supply enough current to produce a strong field at 4 to 5 cm away from the magnet core. At the position of the shrapnel, the field was in the range of 9 to 15 G as measured by a transverse F. W. Bell Gauss/Tesla Meter Model 5080 (Orlando, FL). Fig. 2 (a) shows a real time 3-D rendered image of the shrapnel suspended above an echogenic rubber sheet. Note that a simple thresholding algorithm would fail to locate the shrapnel relative to the rubber, just as bone or bright speckle may act as a distracter *in vivo*. To distinguish between the shrapnel and the rubber, the volumetric scanner's color flow Doppler function was used to acquire an image volume with the moving needle. Fig. 2(b) shows a single slice from the 3-D color Doppler scan. A trigger signal then started an autonomous cascade of events that begins with the transmission of this volume of data via a local network to a computer and ends with the linear robot moving to touch the probe to the shrapnel target.

The data transmitted to the computer are a volume of echo and color Doppler data in r , ϕ , and θ as described in Smith *et al.* [4]. Each 3-D ultrasound scan is composed of $64 \times 64 = 4096$ B-mode lines, including 512 samples per image line, yielding 2 MB of data per 3-D scan for echo data [2]. The Doppler data file size depends on width and depth of the gates set by the user, but is roughly 1 MB in size. These data are converted to rectangular coordinates and thresholded by Doppler intensity magnitude to find the position of the shrapnel relative to the transducer [Fig. 2(c)]. The size of the pyramid of data is determined interactively by the width of the Doppler gates and the depth chosen on the scanner. Finally, the coordinates for the shrapnel chosen as the centroid of the thresholded Doppler data are transferred to the linear robot which takes the necessary steps to place the probe in contact with the target shrapnel. Error was calculated by using the robot's jog function to back off the shrapnel or move until the probe is just in contact with it. Success was confirmed both visually [Fig. 3(a)], and with the scanner's C and B planes [Fig. 3(b) and (c)]. The time required for the entire task was 76 s.

III. Results

The data acquired using the 38.1-mm magnet showed an average rms error of 1.06 mm for 5 trials that lead to a 1.68% error relative to the distance traveled by the probe ($\langle d \rangle = 60.478$). Maximum rms error was 2.86 mm, while the minimum was 0.37 mm. Displacements generated in the needle fragment are invisible to the naked eye and velocities are in the 90 to 120 cm/s range. Five further trials were conducted using only echo data to find the target as in previous studies [2]. The rms error for these trials was 1.14 mm. Error is due to the limited spatial resolution of the transducer and the alignment of the transducer to the coordinate system of the robot. The speed of sound in water was not compensated for. It is expected that the farther from the face of the transducer the fragment is placed, the higher the error will be.

IV. Conclusion

We have developed an image-guided robotic system that can locate a ferromagnetic target within a water bath that may be robust enough to ignore echogenic distracters and direct a needle probe to the target's position. The ability to automatically guide a probe to a vibrating metallic target in this manner expands the range of practical tasks for an autonomous surgical robot.

Acknowledgments

A. Rogers would like to acknowledge Nik Ivancevich for his assistance in troubleshooting scripts and providing an algorithm for scan conversion. This study was supported by grant HL089507 from the National Institutes of Health.

References

1. Pua EC, Fronheiser MP, Noble J, Light ED, Von Allmen D, Smith SW. 3-D Ultrasound guidance of surgical robotics: a feasibility study. *IEEE Trans Ultrason Ferroelectr Freq Control* 2006;53(11):1999–2008. [PubMed: 17091836]
2. Whitman J, Fronheiser MP, Ivancevich NM, Smith SW. Autonomous surgical robotics using 3-D ultrasound guidance: Feasibility study. *Ultrason Imaging* 2007;29(4):213–219. [PubMed: 18481593]
3. McAleavey SA, Rubens DJ, Parker KJ. Doppler ultrasound imaging of magnetically vibrated brachytherapy seeds. *IEEE Trans Biomed Eng* Feb;2003 50(2):252–255. [PubMed: 12665040]
4. Smith SW, Pavy HE, von Ramm OT. High speed ultrasound volumetric imaging system part I: Transducer design and beam steering. *IEEE Trans Ultrason Ferroelectr Freq Control* 1991;38(2):100–108. [PubMed: 18267563]

Fig. 1. Experimental setup with linear motion robot with attached probe, transducer and electromagnet, and suspended needle fragment in a water bath.

Fig. 2. 3-D rendered shrapnel target and rubber absorber (a), shrapnel target displayed with color flow Doppler (b), and rendered data volume with shrapnel (c).

Fig. 3.

Image of experimental setup with drained water bath after successful run (a). C-scan (b) and B-scan (c) of probe touching target with Doppler.