A 5 Degree Of Freedom Haptic System for Transrectal Prostate Biopsy and Tissue Palpation with MR Image Guidance

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Introduction: The Magnetic Resonance (MR) environment imposes great restrictions on robotic systems for image guided interventions inside a scanner, which highly limits the use of electronics and ferromagnetic materials to avoid degradation of Single to Noise Ratio (SNR) and generated artifacts. A small and compact 5 DOF master-slave manipulator for prostate biopsy and tissue palpation is presented, which includes force feedback (haptics) and fiducial tracking technology. The MR compatibility of the actuators, encoders and force sensors has been demonstrated near the isocentre, allowing the system to be used in most areas of the scanner room. The needle insertion axis has incorporated haptic force feedback, which enables the robotic system to transfer the sense of touch from the biopsy needle back to the surgeon master console. This can give useful information for example by sensing the instant the needle pierces through the rectum wall or when it hits a tumour tissue in the prostate. An in vitro experiment demonstrated that the system was capable of distinguishing the stiffness of normal lamb liver tissue and a phantom tumour, which can assist interventions to diagnose the characteristics of a suspected tissue.

A 5 DOF robotic system coupled with a master-slave haptic needle axis: A 5 DOF robotic system for transrectal prostate biopsy as shown in Fig 1(a) and (d) has been developed. The robot consists of three active linear modules in X, Y and Z axes, each coupled with two piezoceramic motors and an optical encoder for actuation and position control; and two rotational joints (two passive DOF) linked to a haptic needle axis as indicated in Fig 1(b) with a pair of MR compatible force sensors for bi-directional force measurement. Detailed specifications and demonstration of MR compatibility have been previously published [1, 2]. The robotic system moves an endorectal probe in the rectum, which contains an imaging coil and two passive fiducial markers as shown in Fig 2(a). A fiducial tracking algorithm has been integrated into the system and programmed in the scanner software for real-time tracking of the biopsy needle, probe and slice orientation with accuracy of 0.2mm, and this information can be verified by the position data from the encoders in the system. Sense of touch is reconstructed in the master interface shown in Fig. 1(c) which allows real-time telepalpation. The force profile when the needle punctures a rectum and a targeted tissue in the prostate can be captured for analysis. Investigation of the stiffness of a suspected lesion relative to the adjacent tissue can facilitate practitioners to perform tumour diagnosis. The haptic axis demonstrates an excellent force and displacement response with less than 10 ms phase lag. The specifications of the haptic needle axis are presented in Table 1.

Detection of a tumour in soft tissue and tissue palpation: Force profiles were generated, with an experimental setup shown in Fig 2(b), where a 17-gauge biopsy needle was driven by the robot system to penetrate a lamb liver, with the sense of touch reconstructed in the master system. A phantom tumour (made of plasticine) with a stiffness 10 times greater than the liver was implanted inside. A force vs. displacement graph is shown in Fig. 2(c) and compared with that for a control experiment of liver needle insertion without the phantom tumor. The graph shows that for the case of the tumor present, puncture of the liver starts at a displacement of 12 mm while the target is hit at around 17 mm, as can be observed by the increase in stiffness. For the normal liver, fluctuation was detected in the force profile from 30 mm to 36 mm where internal structures of a hepatic artery and a portal vein were pierced.

(a) *(b)* *(c)* *(d)*

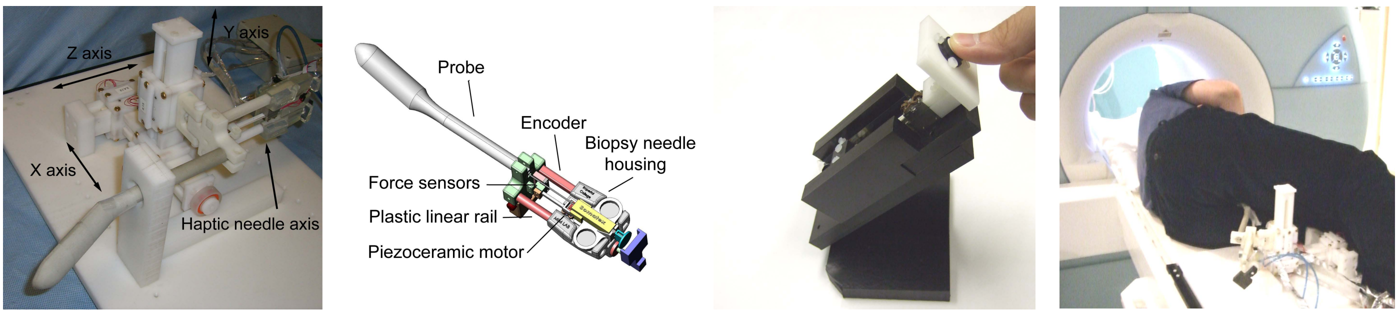

Fig. 1: (a) A 5 DOF robotic system with a haptic needle axis for prostate biopsy, (b) CAD rendering of the haptic needle axis (c) haptic master interface for needle insertion, and (d) setup of the system with a patient in decubitus position

Table 1: Specifications of the system

	Needle axis	X,Y & Z axes
Range	90 mm	100mm
System Resolution	80 μm	80 μm
Max. Holding Force	7.3 N	17N
Max. Speed	17.6 mm/s	2.7mm/s

(a) *(b)* *(c)*

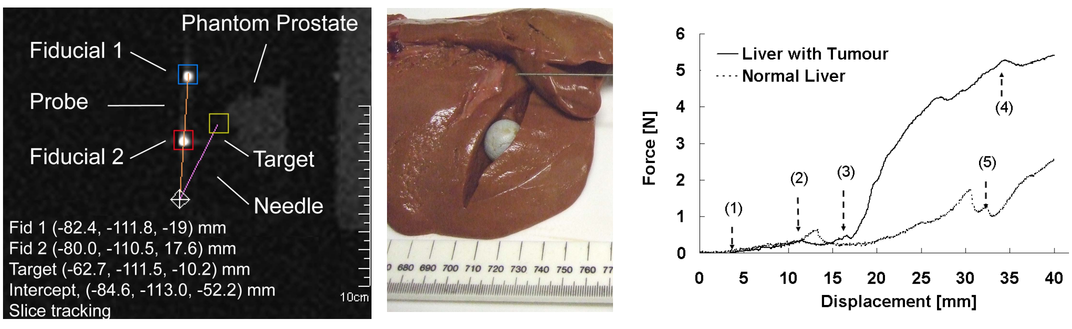

Fig. 2: (a) MR image of two passive fiducial markers with image processing algorithm for real-time tracking (b) A lamb liver with a phantom tumour. (c) Stiffness measurement of a lamb liver with a phantom tumour versus a normal liver. Stage (1) needle in contact with the surface of the liver, (2) liver is punctured, (3) tumour is hit, (4) needle piercing through tumour, and (5) puncture of the internal structure of the liver.

Conclusion: The haptic functionality of the 5 DOF robotic system has been demonstrated in the experiment to detect a force profile of piercing a phantom tumor and compared with that of a healthy lamb liver tissue. The master-slave prostate biopsy system with the ability of reproducing the sense of touch will be applied to clinical trials in the coming year for practitioners to characterise a target tissue. Haptic feedback provides extra information besides visual information from MRI images for verification of the movement of surgical tools in key-hole surgery and is believed to be capable of enhancing the quality of the surgery.

References:

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