Sunram 5: An MR Safe Robotic System for Breast Biopsy

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INTRODUCTION

The conventional MRI-guided breast biopsy procedure is inaccurate due to manual needle insertions and the necessity of rescanning. Therefore, the procedure would benefit from an MR safe robotic system to manipulate the needle precisely towards suspicious lesions under near-realtime MRI guidance. The main challenge is to design a system consisting of non-metallic, non-magnetic and non-conductive materials in order to eliminate safety hazards and imaging artifacts due to interference with the MRI's magnetic field.

Pneumatic stepper motors have been proved an effective actuation method in several state-of-art robotic systems[1, 2]. These systems are limited in bandwidth as 5 m long pneumatic tubes are needed between the valve manifold and the robotic system. This results in a stepper motor frequency of approximately 10 Hz when maximum force is necessary. The Stormram 4 needs approximately one minute to move from one position to another considering an axis of 640 steps. Higher velocities are desirable for practical applications[2].

Workspace is important for the breast biopsy robot: a suspicious lesion may be identified at the medial side or close to the chest wall. These locations are difficult to reach in state-of-art systems. Safety is also a concern: in case of emergency (including loss of pressure or mains power), the system should be able to eject the needle from the patient within one second.

This research aims to develop a new robotic system addressing the aforementioned challenges. The specific novelties are enhanced speed and accuracy, enlarged workspace and improved safety.

MATERIALS AND METHODS

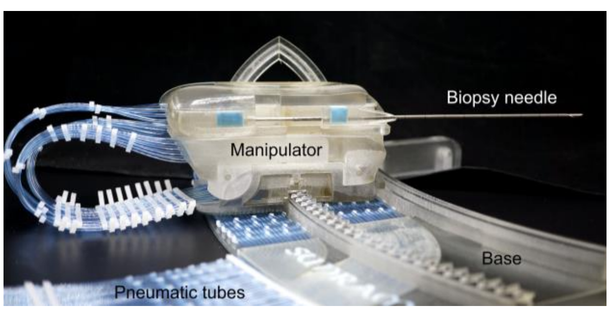

Fig. 1 Photo of Sunram 5.

The Sunram 5 robot is shown in Fig. 1. The five degree of freedom manipulator is actuated by six pneumatic stepper motors, measures 107 x 72 x 56 mm and has a mass of 260 g. Two of the motors have a relatively large step size of 1.7 mm, allowing for high-speed lateral and needle insertion movements. These motors are coupled with small-step motors (step size 0.3 mm) to maintain sub-millimeter accuracy in the same direction.

Each stepper motor consists of two or three pneumatic cylinders which alternatingly press against a straight or curved rack to make discrete steps[2]. Besides these six stepper motors three individual cylinders are also present to fire the biopsy gun and activate the needle ejection safety mechanism.

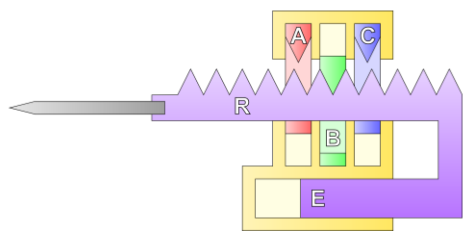

Fig. 2 Needle insertion actuator with safety ejection mechanism.

Fig. 2 shows a schematic of the three-cylinder needle insertion stepper motor with integrated safety ejection mechanism. In normal operation pistons A, B and C are alternatingly pushed down and up, nudging the rack (with needle) to the left or right in discrete steps. In case of emergency all three pistons A, B and C are lifted up and piston E is pushed to the right by a separate cylinder. As piston E is connected to the rack holding the needle, the needle is retracted out of the breast.

The robot is attached to a breast fixation system inspired by Machnet's device to immobilize the breast[3]. It can be manually positioned at a range of orientations relative to the breast allowing to adapt the compression direction and biopsy access window to the specific location of the lesion to be targeted. Fig. 3 shows a photograph of the entire system during the biopsy process.

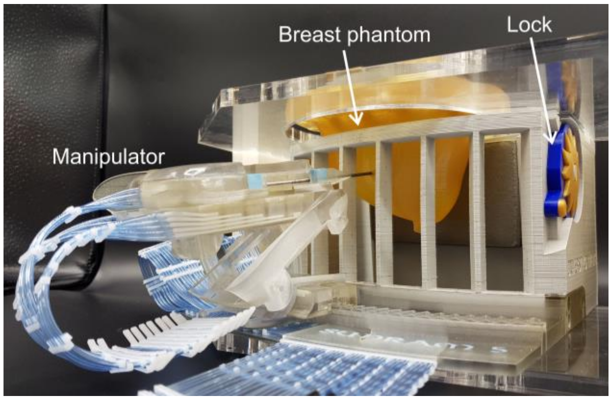

Fig. 2 Sunram 5 (left) targeting a breast phantom inside the fixation system (right).

The majority of the Sunram 5 parts was printed using a high-resolution polyjet printer. Acrylic rods support the hinges and laser-cut silicone rubber seals make the cylinders airtight. The removable 14G (2.1 mm) MR conditional titanium needle is the only metallic component of the system.

Three aspects of the robotic system were tested including speed/accuracy, workspace and safety. The highest manipulation time from one configuration to another is based on the range of motion of the different motors expressed as the number of steps, while the step sizes determine the theoretical positioning accuracy. The workspace was evaluated by estimating the volume percentile of the breast phantom which can be reached by the biopsy system, taking both the positioning freedom of the fixation system and the range of motion of the robot into account. The safety aspect was evaluated by first inserting a needle in the phantom to a depth of 50 mm and then activating the safety mechanism at pressures ranging from 0.1 to 0.4 MPa while recording the needle movement with a high-speed camera to measure the needle ejection time.

RESULTS

Speed and accuracy

The six stepper motors have a range of motion varying from 61 to 167 steps. At a stepping frequency of 10 Hz the upper bound of the manipulation time from one position to another is 16.7 seconds. When starting in a mid-way position and/or taking into account that two motors can work together in certain directions the effective maximum manipulation time is reduced to 8.4 seconds.

In the lateral and needle-insertion directions the small-step actuators yield a step size of 0.3 mm. In vertical direction two rotational joints have a step size of 0.3°, which translates to a 0.52 mm displacement at 100 mm from the rotation axis. Based on these step sizes, sub-millimeter accuracy can be achieved. Further enhanced accuracy is possible by coordinating movements of two motors: in collinear motor pairs, the smallest achievable step is 0.1 mm which is the greatest common divisor of its individual step sizes.

Workspace

The orientable fixation system significantly enhances workspace when the approximate location of the target lesion is already known. In combination with the high dexterity of the robotic system, any lesion that is situated below the fixation system's top surface is reachable by the robotic system.

Safety

A minimum pressure of 0.2 MPa is required to successfully activate the safety mechanism, ejecting the needle out of the phantom in 1.8 s. At 0.3 MPa, the time is reduced to 0.53 s, while at 0.4 MPa the needle is ejected in 0.31 s.

DISCUSSION

Pneumatic stepper motor technology has shown to be an effective actuation method for the Sunram 5. The six degrees of freedom combined with a versatile breast fixation system has potential to target lesions in the whole breast. Thanks to the dual-speed motors the manipulation time is under ten seconds, making it an order of magnitude faster than state-of-art robotic systems without compromising on accuracy. In case of emergency the safety mechanism is able to eject the needle out of the breast within one second at a pressure of 0.3 MPa or higher. A limitation might be that no direct position feedback is employed, so a calibration routine based on MRI or visual feedback may be necessary prior to the procedure.

The next steps in this research involve quantitative evaluation of targeting accuracy when performing biopsies in phantoms under MRI guidance. Needle-tissue interaction may contribute to deformations of the needle and/or the breast, potentially introducing localization errors which need to be assessed and mitigated. While the Sunram 5 has shown to be a major advancement over its predecessors, additional work is required concerning the placement of RF coils inside the breast fixation system and in sterilization of the device.

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