Stormram 2: A MRI-Compatible Robotic System for Breast Biopsy

V. Groenhuis[1], J. Veltman[2], S. Stramigioli[1]

[1]*Department of Robotics and Mechatronics, University of Twente, The Netherlands*
[2]*Ziekenhuis Groep Twente, The Netherlands*

v.groenhuis@utwente.nl , j.veltman@zgt.nl

INTRODUCTION

In breast cancer screening, the doctor looks for lesions using mammography, ultrasound, palpation and/or MRI. A suspicious lesion may need to be biopsied; if the lesion is only visible on MRI, then a MRI-guided biopsy is required which is a long and costly procedure. Also, because manual needle insertion takes place outside the scanner, there is no real-time imaging feedback resulting in insertion accuracies which needs to be compensated by taking away a large amount of tissue material, causing discomfort. For the previous reasons, there is strong request for new systems for MRI-guided biopsy which allow real-time imaging feedback, more or less implying the use of a MRI-compatible robotic device.

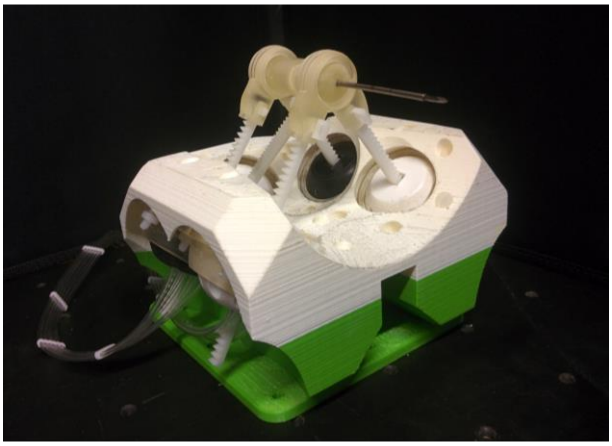

Fig. 1 The Stormram 2 biopsy robot.

In this paper, a novel 5 DOF needle manipulator (Fig. 1) driven by custom pneumatic linear stepper motors is described. Compared to its predecessor described in [1], all dimensions have been roughly cut in half, making the Stormram 2 small enough to easily fit inside the bore of the scanner together with the patient in prone position. It also has sufficient speed, force and dexterity to manipulate the needle towards a chosen target in a soft breast phantom.

MATERIALS AND METHODS

Because of the strong magnetic field in the MRI scanner, the use of metallic materials is severily restricted. Therefore, the whole robot (except for the needle) is made out of plastic materials. For the actuation system, pneumatics was preferred over hydraulics because control is easier and small leakages are acceptable.

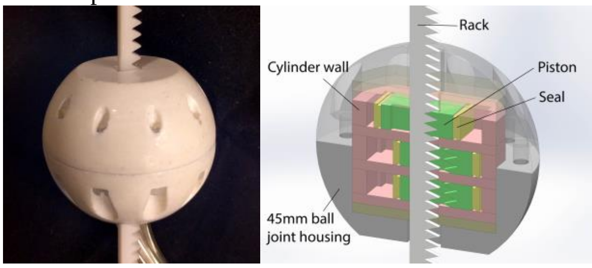

Fig. 2 Left: assembled actuator. Right: cutaway view, exposing three pneumatic cylinders with toothed pistons.

The actuators (Fig. 2) are custom-developed pneumatic linear stepper motors. In each stepper motor, three laser-cut rectangular pneumatic cylinders are embedded which together drive a rack in steps of 1mm. For a more detailed explaination of the mechanism, see [1]. The housing of each actuator also acts as a passive ball joint, with a ball diameter of 45mm.
The robot's frame was fully 3D printed and measures 140x140x100mm. Five actuators are mounted in the frame, driving a needle holder using a five-link parallel platform system, whose kinematic structure is inspired by MrBot [2].
Several different 3D printed needle holders (Figure 3, right) were developed, allowing the mounting of various off-the-shelf (MRI-compatible or MRI-safe) needles and performing different (semi-)automatic needle insertion strategies.

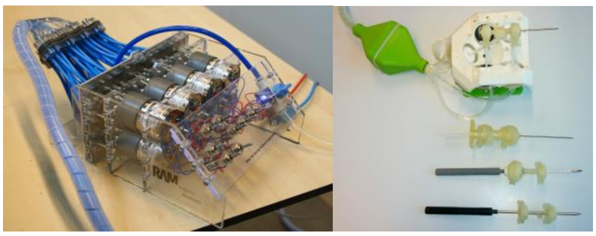

Fig. 3 Left: Pneumatic distributor for manual control of up to eight stepper motors, each controlled by six pneumatic tubes. Right: Four needle holders, for 14 gauge (2.1mm) or 9 gauge (3.8mm) needles, allowing for different biopsy strategies.

The robot is driven by a manually-controlled motorized pneumatic distributor (Figure 3, left) placed outside the MRI room, at a working pressure of 4 bar. It is operated by hand using visual guidance. The maximum actuator and needle insertion forces were measured with spring scales. MRI scans of the robot (with and without needle) were made to check if there is any influence of the robot on scans of a phantom, or that all artefacts can be attributed to the needle.

RESULTS

With short pneumatic lines, the individual actuators can operate at speeds up to 10 mm/sec, with a maximum force of 15N (±2N) at low speeds. The effective maximum tissue penetration force of the 14 gauge (2.1mm) needle, positioned in the center of the workspace, was found to be around 8N. This value is lower than the individual actuator force, because of the particular kinematic configuration and because of resistance in the passive joints.

The robot's needle tip can reach targets with 1-2mm accuracy within a volume of approximately 90x80x50mm (as determined experimentally), and tilt the needle horizontally and vertically at different angles, up to ±30° in the center of the workspace.

The 45mm ball joints have a clearance in the order of 0.2mm, because the 3D printed ball and socket surfaces are not exactly spherical and friction has to be kept low. Parasitic movements of individual links were found to be in the order of 0.5mm, together resulting in a needle tip backlash of up to 2mm in free motion, depending on the actual position in the workspace.

To connect the robot to the valve manifold, 8 metre long and 2mm thick pneumatic lines were used. As air is compressible and airflow in the pneumatic distributor is limited due to the 0.8mm orifices, relatively much time is needed to pressurize the air in the pneumatic lines, effectively limiting the the maximum operating speed to about 3 mm/sec. Manual tele-operation under visual guidance has shown that it is possible to pierce a target lesion in a phantom made of gelatin or PVC (Figure 4).

Fig. 4 Left: Measurement setup in a 0.25T MRI scanner. Right: 3d rendering of the ex vivo tissue phantom, made out of gelatin (yellow) containing four fish oil capsules (red). The fifth marker is attached to the needle.

MRI tests with a Esaote G-scan Brio 0.25T scanner have shown that the robot without needle is completely invisible on the scans and produces no measurable artefacts in scans of phantom tissue. When equipped with the 14 gauge (2.1mm) titanium needle, significant artefacts are present up to a distance of 4mm around needle (Fig. 5) when it is inserted in a gelatine phantom.

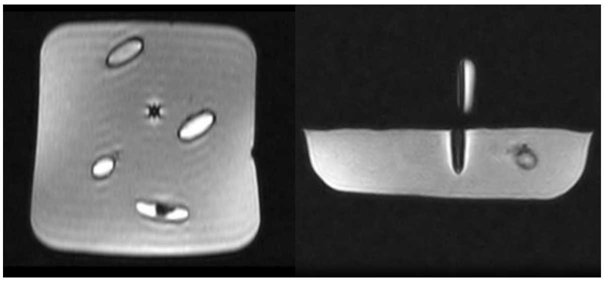

Fig. 5 Slices of a 3D Hyce MRI scan. Left: transversal plane through the phantom, showing four markers (white) and the needle insertion point just above the center. Right: sagittal plane through both the phantom and needle, showing two markers (one attached to the needle) and artefacts around the needle.

DISCUSSION

The developed miniature pneumatic actuators are shown to be strong enough to position and tilt the needle and pierce a soft phantom breast, but to penetrate a real skin a higher force is needed. This could be solved by improving the actuator design, or by driving the needle with a separate, more powerful actuator.

For the needle backlash problem, a possible solution is to change the 45mm ball joints to revolute joints, which can also be manufactured using rapid prototyping techniques with zero clearance and minimal friction. Also, the actuator's step size (1mm) could be reduced, increasing the precision of the system at the cost of lower speed. The operating speed can be increased by using valves with higher airflow and optimizing the pneumatic tubing thickness.

Computerized control of the biopsy robot has to be developed in order to effectively make use of real-time MR imaging, target lesions accurately and assess the robot's performance quantitatively. An electronic valve manifold driven by path planning software needs to be developed for this.

CONCLUSIONS

To conclude, the Stormram 2 has shown that it is possible to develop a fully MRI-compatible needle manipulator actuated by minituature pneumatic linear stepper motors, in which all parts are rapid prototype-able by 3D printing or laser-cutting from commonly available materials.

REFERENCES

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