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Design of a Small Animal Biopsy Robot

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Abstract— **Small animals are widely used in biomedical research studies. They have compact anatomy and small organs. Therefore it is difficult to perceive tumors or cells and perform biopsies manually. Robotics technology offers a convenient and reliable solution for accurate needle insertion. In this paper, a novel 5 degrees of freedom (DOF) robot design for inserting needles into small animal subjects is proposed. The design has a compact size, is light weight, and has high resolution. Parallel mechanisms are used in the design for stable and reliable operation. The proposed robot has two gimbal joints that carry the needle mechanism. The robot can realize dexterous alignment of the needle before insertion.**

I. Introduction

Small animals such as rats and rabbits are widely used to study diseases and therapeutics in biomedical research. Many researchers have depended on small animals to develop drugs or therapies before they are used to treat human diseases. Small animals are used in various applications, but in most cases, the needle is manually inserted to the subject. Manual needle insertion is time consuming and most of the time target tissues cannot be reached due to their small sizes. In this paper a compact robot design to insert needles to small animal subjects is proposed.

Inaccurate needle positioning can destroy cells and organs, and can even cause trauma. In cases of insertion failures or missed targets a new animal is used to repeat the experiment. Therefore, accuracy is an important factor in these experiments. The organ dimensions of small animals are in the order of few millimeters thus factors such as hand tremors and unexpected disturbances can cause inaccurate needle insertion. Robotic-assisted autonomous needle insertion offers a convenient and reliable solution to this accuracy problem.

Small animals have compact anatomy and tiny organs. It is difficult to perceive tumors or cells and perform biopsies manually. Therefore, image guided needle insertion has been preferred for its accuracy and safety [1]. For purposes of needle insertion, researchers have used X-ray computed tomography (CT) [2], magnetic resonance (MR) imaging [3], micro positron emission tomographic (PET) [3], [4], and ultrasound imaging [5], [6]. In these studies, the needle insertion trajectories to be followed were planned based on pre-operated images. In addition, intra-operative image guidance was used to confirm the position of the needle. Even though image guidance is helpful during needle insertion, it is difficult to manually insert the needle to the small sized target.

There have been several studies on image guided needle insertion [2]–[4], [7]. Base on the nature of the problem the robot is required to have a light structure and should have high resolution and accuracy. The objective of this paper is to propose a design for robotic-assisted needle insertion. In this design parallel mechanisms are used for stable and reliable operation. The robot has 5 degrees of freedom (DOF) with two gimbal joints that carry the needle mechanism. It can realize dexterous alignment of the needle before insertion. The design is light weight, and has high resolution.

In the following section, related studies on image-guided small animal biopsy research are summarized. In Section III, the requiements of the proposed robot design are explained. Finally, in Section IV the specifics of the designed robot are given, followed by the planned Future Work.

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II. Image-Guided Small Animal Biopsy

There are several studies on image guided automated robot system for small animal research which focus on the development of robotic systems, their calibration and data registration, and image reconstruction. Huang *et al.* [3] designed a stereotatic image-guided system that consists of an image fusion software and an autonomous robot arm. In this study micro PET images are fused with MR images. For vertical needle insertion a commercial 4 DOF CAST-PRO II robot arm is used, however the needle orientation was constrained despite having installed an additional motor. The position accuracy of this robotic system was about 0.05 mm. Kazanzides *et al.* [4] developed a 4 DOF robot for image-guided procedures using micro PET. Their design consists of a X-Y platform and two vertical slides. A force sensor is attached at the robot for force control. However, the needle is attached at a fixed orientation to the 4 DOF robot. Such constrained orientation can hinder generating various trajectories for needle insertion. Waspe *et al.* [7] developed a 6 DOF remote center of motion (RCM) robot to control needle orientation. In this design the needle tip can pivot when it contacts the skin. For intra-operative image guidance ultrasound imaging is used. However, the positioning accuracy of this robotic system was below 0.1 mm. In a recent study, Ayadi *et al.* [2] installed a pneumatic gripper into a 6 DOF industrial Staubli Rx60 robot. For image guidance

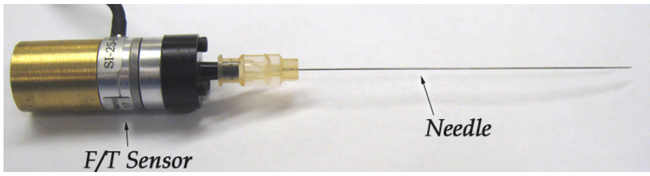

Fig. 1. Force/Torque sensor attached to the needle base to measure the needle insertion and retraction forces.

micro CT was used. The position and orientation of the needle can be controlled freely using this robot, however a large space is needed to install this system due to its size. Generally commercially available robotic systems are bulky to perform operations on small animals.

Needle insertion to small animals cannot be completed using a simple vertical insertion since organs or bones can be in between the entry point and the target point. Therefore, various orientations should be considered for convenient needle positioning. Needle positioning error, including robot error and calibration error, should be below 1 mm to precisely reach target points such as tumors. Therefore, the first step of developing a robotic system for small animal biopsies is achieving high accuracy in the autonomous needle insertion.

III. Design Requirements

We designed a manipulator that can insert and retract a needle at a given position and orientation. This section describes the design requirements to build a such manipulator.

Force Measurement Experiments: We did experiments on a small animal (mouse) to determine the force needed to insert a needle to the animal tissue. Needles were inserted manually, about 1.5-2.0 cm deep, to various locations such as muscle, internal organs, and tumor growths. The forces at the base of the needle were measured with a ATI Nano17, 6-axis F/T sensor with force resolution of $1/160$ N and torque resolution of $1/32$ Nmm [8] (Figure 1). The magnitude of the resultant force was calculated from the recorded force/torque data.

We have collected 3 data sets. Each data recording was 150 seconds long and each set included 5 needle insertions to different locations. Figure 2 shows an insertion and retraction into a muscle tissue. During these experiments, the maximum measured force was 0.8 N that was observed when the needle was inserted to the muscle tissue. Retraction forces were relatively small, around 0.1 N, compared to insertion forces. These measurements constitute one of the basic design requirements of the robot.

Manipulator Workspace: Another design requirement was the workspace needed for inserting the needle to the small animal that is placed within the workspace of the manipulator. Once the robot is placed next to the animal subject, the robot should be able to position the needle in 3-D space. Then, it should align the needle before insertion along the insertion path. In order to achieve this needle movement, a manipulator with a minimum 5 DOF is needed.

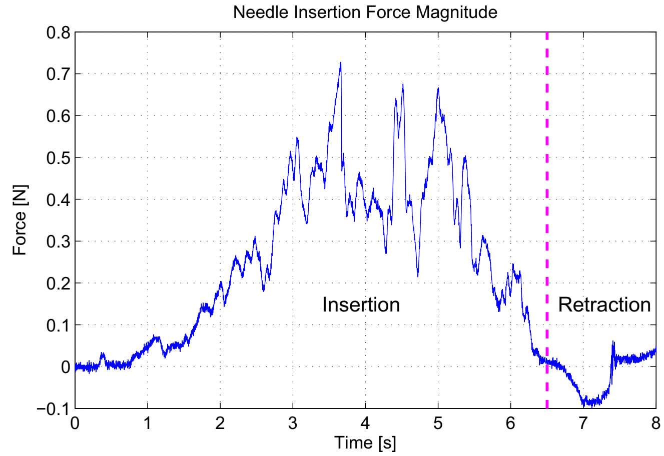

Fig. 2. Needle insertion and retraction forces into muscle tissue. At t =6.5 s operator stops the insertion and quickly retracts the needle.

Safety: The manipulator should have a compact size and be light weight. The maximum kinetic energy that the manipulator can exert should be kept at minimum for safety reasons, and actuators should be selected accordingly. The parts that come in contact with the needle or syringe should be sterilizable.

IV. Robot Design

In Figure 3 the schematics of the 5 DOF robot design is shown. The design consist of two main sections: the front stage and the back stage. The front stage of the robot is a 5-bar linkage mechanism with 2 DOF motion. This section's role is to guide the needle tip before for insertion. The back stage of the robot is also a 5-bar linkage mechanism with an additional pitch rotation around its base link making this stage a 3 DOF manipulator. This section's role is to direct the needle motion and insert the needle to the tissue using the pitch rotation while the 5-bar mechanism positions the needle in coordination with the front stage. In the proposed robotic system biopsies will be possible with high precision.

In the 5-bar mechanism links attached to the base are actuated with a tendon-driven mechanism, where a capstan pulls the tensioned cable that rotates the disk around its axis. This mechanism provides low friction motion without slipping or binding. Two different sized motors are used to drive the tendon-driven mechanisms. Maxon RE-25 Motors with 500 counts per turn (CPT) encoders are used in the front stage, and in the pitch axis of the back stage. At the back stage linkage mechanism Maxon RE-16 Motors with 512 CPT encoders are used [9]. Depending on the orientation of the 5-bar mechanisms, a position resolution of 5-50 μm is achievable with these position encoders. Figure 4 shows the 2-dimensional planar workspace of the 5-bar linkage. A 2 DOF gimbal mechanism is attached to the end of the link with a 45^o angle to provide an almost-symmetric workspace. One of the advantages of the 5-bar linkage mechanism is that bulky parts, such as motors, can be positioned at the base. This provides lighter links hence more safety.

Front Stage

The front stage is a 2 DOF parallel manipulator, which is a 5-bar linkage mechanism that is actuated with two electric motors fixed to the base link. Built prototype of the front stage is shown in Figure 5. This kind of parallel mechanisms are used in medical robot designs [10], [11]. The upper links are connected to the base from the same axis. All four links of the mechanism are 100 mm long. Therefore the mechanism's geometry is always a rhombus, making kinematics of the robot very simple. A 2 DOF gimbal joint is attached to the end-effector of this mechanism to allow the needle to go through its center (Figure 6). The gimbal joint do not exert any bending moments on the needle as a result of its low friction bearings. The gimbal mechanism also involves a replaceable guide in the center of the joint making it sterilizable.

Back Stage

The back stage of the robot has the same 5-bar linkage mechanism as the front stage. In addition, this stage is able to rotate around the base link's pitch axis. This motion provides the push force needed for inserting the needle to the tissue. A 2 DOF gimbal joint attached to the end-effector of the 5-bar linkage mechanism carries the needle mechanism. This robot can be used in a wide range of biomedical applications such as biopsy, drug delivery, or cell-seeding by changing the needle mechanism. For initial experimentation, a needle and syringe mechanism is designed to deliver drugs to the target tissue. In this drug delivery mechanism, an externally threaded housing mounted within an internally threaded cylinder is used as a linear actuator. In this mechanisim, a Maxon RE-10 Motor is connected to the outer housing with a coupling. The motor's rotational motion is transformed into linear motion that is needed to insert or retract the plunger of the syringe. The parts of the drug delivery mechanism

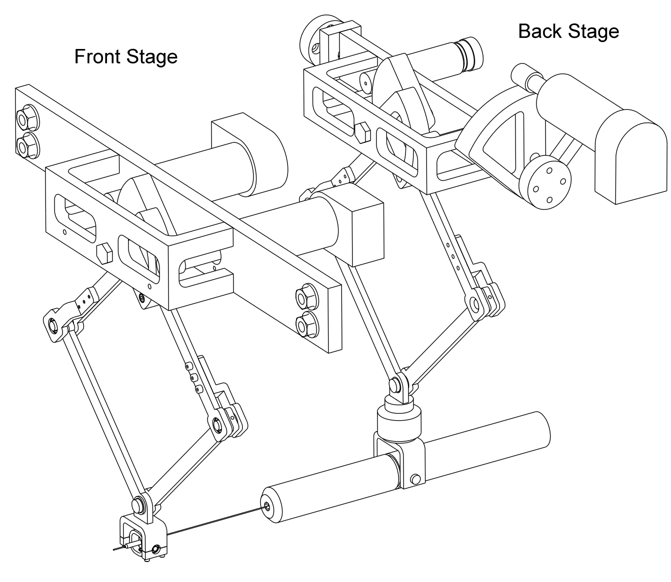

Fig. 3. 5 DOF Small Animal Drug Delivery/Biopsy Robot.

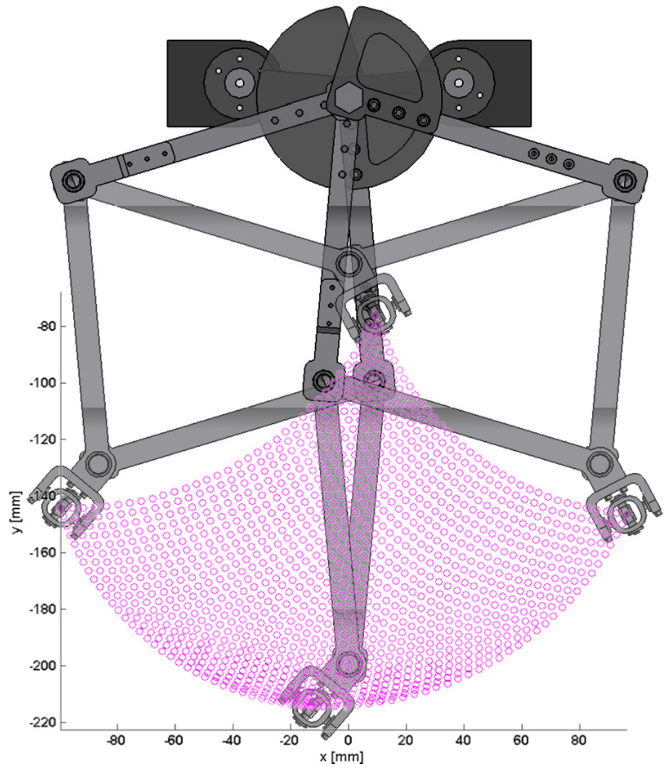

Fig. 4. 5-bar linkage mechanism workspace. The tip has two degrees of freedom with the actuation of the two links attached to the base link. Shaded area shows the planar workspace of the mechanism. (Units in mm).

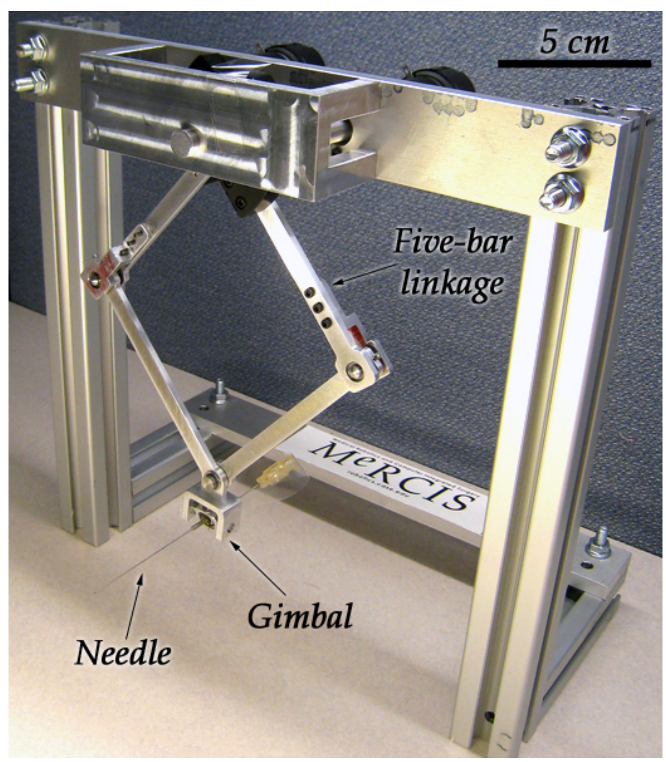

Fig. 5. Built prototype of the front stage of the robot.

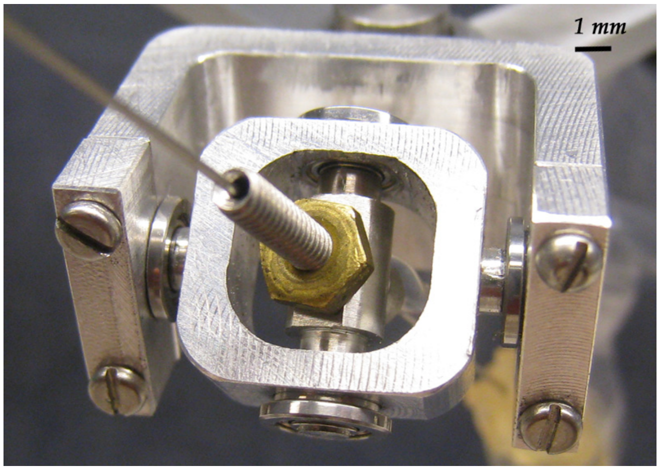

Fig. 6. 2 DOF Gimbal Mechanism: The needle can slide through the guide that is placed in the center.

that come in contact with needle can be separated easily for sterilization.

Future Work

In this paper, a novel 5 DOF robot design for inserting needles to small animal subjects is presented. The front stage of the proposed robot has been completed; the back stage of the robot and the needle mechanism are currently under construction. We will do extensive testing and calibration studies on mock-up test bed systems to determine the precision and accuracy of the final prototype. These steps will be the milestones in developing a high accuracy autonomous small animal research robot.

References

[1] K. Cleary, A. Melzer, V. Watson, G. Kronreif, and D. Stoianovici, "Interventional robotic systems: Applications and technology state-of-the-art," *Minimally Invasive Therapy*, vol. 15, no. 2, pp. 101–113, 2006.

[2] A. Ayadi, G. Bour, M. Aprahamian, B. Bayle, P. Graebling, J. Gangloff, L. Soler, J. M. Egly, and J. Marescaux, "Fully automated image-guided needle insertion: Application to small animal biopsies," in *Proceedings of the 29th Annual International Conference of the IEEE EMBS*, Lyon, France, 8 2007, pp. 194–197.

[3] Y. H. Huang, T. H. Wu, M. H. Lin, C. C. Yang, W. Y. Guo, Z. J. Wang, C. L. Chen, and J. S. Lee, "An automated robot arm system for small animal tissue biopsy under dual-image modality," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 569, no. 2, pp. 230–234, December 2006.

[4] P. Kazanzides, J. Chang, I. Iordachita, J. Li, C. C. Ling, and G. Fichtinger, "Development of an image-guided robot for small animal research," *Computer Aided Surgery*, vol. 12, no. 6, pp. 357–365, November 2007.

[5] P. Abolmaesumi, S. Salcudean, W. Zhu, M. Sirouspour, and S. DiMaio, "Image guided control of a robot for medical ultrasound," *IEEE Transactions on Robotics and Automation*, pp. 11–23, February 2002.

[6] A. C. Waspe, J. C. Lacefield, and A. Fenster, "Registration of three-dimensional high-frequency ultrasound images to a robotic needle-positioning system for preclinical research," in *4th IEEE International Symposium on Biomedical Imaging: From Nano to Macro (ISBI)*, April 2007, pp. 1132–1135.

[7] A. C. Waspe, H. J. Cakiroglu, J. C. Lacefield, and A. Fenster, "Design, calibration and evaluation of a robotic needle-positioning system for small animal imaging applications," *Physics in Medicine and Biology*, vol. 52, no. 7, pp. 1863–1878, 2007.

[8] ATI Industrial Automation, *Nano17, 6-axis Force/Torque Sensor*, ATI Industrial Automation Inc., Apex, NC, USA, 2008. [Online]. Available: http://www.ati-ia.com/products/ft/ft%5Fmodels.aspx?id=Nano17

[9] Maxon, *RE-16 3.2 Watt and RE-25 10 Watt Precious Metal Brushes DC Motors*, Maxon Precision Motors Inc., Fall River, MA, USA, 2008. [Online]. Available: http://www.maxonmotor.com

[10] S. P. DiMaio and S. E. Salcudean, "Needle insertion modeling and simulation," *IEEE Transactions on Robotics and Automation*, vol. 19, no. 5, pp. 864–875, October 2003.

[11] H. Liao, K. Yoshimura, T. Utsugida, K. Matsumiya, K. Masamune, and T. Dohi, "Surgical manipulator with linkage mechanism for anterior cruciate ligament reconstruction," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, San Diego, CA, USA, October-November 2007, pp. 1266–1271.