Lab Report: Develop of A Torque Feedback Interface for Virtual Acupuncture Training

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1. About

Haptic devices provide a straightforward method for mapping simulated forces to the user. This enables the user to actively interact with the virtual environment. This makes them useful in applications like medical training, where users can operate with virtual tissue before moving to real-world patients. Acupuncture is a medical technique that inserts thin needles through patient's skin at body's specific points. This report presents the development of a lightweight, highly backdrivable torque feedback tip for virtual acupuncture training. The tip would be adapted to an existing Phantom device.

2. Hardware

The acupuncture process mainly involves two motions, insertion of the needle and rotation in the tissue. So the haptic device needs to render insert force and rotation torque in order to simulate the acupuncture process on real-world patients. However, most existing commercial haptic devices are equipped with 3 active translation DoF and 3 passive rotation DoF. Such as 3D systems' Phantom[1], Falcon[2], and Omega[3]. For those with additional active rotation feedback hardware, motors and transmission systems are directly mounted on the end-effector of the device. As a result, additional weight and inertia can impact apparently on user's experience. To address this issue, some solutions compensated the tip's weight on the software level with device's dynamic model[4]. This project proposed a tendon-based flex transmission structure that allows the tip's actuation motor to be decoupling mounted on device's base. Which greatly decreases the tip's moving weight. At the same time, an origami-inspired clutch mechanism is designed to reduce the friction of free rotation. The prototype of the tip is shown in Fig 1.

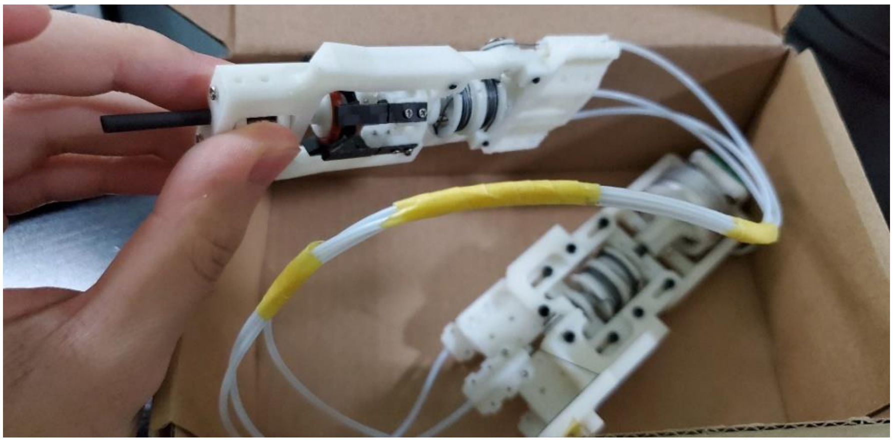

Fig 1 Prototype of the torque feedback tip

The design of the tip follows these guidelines.

Weight – Weight of the tip must be limited, without cause obvious changing on device's dynamic property. Also, it should be easy and comfortable to operate by users.

Workspace – The added tip should not interfere device's original workspace.

Transparency – Tip's actuation system should be low friction, low inertia, and highly back-drivable, which renders the feedback torque directly to users.
Control and sensing – The tip should be torque-controllable with an encoder measuring needle's real-time position and angular velocity.

A. Flex transmission system

To decouple the actuation motor from the tip, this flex transmission system is designed to transparently transfer feedback torque from a fixed base to moving tip. The core of the system is a set of capstans linked by tendons, which converts torque to the tendon's tensile force. The tensile force is then transmitted via a pair of tendons sliding inside a flexible Teflon tube. Nylon tendon and Teflon tube are selected to minimize the sliding friction. CAD drawings of the system are shown in Fig 2 and Fig 3.

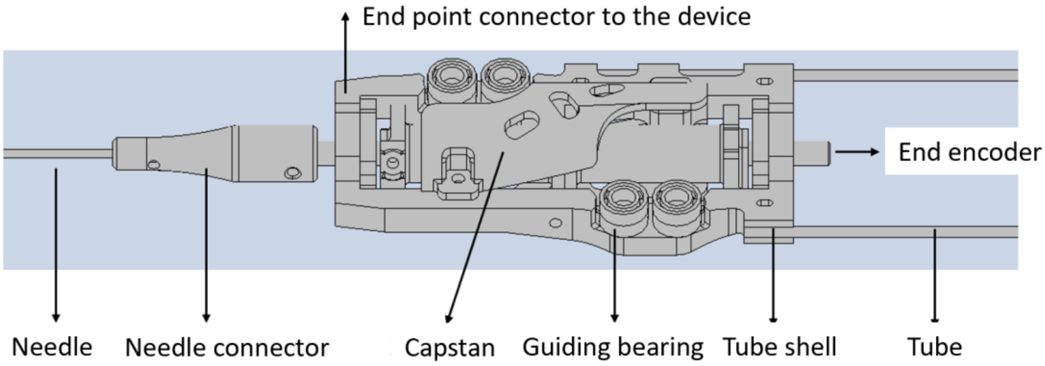

Fig 2 CAD drawing of the moving tip

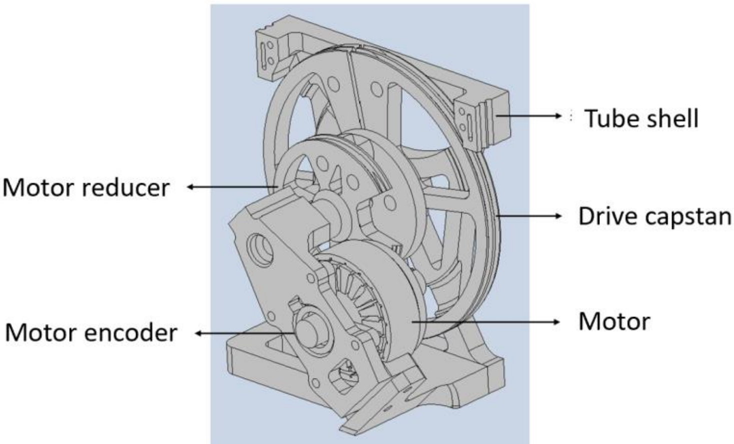

Fig 3 CAD drawing of the fixed motor base

B. Rotation clutch

The diameter of a common acupuncture needle ranges from 1mm to 3mm. Smaller diameter means users' fingertip skin is easier to deform when twisting the needle. As a result, rotation friction is easier to be perceived by users. To reduce the free rotation friction, a clutch mechanism is developed to disconnect the needle when there's no feedback torque, shown in Fig4. The clutch consists of 3 pairs of symmetrical claws parallel linked to a central platform. When the central platform is actuated, claws retract inward to lock a high friction output shaft, which connects directly to the needle. Under retract state, the clutch is able to bypass torque up to 0.4 Nm.

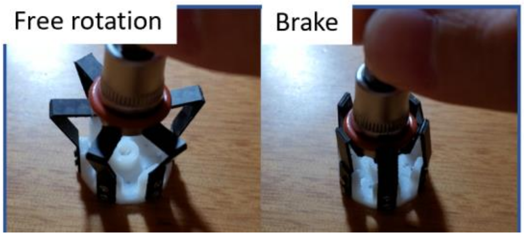

Fig 4 The clutch

Since the clutch is mounted on the tip, an origami-inspired design is adapted to reduce the mechanism's weight. The finished structure weights only 2.1g, shown in Fig 5.

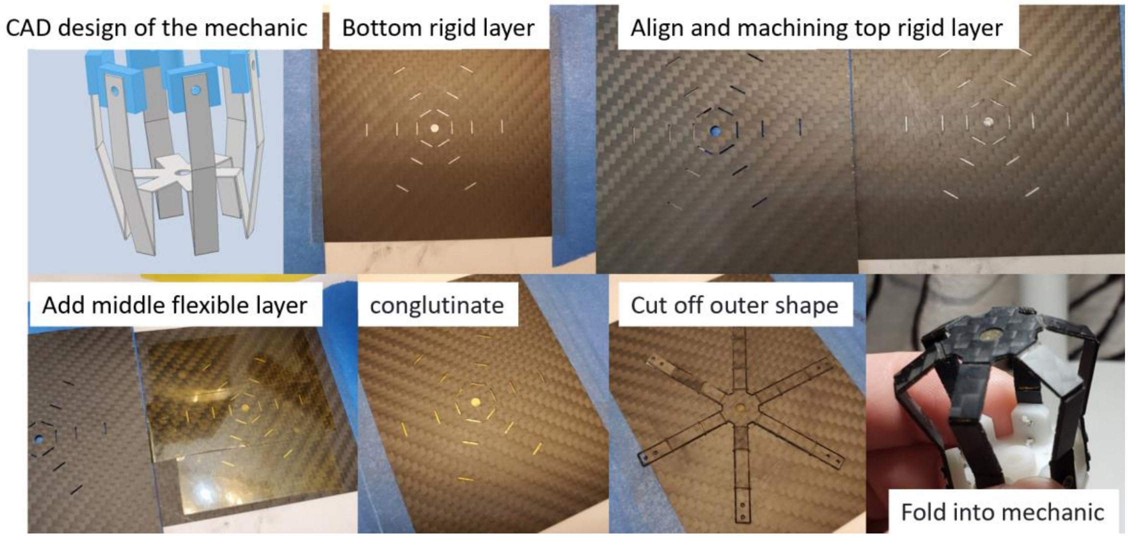

Fig 5 Manufacture process of the clutch

C. Actuation motor

Actuation motor is the defining factor of haptic systems' performance. Most existing applicants use coreless DC motors with planetary gear reducer. However, geared reducer would introduce unwanted friction to the system. The actuators used in this project are 1613 BLDC motors with a KV value of 130, which provides continuous torque up to 0.08Nm under direct drive configuration. Although this torque is lower compared to most geared coreless motors, they're adequate for generating rotation feedback with small diameter needles. Also, the output torque of the BLDC motor has a good linear relationship with the phase current. This enables precise close-loop torque control with current sensing embedded in the controller. Fig 6 shows the motor used in this project.

Fig 6 Motor module

D. Encoder

In acupuncture simulations, the needle's position and velocity must be precisely measured in order to calculate simulated feedback torque. Both tip's rotation shaft and actuator motor are equipped with magnetic encoders shown in Fig 7. Encoders are AMS5600 from austriamicrosystems AG with a resolution up to 0.088°.

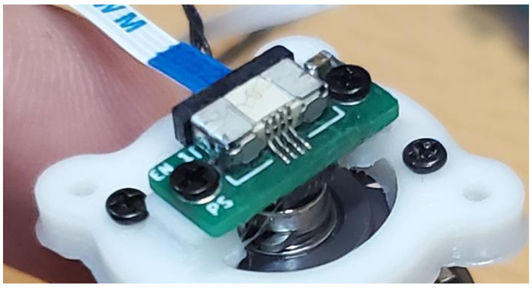

Fig 7 Encoder

E. Controller

A customed controller board is designed as shown in Fig 8. The board contains 2 BLDC motor drivers with phase current sampling, 2 IIC ports to read encoders, and a CAN bus to communicate with the host computer. A dedicated control loop running at 1.5kHz sends measured needle position and velocity to the simulation, then receives calculated feedback torque to actuate the clutch and needle.

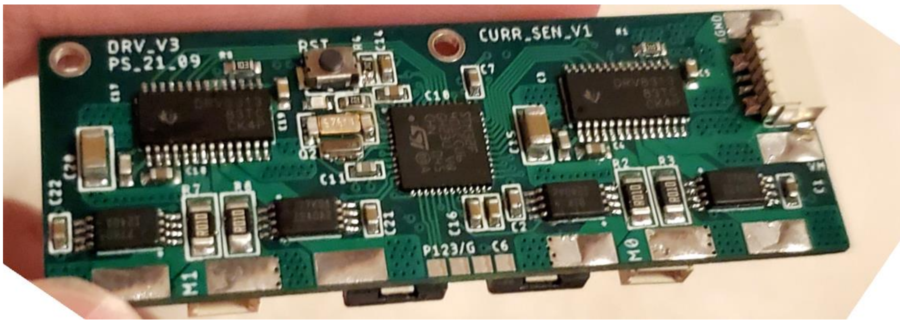

Fig 8 Controller

F. Feedback torque algorithm

With the pose of tip, the insertion depth of virtual needle in tissue can be obtained, shown in Fig 9.

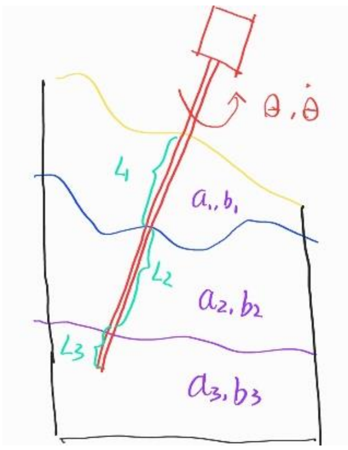

Fig 9 Virtual needle inserted in tissue

The target feedback torque can then be calculated by the following algorithm.

$$\tau = \sum (a_i \cdot \theta + b_i \cdot \dot{\theta}) \cdot L_i$$

Where τ is the calculated feedback torque, a_i is virtual tissue's elastic coefficient, b_i is virtual tissue's damping coefficient, θ is needle's position, and $\dot{\theta}$ is needle's velocity. L_i are needle's stagnations in each layers of tissue. By tuning a_i and b_i, it should be possible to simulate the general texture of different tissues, such as skin, muscle, etc.

3. Preliminary evaluation of the system

An experiment has been designed to test the tip's torque feedback capability. During the experiment, the tip is controlled to render a 0.02Nm step and sine torque output. Torque is measured by a torque sensor shown in Fig 10.

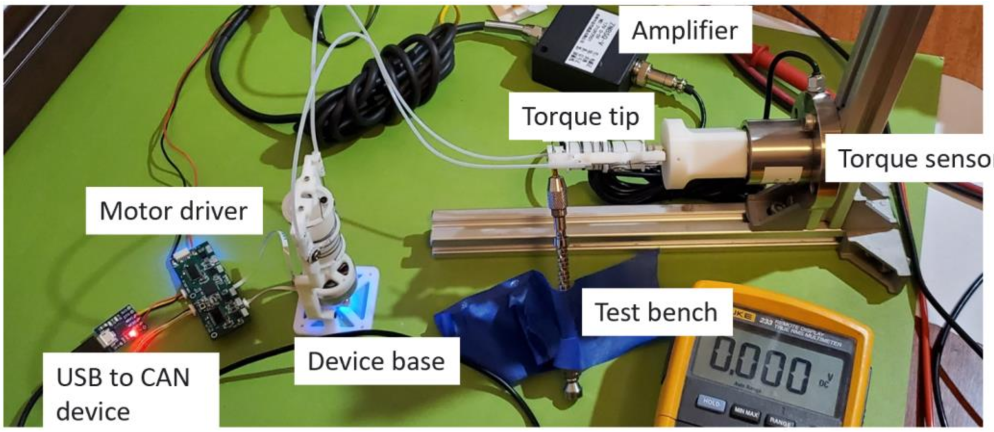

Fig 10 Test bench setup

The measured result is shown in Fig 11. From the plot, it can be seen that the output torque is basically useable. The noise on the signal can be improved via fine-tuning of the motor controller's paraments.

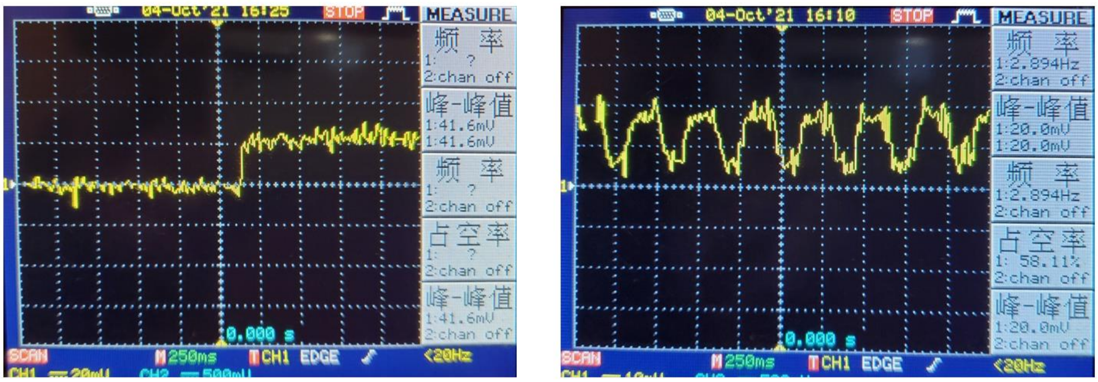

Fig 11 0.02Nm step output and sine output

4. Conclusion

This report presented the development of a lightweight, highly backdrivable torque feedback tip for virtual acupuncture training. The proposed design includes a flex transmission system that minimizes tip's weight and an origami-inspired clutch to reduce free rotation friction. At the same time, a compact controller is developed to control BLDC actuation motors. With a designed evaluation, the system is able to deliver desired feedback torque calculated by the host computer.

The future work will concentrate on the feedback control of the clutch mechanism through a new design with a pressure sensor. This will allow applications where controllable dumping modules are needed.

References

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[4] Karbasizadeh, N., Zarei, M., Aflakian, A., Masouleh, M. T., & Kalhor, A. (2018). Experimental dynamic identification and model feed-forward control of Novint Falcon haptic device. *Mechatronics*, *51*, 19-30.