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CIS II Paper Review

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Introduction:

Over the past twenty years, we have seen steady adoption of robotic systems in the surgical theater. Surgical robotic systems promise to be less invasive, augment the surgeon, decrease recovery time, and improve patient outcomes. Microsurgery is one of the frontiers in surgical robotics. In microscale manipulation, muscle tremor, jerk, overshoot, motion accuracy, and position drift are significant factors in task performance. In the context of inner ear, middle ear, and skull-base surgery, the standard approach is through the temporal bone. Surrounding the temporal bone are an assortment of sensitive and critical anatomy - veins, arteries, nerves, brain tissue, and spinal cord.

There is significant reason to believe that a force-sensing surgical tool opens the door to new advancements in haptic feedback, virtual fixtures, and admittance control. This review paper explores prior work to develop force sensing drills for various surgical applications and discusses development and improvement areas.

Pneumatic Sensing System

In 2020, Gaudeni et al. proposed a tool for hand-held drills composed of a pneumatic force sensing cover and a haptic display for force feedback. The paper asserts that 3-axis force sensors are bulky and not suitable for small devices. By using a pneumatic system with pipes and air pressure sensors, the sensory information can be transferred outside of the operational workspace. The pneumatic system employs a two concentric cylindrical shell structure with a gap for the gas and pipes. The inner shell is rigidly fixed to the drill, and the outer shell is held by the surgeon. In between the shells are gas pipes. These pipes prevent relative motion between the outer shell and the drill when no external forces are applied to the drill.

When the drill bit contacts the environment, the axes of the inner and outer shell become non-parallel. The relative change in position of the outer and inner shell creates an expansion or compression of the underlying gas pipes. The change in pressure is sensed by an air pressure sensor located outside of the operational work zone.

Talk about results of their experiments.

Critiques: they ignored torque, so for any deep drilling, the readouts may be inaccurate.

Using ATI 43 Nano

In 2017, Sang et al. published a feasibility study on a force sensing drilling instrument for robotically assisted otologic surgery using the ATI Nano 43 and da Vinci Research Kit.

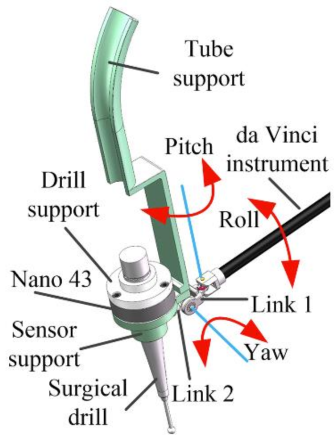

Figure 1: 3DOF tendon-driven surgical instrument

Because this is a teleoperated leader-follower system, DH parameters, kinematics, tooltip-offset transform matrix, and coupling matrices of the instrument is calculated. The paper goes into depth how the force feedback is incorporated into the leader-follower control system. In short, the force feedback is implemented through the joint torques using the transpose of the Jacobian matrix.

One aspect they pointed out which is also relevant to our project is to account for the noncontact forces caused by gravitational and inertial effects. The total force and torque readings by the sensor is a sum of the forces and torques imposed by the environment, gravity, inertia, and bias. To make this calculation easier for our project, it may be a good idea to design the device such that the center of mass of the system is coincident with the center of mass of the ATI F/T sensor in all three dimensions.

$$\begin{bmatrix} \mathbf{F}_S \\ \tau_S \end{bmatrix} = \begin{bmatrix} \mathbf{F}_E \\ \tau_E \end{bmatrix} + \begin{bmatrix} \mathbf{F}_G \\ \tau_G \end{bmatrix} + \begin{bmatrix} \mathbf{F}_I \\ \tau_I \end{bmatrix} + \begin{bmatrix} \mathbf{F}_O \\ \tau_O \end{bmatrix}$$

Figure 2: Force and Torque measured by F/T sensor is a summation of F/T from environment, gravity, inertia, and bias.

The results of this paper lay a solid foundation to implement an ATI Nano 43 F/T sensor onto a surgical drilling instrument. Many of the challenges associated with measuring and processing force-sensing were discussed, and we look forward to building upon this work to design a force-sensing drill attachment for a cooperative controlled surgical robot and for free-hand use.

Using Deformation Elements and Strain Gauges

In 2013, Hessinger et al proposed a handheld surgical drill with integrated force recognition. By monitoring thrust force between the drill motor and casing, one can monitor the depth of the drill in the bone to prevent aggressive breakthrough. For some reason, they neglect transverse forces, and decided to only measure the axial thrust force. A deformation element is positioned right behind the drill casing. Active infrared optical markers are positioned on the proximal end of the drill to enable real-time pose estimation.

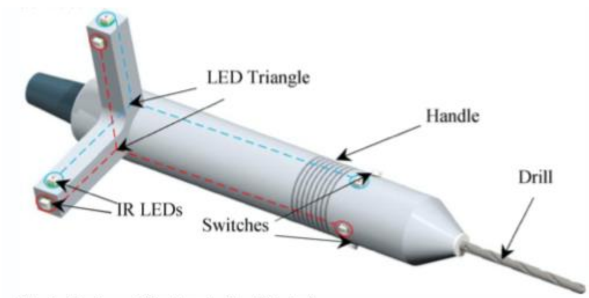

Fig 1. Design of the handheld drill device

To test this device, they drilled several holes into a test specimen consisting of 2x 5mm thick plywood which sandwich a 27mm thick polystyrene. This test specimen is intended to simulate hard and soft bone. I am not sure if there are/were any future work plans to achieve 3-axis sensing. For a concept to successfully achieve clinical translation, I believe it must have 3-axis sensing. A significant majority of bone drilling during otologic surgery is done with the drill at an angle to the drilling surface. The only time when a surgeon would drill perpendicular is if they are making a deep ream, but even so, without the ability to sense torques which cause a moment about the axis of the drill, this concept would fail to capture accurate force data.

This paper also raises the issue of hysteresis during force readings. When the thrust forces exceeded a nominal value of 14 Newtons, the friction between the bearing and brass casings cause hysteresis error.

Conclusions

A force sensing drill has potential to be commercially viable. Building off existing literature and patents, we will apply the learnings to further our goal of developing such a device. For now, it is promising to pursue a design which incorporates an ATI Nano 43 F/T sensor. Further work can be done to select more precise and/or less bulk and/or more economical methods to enable force sensing capabilities.