Friction-Based Robotic Driver for Programmable Bevel-Tip Needles

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Friction Based Robotic Driver for Programmable Bevel-tip Needles

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INTRODUCTION

Minimally Invasive Surgery (MIS) has advanced in the last two decades due to its benefits, such as shorter hospitalization, reduced tissue trauma, and quicker recovery times [1], [2]. Neurosurgical MIS procedures such as biopsies, ablations, and fluid delivery/extraction often use straight catheters. The efficacy of these procedures depends on precise surgical area targeting and avoiding harm to surrounding tissues. Repeated instrument retraction and reinsertion can cause more tissue damage, making the procedure challenging [3].

Robotic steerable needles have become increasingly popular because they can overcome the limitations caused by operator error or catheter deflection [4] and can provide access to complex anatomical features that were previously difficult to target. Development of our robotic platform for precision neurosurgery, EDEN2020 (see Fig. 1), aimed to assess the potential of Convection Enhanced Delivery of chemotherapeutics along preferential pathways that align with anisotropic brain structures [5]. The system's architecture and surgical workflow were tested in pre-clinical trials using the ovine model. The implantation was safe and demonstrated appropriate function [5].

The robotic platform uses bio-inspired steerable Programmable Bevel-tip Needles (PBN) with an outer diameter of 2.5mm. We have been working on reducing the size of PBNs using advanced thermal drawing technology. This allows us to create significantly smaller catheters, with a 1 - 1.3mm diameter, compared to traditional ones. These smaller needles lead to more precise and effective catheters [6], but pose important challenges with actuation, owning to the tiny joining surfaces involved.

In the current ecosystem, lead screw mechanisms are utilized to drive each needle segment. These mechanisms are attached to wing-like structures on the surface of the segments. In a surgical setting, the PBN must be positioned close to the patient skull. However, due to size and weight limitations, the large volume and high weight of the lead screw design require the actuator to be located at the base of the robot, with flexible transmission links used to transfer the motions to the needle segments. To overcome this challenge, an alternative solution based on friction and a gear-like assembly, used to maximise the transfer of contact forces, is proposed here, to achieve a lighter and more portable drive system, suitable for our new generation of small-sized PBNs. As slip is an important consideration when employing friction to create motion, a criterion for measuring and quantifying slip, which we then utilize to investigate different designs for the needle and gears.

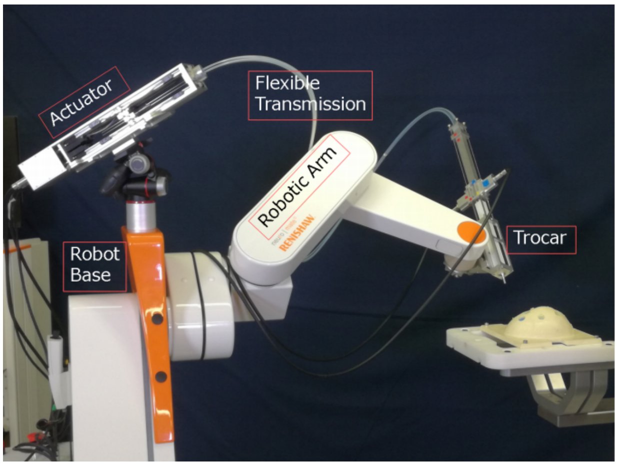

Fig. 1 EDEN2020 robotic system [5]

MATERIALS AND METHODS

The new concept operates based on the interaction between geared wheels and PBN segments. The motors drive the geared wheels, which engage with the teeth on the PBN segments. This process aims to convert rotational motion into linear movement, which propels the needle segments forward.

We created a test rig for 2-segment catheters to assess the performance of the gear-driven mechanism. The catheter segments were made using thermal drawing with polycarbonate material, and the segment surface was modified using a femtosecond laser (Monaco 517 Laser, Optec) to align with the gear teeth to ensure compatibility with the driving mechanism and allow for precise integration.

The test rig, featuring a 3D-printed base and motor platforms, holds needle segments precisely using a central boss to align segments on the insertion axis. Coreless DC Motors (Dynamixel XC330), coupled with x-axis linear stages (SEMX60-AC), adjust the force for optimal needle engagement, as detailed in Fig. 2. The outer layer of the gears employs a mixture of polymer-based Agilus30 - Verowhite materials (Objet Inc.), which emulates the different stiffness properties of rubber to maintain an adequate grip between the gear and the needle.

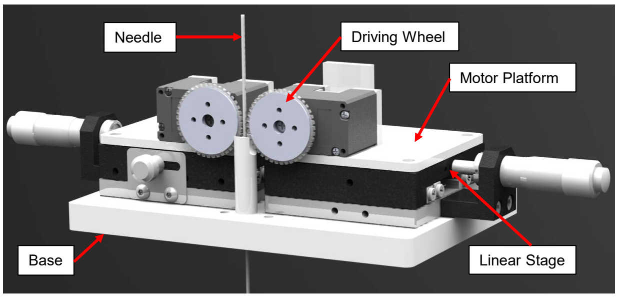

Fig. 2 The CAD Design of the Developed Test Rig

The study employed a video analysis technique to assess potential slippage between the segments and gears. Utilizing a high-resolution camera (Nikon D500, 2K resolution,30 FPS) equipped with a macro lens, detailed observations were made at the contact interface between the needle and the gears. The linear displacement of the needle was measured and compared to the expected linear displacement obtained from the recorded angle of motor rotation. A custom Python script was developed to facilitate this analysis, enabling precise measurement of the needle's linear displacement from the video data. Fig. 3 shows the video analysis setup, with the camera view on the bottom left.

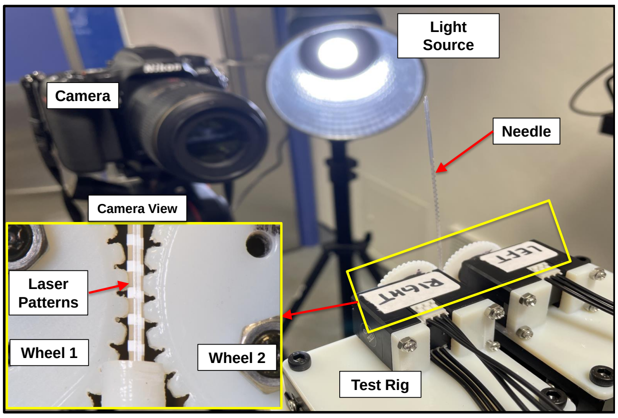

Fig. 3 Video Analysis Setup and Camera view

The video analysis starts with the frame smoothing process to reduce noise. Then, a binary threshold is applied to isolate the edges of the needle teeth. A small region of interest on the needle teeth is analyzed by extracting teeth positions into a binary array using the frame produced in the previous step. Needle movement is quantified by comparing sequential image frames and calculating linear displacement in pixels, which can be converted to millimetres to obtain a final measurement. When measuring the occurrence of slip, we introduce the slip ratio criterion:

$$\text{Slip Ratio} = \frac{\text{Actual Needle Linear Displacement}}{\text{Expected Needle Linear Displacement}}$$

The expected displacement was 10mm and was inputted into the motor through the required angle of rotation. The actual displacement of the needle was determined through the video analysis method described earlier. By doing so, we can determine how much the needle has moved compared to what was expected. The slip ratio is an essential tool in quantifying the extent of slip, with a higher ratio indicating that less slip has occurred.

RESULTS

In the experiments using the custom-designed test rig, the focus was on assessing how changes in the hardness of the gear teeth affected performance. Various material blends were tested, ranging from rubber-like softness to much harder composites. Results indicated that gears from softer materials ranged from 100% to 60% soft material and had poorer engagement with the needle. The gear often slipped completely and failed to convert rotational motion into linear needle movement. However, gears that were too hard (0% to 20% soft) had a smooth and slippery surface. This resulted in large amounts of slip between the needle and the gear. A near-optimal combination of 60% hard and 40% soft was found through iterative testing of different material compositions. The gear was tested under varying normal forces by adjusting its position on the x-axis of the linear stages. The peak slip ratio of 0.92 was observed at an x-axis position of 5.8 mm, indicating a significant reduction in slip. An optimal normal force was identified to be between 5.7 to 5.8 mm on the linear stage, where the slip ratio was stable at around 0.85.

DISCUSSION

The results of our experiments have revealed that our new concept holds the potential to miniaturize the driving mechanism. However, we have identified slipping issues that must be addressed to realise this new concept's potential fully. Hence, we plan to conduct a more extensive study to consider different teeth profiles and the size of teeth on the needle and the wheels, likely in combination with optical sensing of the segments to detect (and compensate for) any residual slip. We will also enhance the data processing method to enable real-time analysis and plan to develop a low-level controller that will allow us to deploy the new system in needle steering applications. Finally, our goal is to expand the setup to four segments to evaluate the effectiveness of our concept in 3D.

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