ICRA2026 Late Breaking Results Poster presented at
2026 IEEE International Conference on Robotics and Automation (ICRA 2026)
June 1-5, 2026. Vienna, Austria

Cable-Driven Parallel Robot-Based Needle Steering for Imaging-Compatible Interventional Procedures

Seongho Son and Ayoung Hong

***Abstract*— Accurate needle steering using bevel-tip needles remains challenging due to nonlinear needle–tissue interactions and structural limitations of conventional robotic insertion systems in imaging-guided environments. This paper presents a cable-driven parallel robot (CDPR)-based needle steering framework that enables curvature-induced steering through coordinated control of the needle base pose. The proposed system provides 6-DoF needle orientation control using eight cables and an additional Bowden cable mechanism for axial rotation. Phantom insertion experiments demonstrate that steering direction can be regulated by bevel-tip orientation and that obstacle-avoidance insertion toward a desired target location is achievable. These results confirm the feasibility of CDPR-based needle steering for imaging-compatible minimally invasive intervention scenarios.**

I. Introduction

Bevel-tip needles naturally follow curved trajectories inside soft tissue due to their asymmetric tip geometry, enabling needle steering for improved targeting in minimally invasive procedures [1]. However, precise control of the insertion direction remains challenging due to nonlinear needle–tissue interactions. Existing robotic needle steering approaches typically rely on rigid-link serial manipulators or base-rotation strategies to control needle orientation during insertion [2].

Despite these advances, conventional steering platforms present structural limitations in imaging-guided intervention environments. Rigid-link robotic systems are often bulky and may interfere with the insertion region, while compatibility with X-ray–based imaging modalities such as fluoroscopy remains limited due to dense mechanical structures near the workspace. Base rotation methods provide simpler implementation but restrict the generation of flexible insertion directions. These limitations motivate the need for an alternative needle steering platform that is both compact and imaging-compatible.

To address this challenge, this paper proposes a cable-driven parallel robot (CDPR)-based needle steering framework for bevel-tip needle insertion. The proposed system enables remote cable actuation to minimize mechanical interference near the insertion region while maintaining compatibility with fluoroscopic imaging environments. This work demonstrates the human-in-the-loop execution of bevel-tip needle steering using a CDPR platform and validates its feasibility through phantom insertion experiments.

This work was supported by the Technology Innovation Program (20023168, Development of clinician collaborative robot platform technology for 3 types of pain interventional procedures based on crossdrug handler and instrument modules) funded by the Ministry of Trade, Industry & Energy(MOTIE, Korea).

Seongho Son and Ayoung Hong are with the Department of Mechanical Engineering, Chonnam National University, Gwangju 61186, Republic of Korea, ahong@jnu.ac.kr

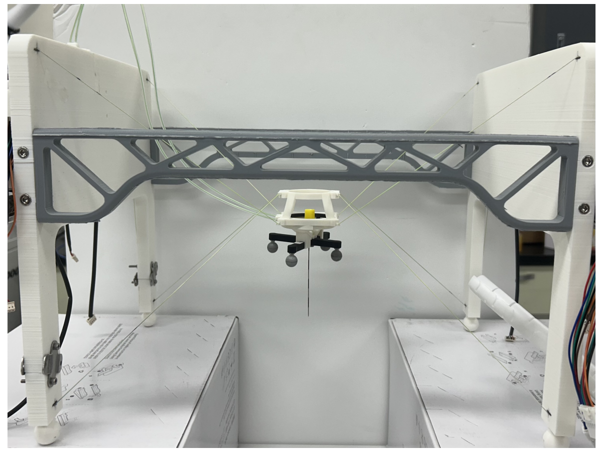

Fig. 1. Overall configuration of the proposed CDPR used for needle steering. The needle orientation is controlled through coordinated cable actuation of the end-effector.

II. CDPR-Based Needle Steering Framework

A. System Architecture

Figure 1 shows the overall configuration of the proposed CDPR-based needle steering system. The system uses eight cables to regulate the position and orientation of the end-effector. Since the cable-driven structure provides only limited rolling motion of the end-effector, an additional Bowden cable mechanism is incorporated to generate rotational motion about the needle axis, enabling full 6-DoF pose control. A needle holder is mounted on the end-effector, allowing coordinated cable actuation to control the base position and orientation of the needle during insertion. Curvature-based steering of the bevel-tip needle is achieved by regulating the base pose of the needle rather than directly actuating the needle tip. Furthermore, the remote actuation capability of the CDPR minimizes mechanical interference near the insertion region, making the system suitable for imaging-guided intervention environments such as fluoroscopy.

B. Steering Principle Using a Bevel-Tip Needle

A bevel-tip needle follows a curved trajectory inside soft tissue due to asymmetric interaction forces generated at the needle tip. This motion can be approximated using a constant-curvature model defined as

$$\kappa = \frac{1}{R} \tag{1}$$

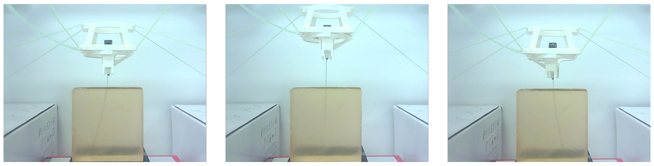

Fig. 2. Insertion trajectories under different bevel-tip orientations and axial rotation conditions. The needle bends toward the bevel direction without rotation, while continuous axial rotation reduces curvature and produces an approximately straight trajectory.

where κ denotes the curvature of the needle path and R represents the radius of curvature. For an insertion step length Δs, the needle configuration can be propagated as

$$\begin{aligned} x_{k+1} &= x_k + \Delta s \cos\theta_k \\ y_{k+1} &= y_k + \Delta s \sin\theta_k \\ \theta_{k+1} &= \theta_k + \kappa \Delta s \end{aligned} \tag{2}$$

Rotation of the needle base plays an important role in determining the steering direction. When the needle rotates with angular velocity ω during insertion, the effective curvature decreases due to curvature-averaging effects, while the steering direction is determined by the base orientation. Therefore, curvature-induced steering can be achieved by controlling the base pose of the needle. In this work, coordinated actuation of the CDPR end-effector is used to regulate the needle's base orientation and generate the desired steering motion.

III. Experimental Validation

A. Experimental Setup

Phantom insertion experiments were conducted to evaluate the steering capability of the proposed CDPR-based needle steering system. A gelatin phantom was used to observe curvature-induced needle motion under controlled base pose variations. The orientation of the needle base was regulated through coordinated actuation of the CDPR end-effector during insertion. Two types of experiments were performed. First, the influence of bevel-tip direction and axial rotation on the insertion trajectory was investigated, as shown in Fig. 2. Second, human-in-the-loop experiments were conducted to validate the feasibility of the system to guide the needle to a desired target location while avoiding obstacles inside the phantom, as illustrated in Fig. 3.

B. Results

In the first experiment, insertion trajectories were observed under different bevel-tip orientations with and without axial rotation of the needle. As shown in Fig. 2, the needle trajectory bends toward the bevel-tip direction when no axial rotation is applied. In contrast, when continuous axial rotation is introduced during insertion, the curvature effect is reduced and the trajectory becomes approximately straight. These observations confirm that curvature-induced steering can be controlled through regulation of the needle base orientation.

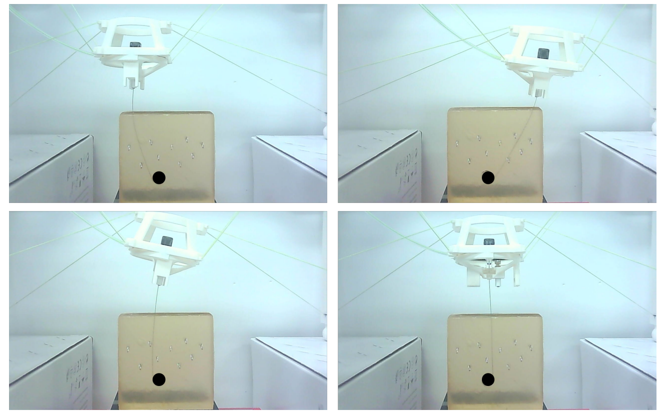

Fig. 3. Obstacle avoidance needle steering experiment inside a gelatin phantom. The needle follows a curved trajectory that avoids obstacles and reaches the target location through coordinated base pose control using the CDPR system.

In the second experiment, obstacle avoidance steering was performed inside the gelatin phantom. As illustrated in Fig. 3, the needle was guided along a curved path that avoided obstacles and reached the desired target location by adjusting the orientation of the CDPR end-effector during insertion. Repeated insertion trials demonstrated that the proposed system enables consistent steering behavior in constrained environments.

C. Discussion

The experimental results demonstrate that the proposed CDPR-based system can effectively control curvature-induced motion of a bevel-tip needle through base pose regulation. In particular, the steering direction was successfully adjusted according to bevel orientation (Fig. 2), and obstacle avoidance insertion toward a target location was achieved without additional sensing at the needle tip (Fig. 3). These results indicate that the proposed platform provides a feasible solution for needle steering in imaging-guided minimally invasive intervention environments.

IV. Conclusion

This paper presented a CDPR-based needle steering framework for bevel-tip needle insertion in imaging-compatible intervention environments. Phantom insertion experiments verified that curvature-induced steering can be controlled through base pose regulation and that obstacle avoidance insertion toward a desired target location is achievable. These results demonstrate the feasibility of the proposed platform for needle steering in constrained intervention scenarios. Future work will focus on image-guided closed-loop steering control and quantitative trajectory tracking accuracy analysis.

References

[1] R. J. Webster, J. M. Romano, and N. J. Cowan, "Mechanics of precurved-tube continuum robots," *IEEE Transactions on Robotics*, vol. 25, no. 1, pp. 67–78, 2009.

[2] R. Alterovitz, K. Goldberg, and A. M. Okamura, "Motion planning under uncertainty for image-guided medical needle steering," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2005, pp. 120–125.