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Simulative analysis of interlocking polygonal concentric tube robots during rotation

J. Mayer[1*], J. Rittelmann[1] and P. P. Pott[1]

[1] *Institute of Medical Device Technology, University of Stuttgart, Stuttgart, Germany*
[*] *Corresponding author, email: juliane.mayer@imt.uni-stuttgart.de*

Concentric tube robots with non-circular, e.g., octagonal, cross-sections can lock relative tube orientation, suppressing inadvertent rotation. This study uses finite element analysis of a two-tube CTR to assess how geometric and material parameters affect the propagation of discrete 45° rotation steps from base to tip. Torsional twist causes tip lag during surface contact, which is fully released once contact ends for short CTR, enabling rapid transition to the next interlocked configuration. Clearance and friction strongly influence threshold torque and tip lag, while tube length limits step propagation. The analysis confirms the feasibility of short shape-interlocked CTR, e.g. as active cannulas.

I. Introduction

Concentric tube robots (CTR), including so-called active cannulas, consist of multiple thin, elastic tubes nested within each other. The robot shape is controlled solely through rotation and translation at the tube bases, which enables compact diameters, e.g. for actuating surgical instruments. CTR are known to exhibit regions of elastic instability where small changes in base rotation cause large tip deflections, usually referred to as snapping [1].

Although tubes are commonly circular, some literature proposes non-circular cross-sections to lock the relative tube orientation during operation and to suppress inadvertent rotation or snapping: Patents describe active cannulas with polygonal cross-sections [2, 3], and one study suggests an elliptical shape [4]. Prior work addressed octagonal CTR as well as CTR equipped with magnetic guides for intentional discrete rotation steps and a threshold torque to transition between configurations, thereby selectively suppressing unintended rotation [5, 6]. These studies confirm the presence of discrete configurations but also report increased torsional twist compared to conventional CTR.

This work aims to determine the general potential of this approach through a finite element (FE) analysis of a two-tube CTR with varying geometric and material parameters. The goal is to identify parameter sets that allow propagation of a discrete rotation step of 360°/8 = 45° from the base to the tip of an octagonal tube pair. The resulting threshold torque and the influence of the parameters are assessed.

II. Material and methods

Assuming that most torsional twist in a CTR arises in the straight transmission section [1], a straight two-tube system was modeled in ANSYS R1 2020 (Ansys Inc., Canonsburg, PA, US). The model comprised an inner tube with an octagonal exterior and an outer tube with a matching interior. A static analysis was performed, accounting for large, nonlinear deflections. The outer tube was constrained by a

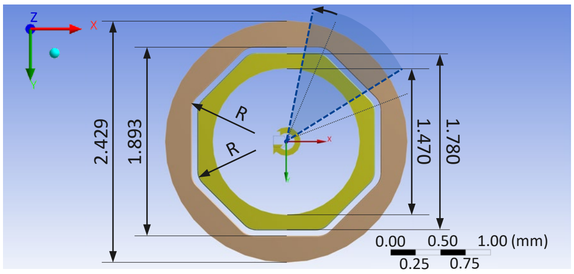

Figure 1: Cross-section of modeled CTR tube pair. The fillet radius R is varied during the parameter study. The dashed blue lines indicate the rotational symmetric cyclic region, which spans 45° and is rotated by 11.25° relative to the corners.

fixed support at the base, while the inner tube base angle was increased from 0° to 45° about the z-axis, with all other degrees of freedom constrained. To reduce computation time, the rotational symmetry of the system was exploited by defining a cyclic region so that only one eighth of the CTR cross-section required modeling. To avoid artificial stress concentrations in regions of interest, i.e. the octagon vertices and the contact area, the cutout was rotated by 45°/4 = 11.25° relative to the corners, as indicated in Fig. 1.

The tubes were assigned polyamide 6.6, consistent with other work [5, 7, 8]. Despite its higher torsional stiffness and although common in CTR, Nitinol was not considered suitable because shaping to a polygonal cross-section would be too costly and difficult. A tetrahedral mesh was applied and manually refined in regions of contact or high stress until mesh convergence was achieved, with element sizes of 0.02 – 0.04 mm in fillets, corners, and contact areas, and up to 0.2 mm elsewhere. Convergence of inner tube stress was achieved by excluding the initial 0.2 mm near the fixed-support boundary condition to remove artefacts from contact. Stress results elsewhere were unaffected. The tube geometry was selected in reference to a prototype by Webster et al. [1], given in Table 1. Starting from the initial configuration, one parameter at a time was varied, and a 45° inner tube rotation was simulated.

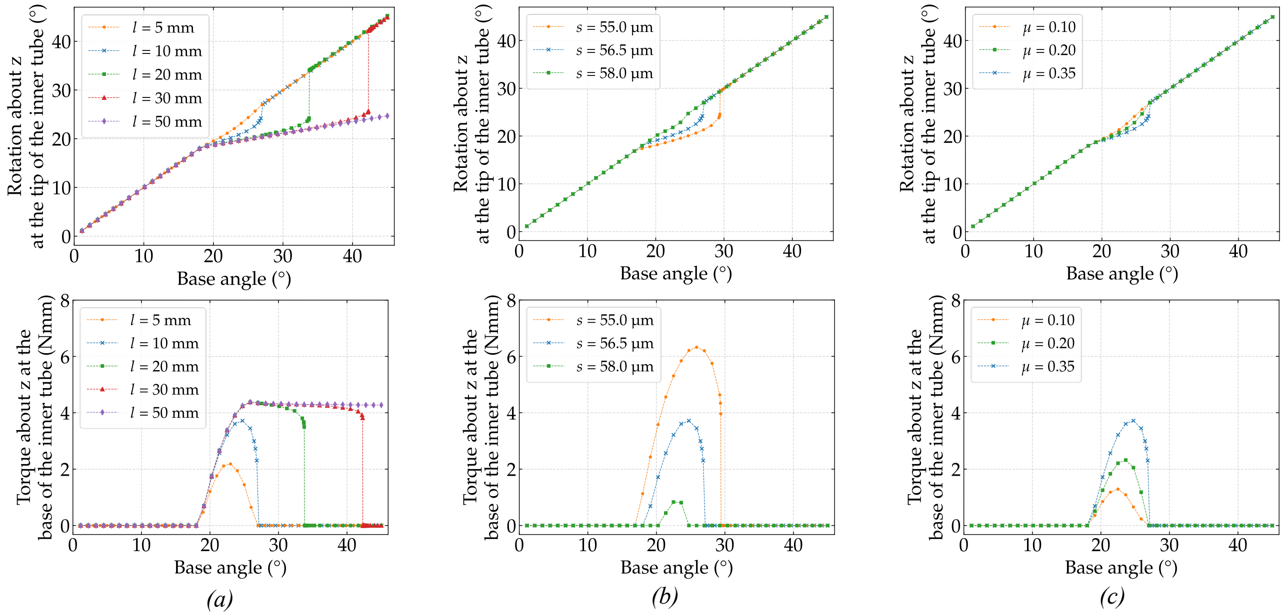

Figure 2: Blue line in all diagrams equals the initial configuration. (a) Variation of CTR length l. (b) Variation of clearance s. Similar behavior was observed for variation of fillet radius R. (c) Variation of friction coefficient µ.

Table 1: Initial values and variations for parameter study.

Parameter	Initial value	Modified values	Unit
Tube length l	10	5, 20, 30, 50, 100	mm
Tube clearance s	56.5	55.0, 58.0	µm
Fillet radius R	0.18	0.15, 0.20	mm
Friction coefficient μ	0.35	0.10, 0.20	-

III. Results and discussion

Fig. 2 shows the z-axis rotation of the inner tube tip for parameters l, s, and μ when rotating the base up to 45°, together with the corresponding base moment. Varying R produces effects comparable to changes in s, and the resulting curves are therefore omitted.

For the initial configuration, surface contact occurs between 18.00° and 26.83° base angle. During this interval, the inner tube tip lags behind due to torsional twist, leading to an increase in stored strain energy. Once contact ends, the stored strain energy and therefore the twist are fully released, and the tip rapidly transitions to the next interlocked configuration. The outer tube is slightly dragged during contact and undergoes minor reversible rotation due to friction. Both was visible in the graphical representation of the deformation field. As the CTR returns to its initial state after the 45° step, subsequent steps can be expected to behave similarly.

All selected values of s, R and μ permit full 45° steps, but this does not hold for lengths $l \geq 50$ mm where the torsional twist is not released within 45° base rotation, and the next interlocked configuration cannot be reached. This agrees with prior observations where increased transmission lengths (even if related to the corresponding diameter) caused the inner tube to "get stuck" [5]. Tube clearance strongly affects the geometric extent of the contact phase and the threshold torque. Lower friction reduces both the torque threshold and the tip lag but does not influence the extent of contact.

IV. Conclusions

With successful propagation of stepwise rotation in short tubes, the concept of shape-interlocked CTR appears most suitable for active cannulas, which typically employ a straight outer tube and a curved inner tube with short transmission lengths. Based on the identified influence of geometry and material, future work will focus on targeted selection of clearance and friction to achieve the desired torque threshold while limiting transient torsional twist. Polyamide tubes can also be manufactured with more edges, providing finer step resolution. The FE analysis confirms the potential of shape-interlocking if suitable parameters are chosen and could be extended to include tool-tissue contact. This approach may suppress unintended rotation and snapping to improve active cannula positioning.

Author's Statement

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