Design of a Modular, Multi-Arm Concentric Tube Robot Featuring Roller Gears

Adrian N. Florea[a], Dominick S. Ropella[a], Ernar Amanov[a], S. Duke Herrell III[b,c], and Robert J. Webster III[a,b,c]

[a]Department of Mechanical Engineering, Vanderbilt University
[b]Department of Urology, Vanderbilt University Medical Center
[c]Vanderbilt University Institute for Surgery and Engineering

1. MOTIVATION

Concentric tube robots (CTRs) have been explored for a variety of surgical applications in confined and narrow spaces in the human body[1] due to their miniaturization potential (can be constructed at submilimeter diameters; typically in the 1-2mm range) and enhanced dexterity in comparison to straight rigid tools. They can be used as needles[2,3] or manipulators[4,5] and can be packaged into hand-held systems.[6,7]

In the design of actuation systems for CTRs, the roller gear has been suggested as a way to transmit both axial rotation and linear motion to a tube of a CTR.[8] Yet to date, this idea has only been applied to single-arm systems. Multi-arm systems are capable of more complex procedures where multiple tools are required simultaneously[6,9,10,13] and facilitate tool changes.[7] In this paper, we explore making a multi-arm robot that utilizes roller gears. The result is a compact, modular, multi-arm concentric tube robot system.

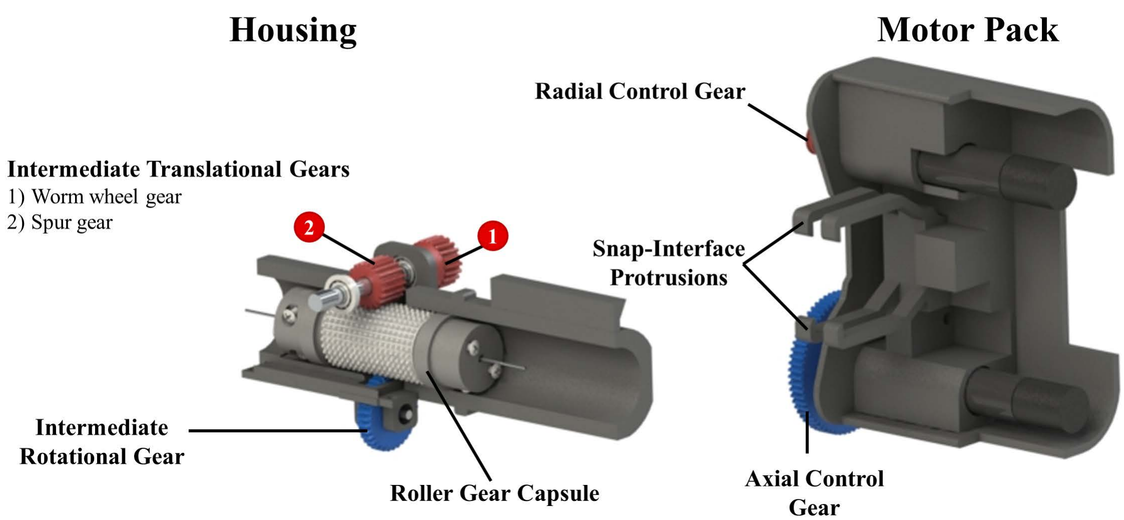

Figure 1. Proposed design showing the roller gear module, motor pack module, and housing module with chosen gear parameters.

1.1 Contributions

The primary contribution of this work is to present the design of a modular, multi-arm CTR actuation unit that facilitates use of two manipulators, created by leveraging the roller gear concept. The system (see Figures 3 and 4) features reusable motor packs, as shown in Figure 1. A useful feature of this design is a non-destructive reversible method of grasping and releasing each tube, using compressed o-rings. A brief preliminary description of a single arm of this design appeared previously in conference abstract form.[14] Here, we extend the concepts

Further author information: (Send correspondence to A.N.F.)
A.N.F.: E-mail: adrian.florea@vanderbilt.edu, Telephone: 1 773 573 3713

introduced there into a multi-arm system and perform new experiments assessing the accuracy of the system and its ability to facilitate ring transfer with two manipulators.

2. MECHANICAL DESIGN AND METHODS

We aim to create a modular transmission which actuates two degrees of freedom (DoF) for a single tube in a concentric tube robot; axial rotation and linear travel along the tube's axis. This transmission can be reversibly attached/detached to a reusable motor pack. Copies of this transmission and motor pack can actuate each tube in a given concentric tube robot. A single unit of this design is described further below.

2.1 Roller Gear Capsule

Given our design objectives, the roller gear concept is a mechanical transmission that enables motion in 2 DoF for CTRs. This roller gear is a cylinder patterned with spur gear profiles both linearly and angularly. Gears arranged axially and radially can interface with teeth on the roller gear to transmit both desired DoF. To enable a smooth, gliding interface with the transmission, caps are attached to the roller gear. Clamps are located at end of the caps and ensure a rigid attachment of each tube. The assembly of the roller gear, caps, clamps, and tube is considered the roller gear capsule and the assembled state is illustrated in Figure 2. Grasping each tube is challenging due the loads applied by the enviroment as well as the loads tubes apply to one another as the robot moves. Our o-rings grasping system provides a non-destructive, reversible way to grasp tubes. When the o-rings are compressed radially inwards, a large frictional force prevents the tube from slipping. The clamps load a tube through 3 o-rings and the radial force is applied from bolts tightened onto the side of the clamps (see Figure 2).

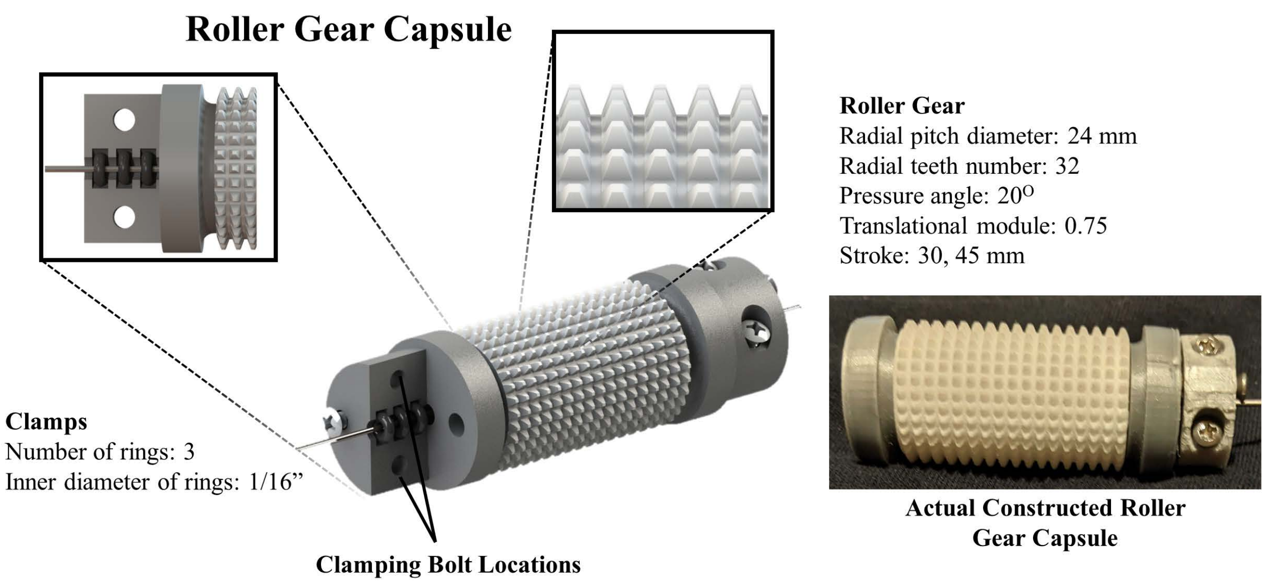

Figure 2. Roller gear capsule along with o-ring clamps for tube grasping.

2.2 Motor Pack

Each motor pack contains the motors and electronics to control a single roller gear and its attached tube. The motor pack contains four rigid protrusions, each with a curved lip that can deflect to enable snap interface around the housing module. Figure 1 illustrates the interface between the motor pack module and housing module. The spur and worm gears on the motor pack configure two motors parallel to each other, in order to make the motor pack compact.

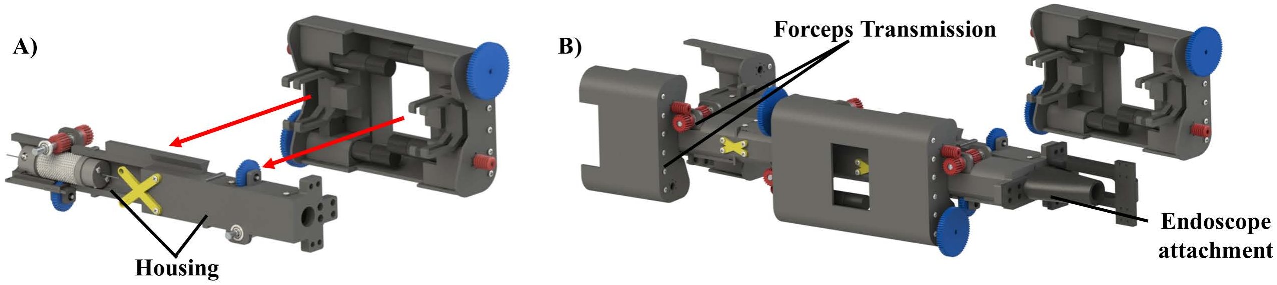

Figure 3. a) Two module sets CTR configuration used in repeatability experiment. b) Six module sets CTR configuration used in bimanual cooperation experiment.

2.3 Housing

The housing of the transmission enables the motor pack to move the roller gear (see Figure 1 and 3). It also serves as a guide for the capsule, enabling the capsule to freely translate and rotate. The exterior of the housing includes intermediate components for transmitting motion from the motor packs to the roller gear capsule. The gear train for the translational DoF includes two intermediate gears, one spur and one worm wheel, colored red in Figure 1, while gear train for the rotational DoF includes two spur gears that are colored blue. Relatively large gear ratios were selected for the system to reduce the end effector displacement associated with backlash between actuation gears and the roller gear. An endoscope interface is also included at the front of the housing as shown in Figure 3b.

3. DEVICE PERFORMANCE

While the roller gears have advantages for designing a modular and compact CTR, they are known to be subject to backlash.[8] Thus, in this section, we characterize the backlash and its effects on manipulator precision. We also describe an experiment illustrating effective bimanual use of our 10 DoF system. Our prototype was actuated with DC brushed motors (DCX10L, Maxon), equipped with optical encoders (ENX10, Maxon), and driven by positioning controllers (EPOS4, Maxon). Table 1 describes the tube parameters that were used for the two identical concentric tube manipulators attached to our actuation system.

Table 1. Tube set parameters used for repeatability and bimanual experiments.

Parameters	Inner Tube	Outer Tube
Outer Diameter (mm)	1.0	1.6
Inner Diameter (mm)	0.8	1.2
Curvature (m^{-1})	25	20
Length of Curved Section (mm)	50	30

3.1 Backlash Characterization

We measured the displacement of the tip of a tube based on the backlash between the connection of the roller gear capsule and the intermediate gears. The roller gear capsule was pushed by hand in both directions until the capsule could not move or rotate any further within the transmission. Each measurement was repeated ten times. Since the backlash propagates from the roller gear capsule to the concentric tube itself, optical encoders (E2 with 512 CPR and EM1 with 128 CPI, US Digital) were attached to a tube extending from the capsule in order to measure displacement. The mean translation and angular backlash were 0.265 mm and 1.65 degrees, with standard deviations of 0.136 mm and 0.45 degrees, respectively.

3.2 Repeatability Experiment

To evaluate the precision of the concentric tube manipulators when driven by our actuation unit we conducted a second set of experiments. In this experiment we used a two-tube manipulator (4 DoF) as shown Figure 3a.

We selected poses of the roller gears that covered the full range of the roller gears travel to evaluate mechanical uncertainties across the range of motion.

The roller gears were sent to three poses (one near each near the start, middle, and end of the range of linear travel, with varying axial rotational displacements). Tubes were extended and retracted so that they visited each of these configurations 6 times, while approaching from varying directions in configuration space. These poses were measured relative to a homing position at one end of the roller gear, and relative to this position were: 1) Inner tube: 45 mm and 90^o, Outer tube: 15 mm and 180^o, 2) Inner tube: 20mm and 180^o, Outer tube: 20mm and 90^o, 3) Inner tube: 30mm and 270^o, Outer tube: 15mm and 180^o; positive values indicate forward and clockwise directions. The resulting tip pose in task space for these joint positions were: 1) (-19.17, 1.73, 1.21), 2) (-13.47, -27.09, 21.67), and 3) (6.03, 34.38, 15.25) mm with respect to the tip's initial homed pose.

A long steel tube was attached at the base of each nitinol tube to enable higher torsional stiffness and interface between the roller gear and manipulator tip, as has been done the literature.[10–12] A 6 DoF NDI Aurora magnetic tracking sensor was attached with adhesive to the tip of the concentric tube robot to measure the overall deviation in tip position. The median error and standard deviation of the tip positions for each pose from this experiment were: 1) 0.002 mm and 0.007 mm, 2) 0.032 mm and 0.059 mm, 3) 0.005 mm and 0.052 mm.

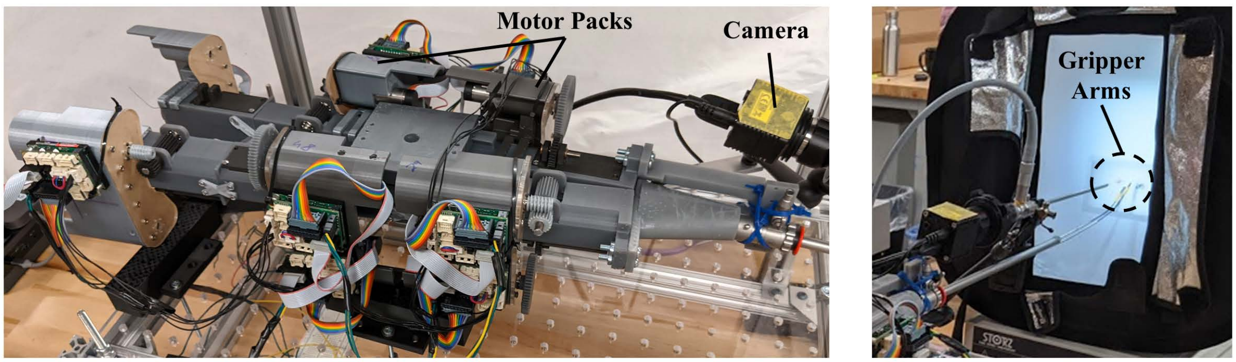

Figure 4. Left: Proposed two-manipulator disposable concentric tube robot with modular motor and electronic packs (10 DoF). Right: View of experimental setup for ring transfer task

3.3 Bimanual Ring Transfer Experiments

To evaluate the coordinated use of both manipulators, we performed a ring transfer experiment. The system was configured as shown in Figure 3b and 4, and consisted of 6 roller gears. Both concentric tube manipulators were equipped with forceps whose tension wires were attached to the rearmost roller gears. Each arm of the CTR consisted of two, 2 DoF roller gear capsules and motor packs for the concentric tubes and 1 DoF roller gear that controlled the tension wire for the gripper. While the design is ultimately intended to be hand held (i.e. operated in a manner similar to that described in Hendrick et al.[6] and Harvey et al.[15]) for purposes of this experiment we sought to evaluate the use of the CTR manipulators independent of motion of entire robot. To facilitate this, we fixed the robot in place on the bench as was done in some of the experiments in Hendrick et al.[6] for the same purpose. The user interface used in our experiments consisted of two independent 3D mice (Spacemice®, 3Dconnexion) with visual feedback provided by the endoscope (26183 V, Karl Storz). The ring transfer task was done as in the fundamentals of laparoscopic surgery, i.e. a ring was removed from one post by one of the manipulators, handed to the other, and placed on the other post (see also Figure 5). The ring transfer was conducted by the authors of this paper, who are engineers with no specific training in surgery. We repeated the experiment four times, and the ring was successfully transferred twice, with two drops. The completion of ring transfer using the system described in this paper indicates that it can facilitate bimanual manipulation in a standard surgical training task.

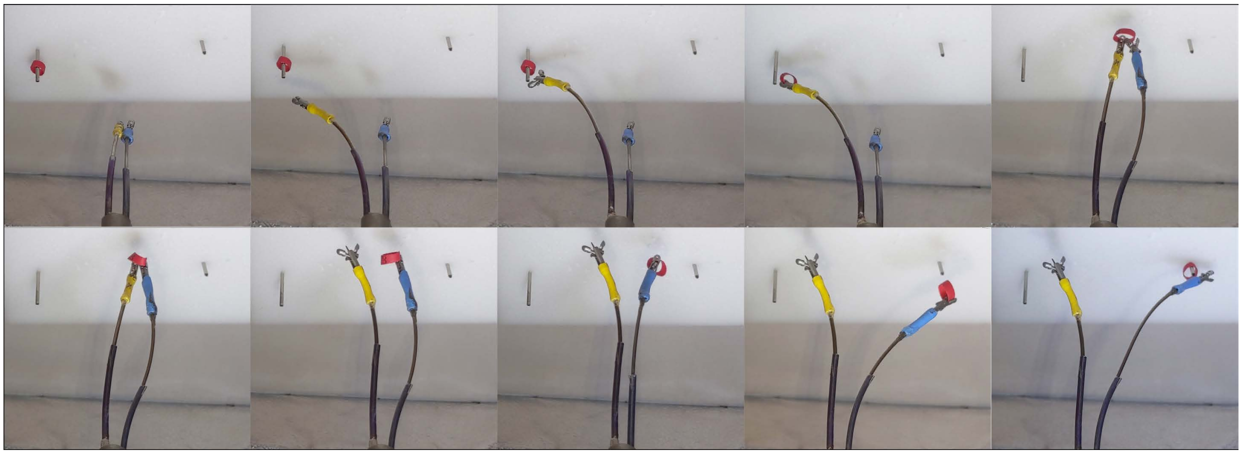

Figure 5. Ring transfer results. From left to right and top to bottom: the initial robot state, left manipulator actuation to target, transfer process to right manipulator, and right manipulator actuation and placement of the ring onto second target are shown.

4. CONCLUSION

This paper described the design of a modular CTR actuation system based on roller gears. The roller gears were proposed by Morimoto et al.,[8] where a single-arm system was created. We extended this concept to create a two-arm system. A system of this design offers a modular and potentially low cost approach to the actuation of multi-arm concentric tube robot systems.

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