DESIGN CONSIDERATIONS FOR CONTINUUM ROBOT ACTUATION UNITS
ENABLING DEXTEROUS TRANSURETHRAL BLADDER CANCER RESECTION

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ABSTRACT
The last decade has seen rapid growth in exploring the potential of continuum robots for a variety of surgical applications. The design of these robots requires unique electro-mechanical architectures of actuation units that satisfy operational requirements of precision, workspace, and payload capabilities. This paper presents the task-based design process of a compact nine degrees of freedom actuation unit for transurethral resection of bladder tumor (TURBT). This actuation unit has a unique modular architecture allowing partial decoupling of actuation, force and position sensing in a compact modular format. The derivation of task specifications based on kinematic simulations takes into account workspace, accuracy and force application capabilities for TURBT. Design considerations for supporting modularity, serviceability, sterilization, and compactness are presented. The detailed exposition of the design process serves as a case study that will be helpful for other groups interested in the development and integration of surgical continuum robots.

1 Introduction
Bladder cancer is the fourth most common cancer among men in the US, with an estimated 74,000 new cancer diagnoses and 16,000 related deaths predicted for 2015 [1]. Transurethral Resection of Bladder Tumor (TURBT) is the current gold standard for staging and diagnosis of bladder cancers and treatment of non-muscle invasive tumors (NMIBC). During this procedure, a urologist inserts a rigid device called a resectoscope inside the bladder through the urethra. Diagnosis or treatment is achieved by first locating the tumors on the bladder surface and then resecting them using an electrocautery loop deployed through the resectoscope by moving the loop back and forth through the tumorous tissue and cutting it away. Typically, TURBT is per-
formed using the standard imaging technique, called white
light cystoscopy and the visualization is provided through
an endoscope rod lens. Although TURBT is a commonly
performed procedure, it is still challenging for surgeons and
patients are often required to undergo re-TURs (repeat
TURBT) multiple times during their course of treatment.
Repeat resections are often due to high recurrence rate, mul-
tifocality of disease, and insufficient resection to allow for
critical disease staging. Insufficient resections may be due
to tool limitations such as lack of intracavitary distal dext-
ernity, ability to precisely control depth of resection, and
optimize in-vivo visualization. To help overcome these dext-
ernity limitations, this work aims to offer robotic assistance
for dexterous surveillance and resection of bladder tumors
in a manner currently impossible using instrumented rigid
endoscopes.

The applications of snake-like robots in surgery have
seen a rapid growth in the last decade. The ability of these
robots to circumvent anatomical obstacles while preserv-
ing dexterity for surgical manipulation has motivated
research on a variety of surgical applications. Examples
include trans-oral surgery of the upper airways [1–3], trans-
esophageal surgery [4], trans-nasal surgery [5, 6], frontal
sinus exploration [7], single port access surgery [8–10]
transurethral bladder cancer resection [11] and resection
[12], neurosurgery and skull base surgery [13, 14], and
orthopedics [15].

One key type of snake-like robots is the multi-backbone
continuum robot (MBCR) shown in figure 2. This design is
a variant of previous wire-actuated continuum robot designs
such as [16]. For the particular TURBT application, the
new design of this robot consists of three segments. Each
segment includes one central backbone, three secondary
backbones, a base disk, spacer disks and an end disk. In
our most recent embodiment, the central backbone is made
of a Polytetrafluoroethylene (PTFE) elastomer and the sec-
ondary backbones are made of superelastic NiTi tubes.
The spacer disks can be made from metallic disks or from a
PTFE elastomer as shown in figure 1. The backbones con-
nect only to the end disk and pass through the spacer disks
via adequately dimensioned holes to ensure circular bend-
ing without significant stress concentration. By pushing or
pulling on the secondary backbones, each segment can bend
in two degrees of freedom (DoF) controlling the pitch and
the yaw of the end disk relative to the base disk. A more
detailed description of the MBCR design are available in [2].

The clinical application motivating the design of the
actuation unit described in this paper was described in de-
tail in [12] where a proof-of-concept telemanipulator plat-
form using a two-segment MBCR slave for TURBT was
presented. Figure 1 shows the current design of a TURBT
slave robot arm that is planned for use in a series of swine

![FIGURE 1: a) TURBT assembled on the static arm](image)

studies comparing the accuracy of robotic resection with
manual resections. A key component of this system is the
robot-integrable resectoscope which was described in detail
in [17]. The figure also shows the three-segment continuum
robot and its actuation unit. The focus of this paper on the
mechanical design of the actuation unit.

The segments of the MBCR are serially stacked to pro-
vide six degrees of freedom. The secondary backbones of
each segment pass through the corresponding secondary
backbones of its preceding segment. With three segments
in an MBCR, three groups of three concentric NiTi back-
bones need to be actuated to control all nine backbones.
The use of three secondary backbones to actuate each two-
DoF segment improves payload distribution and miniatur-
ization [18] and also provides a fail-safe operation in case one
of the backbones fails. The rationale for using concentric
deployment of secondary backbones stems from the resulting
simplification as a result of actuation decoupling between
snake segments. If the backbones are not aligned concentri-
cally, the length of the backbones of the distal segments are
not constant when the proximal segments are bent. This
complicates the control and potentially degrades the accu-
tracy of the end effector’s motion.

The decoupled kinematics of multi-segment MBCR’s
as a result of concentric placement of secondary backbones
poses a challenge in for design of the actuation unit as it de-
mands the actuation of three concentric backbones. Other
works on concentric tube robots (often used as steerable
needles) have had to tackle this challenge [19, 20] but they
typically had less numbers of DoFs. However, MBCR’s re-
quire many more degrees of actuation due to the use of
actuation redundancy. In addition, the surgical applica-
requirement is due to the fact that this actuation unit needs to be manipulated by the surgeon in initial stages of system deployment hence the actuation unit needs to be as compact and the least obstructive as possible.

2. **Sterilizable** which requires that lumens that come into contact with the patient can be sterilized and other parts that do not come into direct contact with the patient can be covered with sterile draping while maintaining a sterile and open conduit for deployment of the interventional functions listed below.

3. **Modularity** in order to facilitate assembly, part interchangeability, and for cost reduction.

4. **Separability of actuation** to allow easy disassembly of the actuation unit from the continuum robot to ensure that the continuum robot can be serviced without having to disassemble the entire actuation unit, thereby avoiding the loss of prior calibration of the actuators.

5. **Robustness to sensory error** is required in order to ensure safety of robot operation in case one of the position sensors (motor encoders) malfunctions.

In addition to the above attribute requirements, the following **task specifications** are required by the surgical application of TURBT:

1. **Multi-functionality** of the robot requires it to support of manipulation, biopsy, ablation, suction and visualization. To achieve these functions, the continuum robot was designed to provide three working lumens as depicted first in [12].

2. **Force sensing** is required to facilitate trans-urethral deployment using compliant motion control as in [21] and sensing and control of interaction forces as in [22, 23]. The actuation unit is hence designed to accommodate load cells on each backbone of the robot.

3. **Intra-vesicular dexterity** is needed to support six degrees of freedom motion and coverage of the bladder volume. This requirement motivated the need for a snake-like robot having at least three segments since each segment provides two degrees of freedom. Consequently, the actuation unit needs to have at least nine actuators since each segment of the continuum robot uses three actuated backbones to bend it using push-pull actuation.

4. **Precision of motion** is required to ensure high precision of ablation during TURBT. We have chosen 0.1mm as the target motion accuracy. There is no known quantification of resection accuracy in the literature so we have conservatively chosen 0.1mm since it is significantly better than the expected tip precision when manually manipulating a resectoscope having a length of in excess of 250 mm.

5. **Motion responsiveness** is needed to provide the surgeon
the ability to move the snake robot with the necessary bending rate. Based on consultation with our clinician authors, we determined a bending rate of ±90° within 1 second as the desired maximal bending rate for each segment.

6. Force interaction was specified as a desirable functionality to support the ability of the robot’s gripper to pull on mucosa during laser-aided resection. Although during normal cautery and laser resection the forces are minimal, we have conservatively specified a desired force application capability of 1 newton at the tip of the robot.

2.2 Derivation of Joint-Level Design Requirements

The kinematics of MBCR was addressed previously by [16,24,25]. The configuration of each segment is represented by \( \mathbf{q}_i = [\theta_{iL}, \theta_i]^T \), where \( i = 1, 2, 3 \) is the segment number, \( \theta_{iL} \) is the bending angle and \( \theta_i \) is the bending plane angle as shown in Figure 2. The kinematic relation between configuration space and joint space is

\[
\begin{align*}
q_{1j} &= r\cos(\delta_{1j})(\theta_{1L} - \theta_0), \\
q_{2j} &= r\cos(\delta_{2j})(\theta_{2L} - \theta_0), \\
q_{3j} - q_{2j} &= r\cos(\delta_{3j})(\theta_{3L} - \theta_0),
\end{align*}
\]

where \( j = 1, 2, 3 \) is the secondary backbone number, \( q_{ij} \) is the secondary joint variable of the segment \( i \) \( \mathbf{q}_i = [q_{i1}, q_{i2}, q_{i3}]^T \) and \( r = 1.725 \text{mm} \) is the radius of the pitch circle determining the positions of the secondary backbones in the snake disks (See Figure 2).

To meet the motion responsiveness design requirement, i.e. bending rate of ±90° within 1 second (section 2.2), each segment actuators are required to provide maximal speeds of 4.7 mm/sec, 4.7 mm/sec and 9.4 mm/sec respectively. These values are obtained by substitution in equation (1).

In order to satisfy the prescribed motion accuracy of 0.1 mm, the instantaneous Jacobian relating the configuration space and the joint space should be determined. Three vector spaces are involved in this process, namely task space, configuration space and joint space. These spaces are related by the Jacobians \( \mathbf{J}_{x\psi} \) and \( \mathbf{J}_{q\psi} \) such that

\[
\mathbf{J}_{x\psi}\Delta\mathbf{q} = \Delta\mathbf{x}_c, \quad \mathbf{J}_{q\psi}\Delta\mathbf{q} = \Delta\mathbf{q}
\]

where \( \mathbf{q} \in \mathbb{R}^{9 \times 1} = [\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3]^T, \mathbf{x} \in \mathbb{R}^{6 \times 1} = [\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3]^T, \mathbf{x}_c \in \mathbb{R}^{3 \times 1} \) are joint-space, configuration-space and Cartesian-space vectors respectively. Derivation of the Jacobians is not mentioned here for brevity and the reader is referred to [2,26] for a thorough discussion. Note that the formulations did not involve the base translation of the robot.

From equation (2) we obtain:

\[
\Delta\mathbf{q} = \mathbf{J}_{q\psi}\Delta\mathbf{q}
\]

where \( \mathbf{J}_{q\psi} \) is Moore-Penrose pseudo-inverse of \( \mathbf{J}_{q\psi} \) as determined by the following equation [27,28]:

\[
\mathbf{J}_{q\psi}^+ = \left( \mathbf{J}_{q\psi}^T\mathbf{J}_{q\psi} + \epsilon \mathbf{I}_6 \right)^{-1}\mathbf{J}_{q\psi}^T
\]

\( \epsilon \) term is added to regularize singular configurations and \( \mathbf{I}_6 \in \mathbb{R}^{6 \times 6} \) is the identity matrix. Substitution of equation (3) in (2) yields:

\[
\mathbf{J}_{x\psi}\Delta\mathbf{q} = \Delta\mathbf{x}_c
\]

where \( \mathbf{J}_{x\psi} \triangleq \mathbf{J}_{x\psi}\mathbf{J}_{q\psi}^+ \in \mathbb{R}^{3 \times 9} \).

Equation (5) can be used to determine the maximal tolerable joint space error vector to guarantee a task-space motion error having norm of less than 0.1 mm in a specified configuration \( \mathbf{q}_i \). Fig. 3 shows the contour plots of the reciprocal of the individual joint motion accuracy to impart a 0.1 mm motion in three world coordinate unit directions \( \mathbf{e}_i, \mathbf{e}_j, \mathbf{e}_k \). The values of the reciprocals are represented for \( \theta_{3L} = 0^\circ, 45^\circ, 90^\circ \). The horizontal and vertical axes are \( \theta_{1L} \) and \( \theta_{2L} \) respectively. Note that \( \theta_{1L} \) do not affect the joint motion norm significantly, therefore they are assumed as zero. The minimum joint motion is 0.0037,0.0014 and 0.0015 mm for \( \Delta\mathbf{x}_c = 0.1\mathbf{e}_i, \Delta\mathbf{x}_c = 0.1\mathbf{e}_j \) and \( \Delta\mathbf{x}_c = 0.1\mathbf{e}_k \) respectively.

In order to determine the minimum required joint motion for all possible \( \Delta\mathbf{x}_c \) directions, we consider equation (5) again. Using singular value decomposition and matrix algebraic manipulations, it can be proved that

\[
\|\Delta\mathbf{q}\| \geq \frac{\|\Delta\mathbf{x}_c\|}{\|\mathbf{J}_{x\psi}\|}
\]

where \( \|\| \) and \( \|\cdot\| \) represent Euclidean norm and maximum singular value respectively. Therefore,

\[
\|\Delta\mathbf{q}\|_{\min} = \frac{\|\Delta\mathbf{x}\|}{\max \|\mathbf{J}_{x\psi}\|}
\]

where \( \mathcal{Q} \) denotes the the entire robot configuration space.
Equation (7) determines the required joint-level motion accuracy to meet a demanded positional accuracy. The robot configuration space was discretized and the maximum singular value was computed numerically at each configuration. The maximum value among the maximum singular values was determined. Using a 0.1 mm task-space accuracy and $\epsilon = 10^{-7}$, the required joint-level motion accuracy was calculated as 0.0013 mm.

The first three columns of Table 1 summarize the simulation results using the task specifications of motion responsiveness as specified in section 2.1. The last column summarizes the simulation results for actuator torques using the interaction force task specification while considering particulars of the actuation unit architecture. At the outset, static simulations using the statics model in [18] were used to determine the required actuator forces for a three segment continuum robot having backbones as in [12], but with additional consideration for flexural rigidity of deployable tools such as a fiberscope and a flexible gripper. The simulations resulted in joint force requirements that ranged from 55 N to 30 N when considering all segments. Taking into account the design architecture of the actuation unit where the actuator of the first segment carries the actuators of the other segments, we have conservatively set the required joint force of the first segment actuator to 150 N.

**TABLE 1: Required joint-level specifications and the corresponding requisite gear motor torques**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Joint stroke required</th>
<th>Min. joint-level position resolution</th>
<th>Max joint speed</th>
<th>Max joint force</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.7 mm</td>
<td>0.0013 mm</td>
<td>4.7 mm/s</td>
<td>150 N</td>
</tr>
<tr>
<td>2</td>
<td>4.7 mm</td>
<td>0.0013 mm</td>
<td>4.7 mm/s</td>
<td>30 N</td>
</tr>
<tr>
<td>3</td>
<td>9.4 mm</td>
<td>0.0013 mm</td>
<td>9.4 mm/s</td>
<td>30 N</td>
</tr>
</tbody>
</table>
3 Actuation Unit Architecture

3.1 Key actuation unit modules

The continuum robot is actuated by a compact, modular and portable 9-DoF actuation unit described in detail in Fig. 4. Referring to Fig. 4-(a), the actuation unit (1) connects to the continuum robot backbones using a detachable actuation interface (2). The backbones are routed from the detachable actuation interface to the continuum robot through an actuation cone (3). The detachable actuation interface provides the conceptual attribute of separability of actuation and supports sterilizability since all the actuation unit components can be contained in a sterile draping while keeping the continuum robot, cone and actuation interface as a contained assembly which has to undergo sterilization.

To satisfy the conceptual attribute of modularity, and compactness, the core of the actuation unit was designed based on three identical backbone actuation modules (100), (200), (300). Each sub-assembly has three cylinders (101), (102), (103) designated for actuating the first, second and third segments of the continuum robot. The three sub-assemblies are held in place between the front plate (4) and rear plate (6). The structural stiffness of the actuation unit is provided by three structural elements, two Aluminium beams (9) on the sides and the attachment base plate (5) on the bottom. When these three elements are connected to the front plate and the rear plate they form the chassis of the actuation unit. Moreover, the attachment base plate connects the slave robot to the insertion stage mounted on an adjustable passive arm shown in Fig. 1.

The conceptual attribute of robustness to sensory error is satisfied by concurrent use of encoder and potentiometer feedback. Figure 4-(d) shows the potentiometers (8) (Panasonic EWA-P10C15A14). These potentiometers also facilitate fast startup time since they provide absolute position feedback while the incremental magnetic encoders are used for high precision real-time control feedback. A significant discrepancy of feedback based on potentiometers and encoders is used to flag an erroneous feedback condition, which triggers a system halt or warning signal based on preference of the user.

3.2 Backbone Actuation Modules

The cross-sectional view in Fig. 5 illustrates the internal structure of the first cylinders (101) and (103) also shown in Fig. 4. The cylinders are equipped with selected motors combinations (18,20) shown in Table 2. They are secured in place using custom made internal collars (22, 19) that rigidly connect the motor to the cylinder. The motors drive pistons (14,29,26) using internal lead screws (10). To compensate eventual small axis misalignment, an Oldham coupling (23) is used to connect the motor shaft and the lead screw. Moreover, the lead screws are also supported by ball bearings (25) held in place using custom-made collars (24,11). Each piston contains two plastic nuts (28) that could be tightened on the respective lead screws with re-
spect to another in order to remove the backlash between the lead screw and the piston.

The first cylinder is rigidly attached to the front plate by a dummy spacer (12) (It can later be replaced by a load cell HONEYWELL Model 31 to measure backbones forces, as well the dummy spacer (15) can be replace with a load cell HONEYWELL Model 11) and is connected to the second and third cylinder using two connection frames (21, 27). The connection frames are clamped on the outer surface of the second and third cylinder and are free to slide on the first cylinder. The second connection frame (27) is also rigidly connected to the first cylinder piston through a press-fit pin that ensures motion transmission. This motion of the first cylinder drives the backbone of the first segment of the continuum robot.

<table>
<thead>
<tr>
<th>TABLE 2: Motor Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Cylinder</td>
</tr>
<tr>
<td>Motor Combination</td>
</tr>
<tr>
<td>Maxon Motor 324553</td>
</tr>
<tr>
<td>Second and Third Cylinder</td>
</tr>
<tr>
<td>MICROMO 1331T006SRIE2-400+14/1 14:1+X0437</td>
</tr>
</tbody>
</table>

The cross-sectional view in Figure 6 shows the internal structure of the second cylinder (102) and the third cylinder (103). The second piston is also equipped with the same motor combination (18), main piston, lead screw, collars and bearings of the previous cross section description. Moreover, there are two secondary pistons in these two cylinders. The secondary driving cylinder (32) is rigidly connected to the primary piston by an aluminum dummy spacer (15). The secondary driven piston (17) is free to slide in the third cylinder. A bridge connector (30) slides to the outer surface of the second and the third cylinder and is rigidly connected to the secondary pistons using shoulder screws. This entire design allows driving three concentric backbones. The first segment backbone is held by the custom-made holder (13), the second segment backbone is carried by the secondary driven piston (17) while the innermost backbone that drives the first segment is held by the custom-made gripper (16).

![FIGURE 5: Cross section of the main cylinder and the third cylinder](image)

**FIGURE 6: Cross section of the second cylinder and the third cylinder**

### 3.3 Continuum robot actuation interface

#### 3.3.1 Detachable actuation interface

A new feature introduced in this design allows to detach the actuation unit from the cone easily and quickly. The most important aspect of this new feature is that it allows to detach the front part of the system without acting at all on the actuation unit. The actuation unit will be totally preserved from re-calibration requirement or mechanical issues coming from a repetitive disassembling process. The concept is based on a concentric system of quick connectors shown in Figure 7.

Referring to Figure 7, the tubes (1, 2, 3) are placed inside each other and connected to their respective quick connectors by shear pins. The aluminum tubes on the actuation unit side are connected to their respective joint actuators using set-screws and metal glue, on the cone side, each brass tube is glued to each relative nitinol backbone using custom-made aluminum adapters (4).

In case of a failure of the backbones, this new design allows an easy and quick replacement of the front part of
the robot. A total time of 10 minutes (2 mins in average for disassembly of the front part and 8 minutes in average for re-assembly) is needed to replace the entire continuum robot and connect a new one to the actuation unit.

3.3.2 Actuation cone The central part of the actuation cone called cone, is a rapid-prototyped part that routes the backbones inside the continuum robot tube. There are three channels inside the cone that curve smoothly converging into the stem. Along the central axis of the cone, there is a channel that drives the tools coming from the back of the actuation unit into the stem.

**FIGURE 8:** Actuation cone: (a) assembly, (b) cross section

4 Component Selection

Tables 2 and 3 summarize the specifications and expected performance of the gearmotors combined with lead screws for driving the backbones of each segment. To arrive at the choice of gear-motors and screws a Matlab code was written to parse the specifications of available lead screws and motors that fit the cylinders. To obtain a first order estimate of the power requirements of the actuators were calculated based on task specification assuming gearhead efficiency of 80% and lead screw efficiency of 70%. Once a list of motors that satisfies the power requirements was made, the Matlab code was used to cull the list down to motor and screw combinations that can satisfy force and speed requirements.

The required torque to raise/lower the piston against/along the direction of an external load $F$ is calculated as:

$$
\tau_{r,l} = \frac{F dp}{2} \tan (\gamma + \lambda) + \frac{F dp}{2} \mu_{roll} b
$$

(8)

where subscript $r$ is for raising and $l$ is for lowering a load. The first part accounts for friction between the screw and nut and the second part accounts for friction in the bearings supporting the lead screw. The lead screw friction angle $\gamma$ is a function of screw geometry and friction coefficient between the screw and nut. The lead angle $\lambda$ is a function of the screw pitch diameter $dp$ and lead $L$. Details of calculation of these angles can be found in [29].

5 Preliminary experimental evaluation

Figure 9 shows the motion of the snake robot in an early experiment aimed to verify the functionality of the concentric actuation scheme with quick-connectors. The control code was written in Simulink package (Version 7.5) and the real-time code generation and implementation was carried out using xPC Target toolbox in Matlab (Presently known as Simulink Real-Timeâ€¢). The MBCR was actuated in the configuration space by trying different banding angle planes ($\delta_i$) and bending angles ($\theta_i L$) of each segment. Figure 9 illustrates the MBCR bending in the $x_i z_i$ plane (See Figure 2). To achieve this, the bending angles of each segment were independently controlled. Note that the maximum achievable bending angles are higher than illustrated and are only limited by the plastic deformation of the backbones.

**FIGURE 9:** Sample motions generated by the continuum robot: (left) banding angles between 0° and 250°, (right) S shape-snake

6 Conclusion

This paper presented the design considerations that guided the design, fabrication and early testing of a modular actuation unit for a continuum robot aimed at transurethral bladder cancer resection. A methodological process for guiding the design of this actuation unit was presented based on taking into consideration conceptual design attributes and task specifications. The conceptual design attributes were used to guide the choice of mechanical architecture of the actuation unit. The task specifications were used to guide the detailed design and component selection for each actuator. The resultant actuation unit is comprised of three modules allowing for modularity, ease of
sterilization and actuation separability, and robustness to sensor errors. Preliminary testing shows that that actuation unit achieves its primary function. Though the design posed several bottlenecks particularly in terms of fabrication, the most critical aspect which demanded several iterations was the actuation detachment module since the backbone are deployed concentrically. Though previous works have presented some actuation units suitable for actuation of continuum robots, the design exposition has been predominately ad-hoc. We believe that this paper provides an example that could benefit others when considering design of actuation units of continuum robots for specific surgical applications.

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