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Interleaved Continuum-Rigid Manipulation Approach: Development and Functional Evaluation of a Clinical Scale Manipulator

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***Abstract*— A new manipulation approach, referred to as interleaved continuum-rigid manipulation, which combines inherently safe, flexible actuated segments with more precise embedded rigid-link joints is described. The redundantly actuated manipulator possesses the safety characteristics inherent in flexible segment devices while gaining some of the performance gains possible with rigid-link joint systems. A demonstration prototype was developed, the purpose of which was to explore the design space as well as demonstrate the feasibility of the approach in a clinically-relevant form. The overall design is described along with performance data evaluating its functionality.**

I. INTRODUCTION

While researchers have developed a variety of minimally-invasive surgical (MIS) robotic systems, the majority of robotic MIS systems have traditionally consisted of either rigid link or flexible continuum manipulators, each having its own competencies and limitations. The class of rigid link manipulators began as, and are most similar to, traditional robotic manipulators. They generally have stiff links with defined joints driven by a wide variety of actuators; elements that can be well-modeled and whose performance characteristics do not change with time.

The most commercially successful in this class, Intuitive Surgical's da Vinci [1], commonly performs laparoscopic keyhole surgeries [2], where the manipulator passes through the outer layers of tissue before entering the abdominal cavity. Having this straight-line access to the target area allows for rigid link construction, enabling the manipulator to locate virtually all of its joints and actuators outside the patient with only a few remotely-actuated revolute joints inside the patient to form instruments. While this arrangement creates some complexity due to remote centers of rotation, the joints and actuators are largely not required to fit or operate within the patient and thus enjoy fewer design restrictions than flexible continuum manipulators..

In situations where there is no clear path to the target area, as in cardiac interventions, the flexible continuum manipulators employed by Stereotaxis' Niobe [3] and Hansen Medical's Artisan [4] systems traverse the patient's anatomy, conforming to its structures while performing some dexterous task. The manipulator's complaint structure makes these manipulators much less likely to cause damage when they come in contact with tissue, lending them an inherent safety that cannot be realized by rigid link constructions. These flexible manipulators have become the dominant, and in some cases only interventional tools for applications where safety is of the greatest concern.

The price of the inherent safety of flexible continuum manipulators is increased modeling and control complexity. These limitations stem from the very features that confer safety: the soft compliant structure, in combination with the internal friction between the control elements and structure, give rise to poor position [5, 6] and force regulation. These aspects limit the dexterity of continuum manipulators with the result that only simple surgical procedures can be performed by these otherwise desirable devices.

When considering applications that would benefit from improved flexible continuum manipulators, perhaps the most compelling are those requiring minimally-invasive cardiac interventions. These operations occur in the chambers of a beating heart and generally require the ability to move throughout a large workspace (relative to the device size) while applying precise forces in the range of 0.05 to 2.0 N [7] along paths defined within ±1 mm [8]. These requirements commonly exceed the capabilities of current manual and robotic catheter devices.

Catheters are actuated by tendons routed along the periphery of a cylindrical elastomer structure such that when one end of a tendon is terminated at the catheter tip, pulling on the other end causes the structure to bend in that direction. Friction between the tendon and elastomer structure leads to nonlinear behaviors that are difficult to control against and which fundamentally limit the configuration and force capabilities of the system. For these and other reasons, alternative actuation methods and constructions have been investigated that depart from the tendon-actuated thermoplastic designs found in the majority of commercially-available catheter systems. One novel approach is that of [9-11], where precurved, concentric tubes form a flexible manipulator whose outward configuration is the result of the relative alignment of the curvatures of each of the concentric tubes. Keeping the device compliance low, for safety, implicitly limits the maximum force capability and additional research is required to determine the extent to which friction similarly limits these novel manipulators [12, 13].

While [9-11] maintained a continuum manipulator and changed the actuation method, [14-17] use a multitude of rigid links which form two concentric tubes. By locking or unlocking the joints between successive segments, an unlocked inner tube can be advanced while the locked outer tube imparts direction, or alternately with a rigid inner tube the outer tube can be advanced. In this way, the manipulator can traverse the anatomy and serve as a rigid platform for other instruments to act against [17, 18].

In addition to considering the construction of a flexible continuum manipulator, improved performance may be realized through closed loop control. In [19] closed-loop control of a continuum manipulator's tip position in both joint- and task-space was presented, and similarly [20] controlled the position and end-point stiffness of precurved, concentric tube manipulators. Other approaches described in [6, 11, 21-31] consider other aspects of the control and operation of continuum manipulators in a surgical environment. Despite these efforts, in the case of tendon-actuated catheters the friction developed between the control tendons and continuum structure still gives rise to nonlinear hysteretic behaviors and exhibit limit cycling, both of which limit the achievable closed-loop bandwidth. For some applications this bandwidth is sufficient to allow operation, but in general extant closed-loop continuum manipulators are unable reject disturbances on reasonable time scales, and are thus unable to perform dexterous tasks. These effects are particularly apparent in multi-segment continuum manipulators, where the nonlinear motions of each continuum segment influence each other and vary as a function of their relative positions and configurations.

II. Interleaved Manipulation Approach

To address the limitations of both rigid link and flexible continuum manipulators, we have developed a new manipulation approach [32] which combines large flexible continuum segments with small, discrete rigid joints to form an *interleaved continuum-rigid manipulator*. As depicted in Figure 1, this concept seeks to combine the best characteristics of both rigid link and flexible continuum manipulators to yield a highly dexterous, precise, and safe manipulator suitable for cardiac and other demanding interventions.

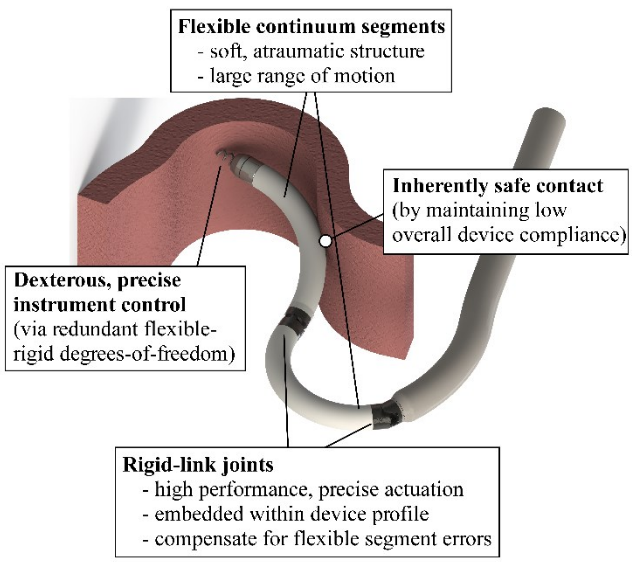

Figure 1. Overview of Interleaved Continuum-Rigid Manipulation Approach.

As described above, the discrete joints and stiff links in rigid link manipulators give a well-controlled manipulator with comparatively poor safety characteristics, while the soft, compliant structure of flexible continuum manipulators yields an inherently safe manipulator which suffers from poor position and force regulation. In an interleaved continuum-rigid manipulator, well-defined rigid link joints are inserted between flexible continuum segments to both compensate for the nonlinear behaviors of the flexible segments and extend the manipulator workspace beyond that achievable with continuum segments.

As shown in [32], both the motion control performance and dexterous workspace of a device based on the interleaved manipulation approach is superior to that of a flexible-segment only device. In the experiments discussed in [32], a one degree-of-freedom evaluation testbed was used to evaluate the potential performance benefits of the proposed approach, finding that the overall position response time was improved by a factor of 3. While the performance and dexterity benefits are significant, major challenges remain in regards to implementation, specifically in the miniaturization of the rigid link joints and the integration of the flexible and rigid link actuation.

As such, we have embarked on an effort to develop a prototype interleaved manipulator, the purpose of which is to demonstrate the feasibility of the proposed approach. The remainder of this paper will describe the design and operation of a clinically-relevant prototype, and conclude with thoughts on the capability and scalability of this class of device.

III. Demonstration Prototype

A. Objectives / Motivation

To explore the design challenges inherent in this approach as well as to demonstrate its feasibility, we have developed a demonstration prototype. The objectives of this design prototype are to demonstrate that the preceding design concepts can be realized in a compact, clinically-relevant form. The term 'clinically-relevant' means here that the concepts demonstrated by this prototype can, to the best of the authors' belief, be integrated into a clinical prototype. That is, there are no design features preventing such a prototype, only that we did not expend the additional design effort required to ensure bio-compatibility, particularize the manipulator to a particular intervention, or integrate the prototype and supporting hardware into a clinical environment.

While there are many possible clinical applications we could consider, the target clinical application selected requires that the manipulator's end-effector can be pointed in an arbitrary direction. Example clinical applications include imaging using a single-beam ultrasonic transducer or orientation of an interventional needle. The applications considered are generally performed within the open chambers of the heart.

A device designed with flexible segments only, such as an EP catheter, would require two active actuation degrees-of-freedom (DoF) to achieve the pointing task. In this case, design choices could include dual-articulation (via two pairs of antagonistic control tendons in a distal segment) or a single articulation along with a torque or roll motion. In the case of an equivalent two DoF interleaved manipulator, both the flexible segment and the rigid-link joint must be capable of spanning this task space independently.

B. Design Description

An overview of the demonstration prototype developed to address the clinical application described above is shown in Figure 3. In the design of the demonstration prototype, a number of critical design characteristics were considered, including the flexible segment design, and, most significantly, the rigid link joint design. These are described below.

1) Flexible Segment Design

The flexible continuum segments provide access to a large workspace and are designed to be compliant to allow bending for safety and ease of articulation. While various approaches to flexible segment articulation have been developed, the vast majority of commercially available devices employ control tendons routed along the length of the device and terminated at the end of the flexible segment. The control tendons are actuated manually or via motors located external to the patient to affect articulation. We have adopted a similar approach in our prototype. In this case, the distal flexible segment has a single control tendon routed close to the surface to drive its articulation. The flexible segment body is constructed from urethane and is 6.35 mm in diameter and 110 mm in length (see Figure 2).

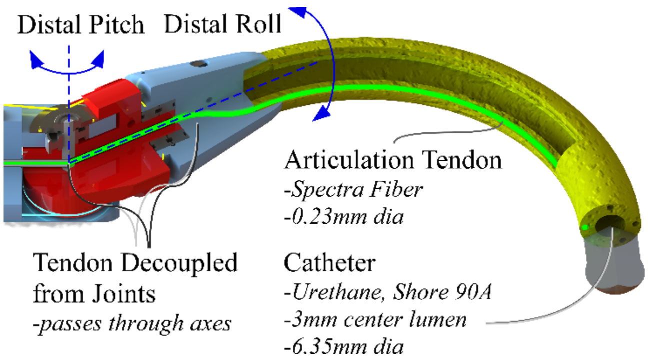

Figure 2. Flexible segment (catheter) body design overview.

It is advantageous to design the interleaved device such that the rigid link joint and flexible segment motions are decoupled. The decoupling is important in light of the physical limits on achievable flexible segment tendon tension (and device limits in regards to carrying this tension) and limits in the available rigid-link output torques (primarily as a consequence of distal gear-hear torque limits). Decoupling flexible segment and rigid-link joint motion can be accomplished in a number of ways.

In the case of the demonstration prototype described here and seen in Figure 2, the control tendons are routed through the rotation axis of rigid joints – such that the tendon length does not change as a result of rigid joint motion, which results in no net work done and thus no cross motion coupling.

2) Rigid-Link Joint Design

The rigid-link joints provide the redundant motion capability to correct for flexible segment motion errors as well as increase the device's dexterity by overcoming the maximum curvature limitations of flexible segment manipulators.

Since the interleaved continuum-rigid manipulator must be able to traverse a patient's anatomy, it is important that the rigid joints remain within the largest profile of the manipulator. Any transitions between diameters should be smooth and when actuated the joint should not expose any sharp features. Minimizing the size of the rigid joints involves considering a wide variety of actuation concepts that vary substantially in complexity, scalability, bandwidth, and force capability. At a minimum, to compensate for hysteretic errors in a distal flexible segment the rigid joint range of motion must span the maximum flexible segment error. Beyond this minimum, any increases in rigid link range of motion will substantially improve device dexterity, while the task performance is dictated by the dynamic characteristics of the rigid link drivetrain.

Developing suitable actuation and drivetrain solutions are a major obstacle toward the successful implementation of the rigid link joints. Moreover, the choice of actuation is driven by the basic joint design approach taken, categorized as local or remote actuation. A local actuation approach would locate the actuator within or adjacent to the driven joint while a remote approach would locate the actuation proximal to the driven joint and use a suitable drive train to connect the actuator to the joint motion axis. Both approaches have advantages and disadvantages in regards to the distinct design objectives of improved performance, accuracy, and dexterity.

Possible local actuators include shape-memory alloys, ionic actuators, piezoelectric motors, electrostatic actuators, electroactive polymers, and miniature electromagnetic motors . However, many of these remain under active research, particularly for millimeter-scale devices. As a result, we have adopted a remote actuation approach here. An overview of the remote actuation approach developed is shown in Figure 4.

In a remote actuation approach the actuation is located proximal to the driven joint – the advantages of which are derived from the proximal placement of the actuation hardware including the ability to use conventional, higher power actuators. If the actuation is located outside of the

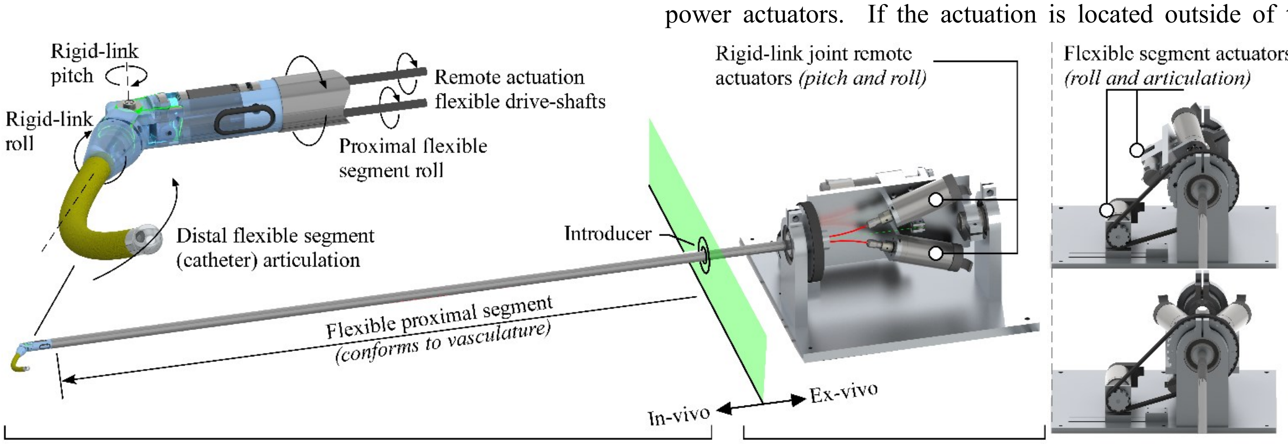

Figure 3. Overview of developed demonstration prototype

patient, many of the design restrictions are eliminated allowing for the use of a virtually unlimited set of conventional high power electromagnetic actuators. In the case of the demonstration prototype described here, the rigid link joints are actuated by high-performance servo-motors (Maxon Motor AG model 273754). Achieving similar performance in an embedded actuator would be virtually impossible.

The disadvantages of remote actuation relate to the need for a connecting drive train and the resulting performance and design limitations that result. Specifically, the need to drive the joint remotely requires a drive train that can traverse the flexible segments and rigid link joints located between the target driven joint and the remote actuator. In this case, we have chosen to use 0.64 mm diameter flexible stainless steel drive shafts.

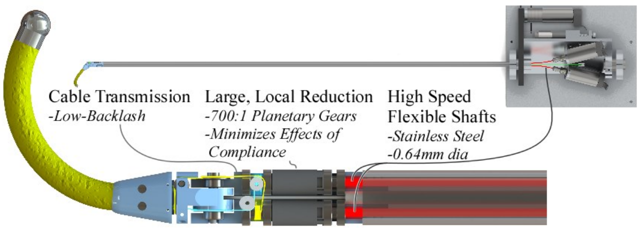

Figure 4. Overview of rigid-link joint remote actuation approach.

Advantages include design simplicity and the elimination of connecting joints or couplings which could introduce backlash. The drivetrain must be designed to traverse joints proximal to the driven joint, minimally restrict proximal segment curvatures, and maximize drivetrain stiffness. The later has the potential to limit the attainable performance, as drive train compliance will limit the achievable closed-loop bandwidth. To overcome this, we have employed a high-velocity power transfer approach similar to [33, 34]. Specifically, power is transferred through a flexible drive shaft rotating at a high velocity. The proximal end of the drive shaft is directly connected to the drive actuator while the distal end drives a high reduction gear (Precision Microdrives #206-108, 4 stage planetary gear, 700:1 reduction) to reduce the output velocity to desired levels. The high reduction gear located at the driven joint increases the output reflected stiffness by N^2, with N representing the gear ratio or equivalently the ratio of flexible shaft velocity to driven joint velocity. The increase in stiffness improves disturbance rejection characteristics and reduces the effect of disturbances on actuator control. While the compliant drive shaft is susceptible to windup, the large distal gear reduction significantly reduces the resulting joint position error. In the case of the demonstration prototype, worst case position errors (due to shaft wind up while delivering maximum planetary gear output torque) are less than 1 degree at the planetary gear output shaft.

The design prototype contains two of these remotely driven, distally-located 700:1 planetary gearheads, each of which drives a rigid joint. As detailed in Figure 3, after the proximal roll joint, the first remotely-driven planetary gearhead drives a pitch joint which articulates to ±72° from the neutral position. This rotation is imparted by a tensioned cable assembly (blue in Figure 4) which communicates the planetary gearhead output, across two pulleys, and to the distal joint. A cable assembly was chosen because it minimizes backlash while allowing control over joint compliance through cable selection and pretension. Here, the cable is a 0.15 mm polyimide line (this choice was sufficient for the present experiment, but more axially-stiff choices may be considered in future work). With a maximum actuator speed of 714 rad/s, this distal pitch joint can attain a maximum rotational velocity of 0.39 rad/s.

The distal roll joint is designed similarly; the output of the remotely-driven planetary gear is again communicated to the joint by a cable assembly, though with the complication of having to traverse the distal pitch joint. While many approaches exist, size constraints limit design freedom. In this prototype the cable traverses the distal pitch via a common pulley, where each side of the cable fully wraps the pulley, as seen in Figure 4. As this pulley is located on the pitch axis the cable length is constant for any pitch articulation. This approach introduces coupling between the two distal joints, but this is easily accounted for by considering joint geometry. After crossing the pitch joint, the cable motions are directed across two pulleys which apply these motions to the distal roll pulley. The current design permits approximately ±120° of roll actuation at up to 0.44 rad/s velocity.

The catheter can actuate through approximately 180º (in which it is U-shaped) while the proximal roll is constrained

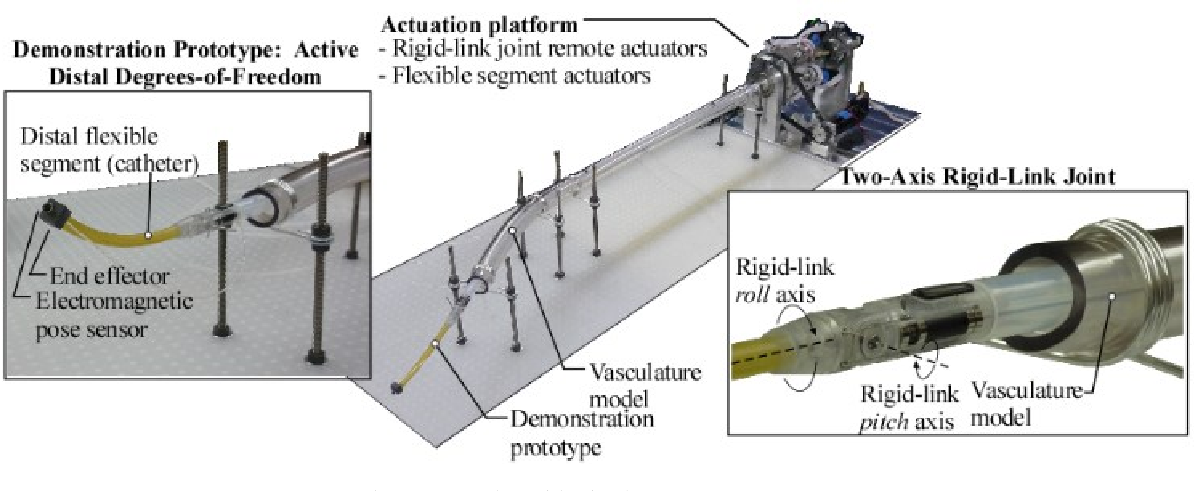

Figure 5. Overview of the development prototype.

only by the power and data cable windup, approximately ±200º. With all joints at zero deflection, the catheter is 100 mm in length, and the distal joint assembly is 57 mm for a total length of device length of 157 mm beyond the proximal flexible segment.

This design prototype is a scaled version of a clinical device, such that the maximum dimensions are informed by medical catheters. The design catheter is 6.35 mm in diameter which is approximately 3x larger than a clinical catheter. The proximal section measures 13 mm in diameter, which is a factor of 2 larger than a typical catheter guide sheath. This 13 mm largest diameter is determined by the planetary gearhead diameters which are each 6 mm in diameter with a 1 mm center bore for the catheter actuation tendon, as seen in Figure 4.

Lastly, the design prototype structure consists of four 3D-printed parts produced on a 3D Systems Viper si2 SLA printer. The decision to 3D print was made early in the design process as it enables part geometries that would, at the very least, be difficult to produce through a traditional, subtractive process. The prototype parts are satisfactory, though a metal structure would allow higher force transmission and higher print resolutions would permit even more compact designs. All of the metal pulleys and shafts were produced in a typical machine shop. This design uses a number of 6 and 3 mm bearings to minimize joint friction, and the catheter tendon is guided through these joints by Teflon 'spaghetti' tubing to avoid inducing substantially more friction through the addition of the rigid joints and during their actuation.

IV. Functional Evaluation

To evaluate the functional performance of the demonstration prototype, a vasculature model test bed was developed. The purpose of the test bed is to provide realistic support conditions for the interleaved prototype device in the context of the cardiac imaging application described earlier. In particular, the vasculature model attempts to emulate the support provided by the femoral vein, which is a common entry path into the right atrium and other chambers of the heart. The model consists of a vinyl tube with an inner diameter of 19 mm and a 27º bend where the femoral vein would enter the heart. An overview of the vasculature model test bed is shown in Figure 5.

As seen in Figure 5 and discussed earlier, the demonstration prototype is approximately three times larger than a clinical version would be. The scalability of the concept will be discussed after the results; for now, note this scaling when considering Figure 5 and the following results.

As a first example of the capability of this approach, Figure 6 demonstrates consistent pointing direction during tip translation. Here, the task is to point at a target while constraining the proximal roll to zero rotation and the catheter to articulate from 0.5 to 2.5 rad. These constraints are typical and were chosen to minimize flexible segment errors while producing a nontrivial motion. The motion lies in a horizontal plane and progresses from the top right to the lower left in the upper panel of Figure 6. The commanded position and pointing angle are given in blue, while the red vectors are measured by the electromagnetic pose sensor located at the catheter tip (as indicated in Figure 5).

As expected (for an open-loop controller), position and pointing angle error slowly increase through the trajectory. Note that the pointing error increases and then decreases over the maneuver. This may be caused by friction in the catheter having a delaying effect, such that the initial control tendon inputs are not immediately realized and thus, the angle strays from the frictionless kinematic model. The catheter and distal pitch are primarily responsible for the motion; the observed error is attributable to unmodeled friction in the catheter and limitations in the fabrication of the rigid joints.

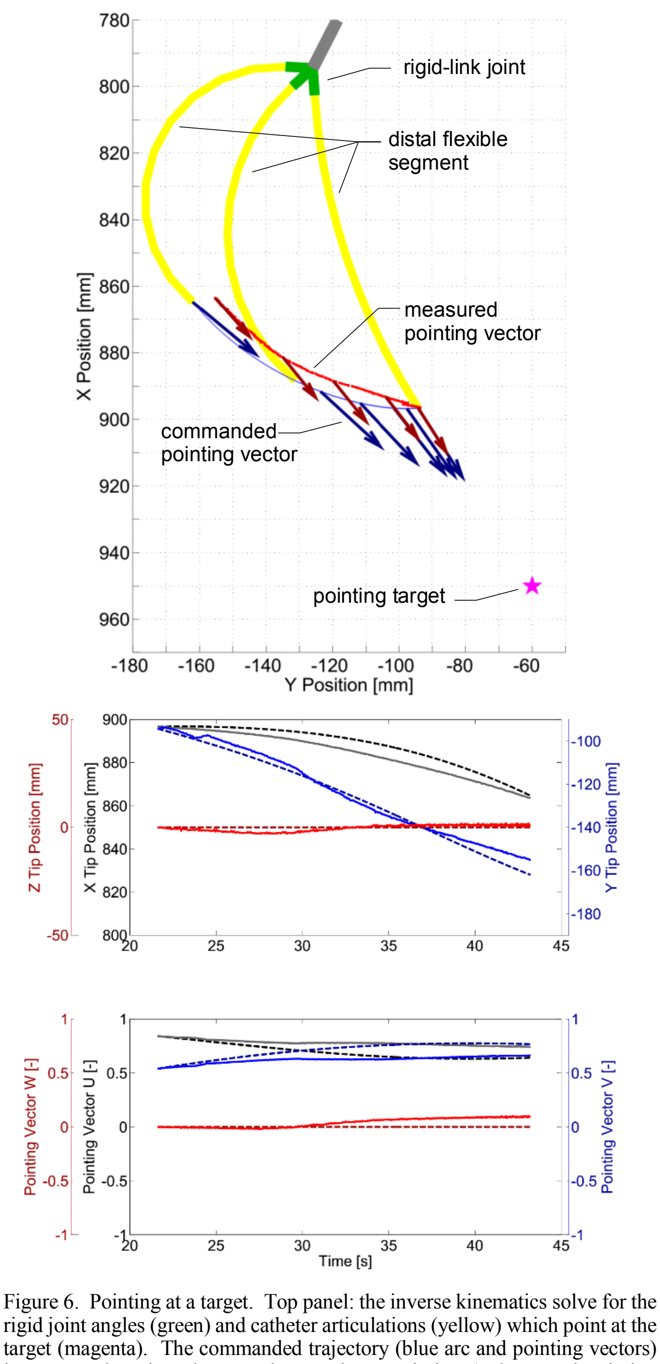

Figure 6. Pointing at a target. Top panel: the inverse kinematics solve for the rigid joint angles (green) and catheter articulations (yellow) which point at the target (magenta). The commanded trajectory (blue arc and pointing vectors) is compared against the open-loop catheter pointing (red arc and pointing vectors) with motion progressing from right to left. Lower panel: The position and vector components from the top panel, showing the commanded with dashed lines (--) and achieved as solid lines (-).

A second test demonstrated the complex motions made possible by the redundant kinematics of an interleaved manipulator. In Figure 8, the manipulator tracks a target which translates along a line according to a sine wave with an amplitude of 20 mm and a frequency of 0.12 rad/s while the distal pitch is driven from -1.4 to -0.5 rad and a catheter-to-tip distance of 60 mm is maintained. The joint motions required are shown in the sequence of snapshots shown in Figure 8. The commanded joint angles to affect the motion shown in Figure 8 is shown in Figure 7.

To track the target under the indicated constraints requires complex motions from all of the joints. This kind of sinusoidal target motion may be anticipated in a cardiac application to compensate for the motion of the heart. At this stage of the development, no effort was made to tie the target motion to actual heart wall movements but it serves to illustrate the utility of the redundancy. The linearly-increasing distal pitch angle alters the manipulator null space such that a constant sinusoidal tip motion results in varying joint commands.

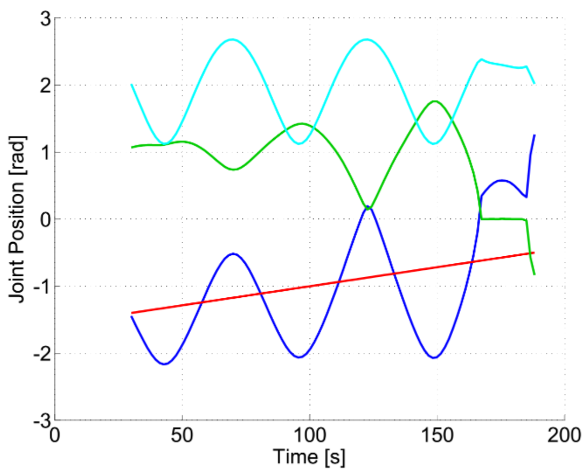

Figure 7. Joint position commands for the motion shown in Figure 8. The distal pitch (red) is constrained to actuate linearly from -1.4 to -0.5 rad, while the proximal roll (blue), distal roll (green), and catheter (cyan) are solved by the inverse kinematics. Not shown is the constant, 60 mm tip-to-target distance of the virtual joint.

The control of the demonstration prototype described here has been entirely open-loop, in that no attempt was made to correct for the flexible segment errors using the motion of the rigid-link joints. To realize the benefit of the proposed approach, particularly in regards to motion control improvements, the use of feedback is essential. In earlier work [32] we described the used of closed-loop control using a one degree-of-freedom testbed. In that work, performance gains were achieved using the interleaved approach both in regards to the speed of the motion and the reduction in motion errors. Similar performance gains are expected for the demonstration prototype described here. Currently, the multi-degree-of-freedom interleaved controller is under development and evaluation. Unfortunately, preliminary results were not available at the time of submission.

Figure 8. Frames from the accompanying video of the motion in Figure 7.

V. Summary

We have described a new manipulation approach, referred to as the interleaved continuum-rigid manipulation, which combines inherently safe, flexible actuated segments with more precise embed rigid-link joints. The redundantly actuated manipulator possesses the safety characteristics inherent in flexible segment only devices while gaining some of the performance gains possible with rigid-link joint and link systems. A demonstration prototype was developed, the purpose of which was to explore the design space as well as demonstrate the feasibility of the approach in a clinically-relevant form. In general, the major design challenge centered on the miniaturization of the rigid link joints. In this case, we have shown, through the development and functional evaluation of the demonstration prototype, that the embedded rigid-link joint concept is feasible. The enabling technology included the use of high-speed remote actuation, implemented via a flexible drive shaft and high reduction, joint-located gear train, and flexible segment – rigid link joint motion decoupling.

VI. References

[1] *Intuitive Surgical, Inc*. Available: http://www.intuitivesurgical.com
[2] C. Bergeles and Y. Guang-Zhong, "From Passive Tool Holders to Microsurgeons: Safer, Smaller, Smarter Surgical Robots," *Biomedical Engineering, IEEE Transactions on,* vol. 61, pp. 1565-1576, 2014.
[3] Stereotaxis. *NIOBE® Magnetic Navigation System*. Available: www.stereotaxis.com

[4] *Hansen Medical, Inc.* Available: http://www.hansenmedical.com/
[5] J. Jung, R. S. Penning, and M. R. Zinn, "A modeling approach for robotic catheters: effects of nonlinear internal device friction," *Advanced Robotics,* vol. 28, pp. 557-572, 2014/04/18 2014.
[6] R. Penning, J. Jung, N. Ferrier, and M. Zinn, "An Evaluation of Closed-Loop Control Options for Continuum Manipulators," presented at the IEEE International Conference on Robotics and Automation, Saint Paul, Minnesota, USA, 2012.
[7] V. Reddy, P. Neuzil, P. Ricard, B. Schmidt, D. Shah, P. Jais, J. Kautzner, A. Natale, G. Hindricks, C. Herrera, Y. Vanekov, H. Lambert, and K.-H. Kuck, "Catheter Contact Force During Ablation of Atrial Flutter and Atrial Fibrillation: Results From the TOCCATA Multi-Center Clinical Study," *Circulation,* vol. 120, pp. 5705-5706, 2009.
[8] T. King, "Catheter Control System System Requirements Specification (Hansen Medical, Inc)," ed. Mountain View, CA, 2006.
[9] P. E. Dupont, J. Lock, B. Itkowitz, and E. Butler, "Design and Control of Concentric-Tube Robots," *Robotics, IEEE Transactions on,* vol. 26, pp. 209-225, 2010.
[10] R. Webster, J. Swensen, J. Romano, and N. Cowan, "Closed-Form Differential Kinematics for Concentric-Tube Continuum Robots with Application to Visual Servoing," in *Experimental Robotics*. vol. 54, O. Khatib, V. Kumar, and G. Pappas, Eds., ed: Springer Berlin / Heidelberg, 2009, pp. 485-494.
[11] R. J. Webster, J. M. Romano, and N. J. Cowan, "Mechanics of Precurved-Tube Continuum Robots," *Robotics, IEEE Transactions on,* vol. 25, pp. 67-78, 2009.
[12] J. Lock and P. E. Dupont, "Friction modeling in concentric tube robots," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, 2011, pp. 1139-1146.
[13] X. Ran, A. Asadian, A. S. Naidu, and R. V. Patel, "Position control of concentric-tube continuum robots using a modified Jacobian-based approach," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, 2013, pp. 5813-5818.
[14] A. Degani, H. Choset, A. Wolf, and M. A. Zenati, "Highly articulated robotic probe for minimally invasive surgery," in *Robotics and Automation (ICRA), Proceedings IEEE International Conference on*, 2006, pp. 4167-4172.
[15] A. Degani, H. Choset, A. Wolf, T. Ota, and M. A. Zenati, "Percutaneous Intrapericardial Interventions Using a Highly Articulated Robotic Probe," in *Biomedical Robotics and Biomechatronics (BioRob), The First IEEE/RAS-EMBS International Conference on*, 2006, pp. 7-12.
[16] H. Choset and W. Henning, "A follow-the-leader approach to serpentine robot motion planning," *ASCE Journal of Aerospace Engineering,* vol. 12, pp. 65-73, 1999.
[17] C. M. Rivera-Serrano, P. Johnson, B. Zubiate, R. Kuenzler, H. Choset, M. Zenati, S. Tully, and U. Duvvuri, "A Transoral Highly Flexible Robot: Novel Technology and Application," *Laryngoscope,* vol. 22, pp. 1067–1071, May 2012 2012.
[18] T. Ota, A. Degani, D. Schwartzman, B. Zubiate, J. McGarvey, H. Choset, and M. A. Zenati, "A novel highly articulated robotic surgical system for epicardial ablation," in *Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE*, 2008, pp. 250-253.
[19] R. S. Penning, J. Jung, J. A. Borgstadt, N. J. Ferrier, and M. R. Zinn, "Towards closed loop control of a continuum robotic manipulator for medical applications," in *Robotics and Automation (ICRA), IEEE International Conference on*, 2011, pp. 4822-4827.
[20] M. Mahvash and P. E. Dupont, "Stiffness Control of Surgical Continuum Manipulators," *Robotics, IEEE Transactions on,* vol. 27, pp. 334-345, 2011.
[21] D. B. Camarillo, C. F. Milne, C. R. Carlson, M. R. Zinn, and J. K. Salisbury, "Mechanics Modeling of Tendon-Driven Continuum Manipulators," *Robotics, IEEE Transactions on,* vol. 24, pp. 1262-1273, 2008.
[22] X. Kai and N. Simaan, "An Investigation of the Intrinsic Force Sensing Capabilities of Continuum Robots," *Robotics, IEEE Transactions on,* vol. 24, pp. 576-587, 2008.
[23] F. Arai, M. Ito, T. Fukuda, M. Negoro, and T. Naito, "Intelligent assistance in operation of active catheter for minimum invasive surgery," in *RO-MAN '94 Nagoya, Proceedings., 3rd IEEE International Workshop on Robot and Human Communication*, 1994, pp. 192-197.
[24] Y. Bailly, A. Chauvin, and Y. Amirat, "Control of a high dexterity micro-robot based catheter for aortic aneurysm treatment," in *Robotics, Automation and Mechatronics, 2004 IEEE Conference on*, 2004, pp. 65-70.
[25] V. K. Chitrakaran, A. Behal, D. M. Dawson, and I. D. Walker, "Setpoint regulation of continuum robots using a fixed camera," *Robotica,* vol. 25, pp. 581-586, 2007.
[26] X. Kai and N. Simaan, "Actuation compensation for flexible surgical snake-like robots with redundant remote actuation," in *Robotics and Automation (ICRA), Proceedings IEEE International Conference on*, 2006, pp. 4148-4154.
[27] A. Bajo and N. Simaan, "Kinematics-Based Detection and Localization of Contacts Along Multisegment Continuum Robots," *Robotics, IEEE Transactions on,* vol. 28, pp. 291-302, 2012.
[28] W. Wei and N. Simaan, "Modeling, Force Sensing, and Control of Flexible Cannulas for Microstent Delivery," *Journal of Dynamic Systems, Measurement, and Control,* vol. 134, p. 041004, 2012.
[29] J. Jayender, M. Azizian, and R. V. Patel, "Autonomous Image-Guided Robot-Assisted Active Catheter Insertion," *Robotics, IEEE Transactions on,* vol. 24, pp. 858-871, 2008.
[30] J. Jayender, R. V. Patel, and S. Nikumb, "Robot-assisted Active Catheter Insertion: Algorithms and Experiments," *The International Journal of Robotics Research,* vol. 28, pp. 1101-1117, September 1, 2009 2009.
[31] S. G. Yuen, D. T. Kettler, P. M. Novotny, R. D. Plowes, and R. D. Howe, "Robotic Motion Compensation for Beating Heart Intracardiac Surgery," *The International Journal of Robotics Research,* pp. 1355-1372, 2009.
[32] B. L. Conrad, J. Jinwoo, R. S. Penning, and M. R. Zinn, "Interleaved continuum-rigid manipulation: An augmented approach for robotic minimally-invasive flexible catheter-based procedures," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, 2013, pp. 718-724.
[33] W. T. Townsend, "The effect of transmission design on force-controlled manipulator performance," Ph.D. Ph.D., Dept. of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1988.
[34] W. T. Townsend and J. K. Salisbury, "Mechanical bandwidth as a guideline to high-performance manipulator design," in *Robotics and Automation, 1989. Proceedings., 1989 IEEE International Conference on*, 1989, pp. 1390-1395 vol.1393.