Design of a Compact Manipulator with Six Degrees-of-Freedom for Flexible Access Surgery

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Introduction: Making life-saving "flexible access" surgical procedures a reality will require novel robotic platforms that can (1) access remote operative target sites through complex pathways from single incisions or natural orifices, and (2) perform dexterous actions within a highly constrained workspace at the target site. While flexible endoscopy can sometimes afford the necessary access, many existing and emerging systems lack adequate instrument dexterity at the distal end required for tissue dissection, destruction, and reconstruction, as reviewed in [1]. Our current study evaluates the feasibility of a remotely actuated compliant mechanism to afford dexterous six-degree-of-freedom manipulation of surgical end-effectors within a tightly confined space at the tip of a flexible endoscope. We present the design, construction, and analysis of a compact, compliant, parallel manipulator. We validate a kinematics model for the device and assess its suitability for surgical procedures.

Materials and Methods: The manipulator design utilizes six compliant spring-steel rods that extend from the endoscope tip and connect to an end-effector platform in a parallel hexapod fashion (Figure 1, middle). These actuation rods pass through low-friction channels in a flexible endoscope, and their bases are translated by a custom actuation module (Figure 1, left) using six linear servo actuators from Firgelli Technologies, Inc. A custom cable-actuated gripper (Figure 1, right) and other tools can be incorporated into the end-effector platform.

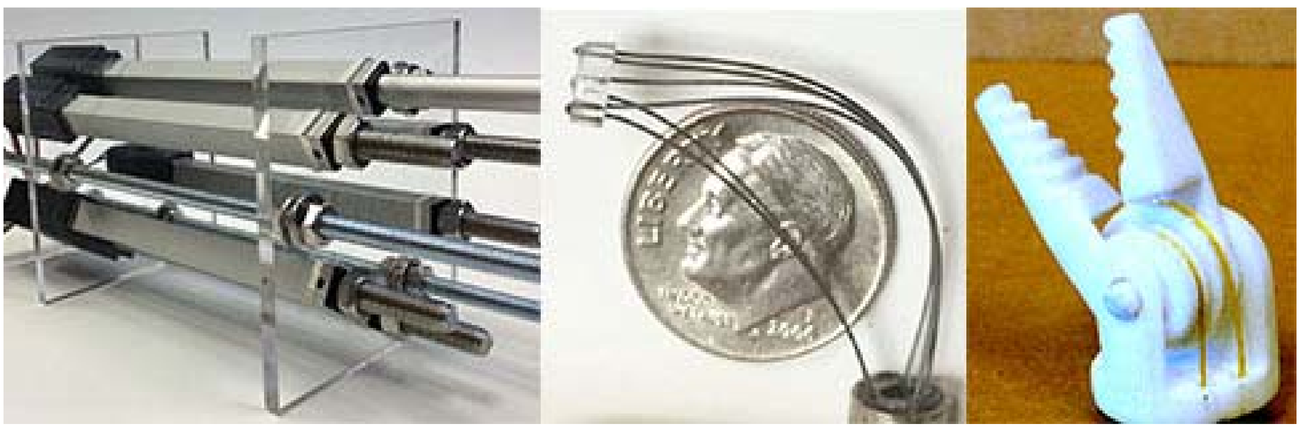

Figure 1. Components of our prototype system used for feasibility and validation studies.

We formulate a rod-mechanics model for the kinematics of the manipulator which calculates the position and orientation of the end-effector platform as a function of the displacements of the control rods by the linear actuation system. This approach also yields the required actuation forces and captures the large deformations that each rod undergoes which collectively give rise to the dexterous motion of the manipulator. We experimentally validated the accuracy of this model using a large-scale prototype structure and a camera measurement system.

Results and Discussion: Over a set of 14 experimental cases, we found that modeling error in the position of the end effector with less than 3% of manipulator length, and angular error was within 3.5°. Toward refining the gripper design, several 12, 10, and 5 mm end-effectors were fabricated that demonstrate ease of miniaturization. Further, our model simulations and experiments demonstrate that the manipulator is capable of a range of dexterous motion in six degrees-of-freedom, which is currently needed for flexible access endoscopic surgery.

Conclusions: We conclude from our experimental results and the fabrication of our prototype system that compact and dexterous distal-end manipulators can be feasibly constructed, modeled, and incorporated into the paradigm of flexible endoscopy. Future work will address model-based teleoperation via a haptic input device.

References:

[1] V. Vitiello, S. Lee, T.P. Cundy, and G.Yang, "Emerging Robotic Platforms for Minimally Invasive Surgery," *IEEE Reviews in Biomedical Engineering,* , vol.6, pp.111-126, 2013.