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Design and Optimization of a Tensioner-Driven Compliant Pulley Mechanism for Supermicrosurgical Robot End-Effectors

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***Abstract*— Supermicrosurgery requires exceptionally high-precision manipulation to perform anastomosis of microscopic vessels and nerves, often involving diameters between 0.3 mm and 0.8 mm. To achieve successful outcomes with robotic systems, it is critical to ensure the stable grasping and delicate manipulation of ultra-fine needles and sutures under varying surgical conditions.This paper proposes a spring-based flexible pulley mechanism designed specifically to overcome the fundamental limitations of conventional cable-driven systems, most notably the unpredictable tension fluctuations. Instead of traditional fixed pulleys, the proposed mechanism introduces a tensioner-driven pulley displacement, allowing the system to maintain optimal tension dynamically.We present a comprehensive mathematical framework that includes a non-linear kinematic model and static equilibrium equations to describe the interaction between spring compression and wire tension. To maximize manipulation performance, we performed optimization of the design parameters using MATLAB simulations, focusing on the guaranteed grasping force and the workspace limits defined by the rotation of the motor shaft.Our results demonstrate that the mechanism ensures a stable grasping force even at significant angular displacements, with a specific rotation range of ±40° optimized for surgical needle manipulation. This compliant pulley system effectively resolves geometric complexities and ensures driving symmetry, providing a robust hardware solution for next-generation supermicrosurgical robots. The integration of this mechanism promises to enhance the control precision and reliability of robotic end-effectors in delicate surgical environments.**

I. INTRODUCTION

Supermicrosurgery involves the anastomosis of minute vessels and nerves, typically 0.3 to 0.8 mm in diameter. [1], [2] Due to the extreme delicacy of these structures, [3] manual procedures are exceptionally challenging, necessitating robotic assistance to overcome human physical limitations. [4], [5] For success, robotic systems must reliably manipulate ultra-fine needles and sutures with sub-millimeter precision.

Recently, surgical robots have adopted cable-driven mechanisms for operations in narrow, complex environments. [6] While these systems allow for a lightweight end-effector by remote motor placement, they suffer from degraded precision caused by cable elongation and tension fluctuations. [7]

To address these issues, this study proposes a novel end-effector utilizing a spring-based flexible pulley mechanism. By replacing fixed pulleys with tensioner-driven displacement, this design resolves non-linear geometric complexities and ensures driving symmetry. Consequently, the mechanism achieves enhanced control precision and hardware stability while optimizing the operational range of motion.

II. MODELING OF TENSIONER-DRIVEN PULLEY MECHANISM

To actuate the end-effector of a cable-driven surgical robot, a reciprocal wound/unwound mechanism is utilized. Theoretically, as the motor rotates, the sum of the wire lengths deployed between each loop remains constant. However, in practice, the total deployed wire length varies due to cable slack or changes in tension.

To minimize these variations, we designed a tensioner-driven pulley mechanism where the pulley undergoes displacement via a spring. The primary design variables and geometric parameters of this mechanism are summarized in Table I.

TABLE I: Parameter of Tensioner-driven Pulley mechanism

Parameter	Description
l_0	Free length of the spring
l	Compressed length of the spring
d	Distance between spring end and pulley
y_{sp}	Vertical (y-axis) distance from shaft to pulley
x_s	Horizontal (x-axis) distance from reference to shaft
F_w	Wire tension
F_s	Spring compressive force
N	Vertical (y-axis) normal force supported by the tensioner

To analyze the static equilibrium, the relationship between F_w and F_s is derived as follows, with the free-body diagram shown in Figure 1:

$$F_w = \frac{F_s}{1 + \sin\theta} \tag{1}$$

where θ is the wound angle defined by:

$$\begin{aligned} \theta = {} & \tan^{-1}\left[\frac{x_s - (l_0 + l + d)}{y_{sp}}\right] \\ & + \sin^{-1}\left[\frac{r_p - r_s}{\sqrt{(x_s - l_0 + l - d)^2 + y_{sp}^2}}\right] \end{aligned} \tag{2}$$

The deployed wire length l_p is defined as:

$$\begin{aligned} l_p = {} & (l_0 - l + d) + r_p\left(\frac{\pi}{2} + \theta\right) \\ & + \sqrt{(x_s - l_0 + l - d)^2 + y_{sp}^2 - (r_p - r_s)^2} \end{aligned} \tag{3}$$

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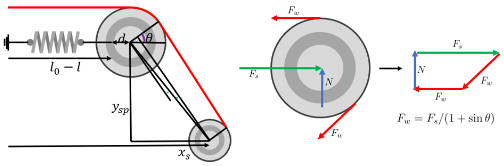

Fig. 1: Modeling of Tensioner-driven Pulley mechanism.

III. Result and Conclusion

To precisely model and optimize the system's behavior, we established a nonlinear kinematic mapping framework. This model calculates the instantaneous contact angle through a functional relationship, $\theta = f(l)$, which serves as the basis for determining both the total wire length ($l_w = f(l)$) and the effective tension ($T = f(l)$). By incorporating these varying geometric factors, the model ensures high fidelity in tension estimation across the entire range of motion.

Furthermore, a numerical approach was employed to maintain the holonomic constraint, defined by the principle that the sum of the wire lengths must remain constant ($l_1 + l_2 = \text{Constant}$). To solve this constraint at each simulation increment, we utilized the fzero function in MATLAB to iteratively track the solution for l_2 corresponding to changes in l_1.(**Fig. 2**)

Building on this framework, a nested optimization routine was implemented to identify the optimal neutral point (l_{t_opt}). This was achieved by developing a calculate torque imbalance function, which systematically searches for a configuration that minimizes the torque deviation at the offset positions of both ends. (**Fig. 3**). This integrated numerical approach ensures that the mechanism achieves maximum static symmetry and consistent performance throughout its operational workspace.

The feasibility of the proposed design was successfully validated through a comprehensive analysis of its performance and safety characteristics. By deriving the optimal neutral point (l_{t_opt}), we ensured static symmetry, which guarantees a symmetric torque output even during bidirectional displacements of up to 2.5 mm. Furthermore, the system's ability to achieve the target torque of 5 mNm at the end-effector was visually confirmed, demonstrating its practical suitability for microsurgical tasks. Finally, we established a "Safe Zone" (l_{safe_low} to l_{safe_high}) by accounting for the maximum allowable tension (T_{sum_max}) and physical hardware limits, providing a robust theoretical foundation for control logic aimed at preventing hardware failure.

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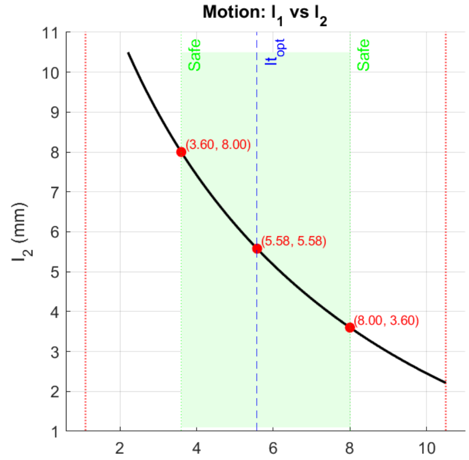

Fig. 2: Numerical relationship between l_1 and l_2

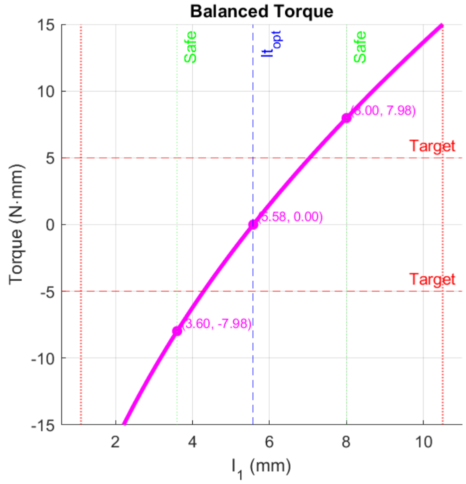

Fig. 3: Optimization of static symmetry

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