

A New Decoupling Method for Cable-Driven Joints Based on an Anti-Parallelogram Mechanism

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Abstract— This paper proposes a novel anti-parallelogram mechanism (APM)-based cable-driven joint that achieves both the kinematic decoupling characteristic of rolling joints and the surface-contact robustness of link structures. Through the optimization of internal idlers, the cable path length remains nearly constant without complex gears or ligaments. Experimental validation using a 2-DOF prototype demonstrated negligible distal joint interference (0.0815° RMSE) during actuation. Furthermore, the system exhibited sub-millimeter positional repeatability (maximum RMSE of 0.2786 mm), establishing the proposed design as a robust, high-precision decoupling solution.

I. INTRODUCTION

As human-robot interaction (HRI) gains significance, safe and agile lightweight manipulators are essential. Consequently, cable-driven mechanisms are widely adopted, as they drastically reduce joint inertia by placing heavy actuators at the base. However, in multi-degree of freedom (DOF) serial manipulators, routing cables to distal joints through proximal links inevitably causes kinematic coupling, severely complicating control. To kinematically resolve this coupling, rolling contact joints are widely used for mechanical decoupling, maintaining constant cable lengths during rotation to prevent interference [1,2]. However, their fundamental reliance on line-contact makes rolling joints highly vulnerable to slip, necessitating problematic constraints like gears or wire ligaments. These additions introduce critical flaws, such as backlash-induced precision loss and ligament stretching, which complicate assembly and maintenance.

To overcome the mechanical flaws of line-contact rolling joints, a link-based anti-parallelogram mechanism (APM) can be considered. Its surface-contact approach eliminates slippage, ensuring robustness under high cable tension without complex gears or ligaments. While previous research attempted decoupling in a 1-DOF APM joint using external Bowden cables, the high friction between the inner wire and outer sheath drastically reduces power transmission efficiency [3]. Thus, a link-based joint that simultaneously achieves decoupling and routes actuation cables directly through its interior—without high-friction external constraints—remains undeveloped.

Therefore, this study proposes a novel cable-driven joint that overcomes both the line-contact flaws of rolling joints and the limitations of existing APM applications. By leveraging the surface-contact architecture of the APM, the proposed

design inherently secures high mechanical robustness. Furthermore, the key distinguishing feature of this study is that the drive cables are routed directly through the joint interior, avoiding high-friction external constraints. By optimizing the cable routing via internal idler positioning, the cable path length remains nearly constant across the entire range of motion, effectively achieving mechanical decoupling. This research focuses on the mechanical validation of this decoupling architecture through the development of a 2-DOF system.

II. JOINT MECHANISM DESIGN

To achieve decoupling in the APM joint, optimizing cable routing via idler positioning is essential to minimize length variations. Figure 1. shows the 2-DOF prototype concept, where optimized idlers maintain a constant absolute angle for the second joint (pin) regardless of the first joint's (APM) rotation.

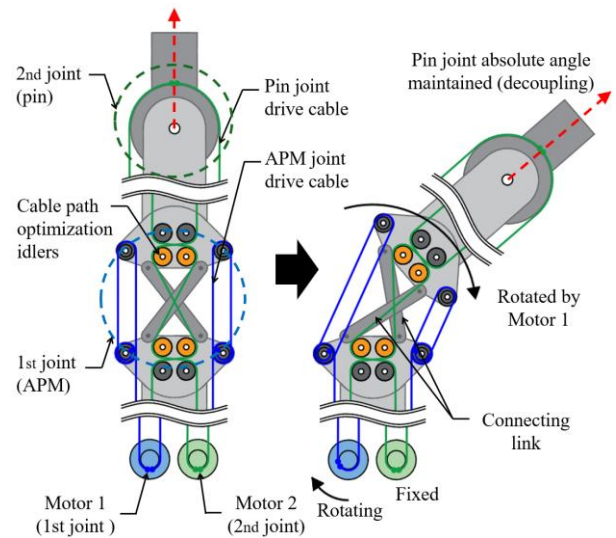


Figure 1. Conceptual diagram of the proposed APM joint demonstrating mechanical decoupling.

Figure 2. shows the variation in cable routing length according to the joint rotation angle when the cable path is optimized by adjusting the idler positions. The joint angle range for the optimization was set to $\theta \in [-90^\circ, 90^\circ]$, and MATLAB's built-in SQP algorithm was utilized. As a result of the optimization, the simulated objective function value

(min-max cable lengths) was only $2.14\mu\text{m}$, confirming that the variation in cable length converges to nearly zero.

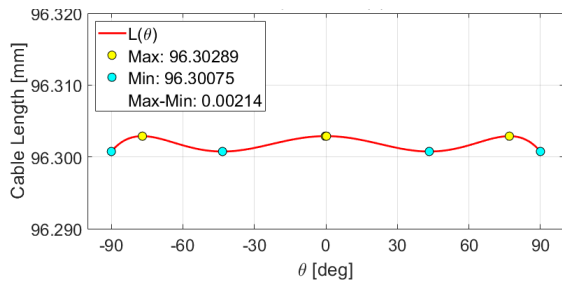


Figure 2. Cable path length variation against joint rotation angle after optimization.

To verify the decoupling and overall performance of the proposed design, a 2-DOF manipulator prototype was fabricated, featuring the APM at the first joint and a conventional pin joint at the second joint, as shown in the Figure 1. Figure 3. shows overall design of the 2-DOF manipulator prototype. The drive system consists of Dynamixel XH430-W350-R motors operated via an OpenCR controller. Tension is transmitted using stainless steel wire cables, with in-line load cells integrated to monitor cable tension.

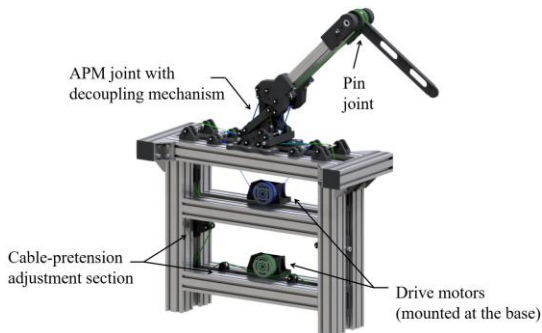


Figure 3. Overall design of the 2-DOF manipulator prototype built to validate the proposed APM joint.

III. EXPERIMENTS AND RESULTS

To validate the proposed design, a 2-DOF manipulator prototype was evaluated using a motion capture system. The experiment consists of two parts: 1) decoupling validation, which measures the pin joint's absolute angle variation during APM joint's rotation, and 2) positional repeatability, which assesses the end-effector's tracking error along a rectangular trajectory.

A. Decoupling Validation

To evaluate decoupling, the APM joint was driven in a $\pm 90^\circ$ reciprocating motion (20s period, 8 cycles) while the pin joint motor remained stationary. As shown in Figure 4., despite the APM joint's large-stroke rotation, the pin joint's absolute angle remained nearly zero. With an RMSE of just 0.0815° , the results confirm that the proposed design effectively isolates the distal joint, achieving robust mechanical decoupling.

B. Position Repeatability

To assess positional repeatability, the end-effector was commanded to track a rectangular trajectory defined by four

vertices (P_1 to P_4) via the simultaneous actuation of both joints, as shown in Figure 5. The tracking motion was performed for 10 consecutive cycles with a 20s period. The measured RMSE values for the four vertices were remarkably low: 0.0623 mm (P_1), 0.2672 mm (P_2), 0.2632 mm (P_3), and 0.2786 mm (P_4). These sub-millimeter errors effectively confirm that the proposed coupled joint system ensures high positional repeatability.

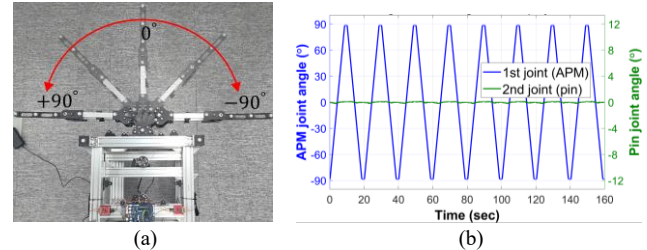


Figure 4. Decoupling validation experiment. (a) APM joint reciprocating between $\pm 90^\circ$ with pin joint fixed. (b) Absolute angles.

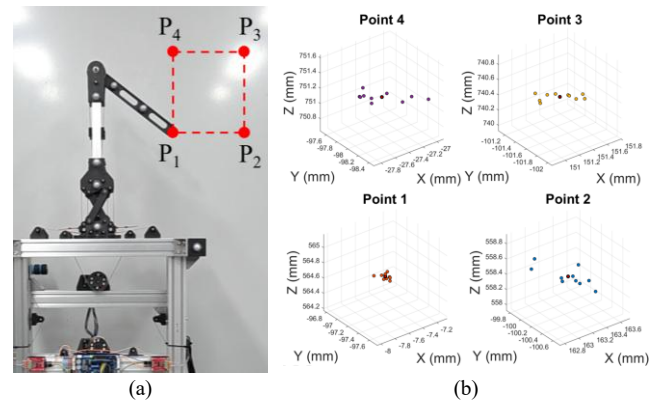


Figure 5. Position repeatability experiment. (a) Rectangular trajectory repeatability experiment. (b) Positional error at each vertex.

IV. CONCLUSION

This paper proposes a novel APM-based cable-driven joint that simultaneously achieves the kinematic decoupling of rolling joints and the surface-contact robustness of link structures. Focusing strictly on validating this decoupling capability, Experimental evaluations on a 2-DOF prototype successfully verified the design's effectiveness, demonstrating negligible distal joint interference and minimal position tracking error. Future work will expand this planar architecture into fully spatial multi-DOF or quaternion joints.

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