OmniDexter: A Modular Tendon-Driven Robotic Wrist with Enhanced Precision and Versatility

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***Abstract*—This work presents OmniDexter, a novel tendon-driven robotic wrist integrating three degrees of freedom (DoF) with an innovative mechanism to enable an additional external DoF. The design tackles the inherent challenges of elliptical wrist motion, which complicates z-axis alignment and hinders the integration of extra DoFs. By introducing a unique anti-parallelogram structure with passive prismatic joints, OmniDexter achieves precise approximation of elliptical motion as circular, enhancing stability and control under high-payload conditions. This approach facilitates seamless adaptation to various end-effectors, significantly expanding the versatility and functionality of robotic arms in demanding applications.**

I. Introduction

The development of cooperative robots has revolutionised human labour, assisting in repetitive, tedious, and risky tasks. Yet, significant safety concerns persist. Robots with large manipulators often exhibit high mass and inertia, posing dangers during high-speed operations. Thus, a critical challenge remains: designing robotic systems that are not only strong and agile but also inherently safe.

A notable milestone in this endeavour is the LIMS2-AMBIDEX (LIMS2) system [1], which introduced a 3-DoF tendon-driven wrist mechanism with unparalleled dexterity and precision. This innovative system employs a parallel link mechanism to achieve pure spherical rolling motion within a compact design. By relocating actuators away from the end-effector, LIMS2 reduces bulk and inertia, enhancing both safety and performance. However, its fixed wrist-to-hand connection limits its versatility, restricting its motion to rotations.

Addressing this limitation, we sought to extend the LIMS2's wrist design by adding an external DoF to facilitate greater functionality. Initial attempts involved a nested structural design. However, the inherent elliptical roll and pitch motion of LIMS2's wrist presented challenges. The z-axis alignment between the wrist's upper and lower bases could not be maintained, resulting in mechanical complexities that hindered the seamless integration of an additional DoF.

To overcome these challenges, we present a novel solution: a passive anti-parallelogram structure equipped with prismatic joints. This mechanism maintains z-axis alignment by compensating for the elliptical motion of the tendon-driven wrist. By eliminating rotational offsets and improving stability, particularly under high payloads, this design significantly enhances the system's precision and adaptability.

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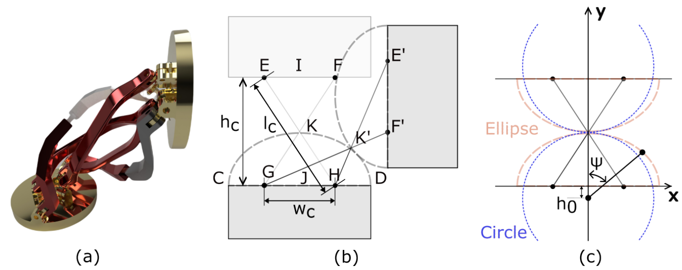

Fig. 1. Design and motion analysis of OmniDexter. (a) A rendering of the tendon-driven wrist mechanism. (b) The geometric configuration, highlighting the trapezoidal structure responsible for elliptical motion. (c) A comparison between the elliptical trajectory and its circular approximation.

Our proposed solution (Fig. 1(a)) not only resolves the mechanical limitations of existing tendon-driven systems but also lays the foundation for future enhancements, including the integration of versatile end-effector tools. In this extended abstract, we present an overview of the design, functionality, and potential applications of this novel system, emphasising its transformative impact on robotic manipulation.

II. System Design and Implementation

The novel contribution of this work lies in the integration of an additional DoF to a tendon-driven wrist mechanism, inspired by the LIMS2's wrist design. This section details the challenges posed by elliptical wrist motion and the innovative solution of the anti-parallelogram structure with passive prismatic joints.

A. Elliptical Motion Challenge

The motion of the LIMS2's wrist mechanism is governed by its unique geometric configuration, based on an isosceles trapezoid, $GEFH$, as shown in Fig. 1(b). The trapezoid's property, $GK + KH = EK + KF =$ constant, ensures an elliptical trajectory for the wrist's roll and pitch motions. This elliptical motion can be expressed mathematically by the standard equation of an ellipse:

$$\frac{x^2}{\left(\frac{l_c}{2}\right)^2} + \frac{y^2}{\left(\frac{h_c}{2}\right)^2} = 1, \tag{1}$$

where l_c and h_c are the semi-major and semi-minor axes, respectively.

This elliptical motion complicates integration with additional DoFs, as the z-axis alignment between the upper and lower base frames cannot be maintained. This misalignment introduces rotational offsets, especially under high-payload conditions, limiting the wrist's adaptability for end-effector tools. To address this, the elliptical trajectory is approximated as circular by introducing a small offset, h_o, as shown in Fig. 1(c). The radial distance, $r(\psi)$, as a function of the angle ψ from the y-axis, is defined as:

$$r(\psi) = \frac{h_o + \sqrt{h_o^2 + \left(1 + \frac{w_c^2}{h_c^2}\tan^2\psi\right)\left(\frac{w_c^2}{4} - h_o^2\right)}}{\cos\psi\left(1 + \frac{w_c^2}{h_c^2}\tan^2\psi\right)}. \quad (2)$$

For sufficiently small h_o, $r(\psi)$ becomes nearly constant, enabling the elliptical motion to be approximated as circular. This simplification is critical to reducing mechanical complexity and ensuring precise alignment.

B. Anti-Parallelogram Solution

To facilitate the addition of a 4^{th} DoF while addressing the challenges of elliptical motion, we propose a novel anti-parallelogram structure with passive prismatic joints. This mechanism effectively maintains z-axis alignment and mitigates rotational offsets during operation.

The anti-parallelogram structure, incorporates six linkages connecting the top and bottom platforms. These linkages form two approximated anti-parallelogram mechanisms, one for the inner and one for the outer circular motion. While the inner structure achieves high accuracy in approximating circular motion, the outer structure initially exhibited significant offsets, as shown in Table I.

TABLE I
EXPERIMENTAL DATA FOR OUTER STRUCTURE OFFSETS

Base's Radius (mm)	Radius of Curvature (mm)	Mean Radius (mm)	Offset h_o (mm)
Inner - 12.2	74	73.5559	0.4441
Outer - 39	53	80.7078	27.7078

To resolve this, the outer structure was redesigned to incorporate passive prismatic joints at the centre of the linkages, and the number of linkages has been reduced to two, shown in Fig. 2(a). This adjustment reduced constraints and allowed the structure to accommodate translational motion, ensuring consistent alignment across the z-axis. The resulting design significantly improves the wrist's compatibility with additional DoFs.

III. Simulation and Validation

The proposed anti-parallelogram mechanism was simulated in a 3D model to validate its performance. As shown in Fig. 2(b), the nested anti-parallelogram structure successfully integrates with the tendon-driven wrist

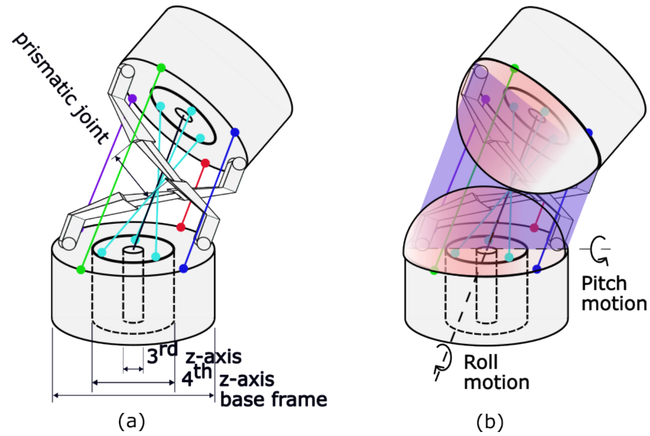

Fig. 2. (a) Anti-parallelogram structure with passive prismatic joints; (b) 3D simulation of the proposed design.

to provide a seamless 4^{th} DoF. The prismatic joints enable precise adjustments to roll and pitch motions while maintaining z-axis stability.

Simulations demonstrate that the pitch motion of the base frame, driven by the anti-parallelogram structure, follows a nearly perfect circular trajectory. This eliminates the rotational offsets observed in previous designs and ensures compatibility with end-effector tools such as grippers, cutters, and saws. The results confirm that the proposed design offers enhanced precision and adaptability for high-payload robotic applications.

IV. Conclusion

This work introduces a novel tendon-driven wrist mechanism with an additional degree of freedom, addressing key limitations of existing designs like LIMS2's wrist mechanism. By employing an innovative anti-parallelogram structure with passive prismatic joints, the proposed system resolves the challenges posed by elliptical motion, ensuring precise z-axis alignment and enhancing stability under high payloads.

The additional DoF expands the wrist's capability, enabling seamless integration with a variety of end-effector tools, such as grippers, cutters, and saws. This versatility significantly enhances the adaptability of robotic arms, making them suitable for a wide range of industrial and precision tasks. Future work will explore real-world implementations and further refinements to optimise performance in dynamic environments.

References

[1] H. Song *et al.*, "Development of low-inertia high-stiffness manipulator LIMS2 for high-speed manipulation of foldable objects", *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2018, pp. 4145–4151.