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Ultra-Low-Impedance Robotic Gripper for High-Bandwidth and Transparent Physical Interaction

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***Abstract*—Conventional robotic grippers relying on external force sensors or high gear-ratio actuators suffer from high mechanical impedance and limited control bandwidth. To address these limitations, this study proposes a novel 9-DOF, three-fingered Direct-Drive Differential (DDD) gripper that integrates DD motors with an low gear ratio (1:2) differential transmission. This mechanism centralizes the actuator mass at the base to achieve an ultra-low inertia design, while the differential architecture couples motors in parallel to amplify torque for flexion movements. Performance evaluations demonstrate that the prototype delivers a nominal grasping force of 15 N and a fingertip force of 3.1 N, while maintaining a remarkably low system inertia (motor contribution of 0.236%) and mechanical impedance (<700 N/m) within the typical human manipulation frequency range. The proposed hardware successfully resolves the trade-offs among torque, transparency, and kinematics, establishing a robust foundation for highly responsive, sensorless proprioceptive force estimation in dynamic environments.**

***Index Terms*—Robotic Gripper, Direct-Drive, Differential Mechanism, Low-Impedance**

I. INTRODUCTION

Dexterous manipulation, such as grasping and in-hand manipulation, inherently involves physical interaction with unstructured environments. Managing these interactions effectively requires a system that is intrinsically responsive to contact force [1]. Therfore, to realize robust and adaptive manipulation, hardware with ultra-low inertia and high physical transparency is needed.

While conventional grippers often employ high gear ratio actuators for torque generation, the resulting mechanical nonlinearities, such as friction and backlash, destroy the system's physical transparency. Because this degraded transparency distorts contact dynamics, conventional systems are forced to rely on external force sensors to perceive environmental interactions. However, these sensors inevitably increase system complexity and introduce low-pass filtering effects that limit control bandwidth [2].

To fulfill this critical requirement of high physical transparency, researchers have turned to highly backdrivable actuator paradigms. Direct-Drive (DD) motors have been employed to completely bypass the structural constraints of gear reduction [3]. While DD systems offer transparent power transmission, resulting in high control bandwidth and the capability for sensorless force estimation, they suffer from low torque output. Alternatively, Quasi-Direct-Drive (QDD) actuators have been proposed to secure both sufficient grasping force and proprioception [4]. Yet, QDD grippers still lack the physical transparency of DD systems and the kinematic degrees of freedom(DOFs) essential for dexterous manipulation.

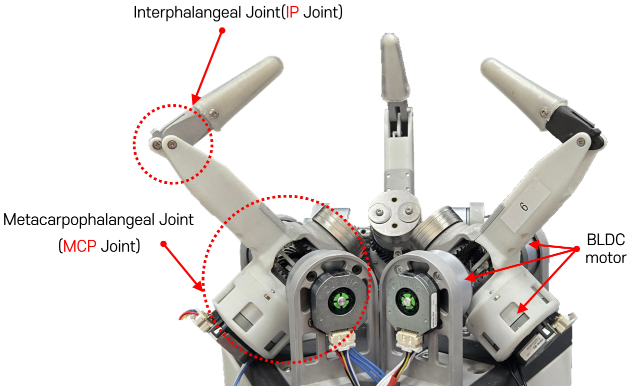

Fig. 1: Overall View of Direct Drive Differential Gripper

Motivated by these trade-offs among torque, transparency, and kinematics, this study proposes a novel 9-DOF, three-fingered gripper mechanism that integrates DD motors with differential gear transmission. This architecture optimizes actuator placement to secure high DOFs while effectively compensating for the torque density limitations of pure DD systems. Furthermore, the proposed mechanism maximizes physical transparency, enabling precise external force estimation relying solely on motor current, ultimately realizing highly dexterous movements.

II. MECHANISM DESIGN

This study presents the mechanism of the Direct Drive Differential (DDD) gripper, which utilizes a total of nine DD motors—three dedicated to each finger—coupled with a differential gear transmission. Fig. 1 illustrates the overall hardware configuration of the proposed DDD gripper. The gripper is composed of three fingers, where each finger features two mechanical joints: the Metacarpophalangeal (MCP) and Interphalangeal (IP) joints. Driven by these joints, each finger possesses 3 DOFs: MCP flexion, MCP abduction, and IP flexion.

As shown in Fig. 2, the MCP joint are actuated by two motors via the differential mechanism. Synchronous rotation of both motors in the same direction produces flexion, whereas rotation in opposite directions results in abduction. The IP joint is driven by the rear motor utilizing a four-bar linkage mechanism. By restricting the linkage to operate within its linear region, the system successfully evades kinematic singularities while ensuring a linear, 1:1 angular mapping between the actuator and the joint.

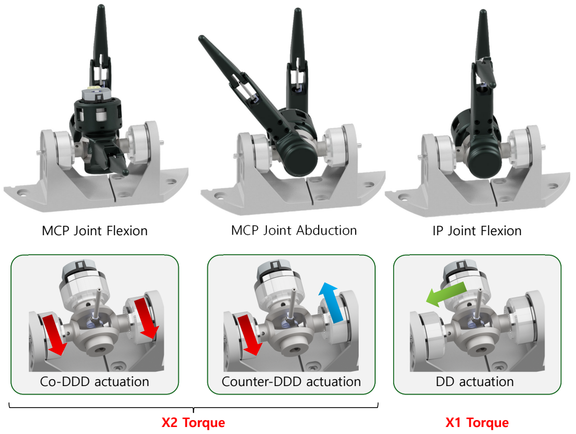

Fig. 2: Operating Principle

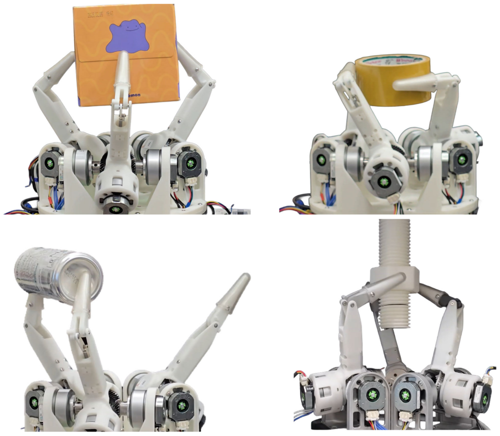

Fig. 3: Grasping Demo

The integration of the differential gear mechanism serves critical purposes in addressing the inherent limitations of pure DD actuators by optimizing both mass distribution and torque output. First, centralizing the relatively heavy motor modules at the base of the finger achieves an ultra-low inertia design, which significantly minimizes moving link inertia and enhances dynamic responsiveness. Second, it strategically allocates actuation power. As the MCP joint requires higher torque than the IP joint due to a larger effective moment arm during object grasping, the differential mechanism couples two motors in parallel during MCP flexion, providing a twofold (2x) torque amplification. To mitigate the friction typically introduced by geared transmissions, the differential employs an ultra-low gear ratio of 1:2. By leveraging this DD foundation, the system facilitates high-bandwidth, high-precision control, maximizing backdrivability and physical transparency for precise, sensorless force estimation.

III. FABRICATION

The prototype of DDD gripper utilizes BLDC motors (GL35, CubeMars). The overall structural frame is fabricated via 3D printing (Form4, Formlabs). A single finger module weighs approximately 800g, resulting in a total gripper weight of 2.4 kg. Since the placement of the DD motors at MCP shifts the center of mass, integrated counterweights are employed. This mass distribution was kinematically optimized to mitigate weight imbalance, thereby reducing the gravity compensation burden on the controllers and achieving optimal equilibrium during dynamic movements.

Performance evaluations validate the efficacy of this design. In terms of force generation, the system delivers a fingertip force of 3.1 N per module and a total nominal grasping force of 15 N. Furthermore, regarding its dynamic characteristic, the motor's contribution to the total system inertia is remarkably low at 0.236%. Under quasi-static conditions, the gripper exhibits low mechanical impedance ($<$700 N/m) within the typical human manipulation frequency range (under 20 Hz).

To demonstrate practical dexterity, grasping experiments were conducted on various everyday objects, including a can, a box, and a roll of tape. Furthermore, the system successfully executed an unscrewing task, validating its capability for complex manipulation. The overall grasping test procedures are illustrated in Fig. 3.

IV. DISCUSSION AND CONCLUSION

In this study, we developed a novel 9-DOF Direct-Drive Differential gripper designed to resolve the inherent trade-offs among torque output, physical transparency, and kinematic dexterity. By integrating DD motors with a low gear ratio differential mechanism, the gripper successfully achieves an ultra-low inertia design while maintaining a sufficient nominal grasping force. These hardware characteristics validate the system's potential for high-bandwidth control and robust physical interaction without relying on external force sensors.

Building upon the high physical transparency achieved by the proposed mechanism, future work will primarily focus on developing a robust proprioceptive force estimation framework. By leveraging the system's low inertia and high backdrivability, we plan to implement sensorless force control algorithms based on accurate dynamic modeling. While further structural optimization of the frame will be conducted as a secondary refinement, our ultimate goal is to demonstrate advanced, sensorless dexterous manipulation in dynamic real-world environments.

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