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Decreasing the Apparent Inertia of Human-Scale Teleoperation Systems

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INTRODUCTION

In unconstrainted movements, haptic devices should allow users to move freely with minimal perceived inertia. Yet, designing devices with a workspace comparable to the human arm often leads to bulky systems with high inertia. To address this challenge, we propose an approach based on inverse dynamics modeling that reduces the inertia experienced by the user. The method has been implemented on a WAM teleoperation system, showing that inverse dynamics can effectively improve transparency in large haptic devices.

MATERIALS AND METHODS

1) Position-Position Teleoperation System

In a Position–Position (P–P) teleoperation system, only the robots' positions are exchanged: the leader's motion defines the follower's trajectory, and vice versa. Transparency in free motion requires accurate position tracking by the follower and low impedance on the leader to ensure smooth operator control. In contrast, during contact tasks, higher leader gains are needed for the operator to feel the interaction forces, and ideally both robots should use identical gains for consistent force–motion behavior. These conflicting requirements create trade-offs, making it difficult to achieve perfect transparency in both free motion and contact.

2) Dynamic-Compensated P-P Teleoperation System

To address the limitations of the basic P–P scheme, we propose a controller that incorporates the inverse dynamics of both the leader and follower robots as feedforward terms. By compensating for the robots' dynamics within the control loop, the follower achieves more accurate position tracking while the leader exhibits reduced impedance, making it easier for the operator to move. This design improves transparency in free motion while maintaining transparency in hard contact, thereby overcoming the trade-offs of conventional P–P systems.

RESULTS AND DISCUSSION

We evaluate our method on a human-scale WAM teleoperation system (Fig 1). To objectively assess performance in free motion, known torques are applied to the leader robot and the resulting positions are recorded. Tracking performance is measured by the position error between the leader and follower, while leader impedance is quantified from the resistance encountered during motion. Ideally, both metrics should be close to zero. We compare the proposed dynamic-compensated controller (2c-DynComp) with the gravity-compensated P–P controller (2c-GravComp). As summarized in Table 1, 2c-DynComp achieves lower position tracking error and leader impedance than 2c-GravComp, with statistically significant improvements ($p\text{-value} < 0.05$).

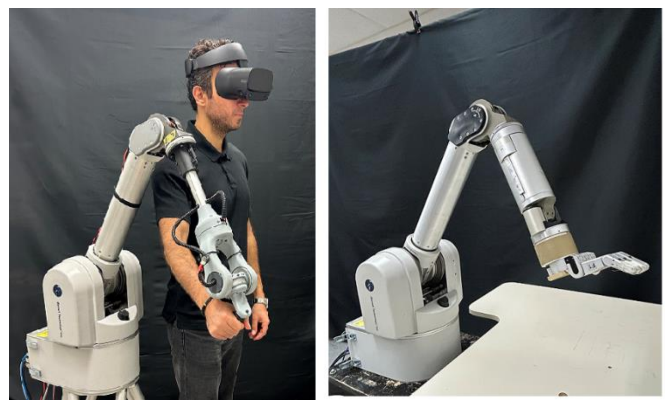

Fig 1 WAM teleoperation system with a 4-DOF leader arm equipped with a haptic wrist (left) and a 7-DOF follower arm (right).

CONCLUSIONS

In this work, we proposed a dynamic-compensated P–P controller to improve transparency in bilateral teleoperation. The method requires no additional sensors or hardware and relies only on robot dynamics. Experiments on a customized WAM system showed significant improvements in free-motion performance, with tracking error and leader impedance greatly reduced.

REFERENCES

[1] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," IEEE Transactions on Robotics and Automation, vol. 9, no. 5, pp. 624–637, 1993.

Table 1: Transparency performance metrics: free motion positing tracking error and leader's impedance.

Controller	Position Tracking Error (NRMSE, %)		Leader's Impedance (Nm/rad)	
	Joint 2	Joint 4	Joint 2	Joint 4
2c-GravComp	1.672 ± 0.660	4.922 ± 2.052	52.319 ± 21.459	24.911 ± 7.854
2c-DynComp	0.412 ± 0.036	0.283 ± 0.081)	10.707 ± 0.851	1.314 ± 0.279