3rd Workshop Toward Robot Avatars
IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
Abu Dhabi, UAE, 2024.

Development of a Collaborative Robotic Arm-based Bimanual Haptic Display

Joong-Ku Lee, and Jee-Hwan Ryu

***Abstract*— This paper presents a bimanual haptic display based on collaborative robot arms. We address the limitations of existing robot arm-based haptic displays by optimizing the setup configuration and implementing inertia/friction compensation techniques. The optimized setup configuration maximizes workspace coverage, dexterity, and haptic feedback capability while ensuring collision safety. Inertia/friction compensation significantly improve transparency and reduce user fatigue, leading to a more seamless and transparent interaction. This research contributes to the advancement of haptic technology by presenting a practical and effective solution for creating high-performance bimanual haptic displays using collaborative robot arms.**

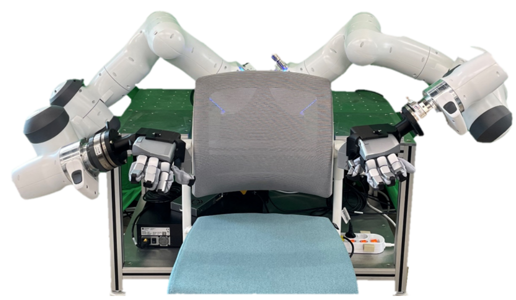

Fig. 1: Bimanual haptic display with Franka Emika Panda robot arm with optimized setup configuration

I. Introduction

The increasing interest in the Metaverse and Extended Reality (XR) technologies, aloing with projects such as ALOHA [1] that aim to emulate human bimanual dexterity, has emphasized the need for advanced bimanual haptic displays. The haptic display capable of tracking human motion and prividing realistic force feedback are crucial for creating immersive and interactive user experience.

Commercially available haptic displays presently face limitations in covering the complete human arm workspace and delivering adequate force/torque feedback. While existing devices can be combined into bimanual systems, these setups are often restricted to desktop environments and offer limited feedback, making them unsuitable for dexterous bimanual interactions. Devices designed to cover the full human arm workspace typically demand significant dedicated space, limiting their practicality. Exoskeleton-based solutions largely remain in the research domain due to limited commercial availability and development complexities [2], [3].

Previous research has explored utilizing collaborative robot arms as the basis for bimanual haptic displays. Examples include the DLR's system based on DLR/KUKA LWR arms [4], [5] and the NimbRo team's Franka Emika Panda robot implementation [6]. However, these previous efforts often overlooked key aspects such as optimizing the robot configuration to balance workspace, force feedback, and human-robot interaction safety. Additionally, they also fell short in addressing the inherent inertia and friction of the robot arms, which can significantly impact the quality of the haptic experience.

This paper aims to bridge these gaps by presenting a comprehensive approach to developing a collaborative robot arm-based bimanual haptic display. We detail the implementation of key techniques, including setup configuration optimization and friction/inertia compensation, to enhance the effectiveness of collaborative robots as haptic devices.

Authors are with the Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea. {iamjoong9, jhryu}@kaist.ac.kr

II. System Design and Implementation

This section details the core technologies that enable the use of collaborative robot arms as haptic displays: setup configuration optimization and inertia/friction compensation.

A. Setup Configuration Optimization

The performance of a collaborative robot-based bimanual haptic display is significantly influenced by its setup configuration, which encompasses the base position and orientation of the robot arms, as well as the grab angle between the human hand and the robot end-effector.

The setup configuration impacts factors such as workspace and haptic feedback force/torque, which directly affect the overall performance of the haptic display. To address this, [7] proposed an optimization scheme to identify the best-performing setup configuration. The optimization process considers several key factors:

1) Workspace coverage: The haptic display should cover the human arm workspace as comprehensively as possible to facilitate seamless and natural human arm movements.

2) Redundancy: Robot arm redundancy is crucial for enabling dexterous human arm movements and mitigating the risk of human-robot collisions.

3) Renderable haptic feedback force/torque: The robot arms must be capable of delivering sufficient haptic feedback force/torque across all directions to ensure realistic and immersive interaction.

4) Human-robot collision: The optimization process prioritizes minimizing the potential for collisions between the human operator and the robot arms, ensuring a safe user experience.

The optimized setup configuration for the Franka Emika Panda robot arm is depicted in Fig. 1. Our bimanual haptic display is built upon this setup configuration.

B. Inertia/Friction Compensation

One of the primary challenges in employing industrial collaborative robots as haptic displays lies in their relatively high inertia and friction levels compared to dedicated haptic devices. The presence of inertia and friction can adversely affect the accuracy and precision of haptic feedback, potentially leading to increased user fatigue, particularly during extended periods of operation.To address the inertia challenge, we implement the inertia reshaping method proposed in [8]. The fundamental principle of this method is to employ joint torque feedback as a control input to modify the effective inertia of the robot arm. The selection of the reshaping ratio BB_{θ}^{-1} is a key design parameter. In our system, we empirically determined this ratio to be 3 for translational movements and 4 for rotational movements to achieve a balance between responsiveness and stability. Inertia reshaping was conducted using measurements from the force-torque (FT) sensor.

While the inertia reshaping method effectively addresses the inertia challenge, residual friction within the system can still impact the performance of the haptic display. To mitigate this, we employ an energy-based friction compensation method proposed in [9]. This method leverages the relationship between input energy, stored energy, and energy dissipated through friction to adaptively estimate and compensate for the time-varying friction coefficient. The core principle behind this approach is the observation that when the stored energy in the system is zero, there exists a clear relationship between the net energy input and the energy dissipated by friction, allowing for friction estimation without requiring explicit model information.

This energy-based friction compensation method offers two key advantages when applied to collaborative robot arms:

1) Independence from robot system model information: The method estimates friction based on the energy levels observed during human-robot interaction, eliminating the need for precise robot model identification.

2) Ease of online implementation: It directly estimates friction coefficients for a given friction model without requiring any system-specific tuning parameters, simplifying the implementation process.

We apply this energy-based friction compensation method on top of the inertia reshaping method. For the experiment, the first joint of the robot was used. Although only a single joint is tested in this study, the proposed method is applicable to all joints of the robot. The result demonstrate a significant reduction in the interaction torque required to move a single robot joint when both methods are combined (blue line in Fig. 2). Furthermore, the combined approach outperforms each method applied individually (purple, green line in Fig. 2), highlighting the effectiveness of their synergistic integration.

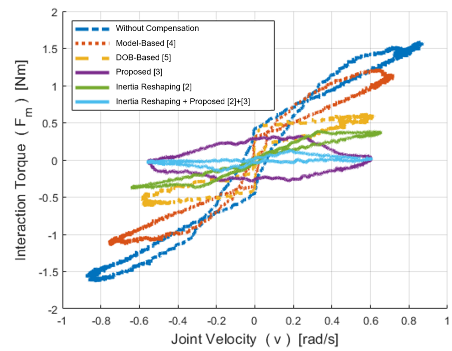

Fig. 2: Joint velocity vs. interaction torque curve with different friction compensation methods. The combination of inertia reshaping and energy-based friction compensation method outperforms other methods.

Fig. 3: A proposed bimanual haptic display combined with a haptic glove and a VR headset

III. Results

The proposed techniques are integrated into the bimanual haptic device depicted in Fig. 3, which utilizes two Franka Emika Panda robot arms. Furthermore, the figure illustrates a potential configuration showcasing our proposed bimanual haptic display in conjunction with a Senseglove Nova haptic glove and a Vive XR Elite VR headset. The dexterity and transparency of our system are anticipated to provide users with a highly realistic and immersive experience.

IV. Conclusion

This paper introduces a collaborative robot arm-based bimanual haptic display that addresses the limitations of existing devices. By optimizing the setup configuration and implementing inertia/friction compensation, we have significantly enhanced the system's performance and user experience. The proposed system's dexterity, transparency are anticipated to enable its application across a wide range of use cases.

Future research will focus on refining the system's capabilities and exploring its integration with diverse haptic interfaces to create even more immersive and interactive experiences.

REFERENCES

[1] Z. Fu, T. Z. Zhao, and C. Finn, "Mobile aloha: Learning bimanual mobile manipulation with low-cost whole-body teleoperation," *arXiv preprint arXiv:2401.02117*, 2024.

[2] M. Mallwitz, N. Will, J. Teiwes, and E. A. Kirchner, "The capio active upper body exoskeleton and its application for teleoperation," in *Proceedings of the 13th Symposium on Advanced Space Technologies in Robotics and Automation. ESA/Estec Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA-2015). ESA*, 2015.

[3] C. Carignan, J. Tang, and S. Roderick, "Development of an exoskeleton haptic interface for virtual task training," in *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2009, pp. 3697–3702.

[4] T. Hulin, K. Hertkorn, P. Kremer, S. Schätzle, J. Artigas, M. Sagardia, F. Zacharias, and C. Preusche, "The dlr bimanual haptic device with optimized workspace," in *2011 IEEE International Conference on Robotics and Automation*. IEEE, 2011, pp. 3441–3442.

[5] F. Zacharias, I. S. Howard, T. Hulin, and G. Hirzinger, "Workspace comparisons of setup configurations for human-robot interaction," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2010, pp. 3117–3122.

[6] C. Lenz and S. Behnke, "Bimanual telemanipulation with force and haptic feedback and predictive limit avoidance," in *2021 European Conference on Mobile Robots (ECMR)*. IEEE, 2021, pp. 1–7.

[7] J.-K. Lee and J.-H. Ryu, "Optimizing setup configuration of a collaborative robot arm-based bimanual haptic display for enhanced performance," *IEEE Robotics and Automation Letters*, 2024.

[8] A. Albu-Schäffer, C. Ott, and G. Hirzinger, "A unified passivity-based control framework for position, torque and impedance control of flexible joint robots," *The international journal of robotics research*, vol. 26, no. 1, pp. 23–39, 2007.

[9] H. T. Dinc, J.-K. Lee, and J.-H. Ryu, "Model-free energy-based friction compensation for industrial collaborative robots as haptic displays," *IEEE/ASME Transactions on Mechatronics*, 2024.