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

Network-aware Shared Autonomy in Bilateral Teleoperation

Xiao Chen[1,†], Youssef Michel[2], Hamid Sadeghian[1], Abdeldjallil Naceri[1] and Sami Haddadin[1]

***Abstract*— In this work, an autonomy allocation approach is proposed for bilateral teleoperation systems to improve user performance under suboptimal communication networks. To achieve this, an autonomous agent is deployed on the teleoperated side, leveraging pre-existing task knowledge for shared autonomy, and the autonomy level is dynamically adjusted based on the monitored time-varying communication quality metrics such as delay and jitter. Additionally, a time-domain passivity approach is employed to maintain communication channel passivity, mitigating the impact of adverse network behavior on task performance. The proposed approach is validated through user study, and the result shows our approach significantly improved the performance of the subjects ($p < 0.01$).**

I. INTRODUCTION

Bilateral teleoperation presents a versatile solution applicable across various scenarios and environments. However, bilateral teleoperation poses several challenges. First, teleoperation demands mental acuity and proficiency and needs time and practice to attain the required skills based on the transparency of the teleoperation interface and the complexity of the task. To tackle this, many *shared autonomy* paradigms have already been proposed to cover different perspectives [1] using the prior task knowledge to assist the human, in free motion [2]–[5] or with physical interaction by the teleoperated robot [6]–[11].

Network quality, including latency and jitter, is another major challenge in direct and bilateral teleoperation, significantly affecting system performance and user experience by impacting system stability, and degrade transparency, diminishing the operator's sense of presence, especially in contact tasks [12]–[14]. Passivity-based approaches [15]–[17] only ensure the stability but degrade the transparency [18]. Therefore, communication network quality should be inversely proportional to the level of autonomy: high network quality allows more human control, and vice versa. Few works have used shared control to mitigate delay effects and improve task performance [19], [20].

II. PROPOSED METHOD

A. Bilateral teleoperation system

A basic Position-Force (P-F) architecture for a bilateral teleoperation system is illustrated in Fig. 1 (block (a)). The leader robot velocity $\dot{\boldsymbol{x}}_l$ and the follower interaction force $\boldsymbol{f}_{ext,f}$ are transmitted through the communication channel to the other side as desired value for the controller.

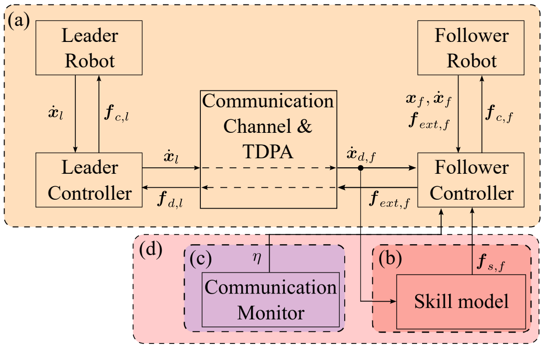

Fig. 1. Illustration of the proposed architecture for network-aware. Block (a) is a P-F bilateral teleoperation system stabilized by TDPA. Block (b) includes skill models and generates force to complete the skill. Block (c) is the communication monitor agent, which measures the quality of communication and allocates autonomy to the follower robot. Block (d) is an autonomous agent (AA) that allocates autonomy and generates autonomous commands.

B. Follower controller with shared autonomy

The autonomy level of the follower robot spans from direct teleoperation to full autonomy [1].

In **direct teleoperation mode**, the follower robot endeavors to track the desired position and velocity provided by the leader robot using a PD controller,

$$\boldsymbol{f}_t = \boldsymbol{K}_t(\boldsymbol{x}_{d,f} - \boldsymbol{x}_f) + \boldsymbol{D}_t(\dot{\boldsymbol{x}}_{d,f} - \dot{\boldsymbol{x}}_f) \tag{1}$$

In **full autonomous mode**, a force $\boldsymbol{f}_s$ is generated from the force field associated with the learned skill, drives the robot to finish the skill. Similar to [11], the force field is designed as a combination of the path [21] and flow control [22] laws:

$$\boldsymbol{f}_s = \begin{cases} \boldsymbol{f}_p = \boldsymbol{K}_p(\boldsymbol{x}_{d,s} - \boldsymbol{x}_f) - \boldsymbol{D}_p\dot{\boldsymbol{x}}_{d,s} & \text{if } \| \boldsymbol{e} \| > e_{max} \\ \boldsymbol{f}_f = \boldsymbol{D}_f(\dot{\boldsymbol{x}}_{d,s} - \dot{\boldsymbol{x}}_f) & \text{if } \| \boldsymbol{e} \| < e_{min} \\ \gamma(\| \boldsymbol{e} \|)\boldsymbol{f}_p + (1-\gamma(\| \boldsymbol{e} \|))\boldsymbol{f}_f & \text{otherwise} \end{cases} \tag{2}$$

Between these two modes, the follower robot exhibits a certain level of autonomy. The resulting control command from autonomy allocation is,

$$\boldsymbol{f}_{a,f} = (1-\eta)\boldsymbol{f}_t + \eta\boldsymbol{f}_s \tag{3}$$

As the level of autonomy η varies from 0 to 1, the robot smoothly transits from direct teleoperation to full autonomy.

C. Network-quality-based autonomy allocation

The network quality is measured in real-time by a *Communication Monitor* located on the follower side, as illustrated in Fig. 1, part (c). In this work, the **Round trip delay**: $D \in [0, \infty)$, and the **Jitter**: $J \in [0, \infty)$, are monitored. We propose a novel quality index of the communication network:

$$Q = \sqrt{\left(\frac{D}{D_{max}}\right)^2 + \left(\frac{J}{J_{max}}\right)^2}, \tag{4}$$

---

[1] Munich Institute of Robotics and Machine Intelligence and the Chair of Robotics Science and Systems Intelligence, Technical University of Munich, Munich, Germany

[†] Corresponding Author (xiaoyu.chen@tum.de)

[2] Human-centered Assistive Robotics, Technical University of Munich, Munich, Germany.

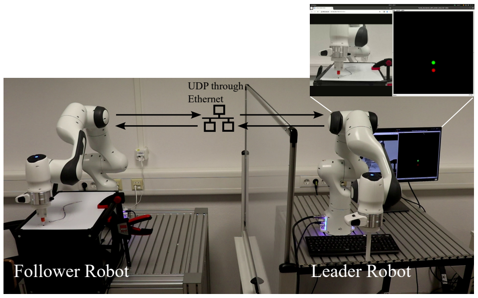

Fig. 2. Experiment setup for a trajectory following skill.

where D_{max} and the J_{max} are the parameters that define the maximum tolerable network condition, designed based on requirements of the application. The level of autonomy is defined as a function related to the quality index Q:

$$\eta = \begin{cases} \frac{\cos(\pi Q+\pi)+1}{2}, & Q \leq 1 \\ 1, & else \end{cases} \tag{5}$$

D. Passivity of teleoperation system under delay

As the main instability source in bilateral teleoperation is the communication channel, the Time Domain Passivity Approach (TDPA) is used to guarantee its passivity.

III. EXPERIMENTAL EVALUATION

A. Experimental setup and procedure

The proposed framework is evaluated with a user study with 6 participants in a trajectory-following scenario using two 7DoF FE Panda robot arms, as depicted in Fig. 2. The users are asked to follow a "S" shape path with follower robot using the leader robot under different conditions $C_i, i = 1 \ldots 3$ as shown in Table I. To learn the task, we follow the approach in [11]. To assess autonomy allocation under varying network conditions, delay and jitter are manipulated through Linux Traffic Control, with monitoring conducted as described in Sec. II-C.

TABLE I
EXPERIMENT CONDITIONS.

	AA	Delay applied	TDPA
C_1	✗	✗	✗
C_2	✗	✓	✓
C_3	✓	✓	✓

In sessions under the *delay applied* condition, after passing the first checkpoint CP_1, a round trip delay of $200ms \pm 20ms$ is applied. Upon reaching CP_2, the delay increases to a fixed $600ms$. Figure 3 shows the delay, jitter, and autonomy level η during one trial. Autonomy η rises to about 0.5 after CP_1 and reaches 1 after CP_2 as conditions worsen, fully autonomizing the follower robot.

B. Experiment result

Fig. 4 illustrates two exemplary trials conducted under conditions C_2 and C_3, depicting the trajectories of the follower robot and the CPs along the desired path. The trajectory under C_2 exhibits a larger deviation from the desired path x_d, which is due to the delayed visual and haptic feedback. Conversely, the trajectory resulting from our shared autonomy approach shows reduced error. Although TDPA only ensures the passivity of the communication channel, no unstable behavior was detected during the experiment.

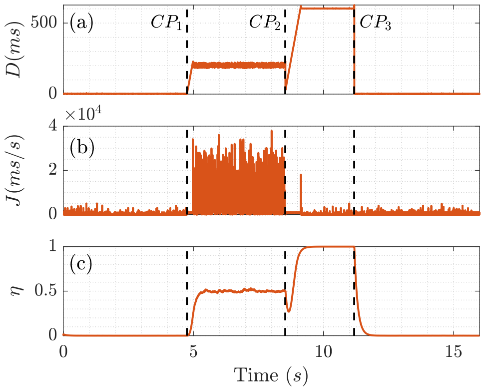

Fig. 3. (a) Delay profile, (b) jitter profile, and (c) autonomy level of one experiment trial. The black dashed line marks the time when the operator passes the checkpoint.

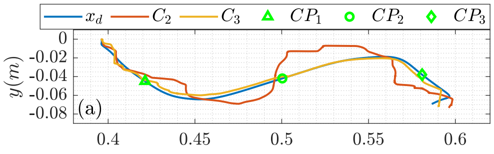

Fig. 4. Experiment result of two trials under different conditions. The green dots illustrate the checkpoints. (a) the follower robot path compared to the desired path.

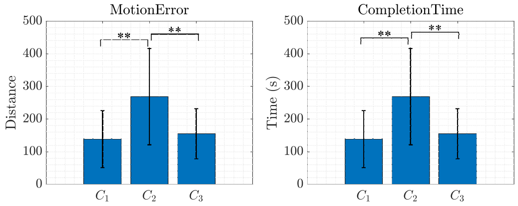

Fig. 5. Experiment results of user study. The left shows the motion tracking error and the right shows the completion time. The blue bars show the mean value under each condition. The vertical black lines show the deviation of the trials. To indicate significance, '**' indicates $p < 0.01$.

In Fig. 5, we show the average of the considered metrics as bar plots as well as the standard deviation. It is obvious that when the delay is present, our approach (C_3) results in a significant improvement in the tracking error metrics and completion time, as compared to C_2, retaining a performance that is comparable to the baseline execution without delays (C_1).

IV. CONCLUSION

In this work, an autonomy allocation approach in a shared teleoperation system is proposed. The quality of communication based on delay and jitter is monitored and used to change the autonomy level between direct teleoperation and an autonomous agent located on the follower side seamlessly. TDPA approach is implemented to ensure the passivity of the communication channel. The experimental scenario shows the superior performance of the system under different communication conditions. Future works will focus on the passivity proof of the whole system and including other communication network metrics.

ACKNOWLEDGMENT

We gratefully acknowledge the funding of the Lighthouse Initiative Geriatronics by StMWi Bayern (Project X, grant no. IUK-1807-0007// IUK582/001) and LongLeif GaPa gGmbH (Project Y). The authors acknowledge the financial support by the Federal Ministry of Education and Research of Germany (BMBF) in the program of "Souver an. Digital. Vernetzt." Joint project 6G-life, project identification number 16KISK002.

REFERENCES

[1] M. Selvaggio, M. Cognetti, S. Nikolaidis, S. Ivaldi, and B. Siciliano, "Autonomy in physical human-robot interaction: A brief survey," *IEEE Robotics and Automation Letters*, vol. 6, no. 4, pp. 7989–7996, 2021.

[2] D. P. Losey, C. G. Mcdonald, E. Battaglia, and M. K. O'Malley, "A review of intent detection, arbitration, and communication aspects of shared control for physical human-robot interaction," *Applied Mechanics Reviews*, vol. 70, pp. 010 804–010 804, 2018.

[3] F. Abi-Farraj, T. Osa, N. P. J. Peters, G. Neumann, and P. R. Giordano, "A learning-based shared control architecture for interactive task execution," in *2017 IEEE Int. Conf. on robotics and automation (ICRA)*. IEEE, 2017, pp. 329–335.

[4] M. J. Zeestraten, I. Havoutis, and S. Calinon, "Programming by demonstration for shared control with an application in teleoperation," *IEEE Robotics and Automation Letters*, vol. 3, pp. 1848–1855, 2018.

[5] A. Pervez, H. Latifee, J.-H. Ryu, and D. Lee, "Motion encoding with asynchronous trajectories of repetitive teleoperation tasks and its extension to human-agent shared teleoperation," *Autonomous Robots*, vol. 43, no. 8, pp. 2055–2069, 2019.

[6] H. Ishida, M. M. Marinho, K. Harada, J. Gao, and M. Mitsuishi, "Virtual-fixtures for robotic-assisted bi-manual cutting using vector-field inequalities," in *2020 IEEE/SICE International Symposium on System Integration (SII)*, 2020, pp. 395–400.

[7] M. M. Marinho, H. Ishida, K. Harada, K. Deie, and M. Mitsuishi, "Virtual fixture assistance for suturing in robot-aided pediatric endoscopic surgery," *IEEE Robotics and Automation Letters*, vol. 5, pp. 524–531, 2019.

[8] R. Moccia, M. Selvaggio, L. Villani, B. Siciliano, and F. Ficuciello, "Vision-based virtual fixtures generation for robotic-assisted polyp dissection procedures," in *2019 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, 2019, pp. 7934–7939.

[9] R. Rahal, F. Abi-Farraj, P. R. Giordano, and C. Pacchierotti, "Haptic shared-control methods for robotic cutting under nonholonomic constraints," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*. IEEE, 2019, pp. 8151–8157.

[10] C. J. Pérez-del Pulgar, J. Smisek, V. F. Muñoz, and A. Schiele, "Using learning from demonstration to generate real-time guidance for haptic shared control," in *IEEE Int. Conf. on Systems, Man, and Cybernetics (SMC)*, 2016, pp. 003 205–003 210.

[11] Y. Michel, Z. Li, and D. Lee, "A learning-based shared control approach for contact tasks," *IEEE Robotics and Automation Letters*, 2023.

[12] G. Niemeyer and J.-J. Slotine, "Towards force-reflecting teleoperation over the internet," in *Proceedings. 1998 IEEE International conference on robotics and automation (Cat. No. 98CH36146)*, vol. 3. IEEE, 1998, pp. 1909–1915.

[13] L. Márton, Z. Szántó, T. Vajda, P. Haller, H. Sándor, T. Szabó, and L. Tamás, "Communication delay and jitter influence on bilateral teleoperation," in *22nd Mediterranean Conference on Control and Automation*. IEEE, 2014, pp. 1171–1176.

[14] X. Chen, L. Johannsmeier, H. Sadeghian, E. Shahriari, M. Danneberg, A. Nicklas, F. Wu, G. Fettweis, and S. Haddadin, "On the communication channel in bilateral teleoperation: An experimental study for ethernet, wifi, lte and 5g," in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2022, pp. 7712–7719.

[15] J.-H. Ryu, J. Artigas, and C. Preusche, "A passive bilateral control scheme for a teleoperator with time-varying communication delay," *Mechatronics*, vol. 20, no. 7, pp. 812–823, 2010, special Issue on Design and Control Methodologies in Telerobotics.

[16] M. Franken, S. Stramigioli, S. Misra, C. Secchi, and A. Macchelli, "Bilateral telemanipulation with time delays: A two-layer approach combining passivity and transparency," *IEEE Transactions on Robotics*, vol. 27, no. 4, pp. 741–756, Aug 2011.

[17] D. Lee and K. Huang, "Passive-set-position-modulation framework for interactive robotic systems," *IEEE Transactions on Robotics*, vol. 26, no. 2, pp. 354–369, 2010.

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

[19] S. Venkataraman and S. Hayati, "Shared/traded control of telerobots under time delay," *Computers Electrical Engineering*, vol. 19, no. 6, pp. 481–494, 1993. [Online]. Available: https://www.sciencedirect.com/science/article/pii/004579069390023K

[20] Z. Ya-kun, L. Hai-yang, H. Rui-xue, and L. Jiang-hui, "Shared control on lunar spacecraft teleoperation rendezvous operations with large time delay," *Acta Astronautica*, vol. 137, pp. 312–319, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094576516304751

[21] A. Duschau-Wicke, J. von Zitzewitz, A. Caprez, L. Lunenburger, and R. Riener, "Path control: A method for patient-cooperative robot-aided gait rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, no. 1, pp. 38–48, 2010.

[22] A. Martínez, B. Lawson, C. Durrough, and M. Goldfarb, "A velocity-field-based controller for assisting leg movement during walking with a bilateral hip and knee lower limb exoskeleton," *IEEE Transactions on Robotics*, vol. 35, no. 2, pp. 307–316, 2019.