Evaluation of a Bilateral Tele-Echographic Architecture in Presence of Time Delay

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***Abstract*—Tele-ecography with force-feedback aims at remotely reproducing ultrasound examination. Current *state-of-the-art* tele-echography systems have been tested on phantoms or humans, but in non-realistic conditions. In fact, most of them do not consider the presence of time delay (that is a source of instability in all teleoperation tasks) or they do not establish sufficient contact forces according to ultrasound requirements. Moreover, none of these architectures take advantage of a robotic solution to relieve doctor's fatigue, which has been demonstrated source of work-related musculoskeletal disorders (WRMSD).**

This paper aims to evaluate the performance of a proposed tele-echography architecture under realistic working conditions, which are the presence of time delay and ultrasound-required contact forces. To deal with instability, two separate transmission networks were implemented and the teleoperation one was passivated according to Time Domain Passivity Approach. Moreover, a user-dependent scaling factor on the force-feedback is proposed to deal with WRMSD. The system has been tested by a single user contacting a custom-made gelatin phantom to identify an immersed screw. The architecture was found successful in the task exhibiting a stable behaviour in presence of $400\ ms$ round trip delay and with contact of $20\ N$.

***Index Terms*—Tele-Medicine, Tele-Echography, Teleoperation, Haptic Feedback**

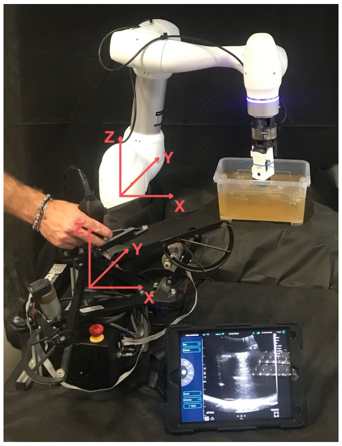


Fig. 1: The proposed bilateral tele-echography architecture is made by a parallel haptic interface with a dummy probe and a collaborative Doosan M0609 robotic arm equipped with a Wi-Fi US probe. The probe sends images to a tablet.

I. INTRODUCTION

The tele-echography, a tele-medicine technology, has gained popularity in recent years due to its ability to provide remote diagnosis, which is particularly useful in distant areas. A tele-echography architecture consists of three main elements:

- doctor-site: a manipulator (leader) guided by a doctor who controls the movements of a dummy probe and receives the ultrasound (US) images
- patient-site: a robot (follower) with the real probe attached to the end effector interacting with the patient
- communication link: allows for interchanging movement and feedback information, video, audio and US information between the doctor-site and the patient-site

Among the first systems developed, there are TER [1] and OTELO [2] in which the doctor bases the diagnosis only on the visualisation of the images. In later years, consideration is given to adding force-feedback to tele-echography architectures allowing the doctor to perceive the patient's body during the examination. Force-feedback enables the doctor to perform an US task more easily and effectively [3], leading to a higher immersivity performing the remote tele-presence task.

Tele-echography is a teleoperation task, thus,*Position-Force measured (PFm)* architectures [4] are often implemented to provide the user with force-feedback. In such a system, the leader is a haptic interface that transmits the position to the follower, which is usually a collaborative robotic arm that sends back to the leader measured-force information. The follower robot allows for a higher doctor autonomy. It is well known that in bilateral teleoperation, time delay over the communication channel leads to instability [5], requiring stabilization methods that often are passivity-based approaches [6]–[8]. Among them, *Time Domain Passivity Approach (TDPA)* is often chosen as passivity layer for its simplicity and effectiveness. However, it is also well known that passivity compromises transparency, which is the ability of the architecture to render the remote impedance to the user [9]. In order to guarantee stability, a passivity-based stabilizing layer is required in presence of time delay, in particular in safety-critical applications where robots are contacting humans.

To perform an effective tele-echography, the implemented bilateral architecture should encounter echographic requirements as defined in [10]. Among these, examination requires a good US image transmission and contact forces up to $27.3\ N$.

In recent years, teleoperation architectures have been developed and tested on phantoms by non-doctor staff applying forces under $12\ N$ [11]–[13], or on voluntary patients by

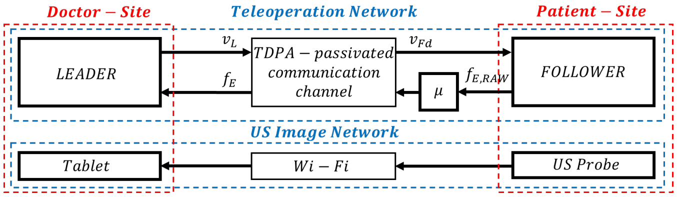


Fig. 2: Network implementation of the proposed tele-echography architecture. Separate teleoperation and a US image networks are highlighted in blue, while local and remote sites in red.

doctors applying forces under 15 N [3], [14]. In all these works, no delay nor a passivity layer was implemented to test the architecture in a realistic scenario. Conversely, Sartori et al. [15] implemented a bilateral tele-echography architecture with a passivity layer in presence of 400 ms round trip delay (RTD). However, applied forces were lower than 4 N with an oscillatory behaviour over a sponge-stiff remote environment. Thus, in the *state-of-the-art (SoA)* it emerges the lack of evaluation of a bilateral tele-echography system under realistic operating conditions in terms of forces and delays.

Moreover, it has been demonstrated that problems known as "work-related musculoskeletal disorders (WRMSD)" [16] affect most doctors as they have to maintain loads with prolonged repetitive movements. Although ergonomic workstations have been proposed, the use of remote robots could help reduce these effects by relieving the doctor to apply high forces. This aspect has never been considered in the most advanced bilateral tele-echography systems.

This paper aims to test a bilateral tele-echography architecture with a passivity layer in realistic scenarios. Tests were performed on a phantom in the presence of a 400 ms RTD. In addition, forces of up to 20 N were applied, according to US requirements. The WRMSD problem has been taken into account introducing an appropriate scaling factor on the rendered force chosen by the user. Moreover, in the proposed architecture teleoperation data and US image data travel on different networks allowing for a reduced effect of the delay on the teleoperation data. The paper is organized as follows. In Section II the bilateral tele-echography architecture is described. Subsequently, in Section III experiments are explained and Section IV presents the achieved results. The paper is then concluded in Section V, where the results are discussed.

II. MATERIALS AND METHODS

This section describes the tele-ecography proposed architecture shown in figure 1 among with the reference frames. The tele-ecography architecture implements a *PFm* architecture made by an haptic interface on the doctor-site side and a collaborative robotic arm on the patient-site side.

A. Leader

The leader robot, on the bottom-left of figure 1, is a 3 Degrees-of-Freedom (DoFs) translational Delta-like parallel haptic interface. The end-effector mounts an ergonomic dummy probe allowing to control the orientation of the remote probe, which results in a 6-DoFs complete pose control. The dummy probe mounts a 9-axis IMU Adafruit BNO055 Absolute Orientation Sensor to measure orientation. The leader's low-level control performs friction and ripple compensation, while the rendering force is commanded in feedforward thanks to the high mechanical transparency of the device. Only forces are rendered since additional orientation DoFs are passive. The control algorithm runs on a real-time target machine running *Matlab*© *Simulink Real-Time* at 5 KHz.

B. Follower

The follower, visible on the top-left of figure 1, is a 6-DoFs Doosan M0609 cobot with a payload of 6 kg and a maximum reach of 900 mm. The robot is equipped with a 6-axis ATI Gamma Force sensor and a flange that allows for Wi-Fi US probe mounting. The low-level control loop is closed on a position reference at 1 KHz on a real-time target machine running *Matlab*© *Simulink Real-Time* that communicates with the robot controller with a proprietary Doosan Real-Time API.

C. Ultrasound System

The Wi-Fi probe CERBERO 4.0, produced by ATL Milano, was placed at the end-effector of the Doosan cobot using a flange. The probe directly sends US images on a tablet placed on the doctor-site using a closed Wi-Fi network. Moreover, a Wi-Fi probe allows to eliminate cables clutter.

D. Communication Network and Passivity Layer

Referring to figure 2, the tele-echography architecture was divided into two separate and non-synced networks. First, a PFm teleoperation network in which the leader sends velocity reference $v_L(t)$ and the follower sends back the interaction measured force. Since WRMSD is a demonstrated consequence of protract US examinations due to the forces applied by the doctors, it was chosen to scale the raw measured force $f_{E,RAW}(t)$ with a μ factor reducing the feedback force while the remote robot is still applying enough force to guarantee best US images (which quality depends on applied pressure). The choice of this parameter is user-dependent and aims to reduce the load on the doctor's arm. On this network, data are transmitted via UDP and time delay T is simulated. Moreover, to guarantee stability, a passivity layer according to *TDPA* [17] was implemented at the two ports of the communication

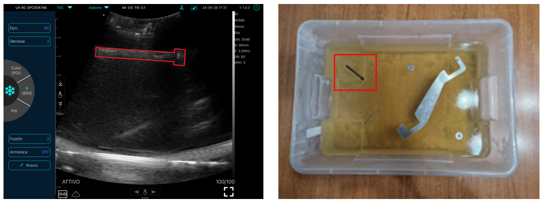
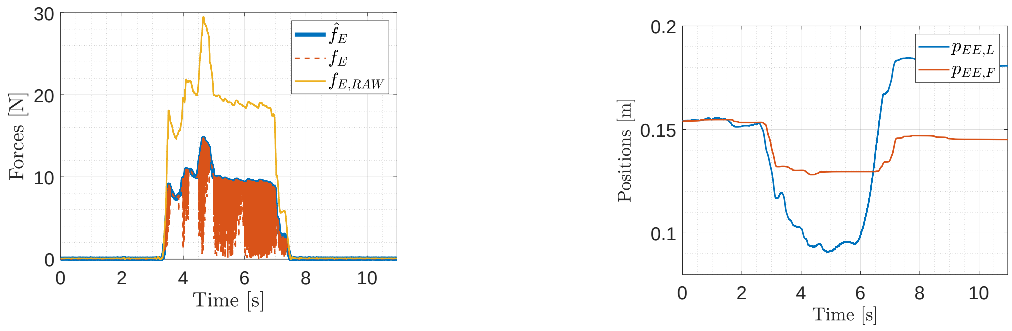
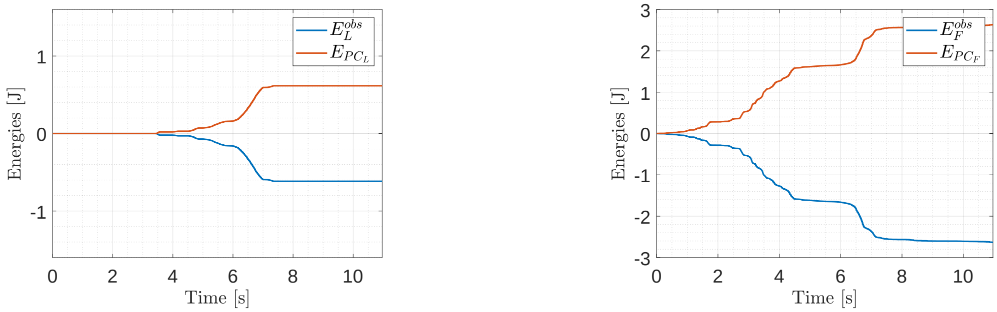


Fig. 3: On the left, US image was sent from the probe and acquired on the tablet. On the right, gelatin custom-made phantom with metal elements. In both images, the target screw was highlighted in red.



(a) Raw (orange), non-passivated (blue) and passivated (red) rendered *z-axis* force.

(b) Leader (blue) and follower (red) *z-axis* positions.



(c) Observed (blue) and dissipated (red) energies by leader's passivity observer and controller.

(d) Observed (blue) and dissipated (red) energies by follower's passivity observer and controller.

Fig. 4: Results of the contact with the phantom. The plots are divided into rows: in the first one there are force and positions during the teleoperation, in the second the observed and dissipated energies by the Passivity Controllers.

channel. Thus, $\hat{v}_{Fd}(t) = v_{Fd}(t-T) = \hat{v}_L(t) = v_L(t-T)$ and $v_{Fd}(t)$ are respectively velocities before and after the passivity controller action, while forces $\hat{f}_E(t) = f_E(t-T) = \mu f_{E,RAW}(t-T)$ and $f_E(t)$ are defined similarly. Note that *hat* has been used as a compact way to show delayed variables and time dependency will be omitted in the following.

Second, a US image Network separate Wi-Fi network is used to transmit only US images. This choice has been taken to reduce the dimensions of transmitted data over the teleoperation network, which suffers from stability problems. In the evaluation of this architecture, the authors decided not to sync the data between the two networks since, in a US examination, doctors make probe placement decisions mainly based on the images and not on the force-feedback. Aim of this paper is also to empirically verify that this choice doesn't compromise the effectiveness of a tele-echography task.

III. EXPERIMENTS

The proposed tele-ecography was tested in a realistic scenario to evaluate its effectiveness. Tests were carried out on custom-made phantom in gelatin with screws and nuts as targets of the US images. Gelatin has a comparable response with that of human tissues to US. The tests were conducted by one subject, in presence of $400\ ms$ RTD. It was realized a contact with the phantom with a duration of about $5\ s$ applying an approximate force of $20\ N$. The value of the contact force is visually displayed to the user among the US images. The scaling factor, selected by the subject after a familiarization phase, μ was set to 0.5. The selected task was to identify as clearly as possible a screw inside the phantom, as in figure 3.

IV. RESULTS

Experiment results are presented in figures 4 limited to the contact *z-axis* for conciseness. Figure 4a shows the raw contact $f_{E,RAW}$ force measured in orange, the scaled non-passivated force fed back to the leader $\hat{f}_E = \mu f_{E,RAW}$ in blue and the passivated force f_E in red dashed line. For better readability of the figure, it was chosen to sync f_E with $f_{E,RAW}$. Figure 4c reports the energy observed E_L^{obs} by the leader's passivity observers in blue and the energy dissipated by the passivity controller E_{PC_L}. Similarly, figure 4b reports synced leader's $p_{EE,L}$ and follower's $p_{EE,F}$ positions during the teleoperation, while figure 4d shows observed E_F^{obs} in blue and dissipated E_{PC_F} in red energies.

The obtained results confirm that the architecture exhibited stable behaviour maintaining a $20\ N$ contact for about $5\ s$ with a phantom in presence of $400\ ms$ RTD. This is clearly visible from figure 4a, where the force trend is almost constant (except for a peak in mid-contact), and from figure 4b, where the follower's position shows a continuous and stable contact with the phantom. Moreover, figures 4c and 4d show the passivity layer's effectiveness in stabilizing the architecture.

The scaling factor chosen resulted in a less loaded condition for the user without compromising the task or the architecture's stability. Similarly, using two separate and non-synced networks for teleoperation data and US images does not seem to affect the task. In fact, in echographic examinations doctors base the diagnosis on the US images, that is the main feedback. However, force-feedback has been proven necessary for more intuitive and natural remote echographic examination [3].

As the passivity layer introduces high-frequency cut in the rendered force (visible in red in figure 4a), the leader suffers from vibrations (force jittering) that make its position not as steady as the follower's as figure 4b shows. This also deteriorates the quality of the feedback, but it is necessary for stability. Figure 4b also highlights another main issue with the passivity controller: due to the dissipating action and the contact, it is visible the position drift error between the leader and the follower. These observed phenomena are well-known issues of the passivity layer, however, they did not compromise the effectiveness of the task and the passivity layer was fundamental to guarantee stability in presence of a high RTD while contacting an environment with high forces.

V. DISCUSSION AND CONCLUSIONS

In this paper, the authors proposed the evaluation of a bilateral tele-ecography architecture. Such a system was successfully tested in a realistic scenario, with 400 ms RTD and 20 N contact forces for 5 s, that are above typical *state-of-the-art* conditions. The experiments confirm that the main feedback in a tele-echography is given by the US images, thus the choice of a scaling factor to relieve doctor's fatigue doesn't compromise the task. Similarly, non-synced US images with force-feedback appear not to prejudice the success of the task, even under the conditions of the applied forces and the chosen RTD. These aspects suggest that it is not necessary for the doctor to have a highly transparent force-feedback when performing a tele-ecography, but that indicative feedback would be sufficient. It is known from the *SoA* that a successful teleoperation task may not require the most transparent feedback, but the most informative to complete that specific task [18]. Effects such as force jittering and drift have been noticed due to the necessary passivity layer. However, various known methods suggest how to treat these effects in order to reduce them, such as [19]. Even if the tele-echography architecture was tested on a custom-made gelatin phantom, that allowed neglecting safety protocols, these are crucial aspects in human-robot interaction and will be studied on this architecture in the future.

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REFERENCES

[1] A. Vilchis Gonzales, P. Cinquin, J. Troccaz, A. Guerraz, B. Hennion, F. Pellissier, P. Thorel, F. Courreges, A. Gourdon, G. Poisson *et al.*, "Ter: a system for robotic tele-echography," in *Medical Image Computing and Computer-Assisted Intervention–MICCAI 2001: 4th International Conference Utrecht, The Netherlands, October 14–17, 2001 Proceedings 4*. Springer, 2001, pp. 326–334.

[2] F. Courreges, P. Vieyres, and R. Istepanian, "Advances in robotic tele-echography services-the otelo system," in *The 26th Annual international conference of the IEEE engineering in medicine and biology society*, vol. 2. IEEE, 2004, pp. 5371–5374.

[3] L. Santos, R. Cortesão, and J. Quintas, "Twin kinematics approach for robotic-assisted tele-echography," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2019, pp. 1339–1346.

[4] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators," *The International Journal of Robotics Research*, vol. 20, no. 6, pp. 419–445, 2001.

[5] J. J. Abbott and A. M. Okamura, "Effects of position quantization and sampling rate on virtual-wall passivity," *IEEE Transactions on Robotics*, vol. 21, no. 5, pp. 952–964, 2005.

[6] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," in *Proceedings of the 1988 IEEE International Conference on Systems, Man, and Cybernetics*, vol. 1. IEEE, 1988, pp. 131–138.

[7] G. Niemeyer and J.-J. Slotine, "Stable adaptive teleoperation," *IEEE Journal of oceanic engineering*, vol. 16, no. 1, pp. 152–162, 1991.

[8] B. Hannaford and J.-H. Ryu, "Time-domain passivity control of haptic interfaces," *IEEE transactions on Robotics and Automation*, vol. 18, no. 1, pp. 1–10, 2002.

[9] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," in *[1992] Proceedings of the 31st IEEE Conference on Decision and Control*. IEEE, 1992, pp. 2649–2655.

[10] M. W. Gilbertson and B. W. Anthony, "An ergonomic, instrumented ultrasound probe for 6-axis force/torque measurement," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2013, pp. 140–143.

[11] K. Mathiassen, J. E. Fjellin, K. Glette, P. K. Hol, and O. J. Elle, "An ultrasound robotic system using the commercial robot ur5," *Frontiers in Robotics and AI*, vol. 3, p. 1, 2016.

[12] J. Schreiter, V. Semshchikov, M. Hanses, N. Elkmann, and C. Hansen, "Towards a real-time control of robotic ultrasound using haptic force feedback," *Current Directions in Biomedical Engineering*, vol. 8, no. 1, pp. 81–84, 2022.

[13] C. Li, C. Zhang, C. Y. Yu, L. Zhang, G. Liu, and J. Zhao, "A novel design of force-feedback master manipulator for remote ultrasound scanning," in *2022 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 2022, pp. 2317–2321.

[14] D. Raina, H. Singh, S. K. Saha, C. Arora, A. Agarwal, S. Chandrashekhara, K. Rangarajan, and S. Nandi, "Comprehensive telerobotic ultrasound system for abdominal imaging: Development and in-vivo feasibility study," in *2021 International Symposium on Medical Robotics (ISMR)*. IEEE, 2021, pp. 1–7.

[15] E. Sartori, C. Tadiello, C. Secchi, and R. Muradore, "Tele-echography using a two-layer teleoperation algorithm with energy scaling," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 1569–1575.

[16] S. Murphey, "Work related musculoskeletal disorders in sonography," 2017.

[17] J. Artigas, J.-H. Ryu, C. Preusche, and G. Hirzinger, "Network representation and passivity of delayed teleoperation systems," in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2011, pp. 177–183.

[18] L. S. Uiterkamp, F. Porcini, G. Englebienne, A. Frisoli, and D. Dresscher, "Emg-based feedback modulation for increased transparency in teleoperation," in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022, pp. 599–604.

[19] F. Porcini, M. Solazzi, and A. Frisoli, "Optimal joint tdpa formulation for kinematically redundant robot manipulators," in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022, pp. 7742–7749.