Tactile sensing with gesture-controlled collaborative robot

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***Abstract*— Sensors and human machine interfaces for collaborative robotics will allow smooth interaction in contexts ranging from industry to tele-medicine and rescue. This paper introduces a bidirectional communication system to achieve multisensory telepresence during the gestural control of an industrial robotic arm. Force and motion from the robot are converted in neuromorphic haptic stimuli delivered on the user's hand through a vibro-tactile glove. Untrained personnel participated in an experimental task benchmarking a pick-and-place operation. The robot end-effector was used to sequentially press six buttons, illuminated according to a random sequence, and comparing the tasks executed without and with tactile feedback. The results demonstrated the reliability of the hand tracking strategy developed for controlling the robotic arm, and the effectiveness of a neuronal spiking model for encoding hand displacement and exerted forces in order to promote a fluid embodiment of the haptic interface and control strategy. The main contribution of this paper is in presenting a robotic arm under gesture-based remote control with multisensory telepresence, demonstrating for the first time that a spiking haptic interface can be used to effectively deliver on the skin surface a sequence of stimuli emulating the neural code of the mechanoreceptors beneath.**

Keywords*— *collaborative robotics, telepresence, neuromorphic vibrotactile feedback, human-robot interaction, hand tracking, gesture-based teleoperation.

I. Introduction

In the last decades, research about the development of human-robot interfaces for the remote control of robotic systems has gained momentum in a variety of contexts like manufacturing [1, 2], search and rescue [3], dangerous operations [4, 5], and robotic surgery [6, 7]. Especially in manufacturing environments, human-robot interfaces are introduced for collaboration and co-working purposes (CoBots), demanding various kind of physical and cognitive interactions between humans and robots. The importance of teleoperation resides in the presence of a human individual in the control loop, especially in critical situations where human supervision can avoid faults or dangers [8, 9]. From joystick and keyboard interface devices, progress in the field of Human Robot Interaction (HRI) introduce accessible easy-training devices [10] which empower users to interact with robot in increasingly natural and intuitive ways.

Vision-based pose estimation and hand tracking techniques are entering the field of HRI, and already proved their application to the remote control of robotic actuators [11] in tele-rehabilitation and telemedicine [12] with untrained persons [10]. Affordable single camera-based vision systems [13, 14] include binocular cameras based on their own IR source [15] to tracking hands and recognize gestures [16, 17].

The delivery of tactile feedback in telepresence operations is fundamental to augment users' immersivity; examples can be found in minimally invasive surgery [6] and manufacturing [18], where robots are mainly involved in object manipulation tasks. Tactile sensation via the hands is fundamental to support high-precision activities [19, 20], however technologies to deliver real-time feedback information are common in literature but there is still a lack of their in-field application.

In this paper, we propose a novel paradigm for controlling a robot interface via vision-based marker-less technology for hand tracking, while vibrotactile feedback is delivered to the user hand. We implement a telerobotic system in which user hand movements are detected by a hand tracking device and serve as commands for a robotic arm performing a task. Vibrotactile feedback is generated via neuronal spiking models and is delivered on the user hand by means of a textile glove equipped with piezoelectric transducers.

II. MATERIALS AND METHODS

A. Experimental apparatus

In this section, we will firstly present the three main subsystems which constitute our experimental setup for the remote robot control with tactile telepresence: 1) a hand tracking device; 2) a vibrotactile glove; 3) an anthropomorphic robotic arm, as represented in Fig. 1.

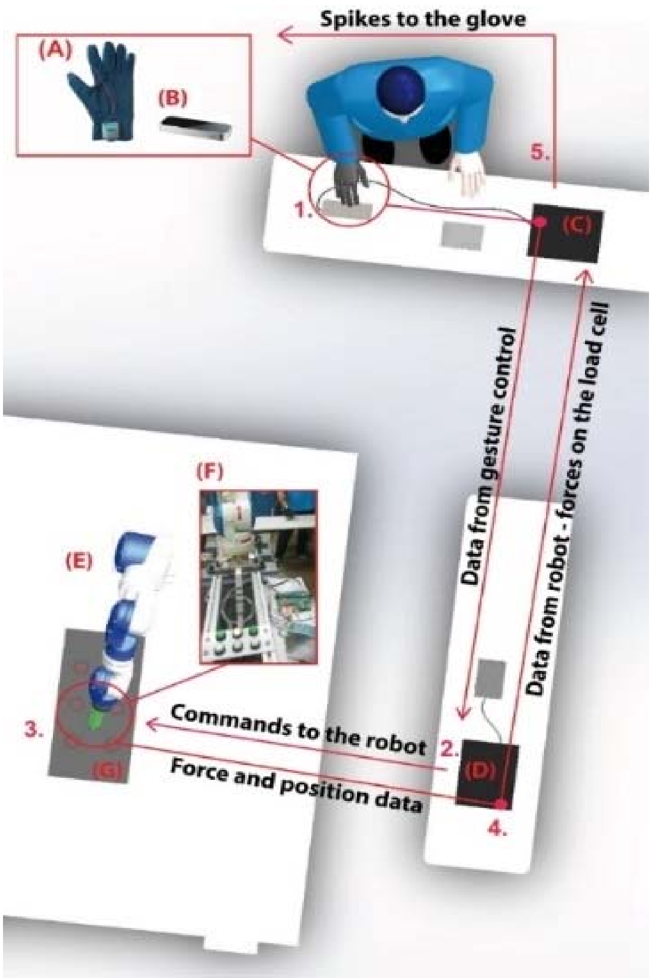

Fig. 1. Scenario of the remote robot control experiment.

Within the experimental set-up, the hand tracking device (Leap Motion controller) is connected to a dedicated Windows laptop (Intel CoreTM i7-6500U processor @3.1GHz, 16GB of RAM) via USB 3.0 connection. The interface to this controller has been designed in LabView leveraging on the MakerHub APIs [15]. Communication between the laptop equipped with the Leap Motion and the PC-based open architecture system for controlling the robot is managed via an UDP channel. The 3D workspace for the user to move is defined via the LabView GUI (National Instruments, USA). At the beginning of each experiment, once the hand is placed over the device, the hand rest position is acquired by the experimenter as a reference position in the workspace. Once the hand is moved within the 3D space over the controller, vibration is delivered to the haptic feedback subsystem according to the current hand displacement with respect to the rest position. If the hand reaches and crosses the boundaries of the working space, the vibration stops. The sampling rate to acquire the hand positions is 50Hz.

Haptic feedback is delivered by means of a spandex glove equipped with two piezoelectric transducers, to provide the user with a wearable vibro-tactile display that could be flexible and light, and to assure a stable positioning of the haptic elements on the user's hand [21]. The embedded actuators are piezoelectric disks (7BB-12-9, MuRata) with a diameter of 12mm and a thickness of 220µm. One vibrotactile actuator is integrated in the index finger of the glove and the second is instead on the palm. They are encapsulated in a polymeric matrix (PDMS, Dow Corning 184 - Silicone Elastomer), thus resulting in a contact area on the skin of approximately 250mm^2. Dimensions of the final elements are 18mm in diameter and 4mm in thickness [22, 23].

The actuation signal delivered to the piezoelectric element on the index phalanx comes from the load cell mounted on the robot end effector. The acquired force is converted in spikes according to a neuronal spiking model and then sent to the glove. The spikes firing activity is proportional to the amplitude of the contact force measured by the load cell, and the presence of the vibration on the index fingertip is representative of the occurrence of a contact event.

Hand displacement data recorded from the hand-tracking device are acquired by the computer. The same GUI implements the neuronal spiking algorithm and spikes are delivered to the glove thanks to dedicated electronics: electronic board (sbRIO 9636, National Instruments) for the communication between the force signal from the robot and the piezoelectric elements in the glove; a switching circuit with relays, for the selective activation of the two transducers placed on the index and palm, together with their on-off behaviour; a piezoelectric evaluation module (DRV2667, Texas Instruments), working in analog mode, for the real-time activation of the piezoelectric transducers with an actuation parameters of 40.7dB gain, a peak-to-peak voltage amplitude of 200V and a Boost voltage of 105V. The on-off activity of the transducers is instead regulated via an implementation of the Izhikevich neuromorphic model [24, 25], that is discretized via the Euler method using regular spiking coefficients (a=0.02s-1V-1; b=0.2s-1; c=65F; d=8mV). During the experiments, the gain K is set at a value Ki=10mA/N for the feedback on the index finger, and at a value Kp=0.6mA/N for the palm in order to obtain spiking vibrotactile patterns with a rate proportional to the intensity of the applied normal force for the index, and to the amount of target robot velocity commanded by the displacement of the palm with respect to the rest position.

The anthropomorphic arm integrated in the experimental setup is a 7-DoFs robot (SIA10F, Yaskawa Motoman Robotics) controlled by an open architecture control system, consisting of a high-speed robot controller FS100 (1ms feedback time constant) running VxWorks real-time operating system and associated Yaskawa MotoPuls SDK PC-based high-level controller. It is equipped with a load cell (CZL602, Dongguan South China Sea Electronic Co., Ltd; rated load 3 kg) on its end effector. The load cell signal processing and the human-machine interface were implemented in MatLab (R2016b, MathWorks, Natick, MA, USA). Force data are acquired and preprocessed by STM 32F415RG ARM Cortex-M4 32-bit RISC core DSP microcontroller, operating at a frequency of 168 MHz. This comprehensive API allows to control and monitor the robot functions through Ethernet interface. A passivity-based control law [26, 27], suitable for human-robot co-working, is used for controlling the robot arm task.

The load cell mounts a spring-like shaped 3D-printed indenter made of PLA, that allows to bend in all directions, thus reducing overall stiffness of the robot arm, to avoid excessive contact forces and breakage. The terminal part of the 3D printed indenter mounts a polymeric soft fingertip to press the selected pushbuttons placed on a test bench. It consists of 6 push-button tasters, equipped with integrated LED indicators switched off when the fingertip properly presses the push-button. A microcontroller controls the random generation of switching order sequences, as well as the electrical state of the push-button tasters.

B. *Experimental protocol and data analysis methods*

Fourteen healthy subjects (1 female and 13 males) aged between 23 and 34, mean age 26.5, participated in the experiments. Haptic stimulation was performed on the subject's dominant right hand. None of them self-reported to have previously performed any activity presumably compromising finger tactile sensitivity, nor had previous contact with our system, nor previous training.

The subject is introduced in the experiment room and briefly informed about the experiment aim and the protocols. Experimenters are always present in the room but do not interfere with the volunteers. The aim of the experiment is the quantitative evaluation of the performance (the number of pressed buttons in each experimental session) of the gesture-based robot control system in two different configurations: 1) without tactile feedback; 2) with tactile feedback. To satisfy this purpose, the subject is asked to remotely guide the robot over the dedicated touch-pad and to press the button corresponding to an ON LED by means of the robot fingertip, being as quick as possible in performing this operation. Before starting the experiment, participants are provided with a self-training session of about 2 minutes to familiarize with the system and with the task. Each experiment consists of 5 sessions and each session is 2 minutes long. In total, duration of the experiment is around 15 minutes, 20 minutes including training. Participants are allowed to rest around 1 minute between each repetition, or even more if they need in order to avoid distress.

The computer simultaneously acquires other relevant data from the robot open-control system: 1) presence of the hand over the hand tracking device, 2) Cartesian coordinates of the robot TCP (Tool Center Point) set to coincide with the robot fingertip, 3) coordinates and timestamps of the TCP contact force generated by the robot during the button pressing sequence (in fact, constrained robot motion), 4) indexes of which button is lighted and of which button is pressed (if any), 5) gesture-based commands generated by the robot operator, 6) timestamps of the spikes generated by the neuromorphic algorithm which activity is proportional to the force measured by the load cell, for the index transducer, and to the hand displacement, for the palm transducer. The time elapsed between the LED lighting and the pushing of the button which switches it off is instead calculated off-line.

Data analysis was performed using the Statistics Toolbox in MatLab (R2016b, MathWorks, Natick, MA, USA). The median and the interquartile range of different experimental parameters were calculated and represented with boxplots, in order to evaluate differences between groups exposed to the gesture-based robot control with or without tactile feedback. This analysis was performed on the number of pressed buttons in each trial, to investigate the participants performance for each condition.

III. RESULTS

The purpose of this experiment is to evaluate whether the hand tracking recognition input, coupled with the neuromorphic vibrotactile feedback, provides an effective channel for bidirectional human-machine interaction.

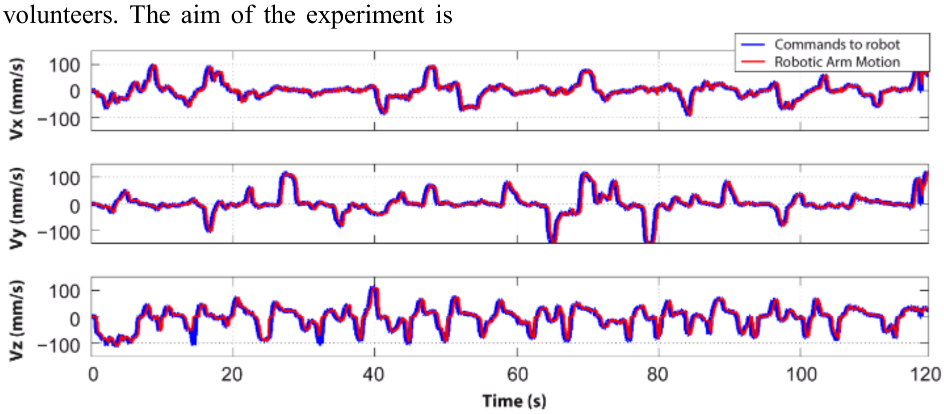

Fig. 2. Speed of robotic arm along the three axes vs. manual commands from the hand tracking device.

The evaluation is undertaken by means of an experimental protocol involving the remote control of the robotic arm with the provision of tactile feedback about the robot movements and contact events. In our protocol, two conditions are evaluated in order to investigate the impact of tactile feedback during a remote-control execution of the same task: without tactile feedback on the user hand or with the provision of tactile feedback via a vibrotactile glove.

The hand position and velocity profiles were acquired during the execution of the task in both the experimental conditions. These profiles were then compared with the trajectory of the robotic arm velocity during the execution of the task. The robotic arm and hand velocity profiles are represented overlapped in Fig. 2. Results showed how the robotic arm is capable to follow the movements of the hand over the hand tracking device. This confirms that the implemented algorithm for the robot control has a suitable dynamics so to enable the robotic arm to follow the hand trajectory and velocity in a reliable manner.

The reliability of the gesture-based control is also detectable from the analysis of the commanded trajectory profile versus the corresponding robot path within the three-dimensional experimental workspace (see Fig. 3).

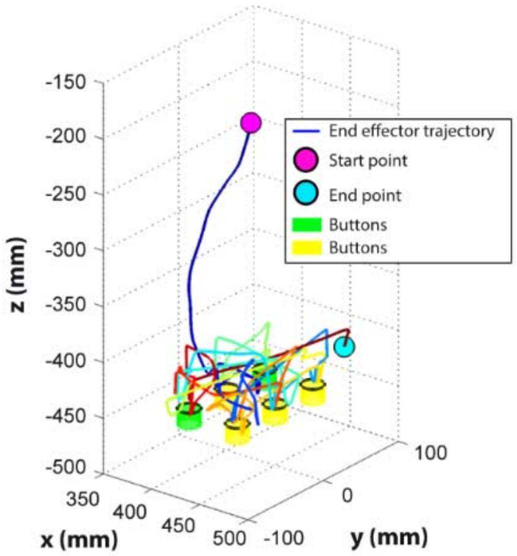

Fig. 3. Example trajectory of robotic arm during the task execution.

Fig. 4 reports an example of spiking activity from the transducers of the haptic glove during the execution of a remote-control task, which is representative of the forces exerted by the robot end-effector and measured by the load cell (exteroceptive feedback). The generation of the spikes is mediated by the Izhikevich artificial neuron spiking model. As the force value increases, the rate of spikes delivered to the index fingertip increases, while the absence of spikes means that no contact events are detected (Fig. 4). The spiking activity on the hand palm is instead representative of the hand distance with respect to the rest position over the hand tracking device (proprioceptive feedback), corresponding to the commanded robot velocity. A higher distance from the rest position generates a more intense spiking activity, while the absence of the hand over the sensor corresponds to the absence of vibration.

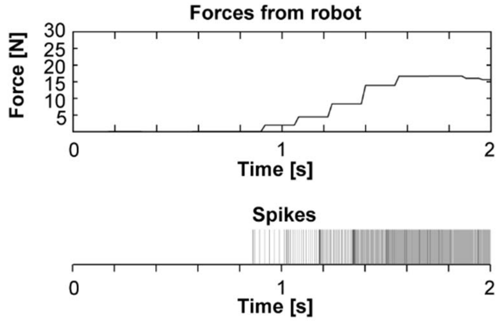

Fig. 4. Spike trains generated by the transducer in one trial.

To evaluate whether the provision of haptic feedback has an effect on the performance during the execution of the task, the median number of completed tasks across all participants is calculated. The median values for the 'feedback' condition are systematically higher than those relative to the 'no feedback' condition. This can be indicative of an effect on the improvement of user learning performance and confidence with the task when tactile feedback is provided.

IV. Discussion and Conclusions

We described an intuitive gesture-based system for the remote control of a robotic arm with tactile telepresence, which allows the users to perform a robot control task mimicking industrial operations. Tactile feedback was delivered via a textile glove equipped with customized piezoelectric actuators. Vibrotactile information was generated according to neuronal spiking models and delivered directly on the hand palm, with a rate proportional to the hand displacement over a hand-tracking device, and on the fingertip of the index, with a rate proportional to the contact forces exerted by the robot end-effector.

Our system has been tested with untrained volunteers, both in the cases where tactile feedback was or was not provided, on an experimental pipeline aimed at emulating activities that can be typically encountered in an industrial context as well as in a whelm of robot remote control applications.

The analysis of experimental data shows that the commands acquired via the hand tracking device are always coherent with the real robot motion executed. Furthermore, all the participants demonstrated to interact with the experimental set-up in a straightforward manner, and none of them needed more than one training session to master it. Furthermore, participants reported an increased awareness of the robot movements and exerted forces when tactile feedback was provided, this making the proposed feedback strategy suitable for enabling collaborative robotics applications. The marker-less technology of the hand tracking device enabled participants to wear the glove and receive tactile feedback during the experimental task without affecting the tracking performance independent from the variation of anthropometry of the human hand.

With our work, we contributed to demonstrate the importance of vibrotactile feedback for human-robot co-working activities, in particular when performing telepresence tasks. Haptic devices can be of paramount importance when used in environments where the interaction with automated machinery can be dangerous for operators. Haptic feedback can in fact be used to deliver information about the occurrence of critical events and thus improve workers safety in collaborative robotic tasks. Tactile technologies such as force sensors installed on the robotic end-effectors can acquire information about contact events and exerted forces, enabling a remote user to easily perform precise manipulations and detect slippages. This research will be complemented with future experiments simulating different and more complex activities such as precise manipulation tasks of small objects.

ACKNOWLEDGMENT

This study had been originally posted as a preprint [28] coherently with IEEE policies.

This research was funded in part by the Italian Ministry of Foreign Affairs and International Cooperation via the Italy-Serbia bilateral project Human-Robot Co-Working as a Key Enabling Technology for the Factories of Future (project ID:PGR00758/2017) and by the Italian Ministry of Education, Universities and Research within the "Smart Cities and Social Innovation Under 30" program through the PARLOMA Project (SIN_00132) and by the EC within the Erasmus+ program agreement n. 2018/KA107 47798-MOB-00004. This project received seed funding from the Dubai Future Foundation through Guaana.com open research platform.

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