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Article

Gesture-based control of a robot arm with neuromorphic haptic feedback

F. Sorgini[1†], G. Airò Farulla[2,3†], N. Lukic[4†], I. Danilov[4†], B. Bojovic[4], M. Milivojevic[4], T. B. Pulikottil[5], L. Roveda[5], P. Prinetto[2,3], T. Tolio[5,6], M.C. Carrozza[1,7], P.B. Petrovic[4,8*‡] and C.M. Oddo[1*‡]

[1] The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
[2] Department of Control and Computer Engineering, Politecnico di Torino
[3] CINI AsTech National Lab, Turin, Italy
[4] Production Engineering Department, Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia
[5] Istituto di Sistemi e Tecnologie Industriali per il Manifatturiero Avanzato (STIIMA) – CNR, Milano, Italy
[6] Dipartimento di Meccanica, Politecnico di Milano, Milano, Italy
[7] IRCCS Fondazione Don Carlo Gnocchi, Milano, Italy
[8] Academy of Engineering Sciences of Serbia-AISS, Belgrade, Serbia

* Correspondence: calogero.oddo@santannapisa.it, pbpetrovic@mas.bg.ac.rs
† These authors share first authorship based on equal contribution
‡ These authors share senior authorship based on equal contribution

Abstract: Research on bidirectional human-machine interfaces will enable the smooth interaction with robotic platforms 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. We complement the gesture-based control by means of a tactile-feedback strategy grounding on a spiking artificial neuron model. 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: telepresence; neuromorphic vibrotactile feedback; human-robot interaction; hand tracking; gesture-based teleoperation.

1. 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, i.e. biological and engineered systems. The importance of teleoperation resides

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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]. Until recently, the main instruments to interact with robotic platforms were relatively constrained gamepad, joystick and keyboard interface devices. Progress in the field of Human Robot Interaction (HRI) is introducing innovative devices which empower users to interact with computer systems in increasingly natural and intuitive ways. Systems adopting these technologies show improved efficiency, speed, power, and realism. Ideally, new interfaces should be accessible without requiring long periods of training and adaptation [10].

Vision-based Pose Estimation (VPE) and Hand Tracking techniques have played a leading role in the field of HRI, and already demonstrated their applicability to remote control of robotic actuators [11] in a variety of domains, including tele-rehabilitation and telemedicine [12]. Furthermore, VPE interfaces are typically intuitive enough to be used even by untrained personnel [10]. Vision systems can be used to control disparate dynamic systems like for example vehicles, aircrafts and submarines, and are classified depending on the number of cameras required in their set-ups. Specifically, single camera-based systems are generally cheaper and easier to build than multi-camera ones [13,14]. An example of camera-based set-up involves the Leap Motion controller [15], a binocular camera system operating in the IR domain (gray-scale system), based on its own IR source. The recent introduction of this hand tracking device has opened new opportunities for hand tracking and hand gesture recognition: it has proven to be precise and reliable both in static and dynamic conditions for hand tracking [16,17]. Differently from RGB-D cameras, the Leap Motion controller explicitly targets the task of tracking the hand pose. Even though its interaction zone is rather limited, the extracted data are very accurate and it is not necessary to perform image processing tasks to extract the relevant points. Authors in [18] report that, although they were not able to achieve the theoretical accuracy of 0.01mm under real conditions, still the controller provided high precision standards, not achievable with RGB-cameras in the same price range (with an overall accuracy of 0.7 mm) [19].

The delivery of tactile feedback in telepresence operations is fundamental to augment users' immersivity; examples can be found in minimally invasive surgery [6] and in industrial operations [3,20-22] and manufacturing [23]. In this context, where robots are mainly involved in object manipulation tasks, tactile feedback can help in performing high-precision activities keeping the human operator in the loop. Tactile feedback technologies to deliver real-time information are common in literature though there is still a lack of their in-field application. The sense of touch is one of the first ways we use to interact with the surrounding world, especially through our hands which represent the most somatosensitive part of the body [24,25]. In particular, human hands' skin is able to perceive a relatively wide range of frequencies when stimulated with a vibrotactile stimulus, with a maximum frequency centered at about 300 Hertz for Pacinian receptors [26-29]. The maximum spatial sensitivity is achieved on the index phalanx, where the location of a presented vibrotactile stimulation is precisely encoded [30].

The importance of tactile sense can be better understood when considering all those individuals who experienced its loss. Without tactile information, actions like using tools, holding objects or motor control tasks can become extremely difficult if not impossible to perform [31]. In all those situations where a fine control of mechanical tools or robotic hands is required, the possibility to deliver information from the environment directly on users' skin via tactile feedback can enhance the performance of executed tasks. The activation of a force feedback real-time channel, coming from the sensing elements on the robot, allows the user to receive the aggregated profiles of exerted forces. Touch feedback allows the user to collect information from the contact points (a force array), and the observed pressure patterns can give information about the surface shape and texture, or about objects' stiffness [32].

In this work, we are focused on distant human-robot bidirectional physical interaction. We propose a novel paradigm for controlling a robot interface via vision-based marker-less technology for hand tracking, involving vibrotactile feedback on the user hand triggered by the output of a neuromorphic artificial neuron spiking model in case of robot constrained motion (a physical contact of robot arm and its environment). We implement a telerobotic system in which user hand movements are detected by a hand tracking device (the Leap Motion controller) and serve as

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commands for a robotic arm performing a generic pick-and-place 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. The haptic feedback subsystem serves two main purposes: 1) proprioceptive feedback about the user's hand position with respect to the rest position of the tracking device; 2) exteroceptive feedback about contact events and the amount of the force exerted by the robot end-effector. To the best of our knowledge, no existing research has already developed a bidirectional communication channel for the remote control of a robotic arm under multisensory telepresence, where input for the robot is provided by means of hand tracking technology, and vibrotactile force feedback is delivered to the users via the implementation of a neuronal spiking model.

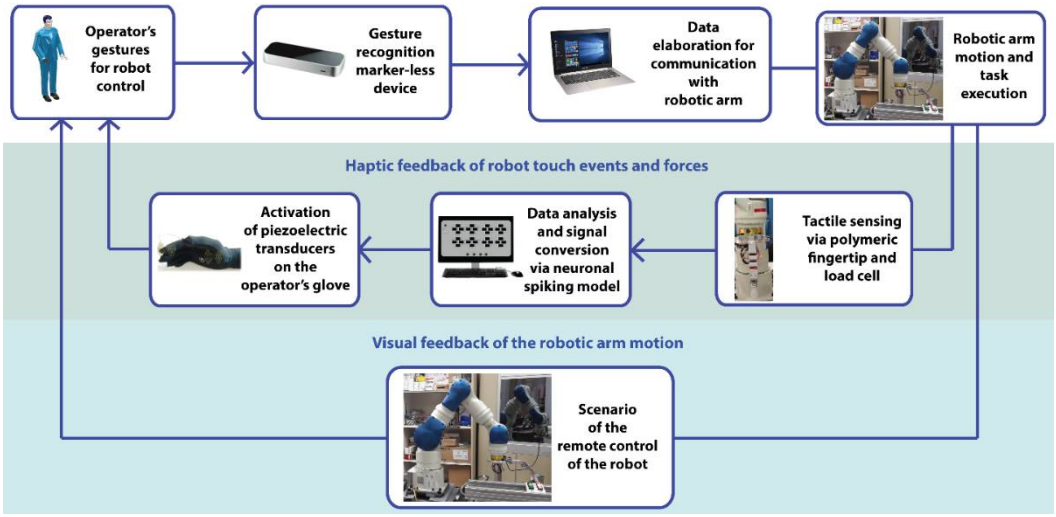

Figure 1. Block diagram of the robotic arm with bidirectional gesture control system. The hand movements of the operator are recognized by means of marker-less infrared stereo camera and delivered to the robot as motion commands while the operator is fed back with spiking vibrotactile stimuli representing the commanded robot velocity and its tactile interaction with the environment.

2. Materials and Methods

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 which is used to detect the movements of the hand during the execution of the experimental tasks and to remotely control a robotic arm; 2) a vibrotactile glove, equipped with two piezoelectric transducers for the haptic feedback on the operators hand [33]; 3) an anthropomorphic robotic arm, which mounts a polymeric soft fingertip and a load cell on the end-effector for the button-pressing task. The experimental protocol is then reported, including description of the participants who took part in the experiments.

2.1 Hand tracking subsystem

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 LabView MakerHub APIs [15]. The GUI continuously tracks the pose of the right hand of the operator and uses its global configuration with respect to the origin of the Cartesian space over the controller to activate the vibrotactile transducer placed on the hand palm with a temporal actuation depending on the hand displacement from the origin of the 3D space. 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.

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The 3D workspace (Figure 2) for the user to move is defined via the LabView GUI. The rest position consists of a sphere with 5cm radius, which center (the home "rest" space) can be set via the same LabView environment. The definition of a rest space allows the robot to stop when the hand enters inside the 5cm boundaries, as well as the glove to stop the vibration activity of the transducer associated to "proprioceptive" feedback. 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.

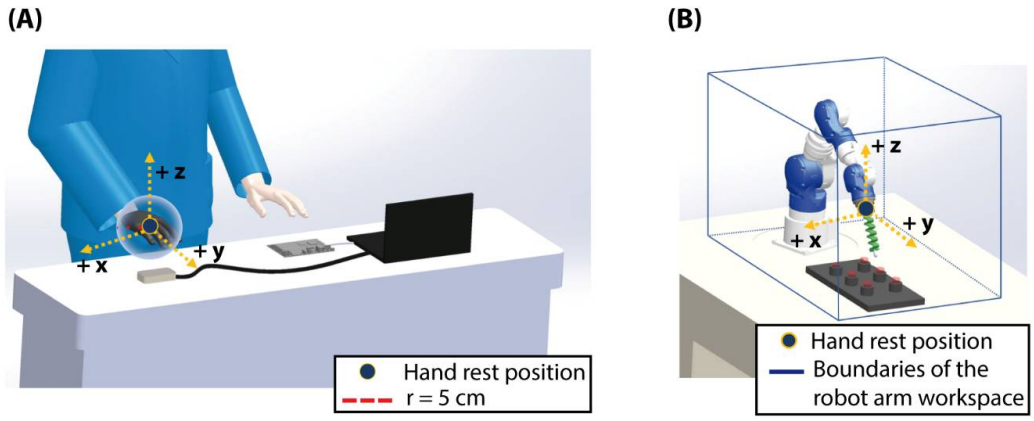

Figure 2. Schematic representation of the robot arm gesture-based control strategy. (**A**) The blue dot represents the hand rest position, a sphere with 5cm radius, corresponding to a stop of the motion of the robot arm. When the hand moves outside the rest position, the robot arm moves following the hand displacement, according to the represented coordinates system. In particular, the hand displacements along the three axes are converted in velocities of the robotic arm along the same directions. (**B**) The robot arm moves according to the received commands from the hand-tracking device, in a space constrained within a 3D cube. If a command from the hand pushes the robot arm outside the workspace cube, the robot stops.

2.2 Neuromorphic haptic feedback subsystem

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 [32]. The embedded actuators are piezoelectric disks (7BB-12-9, MuRata) with a diameter of 12mm and a thickness of 220μm. 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 [33,34].

One vibrotactile actuator is integrated in the index finger of the glove, in correspondence of the index phalanx. The second actuator is instead on the palm.

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. Spikes are then sent to the glove and serve to activate tactile elements. 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. The firing activity of the spikes delivered to the piezoelectric element on the palm is instead related to the hand position along the three spatial axes detected by the hand tracking device. This signal is controlled by the hand tracking device software. For all transducers, the parameters for the neuronal spiking model were selected to operate within a range far from saturation, so that the

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vibrotactile feedback can be proportional to the forces exerted by the robot end effector, and to the displacement of the hand with respect to the rest position defined over the hand tracking device.

The activation of both the transducers embedded in the vibrotactile glove is managed by a GUI developed in LabView that receives via UDP communication the forces read by the load cell on the robotic arm end-effector. 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. This comprises: an 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 activation of the piezoelectric transducers. The analog mode allows the real-time activation of the transducers according to the spikes generated by the model. The actuation parameters for the piezoelectric driver in this mode are a 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 by the implementation of the Izhikevich neuromorphic model [35,36].

The activation of the piezoelectric transducers is triggered by a neuromorphic spiking model which converts the normal force measured by the load cell in spike trains. The Izhikevich neuronal spiking model is discretized via the Euler method, using regular spiking coefficients (a=0.02s-1V-1; b=0.2s-1; c=65F; d=8mV). The current provided as an input to the Izhikevich neuron is proportional to the measured interaction force ($I=K|F_z|$). 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. These values are selected 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 Izhikevich spiking model is implemented via a GUI developed in LabView (2015, National Instruments). The obtained spikes trains are then delivered to the glove by means of the dedicated electronics described in the "Neuromorphic haptic feedback subsystem" Section.

2.3 Anthropomorphic robot arm and test bench

The anthropomorphic arm integrated in the experimental setup is a 7-DoFs robot (SIA10F, Yaskawa Motoman Robotics). It is equipped with a load cell (CZL602, Dongguan South China Sea Electronic Co., Ltd; rated load 3 kg) on its end effector. 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. The robotic arm is 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. This comprehensive API allows to control and monitor the robot functions through Ethernet interface, which is capable to interrupt the execution of the robot controller task in any instant. A passivity-based control law [37,38], well adapted for human-robot co-working, as well as smooth transition from unconstrained to constrained (and vice versa) robot motion are used for controlling the robot arm job-task. The load cell signal processing and the human-machine interface were implemented in MatLab (R2016b, MathWorks, Natick, MA, USA).

The load cell mounts a spring-like shaped 3D-printed indenter made of PLA. The particular spring-like shape of the indenter allows to bend its terminal part in all directions, thus reducing overall stiffness of the robot arm, to avoid excessive contact forces and breakage. On the terminal part of the 3D printed indenter a polymeric soft fingertip is mounted, which is used to press the selected pushbuttons placed on a test bench in front of the robotic arm. This dedicated touchpad was designed and developed to evaluate the performance of the remote-controlled robotic platform. It consists of 6 push-button tasters, equipped with integrated LED based light indicators, together with a microcontroller-based control system for switching the integrated LED indicators, as well as the electrical state of the push-button tasters. The lighting of LED indicators follows randomly generated

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sequences of switching order, and the light is switched off when the fingertip properly presses the push-button.

The three subsystems described above are interconnected in the experimental environment as represented in Figure 3.

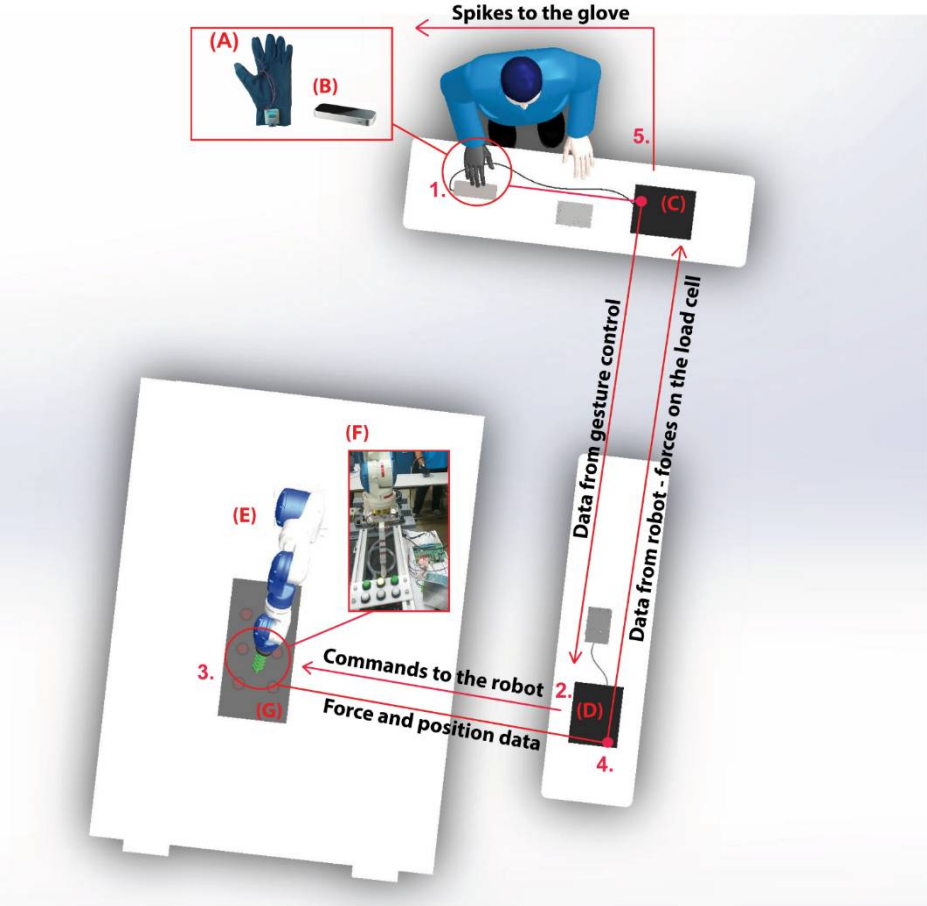

Figure 3. Scenario of the remote robot control experiment. (**A**) Haptic glove for vibrotactile feedback on the user hand, equipped with two vibrotactile piezoelectric actuators; (**B**) Marker-less hand tracking device (Leap Motion controller) used to remotely intuitively control the robot movements; (**C**) PC with dedicated electronics for the Leap Motion data acquisition and elaboration, to control the robot and to implement the neuronal spiking model for the generation of the vibrotactile feedback; (**D**) PC with dedicated electronics for the robotic arm control and activation of the LEDs on the push-button taster. The PC receives data from the hand tracking device; (**E**) Robotic arm; (**F**) Robotic arm end effector on which a polymeric finger is installed by means of a 3D printed compliant support, and a load cell for force measurements; (**G**) Touch-pad made of six push-buttons equipped with LED to be pushed during the experiment following a random sequence. The numbers in figure are representative of the data flow across the components of the experimental scenario.

2.4 Data analysis methods and statistical tests

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 in the two experimental conditions ('no feedback'/'feedback'). This analysis was performed on the number of pressed buttons in each trial, to investigate the participants performance for each condition. Significant differences between groups were analyzed with the Kruskal-Wallis test.

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2.5 Participants

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 right hand, that for all participants was the dominant. None of them self-reported to have previously performed any activity presumably compromising finger tactile sensitivity, nor had previous contact with our system, nor had received any previous training.

2.6 Experimental protocol: remote robot control with tactile telepresence

The subject is introduced in the experiment room, where he/she is 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 (Figure 4): 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 a lighted LED by means of the robot fingertip, being as quick as possible in performing this operation. Subjects are divided in two groups, each one performing the experimental task as first in one of the two conditions (Figure 4) to evaluate whether the introduction of the haptic feedback has an impact on the participant performance. Each experiment consists of 5 sessions. Each session is 2 minutes long and involves the remote control of the robotic arm to press the lighted LEDs in the presented randomized sequence. Before starting the experiment in each condition, participants are provided with a self-training session of about 2 minutes to familiarize with the system and with the task. The 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 task starts when the first LED lightens. The subject moves his/her hand over the hand tracking device to control the robot arm movements. Once the target LED is reached, the subject lowers the hand towards the hand tracking device and the robotic fingertip presses the lighted button. If the pressure operation is applied properly and the button completely pressed, the LED is turned off; when the pressure force is released, a new LED indicator of a new, or even the same, push-button taster is turned on. This action is repeated until the time limit of 2 minutes. The microcontroller which controls the LED indicators simultaneously measures the time required by the operator to reach the position of the button, together with the contact force to switch it off (see Figure 4).

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.

Based on this comprehensive information content (time series), it is possible to evaluate quantitative statistical measures of the human operator behavior.

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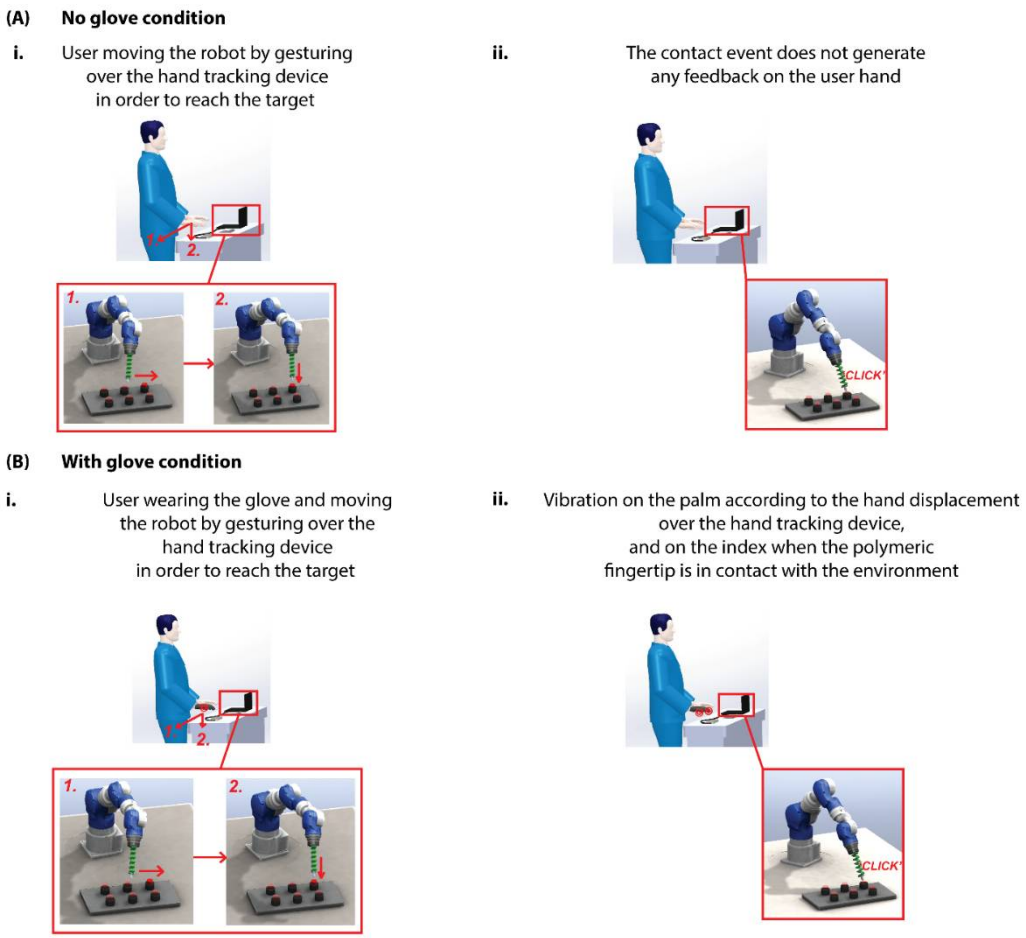

Figure 4. Steps of the experimental protocol for the remote-control experiment with tactile telepresence in the two experimental conditions. (**A**) No-glove condition: i. The user moves the hand over the hand tracking device in order to move the robotic arm laterally (1.), and down (2.) to reach the lighted button; ii. Once the targeted push-button is reached, the user taps over the hand tracking device to lower the robotic arm and pushes the button down; (**B**) Glove condition: i. The user wearing the vibro-tactile glove moves the hand over the hand tracking device in order to move the robotic arm laterally (1.), and down (2.) to reach the lighted button, receiving vibrotactile feedback on the palm; ii. Once the targeted push-button is reached, the user taps over the hand tracking device to lower the robotic arm and pushes the button down, receiving vibrotactile feedback on the index fingertip when the polymeric fingertip on the robot end-effector is in contact with the environment, and on the palm according to the movement of the hand over the hand tracking device.

3. Results

The proposed architecture for the bidirectional remote control of the robotic arm is effective and intuitive, and the introduction of neuromorphic vibrotactile feedback can improve the user awareness during the execution of a task, with measurable effects on performance.

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 task: execution of the task without tactile feedback on the user hand ('no feedback' condition); execution of the same task with the provision of tactile feedback via a vibrotactile glove ('feedback' condition).

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.

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3.1 Robot trajectories and velocities versus commanded movements via the gesture-based control

We first evaluated the capability of the hand tracking device in the detection of the hands movements in order to control the robotic arm. We used an intuitive approach in which hand posture and motion were transformed into specific commands to be sent to the robot (see Figure 2 for the correspondence between the hand commands and the robot movements).

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 velocity profile commanded via the hand tracking device and the corresponding profile of the robotic arm velocity are overlapped in Figure 5 (A). 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 velocity profile versus the corresponding robot velocity (see Figure 5 (B)) within the three-dimensional experimental workspace (see Figure 5 (C)).

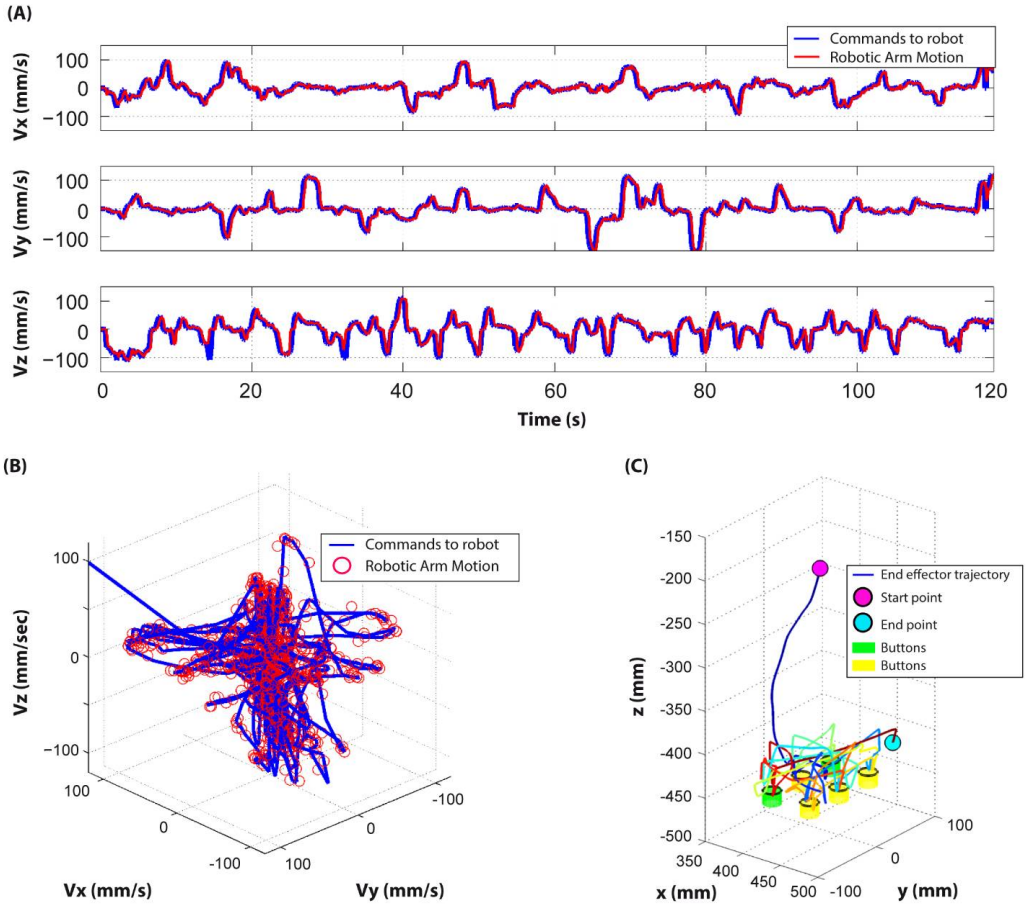

Figure 5. Speed of robotic arm along the three axes vs. manual commands from the hand tracking device. (**A**) Behaviour of the velocity of the hand commands sent to the robot via the hand tracking device (red line) vs. real motion of the robotic arm (blue line); (**B**) Spatial representation of the commanded motion velocity coming from the hand tracking device (blue line) and of the robotic arm velocity (red dots) in the 3D space; (**C**) Trajectory of the robot end-effector while pressing the buttons during the experimental session, with starting and ending points.

3.2 Neuromorphic haptic feedback during the experimental task

Figure 6 reports an example of spiking activity released by the transducers of the haptic glove during the execution of a remote-control task. The spiking activity on the index fingertip is

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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 (see Section 2.2) and is then conveyed to the transducer placed on the index fingertip. 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 (Figure 6 (A, C)). 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 (hand not detected/hand out of the workspace) corresponds to the absence of vibration (see Figure 6 (B, D)).

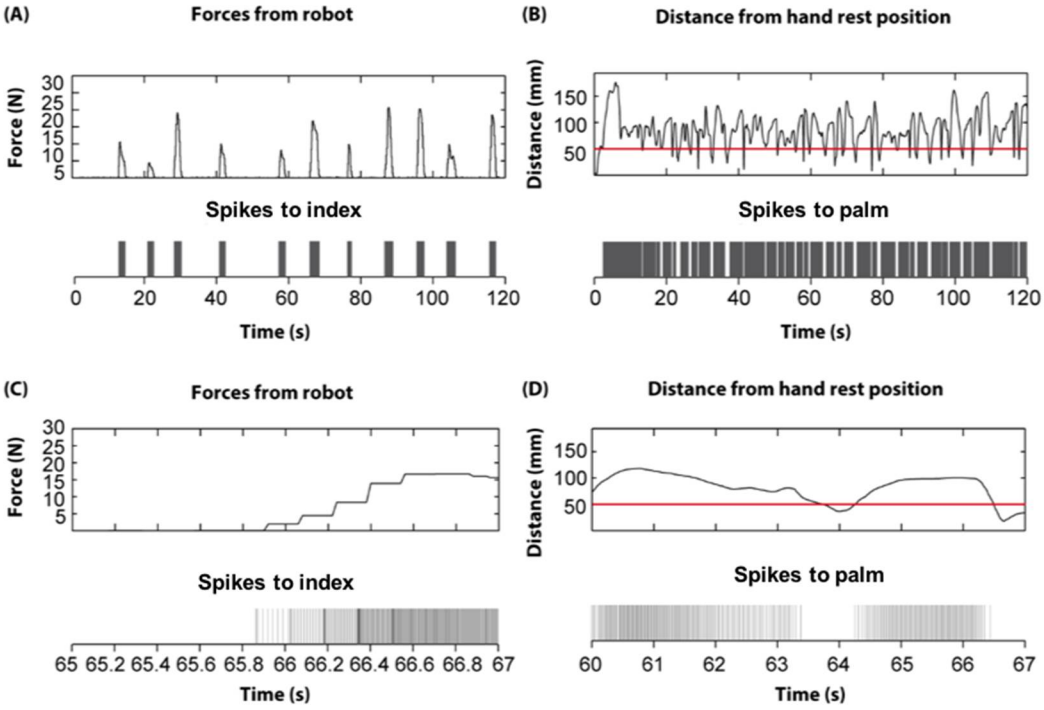

Figure 6. Figure of spike trains for one trial. (**A**) (upper panel) Forces exerted from the robot when indenting the buttons (upper panel); Spike trains transduced to the glove index, which activity is proportional to the amount of force measured by the load cell mounted on the robot end-effector (lower panel); (**B**) Distance from the hand rest position (represented as a red line) acquired by the hand tracking device while the user hand is moving to control the robotic arm (upper panel); (**B**) Spike trains transduced to the glove palm, which activity is proportional to the hand distance respect to the hand rest position (lower panel); (**C**) Forces exerted from the robot during one single button pressure (upper panel); (**C**) Spike trains transduced to the glove index during one single button pressure (lower panel); (**D**) Distance from the hand rest position (represented as a red line) acquired by the hand tracking device during one single button pressure (upper panel); (**D**) Spike trains transduced to the glove palm during the operations executed for commanding one single button pressure, which activity is proportional to the hand velocity respect to the hand rest position (lower panel).

3.3 Evaluation of the participants performance in completing the task via the gesture-controlled robot, with or without tactile feedback

To evaluate whether the provision of tactile feedback has an effect on the participants performance during the execution of the task, we compared the results from the group performing the experiment in the 'no feedback' condition with those from the group performing the 'feedback' condition (Video S1). **Table 1** reports the median number of completed tasks, across all participants, for each experimental session in the two conditions. The median values and interquartile ranges for the two experimental conditions are reported in Figure 7, relative to all the experimental trials for all

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participants. 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.

Table 1. Number of button hits. Median values of the number of button hits for the two experimental conditions.

Trial No.	With glove (median)	No glove (median)
1	7	6
2	11	9
3	10	7
4	10	8
5	12	10
All trials	10	8

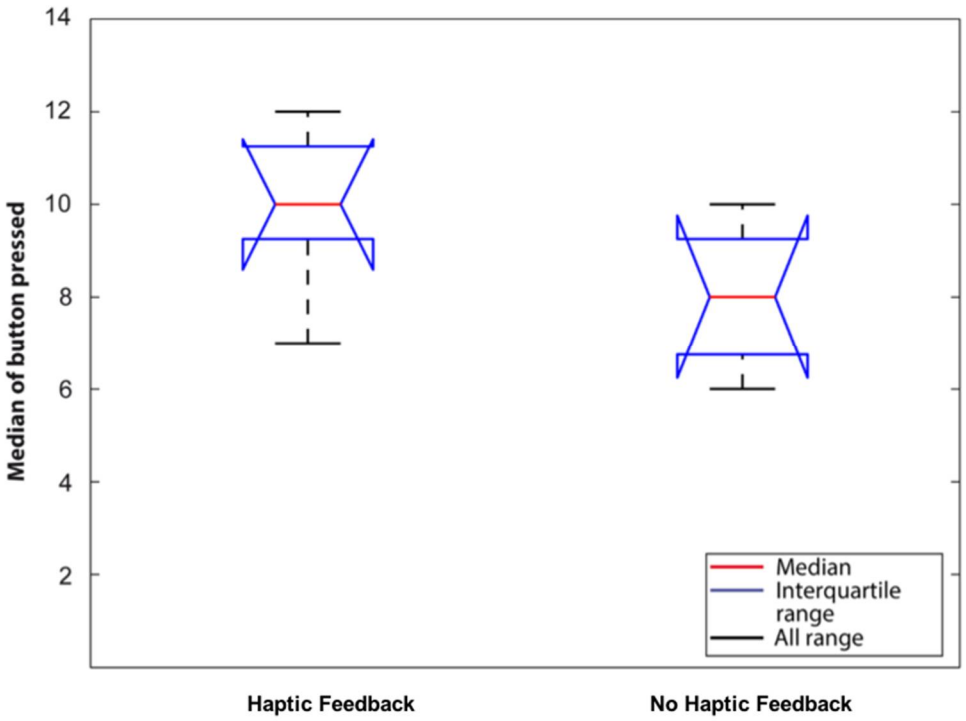

Figure 7. Boxplot of the number of buttons pressed in the two experimented conditions. Median and interquartile range of the number of buttons pressed by all participants in the two experimental conditions. The first box represents the trials performed by the 'feedback' condition group, while the second box represents the trials performed by the 'no feedback' condition group.

4. 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 pick-and-place-like industrial task. 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 easily interact with the experimental set-up, and none of them needed more than one training session to master it. Participants performance in the execution of the task resulted overall good and increased when tactile feedback was provided. Furthermore, participants reported an increased awareness of the robot movements and exerted forces when tactile feedback was provided.

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. Furthermore, since the hand tracking is independent from the variation of anthropometry of the human hand, it can allow a very large applicability.

With our work, we contributed to demonstrate 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.

Supplementary Materials: Video S1: video of the experimental protocol showing the gesture-based robot control task being performed with and without haptic feedback.

Author Contributions: F.S. designed the experimental protocol, developed the haptic glove and integrated the experimental setup, performed the principal experimental protocol, analyzed data, discussed the results and wrote the paper; G.A.F. designed the experimental protocol, integrated the experimental setup, performed the principal experimental protocol, analyzed data, discussed the results and wrote the paper; N.L. co-designed the experimental protocol, developed and programmed the robotic arm system, analyzed data, discussed the results and contributed to writing the paper; I.D. co-designed the experimental protocol, developed and programmed the robotic arm system, analyzed data, discussed the results and contributed to writing the paper; B.B. contributed to designing the experimental protocol, contributed to discussion of results and revised the paper; M.M. designed and fabricated parts of the experimental setup and revised the paper; T.B.P. contributed to analyzing data and revised the paper; L.R. contributed to discussing the results and revised the paper; P.P. provided background in computer engineering, contributed to discussing the results and revised the paper; T.T. provided engineering background in production engineering, contributed to discussing the results and revised the paper, M.C.C. provided background in bioengineering, co-supervised the development of the haptic glove, contributed to discussing the results and revised the paper; P.B.P. co-designed and co-supervised the study, co-supervised the development of the whole experimental apparatus and contributed to its development, co-designed the experimental protocol, contributed to data analysis, discussed the results and contributed to writing the paper; C.M.O. designed and supervised the study, supervised the development of the whole experimental apparatus and contributed to its development, ideated the neuromorphic haptic feedback strategy, designed the experimental protocol, contributed to data analysis, discussed the results and wrote the paper.

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