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Whole-Arm Humanoid Robot Teleoperation with Naturalistic Vibrotactile Feedback

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I. Introduction

As the field of humanoid robotics rapidly advances, there is a growing need for robust ways of teleoperating such robots [1]. In particular, teleoperation systems with rich haptic feedback can greatly enhance operator embodiment, enabling the user to control the robot more intuitively and perform tasks with greater effectiveness [2], [3]. However, these systems still need improvement to effectively translate robot motion and proprioception into a corresponding sense of embodiment for the operator. Thus, this work-in-progress paper demonstrates an upper-body humanoid teleoperation system, driven by a recently proposed retargeting algorithm, OCRA [4], integrated with a practical vibrotactile feedback system, AiroTouch [5], that was originally developed for construction robots. We highlight opportunities to enhance teleoperation performance and motivate further research in teleoperation system design.

OCRA (Optimization-based Customizable Retargeting Algorithm) uses optimization to map motion from one serial linkage, such as a human arm, to another, such as a robot arm, in real time [4]. AiroTouch is a naturalistic vibrotactile feedback system that measures vibrations from a robot end-effector using a high-bandwidth three-axis accelerometer and enables one or more users to feel those vibrations instantaneously through voice-coil actuators [5]. Integrating OCRA and AiroTouch enables an operator to command human-like arm motions to a humanoid robot while feeling the vibrations produced by the robot's motions and interactions.

II. Experimental Apparatus

The operator's pose is acquired via a commercial inertial motion-capture suit (Xsens Awinda). OCRA generates natural, human-like motion commands for the humanoid robot (Aldebaran Nao) by calculating the robot joint angles that minimize the weighted sum of the errors between the human and robot hand orientations and the rescaled shapes of the center lines of these two arms at each step in time [4].

Adhesive firmly mounts the AiroTouch accelerometer (Analog Devices EVAL-ADXL354) to the back of the robot's right hand, a location we selected to improve the perceptual quality of multiple vibration sources (see Section IV). The sensor's output is transferred wirelessly through audio transmitters and receivers (Sennheiser XSW2-Ci1) to a digital audio mixer (Soundcraft Ui24R). Audio software filters and sums the accelerometer's three output channels, and this three-channel sum drives one or more voice-coil actuators (Tactile Labs HapCoil-One) after wireless transmission and amplification. The operator and/or bystanders grasp the actuator to feel the vibrations experienced by the robot (Fig. 1).

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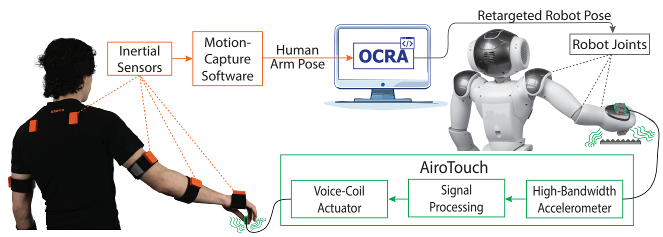

Fig. 1. Block diagram of the haptic teleoperation system.

III. Methods

Successful AiroTouch integration hinges on two key considerations: 1) minimizing the electromagnetic interference of the actuator on the motion-capture system, and 2) improving the perceptual quality of vibrations from different sources. We address the latter via thoughtful accelerometer placement and signal-processing techniques.

1) Minimizing electromagnetic interference: The motion-capture suit we use contains inertial measurement units (IMUs), which are sensitive to magnetic fields. To capture the operator's movements accurately, we must ensure that the voice-coil actuator used to deliver vibrotactile feedback does not interfere with the motion-capture sensors. Thus, the magnetometer readings of the hand and forearm IMUs were monitored while the active actuator was grasped by the operator and brought into contact with the IMUs.

2) Improving vibration signal quality: Ego-vibrations are generated by a robot's internal mechanisms, such as cooling fans and motor gears. Although relaying ego-vibrations can increase operator embodiment, Nao's arm motion (and especially rapid shoulder motion) can produce substantial ego-vibrations. These high-amplitude ego-vibrations can mask low-amplitude interaction vibrations that we want the operator to be able to feel through AiroTouch (Fig. 2). Thus, we improved the perceptibility of lower-amplitude interaction vibrations by carefully selecting the accelerometer's placement and filtering the acquired signals in real time.

We characterized ego-vibrations at four locations to select the accelerometer placement for our experiments. To maintain uniformity, a sequence of free-space motions performed by an operator was recorded using the motion-capture software and replayed on the robot with the accelerometer fixed to the robot's a) head, b) left shoulder pad, c) left lateral forearm, and d) left hand. We analyzed the signal from each accelerometer axis, their sum, and their corresponding spectrograms and power spectra.

We then conducted an additional experiment to choose filters that can improve the discernibility of interaction vibrations. Here, the accelerometer was placed on the robot's right hand, and a right-handed operator teleoperated the robot to perform the following four consecutive tasks (Fig. 2 and supplementary video):

1) Producing unstructured free-space whole-arm motions.
2) Drumming on a mini bongo drum.
3) Stroking three textured surfaces (stone, metal mesh, and Velcro hooks).
4) Simulating a mid-arm collision by elbowing a chair.

We analyzed the accelerometer data from these tasks, and we further investigated signal-processing methods to help tune the contrast between ego- and interaction vibrations.

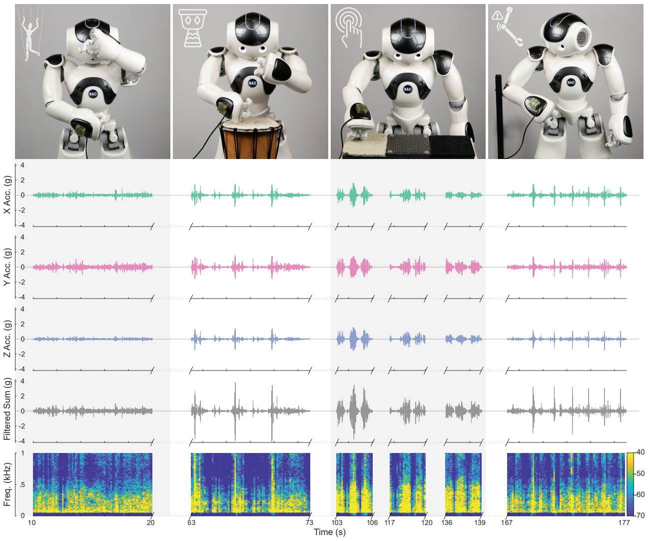

Fig. 2. Representative accelerometer data for the four tasks, including moving the arms freely, drumming both hands three times, stroking each surface two or three times, and elbowing the chair six times. The top four subplots show the x-, y-, and z-axis accelerometer outputs and their filtered sum. The bottom subplot shows the filtered sum's spectrogram.

IV. Results and Discussion

1) Electromagnetic interference analysis: The magnetometers in the motion-capture IMUs suffered substantial interference only when the voice-coil actuator contacted them directly. Therefore, self-awareness is necessary to ensure the operator does not affect motion-capture readings by touching an IMU with the actuator.

2) Accelerometer placement: Data from the accelerometer placement experiment revealed that Nao's ego-vibrations are highly location-dependent: the shoulder produces the strongest ego-vibrations, followed by the elbow, the hand, and the head. Lower-amplitude interaction vibrations were most perceptible when the accelerometer was placed far from the shoulder yet close to the primary point of contact, i.e., on the robot's hand.

3) Acceleration data analysis: Fig. 2 presents sample accelerometer data from all four tasks described in Section III. Similar signal patterns were observed across all three accelerometer axes and their sum; summing the axes increases the signal amplitude, and this approach is easily configured in the audio mixer.

In general, ego-vibrations are dominant below 400 Hz, whereas strong interactions with objects produce a broader frequency range, with a long tail that attenuates above 600 Hz. These frequency characteristics are influenced by both the robot's mechanical design and the task itself.

4) Signal processing: Without filtering, AiroTouch transmits perceivable vibrations even when the Nao robot is stationary; both amplitude gating and band-pass filtering were used to remove this unwanted background noise. Specifically, a -50 dB gate was applied to the output of each accelerometer axis to suppress vibration amplitudes below this threshold, and a pass band from 63 Hz to 1000 Hz was applied to attenuate frequencies resulting from low-frequency robot movement or presenting beyond the limit of human perception. This signal-processing approach allowed us to comfortably perceive both ego- and interaction vibrations from the robot with the accelerometer fixed to its hand. In particular, robot arm collisions were perceptible even when they could not be directly seen by the operator, which improves operator embodiment during teleoperation.

V. Conclusion

Combining human-like robot motion and haptic feedback within the same humanoid teleoperation system could foster greater operator embodiment and improve performance. The work presented here successfully integrates a naturalistic vibrotactile feedback system into a real-time whole-arm humanoid robot teleoperation system. The next step is a comprehensive user evaluation to assess operator embodiment while participants perform a series of tasks, including manipulation and texture perception.

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