Tele-Manipulation with a Humanoid Robot under Autonomous Joint Impedance Regulation and Vibrotactile Balancing Feedback

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***Abstract*— This work presents an enriched human-machine interface for performing effective tele-manipulation using a humanoid robot. To provide the slave with the ability to dexterously interact with the remote environment, we implement an autonomous impedance controller that regulates the slave's joints stiffness and damping according to the manipulation loading conditions. In the proposed strategy, free-space operations are performed with compliant limbs to ensure safe interactions during unforeseen collisions on the whole-arm together with a soft behaviour at the initial phase of contact. During the manipulation task, the designed controller accounts for the arm configuration and the direction/amplitude of the external force sensed at the end-effector to stiffen the humanoid arm joints, permitting to handle the task loads. Experiments performed on the compliant humanoid robot COMAN demonstrate the effectiveness of this human-inspired impedance controller during a teleoperated pick-and-place task. The interaction forces during manipulation can destabilize the floating base humanoid robot. To address this concern we also investigate the operators ability to rely on a cutaneous feedback of the slave's balance state to adjust their teleoperation strategy when required so as to complete the task while maintaining the slave's balance. A comparative study shows that the proposed vibrotactile feedback allows for a proper recognition of the slave's drop of stability during interaction tasks and that the tactile guidance leads to enhanced teleoperation performances characterized by a significantly lower number of falls.**

I. Introduction

A significant amount of work has been done during the last decades to address the mechanical, electrical and control challenges related to the emerging field of human-centered safe robotics. The increasing interest in this research area stems from the evolution of the role of robots that are no longer isolated in factories but are instead expected to evolve in uncertain and dynamically changing workspaces shared with humans. To meet the associated safety requirements, impact forces need to be maintained low during unforeseen collisions so as to ensure the physical integrity of both the robot and its surroundings. Multiple strategies have been investigated to move forward in this direction. One aspect regards the re-thinking of the manipulators hardware characteristics required to achieve a safe behaviour. The design of lightweight structures results in reduced inertia systems exhibiting lower impact loads [1]. In parallel, the effective impedance of manipulators can be reduced through the use of compliant actuation. Inherently soft actuators are obtained by using pneumatic mechanisms such as antagonistic muscles, or by placing flexible elements between the output shaft of the motor and the link. Various types of elastic actuators have been developed with either fixed or variable stiffness and damping mechanisms [2], [3]. Along with the hardware aspect, control plays a central role in the achievement of a safe behavior. Torque control [4] as well as impedance control [5] are two examples of control strategies developed in this direction.
In this work we implement an autonomous joint impedance controller at the slave side to achieve a safe yet dexterous teleoperation of SEA-based humanoid robot COMAN.

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Humans ability to skillfully interact with highly diverse impedance environments is based to a large extent on their ability to modulate their limb's impedance through various mechanisms. It has been shown that such control is essential to complete a wide range of everyday tasks including hopping [6], running [7] and during reaching motions [8]. To transfer these enhanced interaction skills to robotic systems, the joints impedance should be modulated during the different phases of the task so as to effectively adapt to the manipulated environment.
Different approaches have been explored to control online the slave's impedance within the scope of teleoperation. One of them consists in relying on the operator to remotely control the slave's stiffness. The position reference is sent along with the end-effector stiffness profile estimated from the muscular activity of the operator's arm in real time using EMGs [9], [10]. This method, referred to as tele-impedance, constitutes a powerful tool since it provides the operator with a high level of control and thus appears well-suited to applications such as prosthetic arms control [11]. However this solution presents some drawbacks. Besides the need to equip the master station with an EMG device, teleimpedance requires an active participation from the operator. Indeed the impedance needed at the remote site to complete the task has to be evaluated by the operator in order to contract accordingly his arms muscles and send the appropriate stiffness profile. Different types of feedbacks can assist the operator with understanding the environment's resistance, including visual hints through the position mismatch between the reference and the slave positions or tactile cues reflecting the forces developed at the slave side. However, this process requires special attention from the operator and can become a non-negligible cognitive load. Considering the inherent complexity of teleoperating a humanoid robot, such additional burden can rapidly become overwhelming.
In order to get around this difficulty, we propose to integrate a local impedance controller that autonomously regulates the robot's arm joints impedance according to the remote conditions so as to achieve a humanlike behaviour. Besides

alleviating the operator of the impedance control burden, it might appear very convenient to provide the slave with such low-level autonomous behaviour in order to cope with losses of communication or delays within the master-slave communication channel.

The online stiffening of the robot joints allows for the generation of substantial interaction forces at the end-effector, enabling to perform tasks such as carrying heavy loads. This enhanced manipulation capability raises an additional concern. In contrast to fixed-base manipulators or stable-based mobile robots, humanoid robots are intrinsically unstable. As a consequence, high contact forces can lead to a loss of balance. Although stabilizers can handle perturbations issued by the environment, a limitation appears when considering a teleoperation scenario since the balance recovery strategy highly risks compromising the task completion. As an alternative, we propose maintaining the operator aware of the slave's balance state by the mean of a vibrotactile belt. The objective is to analyze whether operators are able to rely on this information to adjust their teleoperation strategy so as to perform the task while maintaining the slave's balance.

This work is organized as follows: Section II introduces the motion capture based teleoperation interface. Section III presents the local joint impedance controller. The benefits of the vibrotactile feedback of the balance state of the humanoid robot are discussed in Sect. IV. Section V addresses the conclusions of this work.

II. Teleoperation interface

A main challenge associated with the teleoperation of humanoid robots stems from their large number of DOFs that make these mechanisms complex to control. Attempts have been done to control the slave's whole-body stance; however these multi-points teleoperation strategies require the definition of a kinematic model of the master system in order to address the kinematic differences corresponding to the joint arrangement, links ratio, angle limits etc. Such model, used to extract motion parameters, may be complex to establish and has to be remade for each couple operator-robot [13]. To address this difficulty while reducing the operator's cognitive demand, we propose to teleoperate a few selected points of the slave. This approach is consistent with humans strategy of focusing the attention on specific points of the body to carry out a task. For instance when grasping the attention is focused on the hand's trajectory whereas when playing football the locus of attention is shifted to the foot [14].
In the proposed framework we rely on the vision-based motion capture system Optitrack from NaturalPoint, Inc [12], to monitor the operator's hands and torso position and orientation X_{op} in real time. The raw data is processed to generate a smooth trajectory for the desired cartesian position and orientation of the robot's hands and torso X_{ref}. The whole-body joints trajectories q_d are then computed through inverse

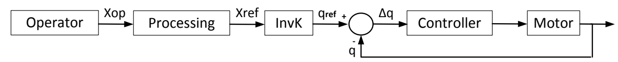

Fig. 1: Teleoperation control scheme

kinematics as shown on the diagram Fig. 1. This human-machine interface allows for an intuive teleoperation of the 29-DOFs compliant humanoid robot COMAN, providing the operator with the control of both arms, the centre of mass Cartesian position through the bending of the legs and the torso orientation.

III. Autonomous joints impedance regulation

To achieve the versatile behaviour required to skillfully interact with time-varying environments, we propose to regulate the slave's response properties to external forces through modifying its joints mechanical impedance parameters. Subsection III-A introduces to the proposed strategy; Subsection III-B details the implementation of the controller. Subsection III-C demonstrates the impedance regulation principle. In Subsection III-D the functionality of the joint variable impedance controller is experimentally demonstrated during the execution of a lifting task which is performed with and without active control of the joints impedance.

A. Varying the impedance to achieve dexterous manipulation

While performing a teleoperation task, the encountered impedance can be subject to sudden changes. This is especially true during transitions between free space and hard contact where high forces can be generated at the endpoint. Such disruptions can induce instability and eventual damages. To tackle with this issue, we propose to initiate the teleoperation with highly compliant arms. Besides preventing the aforementioned abrupt transitions, this strategy guarantees a safe reaction in case of unexpected collision on the whole-arm during free-space operations. To counter the high loads that can appear during the manipulation, joints impedance is actively tuned through modulating the stiffness and damping parameters so as to achieve the endpoint stiffness required to complete the task. The local controller relies on the sensing of the external forces applied at the wrists of the robot to identify active interactions with the environment together with the direction and amplitude of the force to counter.

This approach is directly inspired by humans strategy. To handle an object of unknown weight, the reaching motion in free space is performed with low-impedance limb. The arm muscles are gradually contracted when starting to lift the object in order to overcome the external gravity force sensed at the hand. A similar pattern can be observed when climbing up a step. The foot is raised and put on top of the stair with a compliant leg; the joints are then stiffened to carry the whole-body weight. These observations are corroborated by different studies. In [15] authors show that humans optimize their limbs stiffness to maximize the energy efficiency of a given movement. In [16], human subjects were asked to stabilize a load applied to the wrist.

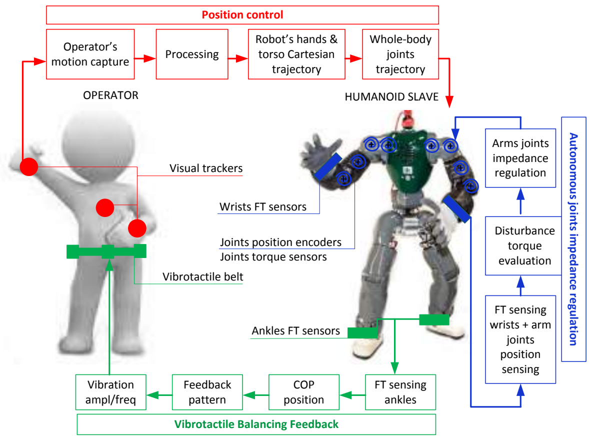

Fig. 2: Overview of the proposed teleoperation framework

Subjects responded to an increase of the force amplitude by increasing the level of co-contraction of the flexor and extensor muscles, resulting in an increased stiffness of the wrist. These studies suggest that humans achieve dexterous contact tasks through the adaptation of their limbs impedance to the external constraints.
Another characteristic of human limb stiffening strategy regards its directionality. It has been shown by [17] that humans voluntarily control the orientation of the maximum stiffness to meet the current task requirements. The proposed controller has been designed to also replicate this behaviour in order to maintain a reduced stiffness along unloaded directions. To achieve such behaviour, the robot's joints are individually stiffened depending on the current arm configuration and the direction of the endpoint force to achieve a stiffness proportional to the joint torque generated by the external loading at the end-effector. In other words, joints are individually stiffened based on their contribution to resist to the endpoint load.

B. Implementation of the controller

The dynamic model of an n-DOFs manipulator in joint space coordinates when interacting with the environment is described in Eq. 1.

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)=\tau+\tau_{ext} \qquad (1)$$

with $M(q)\in\mathbb{R}^{nxn}$ the symmetric positive definite inertia matrix of the manipulator, $C(q,\dot{q})\in\mathbb{R}^{n}$ the vector of Coriolis and centrifugal torques, $g(q)\in\mathbb{R}^{n}$ the vector of gravitational torques, $\tau\in\mathbb{R}^{n}$ the vector of actuator joint torques and $\tau_{ext}\in\mathbb{R}^{n}$ the vector of external disturbances joint torques.
By employing a joint impedance controller that keeps the manipulator inertia the same as that of the physical system (unaffected) the reference joint torque can be computed by the following stiffness and damping control law.

$$\tau_{ref}=K_s(q_{ref}-q)+K_d\dot{q} \qquad (2)$$

In this work the joint stiffness and damping gains K_s, K_d are variable and function of the joint torques induced by the time-varying interaction forces as described in Eq. 3.

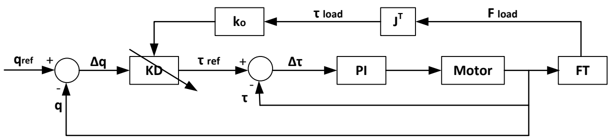

Fig. 3: Joint stiffness regulation - control scheme

$$\tau_{ext}=J^T(q)F_{ext} \qquad (3)$$

with $F_{ext}\in\mathbb{R}^{m}$ the vector of the external forces in task space. In particular, the stiffness and damping gains Ks , Kd are individually tuned according to the contribution of each joint to counteract the end-effector loading for the current arm configuration and interaction force. Moreover, a minimum stiffness/damping setting is specified for free space operations as described by Eq. 4.

$$K_s=\begin{cases} k_o\times J^T(q)|F_{ext}| & \text{if } \; k_o\times J^T(q)|F_{ext}|\geq K_{so} \\ K_{so} & \text{otherwise} \end{cases} \qquad (4)$$

with k_o the torque-to-stiffness gain and K_{so} the minimum joint stiffness level.
The damping gain K_d is modulated so as to keep the joint damping ratio of the joint constant (we consider here that the joint inertia is constant and equal to that in the arm configuration that maximizes it) as shown on Eq. 5. This choice is based on human arm behaviour [18].

$$K_d=\alpha K_s \qquad (5)$$

where α is a stiffness to damping regulation gain. These variable stiffness and damping gains K_s and K_d are used through the position-based impedance controller to compute the desired joint torque as described in Eq. 2. This represents the reference torque of the inner PI torque controller as described on Fig. 3. The final control consists thus of an outer loop computing the joints torque reference with the variable stiffness and damping gains. The joint torque reference τ_{ref} is tracked through the inner PI loop of the internal motor controller, see Fig. 3.

These variable stiffness/damping gains on the basis of the interaction forces effectively implement a stiffening behaviour that resembles the stiffening action performed in human joints during lading conditions through the muscle co-contraction mechanisms.

C. Joints stiffening under static load

The local impedance controller accounts for the limb's configuration and the direction of the interaction force to tune individually the joints impedance according to their loading while counterbalancing the endpoint loading. To illustrate this behaviour, we present the stiffening response to a static force applied at the end-effector in two different arm configurations.
The arm configuration is estimated from the encoders reading of the five joints influencing the spatial orientation of the force sensor mounted at the robot's wrist. In each of the

Fig. 4: Configuration 1

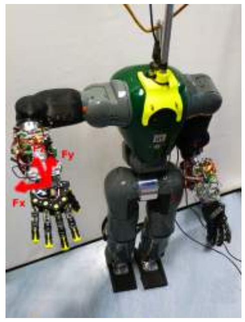

Fig. 5: Configuration 2

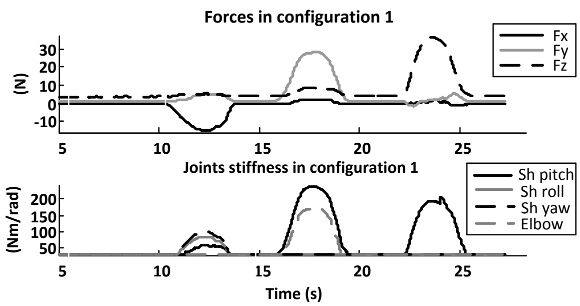

Fig. 6: Joint stiffening behavior in configuration 1

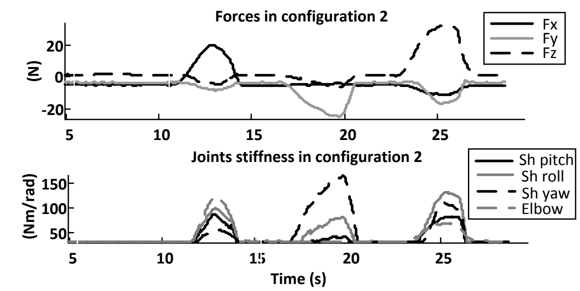

Fig. 7: Joint stiffening behaviour in configuration 2

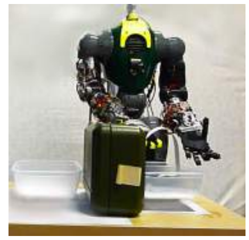

Fig. 8: COMAN robot performing the lifting task

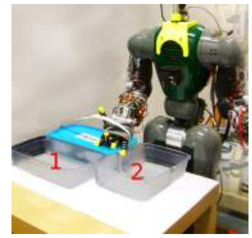

Fig. 9: COMAN robot performing the stacking task

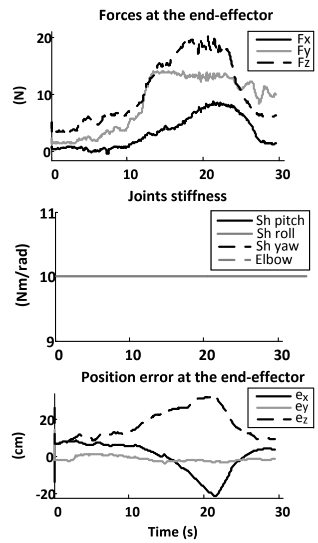

Fig. 10: Lifting task with constant low joint impedance

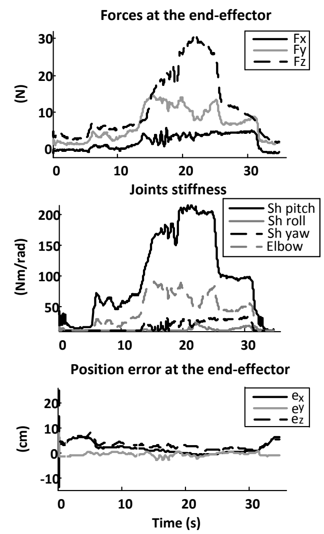

Fig. 11: Lifting task with online joint impedance regulation

two static configurations represented Fig. 4 and 5, a force is applied at the robot's hand along three orthogonal directions. The resulting joints stiffness tuned online by the autonomous impedance controller are presented Fig. 6 and 7. It clearly appears that the arm joints are stiffened according to their individual contribution to counter the external loading.

D. Joint impedance regulation during a lifting task

The performances of the proposed controller are experimentally assessed by comparing the results obtained while executing a lifting task with active control of the joint's impedance versus fixed gains impedance control.

The teleoperation task consisted of lifting with the right hand of the robot a 2kg mass from a box situated on the left side of the robot at a hip's height, transporting it over an obstacle 20 cm high and place it in a box on the right side as depicted Fig. 8. The initial stiffness of the arm's joints was set to 10 Nm/rad for both experimental conditions. The interaction forces, the joints stiffness and the Cartesian position error at the end-effector are reported on Fig. 10 and 11.

The initial end-effector Cartesian error corresponds to the joints deflection under gravity. When activating the local controller, joints are progressively stiffened while lifting the object so as to compensate for the external loading at the end-effector. The task is successfully completed, as indicated by the small position error. In contrast, the position error grows up to 32 cm in absence of joints impedance tuning: the slave is unable to track the teleoperated trajectory because of the external resistance opposed by the environment. As a consequence the load cannot be lifted.

Through the adjustment of the slave's dynamic characteristics to the environment manipulated, the proposed controller allows for dexterous interaction tasks with diverse impedance environments.

IV. Vibrotactile Feedback of the Humanoid Robot's Balance State

The online tuning of the joints impedance allows for the development of high interaction forces, enabling to perform tasks such as carrying heavy loads. This enhanced manipulation capability raises an additional concern. In contrast to fixed-base manipulators or stable-based mobile robots, humanoid robots are intrinsically unstable. As a consequence, the generation of high contact forces can lead to a loss of balance. The robot might tip forwards while trying to the lifting a bulky object or fall backwards while attempring to push a heavy door.

Autonomous stabilizers represent a powerful tool to recover from perturbations issued by the environment such as pushes or sudden changes of the terrain inclination. However a

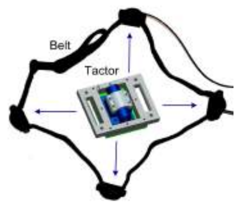

Fig. 12: Vibrotactile belt

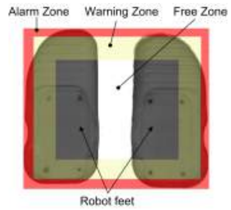

Fig. 13: Feedback pattern

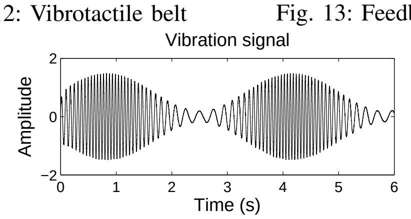

Fig. 14: Vibration signal

limitation appears when considering a teleoperation scenario, where the balance recovery strategy highly risks compromising the task completion. As an alternative, we propose maintaining the operator aware of the slave's balance state by the mean of a vibrotactile belt. The idea is to establish whether operators are able to use this information to adjust their teleoperation strategy so as to complete the task while maintaining the slave's stability, in the same way humans constantly rely on their proprioception - or sense of balance - to perform everyday actions without loosing balance.

Studies suggest that a tactile guidance could be successfully used as sensory substitution to provide impaired persons with balance information. In [19] authors reveal that subjects with vestibular deficits were able to rectify their stance according to a cutaneous guidance provided by a vibrotactile belt so as to achieve an improved postural stability. In a previous study [20] we investigated the feasibility to replicate such scheme within the scope of a humanoid robot teleoperation. Results obtained suggest that the proposed cutaneous feedback, relating the stability margin to the vibrotactile signal, enabled operators to recognize the boundaries of the robot's stable workspace and to adjust their torso orientation when the slave was approaching a loss-of-balance configuration. In this study the slave was teleoperated in free-space such that the balance state was depending only on the body stance. To further the investigation, we aim at establishing whether this feedback can be properly interpreted when the robot's balance state is affected through its interaction with the environment.

A. Vibrotactile balancing feedback

To perform this study, a four-tactor vibrotactile belt has been designed, see Fig. 12. Each tactor consists of an eccentric mass vibration motor mounted on a flexible rubber layer to achieve an enhanced perception of the vibration source. The tactors are arranged at the four cardinal directions so as to provide a directional feedback about the balance state of the robot. The vibration signal is built as a high frequency sine wave carrier modulated by a low frequency sine wave signal, see Fig. 14. Both the amplitude and frequency of the vibration signal's envelope are increased when the stability margin of the robot decreases in one direction. The COP's position is evaluated in real time from the force-torque measurement at the robot's ankles. The distance of the COP from the support polygon's borders is used to compute the vibration signal parameters according to a two-level feedback pattern designed during a previous study [20]. This feedback pattern relies on the division of the support polygon into three concentric zones as shown on Fig. 13. They correspond, from the center to the periphery, to the free zone, the warning zone and the alarm zone. When the COP lies in the free zone no vibration is displayed; the warning zone - represented in yellow - is associated with a low amplitude, low frequency vibration signal and the alarm zone - colored in red - is associated with a high amplitude, high frequency vibration signal.

B. Experimental study

To investigate operator's ability to adjust their teleoperation strategy according to the slave balance state when interacting with the environment, an experimental study has been conducted. The overall framework used is presented on Fig. 2 The task consisted in lifting a box containing a light load (0.5kg) or a heavy one (1.5kg) and stacking it on one of the two piles as represented on Fig. 9. Such manipulation causes the center of pressure of the robot to be shifted forwards. As pile 1 was located further away from the robot's initial center of mass than pile 2, the heavy load could be placed only on top of pile 2 without making the slave loose balance, whereas the light load could be placed on top of both piles safely. Operators were instructed to lift the box and try to stack it on pile 1. If they judged that this would make the robot fall down, they were instructed to place it on pile 2. This type of strategy is used by humans who instinctively bring heavy loads closer to their center of mass in order to not loose balance.

A screen placed between the operator and the slave limited the visual feedback to the robot's arms and reachable workspace, which corresponds to the visual information that would provide a camera mounted on the neck of the robot. To ensure that operators could not rely on auditive cues, they were wearing noise cancelling headphones.

Teleoperation performances were compared under two conditions: with only visual feedback and with visual + tactile feedback of the slave's balance state. The different conditions were presented in a random order to reduce the learning effect. Operators were aware of the feedback condition but not of the load type. Five subjects took part to the experiment (four men and one woman) and performed a total of 20 trials each (5 trials x 4 conditions). Performances were evaluated considering two factors: the number of conservative choices (placement of the light weight on pile 2) and the number of falls when manipulating the heavy load.

C. Results

Results show that conservative choices represent a marginal behaviour with only one occurrence for the overall

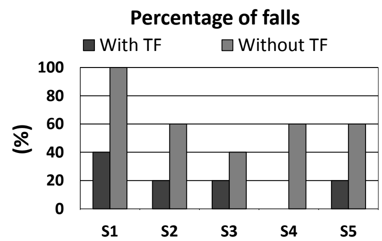

Fig. 15: Comparative number of falls with and without tactile feedback (TF)

experiment: operators tried to place the box on pile 1 when they judged that it could be done safely. The average number of falls under both feedback conditions is presented Fig. 15.

A paired two-tailed t-test on the mean difference in number of falls revealed that the average number of falls is highly significantly lower under tactile feedback+visual feedback than under visual feedback only ($t(4) = 5.88, p = 0.0042$). This result suggests that the tactile feedback enabled operators to understand when the teleoperated robot's stability droped while interacting with the environment. Using the cutaneous guidance, operators were able to rectify their teleoperation strategy in order to to complete the task while maintaining the slave's balance.

V. Conclusion

Teleoperation constitutes a powerful tool to compensate for robots lack of decision-making skills required to operate in dynamic and uncertain environments. However, controlling a humanoid robot in an efficient way can result very complex and demanding. This work presents an enriched human-machine interface for an intuitive yet effective teleoperation of a humanoid robot.

The operator's hands and torso Cartesian position and orientation are monitored through a vision-based motion capture system and used to generate the slave's joints position reference, allowing for an intuitive control of the slave's stance.

In addition, a local controller is implemented at the slave side in order to adjust the joint's impedance to the remote environment. Relying on the interaction forces measurement at the end-effector, the joints stiffness and damping are individually tuned according to the arm configuration and the direction of the external load to counter. Experimental results demonstrate the effectiveness of this human-inspired controller, providing the slave with the versatility required to achieve safe yet dexterous interactions with environments of highly diverse impedances.

To tackle with the humanoid robot loss of balance that can result from high interaction forces, we propose to integrate the operator in the loop by providing a cutaneous feedback of the slave balance state. An experimental study shows that operators are able to recognize when the teleoperated robot stability drops while interacting with the environment. Moreover, results suggest that relying on the tactile guidance they are able to adjust their teleoperation strategy so as to maintain the robot's balance. Finally the vibrotactile feedback of the slave's balance state leads to enhanced teleoperation performances characterized by a significantly lower number of falls.

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