Robust and Dexterous Dual-arm Tele-Cooperation using Fractal Impedance Control

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Abstract—Deploying robots from isolated operations to shared environments has been an increasing trend in robotics for the last decades. However, the requirement of robust interaction in highly variable environments is still beyond the capability of most robots. We proposed to achieve robustness of various interactions by using the Fractal Impedance Control (FIC) and exploiting its non-linear stiffness to adapt to multiple cooperative scenarios, which is applicable to both manipulation and teleoperation applications. The proposed method was evaluated by a wide range of experiments: drilling, moving objects with unknown dynamics, and interacting with humans. The extensive validations demonstrated that the proposed method is very robust in presence of delays and reduced bandwidth in the communication link between master and follower. The results confirmed that the proposed method can enhance the robustness significantly and allow switching tasks freely between manipulation, human-robot cooperation and teleoperation without the need of extensive re-tuning of the controllers.

I. INTRODUCTION

Robots have been strategic assets for the design of modular and flexible production lines in the second half last century. The prosperity brought by these technologies has played a central role in improving our quality of life and generated a demographic shift in our society. The ageing population is currently generating a reduction of the active workforce and an increasing demand for health services related to the ageing-related pathologies. Robots could help satisfying these demands by enabling better healthcare, reducing work-related injuries, and reducing the risk for operators in dangerous environments [1]–[4]. These tasks require the availability of control frameworks capable of switching between different tasks in seconds with minimal intervention from a user/operator, especially when we consider that the operator might not have the technical knowledge required to reprogram the robot’s controller in such scenarios.

Multiple solutions have been proposed to deploy robots in the applications mentioned above that we classify in four categories: high-level algorithms, adaptable controllers, smart sensing, and adaptable mechatronics [5]–[11]. However, all of these components have to come together to render robots sufficiently flexible and robust to enter our daily living. The high-level algorithms category includes all the optimisation and machine learning methods deployed to plan and adapt the robot actions. Adaptable controllers are all these architectures enabling some degree of adaptation obtained from integrating the action plan with the sensor information. Smart sensing methods exploit multiple sensors to generate accurate state estimation and prediction necessary to track both the robot and the environment states. Adaptable mechatronics includes technologies capable of either passive (e.g., soft materials and composites) and active (e.g., Variable Stiffness Actuators and smart materials) adaptation to the environment. Although a final solution would require integrating technologies from all these fields, the analysis presented in this manuscript focuses on adaptable controllers with some consideration on their integration capabilities with the other technologies.

Interaction controllers are based on the Port-Hamiltonian frameworks, and they either rely on admittance or impedance control architectures [11]–[13]. Impedance controllers control the force based on the tracking accuracy. Admittance controller trade-off the robot tracking accuracy based on the interaction’s desired force [12]. A general rule for these controllers is that the impedance controller is preferable when we want robustness of interaction in an unknown environment, and they do not require the deployment of a force sensor. In contrast, admittance controllers performed better when we have controlled interaction conditions, including a well-defined interaction point equipped with a force/torque sensor when using its most common implementation [1], [14]–[17]. A significant drawback of these types of admittance controllers is that they are not back-drivable when the interaction bypasses the force/torque sensor. Thus, they are recommendable for non-redundant mechanisms, where the null-space cannot be exploited to accommodate undesired that do not involve the end-effector (e.g. single joint actuation).

Either admittance or impedance controllers have been integrated into optimised controlled architectures and/or coupled...
with learning algorithms to implement adaptable controllers [1], [5], [10], [14], [18]. Although these methods successfully implemented a proof of concept applications, they susceptible to lack of accurate models, misrepresentation of the interaction conditions, numerical instability, sensor noise and information delay [8], [19]. Furthermore, they are task-dependent, computationally expensive, and require extensive task-specific parameters tuning, limiting their flexibility [16], [17]. In contrast, animals are capable of dexterous robust interaction in challenging environment despite their bio-signals are noisy and transferred with substantial delays. Furthermore, they are also capable of learning, adapt, and transfer motor skills, which have fuelled the interest of both the robotics and neuro-scientific communities for the last few decades [2]–[4], [10], [20].

The dual-arm tele-cooperation set-up shown in Figure 1 is used in this research and is capable of various task executions with minimal intervention from user/operator by implementation of the proposed and studied control architecture in Figure 2 which can be used for teleoperation, manipulation and human-robot collaboration, without requiring a time consuming process of tuning the control parameters. The proposed method is an extension of an architecture developed in [16] which was for dexterous teleoperation. Specifically, here we added interfaces for passing trajectories and improved the adjustment of the impedance characteristics of the controller, and scaled the architecture to perform bi-manual tasks. In summary, the contributions of the proposed method are:

i) Stable and smooth switching between different dynamic tasks without gain tuning, which is validated with/without human interaction while drilling different materials;

ii) Generalised performance for multi-arm set-up exploiting the advantageous superimposition properties of the FIC controller, which is validated with dual-arm human-robot interactions.

This manuscript is organised as follows: section II provides some preliminaries on fractal impedance control, section III introduces the architecture of proposed controller, section IV describes the carried out experiments, section V presents the results that are later discussed in section VI and, finally, section VII draws the conclusions.

II. PRELIMINARIES ON THE FIC

The Fractal Impedance Controller (FIC) is a passive asymptotically stable controller having smooth autonomous trajectories [16], [17]. It relies upon an anisotropic impedance to drive the system, which generates a conservative field rendering the controller stable to communication delays and reduced control bandwidth [16], [17]. The conservative energy of the controller also enable to stack in series and in parallel multiple controllers and perform online tuning without affecting stability [16], [17], [21]–[24].

The controller’s implemented for this work relies on the non-linear stiffness based on the model presented in [17].

\[
K(\ddot{x}) = \text{Diag} \left( \frac{4}{\tilde{x}_{i_{\text{max}}}^2} \int_0^{\tilde{x}_{i_{\text{max}}}} K_{d}(\ddot{x}_i) \ddot{x}_i \; d\ddot{x}_i, \text{ Conv} \right)
\]

(1)

where \( \ddot{x} = x_d - x \) is the pose error, \( x_d \) is the desired state, \( K_{\dot{\ddot{x}}_i} \) is a constant stiffness for the \( i^{th} \) task-space degree of freedom, \( \tilde{x}_{i_{\text{max}}} \), \( K_{\nu_i}(\ddot{x}_i) \) is a variable stiffness profile is the maximum displacement reached during the divergence. The \( K_{\nu_i}(\ddot{x}_i) \) used in this work is:

\[
K_{\nu_i} = \begin{cases} 
\frac{F_{i_{\text{max}}}}{|\ddot{x}_i|} - K_{\dot{\ddot{x}}_i}, & \text{if } |\ddot{x}_i| > x_i^{\text{b}} \\
\exp(\beta_i \tilde{x}_i^2), & \text{otherwise}
\end{cases}
\]

(2)

where \( F_{i_{\text{max}}} \) is the maximum force or torque, \( x_i^{\text{b}} \) is the pose error where the force/torque saturate at \( F_{i_{\text{max}}} \), and \( \beta_i = \ldots \)
\[ \sqrt{\ln \left( \frac{F_{\text{max}}}{x_{\text{max}}} \right) - K_{\text{c}}} \left( x_{\text{max}} \right) \] 

Thus, the controlled system has the following dynamic equation at the end-effector:

\[ \Lambda \ddot{x} - D \dot{x} + K(x) \ddot{x} = 0 \] (3)

where \( \Lambda, D \) are the Cartesian inertia, damping respectively, which is obtained with the following joint torque control signal:

\[ \tau_c = J^T (-D \dot{x} + K(\ddot{x})\ddot{x}) + F_{\text{ND}} + (I - J^T (JJ^T)^{-1}J) \tau_{\text{null}} = J^T \Lambda \dot{x} + (I - J^T J) \tau_{\text{null}} \] (4)

where \( J \) is the Jacobian, \( F_{\text{ND}} \) is the compensation of the non-linear dynamics, \( M \) is the inertia matrix and \( \tau_{\text{null}} \) is the null-space torque.

III. TeleCoop-FIC

The TeleCoop-FIC exploits the teleoperation architecture introduced in [16], based on the architecture in Figure 2. This method has been validated for haptic teleoperation with delays up to 1 s and communication bandwidth as low as 20 Hz between Master (M) and Replica (R) [16]. The experimental setup was composed by a Panda Arm (Franka Emika) as Replica (R) robot, and a Sigma.7 Haptic Interface (Force Dimension) as Master(M) device. The replica is also equipped with a force/torque sensor at the end-effector to measure the interaction force. The previous work in [16] showed dexterous interaction when dealing with a variate set of environmental conditions without re-tuning. This work here extends more results and builds on this architecture to control multiple arms, and use the controller for manipulation, teleoperation, and cooperation with a human operator in multiple tasks. By exploiting the non-linear impedance profile and the stability properties of the FIC, we show that there is no need of re-tuning the proposed controller gains.

A. Haptic Teleoperation

1) Master’s Controllers: The master wrench command for the Sigma-7’s controller is sum of the scaled end-effector force \((A_M)\) and the FICM:

\[ F_M = FICM + A_M(\bar{x}_M)S_M - D_M\bar{x}_M + KA_F_{FB} \] (5)

where \( K_M(\bar{x}) \) is a state-dependent stiffness matrix, \( D_M \) is the damping, \( F_{FB} \) is the measured wrench at the replica’s end-effector, and \( K_A = 1 \) is the scaling factor.

2) Replica’s Controller: The replica’s controller is the combination of the virtual force from the master \((J_R^T K_C x_M)\), and the FICR when the grasp DoF is pressed:

\[ \tau_{\text{FICR}} = J_R^T (K_R (\bar{x}_R)\bar{x}_R - D_R \bar{x}_R) + F_{\text{ND}} + (I - J_R^T J) \tau_{\text{null}} \] (6)

where \( \bar{x}_R = x_M - x_R \). On the other hand when the grasp DoF is not selected the equation is as follows:

\[ \tau_{\text{FICR}} = J_R^T K_C x_M + J_R^T (K_R (\bar{x}_R)\bar{x}_R - D_R \bar{x}_R) + F_{\text{ND}} + (I - J_R^T J) \tau_{\text{null}} \] (7)

where \( \bar{x}_R = x_d - x_R \).

B. Non-Haptic Teleoperation

1) Master’s Controller: The master wrench command in this case is through the GUI that gives the operator the capability of setting new set-points graphically and the robot gets to any new set-point using Polynomial Path algorithm (cubic) along the desired line connecting the previous- and new-set point.

2) Replica’s Controller: The replica’s controller in this case is only the fractal impedance control (FICR):

\[ \tau_{\text{FICR}} = J_R^T (K_R (\bar{x}_R)\bar{x}_R - D_R \bar{x}_R) + F_{\text{ND}} + (I - J_R^T J) \tau_{\text{null}} \] (8)

C. Multi-Arm Implementation

Recently, we have explored the possibility of superimposing and coordinating independent FICs via the synchronization of their desired states [21]–[23]. This property is rendered possible by the conservative energy of the FIC, which guarantees the stability of the superimposition of independent controllers. In other words, each FIC regards the others as a part of the environment, and its global asymptotic behavior guarantees the stability of interaction [17]. It is worth noting that this does not ensure the success of the coordinated task, but it only guarantees that the involved robots will not behave erratically. However, our earlier experiments validated the superimposition either for redundant manipulator [21], [23] or coordination of a swarm of drones [22]. The proposed method extends the experimental validation of the FIC superimposition properties to multiple redundant manipulators, allowing two arms to complete two bi-manual tasks during unknown interaction. The validation of these properties substantially simplifies the algorithmic complexity of the robot interaction controllers deployed in teleoperation and manipulation. Currently, multi-arm manipulation requires the simultaneous observation of the state of both arms through the grasp matrix, which couples the state of the two systems and increasing the algorithmic complexity [25], [26]. In contrast, the proposed architecture allows solving the same problem just considering the simplified dynamics generated by the FIC at the end-effector.

To experimentally validate the property mentioned above, we do not consider either the grasp matrix and the interaction dynamics in the first instance. Instead, for the scope of this work, we have coordinated the two arms by issuing coordinated via point that guarantees contact with the object allowing us to prove that the stability is independent by the grasp matrix. Nevertheless, the grasp-matrix and the object dynamics are required to autonomously plan a coordinated task, which is beyond the scope of this manuscript.

IV. EXPERIMENTAL DESIGN

The preliminary validation of the proposed architecture is presented in [16]. The results show that the method enables dexterous haptic teleoperation in multiple scenarios with the minimum tuning of the controller parameters. Furthermore,
it is extremely robust to the presence of delays and reduced communication bandwidth between the master and the replica. The controllers’ gains used in this manuscript are the same as the ones used for the experiments in [16].

A. Design of Experiments

The experiments presented in this work have been designed to evaluate the performance of the TeleCoop-FIC in teleoperation, manipulation, and human-robot cooperation task, which were beyond and complement the previous work in [16]. Particularly, we aim to verify that it can switch between tasks without an extensive and tedious process for adjusting the controller tuning. To do so, we looked at tasks involving a dynamic interaction such as drilling multiple materials and retaining movement accuracy when carrying a variable mass. The set-up used for the experiments consists of two Panda Arms and a Sigma.7 Haptic Interface. It shall be noted that the teleoperation experiments presented in this manuscript are performed in line-of-sight teleoperation. It shall be noted that the user is always controlling both the linear and the angular components of the end-effector pose. However, the adjustable boundaries of the FIC force saturation (Equation 2) can be used to funnel the interaction in predetermined constraints, which will be exploited in one of the experiments described below to guide a human operator during a slanted drilling task.

The first experiment (Exp. 1) compares the proposed method against a traditional impedance controller (IC) in a drilling manipulation task on a clamped wood brick. The task involved drilling a hole using a Dremel multi-tool. We compare the controller’s ability to penetrate the wood when a similar command is issues and the generated interaction force. The IC control law used for the comparison is:

\[
\tau_{IC} = J^T_R (K_{IC} R \ddot{x} - D_R \dot{x}) + F_N + \left( I - J^T_R J_R \right) \tau_{null} \tag{9}
\]

where \( K_{IC} \) is a constant stiffness and \( D_R \) is the damping.

The second, third, and fourth experiments focus on evaluating the modularity of the proposed framework by performing drilling on multiple materials with the support of an autonomous arm that is securing the work-piece. For these experiments, we evaluate the accuracy and precision of drilling in a predefined location in wood (Exp. 2), 3D printed PLA (Exp. 3) and a deformable cardboard box (Exp. 4).

The fifth experiment involves two scenarios of human-robot collaboration with the robot arms moving autonomously using the manipulation controller in the proposed architecture Figure 2. The first scenario (Exp. 5.1) consists of the two arms are handling the work-piece, and the human is performing the drilling. To successfully execute the task, the two arms have to pick-up the work-piece, carry it near to the operator, supporting the piece during the drilling, and delivering it back to the initial position once the operator has finished the task. During the second scenario (Exp. 5.2), one of the arms is clamping the work-piece against the ground, while the second arm is holding the Dremel, and it is in charge of controlling the tool inclination during drilling by exploiting its non-linear impedance to generate virtual boundaries that funnel the drill towards the desired inclination. Meanwhile, the human controls the drilling action by pushing on the robot’s terminal link.

The final experiment (Exp. 6) is the bi-manual manipulation of the box that is picked up, presented to the operator, filled by the operator and carried back to its initial position by the robot. This is to evaluate the robustness of the proposed method to change of the environmental state (e.g., object inertia) by evaluating its tracking accuracy while carrying a variable mass object (i.e., the box).

B. Controller Parameters

The controllers parameters used for this experiments are reported in Table I. The only adjustment to the controllers parameters performed is lowering the value of \( |x_{ib}| \) to 5 mm for the first experiment to enhance the tracking accuracy.

![Table I. Control parameters for translation and angular degrees of freedom.](image)

|                | Master | Replica |
|----------------|--------|---------|
| \( K_{IC} (N/m) \) | 0      | 100     |
| \( K_{IC} (N/rad) \) | 0      | 100     |
| \( D_R (Ns/m) \) | 2.5    | 2.5     |
| \( D_R (N/rad) \) | 0      | 20      |
| \( |x_{ib}| (m) \) | 0.05   | 0.05    |
| \( |x_{ib}| (rad) \) | 0.0873 | 0.0873 |

V. Results

The results from the first experiment show that the FIC controller is capable of generating an interaction force of 15 N versus the 3 N of the IC controller. The higher force allows to get a penetration dept that is about 1 cm deeper, reducing the final position error along the drilling direction (y-axis) to about 3 mm as shown in Figure 3. Such results are achieved without re-tuning the FIC controller or issuing a deeper desired position thanks to its nonlinear impedance that cannot be stabilised on a traditional IC, as reported in [17]. As a consequence, the FIC will have a stiffness similar to the IC for displacement within \( x_b \) because it can exploit the nonlinear profile to generate high interaction force without requiring a large position error. Thus, if a loss of contact occurs, the FIC will produce a smaller movement. To generate a similar behaviour with an IC controller would require variable impedance controllers that have more complex architecture and are only marginally stable.

The drilling position error for the teleoperation experiments are Exp. 2, 3, and 4 in Figure 6. Meanwhile, Figure 4 shows the work-pieces after the drilling. The mean errors indicates an accuracy between 0.5 mm and 1.5 mm that is mostly affected from the direction of the task on the x-y plane rather than the material. The precision indicates that ranged from 0.5 mm to 1 mm depending on both direction and material. The average interaction forces measured during the three tasks depend from the material rigidity, and they are 10 N, 8 N and 4 N, respectively. Furthermore, the holes...
The trajectory and the interaction force for the FIC and IC are compared when drilling a piece of wood. The results indicate that the FIC exploits the nonlinear stiffness profile to exert a higher force to achieve a deeper penetration while receiving the same control input.

![Fig. 3](image)

Fig. 3. The trajectory and the interaction force for the FIC and IC are compared when drilling a piece of wood. The results indicate that the FIC exploits the nonlinear stiffness profile to exert a higher force to achieve a deeper penetration while receiving the same control input.

The error recorded from two cooperation experiments for drilling are the experiments in Figure 6. They indicate that we can expect sub-millimetre accuracy when the user is holding the drill. The experiment 5.1 proves that the two arm movement can be synchronised issuing coordinated via-points without relying on trajectory planning. The results described in Figure 7 indicate that it is possible to pick up the work-piece, carry it to the user, providing sufficient support to execute an accurate drilling, and retain stability and safety of interaction even in the event of a sudden loss of contact. The experiment 5.2 confirms the robot can constraint the dremel inclination to the predetermined range of ±5° in each direction when drilling on a curve surface, as shown in Figure 5.

The bi-manual manipulation task trajectories (Exp. 6) are shown in Figure 8. The arms start in the first via point and move to third to pick-up the box. The empty box in borough in to the 6th via point where the human loads the box with about 2 kg of material. Regardless of the added mass the robots retain a sufficient position accuracy that enables them to carry the box back to the 3rd via point, which is bounded by the FIC force saturation to a value that is \( \tilde{x}_b \). It is worth noting that the FIC is generating the maximum effort (i.e., forces and torques) selected for a task, and any position error greater than \( \tilde{x}_b \) implies that the current load exceed the controller/robot capabilities. Thus, it will either require a change in the selected maximum effort in the controller, or a change of robot when the load exceed its mechanical capabilities.

![Fig. 6](image)

Fig. 6. Experiments 2 to 4: Teleoperation drilling for objects 1, 2, and 3 in Figure 4. Experiment 5.1: Human-robot cooperation scenario 1 (object 4). Experiment 5.2: Human-robot cooperation scenario 2 (object 5).

The experiments show that the TeleCoop-FIC can easily switch from teleoperation to manipulation, and multiple arms can be easily coordinated by issuing synchronous via-points thanks to the FIC modularity. The second scenario during the third experiment is the only one that includes a parameter change, which was straightforward and had the function of reducing the user effort. The modality of the architecture also allows to pass from manipulation to teleoperation simply by selecting the communication lines between the controller’s modules in Figure 2, enable by the passive nature of the controller, as in dept analysed in [17], [21], [22]. Therefore, it enables to switch between control modes without the need of tuning or changing its architecture, but it can be done

![Fig. 5](image)

Fig. 5. Exp. 5.1: Drilling on a curve surface with a constrained angular motion (±5°).

on the cardboard are less neat and they are often elongated as shown in Figure 4.

The error recorded from two cooperation experiments for drilling are the experiments in Figure 6. They indicate that

![Fig. 4](image)

Fig. 4. Various objects used for experiments: (a) Small wood brick, (b) Flat-surface plastic object, (c) Carton box, (d) Curved-surface plastic object and (e) Large wood brick.

The error recorded from two cooperation experiments for drilling are the experiments in Figure 6. They indicate that
simply by selecting the information source using conditional statements. Additionally, the controller passivity also guarantees that the proposed method is robust to communication delays and reduced bandwidth [16].

The tasks show that the method can exploit its nonlinear impedance to generate higher interaction forces and accurate tracking without need of accurate modelling of the interaction dynamics. This characteristics renders this method extremely robust because it does not requires the knowledge of the environmental dynamics to stabilise its behaviour. Therefore, it presents all the benefits that constant impedance controllers have on variable impedance and admittance controllers, but it does not suffers of their low accuracy [1], [10], [17], [27]. Such accomplishment it is made possible by the tunable non-linear impedance profile that enables to select the required task precision, the maximum effort and/or constant stiffness that the controller produce. Moreover, the selection of these characteristics also upper-bounds the system maximum power and maximum kinetic energy as described in [22], [24].

The nonlinear impedance allows to define low impedance funnels that can be used to guide the task performed by the user, how it has been shown in Exp 5.2 when the user was drilling a curved work-piece. This capability might find application in training on new operators, guiding them on specific action patters, or respecting constraints that are otherwise difficult to respect (e.g. drilling with a constant angle on a curve surface). Furthermore, it is worth noting that the interaction with the robot during the task felt very natural and all the tasks required were successful at the first attempt, and the motor synchronisation was obtained only via the mechanical interaction between the robot and the users. Possible applications for the TeleCoop-FIC can be manufacturing, space robotics, medical robotics, rehabilitation and training.

VII. Conclusion

In Conclusion, the main observed limitation is that the task accuracy and precision should be in the order of millimetre based on our set-up, but it will vary based on the robots used. Especially considering that the tuning of the controller
is straight forward and can be performed by non-technical operators, simply selecting the desired task precision ($\xi_T$), maximum effort ($F_{max}$), and constant stiffness ($K_C$). However, an identification of the maximum parameters is required to limit the parameter range to be within the mechanical capabilities of the robot. An identification procedure for this type of controller has been already developed, tested on multiple robots and is detailed in [17].

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References

[1] Y. Li, G. Ganesh, N. Jarrassé, S. Haddadin, A. Albu-Schaeffer, and E. Burdet, “Force, impedance, and trajectory learning for contact tooling and haptic identification,” IEEE Transactions on Robotics, vol. 34, no. 5, pp. 1170–1182, 2018.
[2] P. Tommasino and D. Campolo, “An extended passive motion paradigm for human-like posture and movement planning in redundant manipulators,” Frontiers in Neurorobotics, vol. 11, p. 65, 2017.
[3] ——, “Task-space separation principle: a force-field approach to motion planning for redundant manipulators,” Bioinspiration & biomimetics, vol. 12, no. 2, p. 026003, 2017.
[4] C. Tiseo, K. Veluvolu, and W. Ang, “The bipedal saddle space: modelling and validation,” Bioinspiration & biomimetics, vol. 14, no. 1, p. 015001, 2018.
[5] D. J. Braun, F. Petit, F. Huber, S. Haddadin, P. Van Der Smagt, A. Albu-Schäffer, and S. Vijayakumar, “Robots driven by compliant actuators: Optimal control under actuation constraints,” IEEE Transactions on Robotics, vol. 29, no. 5, pp. 1085–1101, 2013.
[6] M. Khoramshahi and A. Billard, “A dynamical system approach for detection and reaction to human guidance in physical human–robot interaction,” Autonomous Robots, vol. 44, no. 8, pp. 1411–1429, 2020.
[7] J. Nakanishi, K. Rawlik, and S. Vijayakumar, “Stiffness and temporal optimization in periodic movements: An optimal control approach,” in 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2011, pp. 718–724.
[8] K. Kronander and A. Billard, “Stability considerations for variable impedance control,” IEEE Transactions on Robotics, vol. 32, no. 5, pp. 1298–1305, 2016.
[9] S. Tadele, T. J. de Vries, and S. Stramigioli, “Combining energy and power based safety metrics in controller design for domestic robots,” in 2014 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2014, pp. 1209–1214.
[10] G. Averta and N. Hogan, “Enhancing robot-environment physical interaction via optimal impedance profiles,” in 2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob), 2020, pp. 973–980.
[11] N. Hogan and S. P. Buerger, “Impedance and interaction control,” in Robotics and automation handbook. CRC press, 2018, pp. 375–398.
[12] N. Hogan, “Impedance control: An approach to manipulation,” Journal of dynamic systems, measurement, and control, vol. 107, no. 17, 1985.
[13] ——, “A general actuator model based on nonlinear equivalent networks,” IEEE/ASME Transactions on Mechatronics, vol. 19, no. 6, pp. 1929–1939, 2013.
[14] M. S. Erden and A. Billard, “Robotic assistance by impedance compensation for hand movements while manual welding,” IEEE transactions on cybernetics, vol. 46, no. 11, pp. 2459–2472, 2015.
[15] C. Yang, G. Ganesh, S. Haddadin, S. Parusel, A. Albu-Schaeffer, and E. Burdet, “Human-like adaptation of force and impedance in stable and unstable interactions,” IEEE transactions on robotics, vol. 27, no. 5, pp. 918–930, 2011.
[16] K. K. Babarahmati, C. Tiseo, Q. Rouxel, Z. Li, and M. Mistry, “Robust high-transparency haptic exploration for dexterous telemanipulation,” in Proc. IEEE International Conference on Robotics and Automation (ICRA), 2021.
[17] K. K. Babarahmati, C. Tiseo, J. Smith, H. C. Lin, M. S. Erden, and M. Mistry, “Fractal impedance for passive controllers,” arXiv preprint arXiv:1911.04788, 2019.
[18] F. Ferraguti, N. Preda, A. Manurung, M. Bonfe, O. Lamberey, R. Gassert, R. Muradore, P. Fiorini, and C. Secchi, “An energy tank-based interactive control architecture for autonomous and teleoperated robotic surgery,” IEEE Transactions on Robotics, vol. 31, no. 5, pp. 1073–1088, 2015.
[19] D. Lee and K. Huang, “Passive-set-position-modulation framework for interactive robotic systems,” IEEE Transactions on Robotics, vol. 26, no. 2, pp. 354–369, 2010.
[20] E. Guigon, P. Baraduc, and M. Desmurget, “Computational motor control: redundancy and invariance,” Journal of neurophysiology, vol. 97, no. 1, pp. 331–347, 2007.
[21] C. Tiseo, W. Merkt, W. Wolfslag, S. Vijayakumar, and M. Mistry, “Safe and compliant control of redundant robots using superimposition of passive task-space controllers,” arXiv preprint arXiv:2002.12249, 2020.
[22] C. Tiseo, V. Ivan, W. Merkt, I. Havouts, M. Mistry, and S. Vijayakumar, “A passive navigation planning algorithm for collision-free control of mobile robots,” in Proc. IEEE International Conference on Robotics and Automation (ICRA), 2021.
[23] C. Tiseo, S. R. Charitos, and M. Mistry, “Theoretical evidence supporting harmonic reaching trajectories,” in 2021 10th International IEEE/EMBS Conference on Neural Engineering (NER). IEEE, 2021.
[24] C. Tiseo, W. Merkt, K. K. Babarahmati, W. Wolfslag, S. Vijayakumar, and M. Mistry, “Bio-mimetic adaptive force/position control using fractal impedance,” in Proc. IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2020.
[25] M. Minelli, F. Ferraguti, N. Piccinelli, R. Muradore, and C. Secchi, “An energy-shared two-layer approach for multi-master-multi-slave bilateral teleoperation systems,” in 2019 International Conference on Robotics and Automation (ICRA). IEEE, 2019, pp. 423–429.
[26] H.-C. Lin, J. Smith, K. K. Babarahmati, N. Dehio, and M. Mistry, “A projected inverse dynamics approach for dual-arm cartesian impedance control,” arXiv preprint arXiv:1707.00484, 2017.
[27] M. Minelli, F. Ferraguti, N. Piccinelli, R. Muradore, and C. Secchi, “An energy-shared two-layer approach for multi-master-multi-slave bilateral teleoperation systems,” in 2019 International Conference on Robotics and Automation (ICRA). IEEE, 2019, pp. 423–429.