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A Tutorial Survey and Comparison of Impedance Control on Robotic Manipulation

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SUMMARY
There have been significant interests and efforts in the field of impedance control on robotic manipulation over last decades. Impedance control aims to achieve the desired mechanical interaction between the robotic equipment and its environment. This paper gives the overview and comparison of basic concepts and principles, implementation strategies, crucial techniques, and practical applications concerning the impedance control of robotic manipulation. This work attempts to serve as a tutorial to people outside the field and to promote discussion of a unified vision of impedance control within the field of robotic manipulation. The goal is to help readers quickly get into the problems of their interests related to impedance control of robotic manipulation and to provide guidance and insights in finding appropriate strategies and solutions.

KEYWORDS: Impedance control; Interaction control; Force control; Robotic manipulation; Human–robot interaction.

1. Introduction

Impedance control is a unique control scheme that is employed to achieve desirable dynamic interaction between a manipulator and its environment. The impedance usually refers to the dynamic relationship between the motion variables of manipulators and the contact forces. For robotic manipulation, the target of impedance control is to control this dynamic relationship to fulfill the requirements of a specified interaction task, such as keeping the contact force always in a preset safe or acceptable range when the robotic equipment is tracking the desired motion trajectory.

Compared with other regular robotic control schemes, such as position control, force control, and hybrid position/force control, impedance control has three distinguished features. First, the core idea of impedance control is to control the dynamic interaction between motion and contact force as desired instead of controlling these variables separately. Second, impedance control can be utilized in all manipulation phases consisting of free motion, constrained motion, and the transient process between them, without the need to switch different control modes. Last, impedance control provides a possibility to control motions and contact forces simultaneously by designing a proper interaction between a manipulator and its environment. As a result, the performance of robotic manipulation can be improved, and the safety of human–robot interaction can be guaranteed. With impedance control, the application domain of robotic manipulation can be significantly broadened.

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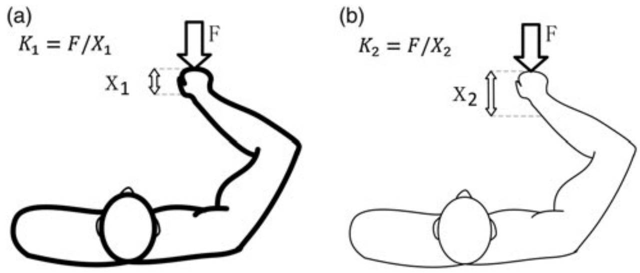

Fig. 1. The impedance of human arm: for simplicity, only stiffness K, as a parameter of impedance, is considered in this figure. (a) Muscles are tensed. (b) Muscles are relatively relaxed, and $K_1 > K_2$.

Human beings have been dreaming that artificial objects can perform like themselves. Impedance control, originated from the observation and investigation of human motor mechanism,[1–7] has the potential to offer robotic manipulators with human-like elaborated operating ability. To understand human motor mechanism, the function of muscles should be addressed. Hogan[1] stated that it is not adequate to simply regard muscle as a generator of forces, but a mechanical impedance adjuster of human limbs. The role of a force generator is to actuate the motion of limbs, whereas the function of an impedance adjuster is to determine the interaction between the limbs and the environment.[6] As shown in Fig. 1, if the human arm is initially kept at the same posture and the same external force F is imposed at the same effect point, then different displacement X of the end-effector can be achieved by adjusting the muscles tension. The ratio of the imposed force to the resulted displacement is the apparent stiffness of arm, that is, the static part of arm impedance. The function of muscles is to change the impedance of the human arm to achieve elaborate manipulation. Human locomotion is another good example to depict how humans interact with environment through impedance. When human is walking, the leg muscles are repeatedly hardened and relaxed depending on the gait phase.[5] Just before the contact of the swing foot with the ground, the leg muscles are relaxed to reduce the leg impedance, which results in a soft landing on the ground.

Inspired by the human motor mechanism, the concepts of impedance and impedance control were applied to the robotic manipulation. The impedance actually defines the dynamic response of manipulator to its environment. This dynamic relationship can be well designed to realize compliant motion or delicate interaction. Commonly, to implement impedance control, the coupled stability of a manipulator and its environment[8–18] should be considered first. Then a proper implementation method should be determined according to the hardware conditions and the actual operating requirements. In general, all these implementation methods can be classified into two main categories: hardware-based approach[19–34] and software-based approach.[10,35–39] In the hardware-based approach, the inherent compliance of some hardware elements, such as stiffness-variable springs and variable dampers, is utilized to achieve the effect of impedance control. By contrast, the software-based approach adopts the well-designed control laws at the software level to impose the desired impedance on the hardware.

After the basic theories and implementations of impedance control have been established, most research efforts were devoted to two main fields: developing more advanced impedance control techniques and expanding the application range of impedance control. Regarding the control techniques, the impedance control is combined with all sorts of advanced control algorithms to achieve the enhanced performance. For example, to promote the force-tracking ability of impedance control, the modified impedance model and different algorithms were adopted[7,40–47]; to increase the flexibility of manipulation, hybrid impedance control[7,48–52] was proposed; to strengthen the robustness[38,40,41,44,50,53–56] and adaptability[7,35,43,50,57–78] toward the model uncertainties of manipulators or unknown environments, various robust and adaptive control algorithms were integrated into the fundamental impedance control methods; In addition, the different learning impedance controllers with the self-adjusting ability in unknown environments were developed by utilizing the diverse learning algorithms.[38,79–89] In the field of applications so far, the human–machine interaction and mechanical manipulation are two main directions to apply impedance control. The applications toward human–machine interaction include rehabilitation robots,[90–111] collaborative robots,[78,112–118] and some expert teaching systems.[60,61,119–121] The applications toward mechanical manipulation involve industrial robots,[37,122–125] micro-manipulation systems,[66,126–128] and other specific manipulation applications.

Utilizing impedance control to achieve compliant motion or elaborate interaction force is the motivation of all these applications.

For the clarity of demonstration, this work is organized as follows: the concept of impedance control and the relevant theories are presented in Section 2. The implementations of impedance control are demonstrated in Section 3. The significant technological developments of impedance control are described in Section 4. Section 5 addresses the practical applications of impedance control. Section 6 presents the conclusions and addresses the outlook on impedance control.

2. Concepts and Principles

In this section, the definition of impedance control is presented at first. Then two important theoretical basics are introduced to help readers understand the implications of this unique control strategy. Finally, comparisons among impedance control and other common control strategies are made with details.

2.1. *Definition of impedance control*

Mechanical impedance refers to the dynamic relationship between an input flow and an output effort at the interaction port between a manipulator and its environment. The input flow is the velocity of the manipulator, and the output effort is the resulted contact force. Therefore, in Laplace domain, impedance $Z(s)$ can be directly written as the ratio of the effort ($F(s)$) to the flow ($\dot{X}(s)$):[50]

$$Z(s) = F(s)/\dot{X}(s) \tag{1}$$

Replacing $\dot{X}(s)$ with $sX_r(s)$ ($X_r(s)$ refers to the relative displacement in Laplace domain), Eq. (1) can be given as

$$sZ(s) = F(s)/X_r(s) \tag{2}$$

Then rewrite Eq. (2) as

$$F(s) = sZ(s) \cdot X_r(s) \tag{3}$$

For a specific manipulation task, if both $F(s)$ and $X_r(s)$ can be controlled properly, an elaborate manipulation can be achieved. But $F(s)$ and $X_r(s)$ are not two independent variables, as they must meet the interaction through $sZ(s)$ depicted by Eq. (3). In this situation, impedance control was proposed to handle this problem in a novel way. Its strategy is to control $X_r(s)$ and regulate the impedance relation $Z(s)$ as desired so that automatically $F(s)$ could be regulated indirectly by Eq. (3). This is one basic working principle of impedance control. In ordinary cases, the impedance $Z(s)$ is usually described as[48,50]

$$Z(s) = Ms + B + K/s \tag{4}$$

The coefficient matrices M, B, and K represent the desired inertia, damping and stiffness values, respectively, to quantify the impedance. This kind of impedance can be employed to determine the contact force in response to the motion input. The detailed implementation of impedance control is demonstrated in Section 3.

The relative displacement $X_r(s)$ can be expressed as the difference between the actual position $X(s)$ and the equilibrium position $X_v(s)$, thus we have

$$X_r(s) = X(s) - X_v(s) \tag{5}$$

Substituting Eqs. (4) and (5) into (3), Eq. (3) can be rewritten as

$$F(s) = \left(M_d s^2 + B_d s + K_d\right) \cdot (X(s) - X_v(s)) \tag{6}$$

After the inverse Laplace-transformation and the reorganization of Eq. (6), this impedance relationship can be expressed by differential equation in time domain as

$$M_d\,(\ddot{x} - \ddot{x}_v) + B_d\,(\dot{x} - \dot{x}_v) + K_d(x - x_v) = F(t) \tag{7}$$

where M_d, B_d, and K_d represent the desired inertia, damping, and stiffness matrices determined by designer, whose dimensions depend on the degrees of freedom; $F(t)$ is the actual contact force

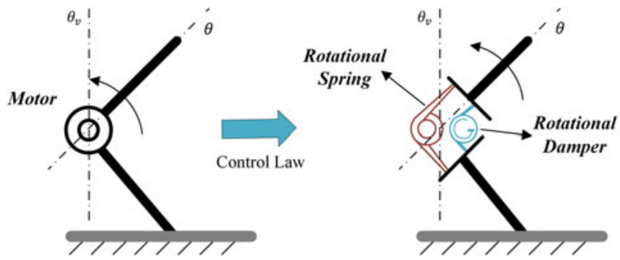

Fig. 2. The dynamic behavior of the entire system is reshaped by the control law defined in Eq. (8).

vector; $x(t)$ is the actual position vector of the end-effector; $x_v(t)$ refers to the virtual trajectory of the end-effector, which defines a series of virtual equilibrium positions for interaction. When the impedance is specified, the virtual trajectory can be regarded as a reference trajectory used for determining a proper force response to the error between the actual position and the virtual position. If there is no contact, the actual trajectory will approach to the virtual trajectory. However, when the motion of manipulator is constrained, the virtual trajectory is difficult to be reached due to physical limitations. This is why it is named "virtual trajectory."

The above explanation implies that impedance actually represents a measure of the dynamic compliance of the manipulator. This compliance is not limited to the intrinsic property of hardware because it can also be modified by the well-designed control law. The philosophy of impedance control is to create different compliances to produce different interactions. In this sense, impedance control can be defined as a control scheme aiming to achieve the desired elaborate interaction between the manipulator and its environment through the well-designed impedance of the robotic equipment.

2.2. *Equivalence between hardware and controller*

Two essential theories about impedance control constitute the foundation for the development of this field. The first theory is the physical equivalence between hardware and controller. This theory states that both the hardware and the control law can change the impedance of the entire control system. The ultimate effect of the controller is not simply to control motion or force, but to modify the dynamic behavior of the entire control system.[129] This theory indicates two different technique directions to implement impedance control, which will be demonstrated in Section 3. One simple case[11] is presented further to illustrate this theory.

For a simple robot with only one torque-controlled motor joint, the applied control law on the motor can greatly shape the dynamic behavior of this robot. For example, the control law is set as

$$\tau_{act} = K(\theta_v - \theta) + B(\dot{\theta}_v - \dot{\theta}) \tag{8}$$

where τ_{act} is the driving torque generated by the motor; θ and θ_v represent the actual angular position and the virtual equilibrium angular position, respectively; the coefficients K and B can be viewed as the virtual rotational stiffness and damping of the joint, respectively. This control law defines the joint torque in response to the motion of robot, reshaping the dynamics of this joint as a spring–damper system.

This example is demonstrated in Fig. 2. The left robot adopting the control law defined in Eq. (8) is equivalent to the right one with the rotational spring and damper in the place of the motor. If the stiffness of the rotational spring is K, and the damping of the rotational damper is B, then the left robot and the right robot have the same joint impedance and dynamic performance. Clearly, this case supports a fact that the dynamic behavior of hardware can be reshaped by the control law at the software level.

Based on this equivalence theory, the classification of the implementation methods of impedance control in Section 3 seems natural and reasonable.

2.3. *Impedance versus admittance*

The second important theory is used to explain the causality between motion and force.[130,131] Hogan[130] defined two opposite concepts to explain this relation, namely admittance and impedance.

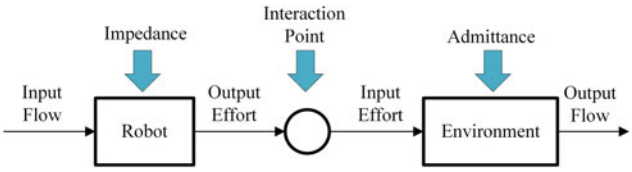

Fig. 3. The roles of impedance and admittance. The "Flow" represents motion and the "Effort" refers to interaction force.

The admittance represents the causality from force to motion, which means the effort (e.g. force) is input and the flow (e.g. motion) is output. Conversely, the impedance represents the causality from motion to force with the flow as input and the effort as output.

For two interacting systems (e.g. the manipulator and its environment), one physically complements the other. At their interaction point, the output of manipulator should be the input of environment, which implies that if one system is regarded as admittance, the other must be treated as impedance and vice versa. This is the complementary theory.

Then the question is whether impedance or admittance should be the proper role of the manipulator in this interaction. Based on the complementary theory, the correct role of manipulator can be determined after deciding the role of environment first. For environment, the force input can always be accepted, but the motion input could be rejected sometimes. If the environment is extremely stable, even a very large contact force cannot make the environment moved. If the environment is assumed as impedance, then the manipulator is admittance. According to the definitions, the motion state should be regarded as the exchanged value to be controlled at the interaction point. In this condition, to achieve the desired motion at the interaction point may produce excessive contact force, which should be avoided. The solution to this problem is to choose the environment as admittance and thus the manipulator as impedance. In this situation, the contact force becomes the exchanged value to be controlled at the interaction point. This relation is shown in Fig. 3.

Based on the above discussions, the impedance should be employed to define the role of manipulator in the interaction. This choice can guarantee the achievement of stable interaction and the avoidance of excessive force. In addition, this causality theory also implies that the intention to control both motion and contact force separately in interaction tasks is not reasonable. Instead, the advanced scheme is to control the motion of manipulator as well as utilize impedance to regulate the contact force indirectly.

2.4. *Comparisons among different control schemes*

In order to reveal the features of impedance control more explicitly, the comparisons among impedance control and other common control modes, such as position control, force control, and hybrid position/force control, are detailed in this subsection.

Position control is the most frequently used control scheme in robotics, whose concern is to track a motion trajectory as closely as possible. This scheme can work well in the free space. The typical applications include robotic welding, spray-painting, and other non-contact tasks. However, once an unexpected contact occurs, the position controller will treat this contact as a disturbance to be rejected, which may lead to position tracking errors and excessive contact force. This high resistance to the external contact reflects that the position controller actually possesses extremely high impedance.

By contrast, the pure force control aims to keep the contact force as the reference without positioning requirements. To achieve the reference contact force, the robot in pure force control tends to move with the environment passively, which means the position of the manipulator cannot be guaranteed. This is because the pure force controller has very low impedance. In fact, both position control and force control can be viewed as two extreme situations of impedance control. In addition, the force control is effective only in the constrained space. If the robot has no contact with the environment initially, perhaps the position control mode has to be applied first to drive the robot to the contact state. Then the force control mode can be switched on successfully. However, this switch between control modes is likely to bring about unstable responses. When the moment to switch control mode mismatches the instant of the actual environment change, these unstable responses may be caused. For example, when the position-controlled manipulator has already touched the environment

Table I. Comparisons among different control schemes.

Control schemes	Work space	Measured variables	Proper applied situations	Control objectives	Potential limits in interaction tasks	Characteristics of impedance
Position control	Task space	Position	Free motion	Desired position	Excessive contact force	Very high impedance
Force control	Task space	Contact force	Constrained motion	Desired contact force	Uncontrolled motion	Very low impedance
Hybrid position/force control	Position subspace	Position	All kinds of motion	Desired position	Prior knowledge about the environment	Very high impedance
	Force subspace	Contact force		Desired contact force		Very low impedance
Impedance control	Task space	Position, contact force	All kinds of motion	Desired compliance of robot	Improper impedance model	Devisable impedance

but the force control mode has still not been invoked, the excessive contact force may be produced. Similarly, when the force-controlled manipulator has just left the contact surface of environment but the position control mode has not been switched on, the manipulator may move disorderly at this moment. The excessive contact force and the unexpected motion that occur in the transient stage of the control mode switch are defined as the unstable responses. The other "unstable responses" in this paper refer to the same situations.

The hybrid position/force control is one type of compliant control methods combining the position control and force control together. In this method, the entire task space is divided into two subspaces, called the position-controlled subspace and the force-controlled subspace. During manipulation, the position control law and the force control law are employed in the corresponding subspaces, respectively. The most important step of this method is to determine a proper division of the subspaces, which relies on the prior knowledge of the structure and geometry of the environment. However, for those tasks performed in the unstructured and dynamically changing environments,[7] it is difficult to obtain the precise geometry information about the environment in advance. This drawback limits its application range. In addition, the different control modes are switched according to the division of subspaces, which may also lead to some unstable responses.

The detailed comparison results are summarized in Table I.[7,12,50,54,132,133] Due to their extreme impedance properties, the position control and the pure force control are only suitable for the specific work conditions. The hybrid position/force control cannot work well in the unstructured or dynamically changing environments. By contrast, impedance control performs better in terms of "flexibility" and "adaptability." The "flexibility" means that the parameters of impedance model can be designed flexibly to change the compliance of robot as needed to meet the different demands of manipulation. The "adaptability" here has two implications. First, impedance control is adaptive to the different stages of one manipulation task. It means one unified impedance model can be employed in all manipulation phases, including free motion, constrained motion, and the transient stage between them, without the need to switch control modes. Second, impedance control is adaptive to many kinds of environments. Even in the unknown environment, a well-designed impedance model can work well. This character reflects the intrinsic robustness of impedance control.

3. Implementation

In this section, the implementation of impedance control on robots is presented. First of all, the design specifications of the servo controller and impedance controller are compared to clarify the implementation procedure. The main design specifications of these two controllers are depicted in Fig. 4.[9] Both of these two controllers have requirements on the "Nominal Stability" and "Command Following." The "Nominal Stability" refers to the stability of the isolated system, such as the manipulator in

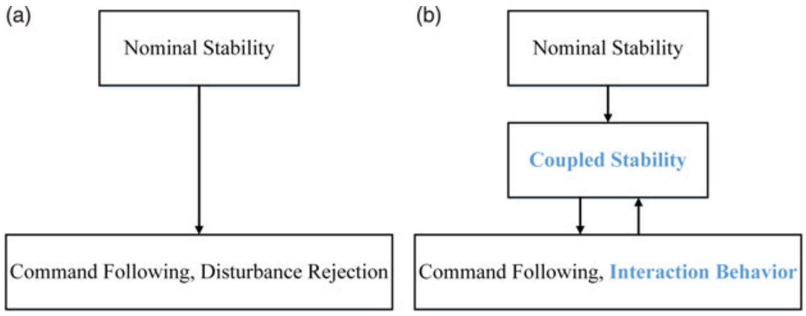

Fig. 4. (a) Design specifications for a servo controller. (b) Design specifications for an impedance controller.[9]

the free space. In Laplace domain, the poles of the isolated system should be kept in the left half s-plane. The "Command Following" refers to the ability of the controlled system to track a reference command. For example, a good servo position controller should track the motion command rapidly and precisely. The basic proportional-integral-derivative controller (PID controller) is widely used to improve the command tracking performance.

It is notable that the "Coupled Stability" is one special requirement for the impedance controller. It refers to the stability of the manipulator coupled with its environment. This specification should be taken into account because an impedance-controlled manipulator is expected to interact with its environment extensively. In this condition, only "Nominal Stability" cannot ensure the "Coupled Stability." Similarly, in Laplace domain, the poles of the entire coupled system should be kept in the left half s-plane.

The manner of the impedance controller to treat its interaction with environment is also different. For a servo controller, its interaction with environment is regarded as the disturbance to be rejected because this "disturbance" may influence the command following performance. Thus this approach is not suitable for interaction tasks. By contrast, the impedance controller accommodates its interaction with environment in the manner defined by impedance. The "Interaction Behavior" of robot shown in Fig. 4 is exactly defined by this impedance. A proper impedance can achieve a balanced trade-off between the command following performance and the desired interaction force. After the determination of the optimal impedance for a specific task, how to implement it on the robots becomes the key problem. Basically, in consideration of the equivalence between hardware and controller, all of the implementations can be classified into two major types: the hardware-based approach and the software-based approach.

In the following contents, the coupled stability is explained first. Then the two types of methods to implement the desired impedance on robots are demonstrated in detail. Furthermore, in the last two subsections, we go deeper to explore how to choose the proper implementation in different situations and how to design the impedance controller for a specific task.

3.1. Coupled stability

The motion of manipulator has two basic types: the free motion and the constrained motion. During the free motion, only the stability of the manipulator alone should be considered to obtain the stable system response. However, in the constrained motion, the manipulator is coupled to its environment. When they have the firm contact, both of them should be regarded as one entire system with new dynamic properties in mass, damping, and stiffness. As a result, the stability of isolated systems is not enough to make sure the entire coupled system is still stable. If the control law used in the isolated system is directly applied to this coupled system without modification, the stability conditions of the coupled system are possible to be violated. Therefore, the coupled stability conditions should be taken into account when designing the impedance controller.

To help analyze the coupled stability, a set of theories regarding "passivity" was proposed.[8] The "passivity" is a concept used to describe the energy feature of systems. A system with "passivity" cannot output more energy at its port of interaction than that which has been put into the same port for all time.[11] The most important conclusion relating the passivity to the coupled stability is that a manipulator with passive impedance can achieve coupled stability when interacting with passive environments. The detailed criteria to judge whether a system is passive or not are given as the following:

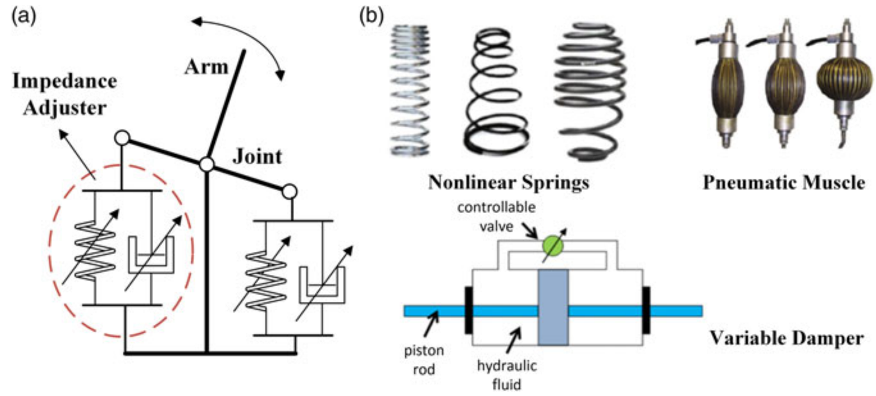

Fig. 5. (a) Schematic diagram of hardware-based approach. The part in the red circle represents an impedance adjuster. (b) Some basic impedance hardware elements.[23]

Criteria. A system defined by the linear one-port impedance function $Z(s)$ is passive if and only if[11]:

1. $Z(s)$ has no poles in the right half plane.
2. Any imaginary poles of $Z(s)$ are simple and have positive real residues.
3. $\mathrm{Re}\{Z(j\omega)\} \geq 0$.

These criteria offer a guidance to design the parameters of impedance model. Apart from the systematic discussion based on "passivity," other instructive research on coupled stability were also conducted in refs. [10, 12].

3.2. *Implementation of the desired impedance*

After solving the stability problem of coupled systems, the next crucial task is to implement the desired impedance on the robots. It is known that the impedance actually represents a measure of the dynamic compliance. According to the different sources of the compliance, all of the implementation methods are categorized into two major types: the hardware-based approach and the software-based approach.

3.2.1. Hardware-based approach. The name of this approach implies that the desired compliance is provided by the well-designed hardware. In this approach, the intrinsic dynamics of the hardware itself is directly utilized to change the impedance of the robots. To acquire the hardware with desired inherent dynamics, a number of impedance hardware elements are developed, such as different nonlinear springs and variable dampers. Through using these elements, various hardware components, such as actuators and joints, are invented to adjust impedance.

The basic working principle of the hardware-based approach is demonstrated in Fig. 5. The robot arm in Fig. 5(a) is required to change its rotational impedance for different tasks. To achieve this target, two impedance adjusters with variable stiffness and damping are placed at both sides of the arm. By changing the impedance of the adjusters, the rotational impedance of the arm is also modified accordingly. The adopted impedance adjuster consists of one stiffness element and one damping element. The stiffness element could be the nonlinear spring or the pneumatic muscle to alter stiffness. The damping element could be various damping-variable dampers.

In the early literature, Hogan[130] stated that it is possible to modulate the impedance of endpoint by exploiting the intrinsic properties of the hardware. Inspired by this viewpoint, a number of impedance-variable hardware were designed. The binary damper and nonlinear tunable spring with self-programmability were developed to realize the "programmable passive impedance."[19] To empower the robot to grasp objects softly, the mechanical impedance adjuster was set at the joints of robot fingers.[20] A variety of impedance elements are also adopted in the design of orthoses.[90,91] For example, the impedance-variable ankle–foot orthoses were developed to assist the drop-foot gait.[90] The pneumatic muscle actuators (PMAs)[91] are used to realize assist-as-needed gait training.

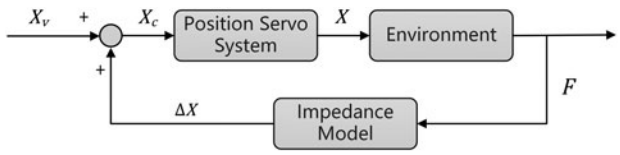

Fig. 6. Schematic diagram of the position-based method.

The series elastic actuator (SEA)[21] is able to offer high fidelity force control with inherent low impedance. In addition, a comprehensive summary about variable impedance actuators was presented in ref. [23].

It is worth noting that most of the hardware-based approaches are passive impedance control. The "passive" here means that the hardware components used to adjust impedance cannot deliver more energy to the environment than the energy absorbed from the environment, just like what a spring can do.[95] As a result, the robotic devices adopting the hardware-based approach usually need to have two subsystems. One subsystem works for the regulation of impedance, and the other one provides the motion power. For the wearable robotic devices, this motion power may be supplied by human body. By contrast, the control law used in the software-based approach can regulate impedance as well as drive the robot moving actively.

3.2.2. Software-based approach. The software-based approach is a kind of active impedance control with continuous system energy input from regular actuators. To drive the robotic equipment to follow the reference trajectory and perform the desired impedance, the control law should be well designed at the software level. Differing from the hardware-based approach, special hardware with proper inherent impedance is no longer required in the software-based approach. In the following contents, three fundamental software-based approaches are presented, including the position-based method,[10,36,37] the torque-based method,[10,37] and the model-based method.[35,38]

Position-based method. The position-based method is one frequently used basic impedance control method due to its simplicity. It usually contains a two-loop structure: the outer loop is used to calculate the command motion trajectory on which the desired impedance can be achieved, and the inner loop is just a position servo controller to track the online command trajectory generated by the outer loop.

The schematic diagram of the position-based method is depicted in Fig. 6. For the unification of description, all of the diagrams in this section are drawn based on a conventional six DOFs motor-driven robot. The capital letter sign X is used to denote the relevant motion vector of the robot. For the simplicity of illustration, the inner loop is represented by the block named "Position Servo System" without further expansion. Therefore, this "one-loop" diagram actually represents an outer/inner loop structure. This kind of inner loop block is also adopted in other diagrams with inner loop in this article.

In the outer loop, the block named "Impedance Model" is used to denote Eq. (7). Based on the pre-determined parameters of impedance and the feedback of the contact force F, the proper path correction $\triangle X$ ($\triangle X = X - X_v$) can be calculated online through the "Impedance Model" block. The X_v refers to the virtual trajectory for reference. Based on $\triangle X$ and X_v, the command trajectory X_c is determined. Then the "Position Servo System" block, as the inner loop, works to track X_c as precisely as possible. If X_c could be tracked precisely, the impedance behavior defined in the "Impedance Model" will be achieved closely. In one word, the X_c is adjusted online to make sure Eq. (7) holds.

Torque-based method. Similar to the principle of the position-based method, the torque-based method also has a two-loop structure. The difference is that the position servo is replaced by the torque servo as the inner loop.

In Fig. 7, the "Impedance Model" block (Eq. (7)) is used to compute the command contact force F_c based on the reference position X_v, the actual position X, and the impedance parameters M_d, B_d, and K_d. Then the command contact force F_c is transferred as the command joint torque τ_c through the transpose of Jacobian matrix J^T. The τ_c is passed into the inner loop "Torque Servo System"

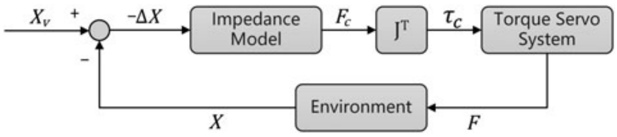

Fig. 7. Schematic diagram of the torque-based method.

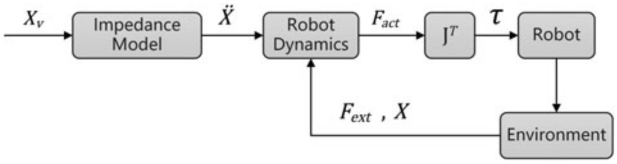

Fig. 8. Schematic diagram of the model-based method.

block to track. If this tracking accuracy is high enough, the achieved dynamics will be close to the impedance defined in the "Impedance Model." In one word, the τ_c is adjusted online to make sure Eq. (7) holds.

Model-based method. This method is different from the above two methods because it requires the prior knowledge of the original dynamics model of robot. The following is the detailed implementing procedure.

First of all, the actual dynamics model of the manipulator should be established. In common cases, it is expressed in work space as

$$M(x)\ddot{x} + C(x, \dot{x})\dot{x} + G(x) + f(\dot{x}) = J^{-T}\tau - F_{ext} \tag{9}$$

Without the loss of generality, we assume that the manipulator has six degrees of freedom. In Eq. (9), x is a six-dimensional vector representing the position and orientation of the manipulator; τ is the 6×1 vector of the joint torque generated by actuators; $M(x)$ is the 6×6 mass matrix; $C(x, \dot{x})$ reflects the effect of Coriolis and centrifugal force; $G(x)$ and $f(\dot{x})$ represent the torques due to gravity and friction forces, respectively; J is the 6×6 Jacobian that relates the joint velocity to the end-effector velocity; and F_{ext} is the contact force between the end-effector of manipulator and its environment.

The second step is to determine the desired impedance model. The target impedance is usually specified as a second-order dynamic equation:

$$M_d(\ddot{x} - \ddot{x}_v) + B_d(\dot{x} - \dot{x}_v) + K_d(x - x_v) = -F_{ext} \tag{10}$$

The parameters and variables in the left of Eq. (10) are the same with those in Eq. (7). Reorganizing Eq. (10), $\ddot{x}$ can be expressed as

$$\ddot{x} = \ddot{x}_v - M_d{}^{-1}\left[B_d(\dot{x} - \dot{x}_v) + K_d(x - x_v) + F_{ext}\right] \tag{11}$$

Substituting Eq. (11) into the actual manipulator dynamics (9) by eliminating the item $\ddot{x}$, a specific control law is obtained as

$$\begin{gathered} \tau = J^T F_{act} \\ F_{act} = F_{ext} + C\dot{x} + G + f + M\left\{\ddot{x}_v - M_d{}^{-1}\left[B_d(\dot{x} - \dot{x}_v) + K_d(x - x_v) + F_{ext}\right]\right\} \end{gathered} \tag{12}$$

The F_{act} refers to the required actuation force in the task space. In the joint space, the driving torque τ generated by this control law can make the manipulator perform the desired impedance behavior defined by Eq. (10).

The schematic diagram of this procedure is demonstrated in Fig. 8. The "Impedance Model" block represents Eq. (10). The original dynamics in Eq. (9) is represented by the "Robot Dynamics" block. The flow direction of the relevant variables is corresponding to the above formula derivations.

In summary, the key step of this method is to substitute the target impedance model into the original dynamics model of the manipulator to derive the required control law. Under the action of the driving torque generated by this control law, the original dynamics of robot is compensated off, and the new dynamics is ideally shaped as the designed impedance. It is also notable that the uncertainty of the original robot dynamics model will weaken the performance of this method, which motivates the development of more advanced impedance control methods. More implementation details of impedance control can also be found in refs. [10, 36, 123, 134–137].

3.3. Comparisons and selection

After the demonstrations of the basic implementations, a comparison and summary can be made to provide a guidance to select the proper implementation for a specific task.

3.3.1. Comparison between hardware-based approach and software-based approach. The impedance implemented by the hardware-based approach is reliable because the adopted physical components have stable dynamic properties. For instance, the springs and dampers have own stiffness and damping which cannot be affected by the control law. The hardware-based approach can provide more customizability to fulfill some special tasks. For example, the prostheses or other rehab devices could be customized according to the categories and degree of injury, and the physical features of human body. This kind of complex and special interactions should be handled by the hardware-based approach.

However, the specific impedance hardware can only be used in some specific conditions. For different tasks, different hardware should be redesigned and fabricated. This is a drawback to limit the wide application of the hardware-based approach. Also, it is difficult to construct the hardware in the small or micro scale, which limits the application range. In general, the hardware-based approach is suitable to be used in the macro-scale, repetitive manipulation work, or special tasks with relatively low requirements on the accuracy but high requirements on the reliability and safety.

The software approach has great flexibility in the design and implementation. It is easy to change the impedance of the controlled manipulator by modifying the impedance parameters in the algorithm without the need to change the hardware. This flexibility makes the software-based approach applicable to all kinds of robotic devices whose dynamics could be reshaped by impedance. In addition, the software algorithms are suitable for the quantitative control of manipulator and could achieve higher control accuracy.

However, to achieve the desired impedance by the software-based approach, all the links of the control system should perform well at the same time. Any non-ideal factor, such as low sample frequency, computational delay, input saturation, and so on, may weaken the total control performance. In some extreme cases, the instability of control system could be caused by improper control law. Basically, the software-based approach is suitable for the manipulators whose hardware cannot be changed, and the manipulation tasks requiring the high accuracy and the adjustable impedance in a wide range.

3.3.2. Comparison in hardware-based approach. The hardware-based approach can be further classified into the impedance-fixed method and the impedance-adjustable method. The hardware adopted in the impedance-fixed method has relatively simple structure with specific impedance. It has consistent response characteristics and should be applied in simple and repetitive tasks.

In the impedance-adjustable approach, more complicated hardware is developed to adjust the impedance according to the various environment and task requirements. This method can promote the flexibility and adaptability of manipulations and expand the application range of the hardware-based implementation.

3.3.3. Comparison in software-based approach. Each software-based method has its own features and the most applicable situation. The high-performance position controller is required to be the inner loop of the position-based method. Whether the desired impedance can be achieved well is directly influenced by the tracking performance of this inner loop. As a result, before the implementation of impedance, a good position controller should be built first. This method is usually used to realize the desired interaction with the low-stiffness environment.

Table II. Comparisons among different implementations.

	Hardware-based approach		Software-based approach		
	Impedance-fixed	**Impedance-adjustable**	**Position-based**	**Torque-based**	**Model-based**
If impedance can be adjusted?	No	Yes	Yes	Yes	Yes
If need to modify the hardware to perform different types of manipulations?	Yes	Usually yes	No	No	No
If need the position feedback?	Usually no	Yes	Yes	Yes	Yes
If need the contact force feedback?	No	Yes	Yes	No	Yes
If need to know the original dynamics model of robot in advance?	Task-dependent	Task-dependent	No	Yes	Yes
If suitable to be used in the stiff environment?	Yes	Yes	Usually no	Yes	Yes
If suitable to be used in the soft environment?	Yes	Yes	Yes	No	Yes
If suitable to be used in the micro-scale?	Possible	Usually no	Yes	No	Sometimes
If suitable to realize the general interactions without high accuracy?	Yes	Yes	Yes	No	Yes
If suitable to realize the accurate control on position and/or contact force?	No	Task-dependent	Yes	Yes	Yes

The torque-based method is mainly applied in the regular robot arm with the torque-controllable joint motors. Although the feedback of contact force is not necessary, the joint torques of robot arm must be controlled precisely. This method is only suitable for the interaction with high-stiffness environment.

The model-based method works well when the pre-built dynamics model of the manipulator is precise enough. If this model is not accurate enough, the realized final effect will not match the target impedance. In this case, the advanced control methods, such as the robust control and adaptive control, should be utilized to deal with the model inaccuracies. When the original dynamics model is difficult to build with good accuracy, this method is not recommended. The feedbacks of both the position of manipulator and the contact force are required to calculate the control torque. This method can work well in both the low-stiffness and the high-stiffness environment.

Based on all the discussions above, the features of various implementation methods are summarized in Table II, which provides a reference and guidance for the selection of proper implementation strategy.

3.4. Impedance design

After the proper implementation method is determined, the next step is to design the impedance parameters to meet the demands of the specific task. Basically, the designed parameters include the virtual trajectory x_v and the impedance parameters M_d, B_d, and K_d.

3.4.1. Design of virtual trajectory. The virtual trajectory defines a series of equilibrium positions to set the effective range of impedance control. The selection of virtual trajectory is the basis for the design of other impedance parameters in the next step.

For the human–machine interaction works, the virtual trajectory can be chosen at an achievable position. For example, the ankle–foot orthosis[90] can provide the buffering effect and back force when the virtual position is reached by foot. In this case, the virtual position should be put in the place where the interaction is expected to occur.

For the mechanical manipulations, the virtual trajectory is usually designed inside the environment where the manipulator cannot reach. In this way, the manipulator can keep contact with the environment to achieve the relationship in Eq. (7). For the stiff environment, it is enough to keep the virtual trajectory slightly inside the environment. For the soft environment, however, the virtual trajectory should be set inside a larger distance from the surface of environment to guarantee a stable interaction.

3.4.2. Design of impedance parameters. Impedance is used to define the desired dynamics between the manipulator and its environment, and this dynamic relationship is quantified by the impedance parameters $\boldsymbol{M_d}$, $\boldsymbol{B_d}$, and $\boldsymbol{K_d}$. If we set

$$\triangle x = x - x_v \tag{13}$$

Then Eq. (7) can be expressed as

$$M_d \triangle \ddot{x} + B_d \triangle \dot{x} + K_d \triangle x = F(t) \tag{14}$$

For the simplicity of description, we assume that only one direction in the interaction is considered. Thus M_d, B_d, K_d, $\triangle x$, and $F(t)$ are scalar. Then based on Eq. (14), the transfer function from the contact force $F(s)$ to the displacement $\triangle X(s)$ in Laplace-domain can be easily obtained as

$$T_{imp}(s) = \frac{\triangle X(s)}{F(s)} = 1/\left(M_d s^2 + B_d s + K_d\right) \tag{15}$$

Adopting the expression convention of the second-order system, Eq. (15) can be rewritten as

$$T_{imp}(s) = \frac{1/M_d}{s^2 + (B_d/M_d)s + K_d/M_d} = \frac{1/M_d}{s^2 + 2\xi\omega_n s + {\omega_n}^2} \tag{16}$$

where ξ is the damping ratio and ω_n is the natural frequency, and they can be expressed by the impedance parameters as

$$\xi = B_d/\left(2\sqrt{K_d M_d}\right) \tag{17}$$

$$\omega_n = \sqrt{K_d/M_d} \tag{18}$$

In general, the static impedance parameter K_d should be determined first based on the steady-state requirements of interaction. Then through Eqs. (17) and (18), M_d and B_d can be selected to fulfill the dynamic specifications.

In addition to this quantitative design, the impedance parameters can also be selected according to their physical significances. This intuitive experience is very important for the trial and error. The K_d represents the desired stiffness. When K_d is large, the collision between the manipulator and its environment will lead to a large contact force. The B_d represents the desired damping. When B_d is large, the motion of manipulator tends to be slow, which can help reduce the oscillatory response. The M_d represents the desired inertial. When M_d is large, the intense interaction may force the manipulator to produce low-frequency and high-amplitude oscillation. These experience rules are useful for the manual parameter tuning.

Some representative tasks are presented further to demonstrate the procedure of impedance design.

Precise manipulation with stiff environment. When the encountered environment of manipulator is stiff, the model-based implementation is often adopted to achieve a balance between the position accuracy and the contact force accuracy. In this case, the selected virtual trajectory is slightly inside the environment. When the desired stiffness $\boldsymbol{K_d}$ is large, the position accuracy is more emphasized but large contact force may be produced. By contrast, when the desired stiffness $\boldsymbol{K_d}$ is relatively small, the contact force can be regulated in a safe range but the position accuracy may be weakened.

The steady-state error analysis is an effective way to determine the K_d. The stiffness of environment is assumed as K_e and its rest position is x_e. When the manipulator and its environment keep in contact, the contact force $F(t)$ can be expressed as

$$F(t) = K_e(x_e - x) \tag{19}$$

where x represents the actual position of the end-effector of manipulator. Substituting Eq. (19) into (7), we have

$$M_d\,(\ddot{x} - \ddot{x}_v) + B_d\,(\dot{x} - \dot{x}_v) + K_d(x - x_v) = K_e(x_e - x) \tag{20}$$

Because only the steady state is considered, Eq. (20) can be simplified as

$$K_d(x - x_v) = K_e(x_e - x_v) - K_e(x - x_v) \tag{21}$$

The steady position error of manipulator is exactly $(x - x_v)$, it can be marked as e^p_{ss}, then Eq. (21) can be rewritten as

$$K_d e^p_{ss} = K_e(x_e - x_v) - K_e e^p_{ss} \tag{22}$$

Reorganizing Eq. (22) as

$$e^p_{ss} = \frac{K_e(x_e - x_v)}{K_d + K_e} \tag{23}$$

Based on the e^p_{ss} and the desired contact force F_d, the desired K_d can be calculated as

$$K_d = F_d/(x - x_v) = F_d/e^p_{ss} = \frac{F_d(K_d + K_e)}{K_e(x_e - x_v)} \tag{24}$$

Further rewriting Eq. (24), the final K_d calculation formula can be obtained as

$$K_d = \frac{F_d K_e}{K_e(x_e - x_v) - F_d} \tag{25}$$

From the inverse direction to consider Eq. (24), the estimated steady-state contact force $\hat{F}$ can be predicted based on the preassigned K_d as

$$\hat{F} = K_d e^p_{ss} = \frac{K_d K_e(x_e - x_v)}{K_d + K_e} \tag{26}$$

Based on Eq. (25), the known virtual trajectory, the prior knowledge of environment, and the desired steady-state contact force, the static impedance parameter K_d can be determined first. Then with reference to Eqs. (17) and (18), the dynamic impedance parameters M_d and B_d can be adjusted to improve the dynamic response of the control system. Usually, the designed impedance parameters should be further verified and adjusted based on the results of simulations or experimental tests.

By analyzing Eqs. (23) and (26), some intuitive design experience can be concluded. In Eq. (23), the increase of K_d can decrease the position error e^p_{ss}. However, if the stiffness of environment K_e is large enough, the e^p_{ss} is still difficult to be reduced. In Eq. (26), the large K_e and improper K_d may lead to a large contact force. To achieve the compliant interaction, K_d should be set small to avoid large contact force.

Manipulation with soft environment. When the environment is relatively soft, the position-based method can work well. In this case, the command trajectory $\boldsymbol{x_c}$ should be designed first. The static relationship among the target contact force $\boldsymbol{F_d}$, the environment properties $\boldsymbol{K_e}$ and $\boldsymbol{x_e}$, and the $\boldsymbol{x_c}$ can be established as

$$F_d = K_e(x_e - x_c) \tag{27}$$

Then x_c can be calculated as

$$x_c = x_e - \frac{F_d}{K_e} \tag{28}$$

In order to make sure this x_c can be generated by the impedance outer loop, the K_d should be chosen as

$$K_d = \frac{F_d}{x_c - x_v} \tag{29}$$

After the K_d is already selected, the M_d and B_d can be further designed according to Eqs. (17) and (18) or the trial-and-error method. In common cases, the damping ratio ξ should be not less than 1 to avoid the oscillation.

When K_e is relatively small and the inner-loop position controller is strong and precise enough, the online command trajectory x_c can be tracked well by the inner loop. After all the parameters of impedance are set ready, how to generate the correct x_c in real time becomes the main problem. Because most impedance controllers are implemented on the digital sampling system, the difference equations can be used to simplify the differential equations. Based on the block diagram of position-based method in Fig. 6, the x_c is generated by

$$x_c = x_v + \triangle x \tag{30}$$

where x_v is the preassigned virtual trajectory, and $\triangle x$ is the adjustment to x_v, which is generated by the measured contact force and the impedance parameters. As a result, the determination of x_c depends on the evaluation of $\triangle x$.

Same as Eq. (13), the $\triangle x$ is defined as

$$\triangle x = x - x_v$$

Then Eq. (7) is rewritten as

$$M_d \triangle \ddot{x} + B_d \triangle \dot{x} + K_d \triangle x = F_c(t)$$

In the practical sampling system, the following difference equations can be employed to compute $\triangle x$:

$$\triangle \dot{x}(k) = \frac{\triangle x(k) - \triangle x(k-1)}{T_s} \tag{31}$$

$$\triangle \ddot{x}(k) = \frac{\triangle \dot{x}(k) - \triangle \dot{x}(k-1)}{T_s} \tag{32}$$

where the k is used to indicate the related values in the kth sampling period, and T_s refers to the sampling period. Substituting Eqs. (31) and (32) into (14), the $\triangle x(k)$ can be calculated online by

$$\triangle x(k) = \frac{F_c(k) {T_s}^2 + B_d T_s \triangle x\ (k-1) + M_d \big(2\triangle x\ (k-1) - \triangle x(k-2)\big)}{M_d + B_d T_s + K_d {T_s}^2} \tag{33}$$

Then using $\triangle x(k)$, the x_c, as the input signal for inner loop, can be determined in real time.

Through observing Eqs. (31)–(33), the importance of sampling frequency for the implementation of the desired impedance is obvious. Theoretically, the sampling rate should be at least twice as large as the frequency of the sampled signal based on the Nyquist–Shannon sampling theorem. However, the sampling rate (usually, it is equal to the control rate in the control system) needs to be 10 times higher than the frequency of the controlled signal to achieve the desired control performance. For this example, the low sampling frequency will greatly weaken the effectiveness of x_c and cause the designed impedance unrealizable.

Interactions without precise requirements. In addition to the mechanical manipulations with requirements on position and contact force, many applications, especially those adopting hardware-based methods, only need impedance controller to realize the general interaction or complete the specific works. In these cases, the design of impedance parameters is not very rigorous. The teaching or trial-and-error methods are utilized widely.

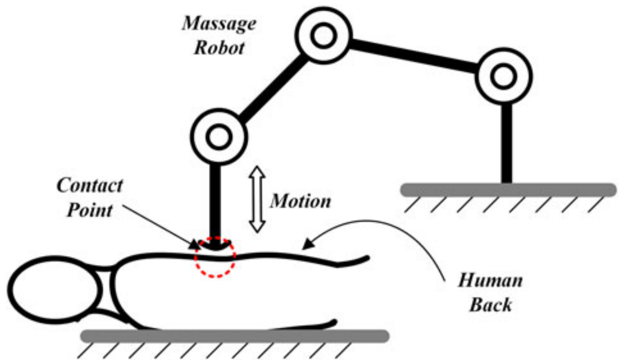

Fig. 9. Massage robot.

If the design target is to keep the contact force in a preset safe range, the simulations and experiments should be performed with changing impedance parameters until the test results are satisfying. Taking the physical significance of each impedance parameter into consideration, the suitable set of parameters can be found through continuous tuning.

There are two methods to validate the selected impedance parameters. One method is process oriented, whereas the other is result oriented. For example, an ankle–foot orthosis is designed to assist the disabled. One way is to collect the data from the motion process of the unaffected person first. Then tuning the impedance of orthosis, the process data, like position, velocity, and contact force, from the subjects wearing this orthosis are collected to match the data from the unaffected person.[90] If the process data can match well, the behavior of the designed orthosis will be similar to the natural behavior of human. The other method cares less about the process data but verifies the effect of impedance by checking the actual testing results. In this case, whether the wearer feels comfortable and whether the walking can be stable are some of the judging criteria.

3.4.3. Design instance. To better demonstrate the detailed design methods and procedures of impedance controller, a design example with practical background is presented in the following contents. The related numerical simulations are also performed in Matlab to further reveal the advantages of impedance controller.

Design target. It is desirable to implement impedance control on a massage robot so that the robot can impose the appropriate dynamic interaction on the human body receiving the massage service. The working scenario of this kind of massage robot is depicted in Fig. 9. In the preliminary stage, the end-effector of the massage robot moves right over the planned contact point of human back, and the distance between the end-effector and human back is kept as 10 mm. When therapy starts, the end-effector of the massage robot moves right up and down periodically to press and release the contact point of human back repeatedly.

The desired steady-state pressure imposed on the human back is set as 200 N. If the stiffness of human back K_e is assumed as 10 N/mm, then the depth of press is expected to reach 20 mm down from the rest position of human back x_e when no contact occurs. Theoretically, if human subjects can keep their body in stable and consistent states during the entire therapy, only using a position controller can achieve the ideal massage performance. However, the states of human tend to be varied. For example, when the tense of muscles on human back is changed, the stiffness of human back K_e will be certainly influenced. Also, if human subject wants to modify his/her pose from initial states, the rest position x_e can also be changed. As a result, impedance controller should be employed to handle the unexpected states variation of human subject to guarantee the comfort and safety of interaction.

Design procedure. In this instance, how to design an impedance controller for the massage robot to achieve proper interactions with human body is the most concerned problem. Because the position-based method is relatively easier to be understood and described, this implementation method is employed for the design of impedance controller. As the description in "Position-Based Method" section, the impedance controller based on the position-based method has a nested structure. For this

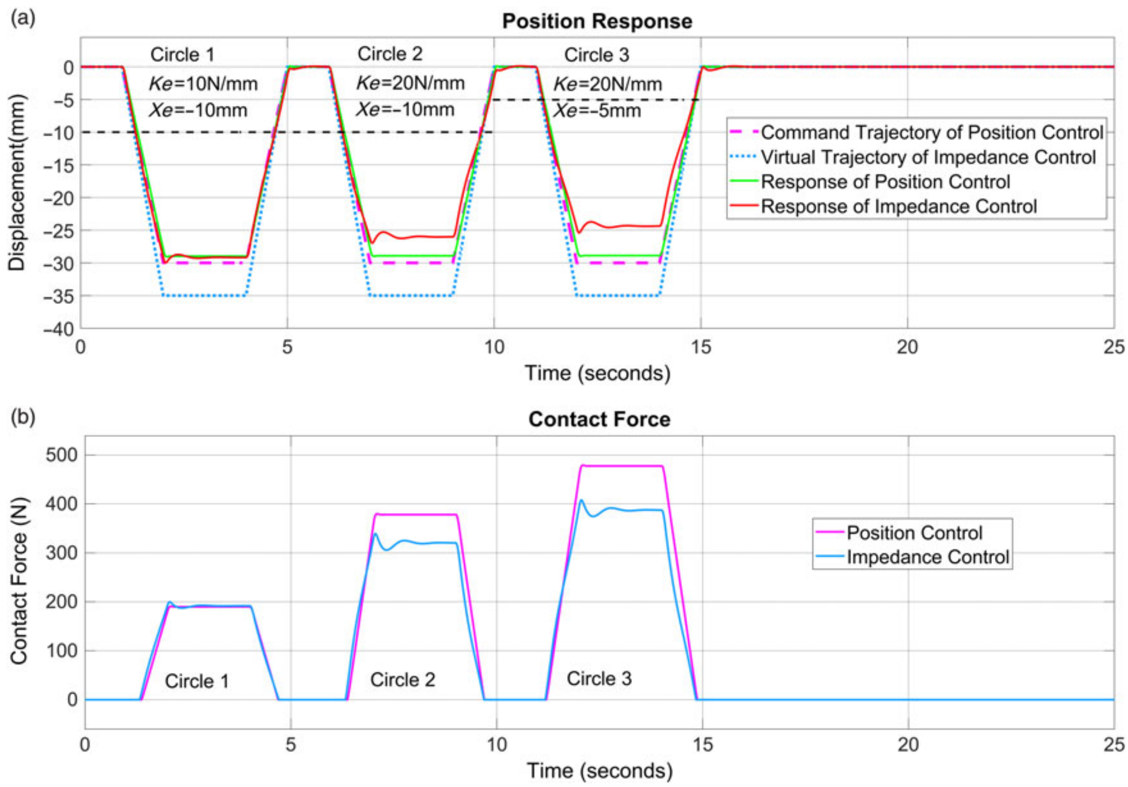

Fig. 10. Impedance control of massage robot. (a) Position responses. (b) Contact force.

massage robot, we assume that the position controller used in the small working motion range is already established and competent to be the inner loop of the impedance controller. The focus of this design procedure should be put on the design of the outer loop.

If the initial height of the end-effector of massage robot is marked as 0 mm, then the desired steady-state position should be set at –30 mm upon the previous analysis in “Design Target” section. Thus the steady-state virtual position on virtual trajectory could be set slightly lower as –35 mm. The adopted complete virtual trajectory x_v is shown by the blue dot line in Fig. 10(a).

Substituting the known data (F_d is 200 N, K_e is 10 N/mm, and x_e is –10 mm) into Eq. (25), the K_d is calculated as 40 N/mm. Then for the selection of dynamic items M_d and B_d, Eqs. (17) and (18) are useful references. M_d is initially selected as a small value as 1 kg to reduce the overshoot. In order to achieve flexible interaction between the end-effector and human body, the desired damping B_d is selected as 6 N $\cdot$ s/mm at first to keep the damping ratio ξ around 0.5. After determining one initial set of values of the impedance parameters, simulations or experiments should be performed to test whether these parameters satisfy the task requirements or need further tuning.

Simulation. For the sake of comparison, the position controller is also employed to conduct the massage procedure. As the rest place and stiffness of human back are already known, the desired effect of therapy can be achieved through proper trajectory planning. The periodic motion trajectory of the end-effector of massage robot is planned as the pink dash line in Fig. 10(a). The end-effector is expected to complete the press manipulation for three times. The movement starts at the 0 mm position, and then pressure occurs after contact. Next, the end-effector continues moving to the steady-state position –30 mm and stays there for 2 s, and finally moves back to the height 0 mm. One complete circle of this press manipulation lasts for 5 s. Under ideal conditions, the position controller can also work well.

To simulate the actual situations in real massage therapy as much as possible, three different sets of conditions are added in the three circles of the press manipulation simulation, respectively. In the first press circle, all the parameters of environment are stable as expected. The stiffness of human back is 10 N/mm and the rest position of human back is –10 mm. In the second press circle, however, the human subject is assumed to tense the muscles on his/her back suddenly, resulting in the back stiffness K_e increased to 20 N/mm. Furthermore, due to the unexpected movement of human subject in the last press circle, the rest position of human back is changed to –5 mm, which means the contact force is generated earlier from the height –5 mm with the back stiffness K_e as 20 N/mm. Based on the simulation data, the position response curves of the position control and the impedance control are drawn and compared in Fig. 10(a), and the produced contact force during the massage manipulation is shown in Fig. 10(b).

Discussions. In the first press circle, when all the parameters of environment (human body) keep consistent with prediction, the impedance controller and the position controller exhibit similar performance in both position response and contact force. However, in the next two press circles, the position controller cannot keep a robust performance when facing the changing environment. The resulted excessive contact force may lead to some injuries on human body. By contrast, without changing the impedance parameters, the impedance controller shows its robust interaction ability with the varying environment and keeps the contact force in a lower range.

To further consider the situations if the pure force control or the hybrid position/force control were applied here, their performances may be predicted. The pure force control is ineffective during the free motion stage from the initial height 0 mm to the contact point. For the hybrid control, because the requirements on position and contact force of the end-effector are located in the same direction, the division of different subspaces seems difficult. Compared to these control schemes, the merit of impedance controller in regulating position and contact force simultaneously and handling unexpected interactions with environment is unique and outstanding.

4. Control Technique Development

Along with the establishment of the fundamental principles and implementations on impedance control, significant research efforts have been dedicated to developing more effective and advanced impedance control schemes. A variety of enhanced impedance controllers have been designed, simulated, and tested. The major advanced control strategies include force-tracking impedance control,[7,40–47] hybrid impedance control,[7,48–52] robust impedance control,[38,40,41,44,50,53–56] adaptive impedance control,[7,35,43,50,57–78] and learning impedance control.[38,79–89] In one advanced impedance controller, maybe several techniques are integrated together to achieve a better comprehensive performance.

4.1. Force-tracking impedance control

It is already known that the fundamental impedance control implementations can realize a desired interaction relationship between the manipulator and its environment. If the stiffness and location of environment are clear, the interaction force can be regulated well by choosing appropriate virtual trajectory and impedance parameters. However, facing the unknown environment, it is hard to determine the virtual trajectory in advance. In this condition, only keeping the target impedance parameters cannot guarantee the contact force well controlled. In fact, the inability to track a reference contact force in some conditions has been considered as the major disadvantage of fundamental impedance control over hybrid position/force control.[43] Therefore, the methods to strengthen the force-tracking ability of impedance control were proposed.[7,40–47]

Some of these methods introduce the reference contact force to build a modified impedance model between the motion error and the contact force error, instead of the basic impedance model between the motion error and the actual contact force. This distinction can be observed by comparing impedance models in Eq. (7) and in Eq. (34). The reference contact force $F_r(t)$ refers to the desired contact force to be tracked. The other variables are the same as those in Eq. (7).

$$M_d\,(\ddot{x}-\ddot{x}_v)+B_d\,(\dot{x}-\dot{x}_v)+K_d(x-x_v)=F(t)-F_r(t) \tag{34}$$

For a typical force-tracking position-based impedance controller, its schematic diagram is depicted in Fig. 11. Compared to the basic impedance controller shown in Fig. 6, the only difference is the addition of the reference force F_r highlighted by the red circle.

The advantage of this modified impedance model in force-tracking performance can be explained by the results of the force error analysis.[43] Through simple mathematical deductions, it is found that

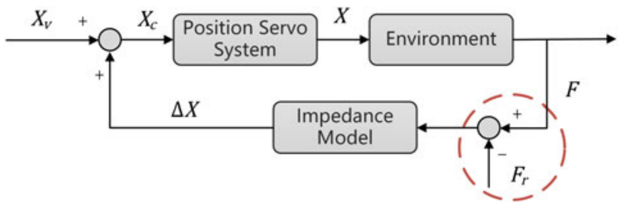

Fig. 11. Schematic diagram of a force-tracking impedance controller. The red circle indicates its difference.

the employment of impedance model (7) can bring more uncontrollable factors affecting the force-tracking error than model (34). These factors are likely to cause the unstable contact force and impair the force-tracking performance. By contrast, adopting the impedance model (34) associated with a proper virtual trajectory X_v can reduce the number of these uncontrollable factors and make force tracking easier. Some researchers combined various algorithms with this kind of modified impedance model to enhance the force-tracking performance of impedance controller. Their algorithms involve generalized impedance control method,[41] sliding mode method,[40] and some adaptive methods.[43,44]

Besides these techniques upon the modified impedance model, there also exist other kinds of solutions. A conventional impedance controller, combined with an online reference motion trajectory generator, can also achieve satisfying force-tracking performance.[42] Another research direction to promote the force-tracking ability of controllers is to actively adjust the impedance gains online according to feedback information like the measured force-tracking error[7] and the estimated stiffness of environment.[46]

4.2. Hybrid impedance control

Hybrid position/force control and impedance control are two main approaches to realize the compliant motion of manipulators. The hybrid position/force control decomposes the entire task space of manipulators into two subspaces: the position-controlled subspace and the force-controlled subspace. In the position-controlled subspace, namely the unconstrained directions, only the position of manipulator is concerned and under control. Similarly, only the contact force is controlled in the force-controlled subspace or the constrained directions. However, the correct division of different subspaces relies on the well-structured environments and their geometrical information.[7] Therefore, when encountering the unstructured or varying environments, the performance of hybrid position/force control is limited. This problem is caused by the extreme impedance properties of hybrid position/force control. In the viewpoint of impedance, the manipulator has extremely high impedance in the position-controlled subspace and very low impedance in the force-controlled subspace.

To overcome this problem and inspired by the idea of impedance control, designing flexible impedances in different subspaces became an effective scheme to improve the robustness and adaptability of the traditional hybrid position/force control. This control scheme is termed hybrid impedance control proposed by Anderson and Spong[48] who combined impedance control and hybrid position/force control into one control scheme. They also presented the duality principle as a guidance to choose proper impedances in different subspaces, which depends on the type of environment. Basically, the specific impedances used in different subspaces should be designed for the practical control purposes. For example, to obtain the precise contact force, the impedance model with zero stiffness was adopted in the force-controlled subspace.[49] Regardless of technical details, the general structure of hybrid impedance control can be illustrated in Fig. 12.[50]

This figure demonstrates a nested structure. The inner loop of this controller is also a position servo. The outer layer should provide the planned motion trajectory for the inner servo to track. In the outer layer of this controller, IMP_p and IMP_f represent the desired impedances in the position-controlled subspace and the force-controlled subspace, respectively; S is the compliance selection matrix to assign IMP_p or IMP_f for corresponding subspaces; I is the identity matrix; X_v is the total virtual trajectory, and X_{vf} refers to the virtual trajectory assigned in the force-controlled subspace; F_r is the reference contact force command, and F refers to the actual contact force. It is worth noting that IMP_p has the form of the basic impedance model, while IMP_f has the form of the force-tracking impedance model because F_r is introduced into the force-controlled subspace.

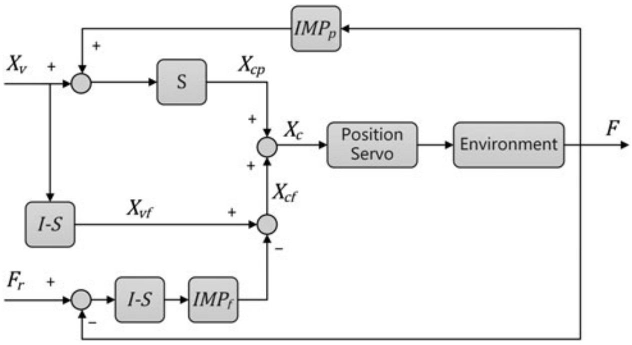

Fig. 12. Schematic diagram of a basic hybrid impedance controller.

In the position-controlled subspace, X_{cp} is the desired motion trajectory calculated from F, IMP_p, X_v, and S. Similarly, the desired motion trajectory X_{cf} in the force-controlled subspace can be also computed based on IMP_f and other variables shown in Fig. 12. Then the general motion command X_c is determined as the sum of X_{cp} and X_{cf} to feed the inner position servo controller.

4.3. Robust impedance control

In practice, the parametric uncertainty, external disturbances, un-modeled dynamics, and other uncertainties can deteriorate the performance of impedance control. Combining robust control techniques with impedance control is helpful to solve this problem.[38,40,41,44,50,53–56] The goal of robust impedance control is to maintain the desired impedance in the presence of parametric uncertainty, unknown environments, external disturbances, and so on.

The sliding mode control, as a crucial robust control method, has been applied into impedance control.[40,54,138] The first step of sliding mode control is to define a region (sliding surface) of the state space by equations, where the system behaves as the desired impedance. Then a control law is designed to bring the system variables onto the sliding surface and keep them there continually.[138] In this way, the original impedance control problem is transferred as the sliding mode control problem with robustness. Based on this idea, researchers have attempted various methods to achieve this kind of transfer and designed different control laws to make the designed sliding surface hit quickly.[40,54]

Besides sliding mode methods, other robust approaches have also been proposed for the enhancement of impedance control. If the impedance parameters can be selected carefully upon the stability conditions, the impedance controller can perform a certain robustness to the dynamic uncertainties[12] or environment stiffness.[41] The highly complex uncertainties are possible to be canceled by the robust position control algorithm.[44] In addition, neural network (NN) techniques are also applied to improve the robustness of impedance controller.[38] The NN control module can generate additional signals to compensate model uncertainties, external disturbances, and force sensor noise. Because this work[38] is representative in the field of robust impedance control, Fig. 13 is drawn to illustrate the implementation principles. Figure 13(a) represents a direct NN robust method and Fig. 13(b) depicts an indirect NN robust method.

In Fig. 13(a), the model-based method (Fig. 8) is utilized in this controller to implement the impedance. The F_a is the compensating signal generated by the NN controller (the block "Direct Robust Control Law"), and other variables are the same as those in Fig. 8. The signal F_a can influence the total control input F'_{act} directly to compensate the disturbances due to model uncertainties.

By contrast, the indirect method in Fig. 13(b) has two differences. First, this method adopts the position-based implementation (Fig. 6). Second, the compensating location is moved from the total control input signal to the reference trajectory. The block termed "Indirect Robust Control Law" represents the indirect NN controller, which can produce the additional compensating signal X_a to modify the initial reference trajectory X_v. Other variables are the same as those in Fig. 6.

4.4. Adaptive impedance control

To reduce the negative effect of model uncertainties and unknown environments on the control performance, adaptive control techniques have also been applied to the impedance controllers.[7,35,43,50,57–78]

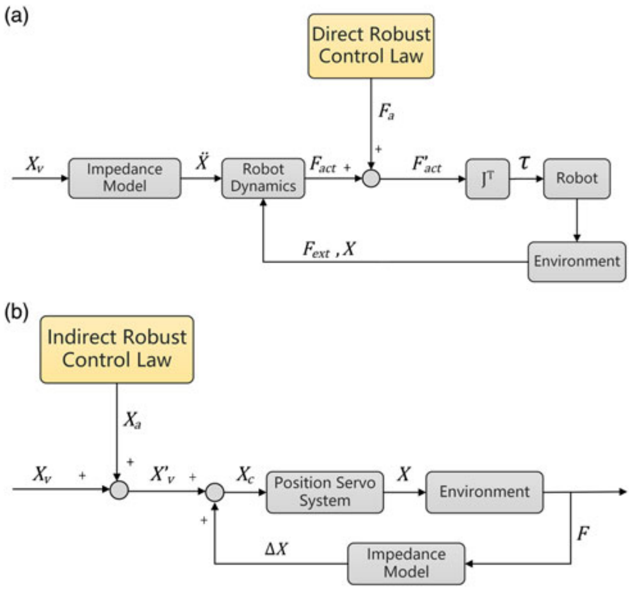

Fig. 13. (a) Schematic diagram of one direct robust impedance controller. (b) Schematic diagram of one indirect robust impedance controller.

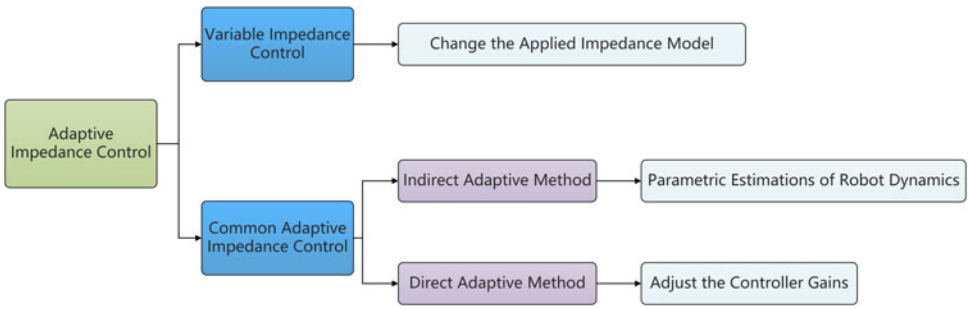

Fig. 14. The classification of adaptive impedance control.

Compared to the robust methods, the adaptive methods usually utilize online modulations to adjust the performance of the controlled system.

The adaptation of adaptive impedance control can be implemented on two different levels, namely the high level and the low level. For the adaptive schemes implemented on the high level, the used impedance parameters are varied online in different environments or manipulation phases to meet the specific operation requirements. This kind of methods is usually termed variable impedance control.[7, 60–62, 64]

On the low level, the adaptation way is similar to the conventional adaptive control. Basically, the adaptive laws are used for the parametric estimation of robot dynamics or the adjustment of control gains. In this way, the desired impedance or tracking performance can be achieved in the presence of model uncertainties or unknown environments. This low-level adaptive impedance control can be further classified into indirect methods and direct methods. The indirect adaptive methods adopt adaptive laws to estimate the robot model parameters. By contrast, the direct adaptive control uses adaptive laws to update the controller gains directly. The classification of adaptive impedance control and the corresponding adaptation mechanisms is shown in Fig. 14.

4.4.1. Variable impedance control. The variable impedance control is mainly applied in the field of human–robot cooperation. It is known that humans can change their body impedance easily to perform elaborate manipulation. This kind of ability is also required for the robot cooperating with

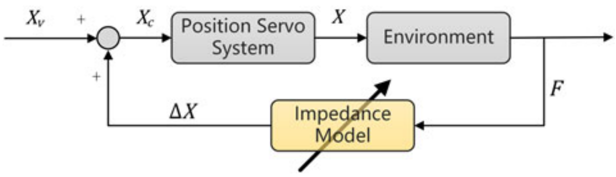

Fig. 15. Schematic diagram of variable impedance control.

humans. Therefore, different methods to vary the impedance of robot properly in different situations were proposed.

The impedance properties of human performed in "human–human cooperation" provide a good reference for the design of the robot impedance in "human–robot cooperation". In this way, the performance of "human–robot cooperation" could be very close to the "human–human cooperation."[60,61] Certainly, these two kinds of cooperation should refer to the same task. For example, the typical carrying task usually has three stages in sequence: picking, moving, and placing. In the picking and placing stage, two human workers usually move carefully and slowly. In the corresponding human–robot cooperation, the robot should have high stability, which means the damping of impedance should be high. However, in the moving stage, the high speed is more emphasized rather than stability, which means the damping of robot impedance should be set to a low level. In the simplest case, the robot can judge the task stage of carrying depending on the motion speed of its human partner. Then the robot can vary its impedance parameters accordingly.

To select the proper impedance parameters in more complex situations, the robot should have the sense to judge human intentions actively.[64] The time derivative of contact force between human and robot could reflect the aims of human operator. Based on this information, the robot impedance can be modified by adaptive laws. To estimate the stiffness of the tip of human arm is another example to judge human intentions.[62] To achieve smooth move in the human–robot cooperative calligraphic task, the damping of robot impedance is adjusted in proportion to the real-time estimated stiffness.

In summary, the keyword of this control scheme is "Variable." When and how to vary impedance is the most important thing to be determined. Based on the position-based method, the schematic diagram of variable impedance control is illustrated in Fig. 15. The only difference between Figs. 6 and 15 is that the "Impedance Model" block in Fig. 15 is adjustable. It means the adopted impedance model can be varied online in accordance with task requirements. More information about this method also can be found in ref. [7].

4.4.2. Common adaptive impedance control. The variable impedance control deals with how to adjust impedance in different situations. Differently, the common adaptive impedance control handles how to keep the chosen impedance or the controlled value stable in the presence of model uncertainties or unknown environments, including the indirect methods and the direct methods. Many adaptive control techniques used in position control are introduced into the impedance control frameworks.[35,43,50,57–59,63,65,66]

Indirect methods. In the indirect methods, the estimations of uncertain parameters of robot dynamics are executed online. Then these estimated values are adopted in the design of adaptive laws or control laws. This method aims to reduce the parameter errors between the actual values and the estimated values to zero[50] rather than control the response error directly, thus it is called "Indirect."

A typical indirect method[43] is illustrated in Fig. 16(a). The position-based implementation (Fig. 6) and the force-tracking model (Eq. (34)) are employed. The adaptation point is located at the generator of the reference motion trajectory X_v. This trajectory is updated online by the adaptive law defined in the generator. The "Parameters Estimator" block is used to estimate the stiffness and location of environment in real time, whose results can determine the performance of the trajectory generator. Finally, the real-time generated X_v is used to lead the robot to keep the desired contact force F_r in the varying environments.

Besides the adaptation problem to the changing environment, the adaptation problem to model uncertainties of robot also attracted much attention.[35,57,58,63,65] In this field, the online parametric

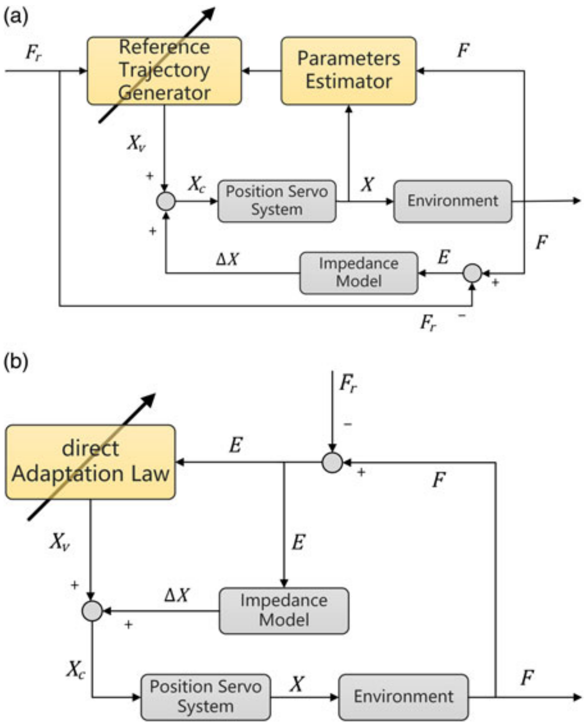

Fig. 16. (a) Schematic diagram of one indirect adaptive impedance controller. (b) Schematic diagram of one direct adaptive impedance controller.

estimation,[35,57,58] force noise suppression,[35] function approximation,[63] and Lyapunov stability analysis[63] are important techniques used frequently. The performances of these methods in the adaptation to model uncertainties are evaluated by simulations and experiments.

However, the parametric estimation needs a pre-known structure or form of the robot dynamic model. If there exist some un-modeled dynamic properties, the performance of this approach cannot be guaranteed.

Direct methods. To overcome this limitation, the direct method was proposed. Its adaptive law utilizes the tracking error directly to adjust the control gains. The primary target of this method is to make the tracking error vector converge to zero.

A typical direct method[43] is demonstrated in Fig. 16(b). Its basic frame is also the position-based implementation (Fig. 6) with the force-tracking impedance model (Eq. (34)). In the "Direct Adaptation Laws" block, the reference motion trajectory X_v is calculated online as a function of the force-tracking error E. With the adaptive laws, a good force-tracking performance can be achieved without the knowledge of the stiffness and location of environment.

Another typical direct adaptive impedance controller[59] has three aspects: a simple "impedance filter," an adaptive controller, and a mapping algorithm. First, the "impedance filter" is used to indicate the reference motion trajectory online. Then the adaptive controller produces the control input in task space to drive the manipulator tracking this reference trajectory. Finally, the mapping algorithm can transfer the control input from the task space to the joint space. In this controller, the control gains are updated directly by the adaptive law derived from Lyapunov stability analysis. Even without knowing the structure or parameters of robot dynamics, this controller can work well by measuring the performance data of the robot. Consequently, this direct method seems very computationally efficient. In addition, the direct adaptive law also can be used to update the switching gain of sliding mode impedance controller.[66] With the optimal switching gain, the sliding mode can be reached and maintained smoothly, which can alleviate the chattering phenomenon of control actions.

In summary, the scheme adopted by direct methods to keep the impedance or controlled values as desired is to update some variables directly upon the system output without any intermedia step.

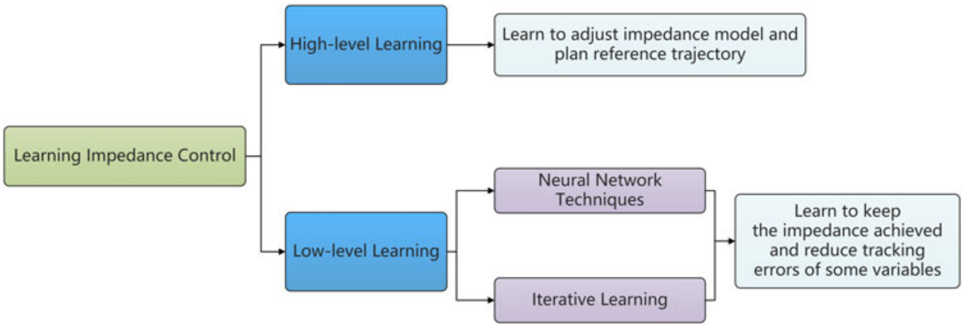

Fig. 17. The classification of learning impedance control.

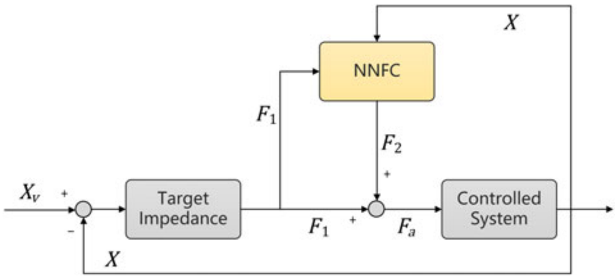

Fig. 18. Schematic diagram of one NN learning impedance controller.[79]

4.5. Learning impedance control

With the development of NN techniques and other learning algorithms, learning impedance control has received increasing attentions.[38,79–89] In fact, learning impedance control can be viewed as a special class of adaptive impedance control, whose adaptation effect is realized by learning techniques. Similar to the adaptive impedance control, learning impedance control also has two-level implications according to its learning objectives. This classification is depicted in Fig. 17. The high-level objective is to learn how to adjust the impedance parameters and plan the reference trajectory actively in various tasks. If an impedance model is already determined, the low-level learning impedance control aims to keep it achieved and reduce the tracking errors of controlled variables in the presence of model uncertainties, unknown environment, and other non-ideal factors.

The high-level learning impedance control can be seen as a kind of variable impedance control. The proper impedance gains and reference trajectory in different tasks are obtained by learning. In most cases, the cost function should be devised to judge the learning results. The parameters of this cost function are the impedance gains and the reference trajectory. For a given task, the impedance gains and the reference trajectory may be chosen arbitrarily at the beginning. However, through continuous trial and error, the learning algorithm will find an optimal set of impedance gains and reference trajectory so that the cost function can achieve the acceptable cost. The design of cost function depends on the task requirements. For example, if the robot is expected to learn to move compliantly and flexibly, the impedance gains causing high impedance should be penalized by the cost function. By contrast, when a stiff movement is required, a set of high gains are likely to be encouraged by the cost function. The specific methods to design the cost function are presented in a reinforcement learning scheme.[81] The learning effect of this scheme is verified by two experiments called “flip the switch” and “open the door.” The achieved advantages include lower energy consumption, less wear and tear, and safer human–robot interaction. This work also proved that the robot has potentials to cooperate with human in stochastic scenarios through guided learning.

The NN[38,79,83–87] and iterative algorithm[80,82] are the most frequently used learning techniques at the low level. The NN can be applied to impedance control in many ways. For example, the NN can be used to learn the inverse dynamic model of robot.[79] Such an NN learning impedance controller is shown in Fig. 18. The “Target Impedance” block is used to generate a driving signal F_1, and the target impedance of robot is defined in this signal. The “NNFC” block refers to the NN feedback controller. The inverse dynamic model of robot can be learned by “NNFC.” Based on this learned

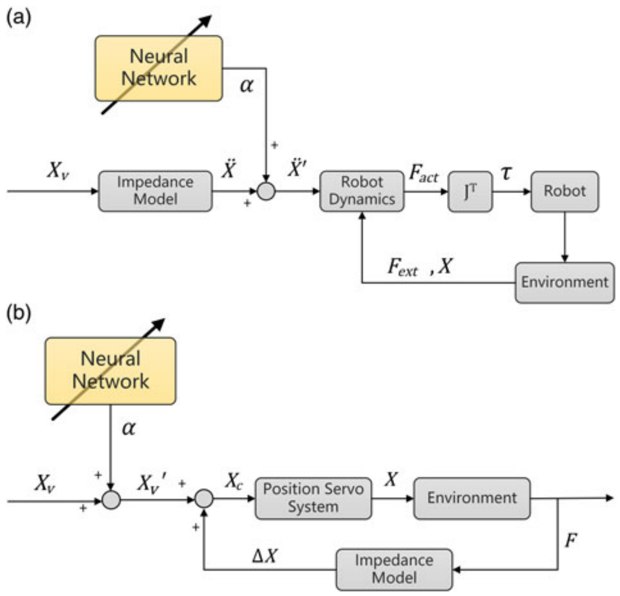

Fig. 19. (a) Schematic diagram of one NN learning impedance controller based on the model-based method. (b) Schematic diagram of one NN learning impedance controller based on the position-based method.

model, another driving signal F_2 is produced to counteract the effect of the original robot dynamics. As a result, the robot will be forced to perform the target impedance under the action of the total driving signal F_a. This learning scheme is called "inverse dynamic model learning." It also has a similar scheme named "nonlinear regulator learning".[79]

The NN also can be used to compensate for uncertainties in the robot dynamics or environments. The NN compensator can be placed at different locations of the control loop, which is shown in Fig. 19.[38] In Fig. 19(a), the NN is applied in the model-based method. The additional signal α generated by NN is used to cancel the uncertainties existing in the "Robot Dynamics" block. This compensation is realized by modifying the control input signal directly. By contrast, in Fig. 19(b), the NN is applied in the position-based method. The additional signal α here is used to modify the virtual trajectory, which is a kind of indirect compensation. Besides the model uncertainties, the problem of input saturation also should be considered sometimes.[83]

The iterative learning algorithm is widely used in the repetitive manipulation tasks. As the operation is repeated, the error between the target impedance and the actual impedance can be reduced gradually through this algorithm. To realize this effect, the system control law usually includes a particular learning term updated by iterative learning rules to adjust the total control input. This kind of methods can work well in the presence of model uncertainties,[80] or even on the robots with unknown structure.[82]

4.6. Other typical control techniques

In addition to these advanced impedance control schemes, some other technical problems have also received attention. The studied techniques include the impedance control of redundant robots,[139–144] the impedance control of flexible joint robots,[145–147] the impedance control of cooperative robots,[134, 148, 149] and the force sensor-less impedance control.[127, 150, 151]

5. Applications

Based on the previous discussions, it is clear that the most important feature of impedance control is its ability to achieve compliant motion or delicate interaction as desired. As a result, this control scheme is particularly suitable for the application scenarios involving human–machine interaction.[152–157] The typical applications in this field include rehabilitation robots,[90–111] collaborative robots,[78, 112–118] and some expert teaching systems.[60, 61, 119–121]

Due to the fact that impedance control has the potential to regulate the motion and contact force of a manipulator simultaneously, mechanical manipulation is another important application

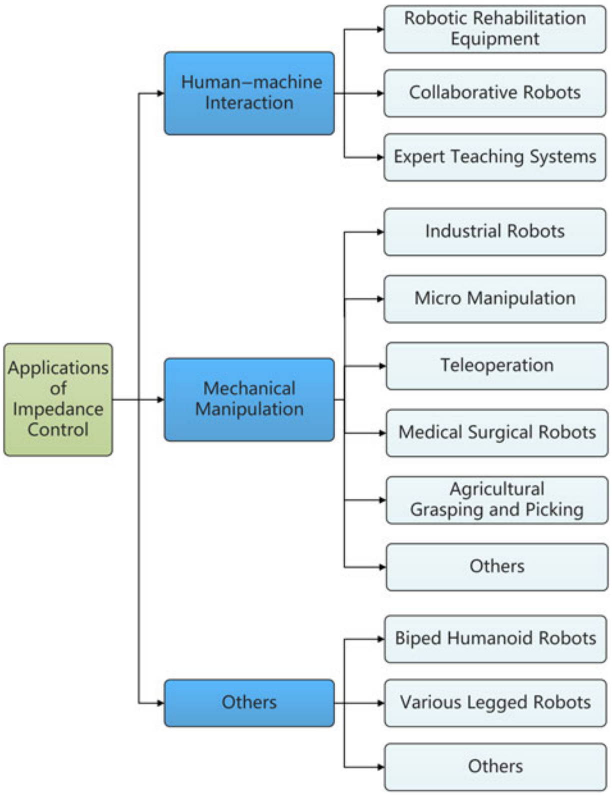

Fig. 20. The classification of applications of impedance control.

field of impedance control. The impedance control can help the controlled manipulator to achieve the customizable trade-offs between the positioning precision and the contact force. The specific applications involve industrial robots,[37,122–125] micro-manipulation systems,[66,126–128] and so on. All the applications are categorized in Fig. 20.

5.1. *Human–machine interaction*

Impedance control can provide the flexibility and safety required by human–machine interaction. The applications in the field of rehabilitation robots are introduced emphatically in this subsection.

5.1.1. Robotic rehabilitation equipment. Many of the aged, the disabled, or other inconvenience groups in action need safe robotic rehabilitation equipment to assist them in physical therapy or daily activities. Using these robotic devices instead of manual assistance can save much human and time cost. Based on the content in Section 3, the measures to realize delicate interactions can also be classified as the hardware-based methods[90,91,110] and the software-based methods.[92–98]

In the hardware-based methods, some compliant joints or actuators are integrated into the rehabilitation robots. SEA is a typical compliant hardware.[24–29] The ankle–foot orthosis with the SEA[90] is able to assist drop-foot gait. This orthosis can be worn on the human foot and shank. The rotation joint is located at the position of human ankle. Variable impedances of the orthosis joint can be produced by the action of SEA. It is known that a normal complete gait can be divided into three phases, including the collision contact, supporting contact, and swing. In order to achieve a smooth gait, each phase should have different requirements on the joint impedance of the orthosis. As a result, the system controller is designed to assign the proper impedance in different gait phases, which can achieve good adaptability.

PMA is another typical compliant hardware.[30,31] It can provide the controllable compliance in wide range. The PMA can be applied to the gait orthosis with multiple joints.[91] In this case, the adaptive controller is used to adjust the robotic assistance according to the sensed driving torque from human subjects. Therefore, the "assist as needed" effect was achieved to ensure the stable motion and proper human–machine interaction.

By adopting the software-based methods, those rehabilitation robots without special intrinsic compliant components can also have controllable compliance. The early attempt in this field is a workstation named MANUS,[92] which is used for manual therapy and training. At its end-effector, a handle is provided for patients to hold. When the patient moves with the handle, the interaction force between MANUS and patient can be kept in a preset safe range by the impedance controller. Along with more and more efforts in this area, it is found that when the subject is coupled with the rehab robot, humans always try to maintain the dynamic properties of the overall system as constant as possible by adjusting own impedance. Based on this theory, a training system was developed.[93] The impedance of the rehab robot is changed in a pre-designed mode at first. Accordingly, the subject will change his/her own impedance by adjusting the arm posture or muscle contraction, which leads to a good training effect. Another training robot is used for the rehabilitation of the wrist, elbow, and shoulder of upper limbs.[94] As the safety of these training or rehabilitation systems is extremely important, the supervisory strategy to handle the potential disturbance or emergency is really needed.[97]

The exoskeleton, as a type of rehabilitation equipment used to provide assistance in human motion, is another significant application area. This equipment is usually wearable, which should be fixed with the disabled part of human body. When the wearer has a certain motion intention, the exoskeleton can produce a proper assistance to help the user to move. To achieve this target, two important problems need to be solved. First, the exoskeleton should know how to measure the exact motion intention of users. The electromyogram (EMG) signal is often used for the estimation of motion intentions.[95,96,98,102] This kind of signals can be collected from the EMG electrodes stuck on the human body. However, the estimation based on the EMG signals may be inaccurate, and the parameters of the EMG controller need to be retuned for each individual. This tuning process may be complicated. In this condition, a proper impedance model has the potential to avoid the drawbacks of EMG controllers.[95] After the motion intention is known, how to produce a proper assistance for the user to achieve the desired movement is the second problem. To solve this problem, the optimal set of impedance parameters should be designed for each individual. Depending on the degree of disability, these parameters can be determined through a number of tests.

5.1.2. Collaborative robots and expert teaching systems. The robots with impedance controller have the potential to replace human in cooperation tasks. These robots able to cooperate with human in safety are named collaborative robots. How to design a suitable impedance model for the collaborative robots is a difficult problem. For a given cooperation task, one effective method is to copy the human impedance to the robots.[60,61] For example, a cooperation task is performed by two persons. Based on the motion data collected from one person, his/her impedance model during the task can be established through computation. Then this impedance model can be applied in the robot to perform the same task with the other person to realize a good human–machine cooperation. In general, the applied impedance model is varied in different phases of the cooperation, which can make the human–robot interaction natural and effective. This procedure actually reflects the principle of some expert teaching systems.[119] To obtain the impedance model of the expert is the first step. Then this expert impedance model is applied to collaborative robots so that the expert skills in a certain manipulation task are learned by the robots.

Another type of expert teaching system is used in the tuning of the powered prosthesis.[120] In most cases, the impedance parameters of a powered prosthesis are tuned by human experts manually. This process can cost much time and resource. Therefore, an expert teaching system was developed to build a database based on the tuning data from experts. When the testing results of a patient are input into this expert system, a corresponding set of the tuned impedance parameters will be output through the fuzzy logic inference methods,[120] which makes the tuning process much more convenient.

5.2. Mechanical manipulation

Impedance control can also be applied to all kinds of mechanical manipulations, especially those require the controllable interaction forces. These manipulations involve industrial robots,[37,122–125] micromanipulation,[66,126–128] cell manipulation,[127] teleoperation,[158–160] medical-surgical robots,[161,162] agricultural grippers,[163] aerial manipulation,[164–166] underwater manipulation,[167] service robots,[168] and so on.

5.2.1. Industrial robots. The early applications of impedance control are mainly toward industrial robots. The tasks performed by industrial robots can be divided into two classes: non-contact tasks and contact tasks. The typical non-contact tasks include spray-painting, welding, or simple pick-and-place operations. In these tasks, motion precision is concerned much more than the contact force. Whereas for the contact tasks, such as assembly, drilling, deburring, grinding, bending, and so on, both of the positioning accuracy and the interaction force between the manipulator and the manipulated object are important design specifications. The impedance control is quite suitable to deal with this situation.

For example, in the robotic deburring task,[122] the motion of manipulator should be divided into two directions to consider. In the tangential direction along the surface of the deburred object, small impedance is employed to prevent the stalling or break of the cutting tool. In the normal direction, however, large impedance is adopted to resist the normal contact force and keep the manipulator close to the command trajectory. For the peg-in-hole manipulation,[37] the impedance controller combined with visual techniques can achieve good performance. The visual module is used to generate the reference trajectory according to the observation of environments. Then, following the reference trajectory, the peg can be inserted into the hole smoothly by the action of impedance controller.

Different from the electrically driven robots, the industrial robots with hydraulic actuators are difficult to control the torques in actuators.[123] Due to this difficulty in torque control, the position-based impedance controller is preferred in this case.

5.2.2. Micro-manipulation. With the development of semiconductor manufacturing, life science research, medical industry, and so on, the robotic manipulators used to handle small objects delicately are more and more needed. In the microscale, the structure, actuator, sensor, and materials of a manipulation system could be quite different to the manipulator in the large scale.

The micromanipulator could be a microgripper or a microinjector. The gripper usually looks like a pair of tweezers. For example, a pair of cantilever thin plates can constitute a gripper.[126] The micropipette is mainly used for cell injection. The actuator used to drive the microgripper is no longer the normal motor. Instead, some microactuators are developed based on basic physical principles, such as the piezoelectric bimorph actuator,[66, 126] electrothermal actuators,[169–171] electromagnetic actuators,[172] and so on.

The feedback information of motion variables and contact force is usually required when implementing the impedance controller. The motion variables can be measured by computer vision. Nevertheless, the contact force between the manipulator and the manipulated object is hard to know. The conventional force sensors used in the manipulation in large scale are difficult to be installed on the microdevices. Instead, the strain gauges are frequently used to measure the contact force. However, in the cell manipulation or other biological manipulation, even the strain gauges are too large to be used. In this condition, computer vision techniques are applied to measure the contact force with the help of microscope. For example, the deformation of cell is relevant to the applied contact force and this deformation can be observed by the microscope. It means that if the relation model between the contact force and the cell deformation can be built, the real-time contact force can be estimated according to cell deformation.[127] The sensed contact force is important to realize the impedance control of biological manipulations. With the help of impedance controller, the improper contact force on the fragile biomaterials can be avoided to increase the success rate and efficiency of manipulations.

It is also worth noting that the creep and hysteresis effect may occur due to the materials of micro-manipulators and the characteristics of micro-actuators. This effect will deteriorate the performance of manipulations. To handle this problem, the proper compensator was designed based on the sliding mode methods.[66] It is effective in micro-assembly tasks, such as the grasp-hold-release operation.

5.2.3. Other manipulation. Impedance control is also applied to some special operating equipment, such as teleoperators,[158–160] surgical robots,[161, 162] agricultural grippers,[163] and so on. Based on the master-slave architecture, the time delay problems of telerobots[158] were alleviated by impedance control. The medical surgeries conducted by impedance-controlled surgical robots are expected to be safer and more flexible. The impedance-controlled grippers can be utilized to pick fruits like human hand without injury on fruits. The aerial robot,[164] which is the combination of a vertical aircraft and a robotic arm, adopts impedance control to interact with the surrounding environment while remaining airborne stably. In addition, the impedance-controlled humanoid service robots are able to interact with human and their surroundings safely and reliably. The wheeled mobile service robot consisting of a mobile platform and an upper body was developed in ref. [168].

5.3. Others

Besides the two major categories of applications above, other impedance control applications mainly aim to realize the motion of robotic devices with adjustable compliance. The detailed applications involve the walking of biped robots,[5,173,174] the compliant motion of various legged robots,[175–179] the grasping of robotic hand,[180,181] and so on.[182,183] To control the locomotion of biped robots, each gait cycle is divided into three main phases upon the research on human walking.[5] In different gait phases, different impedance parameters should be adopted to achieve smooth swing or stable landing. Similarly, the compliant motion of multi-legged robots without passive elements[175] and the adaptive grasping of multi-fingered robots[180] were realized on the basis of impedance controllers. In addition, the impedance control was even applied to solve the docking problem of space station.[183]

6. Conclusions and Outlook

This tutorial review has presented a comprehensive and specific overview toward the impedance control of robotic manipulation. The theory basis, implementation methods, significant technique developments, and practical applications have been overviewed, compared, and summarized. This work is based on the results of the literature published from the 1980s to 2018. First, the definition of impedance control is presented. The physical equivalence between hardware and controller, and the causality of impedance and admittance, as two essential theoretical bases of impedance control, are also explained. Second, the implementation strategies of impedance control are divided into two main categories in terms of hardware-based approach and software-based approach. The examples are given to illustrate the specific implementation procedures, and the detailed design methods of impedance controller are proposed as references. Third, the main technique developments about impedance control are demonstrated in detail, including force-tracking methods, hybrid impedance control, robust methods, adaptive methods, learning algorithms, and so on. Finally, the applications of impedance control have been summarized. Impedance control is quite suitable to be used in human–machine interactions and mechanical manipulations. In fact, any application scenarios requiring motion compliance or delicate interaction should consider impedance control as a potential solution.

Based on the existing research achievements and efforts in impedance control, it may be envisaged that more efforts are needed in the following areas:

- To establish more systematic guidance or methodology on how to specify the impedance parameters, M_d, B_d, and K_d, to reflect the basic dynamic interaction requirements of robotic manipulations raised from the customers who do not have the sense of impedance and impedance control.
- To develop robust and adaptive hardware with devisable impedance so that robotic manipulation can better achieve dynamic interaction in the presence of uncertain dynamics and uncertain environment.
- To integrate more novel advanced robust, adaptive, and learning algorithms into impedance controllers to further improve the dynamic performance. The combination of impedance control with artificial intelligence techniques could be a hopeful direction.
- To add efforts and trials to other applications in robotic manipulation more than the ones overviewed in this work.

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