A Review of Algorithms for Compliant Control of Stiff and Fixed-Compliance Robots

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***Abstract*—This survey presents the state of the art of basic compliant control algorithms in a unified view of past and present literature. Compliant control is fundamental when dealing with unstructured environments, as in the case of human–robot interaction. This is because it implicitly controls the energy transfer to the environment, providing a safe interaction. In this review, we analyze solutions from traditional robotics, usually involving stiff joints, and recent literature to find common control concepts and differences. To this aim, we bring back every schemas and relative mathematics formulation to a common and simplified scenario. Then, for each schema, we explain its intuitive meaning and report issues raised in the literature. We also propose an expansion of taxonomy to account for recent research.**

***Index Terms*—Active compliance, admittance control, compliance, flexible joints, force control, impedance control, interaction control, series elastic actuators.**

I. Introduction

COMPLIANT actuators are attracting a considerable interest in the human–robot interaction (HRI) community, which includes different fields as rehabilitation robotics, haptics, robotic surgery, and legged robots. From the mechanical point of view, several technologies have been explored in the past (pneumatic [1], [2], hydraulic [3]–[5]) and several others are relegated to the future (electroactive polymers, shape memory polymers and alloys). Both pneumatic and hydraulic actuators have been applied in the past to prosthesis/orthoses [6]–[9], haptic devices, humanoids [10]–[14], and legged robots [15], [16] but their need for compressed air or fluid source is usually difficult to satisfy in a mobile system. Electroactive polymers and shape memory alloys or polymers can be a futuristic possibility but they are not mature yet [17]. At the current state of the art, most of the implementations make use of traditional electric motors with the addition of a soft element and/or a compliant controller.

This paper proposes a unified description of compliant control technologies applied to both stiff and soft joints based on electric motors. The literature about compliant control of stiff joints usually considers full body manipulators with related nonlinear and multidimensional dynamics, whereas literature on soft joints is often based on simpler systems, usually linear and single degree of freedom (d.o.f.) devices. Thus, to make a fair comparison and to focus on compliance and control principles, we will consider this simplified scenario also for the stiff joint case. In this process, the complexity addressed in most of the stiff robot literature is ignored. Nevertheless the key points about compliance are kept and the simplification makes them more evident.

Furthermore, while interest in compliant control of stiff joint has a long history in robotics, dating back to the middle of the past century [18], soft joints came forth in the last two decades [19]. This research field sometimes introduces novel terminology, having a meaning similar to other well established concepts in robotics. Therefore, we propose to link new and old concepts and to revise traditional robotic taxonomy in light of emerging research.

This survey can serve as a tutorial for engineers who will design or control a compliant device, to make them aware of advantages and limitations of different mechanical and control choices. In particular, we focus on fixed-compliance mechanisms where compliance is shaped solely by control. From a research point of view, this paper also proposes a taxonomy expansion and a review of future research directions.

The survey is organized in two main parts. First, we aim to give the background of common control concepts. To this goal, Section II introduces the concept of compliant control, Section III defines the graphical notation, and Section IV introduces the relation among compliance, backdrivability, and control. In the second part, we extend the current robotic taxonomy (see Section V), then we focus on the control of stiff and soft joints robots (see Sections VI and VII, respectively). Finally a discussion is given in Section VIII and conclusions are drawn in Section IX.

II. Compliant Control

Compliant control can be defined as the control technology to produce compliant motion. Historically compliant motion was defined as "any robot motion during which the end effector trajectory is modified, or even generated, based on online sensor information" [20]. Nowadays most of the interest in compliant control is related to approaches where the controller shapes the mechanical impedance of the robotic system, i.e., the dynamical relation between robot position or velocity and external forces [21]. Shaping the mechanical impedance allows to safely interact with the unknown environment because, instead of controlling either a position or a force, we control the power transferred to the environment, through the energetic pair force–velocity.[1]

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[1]We highlight that it is not possible for a physical system to control flow and effort independently. There are three possibilities: to control the position/

TABLE I
MECHANICS AND CONTROL: COMPLIANT (C) AND NOT COMPLIANT (NC) ALTERNATIVES

Control Type	Mechanics	Control	Approaches, Nomenclature
Position control of stiff joints	NC	NC	Traditional position control
Position control of soft joints	C	NC	Position control with elasticity compensation
Compliant control of stiff joints	NC	C	Virtual stiffness, programmable springs
Compliant control of soft joints	C	C	Equilibrium controlled stiffness, programmable springs
Control of mechanically adjustable compliance joints	Adj.C	C	Decoupled position and stiffness control

The literature shows a plethora of names for such controllers and *compliant control* is the one used in this review.[2] Regarding terminology we use the terms "soft," "elastic," and "flexible" to describe compliant mechanics, while the term "compliant" may refers to both mechanical and control domains.

In this review, we focus only on systems with fixed mechanical compliance where physical elasticity and damping cannot be changed. The control of such systems is addressed in the literature using different names. A common term is *virtual stiffness control* that highlights the goal of virtually changing the real spring stiffness. Another name is *equilibrium controlled stiffness* [23] because the displayed stiffness is adjusted by dynamically changing the equilibrium position of the physical spring. The term *programmable spring* is used for the compliant control of soft joints in [24] but also of stiff joints in [25]. Despite different names, all these strategies are equivalent to traditional impedance or admittance control over stiff or soft joints. Table I summarizes the described approaches in terms of mechanics, control, and nomenclature.

III. GRAPHICAL NOTATION

In the following, we present several control schemas characterized by the following common notation:

1) controllers are named using the first letter of the controlled quantity (e.g., position controller $P(s)$ impedance controller $I(s)$);
2) position and force references, called θ_r and τ_r, are drawn in gray, with solid and dotted lines, respectively;
3) for space reasons, we sketch the motor block as a pure inertia $1/Js^2$ according to

$$J\ddot{\theta} = \tau_m - \tau_e \tag{1}$$

where J is the rotor inertia, θ is the angular/linear link position, τ_m is the motor input torque/force, and τ_e is the resultant of external torques/forces from the environment;

velocity, to control the force, or to control the dynamical relation between them [22].

[2]Other widely used names are compliance control or active compliance, however, the term compliance usually refers only to the static relation between force and position, thus, we prefer compliant control.

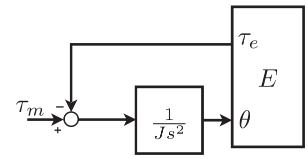

Fig. 1. Backdrivable motor model. Backdrivability is represented by the link from the environmental torque τ_e to the motor input, that is subtracted from τ_m. In the case of nonbackdrivability, the line is missing.

4) the environment block is marked with the letter E and the environmental input-output port is given by the pair θ,τ_e.

IV. DEFINITIONS AND BASIC CONCEPTS

In this section, we define the concepts of mechanical *compliance* and *backdrivability* and their relation with control.

A. Stiffness, Compliance, Impedance, and Admittance

Let

$$f_e = g(x, \dot{x}, \ddot{x}) \tag{2}$$

be the ordinary differential equation modeling a single d.o.f. mechanical system, where f_e is the sum of external or environmental forces and x is a Lagrangian coordinate. At a given position x_0 the stiffness can be defined as

$$k = \left. \frac{\partial g(\ddot{x}, \dot{x}, x)}{\partial x} \right|_{x=x_0}. \tag{3}$$

Mechanical compliance is the reciprocal of stiffness, $c = k^{-1}$. It refers to the ability to exhibit displacement if a force is applied. While stiffness and compliance refer to the static displacement–force relation, impedance, and admittance describe the dynamic relations between force and velocity. In the literature, alternative definitions of impedance and admittance are used by considering the relation between force and velocity instead of position, to account for power quantities. Using Laplace notation, impedance and admittance can be computed as

$$I(s) = \frac{F_e(s)}{JX(s)}, \qquad A(s) = \frac{JX(s)}{F_e(s)} = I(s)^{-1} \tag{4}$$

where $F_e(s)$ and $X(s)$ are the Laplace transform of $f_e(t)$ and $x(t)$, respectively.

B. Backdrivability

Actuators, either stiff or soft, are mechatronic systems usually composed of a motor, a rigid transmission, and a stiff or soft interface, respectively. Usually the motor power is efficiently delivered to the environment interface trough the transmission, and in some cases, the motion can be inverted, meaning that the environmental power can be delivered to the motor. This case is shown in Fig. 1, where the motor is moved not only by the electric forces τ_m but also by the environmental forces τ_e.

In the robotics literature, this is usually referred to as backdrivability. Hence, backdrivability is a mechanical propriety of a

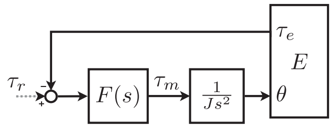

Fig. 2. Backdrivability by control. In this case, the motor is fully nonbackdrivable because the direct link from the environmental torque τ_e to motor input is missing. Instead, we design an outer artificial torque loop.

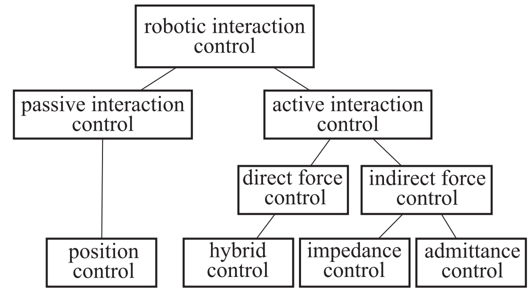

Fig. 3. Interaction control classification as proposed in [37]. Here, the terms direct and indirect refer to the presence of a pure force controller or not.

motor-transmission system, which describes whether the motion can be easily inverted [26], [27]. In particular, backdrivability depends on two factors: the transmission kinematic efficiency and the overall actuator mechanical impedance. Low kinematic efficiency of the transmission in the inverse motion implies that a substantial component of the applied external force is canceled by the kinematic reaction forces. However, even in the case of high kinematic efficiency, the inverted motion can be prevented by a high mechanical impedance of the actuator [27]. For these reasons, backdrivability can be compromised by high-ratio transmissions, which are usually kinematically inefficient in the inverse motion and also increases the reflected motor impedance (e.g., reflected motor inertia and friction). As backdrivability refers to the motor and transmission system, it does not depend on mechanical compliance, thus, it can refer to both stiff and soft joints.

It is important to highlight that backdrivability is absolutely unrelated to mechanical compliance. Both of them refer to external forces that interact with the actuation system, however, in *mechanical compliance, there is no need for a direct power flow from the environment to the motor, while in backdrivability, there is no need for a compliant behavior*. As an example one can think of a soft robot arm powered by geared motors, which is mechanically compliant but not backdrivable (because of the transmission). Conversely, a direct-drive position-controlled robot is backdrivable but stiff (because of the controller) [27], [28].

C. Backdrivability, Mechanical Compliance, and Control

Backdrivability, of either stiff and soft actuators, is strongly related to position and force control. Nonbackdrivability helps position control as it reduces the effects of external forces, which may perturb the controlled position. On the other hand, closing a force loop means to virtually transfer sensed forces to motor input,[3] thus emulating natural backdrivability, as shown in Fig. 2.

Mechanical compliance also shows a strong relation with position and force control. An ideal position-controlled system has desired zero compliance (or infinite stiffness) to track its reference position without being affected by any external forces. On the other hand, pure force control has desired zero stiffness (or infinite compliance) to prevent force modifications due to displacements. In fact, the rendered stiffness and compliance are robustness indexes for position and force controls, respectively [33]. This also indicates that stiff and soft joints are the best candidates for position and force controls, respectively.

The benefit of mechanical compliance in force control was first analyzed by Whitney who modeled the actuator as a simple mass and the environment as an elastic system, and found that stability margins improve when the plant is coupled to a soft environment [30]. More precisely, he derived the following stability condition among the proportional feedback gain g, the environmental stiffness k_e, and the sampling time T

$$0 < gk_eT < 1. \tag{5}$$

This shows that the environment compliance $(1/k_e)$ can improve control robustness: as it increases, the gain and delay margins increase too. However, the closed-loop performance depends on the product gk_e so that if k_e decreases g should be increased to retain performance. An interpretation of the Whitney equation can be that, given a proportional force controller, it is always possible to find a stiff enough environment to bring the system to instability. Interestingly, if we apply the Whitney analysis considering an elastic actuator, we can find that there always exists a proportional force controller that is unconditionally stable, regardless of environmental stiffness [34]. This explains why mechanical compliance can effectively solve stability issues in force control.

On the other hand, in the case of position control, the presence of elasticity can lead to instability because of *noncollocation* of sensor and actuator [35]. In fact, the motor is not located on the same rigid body of the sensor and some mechanical dynamics exists between the two. Thus, the system has two additional poles that can compromise stability [31], [36].

V. Taxonomy and Classification

The control of a task in an environment having kinematic and/or dynamic constraints is generically termed *interaction control*. In the traditional robotics literature, there are several approaches to solve this problem, which are schematically organized in Fig. 3 [37]. The main distinction is between *active interaction control* and *passive interaction control*. In active interaction, the compliance is entirely due to control, while in

[3]It has been shown that by using an appropriate force control structure, it is possible to reduce the friction and the apparent inertia. However, several limitations exist. For instance, the mass cannot be reduced below its half if we want to retain system passivity [29]. Also it is worth mentioning that force control is historically considered a delicate task. To address basic force control issues, the interested reader is referred to [30] and [31]. For force control reviews, see [25] and [32].

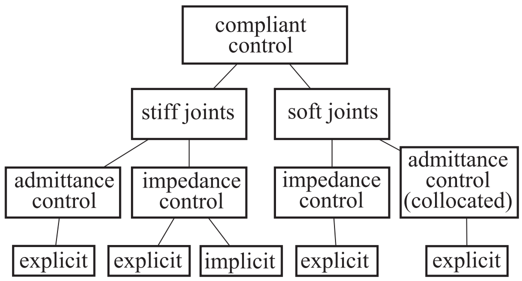

Fig. 4. New interaction control classification. The explicit/implicit node indicates the presence/absence of a force feedback. Note that the passive interaction control and the hybrid force/position control in Fig. 3 are not included because they aim to control position or force independently and not their relation.

passive interaction, it is entirely due to mechanics. The passive interaction control category is in practice the position control of a manipulator equipped with a soft interface to the environment, e.g., the remote center of compliance [38], [39]. This approach does not aim to control the interaction, so it will not be discussed in this paper.

Active control is divided in *direct* and *indirect* subcategories. The direct force control category includes algorithms that control separately the force and the position subspaces, called hybrid position–force control [40], [41]. These algorithms are not of interest in this survey because they switch between force and position control, without guaranteeing a fully compliant behavior. On the other hand, indirect force control leads to techniques for shaping robot impedance or admittance. This concept is successful when the robot is in free space and also when it is in contact with the environment, thus it can also be used in cases of unknown environments.

In the recent literature on soft joints, a mixed active/passive approach is very common and it cannot be collocated in the taxonomy of Fig. 3. For this reason, we propose the classification shown in Fig. 4, where the parent node is named *compliant control* and it has the same meaning of *indirect force control*, but it is a wider used term.

In our classification, we make a primary distinction based on the physical presence of elasticity, distinguishing the control of *stiff joints* from the control of *soft joints*. This conceptual distinction is fundamental because a soft system has a higher order dynamics than its rigid counterpart, which implies different position and force control behaviors. Analogously to the case of stiff joints, the soft joint taxonomy is inspired and derived by the established concepts of impedance and admittance control, dividing between *explicit* and *implicit* implementations. Explicit implementations make use of a force sensor, while implicit implementations deliver forces in open loop. The next sections are organized approximately following the structure of Fig. 4.

VI. Compliant Control of Stiff Joints

Compliant control of stiff joints is an extensively investigated topic and is considered quite mature to date [25], [37], [42], [43]. The two main implementations of interaction control are impedance and admittance control [44] both aiming at shaping the dynamical relation between actuator velocity (or position) and applied external forces. The difference between them is that the admittance schema uses an inner position loop and an outer force loop, while the impedance schema does the opposite, as shown in Figs. 5 and 6, respectively. In both cases, the desired impedance/admittance is implemented in the outer loop, while the inner closed loop is supposed to be fast enough so that its dynamics can be neglected. Depending on the schema, it is convenient to represent the environment differently: in impedance control, it is an admittance and in admittance control it is an impedance.[4] Next sections describe the basic schemas and their main variants.

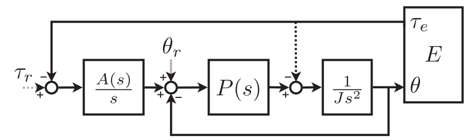

Fig. 5. Admittance control schema. The black dotted line represents the effect of backdrivability when present.

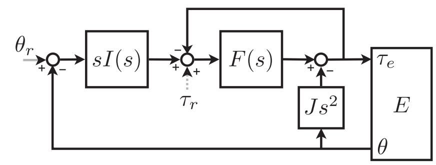

Fig. 6. Impedance control schema. Since τ_e has the direction of forward drivability, from the actuator to the environment, it is not possible to represent the effect of nonbackdrivability, which occurs in the opposite direction.

A. Admittance Control (Explicit)

The admittance control schema in Fig. 5 is a common choice when using stiff actuators. When in 1985 Whitney published his historical survey almost all the presented algorithms—that he termed stiffness, damping, and impedance control—were instances of the admittance schema [45].

One advantage of the admittance schema is its robustness to stiction effects thanks to the inner position loop. In the admittance implementation, the goal of the inner position loop is to be as fast as possible, while the outer force loop is responsible for shaping the force–position relation. In the case of a first-order desired admittance, the outer controller is implemented as

$$\frac{A(s)}{s} = \frac{1}{d_d s + k_d} \tag{6}$$

where d_d and k_d are desired damping and stiffness. In practice, the force loop computes a motion reference as τ_e is sensed, thus, creating a virtual backdrivability. Therefore, the admittance schema does not need an inherent backdrivable actuator. The main limitation of admittance control arises when a low impedance is desired. This is because a low desired impedance

[4] In this paper, admittance and impedance are regarded as equivalent representations. Note that, this is not the case if we need to write system equations because of kinematic constraints, nonlinearities and causality. However, we do not aim at system modeling here but only at discussing the main proprieties of the algorithms.

implies high gains for $\frac{1}{s}A(s)$, leading to instability [46], [47]. In this case, the actuator results "stiffened" by the inner position loop, and "softened" by the outer loop. A further limitation is due to the unavoidable position loop dynamics that may cause an inaccurate impedance rendering. In this review, accuracy is intended as a measure of the distance between the closed-loop transfer function and the desired force–velocity dynamics (the transfer function $A(s)$) in terms of poles/zeros locations and gain values [48]. Some literature examples of admittance control are [20] and [49]–[51].

B. Impedance Control (Explicit)

Impedance control uses an inner force loop and an outer position loop as shown in Fig. 6. $F(s)$ is the force controller and $sI(s)$ implements the desired impedance. In the case of a first-order desired impedance, the outer controller is implemented as

$$sI(s) = d_d s + k_d \tag{7}$$

where d_d and k_d are desired damping and stiffness. Thanks to the inner force loop, the impedance control can be very accurate and has no need of backdrivability. On the other hand, it is difficult to achieve a high impedance because it requires a high gain for $sI(s)$. More precisely, it has been reported that in this schema there exists a tradeoff between accuracy and ability to render high impedances [52]. Dually to the admittance case, in impedance control, the inner loop has a "softening" action, while the outer loop a "stiffening" action. In the case of high desired impedance, this leads to an antagonistic behavior between the inner and the outer loops.

As a final remark, we mention issues related to the high performance requirement for the inner force loop. In fact, depending on the environment dynamics, a low-gain tuning can lead to poor performance, whereas a high-gain tuning can cause instability when touching a hard surface. Solutions to this problem goes from increasing actuator bandwidth [52] to using advanced force controllers (e.g., model-based [53], adaptive or robust approaches [25], [54]). For these reasons, literature examples of impedance control are more recent than admittance implementations [55]–[59].

C. Implicit Impedance Control

A different kind of impedance controller was proposed by Hogan using an inner open-loop force control, thus avoiding force feedback issues [21]. Simplifying this control from complex robotic systems to the single joint case, we draw the schema of Fig. 7. This is in practice a position control that implements the desired impedance exactly as in (7), but delivers forces in open loop by using the motor in current mode. For this reason, it needs inherent backdrivability that can be achieved by using direct-drive motors or low-ratio transmissions. The main reported advantage of this schema is high accuracy [48]. It also shows full-body compliant behavior[5] and improved robustness

[5]In explicit implementations, compliance can be rendered only at the "sensed" ports, i.e., where the force sensors are located. Instead here compliance is rendered at every interaction port.

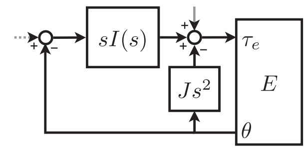

Fig. 7. Implicit impedance control. Although not shown, backdrivability is necessary because there is no explicit force measurement. Similarly to Fig. 6, backdrivability is not shown because when the environment is represented as an admittance τ_e has the direction of forward drivability.

w.r.t. the explicit implementation. Stability analysis of this architecture shows that, in case of delays, high impedances cannot be rendered and instability arises especially when in contact with low impedance environments [46], [47]. A disadvantage of this schema is that, when applied to complex robotic systems, it needs a very accurate robot model. This cannot be shown in the single d.o.f. case, so we refer to [21] for details. Literature examples are [60]–[65].

D. Role of Position and Force References

In compliant control, position and force references do not define the desired position or force. Instead they both determine the rest position of the desired impedance, i.e., the joint position in the case of null environmental forces. Let us consider the impedance controller in Fig. 6 with $sI(s) = k_d$ to display an ideal spring impedance with stiffness k_d. Having θ_r and τ_r as position and torque references, the desired torque profile to be tracked by $F(s)$ is

$$\tau_{e,\text{ref}} = k_d(\theta - \theta_r) + \tau_r \tag{8}$$

meaning that when the virtual spring is in position θ_r its compression is τ_r. However, it is redundant to specify both values because the virtual spring rest position $\theta_0 = \theta_r + \frac{\tau_r}{k_d}$ can be changed using only one reference. Usually θ_r is preferred leading to the intuitive equivalence $\theta_0 = \theta_r$.

Similar considerations can be done in the admittance implementation case of Fig. 5. If we choose $\frac{1}{s}A(s) = 1/k_d$ and references θ_r and τ_r, the position to be tracked by $P(s)$ is

$$\theta_{\text{ref}} = \frac{1}{k_d}(\tau_e - \tau_r) + \theta_r \tag{9}$$

which, in a perfect tracking condition ($\theta = \theta_{\text{ref}}$) is equivalent to (8) and θ_r and τ_r have exactly the same role as discussed previously.

In conclusion, a compliant controller only accepts the rest position reference, which can be conveniently set using θ_r. This can be used in free motion to achieve position tracking, whereas in constrained motion, neither the position nor the forces can be independently tracked. However, the needs of precisely controlling the forces may be fundamental in interaction tasks and some control solutions have been proposed based on compliant control modifications. Two main approaches exist: 1) impedance control with adaptation of θ_r (and eventually of k_d) driven by the force error [66]–[68] and 2) admittance or parallel architectures with integral force control [43], [69], see Fig. 8. Both these approaches are not included in our taxonomy as they aim to

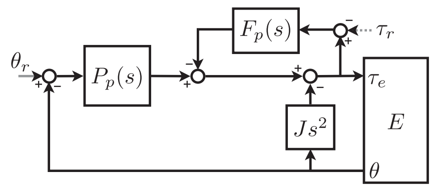

Fig. 8. Parallel force/position schema. It leads to use position control in free space (the force controller is excluded when $\tau_e = 0$) and to dynamically switch to integral force control (which dominates the position loop) in case of contact.

control a single variable rather than shaping the force–position relation.

E. Passivity Results

The range of impedances that can be displayed by a passive compliant controller is called Z-width, where Z stands for impedance [70]. The Z-width of the implicit impedance schema in Fig. 7 has been studied in [63] considering a digital control system and the following motor model $\tau_m = Js^2 + bs$, where J is the motor inertia and b represents the linear friction. Authors found that the maximum Z-width is bounded by

$$b > \frac{T}{2}(1 - \cos\omega T)\mathrm{Re}\{(1 - z^{-1})I(z)\} \qquad (10)$$

where T is the sampling time, $I(z)$ is the desired impedance, and z is the complex variable. In the case of $I(z) = k_d + \frac{z-1}{Tz}d_d$, (10) leads to

$$b > \frac{k_d T}{2} + d_d. \qquad (11)$$

This result means that to passively render a high impedance both high sampling frequency and motor dissipation are required. As passivity is a conservative requirement a further analysis is proposed in [63] considering the stability of the robotic system without human coupling. It has been shown that if the quantity $\frac{J}{bT}$ is small, passivity and stability regions are almost equivalent, otherwise it is easy to have stability outside the passivity region.

A related concept is unconditional stability intended in [47] as the stability of a system when coupled with a passive environment. In fact even a nonpassive controller can lead to unconditional stability. In [47], both the implicit impedance and admittance schemas have been analyzed. In the first case, the maximum Z-width is bounded by

$$b > \frac{T}{2}\frac{(1 - \cos \angle\mathrm{ZOH})|\mathrm{ZOH}|}{\mathrm{Re}\{\mathrm{ZOH}/I(z)\}} \qquad (12)$$

where ZOH represents the zero-order holder transfer function and $I(z)$ is the desired impedance. Again we have that 1) a minimum level of damping is needed and that 2) the digital approximation can prevent high impedance rendering. It is then shown that the admittance case is dual to the impedance case having that 1) a minimum level of softness (i.e., mechanical compliance) is needed and that 2) the limited position performance can prevent high admittance rendering.

Passivity results on the explicit impedance schema are very recent and not yet available in analytical form. Simulation and experimental results showed that a high impedance can be rendered only with high actuator bandwidth and low torque loop gains [52].

TABLE II
ADMITTANCE AND IMPEDANCE CONTROL OF STIFF JOINTS

	Admittance	Impedance	
	Explicit	Implicit	Explicit
Good for	rendering high impedance [46] in a low impedance environment [47]	rendering low impedance [46] in a high impedance environment [47]	rendering low impedances in a high impedance environment
Adv.	robustness [48]	accuracy [48], full-body compliance	accuracy
Disadv.	low accuracy because inner position loop dynamics	it needs high torque motors and accurate robot model	stability issues of force control [31], [36], fast actuator needed [52]
Mechanics	it works good also on nonbackdrivable motors	the lighter the better. Backdrivability is necessary	softness and lightweightness can improve robustness. Backdrivability is not necessary but helps
Z-width	increases with robot softness and high position performance, impedance is bounded from below [47]	increases with robot friction and low sampling time, impedance is bounded from above [47]	increases with actuator bandwidth, decreases with high force control gains [52], impedance is bounded from above

F. Choosing the Implementation

Impedance and admittance implementations are complementary in terms of advantages and limitations. Generally, admittance control leads to higher robustness, while impedance control leads to higher accuracy. This issue is called the "accuracy/robustness dilemma" in [48]. Also robot mechanics is determinant in choosing one solution over the other. Stiff mechanics is preferred for inner position loops (collocation), while inner force loops can benefit of some mechanical compliance (robustness). Table II compares advantages, disadvantages, and main features for each configuration.

VII. COMPLIANT CONTROL OF SOFT JOINTS

The idea to voluntarily introduce elasticities in series to general purpose actuators was implemented about two decades ago at Massachusetts Institute of Technology, Cambridge, MA, USA, where the term series elastic actuator (SEA) was coined [19], [71]–[73]. The original motivation of series elasticity came from the fact that high force and high power density actuators are usually very stiff and difficult to control in force. The series spring aims to improve force control robustness [34] and to decouple the motor from the environment thus reducing disturbances due to environment displacements. Soon it became evident that the benefit of series elasticity also included safety, shock tolerance, lower reflected inertia, bioinspiration, and low-cost collocated force measurement by spring displacement. Moreover, SEAs can also be very efficient in periodic tasks [74], they can increase performance in throwing tasks [75], [76] and exceed motor maximum torque when the load is in motion

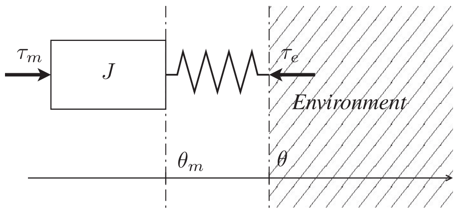

Fig. 9. Representation of a series elastic actuator where angular quantities have been converted to linear equivalents.

[73]. To achieve these capabilities, based on the energy storage property of the spring, the spring design must be tailored to the specific task. Unfortunately when energy is stored in the spring, the safety characteristics may be dramatically reduced because the energy can be suddenly released during impact [77].

From the very beginning, SEAs have been modeled referring to Fig. 9 and using the following equations:

$$\tau_e = k(\theta_m - \theta) \tag{13}$$

$$J\ddot{\theta}_m = \tau_m - \tau_e \tag{14}$$

where θ_m is the motor position, θ is the link position, and k is the in-between spring stiffness. This model does not account for friction and assumes a fully backdrivable motor as power source. Force can be measured by a load cell or through spring deformation, using encoders located both on the motor shaft and on the link side. System equations can also be rearranged as

$$J\ddot{\theta} = \tau_m - \tau_e - \frac{J}{k}\ddot{\tau}_e \tag{15}$$

where the last term $\frac{J}{k}\ddot{\tau}_e$ accounts for motor acceleration to compress the spring and is peculiar of soft systems, see (1) for a comparison.

Recently, it has been shown that some series damping can add substantial benefits to force control performance and stability [78]–[80]. In particular, the series damping can augment force control bandwidth (when coupled with high impedance environment) and can reduce oscillations (arising when coupled with low impedance environment). Also the series damping increases the Z-width. The model of a series elastic/damping actuator (SEDA) can be written as

$$\tau_e = k(\theta_m - \theta) + d(\dot{\theta}_m - \dot{\theta}) \tag{16}$$

$$J_m\ddot{\theta}_m = \tau_m - \tau_e \tag{17}$$

where d is the series damping coefficient. Note that the measured torque is still $\tau_s = k(\theta_m - \theta)$. In the following sections, we present and discuss force, impedance, and admittance control for SEA and SEDA.

A. Force Control of SEAs

Force control of the SEA was discussed first in [19] where the schema of Fig. 10 was proposed. It consists of a PID controller, represented by $F(s)$ plus two feed-forward contributions and a noncollocated acceleration feedback, which compensates for the system dynamics in (15) thus obtaining a well defined closed-loop dynamics. This is an important feature in interaction control, where the uncertain environment dynamics usually affects the control performance [34]. Other linear controllers have been proposed in [19], [72], and [82] sometimes involving an inner velocity (or position) loop to dominate stiction as shown in Fig. 11. Basic examples of SEA force control can be found in [83]–[85], while some advanced controllers have been proposed in [81] and [86]–[89] with the objective of ensuring robust force performance in spite of environment uncertainties.

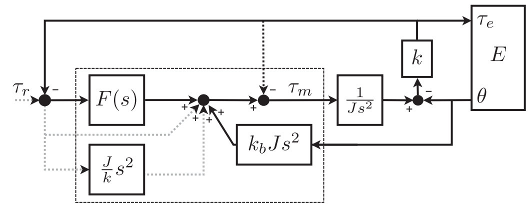

Fig. 10. SEA force control schema proposed in [19]. The proposed solution considers $F(s)$ as a PID and $k_b < 1$ to prevent feedback inversion. The black dotted arrow represents inherent backdrivability when present.

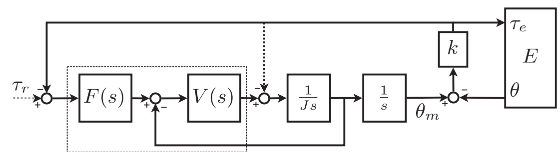

Fig. 11. SEA force control schema that uses an inner loop on motor velocity. This configuration allows to reject stiction disturbances.

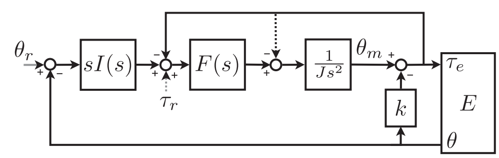

Fig. 12. Impedance control of an SEA. It uses an inner force control loop and an outer noncollocated position loop to shape the impedance.

B. Impedance Control of SEAs

It takes a little step from the design of a high-bandwidth force control to the impedance implementation shown in Fig. 12. Here, the force controller $F(s)$ is fed by an outer position loop that computes the force reference needed to obtain the desired impedance. Similarly to the compliant control of a stiff joint, if we desire a first-order impedance, the outer controller $sI(s)$ should be implemented as in (7). The main advantage with respect to the stiff joint case is the increased force control robustness [34]. It is worth remarking that in the case of elastic joints, a force measurement is always needed to observe the noncollocated subsystem. This means that impedance control is always explicit.

C. Collocated Admittance Control of SEAs

The authors of [90] observed that it makes no sense to close a high gain force control, to get close to zero impedance, if

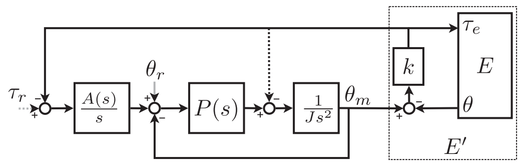

Fig. 13. Collocated admittance control schema proposed in [90]. The position loop is closed on motor position θ_m (collocated) instead of on joint position θ.

we finally desire a high impedance. They proposed to close a collocated position loop (on motor) and use a position reference based on force measurement, as shown in Fig. 13. For example, to render the desired impedance (7), the outer force control computes a position reference as

$$\theta_{m,\text{ref}} = -\frac{A(s)}{s}\tau_e, \quad \frac{A(s)}{s} = \frac{1 - k_d/k}{k_d + sd_d} \tag{18}$$

where d_d and k_d are desired damping and stiffness. This is a kind of admittance schema because it uses an outer force and an inner position loops. Differently from the classical admittance implementation, the position is fed back at the motor level (i.e., θ_m) instead of at the joint level (i.e., θ). In our taxonomy, we call this approach collocated admittance control, see Fig. 4. The overall idea is to control the motor admittance considering the spring as a known part of an augmented environment (E' in Fig. 13). Note that, to remove the high bandwidth requirement in force loop, the authors of [90] introduce a high bandwidth requirement on motor position control assuming $\theta_m \simeq \theta_{m,\text{ref}}$ to compute (18).

D. Passivity Results

For the case of pure force control, a basic passive controller was first introduced in [73] by ignoring the PID integral term in Fig. 10 and proving passivity of the noncollocated acceleration feedback. Another analysis was carried out in [91] by considering the "velocity sourced" force control schema of Fig. 11, where the force and motor velocity controllers are expressed as

$$F(s) = P_f + \frac{I_f}{s} + \frac{D_f s}{\tau_d s + 1}, \; V(s) = P_v + \frac{I_v}{s}. \tag{19}$$

The authors showed that passivity constraint can be meet if (but not only if)

$$P_v > J, \; I_v < 0.5P_v, \; I_f < 0.5P_f, \; D_f > 4\tau_d^2 P_f \tag{20}$$

meaning that pure integrators are allowed both in the velocity and in the force loops. When such force controller is considered within an impedance control architecture the maximum stiffness that can be passively rendered is limited by the physical spring stiffness, namely if $sI(s) = k_d$, then $k_d \le \alpha k$, where $0 < \alpha < 1$ depends on velocity and force gains [91], [92]. Also it has been shown that a parallel spring damper impedance cannot be passively rendered [92]. Things are worse if the force sensor is placed distally, on the end-point inertia. In this case, the maximum passive stiffness may be significantly lower than the physical spring stiffness limit. To move toward this limit, the end-point inertia should be kept as low as possible and a physical damper in parallel to the spring should be considered [93]. A further passivity result has been published in the area of flexible joint robots and it is described in the next section.

E. Passivity-Based Control of Flexible Joints

Flexible joints are elastic joints in which elasticity and damping are usually not included on purpose but they are a side effects of certain transmission design. The resulting dynamics can be described using the SEDA model (16), (17). Basic position control of flexible joint robots was introduced in [94] basing on the passivity theory and using (collocated) motor position feedback. This result was then improved in [95] and [96] by considering a full state feedback (including τ_s and $\dot{\tau}_s$) and an energy shaping interpretation [78]. The idea is to shape the kinetic energy via force feedback and the potential energy through position feedback. Force control is implemented by

$$\tau_m = JJ_d^{-1}u + (1 - JJ_d^{-1})\left(\tau_s + \frac{d}{k}\dot{\tau}_s\right) \tag{21}$$

where $J_d < J$ is a desired inertia and u is an auxiliary input coming from the outer position loop. When we apply (21) in (17), the following passive dynamics is obtained

$$J_d\ddot{\theta}_m = u - \tau_e \tag{22}$$

and the parameter J_d can be used to shape the kinetic energy. To shape the potential energy, a passive (thus, collocated) position feedback is used by defining

$$u = -\bar{k}(\theta_m - \theta_r) - \bar{d}\dot{\theta}_m \tag{23}$$

where $\bar{k}, \bar{d} > 0$, and θ_r is the desired link position when $\tau_e = 0$. With this controller, the dynamics of (22) is modified to

$$J_d\ddot{\theta}_m + \bar{k}(\theta_m - \theta_r) + \bar{d}\dot{\theta}_m = -\tau_e \tag{24}$$

where the control potential energy is shaped via $\bar{k}$ and the dissipation through $\bar{d}$. By considering a small J_d (this is the aim of the force loop), this solution makes the overall impedance seen at the environment port (τ_e, θ) to behave approximately as

$$k_d(\theta - \theta_r) + d_d\dot{\theta} = -\tau_e \tag{25}$$

where k_d is the stiffness resulting from the series of k and $\bar{k}$ and d_d is the damping resulting from the series of d and $\bar{d}$. Thus, in the limit case of $\bar{k} \to \infty$ and $\bar{d} \to \infty$, the maximum achievable stiffness and damping are k and d. Such limitation gives a bound for the Z-width. In particular, the rendered stiffness k_d and damping d_d cannot increase over the physical joint stiffness and damping, respectively, having again that "SEAs cannot display a higher pure stiffness than the spring stiffness." Interestingly the same result can be also extended to the collocated admittance schema in Fig. 13, by rearranging it as a collocated impedance.

From the architectural point of view, the energetic interpretation of the control law (21)–(23) resembles an impedance schema but with collocated position feedback, see Fig. 14. However, the actual implementation in [78] is an equivalent parallel force/position architecture. In both cases, positiveness

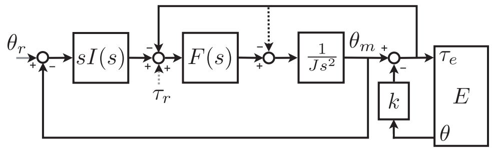

Fig. 14. Passivity-based controller proposed in [78]. This architecture is referred to its energetic interpretation. The main difference with respect to impedance control is that motor position is fed back instead of joint position.

of proportional and derivative force and position gains ensures passivity.

The algorithm as explained is oversimplified with respect to [78] because robot kinematics and dynamics are not considered. An important issue (that affects even static conditions) is due to gravity compensation that depends on the noncollocated joint position θ. To overcome this problem, the collocated approximation $\hat{\theta} = \theta_m + k_d(\theta_m - \theta_d)/k$ is proposed in [78], that is equal to θ in static conditions. Unfortunately gravity compensation is not explicit in $\hat{\theta}$ and a fixed point iteration is proposed as $\hat{\theta}^{(k+1)} = \theta_m + k_d(\theta_m - \theta_d)/k + g(\hat{\theta}^{(k)})$, where $g(\theta)$ represents the torque due to gravity.

VIII. Discussion

This section summarizes the reviewed approaches and discusses future research directions.

A. Summary of Stiff Joint Control

1) Admittance and impedance implementations are composed of cascaded position and force loops, where the inner loop is supposed to be faster and the outer loop is responsible for shaping the impedance or admittance.
2) Admittance control cannot display a low impedance, whereas impedance control cannot display a high impedance. We observed that in these situations, the inner and outer loops exhibit a conflicting stiffening/softening behavior. Conversely, implicit impedance control uses a single position loop in which the joint is simply stiffened as much as needed. The admittance schema and the implicit impedance schema are historically the most popular in the literature, probably because their core is based on well-behaved position control. Explicit impedance implementations are more recent and rapidly growing.

B. Summary of Soft Joint Control

1) The main advantage of series compliance is to facilitate force control and the main disadvantage is noncollocation. For this reason a) the most common schema is impedance control and b) the admittance implementation closes the position loop at the motor level to avoid noncollocation.
2) As in the stiff joint case, both impedance and admittance controls require a fast inner loop and an outer loop to shape the impedance or admittance.

TABLE III
Stiff and Soft Joints: A Comparison

	Stiff	Soft
Good for	rendering high impedances	rendering low impedances
Main advantages	simple and compact mechanics, robust/accurate position control	safe, robust force control, efficiency in harmonic tasks, higher peak force and output work [45], [73]–[75]
Main disadvantages	difficult force control, high forces during impacts	difficult position control, efficiency and performance are task dependent
Compliance above force ctrl bandwidth	almost zero compliance	the compliance of the physical spring
Backdrivability	needed in the implicit schema	not needed, all existing schemas use force feedback
Force bandwidth	limited by environment max stiffness [34]	limited by joint compliance [34]
Position bandwidth	high	low, due to noncollocation
Impedance control	accurate but may be not robust, suited for low impedance rendering [46]	both accurate and robust, good for low and accurate impedance rendering [97]
Admittance control	good for high impedance rendering [46]	good for middle impedance rendering [90]
Instability issues	when trying to achieve low impedance	when trying to achieve high impedance
Passivity constraint	mechanical dissipation (impedance) and softness (admittance) are required [63], accuracy is limited (explicit impedance) [52]	limited stiffness and damping: less than the physical ones [78], [97]

3) The control of a flexible joint is conceptually similar to the control of an SEA even if mechanical parameters may be order of magnitude apart. Proposed control architectures for flexible joints could work for SEAs/SEDA's and vice versa. In fact, SEAs are usually provided with force and position sensors and the same trend can be seen on flexible joints.

C. Choosing Between Stiff and Soft Joints

Both stiff and soft joints are suitable candidates to build a compliant actuator, but in practice, the final result strongly depends on the mechanical choices as summarized in Table III. This table reports an overall comparison between stiff and soft mechanics and can guide the design. These considerations are based on nonbackdrivable motors both in the case of stiff and soft joints.

D. Future Research Directions

Compliant control technology is quite mature but several issues are still open for research, especially in the area of elastic joints.

1) The *Z*-width analysis is incomplete. Most of the schemas still need to be analyzed accounting for motor and spring friction and eventually considering a sampled-data system approach.
2) Elastic actuators allow to robustify force control stability. Recent trends in the literature are working to guarantee not only robust stability but also robust performance, in spite of environment uncertainties [81], [89], and the

same approach is going to be extended to impedance control [98].

3) The control of multiple d.o.f. soft joints robots is an active and challenging research area with several open issues. For example, solutions are needed to passively compensate robot dynamics. Up to now, this can be obtained in static conditions only, using a collocated estimation of link position, see the end of Section VII-E. Another open issue is the control of contact forces, which are noncollocated and different from joint level forces.
4) Soft skin robots may represent a promising alternative to soft joints robots. These robots can potentially combine robust position control (of inner stiff mechanics) with robust force control (of outer soft skin).
5) Theoretical results on SEAs have been based on backdrivable models, while experiments usually employ nonbackdrivable prototypes. It is known that nonbackdrivability can have both positive effects (e.g., antiresonance mask, efficiency in static condition) and negative effects (e.g., slow dynamics, inefficiency in dynamic conditions) that should be analyzed. Also advantages and disadvantages related to the employment of backdrivable motors on SEAs have not been investigated yet.

IX. Conclusion

In this paper, we presented a review of fundamental admittance and impedance controllers for the cases of stiff and soft joint robots. Regarding stiff joint, we overviewed well-established control concepts, providing an organized view and details on practical issues. Regarding soft joint control, which is a less mature technology, we presented recent progresses describing contributions paper-by-paper following a historical timeline. We overcome the lack of a unified nomenclature by proposing an expanded taxonomy to merge concepts developed in different historical periods and research areas. We reviewed a hundred papers comparing their control solutions on a common ground. The literature has been organized, summarized, and graphically illustrated using a unified notation. Finally, we highlighted the key meaning concepts and limitations of each control strategy.

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