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An introductory review of active compliant control

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HIGHLIGHTS

- A review on active compliant control focusing on rigid systems.
- Based on a transparent and systematic literature research methodology.
- Characterization of active compliant control concepts and many of their variants.
- Basic concepts: Hybrid and parallel force/position, impedance and admittance control.
- Schematics to guide novices in application specific selection of control approaches.

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ABSTRACT

Active compliant control enables to quickly and freely adjust the properties and dynamic behavior of interactions of mechanisms within certain limits. According to the emerging applications in many robotic fields and related areas, the number of publications has also strongly increased. This paper meets the need for a recent comprehensive review, including a profound and concise characterization and classification of compliant control approaches extending the basic concepts, hybrid and parallel force/position, impedance and admittance control, by a survey of their variants and combinations. It mainly focuses on individually operating, stiff, non-redundant systems. Unlike previous reviews, this work is based on a transparent and systematic literature search methodology, which can easily be adapted or updated by any reader, hence remaining enduringly up-to-date over time. Also, a novel selection scheme is proposed, which facilitates the choice of appropriate control approaches for given requirements, particularly for newcoming researchers to the field.

1. Introduction

The emerging field of compliant control has evolved from hybrid to parallel force/position control and to impedance and admittance control. Compliant control is a subdomain of continuous feedback force control and allows to virtually manipulate the compliance properties and respective dynamic behavior of a controlled system. Alongside with the realization of passive compliance within mechanical design [1–4], active compliant control realized within software is increasingly applied in the wider field of robotics including among others industrial settings, such as peg-in-a-hole tasks [5] or human-robot cooperation and co-manipulation [6], medical devices, such as exoskeletons [7] or surgery robots [8], and legged robots [9]. Moreover, compliant control approaches enter industrial practice and, recently, an increasing number of robots is equipped with the required joint force/torque sensors, e.g. Panda (Franka Emika GmbH) [10] and KUKA IIWA (KUKA AG) [11]. These technical systems already have a huge influence on many parts of the society, however, in the future, they will more and more conquer everyday life of individuals in their private as well as in their working environment. That humans and machines get closer in physical interaction - e.g. from collaborative to wearable robots - provides great potential, but also raises the risk of injury in case of unpredicted behavior of human or machine. Hence, safety requirements gain increasing influence, while traditional performance metrics as tracking accuracy remain [12]. Compliance allows to compromise between these conflicting criteria [13,14]. Passive compliance can improve actuator characteristics such as backdrivability, motor-link decoupling, peak torque and power requirements and energy storage capabilities, but also increases the system complexity and control effort, e.g., to suppress undesired oscillations, and decreases the position or force control bandwidth [14–16]. A solution within software, which is the topic of this review, limits

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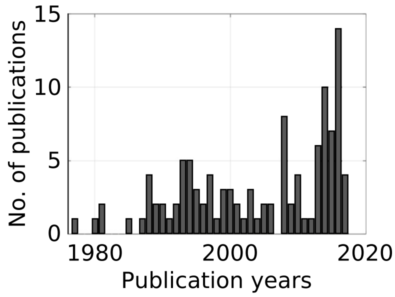

Fig. 1. Timeline of publications selected for this review.

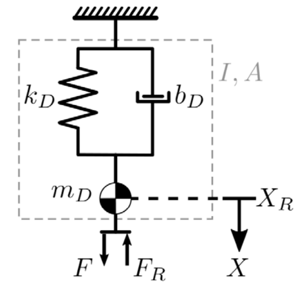

Fig. 2. Second order impedance or admittance with the mass m_D, damping b_D and stiffness k_D.

the bandwidth according to the sensor, the actuator and the controller frequency resulting in a rigid behavior for high speed impacts, but keeps the apparent system dynamics more easily adjustable and the mechanical design within certain limits independent of the target apparent impedance [15]. Depending on the reflected motor and link inertia as well as the environment's impedance in contact, already a low passive reflected joint elasticity, such as induced by a Harmonic Drive, can decouple motor and link and hence achieves similarly fast impact characteristics as its more compliant counterpart [14].

The timeline of publications identified and selected during our literature analysis (Fig. 1) underlines the long-lasting and ongoing interest of the research community in the topic of compliant control and hence its maturity but also actuality. The latter gets apparent in the high quantity of recent publications, revealing the importance of a new and enduringly up-to-date review for the scientific discourse. Compliant control has been thoroughly reviewed with respect to the four basic approaches which are *Hybrid Force/Position Control* (HC), *Parallel Force/Position Control* (PC), *Impedance Control* (IC) and *Admittance Control* (AC) [17–32]. Vukobratović [18] provides an extensive introduction into the background and classification of compliant control as well as some variants and combinations of the basic concepts. This is complemented by an overview of the historical development of interaction control presented in Leylavi Shoushtari et al. [31], where also an analysis of the approaches with respect to the criteria stability, generalization, impedance variability, and controllability is given. Further authors focus specifically on insights into the stability properties [17,26], robustness characteristics [27], and an in-depth study of the characteristics of basic impedance and admittance control for rigid or fixed-compliance systems [29].

While previous reviews analyzed the basic concepts as well as some variants and combinations [18,28,31], a recent, systematic, and hence transparent and comprehensive survey of the emerging field of compliant control does not yet exist. With the present review we intend to close this gap. A detailed documentation of the literature research yields a clearly stated baseline for further research or adaption to individual needs, since the results are easily extendable with respect to the content and considered time span in the future. This reveals the lasting quality of the paper. An elaborate analysis of the basic concepts for compliant control results in a multisided and concise summary of their characteristics and a classification of a large number of state-of-the-art variants of compliant control approaches alongside with their particular objectives. Although providing some remarks on the treatment of more complex systems, the main focus of this review is on individually operating, stiff, non-redundant mechanisms. Hereby, a broad and at the same time deep insight into compliant control is facilitated to the readers. To guide through the complex task of selecting the adequate approach from the variety of existing methods and ease the access to the topic, we subsequently derive and propose a selection scheme. Consequently, the presented review enhances and accelerates the above described scientific and technological developments.

This review is organized into four sections: Following this introduction, Section 2 introduces general background concepts and the methodology applied to the literature research in this paper. Section 3 introduces the selection scheme, classifies the literature findings and characterizes the basic control concepts for modifying the compliance of a system as well as their variations and combinations. The main findings are discussed in Section 4. Finally, Section 5 concludes the paper with a summary of the main contributions and an outlook to future trends.

2. Background and methodology

The stiffness, compliance, impedance and admittance characteristics of a mechanism are aimed to be modified by compliant control. Backdrivability as an inherent system property influences the selection and implementation of a particular control approach. In this section, these terms are defined and introduced alongside with the literature research methodology for the further use in this paper.

2.1. Stiffness/impedance and compliance/admittance

Stiffness and compliance describe the static relation, while impedance $I(s)$ and admittance $A(s)$ refer to the dynamic relation

$$I(s) = \frac{E_F(s)}{E_X(s)} = A^{-1}(s) \tag{1}$$

between the deviation in force $E_F(s) = F_R(s) - F(s)$ and displacement $E_X(s) = X_R(s) - X(s)$ with the Laplace variable s. $X_R(s)$, $X(s)$, $F_R(s)$ and $F(s)$ refer to the reference and measured position and force respectively. The order of an impedance or admittance then refers to the highest exponent of s which reveals stiffness/compliance to be equal to the zeroth order case of impedance/admittance. Fig. 2 illustrates the second order case. Alternatively, some authors define impedance and admittance as the force-velocity relation [17,19] instead of the force-position relation [18,31,33]. This complies with Hogan [34], who analogously defined impedance to convert flow input into an effort output and admittance to accept effort as an input and return flow as an output. If two systems dynamically interact with each other, they must complement one another, meaning that, if the environment exhibits admittance characteristics, the mechanism should have impedance behavior and vice versa.

2.2. Backdrivability

In case of an ideally backdrivable mechanism, the force that needs to be overcome externally to cause a user-driven displacement [35], tends to zero. In a non-ideal scenario, backdrivability is limited by acceleration- and velocity-dependent influences and hence the required external force does not reach zero. The acceleration-dependent backdriving, i.e. impeding, force is caused by the moving mass or inertia, whose magnitudes usually raise with the peak torque, the actuation is designed for. Velocity-dependent backdriving forces stem from friction and damping [36]. The dominance of either of the influences also depends on the mechanical design as well as the application: non-fading, i.e., sudden, loads, such as occurring in case of a collision with a stiff environment, provoke high acceleration-dependent peaks in the backdriving force. Contrarily, in case of fading loads, e.g. resulting from impacts with soft environments, the acceleration-dependent influence is low relative to the velocity-dependent terms.

High transmission ratios increase the ability to deliver motor force to the environment but decrease or even impede backdrivability as inertia and friction reflected to the output are magnified. Apart from mechanical design considerations, backdrivability can be improved by closed-loop control with a force sensor at the end-effector of the mechanism [37] or by compensation methods [35,37–39].

2.3. Literature research methodology

For a profound and comprehensive analysis of compliant control approaches, a detailed systematic and free literature research was conducted. The scope of this review is limited to English language journal articles, conference proceedings, PhD theses, and books.

The systematic research involved seven scientific online databases (ScienceDirect,[2] Web of Science,[3] IEEE Xplore,[4] SAGE journals,[5] WTI Tecfinder,[6] Engineering Village,[7] science.gov[8]). To target comprehensiveness, five search cycles were performed with different thematic fields for search term generation, each of them refined step-by-step until the respective search engine found a maximum of 50 results. The limitation to 50 findings appeared reasonable as it helped to suppress publications of other contexts such as electrical instead of mechanical impedance, but already included cross-references. For an emphasis on recent publications, while still relevance is given to development over time, each search cycle was carried out twice, once limited to publications until 2015 and once restricted to publications of the last three complete years, 2015 to 2017, revealing a total of more than 1,000 results. Based on a first scanning eliminating redundancy and assessing titles, abstracts and keywords, 221 publications were selected. In a second step, further filtering additionally included the full text and especially control relevant sections as well as the novelty of the control approach with respect to the other publications. Finally, a total number of 76 publications was selected for this review.

The complementing free research was realized in three further search engines (Google Scholar,[9] library search engine of TU Darmstadt,[10] Springer Link[11]). Hereby, keywords were not fixed, but key references or authors of previously analyzed publications were traced to get a deeper insight into the topic. This resulted in 33 additional publications to be considered.

Fig. 3 summarizes the literature research methodology. A detailed documentation can be found in the Appendix. The results are presented in the following section.

2 https://www.sciencedirect.com/.
3 http://apps.webofknowledge.com/.
4 https://ieeexplore.ieee.org/.
5 http://journals.sagepub.com/.
6 https://tecfinder.wti-frankfurt.de/.
7 https://www.engineeringvillage.com/.
8 https://www.science.gov/.
9 https://scholar.google.com/.
10 https://www.ulb.tu-darmstadt.de/.
11 https://link.springer.com/.

Table 1
Classification of fundamental approaches of compliant control.

	Explicit control	Implicit control
Direct control	• Hybrid force/Position control • Parallel force/Position control	-
Indirect control	• Impedance control • Admittance control	• Impedance control

3. Control concepts

Compliance can be achieved and manipulated by changing the inherent characteristics of a mechanism (passive compliance) or by control (active compliance). With the term *active compliant control* not being consistently specified in literature [18,29,40], for this work, it is defined as the simultaneous and purposeful control of deviations in position and force. Similar to [18], the four fundamental compliant control approaches, hybrid and parallel force/position control, impedance and admittance control, can be organized as depicted by Table 1.

In direct force control, the force feedback loop is closed by a force controller. By contrast, in indirect force control, force control is realized through motion control. This inner or outer motion control loop enables the establishment of a desired relation between system motion and force [26,33,41].

Explicit force control is characterized by force feedback with the use of a force sensor, while in the implicit case the actuator input is provided by open loop control and through the difference between the target and measured motion [33,42]. Implicit force control is only applicable for backdrivable systems [37] with negligible friction influence and, due to its impact reaction characteristics, only advisable for slow velocities and soft environment surfaces [42]. To alleviate these limitations by predicting the missing force sensory information, a system and environment model is required.

In this review, it is assumed that lower level controllers linearize and decouple the system dynamics while a higher level controller shapes the required compliant system behavior.

3.1. Selection scheme

Apart from the four main concepts of compliant control, numerous specialized variants and combinations of approaches can be found in literature. For an easy orientation and support for the selection of an appropriate approach, we propose the scheme illustrated by Fig. 4.

Most compliant control approaches require force/torque (F/T) data to be available, which can be provided by sensors or observers. Otherwise, the implementation is limited to implicit impedance control, which is also indicated by Table 1. The control objective is a design decision. While hybrid and parallel force/position control aim at tracking a target force or position, impedance and admittance control regulate their relation, but not explicitly their individual trajectories. The level of this relation or impedance is an indicator whether impedance or admittance control is more beneficial for the stability characteristics of the closed-loop system. The hybrid force/position control approach requires the system to have multiple degrees of freedom (DOF) and a detailed environment and task model to enable the division of the working space in position- and force-controlled subspaces according to the environmental constraints. If these conditions are fulfilled, it can be beneficial to be applied as it allows to exploit the model knowledge and it provides faster dynamics and reduced design complexity compared to the more robust parallel force/position control approach.

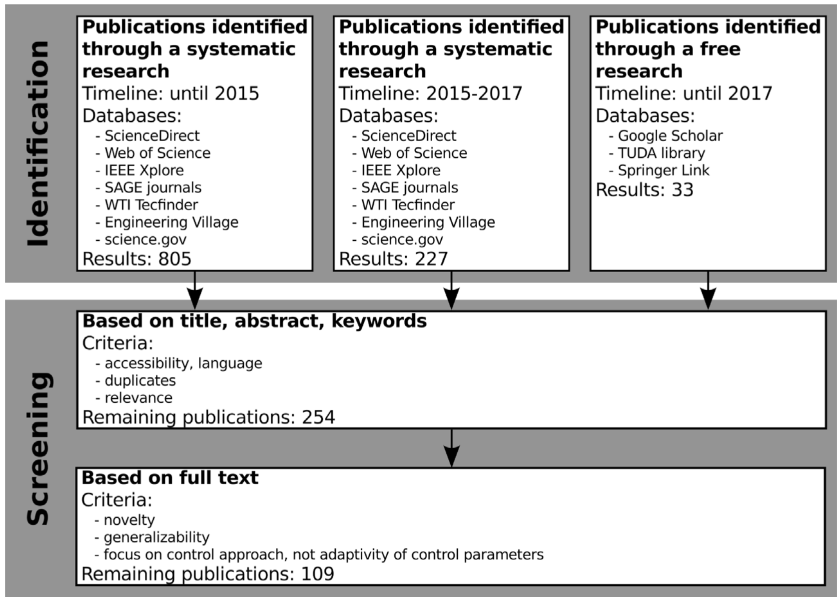

Fig. 3. Applied literature research methodology.

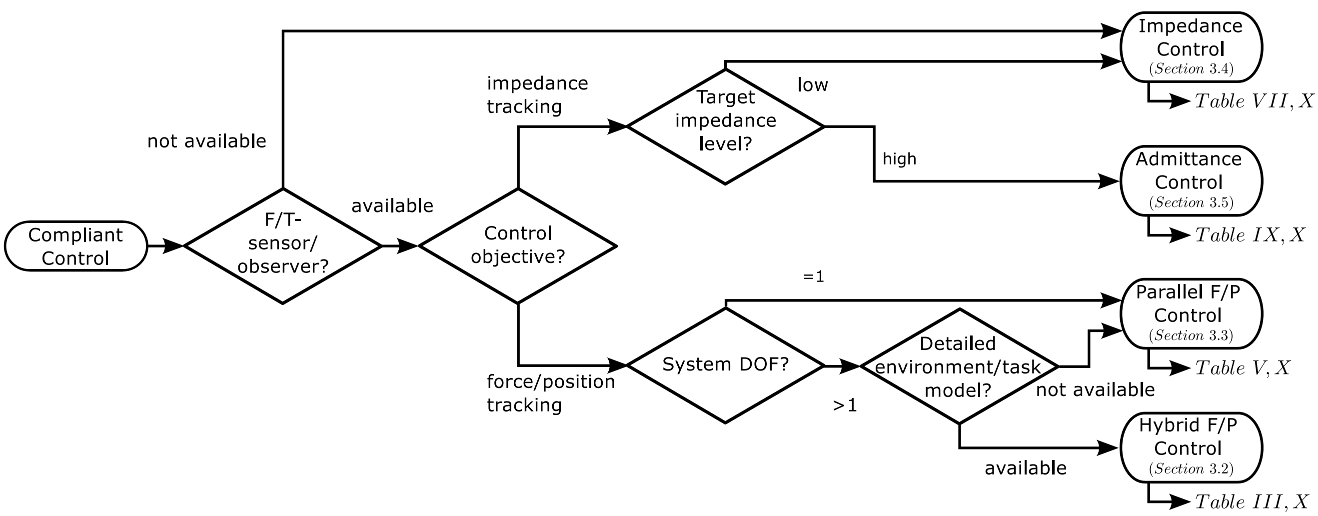

Fig. 4. Selection scheme for compliant control approaches.

Table 2
Strengths and weaknesses of hybrid force/position control [17,18,20,22,23,25,31,41,43–45].

⊕ Possibly mature	⊖ No standard feature of industrial robots
⊕ Independent design and implementation of position and force control law	⊖ Orthogonal subspaces
⊕ Force and position trajectory tracking within respective subspaces	⊖ Stability issues due to discreteness
⊕ Low complexity for planar surfaces	⊖ No specific manipulator impedance
⊕ Effective for high stiffness environments	⊖ Complexity for non-planar surfaces
	⊖ Requires detailed environment model
	⊖ Force measurement required
	⊖ Not robust to (unpredicted) task changes
	⊖ Performance depends on system configuration

All in all, the scheme is an attempt to summarize the main restrictions for the implementation of compliant control approaches and guide an appropriate selection from the main control concepts. After identifying one of them as suitable, Section 3.2 to 3.5 provide a deeper analysis of their characteristics and variants. Especially the latter and in particular their individual objectives can be employed for fine tuning. If the characteristics of more than one main approach are required, a compound control approach, as reviewed in Section 3.6 might be an adequate fit.

3.2. Hybrid force/position control (HC)

The force-based or explicit hybrid force/position control approach goes back to Mason's concept published in 1981 [47] and was firstly proposed in its present form by Raibert and Craig, [44]. The compliance selection matrix $S = \mathrm{diag}(s_j)$, with $j = 1 \ldots n$ and n being the number of degrees of freedom, divides the workspace into complementary orthogonal subspaces, which are either motion- or force-controlled. While motion-constrained directions must be force-controlled ($s_j = 0$), free

Table 3
Variants of hybrid force/position control.

Approach	Objective	Ref.
Position-based or Implicit HC: At the price of reduced force tracking performance, the environment model is used within the force control in order to map the force error to an equivalent position which is then added to the reference input of the unchanged inner loop position control.	→ reliability (standard inner position control loop) → robustness to parameter/task variation	[23,25]
Implicit/Explicit Force Control: The approach combines force- and position-based HC by merging their force control laws.	→ combines strengths of both individual concepts	[25]
Adaptive HC: The division in subspaces is realized through the reference trajectory which serves as input for a position controller. The desired force is scaled depending on the environment stiffness.	→ interaction with unknown stiffness environment	[46]
Resolved Acceleration Based Approach: System dynamics are included into the control law.	→ compensation for system dynamics	[23,25,26]
Not-Orthogonal Hybrid Control: Extension of dynamic hybrid control, that transforms the mechanism and environment models into two independent equations, creating two not necessarily orthogonal subspaces.	→ no need for orthogonal subspaces	[43]

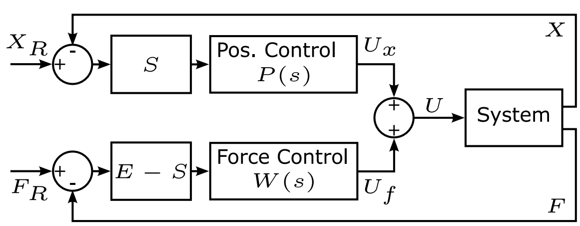

Fig. 5. Hybrid force/position control scheme [17,23].

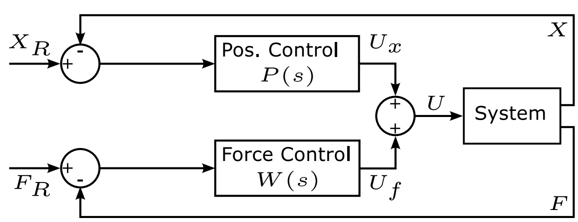

Fig. 6. Parallel force/position control scheme [45].

directions need to be motion-controlled ($s_j = 1$). The subspaces and their corresponding constraint types are derived from a detailed environment model, which is always required for hybrid force/position control [41]. Furthermore, the implementation on standard industrial robots is generally limited as the latter are mostly only position-, but not force-low-level-controlled and hence do not support the hybrid structure [22]. The knowledge of system dynamics is not mandatory [48]. In Khalil et al. [23] and An et al. [48], possible stability issues are discussed. Fig. 5 illustrates the control concept given by

$$U(s) = S \cdot P(s) \cdot [X_R(s) - X(s)] + [E - S] \cdot W(s) \cdot [F_R(s) - F(s)] \,. \quad (2)$$

Hereby, $U(s)$ represents the control output with the indices x for position and f for force. $P(s)$ and $W(s)$ are the position and force control law and their structure and parameters can be selected according to the system characteristics and implementation objectives. In literature, they are often selected following a PID approach [17,18]. The respective lower case characters refer to the upper case variable in time domain. E is the identity matrix of size $n \times n$. The system block can include an inner control loop as in Yoshida et al., [49].

Table 4
Strengths and weaknesses of parallel force/position control [21,41,45,50].

⊕ Force and position trajectory tracking	⊖ No standard feature of industrial robots
⊕ Robustness and safety in the presence of environment model uncertainties and planning errors	⊖ No specific manipulator impedance
⊕ Robustness to (unpredicted) task changes	⊖ Force measurement required
	⊖ Slower dynamics and increased complexity compared to hybrid approach

Table 2 summarizes the strengths and weaknesses of the basic hybrid force/position control approach. Hereby, maturity is justified by the stagnation w.r.t. recent publications, which would highlight new issues [22], however, it might also be argued, that the research interest has rather been shifted to other basic approaches. Variants and advanced configurations of hybrid force/position control are introduced in Table 3 and address the solution of some of these drawbacks, such as the implementability for standard position-controlled industrial robots, the requirement of an environment model, and the limitation to orthogonal subspaces. The robustness to unpredicted task changes remains an open challenge [31], to which the parallel force/position control approach described in the next section is directed.

3.3. Parallel force/position control (PC)

Parallel force/position control has been firstly proposed by Chiaverini and Sciavicco in 1988 [55]. As well as for hybrid force/position control, the objective consists in tracking the reference motion trajectory in unconstrained directions and in controlling the contact forces arising in constrained directions. Unlike in hybrid force/position control, in parallel force/position control the force and motion controller outputs are superimposed and can hence act on the same directions. In literature, the combination of a PD position and a PI force control approach is proposed [18,21]. The dominant integrator as part of the force control law causes the steady-state force error to be driven to zero at the expense of a motion error [21]. The influence of position and force control can be weighted by their feedback gains [22] and the control law can be extended by a system dynamics compensation term [20,45]. The system stability and

Table 5
Variants of parallel force/position control.

Approach	Objective	Ref.
Parallel Force/Position Regulation: Static instead of dynamic model-based compensation is applied.	→ simplified system model at the cost of tracking performance	[21,41]
Adaptive Force/Position Regulation: An adaptation law for gravity compensation within parallel force/position regulation is presented.	→ loosens the requirement for exact gravity force model parameters	[41]
Passivity-Based Control: The dynamic model-based compensation parameters are adapted online.	→ robustness to model parameter errors	[41,50,51]
Robust Adaptive Force/Position Control: A model-based parallel force/position control approach is extended by an error compensation term.	→ robustness to model errors, joint friction, environment disturbances	[52]
Output Feedback Control: A (non)linear observer replaces the need for velocity feedback within force/position regulation and passivity-based control respectively.	→ no velocity measurement required	[41]
Force/Position Control with Full Parallel Composition: The force controller contains a double integration of the force error.	→ force error dynamics independent of position error dynamics	[41]
Contact Stiffness Adaptation: Contact stiffness estimation and the derivatives of a time-varying desired force are included into the control law which is based on full parallel composition.	→ improved (transient) force tracking behavior at the cost of a larger position error	[41]
Multi-Manipulator Parallel Force/Position Control: The target trajectory is commanded in the cooperative task space and then transformed into the respective manipulator task spaces.	→ cooperative multi-manipulator control	[53,54]

Table 6
Strengths and weaknesses of impedance control [21,31,33,34,56–60].

⊕ Implements motion/force relation	⊖ No standard feature of industrial robots
⊕ Robustness to task uncertainty (e.g. environment) and changes	⊖ No exact tracking of position and force
⊕ Physically meaningful parameters ($m \leq 2$)	⊖ Sensitive to system modeling errors
⊕ Accuracy (compared to AC)	⊖ Accuracy/Z-width dilemma
⊕ Superposition property	⊖ Stability issues for high target impedances and due to force control (explicit)
⊕ No force measurement required (implicit)	⊖ Backdrivability necessary (implicit)

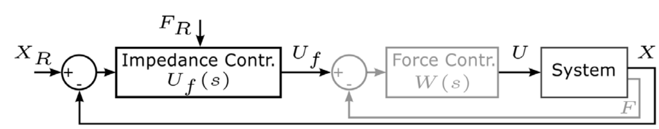

Fig. 7. Implicit (black) and explicit (black and gray) impedance control scheme [33,61].

an inner position control loop for friction compensation are discussed in Flixeder et al. [30]. Fig. 6 shows the general control concept given by

$$U(s) = P(s) \cdot [X_R(s) - X(s)] + W(s) \cdot [F_R(s) - F(s)] \,. \quad (3)$$

Table 4 summarizes strengths and weaknesses of parallel force/position control and its extensions and variants are introduced in Table 5. The first five approaches discuss and modify the influence of the system model on the control performance. Further approaches aim at decoupling the position and force control loop, an improved force tracking and an adaption of the parallel concept to cooperative multi-manipulator control. Compared to the hybrid approach, parallel force/position control does not require knowledge about the task and environment. A thorough analysis and comparison are provided by Chiaverini et al. [45].

3.4. Impedance control (IC)

Impedance control is synonymously called force-based impedance control, impedance control without force feedback or equilibrium point control. It goes back to Hogan's proposal of 1985 [34] and focuses on the implementation of a target relation between force and motion, but does not necessarily track their individual trajectories [21]. Therefore, $X_R(s)$ is also called rest instead of reference position. The position $X(s)$ is measured and conclusions for the inner loop reference force $U_f(s)$ are drawn by means of the mechanical impedance $I(s)$ which is reflected by the linear impedance control law as polynomial of mth order with the parameters a_k:

$$U_f(s) = I(s) \cdot [X(s) - X_R(s)] + F_R(s), \quad \text{with} \;\; I(s) = \sum_{k=0}^{m} a_k \cdot s^k. \quad (4)$$

As illustrated by Fig. 7, impedance control can be implemented explicitly or implicitly [33,37], where in the first case, a compromise for a well performing but stable force controller is to be found [33].

Choosing the impedance parameters means deciding for a tradeoff between the allowed contact force and deviation from the reference motion trajectory. For a targeted high system to environment stiffness ratio, the system endpoint tends to reach the desired steady-state rest position at the expense of penetration into the environment. For a low ratio, the endpoint rather adopts to environmental constraints [62]. A method for impedance controller synthesis by optimization is introduced in Hogan (1985) [34]. An analysis of the stability and passivity of

Table 7
Variants of impedance control.

Approach	Objective	Ref.
Computed Torque IC: Model-based approach which uses force sensor information to compute the control output.	→ acceleration not required	[62,63]
Steady State Approximation: Velocities in the dynamic model-based compensation are assumed zero, the inertia constant at the price of reduced accuracy.	→ no inverse Jacobian required → computational effort reduced	[63]
Task-Space Control With Null-Space Compliance: The redundant DOF of a task-space position controlled robot are used to achieve computed torque impedance control in joint space. Observers to replace F/T-measurement are proposed.	→ position control in task-space, IC in joint space → no F/T-measurement required	[64]
Model-Based Generalized IC: The generalized target imp. is defined by $(m_D s^2 + b_D s + k_D) \cdot (X - X_R) = k_f (F - F_R)$, where k_f corresponds to the so-called force stiffness and an extension by an environment model is optional. In case of positive m_D, b_D, k_D, k_f, the controlled system is stable.	→ considers reference force trajectory → additional DOF k_f for controller tuning → environment model instead of F/T-measurement	[65,66]
Inertia Shaping Avoiding IC: In task space second order IC with dynamics compensation, the target inertia θ_D is set equal to the system inertia. Centrifugal and Coriolis terms are considered within the target damping b_D.	→ no F/T-measurement required	[61]
Virtual Model Control: The reference force trajectory is generated by a simulation of virtual components inspired by physical counterparts. Inverse dynamics are not used.	→ generalization of the target impedance	[67]
Model-Feedforward Open-Loop IC: The time-dependent target parameters for an implicit IC are deduced from the collision simulation of virtual objects.	→ generalization of the target impedance	[68]
Indirect Stiffness Control: The virtual spring model for stiffness control is replaced by a potential energy approach.	→ overcomes its limitation to linear virtual springs	[69]
Intelligent Control: The angle of attack of the actuator force is adjusted according to the deviation from the reference position trajectory.	→ results in nonlinear stiffness control	[70]
Force Field Control: The commanded motor torque is divided into a component normal and tangential to the target position trajectory. Both are exponentially related to the position trajectory error.	→ nonlinear stiffness control → position tracking in time and space → safety: position tracking without high torque peaks	[71]
Tanh-D IC: The computed torque IC is extended by additional terms accounting for deviations between the target and measured impedance.	→ target impedance tracking	[72]
Tanh-Tanh-Type Control: Simulates the behavior of a nonlinear virtual spring with a saturated dissipative term.	→ reduced deviation between actual and rest position	[69]
Reciprocal-Quadratic-Type Control: Simulates the behavior of a nonlinear virtual spring with a dissipative term, with the control output being inversely proportional to the position deviation.	→ drives the deviation between actual and rest position to zero	[69]
Force Tracking IC: Assuming the knowledge of the external force and environment position, the reference position for the IC is modified.	→ focus on force tracking	[73]
Force Overshoot-free IC: The rest position (and target impedance parameters) are modified online based on environment and base impedance estimations.	→ focus on force tracking → avoid force overshoot	[74–77]
Acceleration-Based Force-IC: An inner acceleration tracking controller is encased by a middle IC loop and an outer nonlinear force control loop.	→ limited contact force → robustness to environment uncertainty	[57]

(*continued on next page*)

Table 7 (*continued*).

Approach	Objective	Ref.
Sliding Mode IC: Variant of (generalized) IC implemented by sliding mode control, possibly extended by disturbance estimation.	→ robustness to model uncertainties, disturbances → stable despite of nonlinear system dynamics	[65,66,78,79]
Robust Compliant Control Using Time Delay Estimation: Time delay estimation with ideal velocity feedback (C1) or modified target damping (C2) or internal model control (C3) suppresses the effects of (dis-) continuous uncertainties in the system dynamics.	→ no system model required (C1-C3) → target impedance tracking (C1, C3) → position tracking (C2)	[80–83]
Pose Improved Stiffness Control: Extension of stiffness control which exploits the redundancy of the manipulator for null-space pose adjustment.	→ optimal stiffness feasibility region → minimal gravity effect → avoid torque saturation	[84]
Object IC: This version of computed torque IC implements the target impedance related to the manipulated object instead of the mechanism's endpoint.	→ multi-robot object handling → object dyn. compensation → weightable load/DOF distribution	[85,86]
Multiple IC: This extended version of object IC establishes a target impedance at the cooperating mechanisms' endpoints and at the commonly manipulated object's level.	→ multi-robot object handling → improved stability → smooth dynamic behavior	[85]
Internal Force-Based IC: Within the computed torque IC approach, the total measured force is replaced by the non-motion-inducing internal force.	→ multi-robot object handling → object dynamics not required	[87]

impedance control and a deduction of a procedure for the controller design are provided in Ott [61] and Boaventura et al. [60]. Yoshikawa [20] mentions a progressive learning method. General recommendations for the impedance controller synthesis can be found in Khalil et al. [23]. The achievable range of the end-effector target impedance and its corresponding feasibility region with respect to X_R are limited by the design of the mechanism, which influences its configuration and actuator boundaries [84] as well as the occurrence of singularities [61].

Impedance control is suitable for small desired impedance levels. Contrarily, the resulting high control gains possibly cause stability issues or conflict with accuracy requirements. Countermeasures are increased friction (implicit) or actuator bandwidth (explicit) [33]. As in constrained space, an end-effector impedance always counteracts an environmental admittance, which converts the incoming sum of forces to a change in motion, multiple parallel impedances even related to different X_R can be superimposed. In free space, impedance control behaves like a motion controller [72]. While in certain cases a model-free implementation might be sufficient [34], target impedance tracking can be improved by a dynamic system model as introduced for example in Yoshikawa [20], Siciliano et al. [41], and Valency et al. [59]. The characteristics of the controller implementation in joint or Cartesian space are discussed in Khalil et al. [23]. In Sharifi et al. [8], a master-slave approach is proposed. In the case of contact with a stiff environment, impedance control can be related to explicit force control [88]. In Table 6 the strengths and weaknesses of impedance control are summarized.

In the following, the special cases $m \in \{0, 1, 2\}$ are considered in more detail. While the general approach theoretically allows for $m > 2$, the reviewed publications do not mention the practical implementation of such higher order impedance controllers. Subsequently, variants of impedance control found in literature are introduced in Table 7. They aim at improvements concerning implementation issues, target position, force and impedance tracking or the intelligent management of system redundancies, loosening system model or F/T measurement requirements, reduced F/T peaks at contact, the generalization of the (linear) impedance concept or its extension to the multi-robot and object handling case. While most previous considerations were related to the control of the end-effector impedance, object handling requires the consideration of not only the external forces which affect the object dynamics, but also of the internal forces, which affect the object's internal stresses [85–87]. This is related to the control of the external impedance between the object and environment and the internal impedance between the end-effector(s) and object [89]. Compared to the other main concepts, the quantity of variants and their objectives is significantly higher, indicating a certain maturity. Nevertheless, the ongoing research interest is revealed by the distributions of publication dates.

$\mathbf{m = 0 \Leftrightarrow I(s) = a_0 = k_D}$:

Impedance control of zeroth order or stiffness control [20,90] has first been mentioned by Salisbury in 1980 [91] and, in its implicit case, is formally equal to a P position controller. k_D then represents the target stiffness which for free motion should be set to a high and for contact cases to a low value [23].

Generally, for (implicit) stiffness control without or with static model-based compensation [21,23,41], force measurement is not required [21]. However, it can be useful for k_D adjustment [21]. Explicit stiffness control shows increased force sensitivity [91]. Moreover, for an emphasis on force control, a feedforward force term can be added [23,48,91].

Stiffness control is less computationally demanding, complex and sensitive to model uncertainties than high-order and dynamic model-based impedance control [23,59], but also possibly reduces stability and accuracy in the explicit case [20]. Implicit stiffness control is passive [92].

$\mathbf{m = 1 \Leftrightarrow I(s) = a_0 + a_1 s = k_D + b_D s}$:

In damping control, the velocity error $\left[\dot{X}_R(s) - \dot{X}(s)\right]$ is fed back multiplied by the target damping coefficient b_D [37]. However, pure damping control can barely be found in the literature. Generally, a stiffness term is added which then results in impedance control of the first order [23,62,90]. In the implicit case, first order

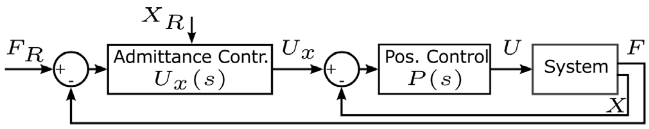

Fig. 8. (Explicit) admittance control scheme [61].

Table 8
Strengths and weaknesses of admittance control [21,33,41,58,59,89,94,95].

⊕ Implements motion/force relation	⊖ No exact tracking of position and force
⊕ Robustness to task uncertainty and changes	⊖ Force measurement required
⊕ System/environment model not required	⊖ Impedance tracking accuracy (compared to impedance control)
⊕ Backdrivability not required	⊖ Stability issues for low target impedances
⊕ Inner position loop: standard feature of industrial robots, free space position tracking, disturbance rejection	
⊕ Physically meaningful parameters ($m \leq 2$)	
⊕ Acceleration not required	

impedance control is formally equal to a PD position controller, possibly extended by a static model-based compensation [93]. Damping has a significant influence on stability. The damping coefficient b_D compensates for natural and induces active damping [90].

$\mathbf{m = 2 \Leftrightarrow I(s) = a_0 + a_1 s + a_2 s^2 = k_D + b_D s +} \boldsymbol{m_D} \mathbf{s^2}$:

Generally, the target impedance can be selected to be of arbitrary order, however, already Hogan [34] stressed the advantages of the second order as thereby, the mass (or interia) dynamics of the system can be manipulated aiming at the target mass m_D (or inertia θ_D), while the parameters a_k remain physically meaningful. Implicit second order impedance control is formally equal to PID velocity control. The discrete formulation is given in Xu [78].

3.5. Admittance control (AC)

Admittance control (AC) which is also called position-based impedance control or impedance control with force feedback is an approach dual to impedance control. As presented by

$$U_x(s) = A(s) \cdot [F(s) - F_R(s)] + X_R(s) \quad \text{with} \quad A(s) = \left(\sum_{k=0}^{m} a_k \cdot s^k \right)^{-1} \tag{5}$$

for the linear case, the mechanical admittance $A(s)$ relates the measured external force $F(s)$ to the reference motion $U_x(s)$ for the inner position control loop. The computation of the reference motion in time domain requires numerical integration.

Admittance control can be implemented explicitly as shown in Fig. 8 or implicitly. For implicit admittance control, the outer force feedback loop is excluded. Therefore, depending on the selection of the inner loop position control law, implicit admittance control is equivalent to implicit impedance control. Hence, implicit admittance control is commonly not considered [33].

Impedance and admittance control distinctly differ in their capabilities to render certain target impedance levels and in the key characteristics of their inner control loop. While for IC a high target impedance level results in high control gains, which possibly cause instability, AC is prone to instability in case of a low target impedance level. For both, IC and AC, a high target impedance level can cause stability issues during contact with a stiff environment. As methods for setting the admittance parameters, the linear quadratic control approach [96] and a learning approach based on the betterment scheme [97] are proposed. Moreover, for impedance control, a compromise between good disturbance rejection and target position tracking accuracy, which require a high stiffness gain k_D, and compliant behavior, which needs a low stiffness gain, has to be found. Admittance control overcomes this conflict due to the inner motion control loop [98], which is a standard feature of industrial robots and has the potential to suppress unwanted influences of the system dynamics such as friction without the requirement of a model. Table 8 summarizes further strengths and weaknesses of admittance control.

The control structure of the inner motion control loop can be selected arbitrarily, but stable [59]. It is further necessary to compute the inner loop with a significantly higher bandwidth than the outer loop [99]. In literature, a broad variety of approaches, ranging from PID control [9,59,94,95,100,101] to more sophisticated concepts [97–99,102], are proposed for combination with admittance control.

Subsequently, the special cases of admittance control with $m \in \{0, 1, 2\}$ are considered in more detail. While the general approach theoretically allows for $m > 2$, the reviewed publications do not mention the practical implementation of such higher order admittance controllers. This is followed by an introduction of the variants of admittance control found in literature in Table 9. They aim at loosening the F/T measurement requirement, an improved target position, force or admittance tracking performance including a suggestion for a compromise for the accuracy/robustness dilemma, solving the stability issue of high target admittances, a generalization of the admittance concept or the extension to a cooperative control of multiple robots. It is worth to remark that all drawbacks listed in Table 8 are addressed by at least one of the variants. Hence, the admittance control approach might be a good option for a compromising, general purpose control.

$\mathbf{m = 0 \Leftrightarrow A(s) = a_0^{-1} = k_D^{-1}}$:

Admittance control of zeroth order or compliance control [42] is the counterpart to stiffness control. The control parameter selection can be related to the system stability [103,104]. Stiffness and compliance control can also be referred to by a generalized spring as in [47] or by artificial or active compliance [37].

$\mathbf{m} = 1 \Leftrightarrow \mathbf{A(s) = (a_0 + a_1 s)^{-1} = (k_D + b_D s)^{-1}}$:

Admittance control of first order or accommodation control [42,58] has already been mentioned by Whitney in 1977 [105]. It is an approach dual to damping control and synonymously named active accommodation or generalized damping [37,47]. Accommodation control is especially relevant for slow motion applications as the inertia characteristics of the closed-loop system are negligible in this case [100]. The system stability has been analyzed by Whitney [104,105] and Ugurlu et al. [9]. A discretized form can be found in [106]. In Tang et al. [5], it is proposed to learn the state-dependent admittance parameters by Gaussian Mixture Regression.

$\mathbf{m = 2 \Leftrightarrow A(s) = (a_0 + a_1 s + a_2 s^2)^{-1} = (k_D + b_D s + m_D s^2)^{-1}}$:

Admittance control of second order allows to manipulate the mass/inertia characteristics of the system. Nevertheless, unlike for impedance control (without force measurement), the computation of the possibly noisy second order derivative of the position measurement can be avoided. In Volpe et al. [94], (second order) admittance control is related to direct force control and their conversion is derived. An instability index can be used to adjust the admittance parameters according to the environment characteristics [6]. Alternatively, conditions which need to be met by the admittance parameters can be derived from passivity criteria [9].

Table 9
Variants of admittance control.

Approach	Objective	Ref.
AC without Force Sensor: The external force is estimated based on a generalized momentum based observer.	→ no force measurement required	[95]
Frequency-Shaped IC: A disturbance observer modifies the apparent target compliance depending on the frequency of the external force.	→ safety, position tracking, robustness to perturbation → no F/T-measurement required	[107]
Instantaneous Model IC: The target impedance is solved for $\ddot{x}_R$, integrated and fed into the inner loop position control. Thereby, the integration is re-initialized to the current state of the manipulator at each time step.	→ tradeoff between robustness to modeling errors (AC) and target impedance tracking accuracy (IC)	[59]
Force/IC with Feedback Linearization: The AC is extended by an exact linearization control loop. The latter computes the reference force for the AC which is required to achieve a desired force. An environment model is needed.	→ force tracking	[108]
Iteratively Learned and Temporally Scaled Force Control: Iterative learning control is applied to modify the target position trajectory for a first order AC.	→ increased execution speed while maintaining target force trajectory	[109]
Natural AC (NAC): The outer first order AC loop undergoes a model-based modification. The inner velocity control loop consists of a target impedance and a proportional admittance tracking error compensation term.	→ passivity including for high admittances	[110,111]
Neuromechanical Control: The virtual model is composed of an antagonistic pair of muscles, represented each by a first order admittance with a parallel contractile element (Voigt's muscle model), connected to an inertial joint. The contractile elements are regulated by a neural network and serve as exciting element.	→ biological analogy	[112]
Admittance Feed Control: The zeroth order admittance is multiplied by a newly introduced time-varying matrix to provide a framework for constrained AC.	→ anisotropic constrained AC	[113,114]
Cooperative AC: Approaches similar to the internal force-based IC and the object IC are combined to achieve internal and external impedance control.	→ multi-robot object handling → geometrically consistent stiffness	[89]

3.6. Compound control

Combinations of the four basic approaches and their variants, as presented in Table 10, generally aim at unifying their strengths, if not indicated otherwise. The first five concepts replace a position or force control loop within hybrid or parallel force/position control by impedance or admittance control, thereby modifying the control objective of this direction. Unified impedance and admittance control is especially interesting to improve stability and performance in the presence of an environment with diverse impedance properties. Nested compliant admittance control focuses on the reduction of geometric misalignment and interaction forces during peg-in-hole tasks. The last approach addresses compliant control of wheeled manipulators.

3.7. Further concepts

Compliant control develops its full potential when the task involves contact scenarios. In Yoshikawa [20] and Volpe et al. [122], special consideration of the transition phase between free and constrained motion is proposed for stable contact. Suggestions include maximal active damping, integral explicit force control, proportional force control with reaction force compensation or with negative gain and feedforward signal or second order impedance control with a large target mass. These considerations might find their way into the improvement of the contact stability of the main concepts.

The approaches related to the four main compliant control concepts reviewed above are prominent in literature; however, it is worth to mention that compliance can also be achieved by learning strategies such as Fuzzy Reinforcement Compliance Control [123] or Dynamic Movement Primitives [124]. A detailed review of learning strategies for compliant control is outside the scope of this paper.

4. Discussion

The chronological order of the above presented findings as well as a comparison with the previous review of Vukobratović [18] indicate a shift of the research interest from the earlier approaches HC and PC to the more recent impedance and admittance control concepts since the beginning of this millennium. This shift is less pronounced for the compound approaches, where HC or PC are combined with IC or AC to unify their strengths. Compared to the other fundamental compliant control concepts, an outstanding amount of variants of IC reflects its continued popularity during the last decades.

A comparative discussion of different approaches reveals important findings concerning the application of HC, PC, IC, and AC for different purposes. (Implicit) impedance control is the

Table 10
Compound control concepts.

Approach	Basic Concepts	Ref.
Hybrid IC: Position- or force-controlled subspaces can be replaced by impedance- or admittance-controlled subspaces, thereby assigning individual target impedances to them.	• HC • IC and/or AC	[17,22,27,115,116]
Unified IC and HC with Kinestatic Filtering: Within HC, position control is replaced by IC. The selection matrix is realized through kinestatic filtering for invariance to reference frame transformations.	• HC • IC	[117]
Force/IC: Certain subspaces of HC can be selected to behave compliantly while their orthogonal counterparts are characterized by force control.	• HC • computed torque IC	[101]
Hybrid NAC/Position Control: Certain subspaces of HC can be selected to behave compliantly while their orthogonal counterparts are characterized by position control.	• HC • NAC	[111]
Parallel Admittance/Position Control: Within the PC framework, the force controller is replaced by AC.	• PC • AC	[118]
Unified IC and AC: Realizes time-based interpolation between IC and AC.	• IC • AC	[119]
Nested Compliant AC: An IC is encased by an AC to estimate the environment position and thereby reduce contact forces and compensate for position misalignment.	• IC • AC	[120]
Whole-Body IC for Wheeled Manipulators: Impedance and admittance controlled subsystems are interconnected with the aim of compliantly whole-body controlling mobile, including nonholonomic, systems.	• IC • AC	[121]

Table 11
Comparison of the main distinguishing features of the basic control concepts and the potential of their variants to improve them (c. stands for control, env. for environment, dom. for dominant, opt. for optimal, and backdriv. for backdrivability).

	HC	PC	IC	AC
C. target	X, F	X, F (dom.)	$I(s)$	$I(s)$
System model	to improve c. performance	to improve c. performance	to improve c. performance	not required
Env. model	required	not required	not required	not required
Task change robustness	no	yes	yes	yes
F/T data required	yes	yes	impl. IC: no expl. IC: yes	yes
Low-level c.	X, F	X, F	F	X
Advantageous contact type	stiff	not specified	stiff	soft
Backdriv. required	no	no	impl. IC: yes expl. IC: no	no
Main potential of variants	low-level F-c. not required, task change robustness, unknown stiffness interaction, non-orthog. subspaces	robustness to sys. model uncertainty, independent X-/F-error dynamics, transient F-tracking	F/T data not required, generalized target $I(s)$, X-tracking, F-tracking, robustness to sys. model uncertainty, opt. feasible k_D region	F/T data not required, X-tracking, F-tracking, stability, generalized target $I(s)$

only approach which can be implemented without force information available. It is especially suitable to render low-impedance tracking with high accuracy if a good system model is provided. Admittance control contrarily is not in need of a model and is suitable for tracking high impedance values. The outer admittance control loop embraces an inner position loop which is a standard feature of industrial robots and equips admittance control with good robustness to disturbances. The control objective of hybrid and parallel force/position control consists in tracking a target force and position instead of a target impedance. Hybrid force/position control divides the working space of the mechanism in force or position controlled subspaces and hence can only be employed for multi-DOF systems and a detailed environment model available. It is especially effective for high stiffness environments as then in the corresponding subspace pure force control can be applied. Table 11 provides a comparison of the main features, which distinguish these control concepts, as well as a summary of the potential of their variants to overcome weaknesses of the basic approaches. A comparing simulative case study applied to the same set of system, task and environment models would provide additional insight into their performance and should be considered in future work. Ideally, such a set would span the entire space of application characteristics. For example, a multi-DOF robotic system operating in a stiff/soft, planar/non-planar, known/uncertain environment with a previously defined/changed task of different complexities might be considered.

Due to the many variants found by the systematic literature research method, the results of Leylavi Shoushtari et al. [31] concerning solutions to the issues of HC and IC have been extended and furthermore, PC and AC were additionally considered in the analysis. This widens the application limitations of compliant control and the basic approaches and sheds further light on their extended performance capabilities. Due to this and due to the broader definition of compliant control involving PC and HC, this review complements the recent overview of Calanca et al. [29] on IC and AC of rigid and fixed-compliance systems and their passivity characteristics.

5. Conclusion

This review presents a comprehensive and concise overview of compliant control. Based on a systematic literature analysis, the general design and characteristics as well as variants and combinations of the four main concepts, i.e., hybrid and parallel force/position control, impedance and admittance control, are analyzed.

The findings are included in a proposed new scheme to facilitate and systematize the selection process of an appropriate control approach. This scheme provides valuable assistance particularly to researchers new to the field to navigate through the multitude of different approaches (Fig. 4). The scheme guides its user to one of the four main concepts which should be seen as a starting point. Subsequently, Tables 3, 5, 7, 9 and 10 summarize the characteristics of the numerous versions, compound approaches and exceptions of the basic concepts which are generally targeted to a specialized aim. Thus, they provide support for further adapting the selection of a specific compliant control method to specific needs.

The main contributions of this review are

(1) a recent review of active compliant control based on an extensive systematic and free literature search providing the reader with the most comprehensive and transparent overview on compliant control that is available today (Section 2.3),
(2) a classification of the very many different approaches developed with respect to the four fundamental concepts (Section 3.2 to 3.7),
(3) a unified and concise summary of the characteristics of these four concepts considering multiple perspectives, and a brief description including objectives of their different variants, combinations, and non-classifiable exceptions (Section 3.2 to 3.7), and
(4) a novel unified selection scheme to support particularly researchers newly entering the field in finding and selecting a compliant control approach suitable for a given task (Section 3.1).

Apart from variable impedance actuation, continuum and soft material robotics are promising future trends to create intrinsic compliance. In such distributed systems, blending passive and active compliance to a desired apparent system compliance poses several new challenges to system dynamics modeling and controller design, which may be tackled by optimization [125–127] or learning methods. Calanca et al. [29] and Ott [61] give an insight on the influence of fixed valued passive compliance in the context of impedance and admittance control. Moreover, the increasing system complexity could possibly raise the relevance of uncertainties and result in increasing robustness requirements. Hence, the review on active compliant control provided in this paper also serves as an important reference and baseline for the emerging field of distributed compliant control where impedance properties are achieved by combinations of passive mechatronic hardware design and active digital control concepts.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A.1 provides a detailed documentation of the systematic literature search.

Table A.1
Documentation of the systematic literature research.

↻	Database	Search terms	Results
1	ScienceDirect	force control AND impedance AND KEYWORDS: (control AND review) AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	6+2[a]
	Web of Science	TOPIC:[b] (force control AND impedance) AND TITLE: (review OR overview) AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	21+2
	IEEEXplore	force control AND (review OR overview) AND AUTHOR KEYWORDS: impedance AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	31+12
	SAGE journals	force control AND (review OR overview) AND KEYWORDS: impedance AND (TIMESPAN(first-2015) OR TIMESPAN(first-2015))	13+17
	WTI Tecfinder	force control AND (review OR overview) AND impedance AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	40+6
	Engineering Village	SUBJECT/TITLE/ABSTRACT: (force control AND (review OR overview) AND impedance) AND CONTROLLED TERM:[c] control AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	37+6
	science.gov	(force control AND (review OR overview) AND impedance AND TIMESPAN(first-2015)) OR ("force control" AND (review OR overview) AND impedance, REFINE: (Topics/Technology/Robotics AND Topics/Research and Development/Robotic AND Topics/Literature Review) AND TIMESPAN(2015-2017))	0+10

(continued on next page)

Table A.1 (*continued*).

⟳	Database	Search terms	Results
2	ScienceDirect	(compliant control AND impedance AND LIMIT-TO (topics, "control") AND LIMIT-TO(topics, "force control, contact, control law, impedance control, contact force, control system") AND TIMESPAN(first-2015)) OR (compliant control AND impedance AND LIMIT-TO (topics, "control") AND LIMIT-TO(topics, "force control, contact, control law, impedance control, control system") AND TIMESPAN(2015-2017))	14+4
	Web of Science	compliant control AND impedance AND force AND stiffness AND NOT series elastic actuator AND NOT soft AND NOT adaptive AND (TIMESPAN(1990-2015) OR TIMESPAN(2015-2017))	48+8
	IEEEXplore	(METADATA[d] ONLY: (compliant control AND impedance) AND AUTHOR KEYWORDS: control AND TIMESPAN(first-2015)) OR (METADATA ONLY: (compliant control AND impedance AND force AND stiffness) AND AUTHOR KEYWORDS: control AND TIMESPAN(2015-2017))	38+13
	SAGE journals	(compliant control AND impedance AND TIMESPAN(first-2015)) OR (compliant control AND impedance AND force AND stiffness AND NOT series elastic actuator AND NOT soft AND TIMESPAN(2015-2017))	31+10
	WTI Tecfinder	(compliant control AND impedance AND force AND TIMESPAN(first-2015)) OR (compliant control AND impedance AND force AND stiffness AND TIMESPAN(2015-2017))	37+3
	Engineering Village	SUBJECT/TITLE/ABSTRACT: (compliant control AND impedance) AND force AND stiffness AND NOT series elastic actuator AND NOT soft AND NOT adaptive AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	39+13
	science.gov	(compliant control AND impedance AND TIMESPAN(first-2015)) OR ("compliant control" AND impedance AND TIMESPAN(2015-2017))	21+4
3	ScienceDirect	compliant control AND admittance AND LIMIT-TO(topics, "control") AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	12+4
	Web of Science	compliant control AND admittance AND force AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	32+9
	IEEEXplore	(METADATA ONLY: (compliant control AND admittance) AND TIMESPAN(first-2015)) OR (METADATA ONLY: (compliant control AND admittance AND force) AND TIMESPAN(2015-2017))	36+9
	SAGE journals	(compliant control AND admittance AND TIMESPAN(first-2015)) OR (compliant control AND admittance AND force AND NOT series elastic actuator AND TIMESPAN(2015-2017))	7+5
	WTI Tecfinder	compliant control AND admittance AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	9+4
	Engineering Village	(SUBJECT/TITLE/ABSTRACT: (compliant control AND admittance) AND TIMESPAN(first-2015)) OR (SUBJECT/TITLE/ABSTRACT: (compliant control AND admittance) AND force AND TIMESPAN(2015-2017))	38+13
	science.gov	(compliant control AND admittance AND TIMESPAN(first-2015)) OR ("compliant control" AND admittance, refine: Topics/Robotic AND TIMESPAN(2015-2017))	4+3
4	ScienceDirect	(("human compatible" OR "human compatibility") AND (TITLE-ABSTR-KEY: control OR LIMIT-TO(topics, "human,robot,cognitive architecture") OR (compliance AND LIMIT-TO(topics, "human,contact"))) AND TIMESPAN(first-2015)) OR (("human compatible" OR "human compatibility") AND (TITLE-ABSTR-KEY: control OR (compliance AND LIMIT-TO(topics, "human,contact"))) AND TIMESPAN(2015-2017))	45+13
	Web of Science	("human compatible" OR "human compatibility") AND control AND safety AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	4+0
	IEEEXplore	("human compatible" OR "human compatibility") AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	11+2
	SAGE journals	("human compatible" OR "human compatibility") AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	21+5
	WTI Tecfinder	("human compatible" OR "human compatibility") AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	4+2
	Engineering Village	("human compatible" OR "human compatibility") AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	43+8
	science.gov	("human compatible control" AND compliance AND TIMESPAN(first-2015)) OR ("human compatible control" AND compliance, REFINE: Topics/Human Factors AND TIMESPAN(2015-2017))	9+0
5	ScienceDirect	TITLE-ABSTR-KEY(active compliance AND control AND force) AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	24+8
	Web of Science	("active compliance" OR "passive compliance") AND control AND force AND (impedance OR admittance) AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	19+5

(*continued on next page*)

Table A.1 (*continued*).

	Database	Search terms	Results
	IEEEXplore	(((“DOCUMENT TITLE”: (“active compliance” OR “passive compliance”)) OR “ABSTRACT”: (“active compliance” OR “passive compliance”)) OR “AUTHOR KEYWORDS”: (“active compliance” OR “passive compliance”)) AND METADATA ONLY: (control AND force) AND SEARCH WITHIN RESULTS: (impedance OR admittance) AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	17+7
	SAGE journals	TITLE: (“active compliance” OR “passive compliance”) OR ABSTRACT: (“active compliance” OR “passive compliance”) OR KEYWORDS: (“active compliance” OR “passive compliance”) AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	18+5
	WTI Tecfinder	(“active compliance” OR “passive compliance”) AND control AND “force control” AND (TIMESPAN(first-2015) OR TIMESPAN(2015-2017))	24+1
	Engineering Village	(SUBJECT/TITLE/ABSTRACT: (“active compliance” OR “passive compliance”) AND control AND force AND (impedance OR admittance) AND TIMESPAN(first-2015)) OR (SUBJECT/TITLE/ABSTRACT: (“active compliance” OR “passive compliance”) AND control AND “force control” AND (impedance OR admittance) AND TIMESPAN(2015-2017))	16+6
	science.gov	(active compliance AND control AND force AND TIMESPAN(first-2015)) OR (“active compliance” AND control AND force, REFINE: (Topics/Control System/Control Strategy AND Topics/Robotic AND Topics/Human Factors) AND TIMESPAN(2015-2017))	36+8
Total results:			**1032**

[a]The first addend refers to the number of findings for the time span until 2015, the second addend to the number of findings for the time span between 2015 and 2017.
[b]Includes title, abstract, author keywords and keywords plus.
[c]Subject term which describes the content of a document in the most specific and consistent way possible.
[d]Includes abstract, index terms and bibliographic citation data (title, publication title, author, etc.).

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