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SURVEY

Engineering and Technology Applications of Control Co-Design: A Survey

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ABSTRACT Control-inspired design, as the name suggests, involves drawing inspiration from control theory to design other engineering systems. Engineers may use the principles of feedback control to design systems that can adapt and self-correct in response to changing conditions. This technique is known as Control Co-design (CCD), and it focuses on the redesign of dynamics and subsystem interactions. CCD offers several benefits, such as improved performance, reduced design time and cost, and increased reliability, and has been applied to a variety of areas. In this paper, we present a review of 197 articles related to CCD and highlight the main topics of its applications, such as renewable energy, vehicular and aircraft control systems and communication systems in control. We delimit the applications of CCD in the field of engineering, providing an introductory understanding of this topic and presenting the main works developed in this field in recent years, as well as discussing the tendencies and benefits of CCD. The paper offers an in-depth conceptualisation of CCD. A theoretical example is provided to illustrate CCD's application in a Hybrid Wind-Wave Platform (HWWP), detailing the interaction between aerodynamic and hydrodynamic design domains and their control challenges, along with discussions on simultaneous and nested CCD formulations.

INDEX TERMS Control co-design, control parallel engineering, renewable energy, networked control systems, vehicular control systems.

I. INTRODUCTION

In engineering control system, designing a controller involves selecting a fitting control approach, analysing the system's dynamics, and determining the controller's parameters. The controller's design should take into account various factors such as the system's stability, performance, and robustness to uncertainties and disturbances. Proportional-integral-derivative control (PID), model predictive control (MPC) and adaptive control are some commonly used control strategies. The controller's design plays a crucial role in determining the system's response and performance under various operating conditions, and usually is designed in a sequential approach. It basically means, that the controller usually is the last step developed in a project.

A novel approach considers the optimisation of both the system and the controller from the initial design stages. Optimising the control system and the physical system together could result in enhanced system performance and increased efficiency. Additionally, it could lead to a reduction in the cost of system realisation as the new system could be less complex, require fewer resources and be more reliable. This approach is known as control co-design (CCD) and has been compared to the traditional approach across a variety of control technique sub-areas, including state feedback [1], robust control [2], PID [3], fuzzy control [4], [5], MPC [6], [7]

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event-triggered control (ETC) [8], [9], among others. Thus, CCD refers to an approach for designing and optimising control systems that consider the interplay between the control system and the physical system it regulates.

The historical development of CCD has evolved through several key phases, each marked by significant advances in theory and methodology [10]: During the 1980s and 1990s, the groundwork for integrated design methods was laid, characterised by Control Structure Interaction (CSI) and the ongoing Multidisciplinary Design Optimisation (MDO) [11]. Initial research into CCD began to gain traction in the late 1990s and early 2000s, focusing on the development of theories and methods that often relied on unidirectional design coupling and Linear Quadratic Regulator/Gaussian (LQR/G) control strategies. However, these early models could not fully address complex plant design considerations. More recently, Direct Transcription (DT), which is a class of discretize-then-optimise optimal control methods, was incorporated into the CCD formulation [12]. Then, the CCD theory was revised to cater to bi-directional problem-solving, which enhanced the robustness and applicability of the method [13].

Recent applications of CCD include drones [14], edge computing [15], microfluidic biochips [16], [17], [18], cyber security [19], robotics [20], [21], system decarbonization [22], electric vehicles [23], [24], among others. This elucidates the enormous range of works developed and how CCD has found numerous applications in various fields in recent years.

In [25] a strategic vision for the future of control systems was outlined, identifying several key sectors where these systems could significantly influence outcomes in the coming years. It suggests that adopting co-design and model reduction techniques could promote advancements, emphasising collaborative efforts in design processes and streamlined modelling as essential steps toward progress in this field.

One area of vast application and increasing interest is renewable energy, with emphasis on technologies involving offshore energy generation, which is an emerging field with great potential for development and is discussed in this paper. Another example of a field with many co-design applications is communication in control systems (networked control systems (NCS)), embedded systems in automobiles and aircraft, as well as in others electrical and mechanical frameworks, which we also discuss in this paper. However, the application is not restricted to these areas, instead, the technique has been applied to a wide variety of other systems, showing its numerous benefits. Nevertheless, There is a lack of works that summarise this range of different applications.

To the best of the authors' knowledge, only three reviews have been written on CCD: The first one addresses the control co-design of wind turbines [26], a second review focuses on control and communication scheduling CCD for NCS [27], and the last one [28] explores the various tools available for control co-design applications.

In the first review [26], Pao et al. deliver a summary of the latest advancements in CCD for wind turbines (WT), covering design goals and limitations, the critical role of modelling for precise performance forecasting, and how control mechanisms are seamlessly incorporated through CCD. A particular focus is on refining design parameters to lower the Levelized Cost of Energy (LCOE). It also addresses advanced control techniques such as baseline control, peak shaving, individual pitch control, and floating feedback. These control methods are adeptly into the CCD framework. The document further investigates the present and future of modelling codes and software tools for CCD in wind turbines, highlighting the significance of open-source platforms and the exciting prospects for advancements in automation, machine learning, and artificial intelligence to make the CCD process more efficient. Additionally, it considers the potential for extending CCD to optimise wind farm layouts and to facilitate the integration with other forms of renewable energy. However, the referred work limits itself only to the world of wind turbines.

In the second paper [27], Lu and Guo review advancements in control and scheduling co-design for NCS, focusing on various scheduling schemes: static, dynamic, and random. They discuss challenges such as communication constraints and propose solutions like event-triggered communication and transmission power control. They also highlight hybrid scheduling techniques, address communication issues like packet dropouts, design practical communication protocols, explore computation-control co-design, and develop application-specific designs for systems like vehicular networks, as topics for future research. The review emphasises the need for innovative approaches to enhance system efficiency and robustness against disturbances and cyber-attacks. However, the review once again encompasses only the specific field of NCS.

Torngren et al. [28] compares different tools for CCD, aiding in understanding their capabilities, limitations, and unique features. It also evaluates whether the tools are oriented towards analysis or synthesis, facilitating the selection of the most suitable tool for specific applications. This foundational work laid the groundwork for subsequent advancements in the field, although more recent studies are necessary.

In the present work, unlike previous reviews, we address the control codesign theme more broadly, elucidating each field of application and highlighting the main commonalities, divergences, and advantages of CCD in each of these fields. The motivation for writing this new review article stems from the distinctiveness of its references compared to previous reviews. A thorough comparison of the citations reveals that this latest review incorporates 124 references not previously explored in earlier works. This significant divergence highlights the progression of research and the necessity of a new paper summarising advancements in the research topic. Thus, this work delimits the applications of CCD in the field of engineering and technology, providing an introductory understanding of this topic and also presenting the main works developed in this field in recent years, allowing one to understand the variety of applications and the benefits that these applications have experienced through CCD.

The novelty of this article lies in its interdisciplinary approach, rather than focusing on a single field as previous reviews have done. Additionally, it charts the evolution of CCD theory and methodologies, demonstrating how they have matured to address dynamic challenges across various engineering and technological domains. The survey elucidates strategic visions for future control systems, emphasising the impact of CCD on sectors such as renewable energy and vehicular control systems, and highlights the potential advancements achievable through collaborative design processes.

The contributions of this paper are summarised as follows:

- The paper offers an in-depth conceptualisation of CCD, drawing on a range of works from the literature to provide a nuanced understanding (Section II).
- The role of CCD in renewable energy systems is explored in detail, with a focus on its application to floating offshore wind turbines and wave energy converters, including the challenges faced and progress made (Section III).
- An analysis of CCD in NCS is provided, particularly its integration within control engineering to address constraints such as network delays and packet dropouts (Section III).
- CCD's application in the automotive and aerospace sectors is examined, with highlights on innovations in vehicular platoons and active suspension systems (Section III).
- The paper extends its exploration of CCD to include applications in other domains, such as robotic arms, building energy systems, and complex mechanical systems, showcasing its versatility (Section III).
- A theoretical example is provided to illustrate CCD's application in a Hybrid Wind-Wave Platform (HWWP), detailing the interaction between aerodynamic and hydrodynamic design domains and their control challenges, along with discussions on simultaneous and nested CCD formulations (Section IV).
- The significance of the findings from the reviewed literature is discussed, summarising the trends, advantages, challenges, and potential of CCD across the various domains covered (Section IV).
- Finally, the authors offer a summary of the insights garnered from the survey, emphasising the impact of CCD on engineering design and proposing directions for future research (Section V).

II. CONTROL CO-DESIGN: INITIAL CONCEPTS

Garcia-Sanz [29] presents the Wright brothers and Charles Brush as the pioneers of CCD. Their revolutionary projects, the first heavier-than-air powered aeroplane and the first successful automatic wind turbine, respectively, showed how a redesign in the structure of a general plant can lead to a different and simpler strategy of control and achieve better results in the project objectives. Thus, co-design is defined as an emerging field that aims to integrate control engineering with other design disciplines such as mechanical, electrical, and software engineering. The author argues that CCD has the potential to revolutionise the engineering industry by improving the efficiency and effectiveness of the design process.

According to Garcia-Sanz, CCD is usually delimited by co-optimisation, co-simulation, and control-inspired paradigms, as shown in Figure 1. Co-optimisation involves optimising both the control system and the physical system simultaneously, rather than optimising them separately as in traditional design processes. This approach can lead to improved system performance and reduced design time. Co-simulation is another technique that involves simulating both the control system and the physical system together, allowing engineers to test and optimise the system as a whole. This approach can help identify potential issues and improve system performance. Control-inspired design, as the name suggests, involves drawing inspiration from control theory to design other engineering systems. For example, engineers may use the principles of feedback control to design systems that can adapt and self-correct in response to changing conditions.

Control co-design is more suitable for systems with high dynamic coupling, therefore, it is not common to encounter applicability in non-complex systems in the literature. Therefore, some examples of CCD applied to systems with high dynamic complexity include satellites [30], control of vehicular platoons [31], [32], [33], [34], vehicular suspension [35], robotics [36], [37], and aircraft [38], [39]. The methodology has gained significant attention within the wind and hydro-kinetic systems research programs funded by the Department of Energy's Advanced Research Projects Agency (ARPA-E) [40]. Figure 2 highlights the potential areas to apply control co-design according with ARPA-E initiative.

The CCD approach can be summarised by three model-based strategies: iterative, simultaneous, and nested [41], [42]. The iterative approach optimises the plant design by initially keeping the control design fixed. It then optimises the control design based on the selected plant design, and this process is repeated until convergence is achieved or the design objectives are satisfied. The simultaneous approach encompasses all dynamic system-control interactions within a single optimisation model. The nested approach, often known as bi-level optimisation, consists of an outer optimisation loop responsible for selecting optimal system parameters. Within this loop, there is an inner optimisation loop that determines the optimal control for each feasible system configuration chosen by the outer loop. In contrast to the sequential approach, any of these co-design

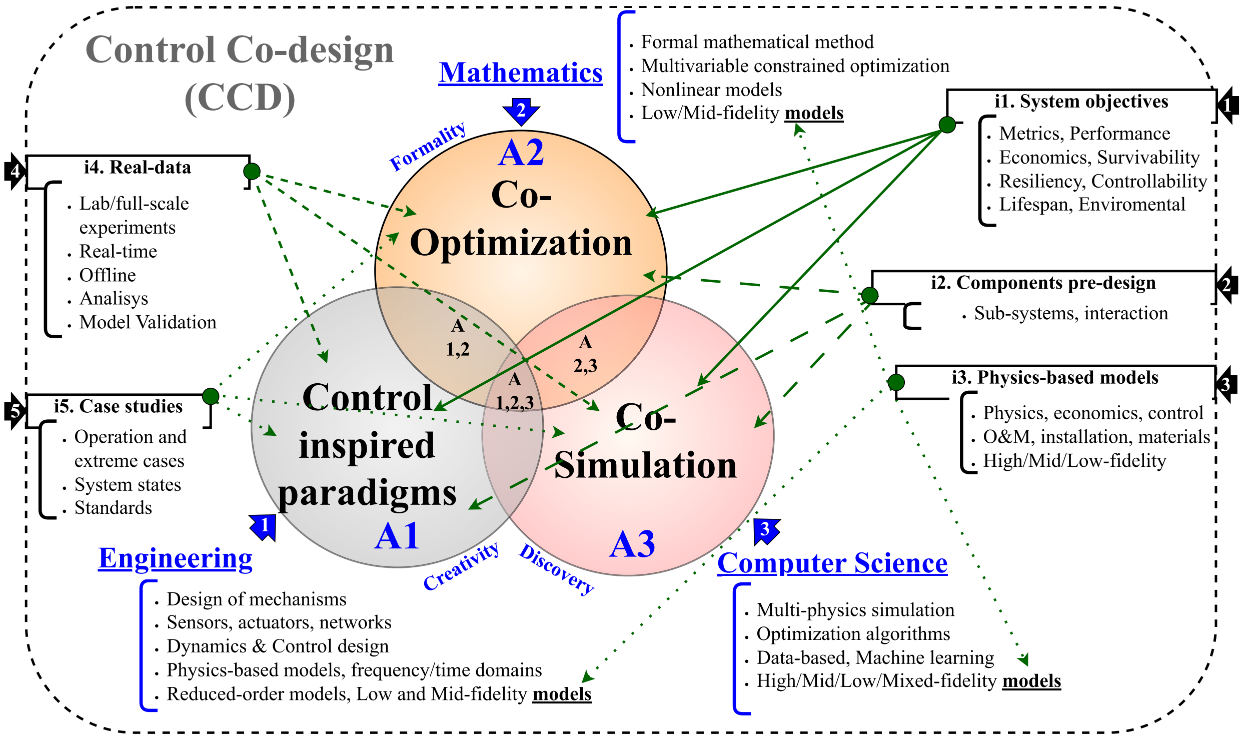


FIGURE 1. **Control Co-Design areas: control-inspired paradigms, co-optimisation, co-simulation. First area (A1) proposes new design solutions based on a practical engineering understanding of dynamics and control. Second area (A2) uses a formal mathematical methodology with nonlinear low/mid-fidelity models and multi-variable constrained optimisation theory. Finally, third area (A3) uses multi-scale, multi-physics, high/mixed-fidelity dynamic models in an iterative simulation process.** ***Source: Adapted from [29] (open access).***

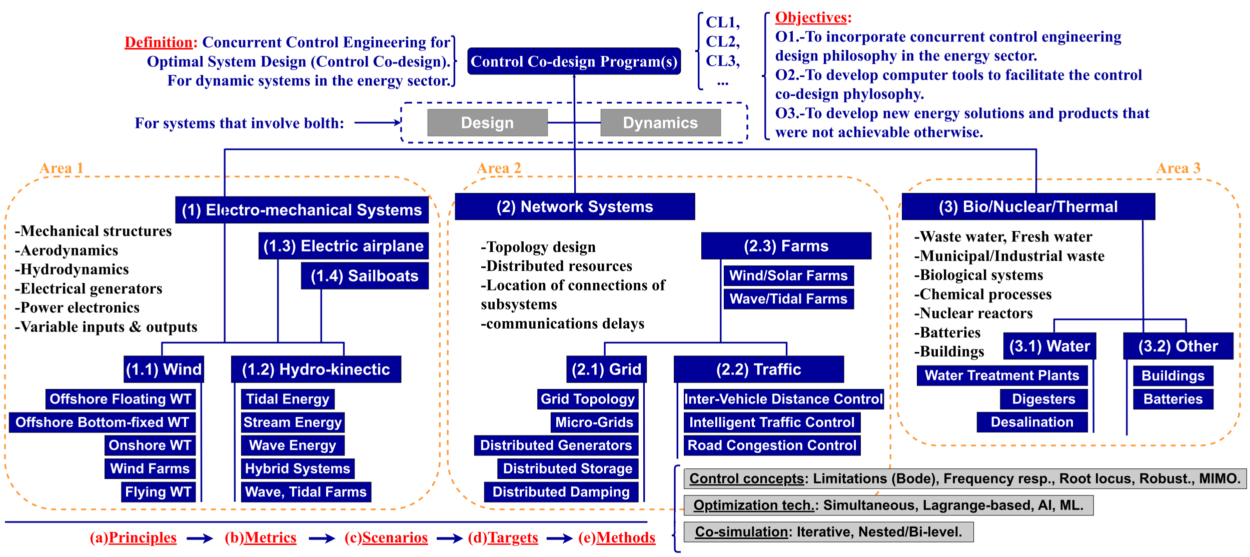


FIGURE 2. **Potential areas to apply control co-design. Systems that possess substantial dynamic characteristics and involve the interaction of mechanical, electrical, aerodynamics, and hydrodynamics subsystems are ideal candidates for control co-design optimisation.** ***Source: Adapted from [40] (open access).***

methods solve the system and control design optimisation concurrently, incorporating bidirectional coupling. As a result, they offer system-level optimally guarantees for the designs.

Although several well-developed approaches in control exist with a huge range of applicability, these approaches sometimes do not consider the optimisation of subsystems. On the other hand, CCD focuses on the redesign of dynamics and subsystem interactions. Frequently, control systems are designed as a sequential process, where the best control strategy is chosen, applied, and the controller is designed only after the system has been modelled. In this new strategy, a sequential approach can still be applied, but the control problem is considered from the first steps of the project to achieve better results and a more suitable control system. A key aspect of this strategy is to identify how the dynamics of subsystems interact in a specific case study and establish a simplification of these interactions, meaning that each interaction is optimised to increase controllability, energy consumption, general performance, and lead the system to the desired state.

An example of co-design is presented in [43], where the authors indicate that a common approach to modelling nonlinear systems is by using linear approximation and adding nonlinear terms. In this paper, the authors suggest a more suitable linear approximation to model a wave energy converter (WEC) and a power take-off (PTO) by applying a co-design strategy. Then, the authors show how the mathematical parameters of the new model allow for a better understanding of the system and how it is possible to alter the design to achieve higher overall performance in terms of energy conversion in the WEC. Generally, a CCD solution applies the same strategy of altering the design formulation and modelling to allow for better understanding of a real system. Then, by changing those parameters, simulating the results of the model, and choosing the best parameters based on the best results, changes can be proposed to the real system. The final effect of these changes is that they can allow for better control of a complex system.

However, it is important to highlight that a theoretical approach does not always match with physical realisation. Both the control strategy and the design parameters must be analysed with a real application overview. In other words, physical constraints must be considered, and the most suitable control method must be determined for real applications. Example of this approach is described by Coe et al. [44], where the authors illustrate an optimisation process for a WEC, shown in Figure 3. In that paper, an experimental WEC called ''WaveBot'' was proposed, and the co-design process was elucidated by varying some parameters of the WEC such as the outer radios, the maximum PTO force exerted in the WEC, and the maximum PTO stroke (the maximum displacement position of the WEC). The authors proposed a case study with three approaches: first, a comparison of three control types (Complex Conjugate Control, Proportional Damping, and Pseudo-Spectral controllers) using the same WEC design; second, by proposing an objective function that evaluates the relation between the average generated power and the WEC volume (and, consequently, the outer radios); and finally, a multi-objective design approach where, in addition to the parameters considered in the previous case, the PTO stroke was also considered, and only a Pseudo-Spectral controller was employed. The authors highlight how physical constraints must be designated to the parameters in the theoretical model to achieve realistic outcomes. They also show how one objective function delimited in that paper was strongly tied to the chosen controller, leading to the conclusion of the importance of CCD, where the design of the controller is conceived in parallel with the full system.

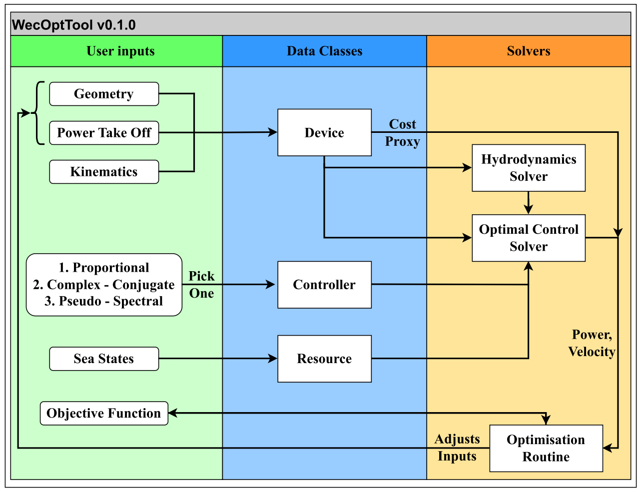


FIGURE 3. Schematic of data flow used in [44] to determine an optimal control co-design. The flow from left to right defines the necessary user inputs, how those inputs are mapped to the solvers to determine an optimal design. The system is subject to constraints that reflect a real environment, and the measurement of the outputs determines the parameters for the optimisation process. These parameters are then fed back into the system, which operates on the geometry. As a result, the system is redesigned until it reaches an optimal point. *Source: Redrawn from [44] (open access).*

In summary, the traditional approach often results in suboptimal control systems that do not fully exploit the capabilities of the mechanical or electrical system. Control co-design, on the other hand, offers several benefits, such as improved performance, reduced design time and cost, and increased reliability. However, there are challenges that need to be addressed to fully realise the potential of CCD, such as the need for interdisciplinary collaboration and the development of new design tools and methodologies. Nevertheless, CCD has the potential to significantly improve the way we design and build complex systems.

III. DISCUSSION

Some articles elucidate methods of optimisation and approach the general theory of control in a manner that allows a comparison between control techniques applied alone and together with CCD. In these articles, the author sometimes utilises benchmark systems to demonstrate the efficacy of CCD, but usually approaches the theme in a more general way. Examples include CCD applied to stochastic systems [45], [46], control systems with time delay [47], switching control systems [48], [49], educational approaches in control [50], scheduling control models [51], [52], [53], optimisation [54], [55], [56], robust control [57], [58], [59], [60] and MPC techniques [61], [62]. On the other hand, the majority of articles are applied to specific fields, which allows for more specific categorisation due to the huge number of articles in these fields. This section discusses and summarises the main works in five areas, namely: renewable energy systems, communications in control systems, vehicular and aircraft systems and other mechanical and electrical systems.

A. RENEWABLE ENERGY

Due to the great potential of offshore wind and wave energy, these types of energy have experienced significant research and practical implementation in recent years. However, the majority of wind and wave energy potential is associated with areas that are more than 60 meters deep in the ocean, making fixed-bottom wind turbines and structures unsuitable while floating platforms are more appropriate. One of the problems with floating offshore wind/wave platforms is the control of motion and its impact on energy generation and the structure's stability, which constitutes a 6-degree-of-freedom control problem. Due to the intrinsic complexity of both types of energy, they have been investigated under the co-design approach. Furthermore, the dynamics of waves and winds are nonlinear and time-varying, and the alteration of speed and direction produces a high degree of uncertainty that leads to difficulties in prediction and forecasting. This results in complexity in the control strategy.

The literature is rich in applications of CCD for renewable energy. Most examples consider floating offshore wind turbines (FOWTs) [63], [64], wave energy converters (WECs) [65], [66], ocean kites [67], and ocean current turbines [68]. Some studies applied to FOWTs consider the control of variable-speed, yaw, and tuned mass damping. On the other hand, WEC control focuses on maximising the power conversion ratio. The objectives of the co-design approach usually aim to increase energy efficiency, reduce the weight of structures, increase energy capture, and minimize the LCOE [69], [70], [71].

For example, Figure 4 shows the paradigms of control co-design applied to a WEC. The design of the WEC, including its geometry, mooring system configuration, and storage technology, is considered alongside constraints from the PTO system. The CCD process begins with parameter selection, which is then specified and applied in the control design of the WEC. If the result is not the overall optimal system, the parameter values are updated, and the process iterates. The control design is influenced by sea states, WEC geometry, and the mooring system, underlining the importance of a holistic design approach that considers the dynamic interactions between the WEC's physical design and its control system. This integrative approach aims to optimise the performance and efficiency of the WEC by aligning the control strategies with the structural and operational aspects from the outset.

Pao et al. [70] apply co-design to reduce the LCOE by 25% for a 13 MW wind turbine energy generation system. Starting from a well-known turbine, the authors demonstrate the impact of modifying the design or configuration of some key components of the system, such as the number of blades in a turbine, the length, and slimness of the blades, the shape, and angle of the blades, the direction of the turbine (upwind or downwind) and the aeroelastic adaptivity of the system. The results show that reducing the mass of the rotor by 25% represents a reduction in the LCOE by 7%. The previous modifications, combined with longer blades, lead to achieving the 25% total reduction in LCOE. Also, it was noticed that increasing the rotor size by the same rating generation can contribute to a reduction in the LCOE. Furthermore, there is a trade-off between using a lower axial induction rotor with bigger and slimmer blades (leading to a reduction in LCOE) and the power generation.

Sundarrajan et al. [71] proposes an open-loop CCD methodology for FOWTs using linear parameter-varying (LPV) models. The LPV models are used to capture the nonlinear and time-varying dynamics of the FOWT system, and the co-design approach optimises the control design and system parameters simultaneously. The proposed methodology is demonstrated on a 5 MW FOWT model, and the results show improved performance compared to a conventional controller design. The results show that it is possible to improve the performance and reduce the structural loads of FOWTs. It also demonstrates that the LPV-based CCD approach can effectively mitigate the impact of environmental disturbances and reduce the fatigue loads on the FOWT structure.

Usually, control strategies consider non-causalities by estimating future incoming waves. However, Bacelli and Coe [43] present another strategy based on a simple PI controller or a broader feedback resonating (FBR) to approximate the non-causal complex conjugate control of a limited frequency range. Instead of approaching the problem of maximisation of power through the typical approach, where mechanical power is tentatively maximised, this paper focuses on presenting a method that combines the intrinsic mechanical impedance of the system with the dynamic model of the PTO. While common approaches could lead to net negative absorption of power, where more power is dissipated than absorbed due to the effects of reactive power, the method presented in this paper prevents the referred effect by taking into consideration the intrinsic characteristics of the power takeoff, i.e., the losses in the PTO. The result is a mathematical modelling of the PTO using the maximum power transfer approach, where the mathematical parameters of the model could easily indicate how to modify the design of the PTO to achieve higher overall performance in the amount of energy conversion problem.

Some articles discuss CCD approaches for wind turbines, with a focus on improving system reliability and performance. The authors in [72] focus on improving wind turbine performance by finding an optimal balance between tower thickness and blade pitch control. The authors develop a model-based optimisation algorithm that accounts for wind turbine dynamics and constraints, such as fatigue and load limits. Through simulation studies, they demonstrate that

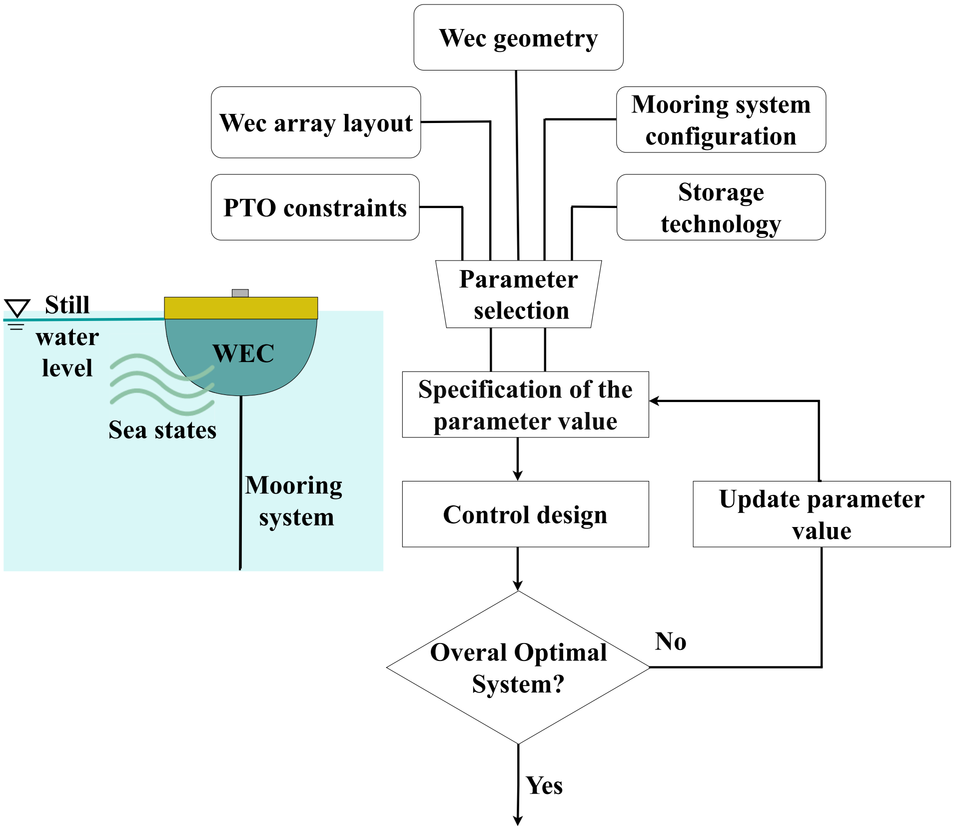


FIGURE 4. Paradigms of control co-design applied to a WEC. *Source: Elaborated by the authors.*

their co-design approach can lead to significant improvements in power output and reduction in structural loads, compared to existing designs. Cui et al. [73] propose a CCD framework for horizontal axis wind turbines. The approach utilises models to optimise the control design and ensure operation under various conditions. In contrast, the article by Du et al. [74] focuses on the co-design of rotor blades for FOWTs. The proposed approach considers both aerodynamic and structural performance to optimise the rotor blade design and control system.

Both papers [75] and [76] exemplify the use of CCD to optimise the design of hydrokinetic turbines in order to maximise power output. The first article proposes to optimise the design of the turbine blades and control system by emphasising the hydrodynamics and structural mechanics of the system, using open-loop optimal control to maximise power output. In contrast, the second article focuses on CCD by adjusting the buoyancy of the turbine. The authors use a nested optimisation strategy that considers both the spatial and temporal dynamics of the system. In both cases, CCD was essential for improving the performance of hydrokinetic turbines and making them more economically viable. It also allowed for more efficient and effective control of the turbine, leading to increased power output and making them more competitive and viable for widespread use.

Finally, two other different applications for co-design are in the possibility of decarbonization and in the optimisation of a system for the production of water and electricity. Ilić and Carvalho [77] highlight the importance of co-design in enabling the integration of flexible and interactive electricity services, which is essential for decarbonizing the energy sector. The authors argue that traditional hierarchical control systems are not suited for the integration of distributed energy resources and demand-side management. Therefore, the development of co-design methodologies is necessary to achieve a more flexible and interactive electricity system. Meanwhile, Gambier et al. [78] emphasise the importance of co-design in optimising the operation of integrated water and energy systems, specifically in a European project. The authors were able to develop an integrated control system that optimises the operation of a combined hydroelectric power and water supply system.

B. COMMUNICATIONS IN CONTROL SYSTEMS

This section provides an overview of several recent articles in the application of CCD for networked and wireless systems, highlighting their contributions to the field and discussing how they relate to one another. The study of NCS and communication control has seen an increase in interest recently. According to Zhang and Hristu-Varsakelis [79] and Zibao and Ge [80], one of the most important factors in ensuring the effectiveness and stability of NCS is the co-design of communication and control strategies. It has been found that designing resilient control strategies with modulation and scheduling control tasks are particularly effective ways to boost the efficiency and dependability of NCS. An illustration of a control loop for use in communication systems can be found in Figure 5.

According to Zhao and Ji [81], an innovative method called model-reference scheduling and CCD with two routes has been developed as a way to maximise both the scheduling of control tasks and the design of control strategies at the same time. The authors propose a two-path model-reference scheduling and CCD framework. In this framework, the communication network is divided into two paths: a direct path for high-priority control tasks and a relay path for low-priority control tasks. The authors suggest using the direct path for high-priority control tasks. The authors demonstrate that the suggested method may achieve greater performance in comparison to conventional methods by taking into account the trade-off between control performance and communication restrictions.

Resilient CCD with modulation has also been shown to increase networked control system reliability [82]. The referred paper presents a model reference scheduling CCD framework with modulation schedules control tasks based on the modulation scheme to improve communication failure resilience. Simulations and experiments prove the strategy works. In addition, scheduling strategy design frameworks have also been presented to handle cyber-physical systems (CPS) with non-negligible propagation delay [83]. The propagation delay in the communication network may considerably impact the performance and stability of NCS, hence the authors suggest a scheduling strategy design approach that accounts for it. The suggested framework offers a systematic way to designing scheduling techniques that reduce propagation delay's influence on system performance.

A developing area called cooperative control of CPS attempts to maximise the effectiveness and performance of CPS by coordinating the activities of many actors. The integration of sensing and control in industrial cyber-physical systems (ICPS) has been significantly aided by edge computing technologies [84]. Furthermore, there are several aspects of CCD in the context of CPS and ICPS cooperative control, such as:

- Resource allocation: The DRUID-NET framework was suggested by Dechouniotis et al. [85] for allocating edge computing resources in dynamic networks. The framework includes methods from graph theory, machine learning, contemporary control theory, and network theory in addition to dynamic modelling of resources, workload, and networking environment. To provide clearly stated Quality of Service (QoS) measures, the authors seek to create unique resource allocation algorithms that explicitly take service differentiation and context-awareness into account.
- Scheduling: Choosing the time and sequence of various agents' activities inside a cooperative system is known as scheduling. A dynamic scheduling and CCD technique based on binary sequences was put out by Wen et al. [86] in their paper for CPS. In this method, scheduling choices are represented as binary sequences, and control algorithms and scheduling decisions are collaboratively designed to maximise system performance.
- Decision-making: For probabilistic Boolean control networks, Acernese et al. [87] developed a model-free self-triggered CCD technique. The method makes use of a self-triggered mechanism that decides when to update the control choices, as well as a model-free control strategy that updates control decisions based on system measurements. The authors demonstrated that even in the face of uncertainties and disruptions, the suggested technique may provide the desired system behaviour.

Another crucial consideration while developing edge sensing and control algorithms for the ICPS, is observability. Observability is often taken for granted as a need for later sensing and control systems in current works. Yet, it gets increasingly difficult to explicitly meet the observability requirement in sensing architecture as the network size increases. An observability guaranteed method (OGM) for edge sensing and CCD has been suggested as a solution to this problem [15].

Several studies have been published that use diverse methodologies to investigate various elements of networked stabilisation and system stability. In this context, we separate three articles that help to understand how CCD can be used in multi-input systems. First, Chen et al. [88] suggested a networked stabilisation strategy for multi-input systems across shared channels with scheduling/CCD. The authors suggested a unique co-design technique that optimises the scheduling of data packets and the control input simultaneously, with the goal of minimising network-induced delays and improving system stability. In a related work, Srazhidinov et al. [89] investigated the stability of discrete-time single-input single-output (SISO) systems employing multiple-input multiple-output (MIMO). Furthermore, Chen et al. [90] addressed the stability of networked multi-input systems via a common bus. The authors introduced a collaborative optimisation approach with the goal of reducing network-induced delays and improving system stability.

1) WIRELESS SYSTEMS

In order to solve the communication and control requirements of wireless edge industrial systems, the article [91] suggests a co-design method. The author makes the case that conventional designs that treat communication and control as distinct issues can result in unstable operations. As shown by various case studies, the suggested co-design method takes both communication and control requirements into account at the outset, which improves performance and stability. The same is true for Ma et al. [92], who propose

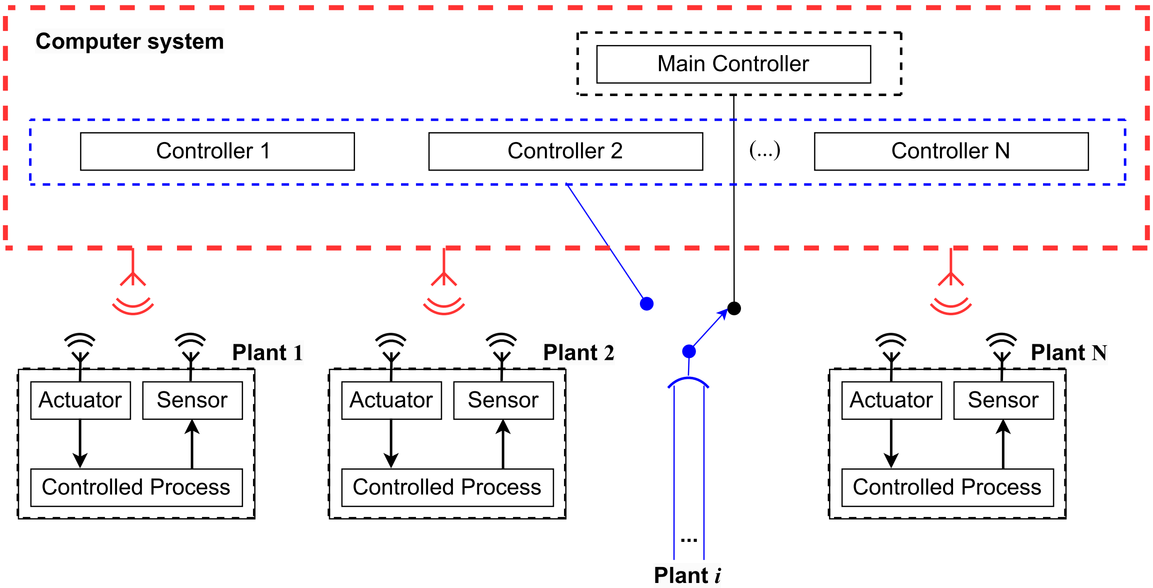


FIGURE 5. **A wireless communication network-controlled computer system for controlling *N* plants. This computer system acts as a remote controller, providing each plant with a control input upon the arrival of sensor data. It can incorporate either a single main controller or *N* individual controllers for *N* distinct plants. *Source: Elaborated by the authors.***

a smart actuation framework that combines edge computing, wireless connectivity, and machine learning to enhance the performance of end-edge industrial control systems. The authors contend that centralised control, which is what traditional control systems rely on, can be ineffective and prone to failure because of network congestion, delays, or other problems. Additionally, they offer a case study of a smart actuation system for a robotic arm to show how their method works in practise by cutting down on control latency and enhancing system stability.

The topic of rate selection in wireless control systems is discussed by Saifullah et al. [93] in their paper titled "*Near Optimal Rate Selection for Wireless Control Systems*" in a related article. The authors suggest a nearly ideal rate selection algorithm that considers both the system's control requirements and the communication channel's features. The suggested technique employs a combined optimisation strategy to choose the ideal rate that maximises control performance while requiring the fewest amount of communication resources. Through simulations and experiments, the authors explain how their strategy is effective and how it outperforms current rate selection methods.

Chen et al. [94], employing MIMO transceivers with pure fading subchannels, established a majorization criterion for the stabilizability of MIMO systems. The authors demonstrated how a MIMO transceiver with only fading subchannels can be used to create a MIMO stabilizable system. For wireless sensor networked control systems (WSNCS), communication and CCD were examined in [95]. The authors provided a design framework for the WSNCS that includes a routing algorithm and the best possible power allocation. The scheduling-event-control co-design issue for hybrid event-time-triggered networked control systems was addressed in [96]. They put forth a scheduling technique that considers both communication resource usage and control performance.

A utilisation-based schedulability study for wireless sensor-actuator networks (WSANs) was created by Ismail et al. [97]. The suggested method can guarantee that the necessary control tasks are finished by the deadlines while accommodating the limitations on communication resources. Mady et al. [98] also describes the key elements of the suggested approach, such as the user interface, the optimisation algorithms, and the WSAN design model. The strategy is shown to be beneficial in raising a building's energy efficiency and comfort levels by the authors' presentation of a case study.

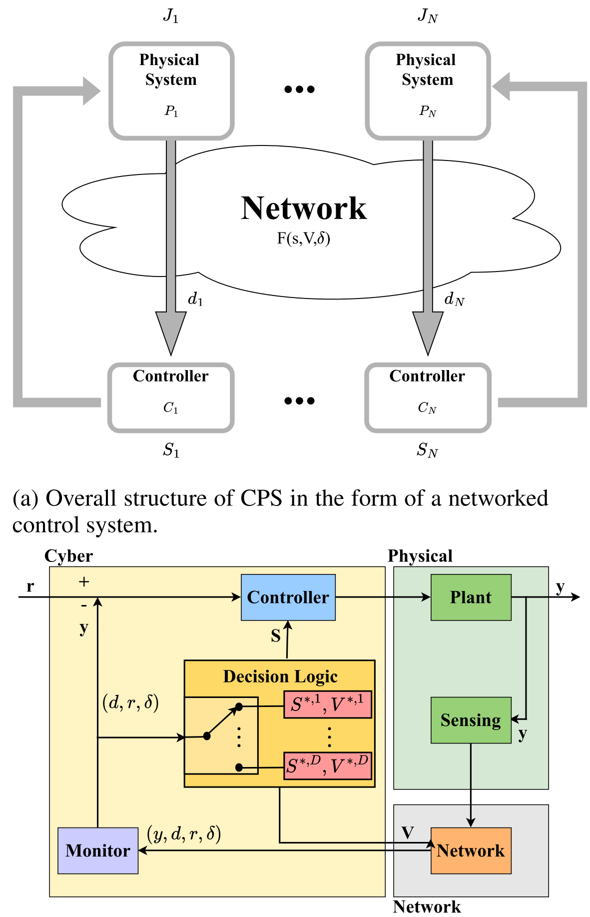
In the context of wireless networks, where communication channels are frequently susceptible to different sorts of uncertainty and interference, CCD has been the focus of several papers. For instance, the authors of [99] concentrate on the creation of a resilient architecture that can manage wireless channel uncertainties in CPS, and they demonstrate how their method can maintain system performance even in the presence of sizeable wireless channel uncertainties.

Figure 6 highlight the differences between a common architecture of CPS in the form of a networked control system and a redesign architecture proposed by Kim et al. [99]. In Figure 6a the system consists of N physical systems and N controllers. The physical systems periodically transmit sensed data to their respective controllers through a wireless network. Each controller operates with a specific sampling period denoted by S_n, which determines the frequency at which the sensed data is sampled and transmitted. The network introduces a delay, denoted by d_n, in each feedback loop. S and V are respectively the set of the sampling periods and the network parameters such as contention window size and re-transmission count. The network setup, encompassing network topology and the number of nodes, is captured by the variable δ. The control performance of each physical system is evaluated using a control cost function J_n, which considers its sampling period, network delay, and packet loss probability. In contrast, Figure Figure 6b presents a switching architecture for the PHY data rate $r_n(\varepsilon)$. The values of S and V must be carefully adjusted based on $r_n(\varepsilon)$. Thus, once the data rate is determined according to the channel condition, S and V are switched to appropriate values to satisfy both the network and control performance. A cost function is employed to minimise S and V in order to optimise the system's performance. The proposed architecture and optimisation technique offer a promising approach to enhance the robustness of these systems in the presence of unpredictable wireless channel conditions. The W-Simplex method, as used by Kim et al. [100], provides a robust network and CCD strategy for CPS when facing wireless channel uncertainties.

Similar to this, [101] proposed a CCD method and transmission power scheduling for wireless sensor networks. Chang's research concentrated on the development of ultra-reliable and low-latency communication (URLLC) for real-time control in wireless control systems [102]. The authors Wang et al. [103] also use URLLC to packetized predictive control, a control method that makes use of predictive models to enhance system performance. The suggested scheme's packet structure, scheduling algorithm, and error control techniques are all covered in detail. To assess how well the scheme performs in various circumstances, including those with varied packet sizes and channel conditions, the authors also run simulations.

Lastly, five more articles investigate other facets of this technology, such as transmission control, power distribution, and communication QoS planning. The performance and dependability of wireless control systems are improved by the authors' investigations into techniques for optimising these characteristics.

- He et al. [104] suggest a co-design approach for wireless control systems that takes into account both the transmission and control facets. By dynamically altering the transmission rate in response to the needs of the control system, this technology seeks to decrease communication overhead and enhance control performance.
- Hong et al. [105] concentrate on multi-agent coordination with second-order dynamics and suggest an adaptive communication and CCD strategy that considers the dynamics of the system.
- Xie et al. [106] propose an optimal power allocation method for relay-assisted wireless packetized predictive control systems, which aims to minimise the power consumption while maintaining the control performance.



(a) Overall structure of CPS in the form of a networked control system.

(b) A resilient architecture that can adaptively tune the network and control parameters against wireless channel uncertainty.

FIGURE 6. Comparison between a common architecture for networked control systems and an redesign architecture proposed by Kim et al. [99]. ***Source: Redrawn from [99] (open access).***

- Chang et al. [107] present the fourth article titled "*Dynamic Communication QoS Design for Real-Time Wireless Control Systems*", which introduces a new approach for designing QoS in real-time wireless control systems. The proposed technique focuses on reducing communication delay and jitter, while maintaining dependable communication to ensure the system's reliability.
- Proposing a co-simulation method for the design and testing of wireless control systems, Björkbom et al. [108] present a method that integrates communication and control simulation tools, allowing for the evaluation of system performance under varying communication conditions.

The 19 papers that are included in this section show the broad range of uses for CCD in wireless systems. By taking into account the particular characteristics of wireless communication channels and the dynamics of control systems, the solutions suggested in these articles seek to enhance the performance of wireless control systems. The suggested techniques can be used in a variety of fields, including robotics, industrial automation, and transportation systems.

2) NETWORKED SYSTEMS

Networked Control Systems are systems in which the sensors and the actuators communicate with the controller through a network. Figure 7 provides a illustration of a typical NCS and its 4-layers architecture. The articles in this section explore various aspects of NCS design, including energy awareness, uncertainty, constraints, and fault tolerance, highlighting the opportunities and challenges in this area.

De Castro et al. [109] and Wang et al. [110] discuss how much energy is used by the communication network. In [109], the authors propose a joint optimisation framework that reduces the amount of energy used by the communication network while meeting the performance requirements of the control system. They construct a sufficient condition for the stability of the overall system using the Lyapunov-based control technique. While [110] lays out the necessary criteria for the exponential mean square stability of a single plant, it also suggests a scheduling-and-control co-design process that can stabilise the entire set of plants with a specified transmission energy budget and guaranteed system performance.

Two papers by Basit et al. collectively underscore the critical importance and evolving complexity of ensuring robust, secure, and efficient operation NCS. The first one [111], addresses the distributed state and unknown parameter estimation problem for discrete-time nonlinear systems that have known linear dynamics and unknown nonlinearities, subject to deception attacks. They introduce a neural-network-based unified estimation framework that estimates the unknown nonlinear function alongside the system state and unknown parameters. The framework leverages a dynamic event-triggered strategy to alleviate resource consumption, ensuring stability through uniformly ultimately bounded error.

The second one [112], addresses the specific challenges posed by denial-of-service (DoS) attacks on distributed state estimation, proposing a novel dynamic event-triggered approach. This method not only ensures robust estimation under malicious attacks but also significantly reduces network communication overhead. While the first paper explores broader aspects of NCS operation and efficiency, the second one presents a novel framework for addressing joint state and unknown input estimation (JSUIE) in nonlinear systems compromised by DoS attacks and stochastic disturbances. It proposes an improved dynamic event-triggered mechanism to conserve network resources and reduce unnecessary transmissions, a crucial consideration under DoS attack conditions.

A technique for dual scheduling and quantized control for NCS with communication limitations is presented by Lu and Zhou [113]. The authors suggest a scheduling technique that chooses each sensor-controller pair's optimal communication schedule, as well as a quantized controller architecture that ensures performance and stability within the specified communication limitations. On the other hand, Zhihong et al. [114] discusses information scheduling-based fault-tolerant control of NCS. They suggest using a fault-tolerant controller that can recover from communication failures by using a linear matrix inequality-based design technique. The approach is based on scheduling information exchange between the controller and the sensors.

The co-design of model-dependent scheduling and control for NCS is investigated in Zhao and Ji [115] and Zhao et al. [116]. A co-design strategy that takes into account the medium access constraint and the system model for scheduling and control design was proposed in [115]. With the suggested approach, performance and communication expense are better balanced. Ultimately, a generalised model reference scheduling and CCD technique for NCS with guaranteed performance was presented in the work [116]. The approach is founded on a generalised model reference control framework that takes into account the scheduling and control design jointly. The authors demonstrate that the suggested strategy can perform more effectively than the ones already in use.

We can reference Dai et al. [117], [118], [119], [120], [121] to evaluate the effects of communication delays on the system's performance. The authors in [117] suggest a switching system model that captures the uncertainty in the delays and demonstrate how to simultaneously construct the control and scheduling methods. This method, which is based on the average dwell time technique, produces a controller that ensures the closed-loop system's exponential stability. For NCSs with random delays, Zhao [118] suggests a model reference scheduling and CCD methodology. This method is based on a switching system model that accounts for the delays' time-varying nature. As Cao et al. [119] addresses the issue of H_∞ reliable control for networked jacket platforms against earthquakes and stochastic actuator faults. They provide the necessary conditions for the stability of the closed-loop system using the Lyapunov-based method, and they perform numerical simulations to evaluate the efficiency of their strategy. Finally, co-design strategies for event-triggered communication are put out in [120] and [121]. Aibing et al. [121] approach's focuses on fault-tolerant control based on fault diagnosis observer, while Peng and Yang [120] approach focuses on H_∞ control. Both papers seek to increase control performance while minimising data transmission.

Communication constraints, such as limited bandwidth and sample rates, must be taken into account in the control design process to achieve optimal system performance. The article by Sun and Wu [122] focuses on the co-design of scheduling and control for NCS with bandwidth constraints. The authors suggest a strategy for optimising the performance of NCS with constrained bandwidth resources that takes

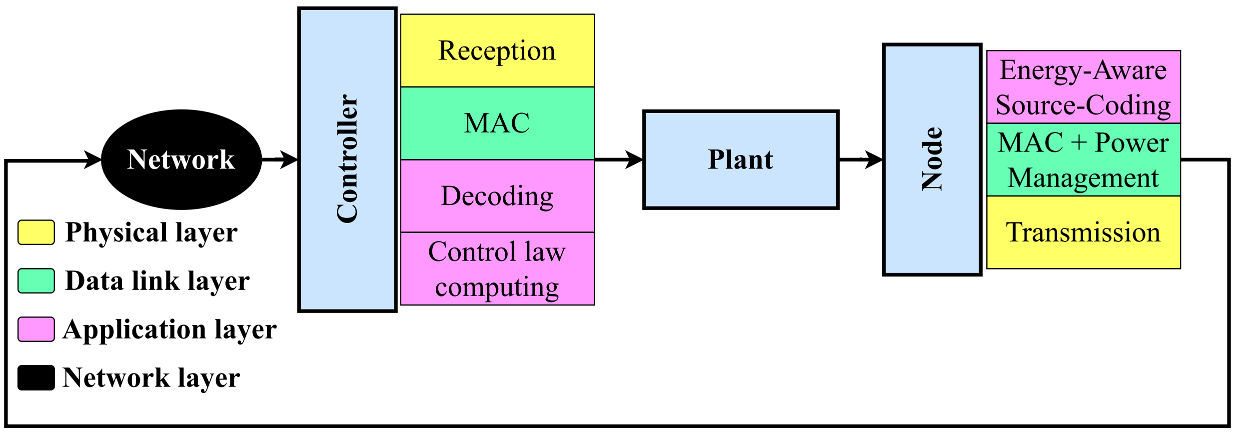


FIGURE 7. Illustration of the four layers of the NCS (Physical, Data Link (MAC), Network and Application) on a control block diagram of a NCS, according to [109]. The Physical layer performs the radio modulation of the digital data. The Data Link (MAC) layer defines how to use and share the transmission medium. The Network layer routes the data through the network. Finally, the Application layer concerns the source encoding and decoding, and computes the control law. *Source: Elaborated by the authors.*

both scheduling and control design features into account. They provide a complete framework that uses scheduling, feedback management, and limits on communication to meet goals for system stability and performance. Similar to this, Li et al. [123] examine the co-design of sample rate scheduling and optimum control for NCS. To enhance the overall performance of the system, they recommend a joint optimisation strategy that takes into account both the scheduling of the sample rate and the control design. The authors stress how crucial it is to incorporate communication restrictions into the control design process in order to get the best possible system behaviour.

A more recent study by [124] focuses on the feedback linearization (FBL) regime of communication and control in the age of loop-oriented wireless networked control systems. The trade-off between communication expense and control effectiveness under the FBL regime is taken into account by the authors' unique approach. They examine the impact of information age on control performance and create a collaborative optimisation approach that takes both communication and control design goals into account.

Ultimately, in their discussion of real-time control in future wireless networks, Zhao et al. [125] emphasise the significance of communication-control co-design. To create effective and dependable wireless networked control systems, they point the significance of integrating communication and control aspects. They give a cogent explanation of the challenges and opportunities in this field. The authors in [126], on the other hand, concentrate on CCD for NCS and static-dynamic hybrid communication scheduling. They give a thorough overview of their suggested strategy, which combines static and dynamic scheduling techniques to enhance the performance of networked control systems' communication and control. They go over the benefits and drawbacks of their method and offer tips on how to use it in real-world situations.

In general, all the articles that were presented in this section offer useful information in the field of communication CCD. These articles highlight the necessity for integrated approaches that take into consideration both the communication and control aspects of NCS in order to create systems that are reliable and efficient. There are additional articles available on the internet that discuss this subject, and references to those studies can be found here [127], [128], [129], [130], [131], [132].

C. VEHICULAR AND AIR VEHICLES/AIRCRAFT SYSTEMS

The level of information circulation in the electro-electronic circuits of new vehicles has increased, resulting in greater software complexity and a need for more processing capacity. Some specific functions require smaller processors, in addition to a control centre. To handle this complexity, vehicles and aircraft utilise embedded microprocessed systems that are designed exclusively for the control and operation of a specific model, integrating the operation of various subsystems. As a result, there is a wide range of electronic systems available for different models, each with a unique architecture based on the project's needs. Due to the high degree of dynamic coupling between subsystems, vehicle and aircraft systems are excellent candidates for CCD experimentation. Figure 8 shows the resume of applications in vehicle and aircraft systems. The following section highlight the main articles on CCD applications for vehicles and aircraft systems.

Several papers are concerned with the problem of vehicular platoon control and connected vehicles [133], [134], [135], [136], [137]. Guo and Wen address the challenges of communication scheduling and control in a platoon of vehicles in Vehicular Ad-hoc Networks (VANETs) [133]. The framework proposed by the authors considers the communication latency and the transmission reliability of wireless communication channels and uses a scheduling

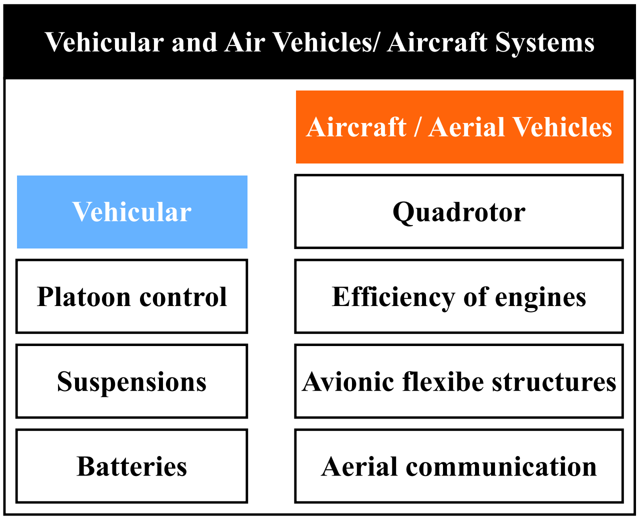


FIGURE 8. Resume of vehicular and air vehicles/aircraft applications. *Source: Elaborated by the authors.*

algorithm to optimise the communication scheduling of vehicles in the platoon. Another approach presented in [134] describes the CCD of vehicle platoons in Long-Term Evolution Vehicle-to-Vehicle (LTE-V2V) networks. The study proposes a new communication topology assignment algorithm, which considers both the communication range and the vehicle's speed, and a CCD method based on LQR and Kalman filter. On the other hand, Ge et al. aim to enhance the efficiency and reliability of vehicle platooning through dynamic event-triggered communication scheduling [135]. The proposed approach adopts a distributed architecture, where each vehicle communicates with its neighbours to adjust the event-triggered sampling period and obtain the latest state information. In addition, Xiao and Xie demonstrate the application of a new methodology in vehicle platooning by using a stochastic Lyapunov function and a generalised It's formula [136]. They discuss the problem of feedback stabilisation over stochastic multiplicative input channels in the continuous-time case and guarantee the exponential stability of the closed-loop system with high probability, even in the presence of unknown multiplicative noise.

Another example of co-design is for the application in a vehicular system with active suspension. Through co-design, Haemers et al. [138] demonstrate the effectiveness of the proposed approach in mitigating the effects of uncertainties and non-linearities in the hardware and control parameters for an active car suspension system. The results show that the optimised active suspension system can provide up to a 46% reduction in the maximum body acceleration and up to a 34% reduction in energy consumption, compared to a conventional passive suspension system. Sundarrajan and Herber [139] use an active suspension case study to compare the effectiveness of nested and simultaneous CCD methods for mechatronic systems. It was shown that both nested and simultaneous CCD methods can result in high-performance. However, the simultaneous method tends to be more computationally efficient, while the nested method provides more flexibility in terms of control design. The authors also highlight the importance of understanding the underlying assumptions and limitations of each method when choosing a co-design approach.

Cui et al. [140] and Cui and Wang [141] describe the application of co-design to address the issue of fast-charging and cycle life performance of Lithium-Ion batteries as enablers of electric vehicles. They discuss the challenges associated with fast-charging and its impact on the battery cycle life. The authors propose a co-design framework that integrates the control system design and the battery pack design to improve the overall performance of the battery system. Their aim is to achieve a balance between fast-charging and battery cycle life by optimising the battery pack design and control algorithms. The proposed approach takes into consideration the uncertainties and variability in battery characteristics, such as capacity degradation and ageing effects. Therefore, while both articles focus on enhancing the performance of lithium-ion batteries, the first one emphasises a balance between fast-charging and cycle life through CCD, while the second one highlights a reliability-based approach that considers uncertainties and variability in battery characteristics.

Regarding aircraft's systems, the author in [142] presents a model-fidelity-based decomposition framework for hierarchical CCD, which is applied to a case study of a quadrotor UAD. The proposed framework involves a systematic approach to decompose a control system into multiple levels of control, where each level has a different model fidelity. The higher levels use more abstract models, while the lower levels use more detailed models. The co-design problem is formulated as a multi-objective optimisation problem, where the objective is to simultaneously optimise the performance of each level of control and the overall performance of the system. The results show that the proposed approach achieves better performance than traditional approaches in terms of both closed-loop performance and computation time. Finally, the method is also compared with other CCD methods.

Alazard et al. propose a methodology for avionics CCD of large flexible space structures [143]. The system is modelled using a finite element method to model the structure and a modal approach to model the dynamics. Key variables are identified using a sensitivity analysis, and control laws are synthesised using LQR and a PID controller. Finally, simulations are performed to evaluate the performance of the designed control laws. The proposed methodology is demonstrated on a case study of a flexible space structure.

Jaddivada et al. [144] focus on the development of an energy modelling and control approach with the goal of enhancing the stability and efficiency of engines used in air vehicles. They stress the significance of engine stability and efficiency in minimising fuel consumption, emissions, and maintenance expenses. The proposed approach involves creating a dynamic energy model that considers the engine's physical characteristics, such as airflow, combustion, and heat transfer, and employing MPC algorithms to optimise engine performance. The authors present simulation outcomes that demonstrate the effectiveness of the suggested approach in improving engine stability and efficiency, as well as reducing emissions and fuel consumption.

Finally, Li et al. [145] present a design and implementation approach for aerial communication using directional antennas, with a focus on learning control in unknown communication environments. The authors first design a directional antenna system based on the needs of aerial communication, including the antenna structure, feeding network, and control circuit. They then develop a learning-based control algorithm using a neural network to optimise the antenna direction and the transmit power in real-time. The algorithm is trained using simulations and tested in a real-world environment using an unmanned aerial vehicle (UAV) equipped with the directional antenna system. The experimental results show that compared with the traditional control method, the proposed learning control method can achieve higher throughput, lower bit error rate, and better signal-to-noise ratio in unknown communication environments. The directional antenna system also effectively suppresses interference signals and improves the communication performance.

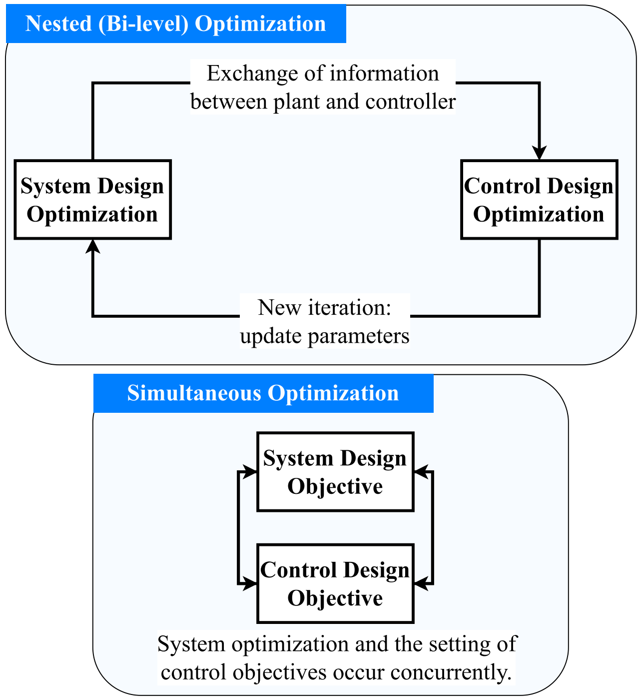


FIGURE 9. Two different CCD approaches that provide system-level optimally guarantees according to Bhattacharya et al. [42]. ***Source: Elaborated by the authors.***

D. OTHER MECHANICAL AND ELECTRICAL SYSTEMS

Some articles approach the classical problem of controlling a pendulum or a set of pendulums. In [146] Tsai and Malak employed two benchmark problems, namely a single and a double inverted pendulum on a cart, which are nonlinear systems, to introduce a new approach for designing an MPC feedback controller utilising parametric optimisation. The approach involves tuning a set of parameters to trade-off between the accuracy of the approximation and the computational cost. Another paper of these authors [147] utilises a state-parameterised nonlinear programming control (sp-NLPC) to design nonlinear feedback controllers and elucidates the technique through an example of controlling a double inverted pendulum. The sp-NLPC approach circumvents the limitations of other methods that require making strong assumptions about model form, such as linearity, and online optimisation processes. Peng and Han [148] presents an $\mathcal{L}_2$ CCD method, which involves jointly designing an event-triggered transmission scheme and the controller parameters to optimise the control performance. The proposed approach aims to reduce the number of transmissions between the controller and the plant while maintaining satisfactory control performance. The effectiveness of the method is demonstrated through an example of an inverted pendulum.

Bhattacharya et al. [42] present a methodology that uses Bayesian optimisation to co-optimise the control parameters of a building's chiller plant and energy management system. Figure 9 illustrated the difference between a nested and a simultaneous co-design approaches discussed by the authors. The iterative approach enhances the design of the plant by initially maintaining a fixed control design. It then proceeds to optimise the control design based on the chosen plant design, and this process continues until convergence is achieved or the design objectives are met. However, like the sequential approach, the iterative approach does not offer guarantees for system-wide optimally. On the other hand, the simultaneous approach considers all dynamic interactions and system-control relationships within a unified optimisation model. The proposed approach takes into account the interdependence of the subsystems of the plant and provides a unified framework for CCD. The effectiveness of the methodology is demonstrated through a case study of a commercial building, showcasing significant energy savings while ensuring occupant comfort. Furthermore, the authors discuss the potential of the approach to be extended to other building systems such as air conditioning (HVAC), heating and ventilation.

Hormozabad and Soto [149] propose an approach to use a neural dynamic model to capture the complex nonlinear behaviour of controlled rocking steel braced frames and their interactions with the building structure. This model is then utilised to design a performance-based control strategy that optimises the structural response to seismic loading while ensuring occupant safety. The authors utilise a co-design framework that considers the interdependence between the structural design, control design, and performance objectives. The effectiveness of this approach is demonstrated through numerical simulations of a multi-story building structure subjected to different earthquake scenarios.

Vercellino et al. [150] introduce a CCD optimisation technique for natural gas power plants that include carbon capture and thermal storage. The authors utilise a thermodynamic model to simulate the behaviour of the power plant and formulate a dynamic optimisation problem that jointly optimises both the plant design parameters and control inputs. Through a case study of a natural gas power plant with carbon capture and thermal storage, the proposed approach is shown to be effective in achieving significant economic savings and reducing emissions.

Watt et al. [151] aimed to apply an integrated structure/control optimisation methodology to the BIOMASS earth observation mission. The authors emphasised the significance of simultaneous optimisation of the spacecraft's structure and control system to enhance its performance and efficiency. Their proposed approach utilised a coupled model of the spacecraft's structure and control system, where the structure was modelled using the finite element method, and the control system was modelled using a linear quadratic regulator. The study's findings revealed that the integrated structure/control optimisation approach could considerably enhance the spacecraft's performance, such as reduced weight, improved stability, and better pointing accuracy.

Regarding electrical systems, Wu et al. [152] proposed an electrothermal-control co-design methodology for a dual inverter system utilised in heavy-duty traction applications concerning electrical systems. The authors emphasise the significance of considering the thermal effects on the system due to the susceptibility of silicon carbide (SiC) devices to thermal stress and failure. The co-design approach proposed by the authors comprises thermal-aware optimisation of the power module layout, heat sink design, and cooling strategy, as well as the control algorithms for the inverter system.

Finozzi et al. [153] propose a parametric sub-structuring model for large space truss structures. The authors use a finite element model to represent the structure and develop a sub-structuring approach that can capture the coupling between the structural and control parameters. Ning et al. [154] propose an approach for inverse kinematics and planning CCD for a redundant manipulator used in precision operations. The authors use a dynamic model of the manipulator and develop a co-design methodology that co-optimises the manipulator's design parameters and control inputs. Wu and Zhou [155] present a CCD methodology for actively controlled lightweight structures used in high-acceleration precision motion systems. All the three articles demonstrate how a co-design approach can optimise both the control input and structural design parameters to achieve the desired performance.

Other general examples of CCD are given by Alazard et al. [156] and Nash et al. [157]. In the first article, the authors propose a model that simplifies the analysis and design of complex mechanical systems by breaking them down into smaller subsystems that can be interconnected in a modular way. The article presents the mathematical framework of the model and shows how it can be used to derive the equations of motion for mechanical systems, such as spacecraft and robots. The second article focuses on a receding-horizon MPC framework that optimises control performance while handling uncertainties and disturbances in system dynamics. The authors conduct a thorough analysis of the proposed method, including stability and performance guarantees, and validate its effectiveness through simulations of several benchmark control problems. The article also highlights the potential of the proposed approach to be applied in real-world control problems, including those in the aerospace and automotive industries.

IV. RESULTS

A. A THEORETICAL EXAMPLE AND CCD FORMULATIONS

Let's consider an example, as the one depicted in Figure 10, and analyse it in two design domains: aerodynamic (x_A) and hydrodynamic (x_B). As discussed in previous sections, a HWWP exemplifies a typical application of CCD due to the number of subsystems composing it and the dynamic interference between them. The challenge of coupled dynamics relates to how alterations in one domain affect the other. If the design in domain A influences domain B, an optimal design for domain B could be contingent on the choices made in domain A. In practice, one might design the best WT by focusing solely on aerodynamic aspects, but the overall system performance would likely be suboptimal because the wave interactions at the floating platform's base could significantly impact performance.

In this example, a hypothetical scenario with various wind conditions of relatively high average speed is contemplated, leading to a control problem centred on adjusting the pitch angle of the blades to maintain turbine operation within a specific range of nominal and consistent power. A typical CCD approach would involve considering alterations in the physical parameters of the wind turbine in conjunction with controller application. The potential efficiency of modifying the turbine's physical parameters over solely focusing on controller design, as observed in previous sections, is notable. An optimisation scenario might entail determining the optimal radius of the wind turbine rotor, the curvature of the blades, and the cone angle at which the blades are positioned relative to each other, combined with MPC to collectively adapt the blades pitch angle. In this context, designing WT control solely based on a decoupled aerodynamic model of the turbine could result in suboptimal control. However, a more precise model that considers the coupling between multiple domains is warranted. For instance, the waves at the platform's base could be regarded as disturbances in the system.

Also, in an HWWP, it is of interest to the designer that control is applied to the WEC. In an exclusive context of the domain x_B, the objective would be to use, for example, impedance matching control to maximise energy capture by

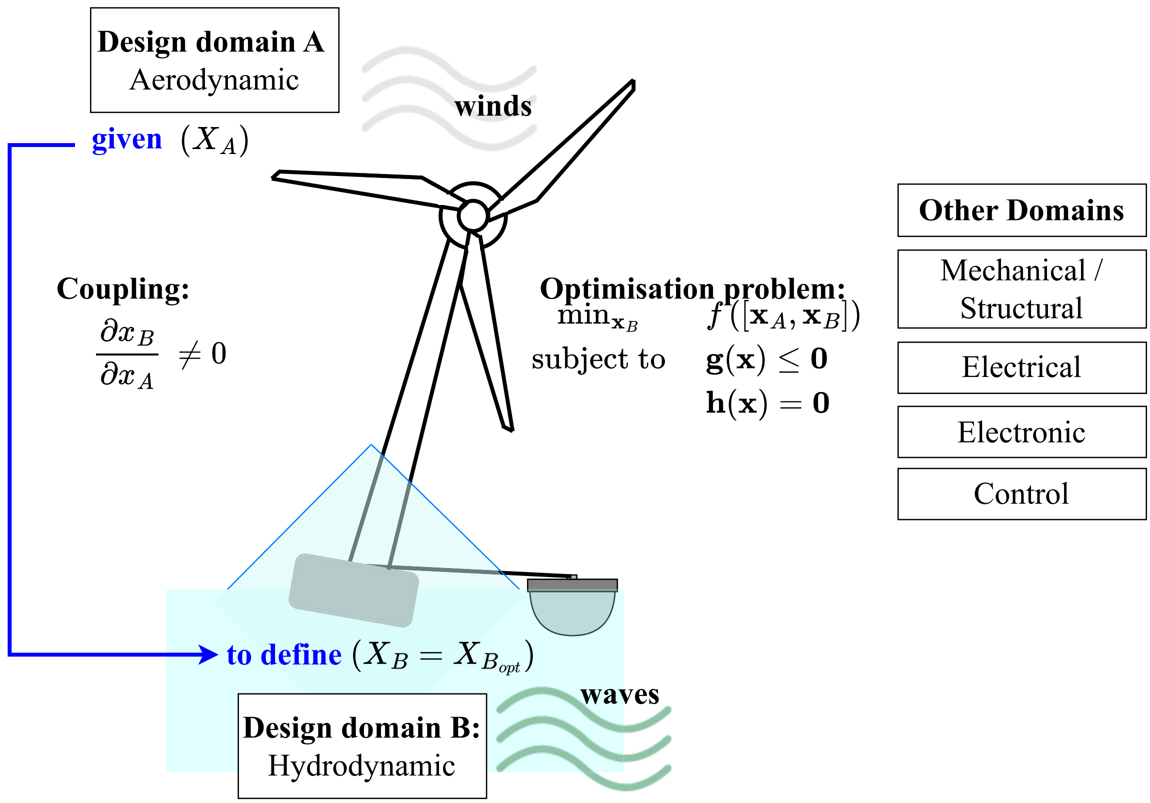


FIGURE 10. An illustration of the various domains within a hybrid wind-wave platform. The interaction between these domains is assessed based on the degree to which changes in one domain affect the others. A simultaneous CCD approach would consider multiple domains to optimise at the same time. *Source: Elaborated by the authors.*

the WEC. However, considering the aerodynamic domain now, where the same objective of energy maximisation applies to the WT, the interaction between these two controls can be negative. The optimal control for one domain may not be optimal for the system as a whole. A reformulation could be to consider a multi-objective optimisation problem now, in which not only the maximisation of WEC energy is considered, but also the stabilisation of the platforms, thus also influencing the generation of energy by the wind turbine.

An approach could, therefore, be to first find an optimal design considering domain A, and then to find the optimal design solution $x_{B_{opt}}$ for domain B. The strength of the coupling between the domains can be measured by $\frac{\partial x_{B_{opt}}}{\partial x_A}$, which quantifies how sensitive the optimal value of the design variable in the hydrodynamic domain $x_{B_{opt}}$ is to changes in the design variable in the aerodynamic domain x_A. A nonzero value indicates that there is a coupling effect between the two domains; changes in one domain influence the outcomes or optimal values in the other. The strength of this effect is indicated by the magnitude of the derivative: a larger absolute value suggests a stronger coupling.

Similarly, the interplay between plant and controller design parameters can be measured by Equations 1 and 2, which quantify, respectively, how strongly a change in a controller parameter influences the choice of a physical parameter of the plant, and vice versa.

$$\frac{\partial x_{P_{opt}}}{\partial x_C} \tag{1}$$

$$\frac{\partial x_{C_{opt}}}{\partial x_P} \tag{2}$$

In a sequential approach, each subdomain depicted in Figure 10 would undergo independently, with the control design being the final step. In a CCD simultaneous approach, both the plant and controller would undergo optimisation simultaneously. The decision of how many domains to consider in the optimisation problem is left to the designer. Herber and Allison [158] compared the conventional nested CCD formulation with a simultaneous one.

The simultaneous approach is usually formulated as a nonlinear dynamic optimisation problem, represented by Equation 3.

$$\min_{\boldsymbol{x}_p, \boldsymbol{x}_c} \Psi = \int_{t_0}^{t_f} \mathcal{L}\left(t, \boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p\right) dt + \mathcal{M}\left(\boldsymbol{\xi}\left(t_0\right), \boldsymbol{\xi}\left(t_f\right), \boldsymbol{x}_c, \boldsymbol{x}_p\right),$$

subject to:

$$\dot{\boldsymbol{\xi}} - \boldsymbol{f}\left(t, \boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p\right) = \mathbf{0},$$

$$
\begin{aligned}
&\boldsymbol{C}\left(t, \boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p\right) \leq \mathbf{0}, \\
&\boldsymbol{\phi}\left(\boldsymbol{\xi}\left(t_0\right), \boldsymbol{\xi}\left(t_f\right), \boldsymbol{x}_c, \boldsymbol{x}_p\right) \leq \mathbf{0},
\end{aligned} \tag{3}
$$

the equation integrates system design (physical parameters, denoted by x_p) and control strategy (control parameters, denoted by x_c). The objective is to minimise the cost function Ψ, which typically represents the total expected cost over a time horizon from t_0 to t_f, including the running cost $L(t, \xi, x_c, x_p)$ and the terminal cost $M(\xi(t_0), \xi(t_f), x_c, x_p)$. The system dynamics are given by $\dot{\xi} = f(t, \xi, x_c, x_p)$, which must be zero (the dynamics constraint), ensuring that the proposed trajectories ξ are physically feasible according to the system's dynamics. The path constraint $C(t, \xi, x_c, x_p) \leq 0$ ensures that the state and control variables meet certain conditions at all times (like safety or operational constraints). The boundary condition $\phi(\xi(t_0), \xi(t_f), x_c, x_p) \leq 0$ ensures that the initial and final states of the system satisfy certain specified conditions, which could be related to state values or conservation laws.

Pontryagin's Minimum Principle (PMP) [159], in Equation 4, provides a framework for determining control laws u that minimize the objective function while satisfying the system's dynamics and constraints. A simultaneous approach, with $x_c := u$, utilising the PMP, can be described as follows:

$$
\begin{aligned}
\dot{\boldsymbol{\lambda}}^* &= -\left[\frac{\partial H}{\partial \boldsymbol{\xi}}\right]^*, \\
\mathbf{0} &= \left[\frac{\partial H}{\partial \boldsymbol{u}}\right]^*, \\
0 &= \left[\boldsymbol{\mu}^T \boldsymbol{C}\right]^*, \\
0 &= \left[\boldsymbol{\nu}^T \boldsymbol{\phi}\right]^*, \\
\boldsymbol{\mu}^* &\geq \mathbf{0}, \quad \boldsymbol{\nu}^* \geq \mathbf{0}, \\
\mathbf{0} &= \left[\boldsymbol{\lambda} + \frac{\partial \mathcal{M}}{\partial \boldsymbol{\xi}} + \boldsymbol{\nu}^T \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{\xi}}\right]^*_{t_0}, \\
\mathbf{0} &= \left[\boldsymbol{\lambda} - \frac{\partial \mathcal{M}}{\partial \boldsymbol{\xi}} - \boldsymbol{\nu}^T \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{\xi}}\right]^*_{t_f}, \\
\mathbf{0} &= \left[\frac{\partial \mathcal{M}}{\partial \boldsymbol{x}_p} + \boldsymbol{\nu}^T \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{x}_p}\right]^*_{t_0} \\
&\quad + \int_{t_0}^{t_f} \left[\frac{\partial \mathcal{L}}{\partial \boldsymbol{x}_p} + \boldsymbol{\lambda}^T \frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}_p} + \boldsymbol{\mu}^T \frac{\partial \boldsymbol{C}}{\partial \boldsymbol{x}_p}\right]^* dt,
\end{aligned} \tag{4}
$$

where, the rate of change of the adjoint variables $\boldsymbol{\lambda}^*$ indicates how the shadow prices of state variables evolve over time, reflecting the sensitivity of the objective function to changes in these variables. The condition for the optimality of control actions, $\mathbf{0} = \left[\frac{\partial H}{\partial \boldsymbol{u}}\right]^*$, ensures that the Hamiltonian is minimised with respect to the control variables, signifying the most cost-effective direction for system control. Conditions involving Lagrange multipliers $\boldsymbol{\mu}^*$ and $\boldsymbol{\nu}^*$ for path constraints become zero whenever the constraints are inactive, enforcing adherence only when necessary. The non-negativity of the Lagrange multipliers aligns with the principle that constraints should not incentivise the violation of physical or operational limits. The transversality conditions at the initial and final times, t_0 and t_f, relate to how the optimisation problem's boundary conditions affect the adjoint variables, ensuring the system's initial and final states optimally align with the objective function's goals. Additionally, the last condition integrates the effects of design decisions on the system's performance over the entire planning horizon, ensuring that the chosen design optimally balances the objective function against the system dynamics and constraints.

On the other hand, a nested co-design approach would involve addressing a problem where each overarching physical parameter is optimised, and during each iteration of this optimisation problem, the controller would also be optimised, albeit constrained by the current value of the physical parameter. Put differently, an outer loop would optimise the plant values, while an inner loop would optimise the controller. Equation 5 outlines the plant's outer loop optimisation process, whereas Equation 6 delineates the inner loop for optimal control.

$$
\begin{aligned}
&\min_{\boldsymbol{x}_p} \psi\left(\boldsymbol{x}_p\right) \\
&\text{subject to: } \boldsymbol{\phi}_o\left(\boldsymbol{x}_p\right) \leq \mathbf{0} \\
&\qquad\qquad\quad \boldsymbol{F}\left(\boldsymbol{x}_p\right) \leq \mathbf{0}
\end{aligned} \tag{5}
$$

where, ϕ_0 are constrains dependent on the plant design and $F(x_p)$ other outer loop constraints, and ψ the optimal objective function.

$$
\begin{aligned}
&\min_{\boldsymbol{x}_c} \Psi\left(\boldsymbol{x}_p^{\dagger}, \boldsymbol{x}_c\right) \\
&\text{subject to: } \dot{\boldsymbol{\xi}} - \boldsymbol{f}\left(t, \boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p^{\dagger}\right) = \mathbf{0} \\
&\qquad\qquad\quad \boldsymbol{C}\left(t, \boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p^{\dagger}\right) \leq \mathbf{0} \\
&\qquad\qquad\quad \boldsymbol{\phi}_i\left(\boldsymbol{\xi}\left(t_0\right), \boldsymbol{\xi}\left(t_f\right), \boldsymbol{x}_c, \boldsymbol{x}_p^{\dagger}\right) \leq \mathbf{0}
\end{aligned} \tag{6}
$$

here $x_p^{\dagger}$ is a candidate plant design, ϕ_i are the constraints of ϕ, and g_i are the inner-loop constraints. Each interaction of Equation 5 is associated with an interaction of Equation 6.

In the aforementioned example, by using a nested approach, for each iteration of the optimisation of the WT, one would identify the optimal multi-objective control law for the WEC, taking into account both WT and WEC power maximisation and overall platform stabilisation. Conversely, in the simultaneous approach, the WEC controller and the WT plant would be optimised together. A Pareto diagram result at the end of the process could determine the better solution, considering both controller and physical design. In a practical, real-world implementation, the goals often encompass both maximising energy efficiency and minimising costs.

For further understanding, with an example applied to a WT, refer to [160]. In the referenced work, Cui, Allison, and Wang explore the integration of Reliability-Based Design Optimisation (RBDO) with co-design approaches. Co-design methodologies have historically been applied deterministically, neglecting the impact of uncertainties on system performance. This study introduces a framework that combines co-design with RBDO to ensure that optimal system designs satisfy reliability constraints under parameter uncertainties. The authors present a comparative analysis of different problem formulations and solution strategies for reliability-based co-design.

Once more, Allison and Herber [161] approach the topic of co-design in a general manner by introducing the concept of Multidisciplinary Dynamic System Design Optimisation (MDSDO) and highlighting the importance of models that precisely capture system dynamics and offer design flexibility. They argue that dynamic systems, particularly those with active and autonomous features, necessitate integrated design strategies that consider multidisciplinary interactions and dynamic behaviours. The authors point out that conventional MDO approaches, mainly tailored for static systems, are inadequate for the distinct challenges posed by dynamic system design. They review the existing MDO approaches and also highlight the necessity of integrating RBDO and CCD.

Other approaches have also been presented, such as the one by Matni and Chandrasekaran [54], which is centred on the co-design of architecture and control laws by enhancing controller synthesis with convex regularisation functions. These functions aim to simplify controller architectures by penalising complexity. The distinction is made between sparse and dense architectures, considering the number of atomic subsystems in a controller. A single atomic subsystem is defined as a controller with a single actuator. Given the trade-offs between closed-loop performance, maintenance, and implementation costs, the necessity of approximating an optimal controller with fewer subsystems is highlighted. They propose a "Regularisation For Design" framework that employs these regularisation functions for controller synthesis, based on convex optimisation problems.

B. METADATA

This section demonstrates the current trends in the implementation of the theme by visually showcasing the state of the art. Furthermore, we present the timeline of applications across different areas where CCD has been utilised.

Figure 11 presents the classification of the number of publications by area over the years. It can be seen that the highest number of publications on the topic is in the year 2021, with emphasis on the area of CCD applied to vehicular systems, on that year, followed by renewable energy systems. Between 2011 and 2021, the topic has shown a predominantly upward trend, meaning there is a tendency for the number of applications for CCD to increase over the years.

Unlike, Figure 12 demonstrates which areas the applications are predominant in, without categorising the number of articles per year. Thus, it can be noticed that there is a highlight on the area of communication in control systems, including wireless and networked systems. Applications in these areas represent, collectively, 39.06% of all publications. Publications addressing CCD applied to vehicular systems added to applications in aircraft and aerial vehicles represent 13.70% of the total publications. Another highlight is in the field of renewable energies, where works applied to the co-design of wind turbines, WECs, and other renewable energy generation subsystems represent 10.15% of the publications.

We evaluated the keywords that were most frequently repeated in the portfolio of articles. The main keywords are shown in Figure 13, highlight again for networked systems

TABLE 1. References categorised by sub-areas.

Area	Reference
5G / 6G	[3, 102, 162–166]
Aircraft systems	[38, 39, 142–145, 167, 168]
Carbon emission	[22, 77]
Communication in control systems	[3, 4, 6, 9, 15, 32, 33, 58, 61] [62, 65, 79–83, 86, 88–97] [99–103, 105–109, 117] [120–132, 136, 145, 148] [169–172]
Control algorithms	[14, 33, 85–87, 142, 148] [154, 157, 173, 174]
Control co-design concepts	[29, 41, 44, 47, 54] [158, 160, 161, 175]
Control fuzzy	[4, 5, 45]
Cyber security	[19, 176]
Drone	[14]
Edge computing	[15, 84, 85, 92, 177, 178]
Electric motors	[5, 20, 23, 35, 68]
Energy consumption	[103, 105, 106, 109, 129]
Event-triggered control	[4, 6, 8, 9, 119, 130, 179–183] [148, 169–171, 184–191]
Fault tolerant control	[57, 85, 114, 121] [169, 192, 193]
Harmonic task scheduling	[51]
HVAC systems	[38]
Inverted pendulum	[146–148]
Inverters	[152]
Micro-fluid biochips	[16, 17, 194–196]
Microgrids	[18, 38, 77] [6, 7, 19, 22, 34, 53]
Predictive control	[55, 61, 62, 83, 92, 103] [105, 106, 146, 147, 157, 195]
Networked control systems	[52, 57, 58, 65, 79–83] [27, 87, 111, 112, 126, 179] [113–124, 129, 197] [148, 162, 172, 179, 198–204]
Renewable energy	[43, 44, 63–76, 78, 205–209]
Robotics	[20, 21, 36, 91, 169, 178]
Robust control	[30, 57–59, 72, 157, 192]
Sample-data control systems	[56, 101, 134, 148]
Satellites	[30]
Space mission platforms	[151, 153]
Stabilisation of batteries	[22, 39, 110, 140, 141, 210]
Stochastic systems	[46, 47, 60, 119, 136, 169]
Thermal systems	[2, 142, 150, 152, 157]
Vehicular systems	[3, 7, 23, 24, 31–35] [60, 133–141, 144] [170, 191, 211, 212]
Wave energy converters	[43, 44, 65, 66, 68, 69, 205]
Wind turbines	[63–65, 70, 71, 73, 74, 72] [3, 31, 32, 85, 91–95, 126]
Wireless systems	[97–100, 102–109, 125, 127] [162–166, 213, 214, 198, 199]

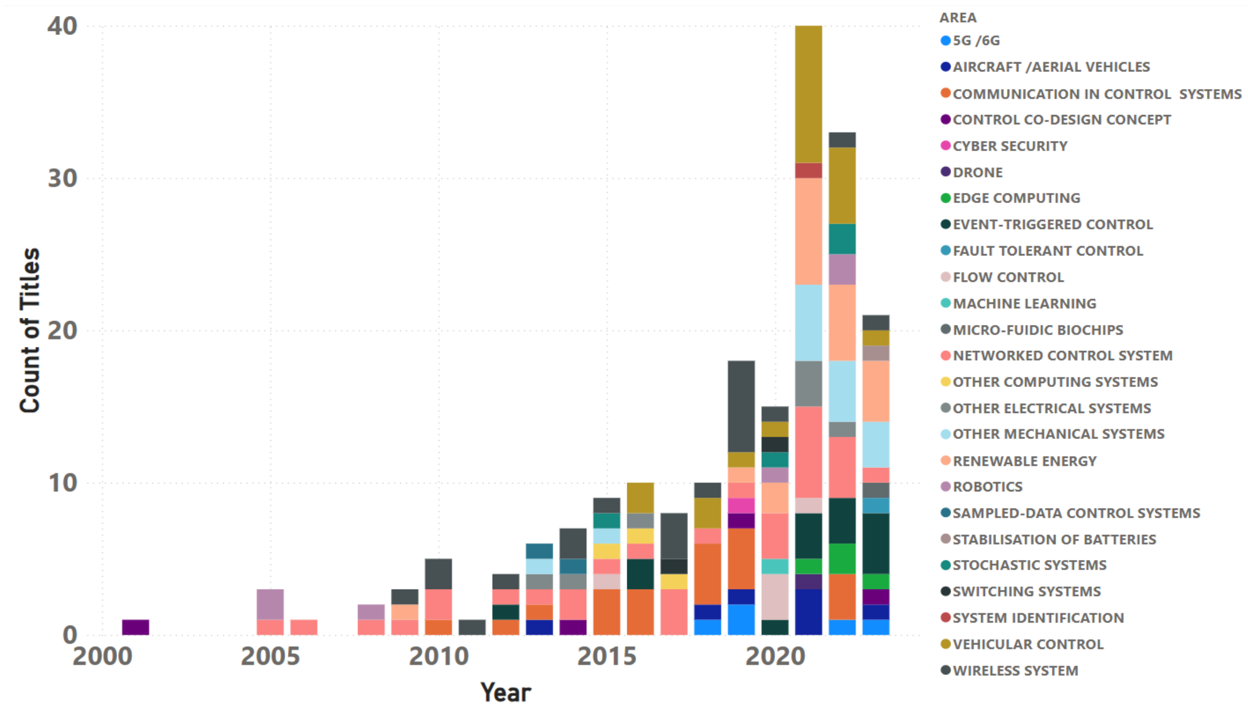


FIGURE 11. Number of articles published over the years by application area. *Source: Elaborated by the authors.*

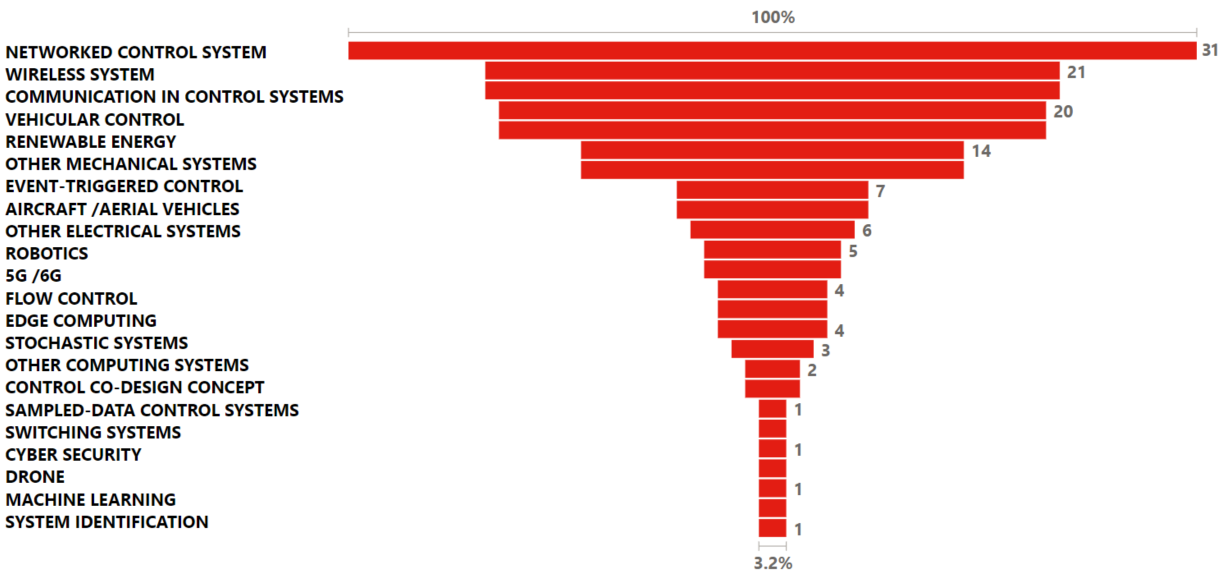


FIGURE 12. Predominant areas of application of CCD. *Source: Elaborated by the authors..*

and also for nonlinear systems. Additionally, we referenced the articles in important subcategories, as shown in Table 1. As an article can belong to multiple categories, if it addresses more than one category, it will appear in all relevant categories. For example, an article discussing CCD applied to the communication subsystem of a vehicle control will be included in both communication systems in control and vehicular systems categories.

C. COMMENT

As previously discussed, considering that having a plant with dynamically coupled subsystems is a prerequisite for applying CCD, the technique can be applied to any system. It means that there are no significant limitations for the application of CCD considering the area.

So far, we have highlighted the numerous advantages of using CCD. However, it is worth noting the limitations and

FIGURE 13. Main keywords. ***Source: Elaborated by the authors.***

the need to apply the technique from the perspective of achievable systems. This means that it is essential to consider the physical limitations of a real system. Furthermore, we have elucidated that CCD usually leads to better system performance, which can result in a simpler system. However, it is necessary to observe that the opposite can also be true. In aiming to achieve better system control, applying CCD can result in more complex systems.

The articles evaluated in this paper usually mention the limitations but do not typically mention any disadvantages of CCD. However, to the best knowledge of the authors, it is important to consider that there may be some possible disadvantages to applying CCD. One disadvantage is that, since it involves understanding the dynamics of multiple subsystems, it could require an interdisciplinary approach, which could mean the necessity of involving multiple domains and stakeholders. Another disadvantage is the potential for increased complexity in the system. Additionally, the CCD process may be resource-intensive, requiring significant time, effort, and financial investments. Hence, it is crucial to consider these potential disadvantages to determine whether CCD is an appropriate approach for a particular project or application.

Despite mentioning the disadvantages, we strongly encourage the application of the CCD technique for various types of systems, combined with various control techniques. As shown in the discussions section, there are numerous advantages to applying simultaneous control, in which the controller and the controlled system are cohesively redesigned to obtain optimal performance. Further, It was shown that applying CCD with a specific control technique often proves to be more advantageous than applying the control technique alone.

Since there are numerous examples of systems that apply CCD, it is difficult to establish a requirement or even a trend for future areas of application. However, as the results have shown, it is evident that complex systems involving countless subsystems are the ideal candidates for CCD application. This is the case for systems that fit into the categories highlighted in the previous section. Therefore, we encourage, for example, the investigation of integrating machine learning and artificial intelligence techniques together with control system design. Another option would be to investigate the redesign of already established energy generation or computational systems, such as electric motors, wind turbines, and embedded systems for generation systems, for the purpose of exploring potential benefits.

V. CONCLUSION

We have conducted a thorough study that demonstrates the significance of CCD as a critical approach for developing control systems that cater to the requirements of modern complex systems. This approach enables the integration of expertise from multiple domains and stakeholders, resulting in the creation of more efficient, reliable, and optimised control systems. Moreover, it encourages interdisciplinary dialogue during the design of such systems. The continuous development and implementation of CCD hold significant potential for addressing the challenges posed by modern complex systems and improving the overall performance of control systems.

This work demonstrated the numerous advantages of using CCD, as well as drew attention to possible limitations and disadvantages. We categorised the various studies found in the literature, discussed their implications, and summarised them in an elucidating way. Thus, this work is a powerful guide for researchers interested in the theory of control, its applications and new alternative ways to apply it.

As any application of CCD is computationally demanding, crafting guidelines and methodologies to mitigate the computational expenses associated with various categories of co-design challenges represents a promising direction for forthcoming research. Additionally, studies that compare simultaneous and nested co-design for the same application could reveal which is more challenging. The development of new tools to enable CCD implementation, combining different control approaches, could also be a valuable area of future work. The optimisation of a plant's physical parameters can be represented as uncertainties within these parameters, akin to the approach taken in robust control. Therefore, research aimed at integrating the principles of these two domains could prove to be highly beneficial.

As CCD continues to evolve, several areas of future research can be explored. Considering vehicular systems as an area with vast applications of CCD, further exploration could approach the emerging field of autonomous vehicles. Another possibility for future work could be addressing the provision of accessible tools and frameworks for CCD implementation, encompassing new areas, such as ARPA-E is for renewable energy, ensuring that it becomes more widely adopted.

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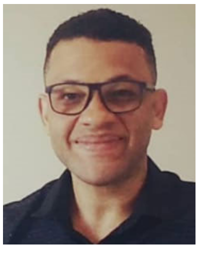

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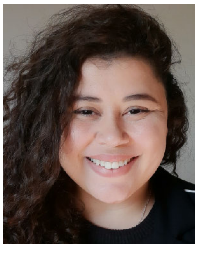

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