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INTEGRATED DESIGN OF DYNAMIC SUSTAINABLE ENERGY SYSTEMS

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Abstract

Recent advancements in the development and investigation of integrated methods for the design of dynamic engineering systems have made possible the achievement of new levels of system performance and now support the ability to systematically identify synergy mechanisms that can improve the effectiveness of system design processes at both early and late stages. Significant efforts in the last several years have focused on using integrated dynamic system design methods to enhance the performance and economic competitiveness of sustainable energy systems. Improvements in energy sustainability include both renewable energy production (e.g., wind, wave, and solar energy) and improved efficiency of energy consuming systems (e.g., buildings, manufacturing, transportation systems). This article reviews important results of these efforts and presents integrative concepts based on these studies in a single cohesive article. Three case studies are reviewed, and generalizable design concepts are presented for the design of dynamic sustainable energy systems.

Keywords: Early Design Phases, Integrated Product Development, Optimisation, Design Process

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1 INTRODUCTION

Recent advancements in the development and investigation of integrated methods for the design of dynamic engineering systems have made possible the achievement of new levels of system performance and now support the ability to systematically identify synergy mechanisms that can improve the effectiveness of system design processes at both early and late stages. Significant efforts in the last several years have focused on using integrated dynamic system design methods to enhance the performance and economic competitiveness of sustainable energy systems. Improvements in energy sustainability include both renewable energy production (e.g., wind, wave, and solar energy) and improved efficiency of energy consuming systems (e.g., buildings, manufacturing, transportation systems). This article reviews important results of these efforts and presents integrative concepts based on these studies in a single cohesive article.

Moreover, this article envisions a role for integrated dynamic system design methods in helping society transition to greater levels of energy sustainability. Conventional energy generation systems have been refined over many decades, whereas in many cases renewable energy systems are still evolving. Integrated design methods are essential for making rapid progress in producing effective renewable energy systems by supporting transformational as opposed to incremental improvements. This article focuses on design methods that lead to significant technical improvements for individual systems. We acknowledge that other advancements are needed; including enhanced system-of-systems design (e.g., integration of renewables into the existing energy grid) and complementary economic and public policy efforts.

This article reviews core concepts underlying advanced dynamic system design methods that provide new levels of system integration, particularly the management of system design coupling. We then discuss the role that integrated design methods are playing in the advancement of sustainable energy systems, and highlight three complementary case studies. Generalizable concepts are drawn from the results of these case studies, and suggestions for future work are provided.

2 RECENT DEVELOPMENTS IN DYNAMIC SYSTEM DESIGN

Optimal design of dynamic systems differs fundamentally from the design of static systems because dynamic system performance depends on how system states evolve through time. Time-varying system inputs such as wind speed for wind turbines or ocean wave elevation for wave energy converters must also be accounted for. Many modern engineering systems also involve active control systems. Design of these systems requires decisions about both physical- and control-system specifications. This section reviews recent developments in dynamic system design optimization methods that are relevant to the advancement of sustainable energy systems.

Optimizing physical or control systems independently without considering the potential synergy between these domains leads to sub-optimal performance. Often control systems are developed only after physical-system design is complete, with limited interaction between mechanical and control system engineers. This sequential design approach cannot account fully for design coupling between physical and control systems. More integrated design strategies support the exploration of true system performance limits. Co-design is a specific class of integrated design methods for actively-controlled dynamic systems that produces system-optimal designs by accounting fully for the coupling between physical- and control-system design (Fathy et al. 2001, Allison 2013a, Allison, Herber 2014, Allison, Guo & Han 2014).

Co-design is a promising strategy for developing high-performance sustainable energy systems that capitalize on the relationship between physical- and control-system design. Improving the economic competitiveness of sustainable energy systems may be achieved via tighter integration between physical and control design throughout the design process. Co-design is particularly important for enhancing integration at early design stages when high-impact decisions are made.

Co-design optimization formulations involve a design objective that captures the influence of both physical- and control-system design decisions on system performance. Allison and Herber (2014) provided a detailed taxonomy of co-design formulations. We include the simultaneous co-design formulation here and exclude the rest for brevity.

$$\min_{\mathbf{x_p},\mathbf{u}(t),t_0,t_f} \quad \int_{t_0}^{t_f} \mathcal{L}\left(t,\boldsymbol{\xi}(t),\mathbf{u}(t),\mathbf{x_p}\right) + \mathcal{M}\left(t_0,\boldsymbol{\xi}(t_0),t_f,\boldsymbol{\xi}(t_f),\mathbf{x_p}\right) \tag{1a}$$

$$\text{subject to:} \quad \dot{\boldsymbol{\xi}}(t) - \mathbf{f_d}\left(t,\boldsymbol{\xi}(t),\mathbf{u}(t),\mathbf{x_p}\right) = \mathbf{0} \tag{1b}$$

$$\mathbf{C}\left(t,\boldsymbol{\xi}(t),\mathbf{u}(t),\mathbf{x_p}\right) \leq \mathbf{0} \tag{1c}$$

$$\boldsymbol{\phi}\left(t_0,\boldsymbol{\xi}(t_0),t_f,\boldsymbol{\xi}(t_f),\mathbf{x_p}\right) \leq \mathbf{0} \tag{1d}$$

Note here that the performance objective depends both on the physical design variables $\mathbf{x_p}$, states $\boldsymbol{\xi}(t)$, and control inputs $\mathbf{u}(t)$. The state dynamics are enforced through the dynamic constraint in Eqn. (1b). The path and boundary constraints in Eqns. (1c) and (1d) enforce other constraints in the system (Herber 2014b).

Co-design is an important strategy for investigating and understanding mechatronic system performance limits, a practical means for exploiting synergistic relationships to improve performance, and a tool for revealing synergistic properties of a system. Co-design may also be viewed as a special case of multidisciplinary design optimization (MDO), where one of the coupled disciplines is control system design, and physical-system design is addressed using one or more disciplines (see Allison, Guo & Han (2014) for a comparison of several MDO and co-design formulations). The following subsections detail the method to solve the general co-design problems that are relevant to the sustainable energy system design case studies presented here.

2.1 Direct Transcription in Optimal Control and Co-Design

The optimal control part of Prob. (1) can be solved using two approaches: using indirect optimal control methods such as those based on Pontryagin's minimum principle or direct methods such as direct transcription (DT) (Biegler 2010). One advantage of direct methods that is relevant to co-design is the ability to accommodate general inequality constraints on states, control inputs, and other quantities. DT is a ‘discretize-then-optimize’ method where an infinite-dimensional optimal control problem is discretized to form a finite-dimensional nonlinear program (NLP). This NLP can then be solved using standard large-scale nonlinear optimization algorithms.

A DT solution approach identifies, through an optimization routine, both the control input trajectories and the state trajectories corresponding to an optimal control design. Both sets of trajectories are discretized using function approximation. State trajectories found through the optimization algorithm search process must satisfy state equations (i.e., they satisfy physics-based relationships) as opposed to satisfying physics implicitly via simulation. DT ensures valid state trajectories by enforcing discretized state equations using optimization equality constraints, termed defect constraints. Therefore, co-design implementations utilizing DT optimize with respect to not only control and physical-system design variables but also the discretized states. Various methods can be used to discretize state equations (differential equations) and form (algebraic) defect constraints. While DT problems are often large-scale, problem sparsity can be exploited to support efficient solution (Herber 2014b, Biegler 2010, Wang, and Arora 2009). The extension of DT for co-design has been investigated by Allison et al. (2014), Deshmukh and Allison (2013), Herber (2014b) and Tava and Suzuki (2002).

Realistic co-design problems exhibit bi-directional plant and control design coupling, i.e., control design depends on physical design, and vice versa. As a result, physical design constraints depend on both state and plant design variables, increasing constraint Jacobian density. Please see Allison et al. (2014) for an investigation of co-design with DT sparsity patterns.

While initial studies have addressed these challenges for specific co-design problems, many open questions remain regarding the extension of DT for co-design. For example, utilizing high-fidelity models that capture interactions accurately in early-stage co-design studies would help reveal potential interaction problems that might otherwise surface only after physical prototype testing. Most prior co-design studies have been based on simplified system models because high-fidelity models are computationally impractical when using standard co-design formulations. Recent work in derivative function surrogate modeling has demonstrated an order of magnitude improvement in computational efficiency for high-fidelity co-design problems (Deshmukh 2013). Additional work has been done to include Simscape and Simulink models in DT formulations (Herber 2014a).

Other DT co-design formulations are possible. Herber described the various ways to combine optimal control methods (e.g., indirect, shooting, and DT) with co-design solution approaches (e.g. sequential, nested, and simultaneous) (Herber 2014b). Another proposed approach is to use DT to solve an augmented Lagrangian coordination (ALC) controls sub-problem, similar to the indirect optimal control approach used with ALC by Allison and Nazari (Allison, Nazari 2010). Even more solution procedures can be constructed if MDO is involved (Allison, Herber 2014).

2.2 Capitalizing on Natural Dynamics

Natural (or passive) dynamics refers to the dynamic behavior of a dynamic system without active control. Many systems are designed to operate passively, relying only on their natural dynamics (e.g., most automotive suspension systems (Lu, Li & Papalambros 1984, Deo 2007), vibration absorbers (Dimitrovova 2010), and passive walkers (McGeer 1990)). This design approach can help reduce system complexity and improve stability and reliability. However, natural dynamics also play a critical role in active systems. The physical elements of a system should be designed so that their natural dynamic properties combine synergistically with active control to enhance performance (Sunar, Rao 1993, Smith, Grigoriadis & Skelton 1992, Pitti, Lungarella & Kuniyoshi 2006, Williamson 2003). Doing so can have a profound impact on dynamic performance, including energy efficiency improvements in diverse applications areas such as building design (Oldewurtel et al. 2010) and robotic systems (Allison 2013a, Allison 2013b).

Most natural dynamics studies to date have employed sequential design approaches that cannot achieve system optimality. These studies often use distinct physical- and control-system design objectives. In contrast, co-design methods can help reveal physical designs with passive dynamic properties that combine synergistically with active control to enhance overall system performance. The passive dynamic properties that work best for passive operation usually are not the same as the properties that maximize active performance. Allison (2013a) used co-design to identify robotic manipulator designs with natural dynamic properties that combined ideally with active control to reduce energy consumption significantly. Design approaches such as these help to reduce reliance on active control, reducing control system complexity and energy requirements.

2.3 Balanced Co-Design

Most co-design studies have been performed with a strong emphasis on control design but tend to deemphasize physical-system design (Zimmermann 1991, Fathy 2003). While controls engineers often recognize the importance of integrating physical and control design, they often construct co-design implementations with simplified physical system design formulations. For example, Fathy et al. treat spring and damper coefficients as design variables (Fathy 2003, Fathy et al. 2003), when in reality, these quantities depend on detailed geometric design variables, such as spring wire and helix diameters. These strategies also often neglect physical-system constraints (Allison2014b). As a result, many existing co-design formulations cannot accommodate comprehensive physical design models. For example, nested co-design formulations that use LQR cannot accommodate general inequality constraints for physical-system design (Fathy, Reyer & Papalambros, P. & Ulsoy, A. 2001). Replacing LQR with DT permit physical constraints, but this type of realization is only possible when both physical and control design concerns are considered in a comprehensive and balanced manner.

Another significant issue that has arisen due to control-centric co-design investigations is the assumption of unidirectional coupling between plant and control designs, in which control performance depends on plant design but not vice versa. This assumption is aligned with the legacy design mindset where control systems are viewed as an “add-on” to existing physical systems. In most realistic co-design problems, however, physical-system design decisions do depend on control-system designs. Unidirectional co-design formulations, therefore, cannot capture mechatronic system design coupling completely. Many physical constraints depend on dynamic response, which depends on both plant and control design. For example, material fatigue constraints depend on stress oscillations, which are a function of state trajectories (Allison, Guo & Han 2014). Bi-directional coupling, along with flexibility in physical design, control design, and state spaces, present significant modeling challenges. Developing appropriate models is perhaps one of the most significant challenges in the adoption of co-design, but it is essential for achieving completely new levels of performance in dynamic system design, including the design of advanced sustainable energy systems.

3 ROLE OF CO-DESIGN IN DYNAMIC SYSTEM DESIGN

3.1 Incorporating Co-Design into the Complete System Development Process

Co-design formulations that have been presented in the literature capture important design interactions but solve a relatively narrow problem. With a few exceptions, they typically consist of an optimal physical-system design vector and optimal open-loop control (OLC) trajectories. These results can provide great insights into maximum system performance limits and system dynamics at early design stages. OLC trajectories, however, cannot be used directly in the implementation of a feedback control system. Co-design formulations do not address elements of mechatronic system design such as digital feedback control systems. This does not mean that co-design is useless in mechatronic system design practice: it can be utilized at early design stages to 1) identify physical system designs that account explicitly for coupling with (simplified) control system design, 2) produce optimal control trajectories that can serve as the basis for implementable feedback control systems, and 3) reveal insights such as specific synergy mechanisms that can be used to guide later stages of the design process.

Deshmukh et al. (2015) describes one concept for how co-design might fit within a larger design framework. Co-design methods-based on OLC are used to compare candidate physical-system architectures $\mathbf{a}_i$. Here architecture design refers to the set of physical system components and their relationships. Given $\mathbf{a}_*$, Stage 2 utilizes co-design based on closed-loop control (CLC) to find the optimal controller architecture (control laws, $\mathbf{c}_*$) and optimal physical system design ($\mathbf{x}_{\mathbf{p}*}$). CLC design is informed by the OLC trajectories. Stage 3 realizes the digital controller design. Stage 1 will be typically handled by the mechanical engineers while Stages 2 and 3 will be addressed by control engineers. As more is learned about the design problem, adjustments can be made to co-design formulations to account for previously unanticipated effects or interactions.

While co-design methods cannot generate comprehensive system designs that are ready to implement, co-design is critical for transitioning to a much more integrated design process. Existing modeling tools can account for analysis coupling in mechatronic systems (i.e., how behavior or properties of system elements affect other system elements) but cannot account for the fundamentally different matter of design coupling (how design decisions in one domain influence the ideal design decisions in other domains). Balanced co-design methods are multidisciplinary design methods that account fully for design coupling specifically between physical- and control-system domains and are essential for realizing new levels of performance in sustainable energy systems.

3.2 Identifying Synergy Mechanisms using Co-Design

A synergy mechanism is defined here as:

A specific underlying design mechanism that facilitates overall system performance improvements when two or more design elements are varied synergistically.

Here we look specifically at synergy mechanisms involving physical- and control-system design. Co-design exploits synergy mechanisms in an automated way to improve system performance, but a single quantitative co-design solution most often cannot reveal the qualitative mechanism that facilitated performance improvement. A set of systematic co-design studies, however, can reveal trends and qualitative insights that can help identify underlying synergy mechanisms. Once these mechanisms are revealed, their impact extends well beyond the optimal system designs produced at early design stages such that they can provide a basis for guiding decisions at later design stages where established co-design methodologies may be impractical to use directly.

A solid understanding of the synergy mechanisms at play within a particular system can help engineers make design decisions that lead to significant performance improvements. Identifying synergy mechanisms through careful co-design studies may be viewed as a new strategy for developing new design paradigms tailored for a specific system design problem or as a way of generating new decision heuristics that may be significantly more effective than existing rules of thumb. This new approach may prove to be especially important when system interactions are particularly complex and engineering intuition needs to be supported by a rigorous understanding of design coupling.

These concepts are explored in greater depth in Sections 4 and 5 based on selected case studies of sustainable energy systems. We observe that synergy mechanisms allow the exploration of designs that are unreachable via sequential design. Qualitative synergy mechanisms highlight specifically how design decisions from different domains should be made together to better reallocate resources to enhance overall system performance.

Knowledge of how to specify co-design studies to reveal synergy mechanisms is embryonic. In simpler cases subject matter experts (SMEs) could suggest a set of studies to reveal suspected synergy mechanisms in a more complete manner than intuition alone. For example, larger wind turbine blades and towers produce more energy but result in higher mass and larger structural loads that reduce system life; however, new control strategies can be tailored to support larger component sizes while maintaining system reliability.

More formal approaches for defining co-design studies capable of revealing synergy mechanisms beyond the intuition of SMEs are needed and are the subject of ongoing work. One possible strategy is to compare designs that result from sequential and co-design methods, including extensive analysis to determine fundamental qualitative differences between designs, a strategy based on the assumption that co-design results account for design coupling completely, whereas sequential methods do not. An extensive set of comparisons may be required to identify generalizable differences between sequential and co-design results. In addition to adjusting design objectives and strategies, comprehensive knowledge of synergy mechanisms may serve as a basis for making adjustments within a design organization, such as changes in communication patterns, resource allocation, and other policies, to bring the organization into alignment with the design coupling properties of the system being designed (Sosa, Eppinger & Rowles 2003, Sosa, Eppinger & Rowles 2004).

4 CASE STUDIES OF SUSTAINABLE ENERGY SYSTEMS

In many engineering domains, dynamic system energy flow is critical to system performance. This section describes three case studies covering both energy production and energy consuming systems.

4.1 Horizontal Axis Wind Turbines

One important objective in wind turbine design is to maximize the annualized energy production (AEP). The AEP is an approximate estimate of the energy produced by a wind turbine over a year for an assumed probabilistic wind speed distribution $p(v)$ (often a Weibull distribution):

$$AEP = 8760 \times \int_{v_i}^{v_o} P_w(v)p(v)dv \quad (2)$$

AEP depends on the wind turbine rotor power, $P_w(v)$, is modeled using the following formula:

$$P_w(v) = \frac{1}{2}C_P(\lambda,\beta)\rho\pi {R_r}^2 v^3 \quad (3)$$

where the power coefficient, $C_p(\cdot)$, is a nonlinear function of blade tip speed ratio, λ, and blade pitch angle, β. The air density is ρ, R_r is the rotor radius, Ω_r is the rotor speed, and v is the wind speed. For a given physical turbine design and wind speed, the power capture maximization problem reduces to tracking the optimal power coefficient by controlling λ, (via generator torque) and β. AEP depends on both physical design (e.g., blade and tower geometry) and control inputs (such as generator torque and blade pitch angles), so co-design is an important strategy for turbine design (Deshmukh 2013).

To illustrate the benefits of using co-design to investigate synergy mechanisms, the AEP maximization problem was solved for each of the three formulations: sequential design, nested co-design, and simultaneous co-design. In each case constraints on blade and tower bending were imposed. AEP for both co-design formulations is 3231.5 kWh (demonstrating mathematical equivalence), whereas the sequential design formulation achieved only 2996.9 kWh. The co-design solution is 8.03% larger than the sequential design result, which is a very significant increase (particularly for high-capacity turbines).

4.2 Heaving Cylinder Wave Energy Converter

One type of wave energy converter (WEC) is the heaving cylinder WEC (HCWEC) (Fig. 1a) that is connected to a power take-off (PTO) moored to the ocean floor. The cylinder radius is a, the draft of the cylinder, b, is the submerged length in still water, and the wave elevation is $\eta(t)$. The vertical position of the buoy mass center z is measured from the still water level (SWL). As buoyancy forces the heaving cylinder upward, the PTO resists buoy motion. Work is done on the PTO at the rate:

$$P(t) = F_{\text{PTO}}(t)\dot{z}(t) \tag{4}$$

where $F_{\text{PTO}}(t)$ is the PTO force on the buoy and $\dot{z}(t)$ is the vertical velocity of the heaving cylinder. Here the design objective is to maximize energy produced over a desired time horizon $t_0 \rightarrow t_f$

$$\max \quad \int_{t_0}^{t_f} P(t)dt \tag{5}$$

The disturbance is the ocean wave expressed as a linear superposition of regular wave components:

$$\eta(t) = \sum_{i=1}^{N_I} \eta_i(t) \qquad \text{where: } \eta_i(t) = \frac{H_i}{2} \sin\left(\frac{2\pi}{T_i}t + \theta_i\right) \tag{6}$$

where N_I is the number of regular wave components, and H_i, T_i, and θ_i are the wave height, period, and phase for component i. Many studies on consider regular waves, i.e., $N_I = 1$. However, real ocean waves are irregular, so WEC designs need to maximize energy harvesting from irregular ocean waves.

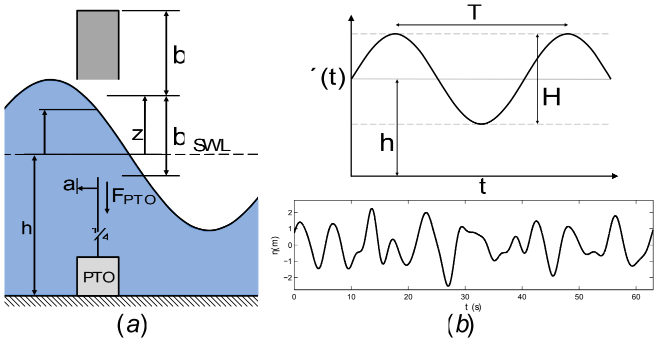

Figure 1. (a) Heaving cylinder wave energy converter and (b) Regular (top) and irregular (bottom) ocean wave profile.

Designing for regular waves without any constraints on the power or force trajectories could be performed in the frequency domain (Falnes 2012) leading to a reactive PTO (power follows both into and out of the PTO). Co-design with DT (based on similar assumptions) resulted in similar harmonic dynamics. However, reactive control has a number of potential issues including high forces and amplitudes, motivating alternative formulations that place restrictions on the PTO power ($P(t) \geq 0$), PTO force ($F_{\text{PTO}}(t) \geq 0$), and amplitude ($|z| \leq c$). DT was a natural solution approach for solving the problem with these constraints.

From these constrained (but potentially more implementable) formulations came general physical and control design solutions. In addition to reactive control, 'latching' ($\dot{z} = 0$ for an amount of time) and 'declutching' ($F_{\text{PTO}} = 0$ for an amount of time) were identified. These general control themes have been reported in literature but came as a result of various studies over a long period of time rather than a single flexible formulation. In addition, co-design studies revealed the benefit of disk-like buoy designs (large a, small b) rather than devices than resonate with the incoming wave.

It is common to apply the control strategies for regular waves to more realistic irregular waves by tweaking the identified structured control laws (latching control is quite commonly done this way). However, this may not lead to the best performance and may not capitalize on the unique properties of the irregular wave. Results using co-design with DT in irregular did show similar dynamics and control (one formulation spent 75% of the time horizon either latched or declutched). However, since the irregular waves had a more dynamic profile, the control strategy favored putting large amounts of energy into the system to position the device exactly to extract large amounts of power during high elevation sections of the wave.

4.3 Energy-Efficient Simple and Counterbalanced Robotic Manipulator

A two-link robotic manipulator was designed for a specific pick-and-place task (without considering the return trajectory) for minimal energy consumption while complying with joint actuator torque and link deflection constraints. Figure 2a illustrates a simple robotic manipulator while Fig. 2b illustrates one that is counterbalanced with m_{c1} and m_{c2} The task, illustrated in Fig. 2c, is defined by initial and

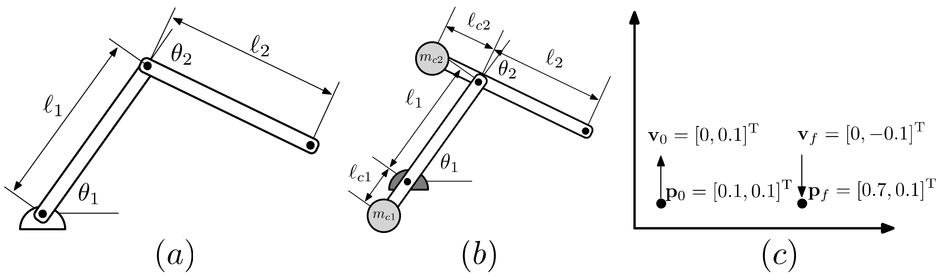

Figure 2. (a) Simple two-link planar manipulator, (b) Counterbalanced two-link planar manipulator, (c) Task initial and final conditions.

final positions and velocities for a 20 kg payload that is to be moved in 2 sec. The links have a tunable hollow tubular cross-section. Then the co-design problem formulation is:

$$\min_{\mathbf{x}=[\mathbf{x_p},\mathbf{x_c}]} \quad E(\mathbf{x}) \tag{7a}$$

$$\text{subject to:} \quad |\tau_{\max,i}(\mathbf{x})| \leq \tau_{\text{allow}} \qquad i = \{1,2\} \tag{7b}$$

$$\delta_i(\mathbf{x_p}) \leq \delta_{\text{allow}} \qquad i = \{1,2\} \tag{7c}$$

$$\mathbf{M}(\mathbf{q},\mathbf{x_p})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}},\mathbf{x_p})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q},\mathbf{x_p}) = \boldsymbol{\tau} \tag{7d}$$

where $E(\mathbf{x})$ is the total mechanical energy required, Eqn. (7b) is the maximum torque constraint, and Eqn. (7c) is the link deflection constraint. Equation (7d) is the nonlinear differential equation used to model manipulator dynamics with $\mathbf{q}$ as the generalized coordinates and matrix terms that depend on state and plant variables. The joint torques are calculated using inverse dynamics, and control design specifies motion trajectory (Allison 2013a, Allison 2013b).

The link lengths and energy consumption for four problem formulations is shown in Table 1. The optimal payload trajectories for both the nominal plant design and co-design formulations follow a 'falling' type motion; this exploits passive dynamics to reduce energy requirements. Co-design produces a larger linkage design, a counterintuitive result. Mass increased, but energy consumption decreased (by a factor of 783) because nonlinear passive dynamics were tailored such that very little control effort was required. A parametric study revealed that for larger task times, passive dynamics dominate, but for faster motions more control effort and energy is required. Results from the counterbalanced manipulator further demonstrate the benefits of passive dynamics designed through combined plant and control design. The difference in energy consumption between the nominal and co-design result is six orders of magnitude. Including counterbalance masses produces a stronger synergistic relationship between natural dynamics and active control.

Table 1. Robotic manipulator case study optimal link lengths and energy consumption.

	ℓ_1 (m)	ℓ_2 (m)	Energy Consumption (J)
Simple, nominal $\mathbf{x_p}$	0.60	0.60	2.13×10^{1}
Simple, co-design	1.77	1.63	2.72×10^{-2}
Counterbalanced, nominal $\mathbf{x_p}$	1.00	1.00	2.76×10^{1}
Counterbalanced, co-design	0.84	0.71	5.86×10^{-5}

5 GENERALIZED DESIGN CONCEPTS: SUSTAINABLE ENERGY SYSTEMS

In this section we look at some of the generalized concepts derived from the above design case studies.

5.1 Synergy Mechanisms

Specific synergy mechanisms were revealed in these case studies that enabled co-design to obtain system-optimal solutions. These are here presented for two of the case studies.

5.1.1 Wind Energy System Deign

Wind turbine size has direct impact on AEP, but structural constraints are more challenging to satisfy for larger turbines. Using co-design, physical-system design is tailored to work in concert with control-system dynamics, and control systems can be designed in a way that makes satisfaction of

physical design requirements easier. For example, the optimal torque trajectory obtained via co-design not only helps maintain an optimal tip speed ratio, but also helps manage structural deflections and stress by reducing rotor speed. Because control design helped to ease plant constraint satisfaction, there was more flexibility in physical design, enabling a larger that increases AEP. These synergistic effects are only available when plant and control design coupling are considered together explicitly.
Optimal geometric blade design influences power coefficient characteristics and AEP significantly. This observation helps to further explain the effectiveness of co-design strategies. In sequential design, AEP can only be improved by adjusting blade geometry during physical design optimization, and then control design is simply a trajectory-matching problem. In contrast, when a co-design approach is used, there is an additional mechanism for increasing AEP: we seek blade and control designs that work together to increase AEP.

5.1.2 Robotic Manipulator Design

In sequential design of the robotic manipulator, even optimal control trajectories waste significant effort in overcoming the inertial resistance in the system. Designing passive dynamics alone is not enough to minimize energy consumption; co-design identifies passive dynamics that work synergistically with active control to produce near-zero energy consumption for tasks that cannot be accomplished using passive dynamics alone.

5.2 Modeling and Design Methods for Energy Systems in Dynamic Environments

An intrinsic element of all of these formulations is the dynamic environment in which they operate. Energy harvesting devices rely on interaction with dynamic environments to generate usable electricity. For example, WECs utilize destructive interference between ocean waves and device oscillation to extract energy. Successful co-design of energy sustainable systems requires models and design methods that adequately account for interaction with dynamic environments.

5.2.1 Modeling

Each case study was designed for a specific quantifiable environment. The wind turbine design operated in a probabilistic distribution of wind speed. The robotic manipulator operated under Earth's gravitational field that has significant influence on optimal link design and control trajectories.
Early WEC regular wave investigations were motivated by the design method (frequency domain analysis) rather than the natural resource. The control strategies developed for regular waves have been shown to have inferior performance in more complex waves (Tedeschi et al. 2010). Complete system-level design of sustainable energy systems should try to accurately quantify dynamic environment interaction to provide usable insights into real system performance.

5.2.2 Design Methods

Due to the presence of the dynamic constraint in Eqn. (1b), design methods suitable for dynamics are necessary for successful and efficient solution procedures. All three case studies were possible through naturally dynamic solution procedures. Often, time-domain solutions and direct optimal control are required to account fully for interaction with the environment and realistic system constraints.

6 CONCLUSIONS

Significantly higher levels of renewable energy generation effectiveness and energy efficiency are possible through recent advances in integrated design methods for dynamic systems. In particular, balanced co-design methods can account for complicated types of design coupling to produce system-optimal designs. In addition, systematic co-design studies are a promising technique for identifying specific synergy mechanisms that can be used at later design stages as a basis for highly effective design strategies that are tailored for a particular system.

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