

Computational Co-Design of Structural Morphology and Control

Research, Teaching and Valorization Proposal of within Computational Dynamics Group (Department of Mechanical Engineering, Eindhoven University of Technology)

BRANDON CAASENBROOD**, Eindhoven University of Technology, the Netherlands



Fig. 1

Abstract: *Computational design*, also referred to as *co-design*, is recently emerging, transformative approach optimizing structure and governing control law. Traditionally, the design philosophy in mechatronic systems has been predominantly driven by user requirements, with structural design and control treated as sequential and largely independent processes. In this paradigm, the mechanical design is established first (often without the consideration control's impact on dynamics) and control strategies are subsequently implemented to ensure robust system operation. Co-design, on the other hand, enables the simultaneous refinement of both the physical architecture and the control algorithms, thereby enhancing system performance and robust environment adaptability. By leveraging dynamic (topology) optimization, the proposed framework seeks to address the limitations of conventional design methodologies, particularly in the context of high-precision applications where the interplay between structure and control are of paramount importance. The anticipated outcomes include improved motion accuracy, vibration mitigation, and adaptive responses to varying operational conditions, ultimately advancing the capabilities of next-generation mechatronic systems.

The optimal configuration of a mechatronic system is inherently linked to its operational dynamics, necessitating a co-design methodology that simultaneously considers both morphology and

control. To address these challenges, the research proposal will explore dynamic topology optimization framework tailored for high-precision mechatronic systems. This approach extends conventional density-based optimization by incorporating temporal evolution, enabling the concurrent optimization of structural layout and actuation strategies for specific dynamic tasks. By employing multi-indexed density variables across the spatiotemporal domain, our method efficiently captures material distribution, actuator placement, and time-dependent control inputs. Gradient-based optimization techniques, combined with advanced simulation methods such as the material point method and automatic differentiation, facilitate robust forward and backward analysis of system behavior.

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Additional Key Words and Phrases: Com

1 Research proposal

Definitions

Before detailing the topic of co-design, us first introduce some definitions. **Morphology**, from the context of biology, refers to the study of the form, structure, and material composition of organisms and their constituent parts, with emphasis on how these attributes determine function and facilitate environmental adaptation. This discipline investigates the relationship between anatomical features — such as shape, size, and material organization — and their functional and adaptive significance in evolutionary and ecological contexts. **Control**, on the other hand, encompasses algorithms by which the system's dynamics achieve a desired behavior. It is often relies on mathematical framework for designing control algorithms that govern system responses, ensuring stability, accuracy, and robustness under varying operational and environmental conditions.

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Author's Contact Information: Brandon Caasenbrood, b.j.caasenbrood@gmail.com, webmaster@marysville-ohio.com, Eindhoven University of Technology, Eindhoven, North Brabant, the Netherlands.



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Sensor placement and actuator placement are critical considerations. Sensor placement involves determining the optimal locations for sensors to maximize observability, minimize noise, and ensure accurate state estimation. Strategic sensor positioning enables effective monitoring of system variables, facilitating robust feedback and enhancing control precision. Actuator placement, conversely, focuses on the spatial arrangement of actuators to achieve desired force transmission, responsiveness, and efficiency. The configuration of actuators directly influences the system's controllability and dynamic performance, affecting both stability and energy consumption. In advanced engineering applications, the co-optimization of sensor and actuator placement is increasingly recognized as essential for achieving superior system performance, particularly in environments demanding high accuracy and reliability.

An excellent example of applied morphology in engineering is found in soft robotics. Soft robots, a modern subdomain of robotics, leverage compliant materials to enhance adaptability and dexterity. The importance of morphology in facilitating control has been widely recognized within this research community, where designs are often inspired by biological systems that simplify controller design. However, in the broader field of engineering, the deliberate integration of morphology into controller design processes remains rare, despite its critical role in the development of **high-precision mechanical systems** that are increasingly demanded by the semiconductor industry and other advanced sectors. From a mechatronic perspective, the morphology of a mechanical system—including:

- Geometric configuration
- Degrees of freedom
- Mass distribution
- Stiffness and damping properties

that together constitutes the fundamental aspects of its dynamic behavior. These morphological parameters govern the system's response to internal and external inputs and directly influence control design. Thus, while the terminology may differ across disciplines, the underlying principle persists: **structure dictates function**, whether in the study of natural organisms, soft robotics, or high-precision engineered systems.

1.1 Problem statement

To highlight the importance of co-design as a framework, let us consider a few illustrative design problems.

Example 1 – Disturbance-rejection: Consider a mechanical structured subject to external vibrations, such as those induced by nearby machinery or environmental disturbances. The design objective is to develop an active structure whose morphology and control strategy are co-optimized to suppress the transmission of floor vibrations to the payload.

1.2 State-of-the-art in co-design

Co-design represents a recent paradigm shift in system engineering frameworks, emphasizing the simultaneous optimization of a mechanical system's morphology and its associated control strategies to maximize performance. Unlike traditional design approaches—which often treat mechanical design and control as sequential, independent processes—co-design seeks to exploit the synergistic relationship between structure and control, enabling the development of systems with superior precision, adaptability, and efficiency.

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Fig. 2. 1907 Franklin Model D roadster. Photograph by Harris & Ewing, Inc. [Public domain], via Wikimedia Commons. (<https://goo.gl/VLCRBB>).

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