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

Research abstract: Traditional mechatronic system design has largely followed a sequential approach, where mechanical structure and control strategies are developed independently based on predefined requirements. In this conventional paradigm, the mechanical design is typically finalized before control considerations are introduced, often neglecting the mutual influence between structural dynamics and control performance. On the other hand, *computational design*—or *co-design*—enables the concurrent optimization of both mechanical structure and control algorithms. This integrated methodology enhances overall system performance and adaptability, particularly in high-precision applications where the interaction between structure and control is of paramount importance. By leveraging on the methods of co-design, the proposed research framework addresses the limitations of traditional design approaches, facilitating improved motion accuracy, disturbance rejection, requirement driven sensor-actuator placement, and adaptability to varying operational conditions.

The research aims to develop a dynamic topology optimization framework tailored for high-precision mechatronic systems. This approach extends conventional density-based optimization by incorporating temporal evolution, allowing for the simultaneous optimization of structural configuration and control strategies. Utilizing multi-indexed density variables across the spatiotemporal domain, the method efficiently captures material distribution, actuator placement, and time-dependent control inputs. Gradient-based optimization, combined with advanced simulation techniques such as the material point method and automatic differentiation, enables robust analysis and optimization of system behavior. The anticipated outcomes include significant advancements in the design and performance of next-generation mechatronic systems.

Additional Key Words and Phrases: Com

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

ACM XXXX-XXXX/2025/7-ART
https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 Research proposal

Before discussing co-design, let us establish some key definitions. **Morphology**, a common term often coined in 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 context. **Control**, on the other hand, encompasses algorithms that govern (closed-loop) system dynamics to achieve desired behavior through mathematical frameworks ensuring stability, precision, and robustness under varying conditions.

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

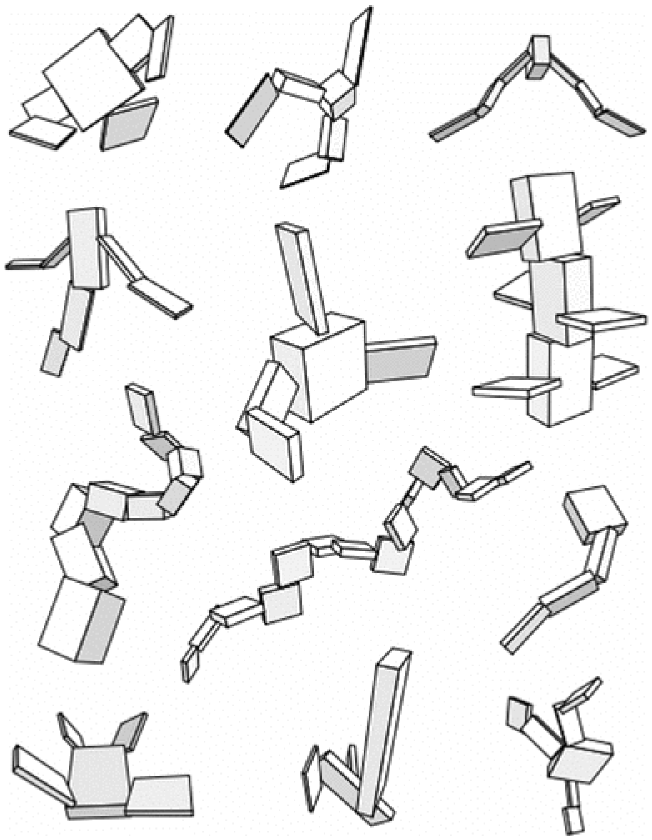

Fig. 2. Numerical examples of Karl Sims co-design of artificial-life locomoting creatures

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. ## 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.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

2 Research approach

Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009