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Computational Robot Design and Customization

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New advances in digital fabrication have increased our ability to create complex geometric structures with an ever-expanding range of materials (rigid, compliant, conductive, etc.). At the same time, computational design tools offer a tremendous opportunity to facilitate robot design by encoding structural, control, or fabrication constraints during the design cycle, enabling roboticists to navigate the vast design spaces enabled by digital fabrication. The combination of these two promises new robot forms and capabilities to expand the applications and performance of future robots.

Decisions made by engineers at various points during a robot design process are heavily influenced by the tools they have at their disposal. These tools may present constraints or new options for how to specify a design, model and simulate it, explore interactions between different subsystems (mechanical, actuation, control, etc.), or fabricate and assemble the design. To complicate the problem, tools used at different stages of the design may present different constraints. In the simplest case, consider a user drawing a part for 3D printing. The 3D modeling software may, through the controls available to the user, restrict the types of geometries the user might create while, at the same time, allowing geometries that cannot be printed. Similarly, the software and drivers associated with the 3D printer automatically produce feasible toolpaths yielding the closest approximation to the inputted geometry but often do not allow the user to determine how choices between geometrically similar but functionally different toolpaths are made. It is then up to the user to navigate between the two and make adjustments to ensure that the product of the combined design and fabrication tools yields the desired final design.

This special issue was born out of discussions on how computation could streamline this process in robotics, where not only mechanical design and fabrication must be considered, but also their interplay with actuation, sensing, control, and planning subsystems. The special issue is centered around two major questions:

1. How can computational approaches enhance workflow and facilitate the design and rapid prototyping of robots?
2. How can new materials and manufacturing approaches lead to uniform processes for fabricating robots on-demand?

The papers featured in this special issue include the authors' answers to these questions from different angles.

Three of the papers consider optimization-based approaches to improving overall functionality. In "Optimal Architecture Planning of Modules for Reconfigurable Manipulators," Dogra et al. propose an optimization-based approach to designing robots where the dynamical behavior is a key aspect.

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Physics-based models for their modular robots are parameterized by mass and geometry, which are then chosen to maximize actuation effort over the desired path. In contrast, “Speeding up Online Route Scheduling for an Autonomous Robot through Pre-Built Paths” by Alves et al. approach the problem from a planning perspective, investigating minimal lengths paths for route scheduling in a known environment. They propose that storing and manipulating pre-built paths within an environment enables real-time scheduling in response to user-inputted target locations without sacrificing path optimality. In the middle of these two, the paper “Advancing Soft Robot Modeling in ChainQueen” by Spielberg et al. argues that the dynamics of a robot and its controllers should both be included in a robot optimization framework to achieve better performance in locomotion and reaching tasks, and they demonstrate how this can be done for soft robots using a differentiable dynamic simulator for compliant designs. It becomes clear from these papers that the interplay between a robot’s physical actuated body and its software control remains an important consideration in customized robots, and more work must continue to be done to understand what assumptions can or cannot be made at each stage of robotic design and usage.

At the same time, new fabrication approaches may also open up new possibilities for robot design. In “FABR – A Functional Assembler of Building Block Robots,” Langford and Gershenfeld propose a new system of electronics modules that can be assembled via pick-and-place into integrated machines. The authors propose that these modular systems will enable fully automated fabrication and assembly for integrated electromechanical devices. In “Fabrication-aware Design for Furniture with Planar Pieces,” Yan et al. consider a different approach, focusing on the geometrical design, and demonstrate that fully 3D models can be designed as flat-packed foldable shapes for simpler 3D assembly. In “Towards One-Dollar Robots: An Integrated Design and Fabrication Strategy for Electromechanical Systems,” Yan and Mehta take this idea one step further by providing design guidelines for foldable electromechanical systems using readily available resources such as paper and SMA wires, producing an electromechanical oscillator with 0.40USD of materials. Fabrication approaches such as those presented in these papers enable computational models for an automated or computer-aided design using materials more easily accessible to those who would build customized hardware.

Zooming back out, computational approaches to both design and fabrication and the interaction between the two have great potential to expand the space of possible robot and engineering designs. Rapid developments currently occurring in the field tackle the associated challenges from multiple angles, from simulation- and optimization-focused design abstractions to bottom-up fabrication approaches enabling new designs. It is clear that a broad and interdisciplinary effort is required to continue to close the gap between the two. As guest editors, we hope that the articles in this special issue will inspire new research in the area of computational design and fabrication for robots. We also wish to thank all of the contributors, reviewers, and editors for their work on this special issue and in this field.