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Editorial

Special Issue: Fabrication of Fully Integrated Robotic Mechanisms

The past two decades have seen immense strides being made in novel fabrication techniques, particularly in additive manufacturing (AM) technologies, also known as "rapid prototyping" and "3D printing," as well as in novel subtractive techniques such as laser-cutting and waterjet-cutting. The most popular practical technologies, such as fused-deposition modeling (FDM), stereolithography, selective-laser-sintering, and laser-cutting, are currently used worldwide and are rapidly becoming even more widespread and inexpensive. While all these processes enable rapid and easy fabrication of parts with complex geometries, they are limited in a number of ways, including a small number of available materials, low strength of fabricated parts, and are generally only capable of producing monolithic components.

Fabricating robotic mechanisms—which generally consist of many moving parts, complicated kinematics, and require the incorporation of actuators, sensors, power sources, interconnects, and power and control electronics—prompts the need for novel manufacturing processes in order to move past the heterogeneity of current approaches, in which many subcomponents are fabricated separately and then assembled together with fasteners to produce the full system. As a result, traditionally fabricated systems are generally more expensive, heavy, inefficient, and/or less durable than is desirable. In order to be able to produce fully integrated robotic mechanisms that significantly extend the capabilities of current techniques, novel approaches to fabricating multipart and multimaterial systems that combine previously disjoint components and/or enable completely new functionality must be developed. Ongoing efforts with processes such as shape deposition manufacturing and origami-inspired folding processes are charting a course in this general direction, but much work remains to be done.

This special issue represents a collection of 15 papers from researchers in seven countries on three continents. The papers generally address new methods and techniques for fabricating robotic mechanisms or subsystems, or methodologies and designs for the effective utilization of emerging fabrication techniques. We organize the papers into three main topic areas: novel AM techniques (four papers); soft robotics and structures (four papers); and folding-based approaches (seven papers).

On the first topic, related to novel approaches for AM techniques, the first two papers focus on the mechanical structure of fabricated components. The first, by Tanner et al., describes a technique by which photolithographic patterning and infiltrating carbon nanotubes with a variety of bulk materials to produce stacked layered parts with submillimeter resolution. Next, Ma et al. describe a technique to utilize traditional FDM in a new way, to print both mechanical structures and sacrificial molds that are then filled with other resins to create multimaterial components. The second two papers describe approaches to enable the printing of electrically conductive components, both using FDM as a basis. The first, by Kim et al., implements a method of laying down conductive wires or meshes via a second extrusion head to embed them within the AM printed part. The second, by Swensen et al., introduces a technique in which parts are printed with hollow traces that are then filled with a low-melting temperature metal in order to produce AM parts with integrated electrical traces and components.

The second major topic area, consisting of four papers, concerns the production and design of "soft" structures and robotics. The first three papers in this group concern the development of soft, compliant grippers, or hands built from multimaterial processes and with integrated electrical and transmission components. Suresh et al. describe a novel membrane-based gripper and a related fabrication technique for the purposes of grasping curved surfaces. Gafford et al. describe a miniature adaptive surgical gripper and its fabrication method designed to fit through small surgical ports. She et al. present a soft robotic hand with embedded shape-memory alloy (SMA) wires in the digits for actuation. The fourth paper in this group, by Chossat et al., describes the development and fabrication of a soft robotic skin sensor that utilizes microchannels filled with an ionic liquid, which are imaged using electrical impedance tomography in order to sense impedance changes due to contact.

The final and largest topic area of papers in the special issue, consisting of seven papers, concerns the design and fabrication of parts based on folding techniques. The first group of these focuses on the folding-based fabrication processes. Firouzeh and Paik present a technique for a fully integrated folding fabrication methodology with embedded actuation and electronics, along with experimental demonstration in a crawling robot. Jung et al. describe a layered manufacturing technique for laminating composites and sheet metal and apply the technique to a folded jumping robot utilizing a bistable spring concept. Finally, Haldane et al. present a method for fabricating folded robots with integrated structure, electronics, and sensing based on laser machining of multilayered laminated structures.

The second group of folding-based papers generally discusses the algorithmic design of components and systems for fabrication by folding techniques. Sung and Rus describe, analyze, and experimentally evaluate a number of design options for joints for foldable structures. Miyashita et al. present a design and fabrication methodology for creating self-actuated folds that have the desired fold angle and experimentally demonstrate the concept on a range of self-folding propellers. Zhang et al. present a concept for creating a simple module based on helical origami fold in order to create the natural contracting, bending, and twisting motions for a worm robot with integrated SMA actuators. Finally, Mehta et al. describe a framework for semi-automatic generation of folded robot design based only on a high-level description of the structure, facilitating the particularly challenging detailed design of folded systems.

We are at an exciting and crucial time in the large-scale transfer of electromechanical and robotic systems from the research laboratory to mass-produced commercial systems. The requirements of real-world applications and inexpensive manufacture have shown many of the traditional ways of manufacturing to be inappropriate for these classes of devices, and new methods of fabrication and subsequent design must be developed. We believe that recent progress in fabrication and design in areas such as additive and layered manufacturing and folding-based fabrication, including the advances described in this special issue, will help to bring those processes closer to being able to be widely utilized.

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