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Editorial

Focus on 4D materials design and additive manufacturing

Mahdi Bodaghi[1,*], **Suong Van Hoa**[2], **Thomas Gries**[3], **Antoine Le Duigou**[4], **Yonas Tadesse**[5], **Lining Yao**[6] **and Ali Zolfagharian**[7]

[1] *Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, United Kingdom*
[2] *Concordia Centre for Composites (CONCOM), Department of Mechanical, Industrial and Aerospace Engineering (MIAE), Concordia University, Montreal, Canada*
[3] *Institut Für Textiltechnik, RWTH Aachen University, Otto-Blumenthal-Straße 1, 52074 Aachen, Germany*
[4] *Polymer and Composites, Bionic-Group, Université Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France*
[5] *The Humanoid Biorobotics and Smart Systems (HBS Lab), The University of Texas at Dallas, Richardson, TX 75080, United States of America*
[6] *Human-Computer Interaction Institute, School of Computer Science, Carnegie Mellon University, Pittsburgh, PA 15218, United States of America*
[7] *School of Engineering, Deakin University, Geelong, Victoria 3216, Australia*
E-mail: mahdi.bodaghi@ntu.ac.uk

Four-dimensional (4D) printing involves the creation of materials that can change their shape, structure, or functionality over time in response to external stimuli. This incredible adaptability opens new possibilities in fields ranging from robotics to biomedical applications. This focus issue in Smart Materials and Structures is dedicated to the latest research in the dynamic field of 4D materials design and additive manufacturing. With a rapidly evolving landscape, we aimed to explore various exciting topics that are at the forefront of scientific advancements. This focus issue shed light on the current industrial applications of 4D printing. In fields such as medical, aerospace, automotive, defence, and mechanical engineering, 4D printing has already made significant strides. From customized implants and prosthetics in healthcare to adaptive structures and components in aerospace and automotive industries, the practical applications of 4D printing are diverse and impactful. This focus issue includes nine original research articles jointly made by involvement of more than 30 active academics in the field from diverse international centres and universities.

Zolfagharian *et al* [1], designed a soft parallel robot electrothermally driven by a linear silicon-based actuator via 4D printing. In their study, they found that the planar parallel manipulator could be driven by silicon-based soft actuators replacing rigid linear actuators. The study shows a promising strategy for using 4D materials in the next generation of additively manufactured (AM) robots. This strategy can improve customizability, flexibility, and manufacturing time and effort efficiency in different industries that use soft robots.

Cheng *et al* [2] published their work on the quasi-static compression behaviour of 3D-printed continuous ramie fibre reinforced biocomposite corrugated structures (CFCSs) with excellent shape memory effects. An analytical model was developed to estimate the in-plane compression strength of biocomposites reinforced with continuous ramie fibre and inverted trapezoid cell shape corrugated structures (CFITCSs), and the results showed excellent agreement with tests. It was said that as the fibre volume fraction goes up, the CFITCS become tougher and easier to shape. The results of the shape recovery tests show that 3D-printed CFCSs could be an important part of lightweight, programmable smart systems.

Zou *et al* [3] proposed a model-free, proxy-based, sliding-mode tracking control method to deal with viscoelastic nonlinearity in dielectric elastomer actuators (DEAs) and achieve high-precision tracking control. The experimental findings demonstrate that the DEA is able to properly track sinusoidal trajectories in the frequency range of 0.1 Hz–4.0 Hz by minimising the influence of intrinsic viscoelastic nonlinearity when using a sliding-mode tracking controller. When compared to open loop tracking performance, this is a huge improvement.

[*] Author to whom any correspondence should be addressed.

Hosseinabadi *et al* [4] 3D printed Energy-absorbing, shape-recovering meta-structures with negative stiffness. The meta-structures were made with a 3D printing method called selective laser sintering. Using the snap-through instability mechanism, elastoplastic deformation growth, and plastic hinges, different negative stiffness structures (NSSs) were made. It was found that all NSSs have a high ability to take in and release energy in the first cycle through mechanisms of plasticity and instability. During further loading and unloading cycles, NSSs show either super-elastic stability or instability, depending on their geometrical parameters and configurations. They can absorb a lot of energy and return to their original shape in full or in part. The presented conceptual design and results are expected to help us learn more about how NSSs work and help us design NSSs that work well for a variety of applications.

Guerra *et al* [5] demonstrated the applicability of Cu-11Al-5Ni-4Fe wt% for producing shape memory alloy by additive manufacturing. Compressive stress testing was performed on the alloy in three different states: as-built (AB), heat treated (AB), and commercial (COM) (cast) (quenched). It has been found that at high temperatures (350 °C), the COM sample damping capacity is improved owing to the activation of the slip system at low stress (around 600 MPa), leading to greater deformation energy dissipation. The study sheds light on how certain phases and their spatial distribution may be used to programme the shape memory features of pseudoelasticity and damping capacity of Cu-11Al-5Ni-4Fe wt% alloy.

Zolfagharian *et al* [6] developed multimaterial 4D printing with a tunable model that could be used in soft robotics. The bending of a 4D composite was regulated by varying the thickness ratio of its two constituent layers, each of which was built from a shape-memory polymer (SMP) and a flexible elastomer. The composite beams were 3D printed using a commercial Stratasys J750 printer and commercial materials Vero-Black (a glassy polymer) and TangoPlus (an elastomer), which were activated by heating at a uniform and consistent temperature. The flat 2D beams were transformed into a 3D structure using 4D printing. Their work also suggests a new way to design products in which parts are made to be able to change into different shapes in demand while in service.

Ali *et al* [7], made a 3D-printed filtering medium with programmable geometric features that changes under in-plane tensile strain and can be used to separate particles. The linear elastic in-plane tensile strain and the lattice size in the suggested metamaterial were discovered to have an empirical relation by numerical analysis. When subjected to a linear strain, the proposed prototype can sort particles between 4 mm and 4.5 mm in size. Their proposed design is scalable, which means it can be used to make a system that can filter particles from the nanoscale to the microscale and the macroscale in a wide range of filtering applications.

Alshebly and Nafea [8] looked into how to control the internal strain of polylactic acid-based actuators 4D printed by fused deposition modelling (FDM). When printing at the same temperature and layer height, it was discovered that raising the printing speed increased the internal strain. All the printing parameters and actuation were linked to the bending angle in a prediction model. This model was used in an eight-arm gripper and a four-arm gripper to show the efficacy of proposed method.

Samal *et al* [9] demonstrated two programming options for SMP processed by FDM: programming during printing (PDP) and programming after printing

(PAP). Using techniques like x-ray diffraction, field emission scanning electron microscopy, and Fourier transform infrared spectroscopy, which are used to look at both macro and microstructural features, the results show that PDP has better shape memory properties than PAP. Their results would help researchers and professionals in the industry figure out how to use 4D printing and choose the best programming strategy for their needs.

The focus issue highlighted some remarkable capabilities of 4D printing, which have emerged as revolutionary technologies in recent years. The 4D printing offers unique advantages such as increased flexibility and adaptability, making it ideal for various applications where conventional 3D printing may not be suitable. These features hold tremendous potential for applications requiring dynamic response and shape-changing capabilities. Understanding coupled mechanical behaviour, fatigue resistance, and aging effects and co-manufacturing with other materials is crucial for their successful implementation in real-world scenarios. Essential elements for achieving functional 4D printed products directly from computer aided design files include AM composite combining stronger and softer materials, as well as vital circuits and wire interconnects. By exploring these topics, their theoretical progress, and industrial applications, we hope to foster a deeper understanding of the potential and challenges associated with 4D materials design and additive manufacturing. This focus issue hopes to provide a platform for researchers to share their insights, latest discoveries, and innovative solutions, further propelling the advancement of this exciting field.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Mahdi Bodaghi https://orcid.org/0000-0002-0707-944X
Suong Van Hoa https://orcid.org/0000-0002-4901-7212
Antoine Le Duigou https://orcid.org/0000-0002-7102-3491
Yonas Tadesse https://orcid.org/0000-0001-6606-7089
Ali Zolfagharian https://orcid.org/0000-0001-5302-360X

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