Materials Advances

ROYAL SOCIETY OF CHEMISTRY

EDITORIAL

View Article Online
View Journal

Cite this: DOI: 10.1039/d4ma90117g

Introduction to 'Multimodal remote actuation and sensing in polymer nanocomposites for advanced applications'

Vinay Deep Punetha, *[a] Lorenzo Bardella [b] and Mohammad Luqman [c]

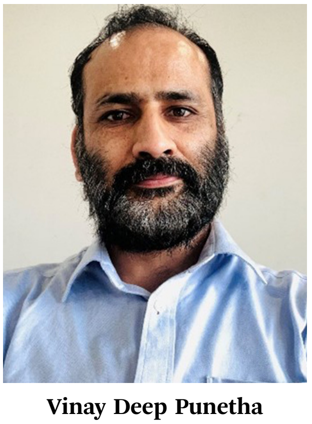
DOI: 10.1039/d4ma90117g

rsc.li/materials-advances

Advancements in science have redefined the traditional use of polymers, leading to innovative applications, particularly in developing actuators and sensors. These remarkable devices are at the forefront of technological innovation, providing versatile solutions across various industries. Actuators play a crucial role in controlling motion, which enables applications in several fields, including electronics, robotics, and healthcare. Sensors provide critical feedback and data, thus enhancing precision and efficiency.

The fundamental feature in the actuation and in the sensing of polymers, is the capability to respond to external stimuli and convert them into a mechanical response and into electrical signals, respectively. This multifunctionality may be achieved by resorting to nanocomposite materials, which exhibit unique properties that can be tailored by leveraging the matrix reinforcement or by the integration of advanced functional materials. At the core of both actuation and sensing, there is the concept of stimuli responsiveness. In actuators, external stimuli such as thermal, electrical, magnetic, or optical inputs cause the material to change shape, size, or state. Integration of advanced functional materials has recently seen significant

[a] *2D Materials and LASER Actuation Laboratory, Centre of Excellence for Research PP Savani University, Surat, Gujarat, India. E-mail: vinaydeep_punetha@yahoo.com*
[b] *Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Brescia, Italy*
[c] *Chemical Engineering Department, College of Engineering, Taibah University, Yanbu Al-Bahr 41911, Kingdom of Saudi Arabia*



Vinay Deep Punetha

Vinay Deep Punetha heads the 2D Materials and LASER Actuation Laboratory, Centre of Excellence for Research, PP Savani University (India). He received his PhD in organic chemistry and materials science from Kumaun University, India. Following his doctorate, he served as a post-doctoral fellow at Konkuk University, Seoul, South Korea. Punetha's research has focused on graphene and other 2D materials, particularly in the development of graphene-based nanocomposite systems for laser-induced remote actuation. In 2020, he was part of a team that patented a crucial graphene manufacturing process from waste plastic, which was subsequently used as technology by the Government of India.

Lorenzo Bardella

Lorenzo Bardella is a professor of solid and structural mechanics at the Department of Civil, Environmental, Architectural Engineering and Mathematics of the University of Brescia (Italy). In 2001 he received his PhD in materials for engineering from the University of Brescia by defending a dissertation mainly focused on the micromechanics of glass-epoxy syntactic foams. In 2009 he was a recipient of the first junior Prize in Mechanics of Solids awarded by the Italian Association of Theoretical and Applied Mechanics. With emphasis on modelling, Bardella's fields of interest include the small-scale irreversible behaviour of metals, the mechanics of composite materials and structures, and the actuation and sensing of electroactive materials.

attention due to the ability of these materials to enhance performance, improve functionality, and enable new applications across various fields, spanning from robotics to healthcare. As an example in this themed collection, Terasawa and Monobe have demonstrated the potential of polyvinyl chloride (PVC), dibutyl adipate (DBA), and various ionic liquids (ILs)-based hybrid gel actuators, which use synergistic effects to improve actuation performance for exceptionally robust and adaptable solutions for applications in wearable technology, transparent electronics, and energy conversion devices (**https://doi.org/10.1039/D4MA00143E**)

The benefits of using polymers in engineering are numerous and transformative, owing to their versatility in advanced applications. One of the key advantages is their customized functionality. Polymers can be engineered to exhibit specific properties that are tailored to the requirements of diverse applications. This adaptability stems from the ability to manipulate the polymer molecular structure, allowing for precise control over mechanical, thermal, and chemical characteristics. Yao *et al.* have demonstrated the significant impact of molecular engineering on the self-assembled architectures of liquid crystal polymers (LCPs). By fine-tuning the terminal groups in the side chains of LCPs, distinct phase transitions and hierarchical structures can be achieved, such as forming smectic E, smectic A, and isotropic phases. The study of Yao *et al.* highlights the importance of understanding the relationships between molecular structures and self-assembled architectures for advanced applications (**https://doi.org/10.1039/D3MA01185B**).

Dual actuation can be applied in sensors, whereby the material response may be used to detect and measure the stimuli. Beyond using nano reinforcements, promising progress in sensor technology has been witnessed through the synergistic integration of one or more advanced materials. For instance, integrating core–shell structures within a metal–organic framework (MOF) can significantly enhance the sensitivity and selectivity of the sensor. Deffo *et al.* have shown that composite core–shell structures of Ag_2S and Bi_2S_3, coated with a MOF (NH2-MIL-125-Ti) and polyaniline (PANI) matrix, significantly enhances the sensitivity and selectivity of uric acid detection in human urine. These advanced composite materials not only detect but also precisely quantify the stimuli, demonstrating the transformative potential of hybrid nanocomposites in both actuation and sensing technologies. These systems can be explored to evaluate their potential to improve the overall performance and reliability of sensors, making them highly effective in accurately detecting and measuring environmental and biological changes (**https://doi.org/10.1039/D3MA01182H**).

Choudhury *et al.* present a fascinating 4D printed shape memory polymer composite infused with magnetic nanoparticles. This study successfully demonstrates *in vivo* applications with a recovery temperature near physiological levels. Interestingly, the authors adopt magnetic actuation, which not only ensures precise deployment but also offers the potential for minimal invasive procedures. The exceptional shape fixity and rapid recovery underscore the composite potential in biomedical scaffolds and soft robotics, where remote actuation is of paramount importance (**https://doi.org/10.1039/D3MA00958K**).

In another innovative approach, Wang *et al.* developed lignin polyurethane-based conductive foam sensors that are both flexible and recyclable. This research is particularly noteworthy for addressing environmental sustainability issues in sensor technology. The foam demonstrates excellent 'resistance change performance' and 'durability' through extensive cycles of compression, thus demonstrating its potential in wearable electronics. Moreover, its capacity to detect both large-scale movements and minute physiological activities, positions it as a versatile component in next-generation health monitoring devices (**https://doi.org/10.1039/D2MA00960A**).

Meanwhile, Hu *et al.* explore the outcome of dynamic ionic crosslinking in dielectric elastomers, a method that evidently revolutionizes the mechanical and energy harvesting properties of these materials. By introducing nucleophile reagents into brominated poly(isobutylene-*co*-isoprene) rubber, the authors achieve enhanced mechanical reinforcement and self-healing efficiency, which are vital for long-term applications. The work highlights how the incorporation of ionic clusters can enhance electromechanical properties, consequently improving energy conversion efficiencies. This marks an advancement in the field of dielectric elastomers (**https://doi.org/10.1039/D2MA00124A**).

Furthermore, progress in the integration of advanced materials necessitate robust modelling approaches to fully harness their potential application in actuation as well as sensing. Boldini introduces a multi-cation model for the actuation of ionic membranes with ionic liquids, addressing the challenges posed by water evaporation in soft actuators. These actuators are crucial for biomedical engineering and underwater robotics. By considering the presence of ionic liquids instead of water, the model

Mohammad Luqman

Mohammad Luqman is currently faculty at Taibah University, Saudi Arabia, and has 17+ years of post-PhD multinational industrial and academic experience in research, teaching, and administration in the field of materials/polymer science and engineering. He has successfully served as a (co)editor on many books, published by world-renowned publishers. He has published numerous high-quality papers, and book chapters. He has attracted important research grants from industry and academia. His research interests include but are not limited to, the development of ionomer/polyelectrolyte/non-ionic polymer nanocomposites/blends for smart and industrial/engineering applications.

captures, through a thermodynamically consistent framework, the complex electromigration of ions, accounting for their interactions. This approach provides an accurate description of the coupled electrochemistry and mechanics, paving the way for enhanced actuator design in diverse applications (**https://doi.org/10.1039/D4MA00097H**).

This themed collection explores various facets of actuation and sensing, ranging from molecular engineering to advanced material integration. It discusses the transformative benefits of polymers in advanced applications due to their versatile nature and the ability to customize their properties for specific needs. It also highlights the impact of molecular engineering on the self-assembled architectures of polymers, the enhanced sensitivity and selectivity in sensor technology through advanced materials, and the necessity of robust modelling approaches to fully utilize and aid these advancements. By focusing on these areas, this themed collection aims to display innovative solutions for applications in diverse fields such as wearable electronics, biomedical engineering, and underwater robotics.

Lastly, the guest editors would like to thank the *Materials Advances* editorial team for their assistance and collaboration in bringing this themed collection to fruition. Hopefully, readers will find these fascinating papers from diverse research domains enlightening, broadening the understanding of the extensive research on stimuli-responsive materials and inspiring new investigations on innovative applications for these versatile materials.