Guest Editorial: Focused Section on Compliant Mechanisms for Mechatronics

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COMPLIANT mechanisms (CMs), along with soft robotics devices formed therewith, may be defined as engineering systems achieving force and motion transmission via the deflection of flexible members. CMs have increasingly gained a strong foothold in the scientific arena owing to their hinge-less nature, shock resistance, potential single-piece manufacturability, safety in human–machine interaction, minimal maintenance requirements, and adaptability to work in unstructured environments. In parallel, current advances in the production of inherently compliant sensory-motor apparatus, as well as progresses in the development of robust control methods, are paving the way to practical CM adoption in a large variety of engineering fields, here including *healthcare*, *manufacturing*, *inspection/maintenance*, and *agrifood*. However, by embracing large deflections as a requirement rather than a design flaw, the conception and the subsequent physical prototyping of optimal CMs requires the following:

1) material models capable of dealing with finite deformations, time-dependent phenomena, and uncertain constitutive parameters;
2) design tools allowing to simulate the behavior of highly deformable structures;
3) reliable and possibly affordable manufacturing methods;
4) more powerful adaptive learning and control techniques.

Within this scenario, this Focused Section (FS) aims at providing a collection of contributions provided by material scientists, robotic/mechatronic engineers, and practitioners from academia or industry presenting their latest theoretical and technological achievements in *Complaint Mechanisms for Mechatronics*. Particular focus has been placed on trans-disciplinary methodological frameworks, hardware development for real-world applications, and out-of-lab experiments. Papers presenting newly emerging fields (such as robotic programmable materials) are also covered. All accepted manuscripts contain both theoretical and experimental results in the following areas:

1) integrated design of compliant mechanisms for robotics and mechatronics;
2) control methods for continuum and reconfigurable robots;
3) computer-aided tools for optimizing adaptive structures;
4) manufacturing methods for soft intelligent machines (such as additive manufacturing and 4-D Printing);
5) optimization of programmable stiffness mechanisms and actuators;
6) architected, functional, and meta-materials for soft robotics;
7) smart-material-based actuation and sensing systems;
8) stretchable/flexible electronics and power sources;
9) applications of compliant mechanisms in surgical robotics, manufacturing, extreme environments, and material handling.

Highlights of the Focused Session

Claiming that the *Focused Session on Compliant Mechanisms for Mechatronics* has garnered an exceptional response from both the mechatronics and the robotics community would not be an exaggeration. A total of 66 submissions have been received, dealing with several applications of CMs in mechatronic systems and soft robots. From a terminology standpoint, at the current state of the art, a consolidated definition of the difference between a *compliant* or a *soft* robotic/mechatronic device is absent. Within this FS, we have intended that any engineering system comprising inherent flexibility as a design goal (rather than a design flaw) may be considered *Compliant* if it embraces large deflections (i.e., geometric nonlinearities) during functioning, although making use of linear elastic materials only. On the other hand, if the employed material cannot be considered linear-elastic, but hyperelasticity, plasticity, and time-dependent phenomena are to be taken into account (i.e., material nonlinearities), we may define the application as belonging to the *Soft Robotics* framework. Among the papers submitted to this FS, several manuscripts deal with the applications of CMs or soft mechatronics systems in manipulation devices or compliant actuators. Examples are [A1], [A2], and [A3]. A review paper deals with actuated palms for soft robotic hands, whereas other contributions are related to the design and optimization of compliant joints for generic applications (such as [A4]). In any case, despite strict definitions that could end up being sterile, the excellent outcome of this FS proves that, as of today, CMs are perceived as an effective solution to several real-world engineering problems. Finally, we believe that our effort in collecting novel research results in flexible mechatronics may represent a first step in bridging the gap between a research topic most commonly covered by scientists in mechanical engineering to the broader community of roboticists worldwide.

The success of the FS is surely due to the effort provided by several people, who have played a crucial role in both the submission and the review process. In particular, the Lead Guest Editor would like to express his sincere gratitude to all

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the authors of the 66 submitted papers, for their scientific and technical contributions, to the four Guest Editors, as well as to all the TMECH reviewers, for dedicating their valuable time to uphold the quality of the review process. A very special thanks goes to Professor Huijun Gao, the Editor-in-Chief of TMECH, for his strong leadership, vision, and timely support throughout the process. A special recognition is also extended to Professor I-Ming Chen, the former Editor-in-Chief of TMECH, for accepting the Guest Editors proposal, and for his early support and leadership in the initiative. The Lead Guest Editor, who is also currently a member of the TMECH Editorial Board, would like to personally thanks Dr. Kara McArthur, TMECH Managing Editor, for the endless help and the extremely effective response to all the Guest Editors' Queries. Recognition goes also to all the TMECH Senior Editors, Professors Jingang Yi, Heiki Vallery, Tomoyuki Shimono, Xiang Chen, Michael Ruderman, Gursel Alici, Hiroshi Fujimoto, Robert Gao, Marina Indri, Seiichiro Katsura, Konstatinos J. Kyriakopoulos, Yunhua Li, Kenn Oldham, Ya-jun Pan, Nikolaos Tsagarakis, Jun Ueda, Qingze Zou, and to all the Technical Editors. The work of Giovanni Berselli was supported by the Horizon Europe Research and Innovation Programme INTELLIMAN under Grant 101070136.

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APPENDIX: RELATED ARTICLES

[A1] S. Ku, B.-H. Song, T. Park, H.-Y. Kim, and Y.-L. Park, "Multifunctional soft gripper with microneedles and integrated sensing for robotic fabric handling," *IEEE/ASME Trans. Mechatron.,* early access, Dec. 5, 2023, doi: 10.1109/TMECH.2023.3334246.

[A2] S. Pulleyking and J. Schultz, "A compliant rolling ellipsoidal thumb joint for the TU hand," *IEEE/ASME Trans. Mechatron.,* early access, Oct. 30, 2023, doi: 10.1109/TMECH.2023.3324185.

[A3] M. Baggetta, G. Palli, C. Melchiorri, and G. Berselli, "A monolithic cable-driven compliant wrist for prosthetic arms," *IEEE/ASME Trans. Mechatron.,* early access, Jan. 9, 2024, doi: 10.1109/TMECH.2023.3345215.

[A4] B. T. Peterson, T. J. Hardin, A. W. Pomeroy, J. B. Hopkins, and T. R. Clites, "Cross-axis flexural pivots in mechatronic applications: stress-based design for combined tension and bending," *IEEE/ASME Trans. Mechatron.,* early access, Dec. 5, 2023, doi: 10.1109/TMECH.2023.3334994.

Giovanni Berselli (Member, IEEE) received the M.Sc. degree in mechanical engineering from the University of Modena, Modena, Italy, in 2004, and the Ph.D. degree in mechanical engineering from the University of Bologna, Bologna, Italy, in 2009.

He is currently a Full Professor and Chair of Design Methods for Industrial Engineering with the University of Genova, Genoa, Italy, where he coordinates the Ph.D. degree in mechanical, energy and management engineering. He is also an Affiliated Researcher with the Advanced Robotics Department, Italian Institute of Technology (IIT), Genova. He held Visiting Professor positions at Monash University, University of Navarra, University of Twente, German Aerospace Agency - DLR, Harvard Medical School and Massachusetts General Hospital, and Karlsruhe Institute of Technology. His research interests include the design, modeling, and experimental evaluation of robot hands and grippers, compliant mechanisms and soft actuators for safe human–robot interaction, and energy-aware industrial robotics.

Dr. Berselli is a Fellow of the American Society of Mechanical Engineers (ASME), the Chair of the ASME Italy Section, and the past Chair of the ASME Technical Committee on Modeling, Dynamics, and Control of Adaptive Systems.

Manuel Catalano (Member, IEEE) received the master's degree in mechanical engineering and the doctoral degree in robotics from the University of Pisa, Pisa, Italy, in 2008 and 2013, respectively.

He is currently a Researcher with the Italian Institute of Technology, Genoa, Italy, and a Collaborator with the Research Center "E. Piaggio," University of Pisa. His research interests include the design of soft robotic systems, human–robot interaction, and prosthetic.

Dr. Catalano was the recipient of the Georges Giralt Ph.D. Award and the prestigious Annual European Award given for the best Ph.D. thesis by euRobotics AISBL.

Mary Frecker received the B.S. degree in mechanical engineering from the University of Dayton, Dayton, OH, USA, in 1991, and the M.S. and Ph.D. degrees in mechanical engineering from the University of Michigan, Ann Arbor, MI, USA, in 1994 and 1997, respectively.

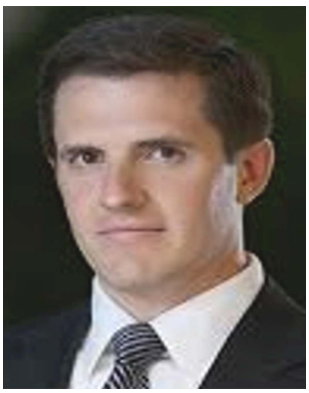
She is currently a Professor of mechanical and biomedical engineering, the Department Head of mechanical engineering, and the Director of the Penn State Center for Biodevice, Pennsylvania State University, University Park, PA, USA. .

Dr. Frecker is a Fellow of the ASME. She was an Associate Editor for the *ASME Journal of Mechanical Design,* Chair of the ASME Adaptive Structures and Material Systems Technical Committee, Member of the ASME Mechanisms and Robotics Committee, and Executive Committee Member of the ASME Aerospace Division.

Just L. Herder received the M.Sc. and Ph.D. degrees in mechanical engineering from the Delft University of Technology, Delft, The Netherlands, in 1992 and 2001, respectively.

He held visiting positions at Laval University, Quebec, QC, Canada, and at Massachusetts Institute of Technology, Cambridge, MA, USA, as a Fulbright Visiting Scholar. He is currently a Full Professor and the Head of the Department of Precision and Microsystems Engineering, Delft University of Technology, Delft, The Netherlands. He has authored or coauthored more than 280 publications in international peer-reviewed journals and conferences, and holds 25 patents in different areas of mechanism design, based on which seven start-up companies have emerged.

Dr. Herder is a Fellow of the ASME. He was the recipient of the several international awards, including six best paper awards. He is an Associate Editor for the *Mechanism and Machine Theory,* a founding Editor-in-Chief of *Mechanical Sciences,* and an Organizer of several international conferences. He gave over a dozen keynote talks at international conferences.



Jonathan B. Hopkins received the B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 2005, 2007, and 2010, respectively, all in mechanical engineering.

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Dr. Hopkins is a Member of the American Society for Precision Engineering, the American Society of Mechanical Engineers (ASME), and the Materials Research Society. He was the recipient of Presidential Early Career Award for Scientists and Engineers honored by the President Barack Obama at the White House and ASME's Freudenstein/General Motors Young Investigator Award in 2016. He is currently an Associate Editor for *Precision Engineering*.