Cover Page

Topical White Paper submitted to the Biological and Physical Sciences in Space

Decadal Survey 2023-2032

FUNDAMENTAL MATERIALS RESEARCH

SOFT RECONFIGURABLE METAMATERIALS - THE NEXT DECADE AND BEYOND IN SPACE MATERIALS RESEARCH

Submitted by Stephan Rudykh

Department of Mechanical Engineering, University of Wisconsin – Madison, Madison, Wisconsin, USA. Email:rudykh@wisc.edu

Co-Authors

AJ Boydston, University of Wisconsin – Madison, Madison, WI, USA.
Nicholas X. Fang, Massachusetts Institute of Technology, Cambridge, MA, USA.
Stephane Bordas, University of Luxembourg, Luxembourg
Mikhail Itskov, RWTH Aachen University, Aachen, Germany
Michel Destrade, National University of Ireland, Galway, Ireland
Konstantin Volokh, Technion – Israel Institute of Technology, Haifa, Israel
Ettore Barbieri, Japan Agency for Marine-Earth Science and Technology, Yokohama-city, Japan

1. Background

Soft materials – elastomers, gels, and biological tissues – can readily develop large deformations in response to various stimuli. The large deformations may lead to the development of elastic instabilities and associated pattern formations. Recently, the new concept of using the rich instability-induced pattern transformations in soft materials has been put forward to design *reconfigurable mechanical metamaterials* with unusual properties [1], photonic [2] and phononic [3, 4] switches, soft robots [5, 6], sensors [7], flexible electronics[8], adhesion [9] and energy absorption [10]. Moreover, the knowledge about the mechanical instability phenomenon can help elucidate the morphogenesis in organs during growth in various biological systems [11-13].

The diverse potential applications of the instability phenomena in soft materials motivated a significant body of theoretical, numerical, and experimental studies. These works addressed the wide variety of elastic instabilities, including buckling, wrinkling, folding, creasing, cavitation, fringe, and fingering in various soft material systems under different stimuli [14-19]. However, there is very limited knowledge about the material systems with extreme soft behavior where the gravity needs to be accounted; for example, the formation of the wrinkling in the stiff-film-soft-substrate system Li, Ge [20], the crease to wrinkle transition in soft materials Liang and Cai [21] induced by gravity. The behavior of the extremely soft materials in *the absence of gravity* (or *microgravity*) remains largely unexplored. This is a rich research avenue for new fundamental knowledge and for developing new materials operating in the extreme unusual environment – in space.

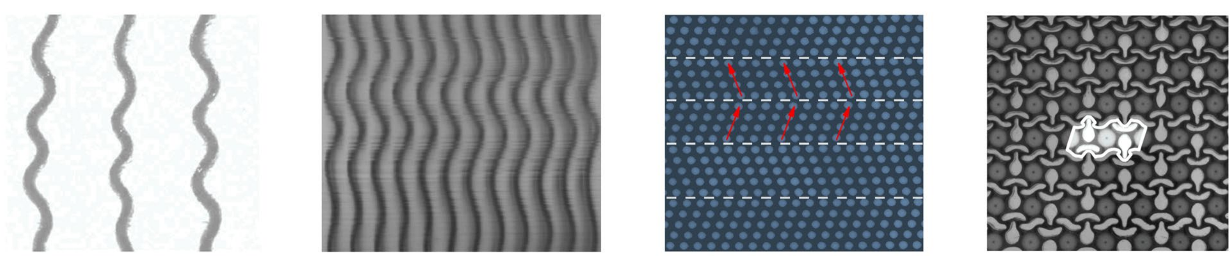
The physical realization of the soft reconfigurable materials relies on the development of advanced material fabrication; the recent development has already allowed the manufacturing of microstructured soft materials across length scales [22-25]. However, the research and development of *soft material* 3D printing *in space* lag behind the more established solid material fabrication techniques. In-space manufacturing is essential for space exploration to produce on-demand tools for a long-term mission in the absence of the supply chain from the Earth and reduce launch costs [26]. The reliability and precision of operations are of vital importance in space. Therefore, understanding the 3D printing process and the behaviors of 3D printed materials in the absence of gravity (or microgravity) in space is indispensable for space exploration and inhabitants in space in the future [27, 28]. This is also in line with the recent report of NASA's Physical Science Research Program in the Space Life addressing the inverse design, additive manufacturing of soft metamaterials, adaptable materials, active and self-sensing soft metamaterials, integration of computers and materials, and microgravity [29].

2. Research Directions for Soft Matter in Space

The unusual behavior of extremely soft materials in the space environment, including the absence of gravity (and microgravity), is needed to be studied to provide a deep understanding and description for reliable development of the technology for space exploration applications. This will require the development of new approaches in theory development, numerical modeling, and innovative soft material 3D printing techniques, and neat physical experiments in microgravity conditions.

Modeling of Soft Matter in Space Environment

Theoretical and computer modeling of the soft reconfigurable matter builds on the solid foundation and background accumulated in modeling (see Fig. 1 for computationally predicted and experimentally realized instability-induced pattern reconfigurations). However, the adaptation of the approaches is required to reflect the significantly different extreme conditions that the materials experience in the space environment. Typically, the modeling of soft reconfigurable materials includes (a) the non-linear regime of large deformation, followed by (b) the (linearized) onset of instability analysis (such as Bloch-Floquet analysis), and concluded by (c) the highly non-linear and extremely sensitive to underlying assumption, post-transformation regime. The modeling of those steps needed to be informed by the experimentally characterized soft material behavior in space conditions. Furthermore, to appropriately model soft living biological materials in space, new constitutive models capable of capturing the high complexity of living biological materials need to be developed [29, 30]. In particular, the coupling of chemical, biological, and mechanical factors with complex interactions between different fields across length scales in living materials presents a challenge even for the classical continuum mechanics approaches [31, 32], and can be significantly transformed in the microgravity conditions. For example, soft living materials frequently developing residual stresses can be affected significantly, and those factors need to be appropriately accounted for for accurate modeling. The complexity is ever increased as far as the reconfigurable soft matter undergoing cascade microstructural transformations is considered, especially so for the multiphysics non-linear coupled processes. The modeling efforts may be facilitated by incorporating the developing approaches of machine learning.



(a) Laminate (b) 3D fiber composite (c) Particulate composite (d) Multiphase composite

Fig. 1. Instability-induced patterns in soft laminate (a) [33], 3D fiber composite (b) [34], particulate composite (c) [35], multiphase composite [36].

Additive Manufacturing and 3D printing of Soft Metamaterials in Space:

Current soft composites are constrained to effectively macroscale bulk properties of constituent soft materials. A significant unmet challenge is the ability to control *multi-material* composition across length scales. A further challenge is understanding the *process-structure-property* relationships across length scales, especially in the largely unexplored regime of *microgravity*. While large length scale geometric variation within monolithic objects is currently possible in regular conditions, diversification of chemical composition and functionality that spans molecular- to nano- to mesoscale structure is severely lacking. Spatially resolved material deposition, such as material extrusion of gels or multi-jetting of photo-resins, can deliver heterogeneous soft material combinations, but at resolutions that are nominally macroscopic. These techniques also result in strong incompatible material interfaces that are prone to catastrophic failure under mechanical and thermal loads. Photomediated polymerizations uniquely provide spatiotemporal control over the synthesis of macromolecular architectures (a typical photo-polymerization 3D printing is illustrated in Fig. 2).

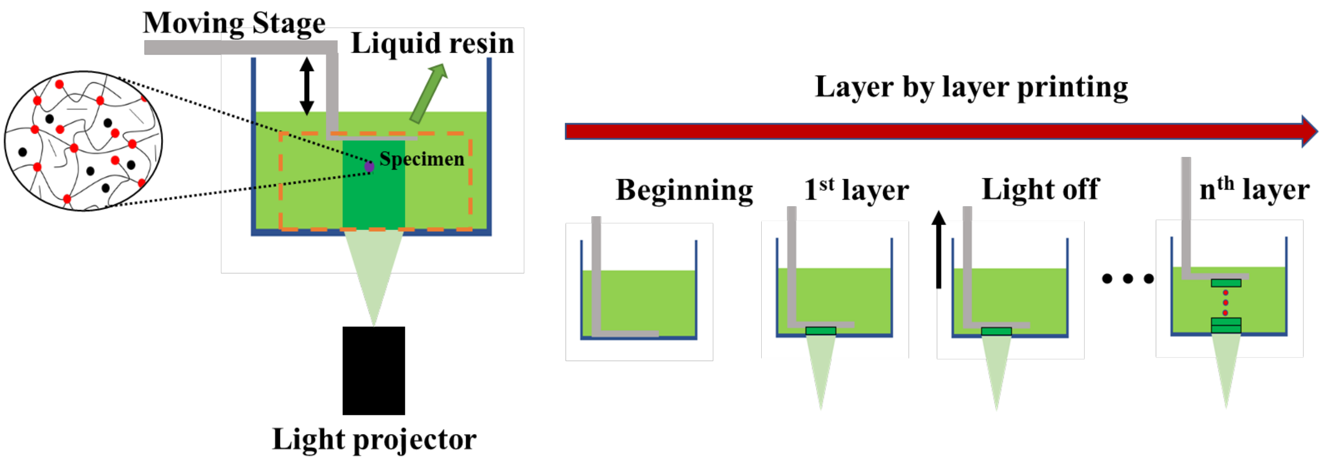


Fig. 2. Schematic of a typical photo-polymerization-based 3D printing. The geometrical features of the specimens are digitally sliced into a series of images and are sequentially projected by the DLP projector into the liquid resin to produce cured exposed solidified features in the layer. The layer-by-layer projection and curing process is repeated until the microstructured specimen is printed.

Since the processes involve conversion from small molecule reagents into polymeric networks during the fabrication process, it may be possible to control small length scale structure, such as nanoscale morphology or graded composition of interpenetrating networks, in ways that are not accessible with spatially resolved material deposition. A recently discovered method for using photomediated polymerizations in additive manufacturing produces unprecedented multi-material objects that arise from multiwavelength light projection during the fabrication process. Multicolor digital images became multi-material 3D objects by using frequency-specific chemistries to control material composition. Now, we are poised to interrogate the underlying fundamental questions that will enable multiscale control and design principles in multicomponent soft materials, such as:

- How does one control the contrast and structure at the interfaces within heterogeneous soft multi-materials? Establishing empirical and predictive models of polymerization kinetics, nonequilibrium dynamics, photophysical properties, and physicochemical properties that govern multicomponent, simultaneous photomediated polymerization of different materials is needed.

- The incorporation of microphase separating soft additives such as block copolymers into the photo-chemistry of the resins can open ways to engineer reconfigurable metamaterials across length scales. How does one control block copolymer self-assembly during multicomponent photomediated polymerization? What are the possible nanoscale morphological outcomes of block copolymer additives within heterogeneous soft material composites?

- What are the effects of multiscale structure with controlled nanoscale and mesoscale heterogeneity on mechanical and dynamic properties of the bulk composite? The relevant heterogeneous and anisotropic mechanical properties from the nanoscale to macroscale need to be measured. The effects of gradient interfaces among multi-materials in architected materials on their mechanical behavior and failure mechanisms to develop materials with delayed and predictable failures needs to be investigated.

These research efforts will also be in synergy with the Zero-G Technology demonstration mission [37, 38] by NASA and Made in Space, Inc., investigating the effect of microgravity on the 3D printing process. This will also advance the understanding of the performance of 3D printed soft materials under long-term exposure to extreme space conditions.

References

1. Kochmann, D.M. and K. Bertoldi, *Exploiting Microstructural Instabilities in Solids and Structures: From Metamaterials to Structural Transitions.* Applied Mechanics Reviews, 2017. **69**(5). https://doi.org/10.1115/1.4037966.
2. Krishnan, D. and H.T. Johnson, *Optical properties of two-dimensional polymer photonic crystals after deformation-induced pattern transformations.* Journal of the Mechanics and Physics of Solids, 2009. **57**(9): p. 1500-1513. https://doi.org/10.1016/j.jmps.2009.05.012.
3. Shan, S.C., et al., *Harnessing Multiple Folding Mechanisms in Soft Periodic Structures for Tunable Control of Elastic Waves.* Advanced Functional Materials, 2014. **24**(31): p. 4935-4942. https://doi.org/10.1002/adfm.201400665.
4. Wang, P., et al., *Harnessing buckling to design tunable locally resonant acoustic metamaterials.* Physical review letters, 2014. **113**(1): p. 014301. https://doi.org/10.1103/PhysRevLett.113.014301.
5. Yang, D., et al., *Buckling of Elastomeric Beams Enables Actuation of Soft Machines.* Adv Mater, 2015. **27**(41): p. 6323-7. https://doi.org/10.1002/adma.201503188.
6. Chen, T., et al., *Harnessing bistability for directional propulsion of soft, untethered robots.* Proc Natl Acad Sci U S A, 2018. **115**(22): p. 5698-5702. https://doi.org/10.1073/pnas.1800386115.
7. Chung, J.Y., A.J. Nolte, and C.M. Stafford, *Surface wrinkling: a versatile platform for measuring thin-film properties.* Adv Mater, 2011. **23**(3): p. 349-68. https://doi.org/10.1002/adma.201001759.
8. Cheng, X. and Y. Zhang, *Micro/Nanoscale 3D Assembly by Rolling, Folding, Curving, and Buckling Approaches.* Adv Mater, 2019. **31**(36): p. e1901895. https://doi.org/10.1002/adma.201901895.
9. Chan, E.P., et al., *Surface wrinkles for smart adhesion.* Advanced Materials, 2008. **20**(4): p. 711-+. https://doi.org/10.1002/adma.200701530.
10. Shan, S., et al., *Multistable Architected Materials for Trapping Elastic Strain Energy.* Adv Mater, 2015. **27**(29): p. 4296-301. https://doi.org/10.1002/adma.201501708.
11. Budday, S., P. Steinmann, and E. Kuhl, *The role of mechanics during brain development.* J Mech Phys Solids, 2014. **72**: p. 75-92. https://doi.org/10.1016/j.jmps.2014.07.010.
12. Garcia, K.E., C.D. Kroenke, and P.V. Bayly, *Mechanics of cortical folding: stress, growth and stability.* Philos Trans R Soc Lond B Biol Sci, 2018. **373**(1759): p. 20170321. https://doi.org/10.1098/rstb.2017.0321.
13. Du, Y.K., et al., *Electro-mechanically guided growth and patterns.* Journal of the Mechanics and Physics of Solids, 2020. **143**: p. 104073. https://doi.org/10.1016/j.jmps.2020.104073.
14. Shen, Y.T., et al., *Icosahedral order, frustration, and the glass transition: evidence from time-dependent nucleation and supercooled liquid structure studies.* Phys Rev Lett, 2009. **102**(5): p. 057801. https://doi.org/10.1103/PhysRevLett.102.057801.
15. Chung, M., G. Fortunato, and N. Radacsi, *Wearable flexible sweat sensors for healthcare monitoring: a review.* J R Soc Interface, 2019. **16**(159): p. 20190217. https://doi.org/10.1098/rsif.2019.0217.
16. Xu, F. and S.C. Zhao, *Thermal wrinkling of liquid crystal polymer shell/core spheres.* Extreme Mechanics Letters, 2020. **40**: p. 100860. https://doi.org/10.1016/j.eml.2020.100860.

17. Lu, T.Q., C. Ma, and T.J. Wang, *Mechanics of dielectric elastomer structures: A review.* Extreme Mechanics Letters, 2020. **38**: p. 100752. https://doi.org/10.1016/j.eml.2020.100752.
18. Goshkoderia, A., Chen, V., Li, J., Juhl, A., Buskohl, P., S. Rudykh, *Instability-induced pattern formations in soft magnetoactive composites.* Physical Review Letters, 2020. **124**: p. 158002. https://doi.org/10.1103/PhysRevLett.124.158002.
19. Psarra, E., L. Bodelot, and K. Danas, *Two-field surface pattern control via marginally stable magnetorheological elastomers.* Soft Matter, 2017. **13**(37): p. 6576-6584. https://doi.org/10.1039/c7sm00996h.
20. Li, K., D. Ge, and S. Cai, *Gravity-induced wrinkling of thin films on soft substrates.* EPL (Europhysics Letters), 2012. **100**(5). https://10.1209/0295-5075/100/54004.
21. Liang, X. and S. Cai, *Gravity induced crease-to-wrinkle transition in soft materials.* Applied Physics Letters, 2015. **106**(4). https://10.1063/1.4906933.
22. Kolle, M., et al., *Bio-Inspired Band-Gap Tunable Elastic Optical Multilayer Fibers.* Advanced Materials, 2013. **25**(15): p. 2239-2245. https://doi.org/10.1002/adma.201203529.
23. Lee, H. and NX. Fang, *Micro 3D Printing Using a Digital Projector and its Application in the Study of Soft Materials Mechanics.* Jove-Journal of Visualized Experiments, 2012(69): p. e4457. https://doi.org/10.3791/4457.
24. Zheng, X., et al., *Ultralight, ultrastiff mechanical metamaterials.* Science, 2014. **344**(6190): p. 1373-1377. https://doi.org/10.1126/science.1252291.
25. Slesarenko, V. and S. Rudykh, *Harnessing viscoelasticity and instabilities for tuning wavy patterns in soft layered composites.* Soft Matter, 2016. **12**(16): p. 3677-3682. https://doi.org/10.1039/c5sm02949j.
26. Xu, W., et al., *3D printing for polymer/particle-based processing: A review.* Composites Part B: Engineering, 2021. **223**. https://10.1016/j.compositesb.2021.109102.
27. Mitchell, A., et al., *Additive manufacturing — A review of 4D printing and future applications.* Additive Manufacturing, 2018. **24**: p. 606-626. https://10.1016/j.addma.2018.10.038.
28. Li, J. and M. Pumera, *3D printing of functional microrobots.* Chem Soc Rev, 2021. **50**(4): p. 2794-2838. https://10.1039/d0cs01062f.
29. Shariff, MHBM, R. Bustamante, and J. Merodio, *A nonlinear constitutive model for a two preferred direction electro-elastic body with residual stresses.* International Journal of Non-Linear Mechanics, 2020. **119**: p. 103352. https://doi.org/10.1016/j.ijnonlinmec.2019.103352.
30. Shariff, MHBM and J. Merodio, *Residually stressed two fibre solids: A spectral approach.* International Journal of Engineering Science, 2020. **148**: p. 103205. https://doi.org/10.1016/j.ijengsci.2019.103205.
31. Funk, R.H., T. Monsees, and N. Ozkucur, *Electromagnetic effects - From cell biology to medicine.* Prog Histochem Cytochem, 2009. **43**(4): p. 177-264. https://doi.org/10.1016/j.proghi.2008.07.001.
32. Levin, M. *Bioelectric mechanisms in regeneration: unique aspects and future perspectives*. in *Seminars in cell & developmental biology*. 2009. Elsevier. https://doi.org/10.1016/j.semcdb.2009.04.013.

33. Slesarenko, V. and S. Rudykh, *Harnessing viscoelasticity and instabilities for tuning wavy patterns in soft layered composites.* Soft Matter, 2016. **12**(16): p. 3677-82. https://doi.org/10.1039/c5sm02949j.
34. Li, J., et al., *Instabilities and pattern formations in 3D-printed deformable fiber composites.* Composites Part B-Engineering, 2018. **148**: p. 114-122. https://doi.org/10.1016/j.compositesb.2018.04.049.
35. Li, J., et al., *Domain Formations and Pattern Transitions via Instabilities in Soft Heterogeneous Materials.* Adv Mater, 2019. **31**(14): p. e1807309. https://doi.org/10.1002/adma.201807309.
36. Li, J., V. Slesarenko, and S. Rudykh, *Auxetic multiphase soft composite material design through instabilities with application for acoustic metamaterials.* Soft Matter, 2018. **14**(30): p. 6171-6180. https://doi.org/10.1039/c8sm00874d.
37. Prater, T., et al., *Summary report on phase I results from the 3D printing in zero g technology demonstration mission, volume I.* 2016. https://ntrs.nasa.gov/citations/20160008972.
38. Prater, T., et al., *3D Printing in Zero G Technology Demonstration Mission: Complete Experimental Results and Summary of Related Material Modeling Efforts.* Int J Adv Manuf Technol, 2019. **101**(1-4): p. 391-417. https://doi.org/10.1007/s00170-018-2827-7.