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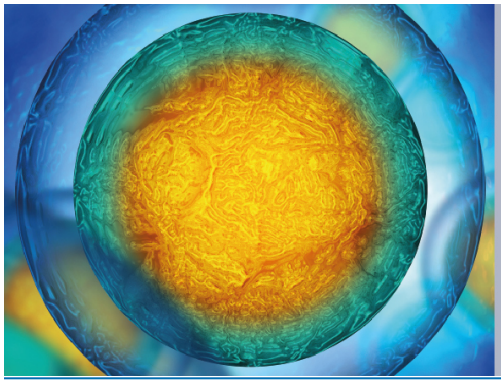

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EDITORIAL

Editorial: Living machines: from biological models to soft machines

Falk Tauber[1,2,*], **Vasiliki Vouloutsi**[3], **Anna Mura**[4] and **Thomas Speck**[1,2]

[1] Cluster of Excellence livMatS@ FIT—Freiburg Center for Interactive Materials and Bioinspired Technologies, University of Freiburg, Germany
[2] Plant Biomechanics Group & Botanic Garden, University of Freiburg, Germany
[3] Autonomous Robotics Research Centre, Technology Innovation Institute, Abu Dhabi, United Arab Emirates
[4] Institute for Bioengineering of Catalonia, Barcelona, Spain
[*] Author to whom any correspondence should be addressed.

E-mail: falk.tauber@biologie.uni-freiburg.de

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Transferring the principles of living nature into living machines has preoccupied philosophers and scientists for more than 2000 years and inspired great minds like Leonardo Da Vinci to deliver outstanding inventions. In the last century, the study of nature and living organisms has led to innovations inspired by nature in a variety of different fields, such as engineering, architecture, materials sciences, medical technology and robotics. The most prominent examples for commonly used bioinspired developments are Velcro (fastening inspired by burs hooks) and self-cleaning paints and coatings based on the principles of lotus plant leaves [1].

As a fairly young field of research, soft robotics has benefited from bio-inspired principles since the beginning. The first soft robotic actuators (McKibben muscles) were developed almost 70 years ago to mimic human musculature [2]. From that point on, the field of bioinspired robotics advanced from flexible continuum robots (inspired, e.g. by the octopus [3]) to entirely soft walkers [4] and highly advanced insect-inspired robotics controlled by neural networks [5]. Within the last decades, the field of soft robotics and biomimetics brought forth almost life-like 'living machines' like the Stickybot [6], the geminoid project [7] and even plant-inspired growing robots [8, 9]. Learning from natural models still holds enormous potential for advancing the field of biomimetic and biohybrid systems [10].

In this spirit, a decade ago, the living machines conference was created to provide a focal point for the gathering of world-leading researchers and the presentation and discussion of cutting-edge research in this rapidly emerging field of biomimetic and biohybrid systems.

This special issue of Bioinspiration and Biomimetics encompasses six invited, peer-reviewed articles whose results were partially presented at Living Machines: The 9th Int. Conf. Biomimetic and Biohybrid Systems, online from July 28th to 30th 2020. The conference is targeted at the intersection of research on novel life-like technologies inspired by natural systems, biomimetics, and research that seeks to interface biological and artificial systems to create biohybrid systems. This issue features a selection of the best research papers from the 2020 edition of the Living Machines conference (Vouloutsi *et al* 2020) [14], chosen by a panel of experts for publication in this special issue, including award-winning papers and posters (1st and 2nd place best papers by Cheng *et al* 2020 [11], and Meder *et al* 2020 [12]; 1st place best poster by Stankiewicz & Webb, 2020 [13]).

The first article of this special issue, by Cheng *et al* [15], is a study on programmable biocomposite material enabling the construction of adaptive self-shaping large-scale architectural structures. These 3D printed meta-structures on the scale of meters were built by combining fused granular fabrication with integrated hygroscopic wood actuators. Through these meta-structures, the authors were able to change the curvature of a meter long architectural structures, simply by modifying the relative humidity of the environment. In addition, Cheng *et al* introduce the parameters for tuning mechanical properties of the bio-composite materials to assess and detail the sequential process of the additive fabrication in an industrial setting.

The second article is a study by Stankiewicz and Webb [16] that hypothesizes a novel insect flight orientation process. The authors propose that bees use a process called transverse oscillating route following to navigate by memorized ground views complementing existing paradigms. Using a wavelet-based band-pass orientated filter approach, their developed model

enabled a quadcopter to fly in areas with minimal horizontal view information. They demonstrate that their vision system can operate with a biologically relevant visual acuity and viewing direction.

The third article by Meder *et al* [17] expands on biohybrid generators based on living plants and artificial leaves. Electricity can be harvested using the outermost structure of plant leaves and the inner ion-conductive tissue to convert mechanical vibration energy induced by the wind into electricity by surface contact electrification and electrostatic induction. By adding an artificial leaf to a living plant leaf, oscillations and mechanical contacts were enhanced and thus, the produced electricity of this leaf-based triboelectric generator increased. The study shows that the energy can be used to power light-emitting diodes and a temperature sensor under real outdoor wind conditions, highlighting the potential use as an autonomous power source for low-power sensor networks and environmental monitoring.

In the fourth article, Conrad *et al* [18] highlight a novel tool changing specialized multi-material fused deposition modelling (FDM) 3D printer for the rapid prototyping of soft robotic elements. The system is equipped with four FDM print heads, which can print from stiff PET to flexible TPU for every filament-based printing material. With a specifically designed post-processing phase, a feature adapted extrusion factor airtight flexible membranes and customizable pneumatic actuators can be created and directly printed into stiff housings combined with robot joints through the tool changing multi-material printing. The authors hypothesize that novel tools could be integrated into the system through the generic design of the coupling mechanism, such as a syringe print head (for silicone or gels) or pikers to lay various types of inlays into print.

The last two articles focus on insect nervous system control strategies for the locomotion of walking robots. Force control and measurement are essential for walking in animals and machines. The campaniform sensilla (CS) takes over the role of a force sensor in insects. The fifth article by Szczecinski *et al* [19] provides a computational model of how CS discharges adapt to tonic forces during cyclic loading during walking. The system can cope with and adapt to many different stimuli and reproduce responses of insect CS, which is shown analytically. By replicating three different CS groups of cockroaches and stick insects, the generalizability of the system is shown, and inversion of the model enables estimation of stimulus force in insect discharge recordings. The model can be used to understand the role of load feedback in insect motor control and enhance the dynamic load feedback in legged locomotion of robots.

In the sixth article, Goldsmith *et al* [20] abstract the control principles of the insect nervous system of a stick insect for femur-tibia (FTi) and joint control networks into a neuromechanical model. By examining and considering the reflex reversal response to joint flexion as primary reflex loops, the authors provide a possible answer to the question of how information is transmitted between the 'lower level' ventral nerve cord and the 'higher level' cephalic ganglia to facilitate locomotor control. Based on the anatomy of the non-spiking interneuron joint control network controlling the FTi joint, this specific network architecture was used to generate motor commands for a robotic limb whose motion and forces generated sensory feedback for the network. Inhibition of the network's afferents for flexion position and velocity resulted in reflex reversal in the FTi joint of the robotic limb. The results suggest that both the reflex reversal and limb strain amplification mechanisms are necessary to generate and maintain a rhythmic step in the limb. Their model aims to improve the understanding of the general nervous system and lead to new robotic controls.

To conclude, since the first conference of Living Machines (2012 at La Pedrera in Barcelona, Spain,) the field of machines inspired by living nature has broadened from slime mould inspired oscillator systems and soft-peristaltic robots to artificial leaves for energy harvesting, programmable compliant biocomposite materials and novel control principles for insect-inspired locomotion and vision using neural networks. This collection of papers highlights the broad range of exciting international research in these fields united by the theme of Living Machines. We hope that the special issue will prove informational and inspirational to readers new to the topic and be a valuable resource for current and future researchers in the area.

We would like to thank the hosts of the conference, workshops and poster sessions held at the Cluster of Excellence livMats at the University of Freiburg. The Living Machines conference and special issue would not have been possible without the invaluable contribution and active participation of its community. We would also like to thank all the authors who every year keep contributing to the field with impactful work, even during the challenging time of COVID-19 and the reviewers who ensure the quality of the published work. Finally, we would like to highlight the support of Springer and most importantly, the IOP journal of Bioinspiration and Biomimetics for their support in the publication of this special issue.

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Data availability statement

No new data were created or analysed in this study.

ORCID iDs

Falk Tauber https://orcid.org/0000-0001-7225-1472
Vasiliki Vouloutsi https://orcid.org/0000-0001-6425-1026
Anna Mura https://orcid.org/0000-0002-5673-1174
Thomas Speck https://orcid.org/0000-0002-2245-2636

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