*liv*MatS - The Vision

Today's materials have largely static properties. For example, they have certain mechanical, optical, and thermal properties, which typically change little in time, apart from inevitable aging. This set of properties allows the use of such materials in everyday life, but also under extreme conditions such as in the deep sea, in the desert, and even in outer space. In contrast to this, in nature everything from simple cells to whole organisms is far from being static. In fact, a key to survival for all living beings is having utmost flexibility, i.e. the ability to adapt to changes in the environment and to overcome the obstacles presented by a sometimes hostile environment. However, the ability to adapt to changing environmental conditions comes at a price: adaptation intrinsically costs energy, which in nature needs to be provided through food or sunlight.

Our vision is to make use of the best of both worlds, the biological and the technological realm, to develop **liv**ing, adaptive, energy-autonomous **Mat**erials **S**ystems. Materials systems developed by the *liv*MatS cluster will adapt their properties in response to changes in their environment and harvest the energy they need from this environment. They will be mobile and don't need a link to an external power supply to show complex adaptive behavior. Such unprecedented properties will not be achieved by one "miracle material" alone, but through the integrated interaction of several material components working in concert, taking nature, especially plants, as an important source of inspiration. However, to go "beyond biology" and to be free of pre-conditions required for the survival of cells such as moderate temperatures and the presence of water, the materials systems envisioned by *liv*MatS do not contain biological cells. These systems are not alive in a biological sense, as they do not exhibit self-reproduction. However, apart from that, they exhibit many features of living entities. They are "vital" in the sense that they are energy self-sufficient, durable, adaptive, self-regulating and self-protecting. They can function even under adverse conditions without encountering system failure, and have the "look and feel" of a living system. The vitality of these materials systems breaks with current paradigms in materials research. The so-called "smart" or "intelligent" materials developed so far, typically respond only to changes in the environment in a fixed way, preprogrammed into the material, and/or rely on a sophisticated infrastructure (motors, controller, and energy supply). We will develop truly new concepts of materials system generation by simultaneously integrating features such as energy harvesting, sensing, simple decision making, adaptation and self-improvement into a single system. Research in *liv*MatS will be carried out in constant, concurrent reflection of the sustainability of the applied approaches and on the societal challenges related to materials systems with lifelike features, throughout the development of the materials systems. Instead of first completing the technological development and then analyzing the implications for society, we will closely interweave technology development, sustainability assessments, behavioral analyses, acceptance, and the philosophical discourse on the interplay between human control and autonomy of systems.

Meeting the Challenge - A Unique Team

To turn this vision into reality, *liv*MatS has assembled a unique team composed of scientists from a broad spectrum of disciplines. This team builds on the established strongholds of the University of Freiburg in energy research, soft matter science ("birthplace of polymer science"), biomimetics and microsystems engineering and combines them with sustainability research, behavioral sciences and philosophy. *liv*MatS draws on a trans- and interdisciplinary research team from six different faculties gathered under one thematic roof and faces the challenge from a novel, holistic point of view. Freiburg offers for this endeavor the ideal setting in terms of expertise, background, diversity and an internationally unique combination of infrastructures. This includes the IMTEK (Department for Microsystems Engineering; microprocessing and cleanroom facilities), the Freiburg Materials Research Center (FMF, material processing and characterization) and the Botanic Garden (bioinspired research) as well as the recently established Freiburg Center for Interactive Materials and Bioinspired Technologies (FIT). To complement its expertise, *liv*MatS has teamed up with the Fraunhofer Institute for Solar Energy Systems (FhG-ISE), one of the leading institutes on energy research worldwide, and the Fraunhofer Institute for the Mechanics of Materials (FhG-IWM). These excellent R&D facilities offer an ideal environment for the development of high-tech materials and devices all the way from basic research up to a pilot plant level. Another important partner in the *liv*MatS consortium is the Ökoinstitut e.V., which plays a defining role in sustainability analysis throughout Germany and beyond, setting standards on this field. Most of the principal investigators in *liv*MatS are active members of the FMF and the FIT and have a strong track record of collaboration in research centers (TRR 141, TRR 123) and graduate research programs (GRP "Microenergy Harvesting", IRTG "Soft Matter Science"). Hence, *liv*MatS builds on a successful history of merging disciplines and mastering interdisciplinary challenges, both in fundamental research and in the translation of blue sky research into real-life applications. While individual aspects of the research program of *liv*MatS are also carried out at other universities and research centers around the world, the interdisciplinary team and its holistic approach to the development of living materials systems is unique at the national and global level.

Turning the Vision into Reality: The *liv*MatS Research Program

In recent decades, materials research has advanced significantly through groundbreaking work on bioinspired materials, efficient energy systems and responsive or self-healing materials. While impressive progress has been made in each of these individual areas, examples of the combination and integration of these different aspects in a single materials system still remain largely elusive. The complexity of the systems with often conflicting requirements and contradictory functional conditions has hitherto prevented the simultaneous and successful integration of all functionalities into a single system. In order to achieve such a deep level of integration within one materials system, four research areas working in close concert with each other, will each tackle one major defining feature of a **liv**ing, adaptive energy-autonomous **Mat**erials **S**ystem (cf. Fig. 1).

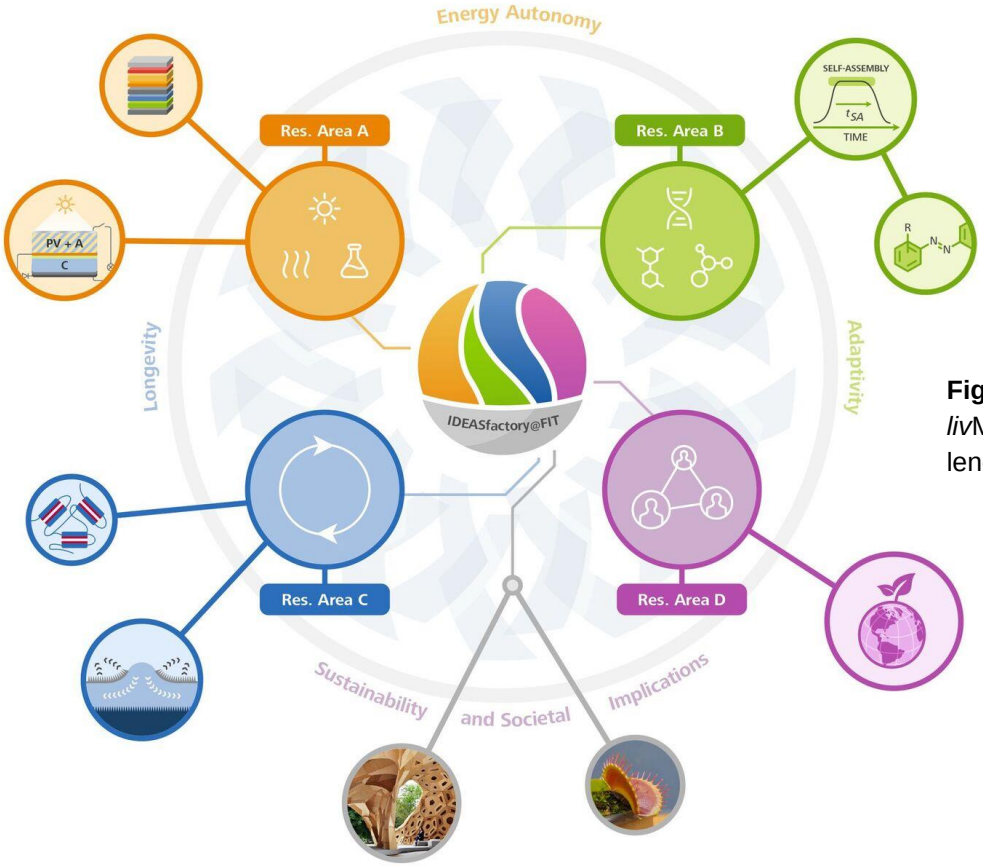

Fig. 1: Structure of the *liv*MatS cluster of excellence

Research Area A focuses on the development of novel and highly integrated energy harvesting and storage units. Light, temperature differences or vibrations will be taken as sources for energy harvesting. The energy will either be used directly, stored for later use or transformed for example into mechanical strains, chemical gradients, or light. In the latter examples the energy can be used for movement of systems parts or photochemical reactions. In **Research Area B** new concepts are developed for adaptivity in materials systems with complex energy landscapes, where - depending on sensory input - different paths of action are taken, that is, simple decision making takes place. Internal feedback loops and the processing of sensory input from the environment will empower such systems to exhibit self-regulating properties. Such material-inherent – not computer-chip-controlled – processing of information will ultimately pave the way for materials systems that possess a memory and thus the capability for a simple form of “learning” and self-improvement. However, such complex systems have a higher propensity to fail and it must be avoided that a small damage can lead to the loss of function of the entire system. **Research Area C** therefore focuses on the longevity of the systems by developing strategies for the training, self-repair or the shedding/replacement of damaged and accordingly superfluous parts. As in the other areas, examples of living organisms, especially plants, will provide important inspiration (e.g. adaptive growth, self-repair, shedding of leafs/branches). **Research Area D** will focus on the societal challenges posed by materials systems with lifelike properties. The influence of a disruptive technology is typically studied only after implementation of the technology has already begun. For example through autonomous vehicles or the replacement of humans by expert systems, society

is becoming transformed as a whole, while the societal discussions on such disruptive changes lag far behind the technological possibilities. We plan to conduct this discourse already at an early stage of *liv*MatS research and to explore sustainability and societal implications already concurrent to the process of technology development. *liv*MatS will address this by integrating sustainability analyses, philosophical and psychological reflections and will further the public discourse on *liv*MatS research by interacting with the general public and the media.

In order to make the results of the research in all four areas tangible and to act as lighthouses guiding the activities of the cluster, we will develop **three different demonstrator lines**: 1) an artificial Venus flytrap, which can snap shut in response to two external stimuli and has the "look and feel" of the natural role model, despite being made from purely artificial materials; 2) a soft autonomous machine that by material-inherent adaptation allows gripping of objects with very different weights and shapes, thereby yielding new impulses to soft-robotics; 3) systems that are shape-morphing and change their appearance and properties depending on e.g. temperature, light or moisture such as adaptive building envelopes, helmets or orthoses and prostheses.

The Ideasfactory@FIT

The home and heart of *liv*MatS will be the **FIT building**, where the **IDEASfactory@FIT** will be established. It will house the platforms for **Multiple Materials Additive Manufacturing** as well as **shared office and lab spaces**, particularly attractive for the cluster's early career researchers. The IDEASfactory@FIT will create an open, interconnecting scientific environment designed to foster communication and interaction in a relaxed atmosphere by bringing researchers from all four research areas into close contact, using "the coffee machine as a catalyst". The aim of this intensified communication is to inspire young researchers to cross and bridge disciplines and be creative – the source of all innovation. The IDEASfactory@FIT will consist of both the "hardware", i.e. the labs and offices in the FIT building, and the "software", which will include activities such as brainstorming lunches, brown bag lectures, power breakfasts and open mindmaps.

Strengthen the expertise and expanding the network

On the basis of its strong setting in Freiburg, *liv*MatS will strategically strengthen its portfolio of expertise with **three new tenured professorships** in the fields of *Soft Machines – Smart Systems Integration*, *Active Soft Matter* and *Bioinspired Materials Concepts*. **Five Junior Research Groups** (JRG) will be recruited and awarded about 1000 €k each. Three of these groups will be offered open topic across all Research Areas, and awarded to the best proposals regardless of the field of expertise (*"dream big and give us your best ideas*"). Two of these groups will be part of the **Agnes-Pockels-Program *designed to support young female researchers***.

The international network of *liv*MatS will be complemented by three strategic partnerships with the Universities of Strasbourg and Tokyo and the National Institute for Materials Research (NIMS) in Tsukuba. *liv*MatS will have strong ties to the *microTec Südwest* cluster as one of the largest high-tech clusters in Europe which will offer a wide range of opportunities for networking with industry. *liv*MatS activities are strengthened through robust cooperation with two excellent univer-

sities in the Upper Rhine Valley, Strasbourg and Basel, allowing internationalization at short distances. This has already been tried and tested over the last 20 years, for example in the joint M.Sc. “Polymer Science” and the joint Graduate Program IRTG 1642. Eucor – **The European Campus** unites these internationally top-ranked universities, in which > 100,000 students and topnotch research facilities provide a unique transnational setting for the planned cluster.

Carrying on the Torch: Early Career Researcher and Transfer of Knowledge into Society

Strategies for early career support in *liv*MatS address all career stages from advanced undergraduates to JRG leaders. These strategies aim at (a) a seamless integration of transition phases between the graduate, the doctoral, and the postdoctoral level through **Young Researcher Awards** and **Booster Grants**, (b) a balanced relationship between the promotion of early academic independence with support from peers and senior researchers, and (c) an increase of the number of female early career researchers to at least 40% at all stages. The early career researchers will be supported by Young Researcher Conferences, the **Scientific Boot Camp** on an introduction to the *liv*MatS vision, good scientific practice und safe handling of research data, regular **Industry Workshops**, and the *liv*MatS **Writer’s Studio**, which is designed to help early career researchers through workshops and one-on-one training by writing consultants to become better writers and enable them to publish their work in highly respected journals**.**

We will develop new formats for public outreach based on the concept *Learning from nature… in nature.* Here we use the University of Freiburg’s Botanic Garden as an ideal entry point to instruct the general public about bioinspired materials and living materials systems. Questions like “Why is a nut so tough?” are of great interest to the public. This concept has proven successful in addressing a broad spectrum of groups ranging from families, high school and college students to teachers and decision makers from industry and politics. Cluster PIs have extensive experience in arts and science projects, which will be used to address the societal implications of *liv*MatS in several participatory discourse formats, including cafés scientifiques and science jams, comic-art projects with Freiburg schools and an online gallery featuring bio-inspired artwork.

*liv*MatS – the Long Term Perspective

The establishment of *liv*MatS as a Cluster of Excellence will enable the foundation of a new multidisciplinary center on bioinspired materials research and systems integration with high international visibility at the University of Freiburg. This center will make a decisive contribution to the university’s well established profile field in *Functional and Bioinspired Materials*. *liv*MatS will perform research across institutional boundaries and help bridge the gap between engineering, natural sciences and behavioral sciences/humanities. We expect that the progress of research in *liv*MatS will help to meet the needs of a future society that relies heavily on new materials and systems and will provide breakthroughs in the development of materials systems that integrate well into the human environment, sustainably serve human needs, and run on clean energy.