The coming decades present a host of challenges for our built environments: a rising global population combined with increasing urbanization; crumbling infrastructure and dwindling resources to rebuild it; and the growing pressures of a changing climate, to name a few.

To become more livable for more people, cities themselves will need to become smarter, with buildings, bridges and infrastructure that are no longer static but dynamic, able to adapt and respond to what’s going on around them. If not exactly alive, these structures will need to be life-like, in important ways. And for that, they’ll need to incorporate living materials.

“Engineers and scientists have worked for hundreds of years with so-called smart materials,” says Zoubeida Ounaies. “Piezoelectricity was discovered in the 1880s.” Smart materials can sense and respond to their environment, she explains, “but they always need an external control system or source of power. Living materials that adapt, respond to the environment, self-power, and regenerate—in the way that materials in nature do—are the next logical step.”

Ounaies, a professor of mechanical engineering at Penn State, is director of the Convergence Center for Living Multifunctional Material Systems, a research partnership between Penn State and the University of Freiburg in Germany. Known as LiMC2, the center is one of only a handful in the world focused on this emerging field.

**A NEW PARADIGM**

Living materials, Ounaies explains, are engineered materials that are inspired by nature. Sometimes they even incorporate biological elements. Their dynamic properties, at any rate, enable them to adapt to changes in their environment, responding to external stimuli. They may change shape, heal themselves, even make simple decisions.

Close-up of a dynamic shading system mounted in the Stuckeman Building at University Park. The system, designed by Penn State doctoral student Elena Vazquez, is made up of panels incorporating a bistable material that allows them to open or close in response to sunlight, without human intervention.
Thomas Speck has been fascinated by biomimetics for 30 years. Trained as a biophysicist, Speck is now professor of biology at the University of Freiburg. He studies the functional morphology of plants—the relationship between structure and function—and how these “biological role models” might be applied to the world of technology. As director of the University’s Botanic Garden, he has over 6,000 species from which to find his inspiration.

Plants, says Speck, have important lessons to offer. “First, they are mobile, although their movement is often hidden from us,” he explains. “A lot of plant movements are very aesthetic—think of a flower opening. We want to transport this aesthetics into our architectural solutions.”

What’s more, Speck says, plants work their magic with a very limited number of structural materials. “Cellulose, hemi-cellulose, lignin, a bit of pectin. Three polysaccharides and one complex polyaromatic polymer. With these materials, which are all relatively easy to recycle, they are able to make fantastic structures, fantastic systems which work incredibly well.”

A simple example is the pine cone, whose paddle-shaped scales open and close in response to changes in environmental humidity. At the Botanic Garden, Speck and his colleagues have analyzed fossilized pinecones 50 million years old and found that they still perform like modern specimens. “And it costs no energy, because humidity changes are brought by sunlight,” he says.

As amazingly robust as the natural mechanism is, the pinecone is merely reactive, Speck notes. “If it’s wet, it’s closed. If it’s dry, it’s open.” In adapting this principle, he says, “We want to design systems that are interactive, that can combine movements, that make decisions. Biomimetics for us means we get inspiration from nature and then reinvent nature. We don’t copy it. We want to combine the best of both worlds: living nature and technics.”

A CENTER IS BORN

Engineering living materials requires a daunting combination of expertise: in biology, materials, engineering, and design, to name a few. It's exactly the sort of problem that Penn State's interdisciplinary institutes were set up to solve. LiMCS got its start when the directors of two of those institutes, Tom Richard of the Institutes for Energy and the Environment and Clive Randall of the Materials Research Institute, saw this emerging field as one in which the University could excel.

Penn State already had a strategic partnership with Freiburg, one of Germany's top universities, and the two institutions had both overlapping and complementary strengths in the area of living materials. Working together, through both research collaborations and educational exchanges, they could become a worldwide leader.
The idea was supported and facilitated by Penn State Global Programs and the International Office in Freiburg, and in July of 2019, Penn State President Eric Barron and the University of Freiburg’s Rector Hans-Jochen Schiewer signed the formal partnership that made LiMC2 a reality. Soon after, the center announced that adaptive architecture would be one of its core research areas.

Adaptive architecture, Ounaies says, is a “no-brainer” for a center built around living materials. “It’s a natural core area for us because of the focus on materials discovery and sustainability, as well as our strengths in smart materials, advanced manufacturing, architecture and design, where the needed expertise spans multiple department and colleges. And it’s also a great platform where all these things can come together to demonstrate what living materials can do.”

Before the center even existed, in fact, Ounaies, whose research focuses on responsive soft materials for sensing, actuation, energy storage and energy harvesting, was collaborating with Penn State architecture professor Jose Duarte and Ph.D. student Elena Vazquez, both in the College of Arts and Architecture.
Top, Jose Duarte, professor of architecture at Penn State, and doctoral student Elena Vazquez adjust panels on the prototype shading system that Vazquez designed. Middle left, A dragon tree, whose branching structure and load-bearing strength make it a good model for tree-like pillars like those in Stuttgart’s international airport, at bottom right. At bottom left, element for a fiber-and-concrete pillar being developed for architectural use at the University of Freiburg.
Duarte’s work focuses on customized buildings that fit into their environmental contexts to create sustainable and affordable housing options. But conventional approaches to customization have their limits. “Once it’s built, it’s static,” he says. So he and his students began to explore the possibilities for buildings that continue to adapt in response to changing conditions.

For her Ph.D., Vazquez designed a shading system that could be added to the façade of an existing building, made up of panels that open or close in response to sunlight, controlling the amount of light and heat entering the building. Because a mechanical system would be expensive and difficult to maintain, Duarte and Vazquez were looking for a materials solution for her design.

“My research interest, broadly defined, is to find new engineered materials and figure out ways of incorporating them into architectural design,” Vazquez says. They turned to Oumaies, aware of her work with electroactive polymers. Vazquez spent time training in Oumaies’s lab, and eventually they settled on bistable materials as a possible solution. With just a little bit of energy, Oumaies explains, a bistable material can be nudged from one stable shape to another—snapping from open to closed, for instance.

Vazquez’s subsequent design incorporates just such a material, actuated by a polymer-based smart material, to open and close its shade panels. The system works in response to sunlight, without human intervention. A small prototype is mounted in the Stuckeman building at University Park and a grant awarded by the American Institute of Architects will allow the collaborators to build a full-scale model.

BEYOND THE FAÇADE

Not surprisingly, the façade or building envelope—what Duarte calls “the membrane that permeates between the interior of the building and the outside”—is a primary focus of adaptive architecture. “Anything you do there has a huge impact on performance, on energy consumption, on environmental conditions inside,” Duarte says.

At Freiburg, Speck and his colleagues are developing their own sun-shading systems, combining the opening and closing movements of a pair of plant models: the Bird-of-paradise and the waterwheel plant. Botanist Linnea Hesse, however, is more interested in a building’s structural elements. During a summer webinar event introducing Penn State and Freiburg researchers to one another, she presented a keynote talk on biomimetic structural design.

Hesse, a group leader in plant biomechanics at Freiburg’s Botanic Garden, noted that the branching structures of trees have already been incorporated into architecture—in the spectacular designs of buildings like Barcelona’s Sagrada Familia basilica and Stuttgart’s international airport, for example. In addition to their beauty, the tree-like pillars in these designs function to spread load-bearing requirements and allow for more interior space.

With the goal of optimizing the load-bearing strength of such components, she is studying the dragon tree, a member of the Monocotyledon family that includes palm trees and bamboo. Monocots have a particularly pronounced fiber-reinforced inner structure, Hesse explains, achieving strength without excess weight and making them a good biological role model.

To better understand how a dragon tree’s inner structure adapts to a load, she turned to medical colleague Jochen Leupold, who trained her in the use of magnetic resonance imaging (MRI). Her time-lapsed scans of living trees, both under load and not, show localized changes in fibrous tissue due to weight-bearing, data that have already been used to improve the design of a fiber-and-concrete pillar being developed for architectural use.

Hesse is also using MRI and CT imaging to study branching mechanisms, how water is transported through monocot tissue, and the growth process itself. Understanding the inner workings of the plant, she says, is only the first step. Her vision is one day to help design houses that can adapt and grow over time, altering their structure to meet changing needs the way plants do. “It’s a bold idea,” she says. “But I think it’s possible. This is where I want to go.”

RE-THINKING CONCRETE

Juan Pablo Gevaudan, in contrast, wants to know how things break down. Gevaudan, an assistant professor of architectural engineering at Penn State, calls himself a modern cement chemist. He is focused on the problem of concrete degradation.
Concrete is the most widely used construction material on Earth. Deployed in the harshest conditions, exposed to relentless attack by environmental acids and salts, concrete degrades over time. Erosion and rusting of embedded reinforcement bars cause eventual weakening and failure. Sometimes that failure is catastrophic, as in the Surfside, Florida condominium collapse of June 2021.

The first step to addressing concrete corrosion, Gevaudan says, is understanding exactly how it occurs. Once that chemistry is better known, researchers will be able to predict degradation before it happens, and to design more durable cements from materials that can respond and adapt to environmental conditions.

Alkali-activated materials are one possible alternative. “These have drawn global attention because they can be produced from the byproducts of industrial processes—steelmaking and coal-burning,” Gevaudan says. “They can also be made from clay, the most abundant material in the world. And they can be produced at ambient temperatures, so they are both local and environmentally friendly.”

Ideally, he says, the materials he develops will not only resist corrosion, they’ll have the ability to repair themselves. Some researchers have even shown that certain types of bacteria embedded and living within concrete can perform this self-healing. But the longevity of these biological solutions is an open question, so Gevaudan and chemical modeler Michael Moseler of Freiburg are pursuing a different route. The two were awarded a LiMC² seed grant to develop a cement material that alters the surface chemistry of the embedded reinforcement bar within a concrete matrix, creating a barrier of ferrous mineral that halts and potentially reverses corrosion. The chemical process, Gevaudan says, mimics the formation of one of the toughest substances in nature: a mussel’s teeth.

RESEARCH HIGHLIGHTS

Rebecca Napolitano’s design inspiration comes more from history than from nature. As an undergraduate majoring in physics and classical languages, Napolitano, now an assistant professor of architectural engineering at Penn State, spent several summers in Italy, where she fell in love with historic structures and learning how they could comingle with modern ones. “It really opened my eyes to the importance of historic structures and how we can keep them as vital parts of communities,” she says.

But it isn’t only monuments that Napolitano wants to preserve. “Over fifty percent of New York City is over 50 years old,” she says. “What are we going to do, tear it all down and start over?” Instead, she wants to design adaptivity into existing structures. By preserving and finding new uses for what already exists, she says, communities can reduce their carbon costs, decrease the amount of solid waste they send off to landfills, and save on new construction materials.

Preservation poses its own challenges, and Napolitano is developing digital technologies to address them. She is making innovative use of eye-tracking software and machine learning to help with detecting existing damage and simulations to aid in diagnosing and predicting problems.

“The way we inspect our infrastructure is really limited,” she explains. “Say it’s a bridge. Right now we send an inspector every two years, and they might have to climb up on scaffolding to look at the underside, or dive to get at the underwater portion. It’s difficult to be really thorough, and it requires a ton of expert knowledge.”
With eye-tracking, we’re trying to figure out how to capture the knowledge of that human expert, then apply machine learning to teach a drone, say, where to look, and have it fly in for a close inspection.” She imagines a future where a single inspector could be aided by a team of autonomous drones, lightening currently heavy workloads.

Another major challenge is the ongoing monitoring of a building’s structural health. Electronic sensors in older buildings may be too few or inadequately networked to provide critical information. They require an external power source and centralized processing. “Plus, embedded electronic sensors eventually stop working,” Napolitano says.

She is working with Wes Reinhart, an assistant professor of materials science and engineering and Institute for Computational and Data Sciences co-hire, who uses artificial intelligence to design so-called metamaterials that could be used in next-generation sensors to eliminate these problems. In one example, a sensor made of photonic material could be designed with an interior microstructure that scatters light passing through it according to prescribed mathematical equations.

“Then you can measure that response,” Reinhart says, creating what is essentially a passive computing technology. “Instead of a sensor that has to send data elsewhere to be processed, the sensor itself is doing the processing. It’s a way that you can compute with very low power—hundreds or thousands of times less power than electronic computing.”

That kind of capability, Napolitano adds, could be invaluable “not just in a city like New York, but in places around the world where electricity is not as easily accessible.”

BUILDING THE FUTURE

“Architecture and building construction are key to our limiting climate change,” says Thomas Speck. According to most estimates, building materials and operations account for over 30 percent of global carbon emissions.

The livMatS Pavilion recently erected at Freiburg’s Botanic Garden points toward one possible alternative. A collaboration between Freiburg and the University of Stuttgart, the cottage-sized structure is made of wound flax fiber bundles, covered with a recyclable (and waterproof) polycarbonate. Its light but strong load-bearing structure, Speck says, was inspired by the reticulate wood structure of the saguaro cactus. In addition to being a renewable resource, flax costs far less energy to produce than concrete and steel and can be harvested every year.

At Penn State, Benay Gursoy, assistant professor of architecture in the College of Arts and Architecture, is exploring in a similar vein, experimenting with mushroom-based composites as sustainable building materials that respond to temperature and humidity.

Engineered systems like passive-computing metamaterials or self-healing concrete would be sustainable in other ways, as well. Imbued with the capacity to sense changes in themselves and their environments and communicate with nearby structures, these materials would save the energy cost of transmitting data, and spread out the burden of decision-making. Instead of overwhelming a central processing center with oceans of data collected from thousands or millions of electronic sensors, a living material set in place could sense and respond on its own. Localizing decision-making in this way could in turn help to address another looming challenge for the hyperconnected smart cities of the future: cybersecurity.

We’re still a long way from the vision of adaptive architecture using living materials, Ounaies concedes. It will require many different types of expertise, working together, to get there. “That’s exactly what we’re putting in place with this partnership,” she says. “And that’s what makes it so exciting.”

“If we can design systems which can adapt, harvest energy, are robust and are sustainable,” says Freiburg’s Jurgen Ruhe, “this will be a truly new paradigm in materials research.”