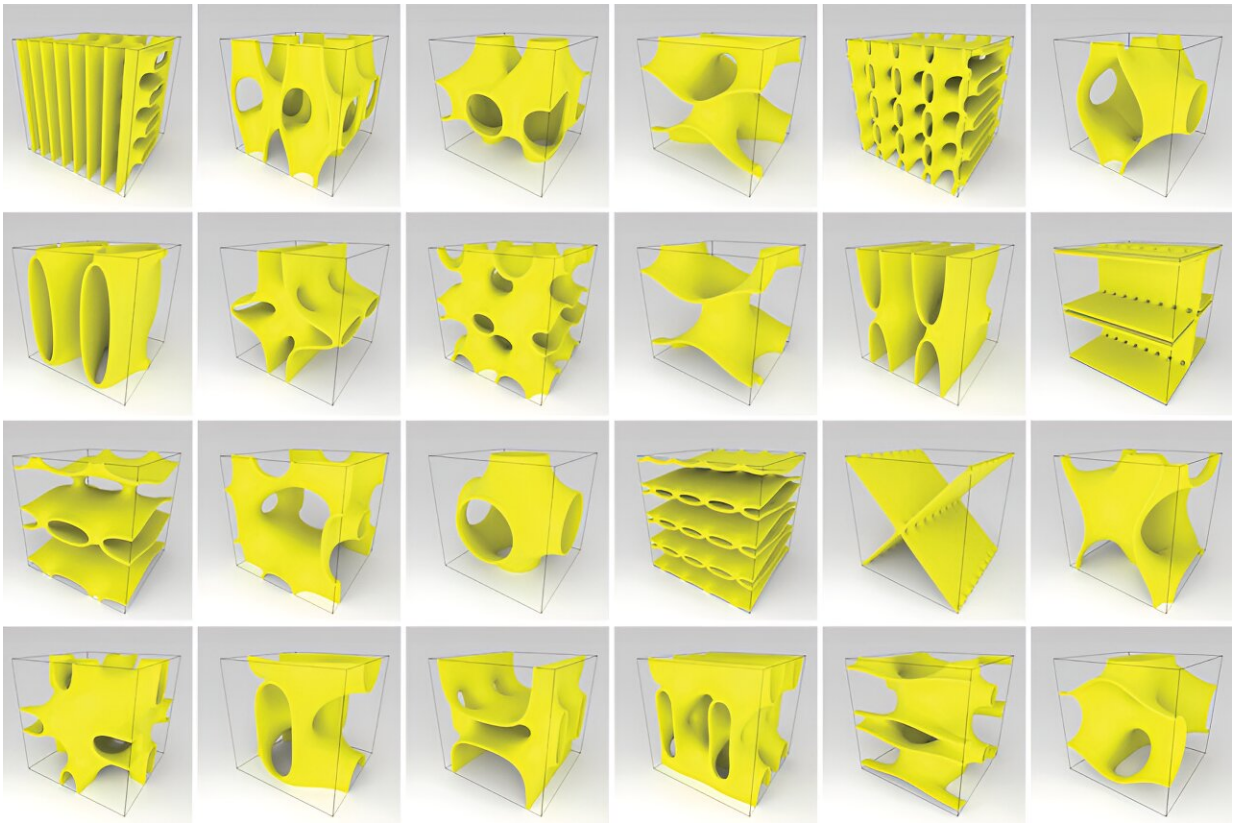
New method simplifies the construction process for complex materials

August 2 2023, by Adam Zewe



Researchers from MIT and the Institute of Science and Technology Austria have created a technique to include many different building blocks of cellular metamaterials into one, unified graph-based representation. They used this representation to create a user-friendly interface that an engineer can utilize to quickly and easily model metamaterials, edit the structures, and simulate their properties. Credit: Massachusetts Institute of Technology

Engineers are constantly searching for materials with novel, desirable property combinations. For example, an ultra-strong, lightweight material could be used to make airplanes and cars more fuel-efficient, or a material that is porous and biomechanically friendly could be useful for bone implants.

Cellular metamaterials—artificial structures composed of units, or cells, that repeat in various patterns—can help achieve these goals. But it is difficult to know which cellular structure will lead to the desired properties. Even if one focuses on structures made of smaller building blocks like interconnected beams or thin plates, there are an infinite number of possible arrangements to consider. So, engineers can manually explore only a small fraction of all the cellular metamaterials that are hypothetically possible.

Researchers from MIT and the Institute of Science and Technology Austria have developed a computational technique that makes it easier for a user to quickly design a metamaterial cell from any of those smaller building blocks, and then evaluate the resulting metamaterial's properties.

Their approach, like a specialized CAD (computer-aided design) system for metamaterials, allows an engineer to quickly model even very complex metamaterials and experiment with designs that may have otherwise taken days to develop. The user-friendly interface also enables the user to explore the entire space of potential metamaterial shapes, since all building blocks are at their disposal.

"We came up with a representation that can cover all of the different shapes engineers have traditionally shown interest in. Because you can build them all the same way, that means you can switch between them more fluidly," says MIT electrical engineering and computer science graduate student Liane Makatura, co-lead author of a paper on this

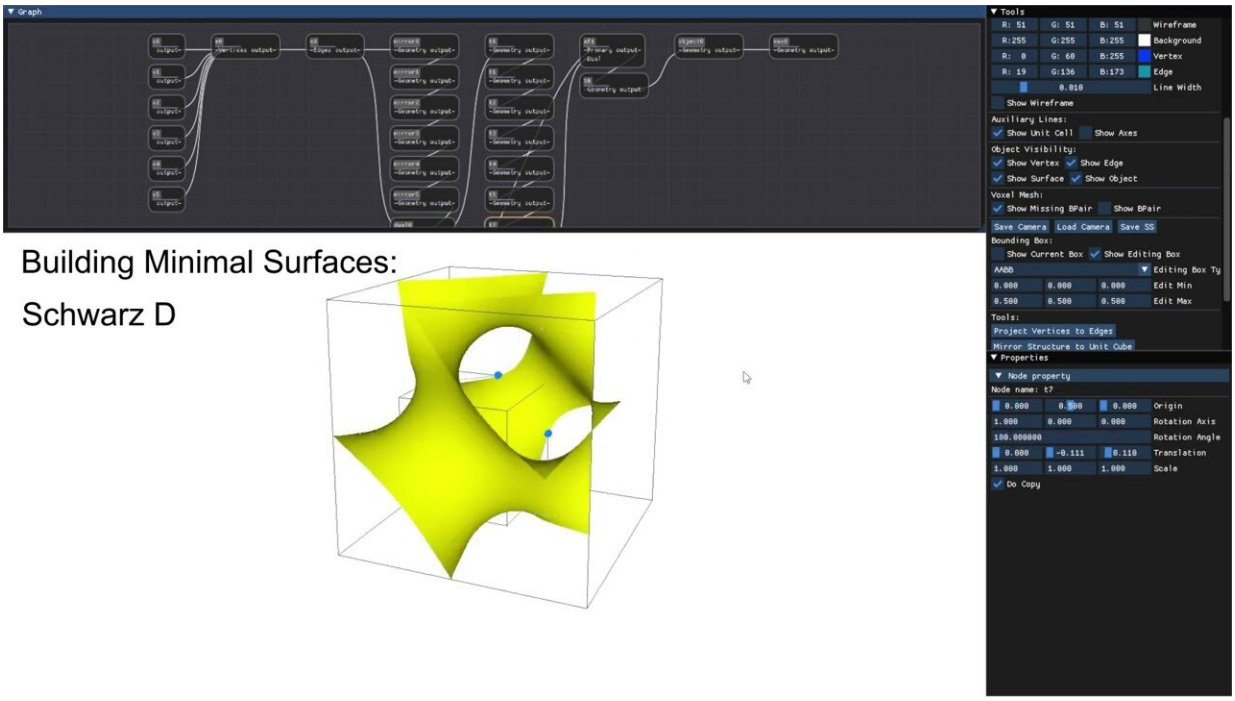
technique published in *ACM Transactions on Graphics*.

Makatura wrote the paper with co-lead author Bohan Wang, an MIT postdoc; Yi-Lu Chen, a graduate student at the Institute of Science and Technology Austria (ISTA); Bolei Deng, an MIT postdoc; Chris Wojtan and Bernd Bickel, professors at ISTA; and senior author Wojciech Matusik, a professor of electrical engineering and computer science at MIT who leads the Computational Design and Fabrication Group within the MIT Computer Science and Artificial Intelligence Laboratory. The research will be presented at SIGGRAPH held August 6–10.

A unified method

When a scientist develops a cellular metamaterial, she typically begins by choosing a representation that will be used to describe her potential designs. This choice determines the set of shapes that will be available for exploration.

For instance, she may choose a technique that represents metamaterials using many interconnecting beams. However, this prevents her from exploring metamaterials based on other elements, such as thin plates or 3D structures like spheres. Those shapes are given by different representations, but so far, there hasn't been a unified way to describe all shapes in one method.



Credit: Massachusetts Institute of Technology

"By choosing a specific subspace ahead of time, you limit your exploration and introduce a bias based on your intuition. While this can be useful, intuition can be incorrect, and some of the other shapes may have also been worth exploring for your particular application," says Makatura.

She and her collaborators took a step back and closely examined different metamaterials. They saw that the shapes that comprise the overall structure could be easily represented by lower-dimensional shapes—a beam could be reduced to a line or a thin-shell could be compressed to a flat surface.

They also noticed that cellular metamaterials often have symmetries, so only a small part of the structure needs to be represented. The rest can be

built by rotating and mirroring that initial piece.

"By combining those two observations, we arrived at this idea that cellular metamaterials could be well-represented as a graph structure," she says.

With their graph-based representation, a user builds a metamaterial skeleton using building blocks that are created by vertices and edges. For instance, to create a beam structure, one places a vertex at each end point of the beam and connects them with a line.

Then the user employs a function over that line to specify the thickness of the beam, which can be varied so one part of the beam is thicker than another.

The process for surfaces is similar—the user marks the most important features with vertices and then chooses a solver that infers the rest of the surface.

These easy-to-use solvers even allow users to quickly construct a highly complex type of metamaterial, called a triply periodic minimal surface (TPMS). These structures are incredibly powerful, but the usual process to develop them is arduous and prone to failure.

"With our representation, you can also start combining these shapes. Perhaps a unit cell containing both a TPMS structure and a beam structure could give you interesting properties. But so far, those combinations really haven't been explored to any degree," she says.

At the end of the process, the system outputs the entire graph-based procedure, showing every operation the user took to reach the final structure—all the vertices, edges, solvers, transformations, and thickening operations.

Within the user interface, designers can preview the current structure at any point in the building procedure and directly predict certain properties, such as its stiffness. Then, the user can iteratively tweak some parameters and evaluate it again until a suitable design is reached.

A user-friendly framework

The researchers used their system to recreate structures that spanned many unique classes of metamaterials. Once they had designed the skeletons, each metamaterial structure took only seconds to generate.

They also created automated exploration algorithms, giving each a set of rules and then turning it loose in their system. In one test, an algorithm returned more than 1,000 potential truss-based structures in about an hour.

In addition, the researchers conducted a user-study with 10 individuals who had little prior experience modeling metamaterials. The users were able to successfully model all six structures they were given, and most agreed that the procedural graph representation made the process easier.

"Our representation makes all sorts of structures more accessible to people. We were especially pleased with users' ability to generate TPMS. These complex structures are usually difficult even for experts to generate. Still, one TPMS in our study had the lowest average modeling time out of all six structures, which was surprising and exciting," she says.

In the future, the researchers want to enhance their technique by incorporating more complex skeleton thickening procedures, so the system can model a wider variety of shapes. They also want to continue exploring the use of automatic generation algorithms.

And in the long term, they'd like to use this system for inverse design, where one would specify desired material properties and then use an algorithm to find the optimal metamaterial structure.

More information: Liane Makatura et al, Procedural Metamaterials: A Unified Procedural Graph for Metamaterial Design, *ACM Transactions on Graphics* (2023). DOI: 10.1145/3605389

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