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ISAI Special Topic 6:
High-end Forum on Intelligent Structure Evolution Robots under the Principle of Metamorphism

Time: 13:30-13:55
Location: CC101C, Floor 1, Hall 18

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Bio-inspired models of rotational geometry and design of metamaterials

Abstract:
The movement of rotation in nature was the inspiration for Giorgio Scarpa's 1978 "transformable fabrics". In this talk, expanding on the pioneering topology work by this Italian artist and designer, a novel flat-foldable and rigid-foldable metamaterial will be introduced. Additional transformable shapes and prototypes, including Scarpa's bionic model of the mouth of the sea urchin, or Aristotle's lantern, will be demonstrated. The biological inspiration for these models will be discussed, based on Scarpa's "search of fundamental organizing components, through which it will be possible to regulate and orient, in a logical way and in a continuity of connections, the transformation and the development of the modular organizations."

Bio:
Pino Trogu is Professor of Information Design at San Francisco State University, where he teaches drawing, drafting, and data visualization. He has studied modular structures since 1973, while first attending the Istituto Statale d'Arte Oristano, Italy, where Giorgio Scarpa was his teacher and mentor. He holds an MFA from the Rhode Island School of Design, and a BFA from Istituto Superiore Industrie Artistiche, Urbino, Italy. He teaches the basics of symmetry operations and polyhedra dissections to the students of his drawing and drafting classes. In the Academic Year 2023–2024 he will be a visiting scholar in the robotics departments of Southern University of Science and Technology (SUSTech), Shenzhen, China, and King's College London, UK.

1
Hello everyone, my name is Pino Trogu and I am a teacher at San Francisco State University. I am honored to be presenting here today and I would like to thank the conference organizers and in particular Prof. Dai for inviting me.

2
Today I will present some new metamaterials which actually have a long history, going back to the 1970s when I was a high school student and had the fortune of being taught by a drawing teacher by the name of Giorgio Scarpa.

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As I go though some images of work by this teacher, artist, and researcher, I will tell that the metamaterials you will see were inspired by his work, by the work of Bas Overvelde, and most recently through a collaboration with Prof. Feng from SUSTech.

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Scarpa started out as a painter but quickly turned his attention to modular geometric structures as they relate to biological systems. He did this as he conducted his parallel teaching of technical drawing at the Art Institute in Sardinia, Italy.

5
While he stopped painting, he was alway careful to consider the aesthetic aspects and the connections to the natural world that can be found not only in art but also in geometry and technical endeavors.

6
I once asked him what was his inspiration for the topological and rotational geometry research that he so creatively pursued, and he mentioned the Swiss painter Paul Klee, whose Bauhaus lectures he studied.

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It was in his lectures that he found inspiration, like this caption for a sketch of the internal planes of a cube, where the word “content” takes on multiple meanings which invite and encourage curiosity.

8

While he officially taught technical drawing drawing and perspective, his lessons were always much more and often involved model making and polyhedra dissections.

9
Scarpa's classroom was a geometric lab with models everywhere, in the same way that a nature lab would have natural specimens everywhere.

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One of his projects, which I still teach myself to my own students in San Francisco, involves the sectioning of a cube in two or three equal and identical parts.

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Once in a while, an adventurous student will take the project further and connect together the sectioned parts to form chains of modules that can fold back into a minimum volume.

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Scarpa always pointed out the difficulty of learning from nature, where we can typically observe only from the outside, whereas the natural processes develop from the inside.

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He had a deep respect for nature and for life…

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… noting for example that not a single sea urchin was sacrificed for the study of the bionic model of the animal's mouth, or Aristotle's lantern.

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The model is made of paper and elastic, and it's a beautiful example of a machine that "does nothing" and yet elegantly demonstrates the animal's intricate cutting and chewing apparatus.

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Only the bottom, where the tip of the teeth are, would be visible in the real animal.

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The top row of this image shows the original model and the bottom row shows a functioning replica which I built in 2015.

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The sea urchin model has inspired new instrumentation, like this prototype of a biopsy harvester developed at Delft university of Technology, which mimics, in reverse, the opening and cutting motion of the teeth.

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Scarpa was also very interested in the structure of DNA, and although he didn't even own a microscope, he was able to create paper models both beautiful and transformable.

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It's quite interesting that already in the 1970s he would discuss his models of rotational geometry in terms of "transformable fabrics".

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In his book on rotational geometry he parallels some of his prototypes, often simply drawn on paper, with biological structures such as the "double-rhombus" muscle fiber, shown next to his envisioned fabric.

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Rotational geometry and sectioning of polyhedra are seen again here as a way to create transformable fabrics…

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… which again are just drawn when a scaled physical model was not feasible. Continuing his research has meant for me, in part, attempting to fabricate those designs available only as drawings, like this scaled model of six hexahedral chains, which …

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… when disconnected from a ring chain into an open chain, reveal a helical structure given by gravity and the constrained rotation of the modules.

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Inspired by Paul Klee's "content" observation, Scarpa dissected the Platonic solids into specular pairs of right-angle pyramids hinged together to form, like in this dodecahedron, a closed chain of 120 modules.

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Inspired by Scarpa's dodecahedron, and using instructions in his book, I built an equivalent chain but of right-angle pyramids belonging to the icosahedron, the solid with 20 regular triangle faces.

27
His transformable cube of aluminum tubes transforms into a different platonic solid as well as into various 2D drawing-like cube versions.

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In 1996 Scarpa invents two "transformable shapes" which are key to the metamaterials that will be shown shortly, although only the first was known to me since then, while I discovered the second only in 2017.

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The first, a prismatic cube, was actually invented in 1926 by Petrie, a mathematician, but Scarpa was probably unaware of this precedent, just as Bas Overvelde was unaware of Scarpa's model when he and his colleagues published the first of their "prismatic metamaterial" articles in 2016.

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The second shape is a prismatic tetrahedron with bisected prism walls, and it is this novel bisection that can render flexible previously rigid metamaterials such as materials #1 and #6 published by Overvelde and his colleagues in 2017.

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You may be familiar with that January 2017 paperwhich had a very detailed appendix…

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… with all the 28 materials that were examined. Materials #1 and #6 were rigid owing to the rigidity of the triangular prisms in the extruded tetrahedrons.

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A comparison of material #6 in it rigid and its flat-foldable form are relatively "open" on account of the truncated tetrahedra solids. I will show this physical model later but now I will show in more detail the bisection process for material #1.

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Without bisections, this material is also quite “open” on account of the double extrusion lengths and the larger octahedra which form when tetrahedrons are assembled together.

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We start with the original material and identify the extruded unit cell.

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We apply the bisection to the walls of the extruded prisms, so each prism will now have six creases instead of three.

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We halve the extrusion length so that all plates are now square.

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We “push-fit” the extrusion pairs to increase the density of the material.

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Compared to the previous view, the material is here seen lying on the extrusion sides instead of laying on the faces normal to the extrusion, allowing to construct a cubic patch of 3 x 3 x 3 tetrahedral unit cells.

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This physical version of the material is composed of 30 x 30 mm 3D-printed plates connected together by 4-mil polypropylene hinges.

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Recently, a kinematic analysis was conducted by Feng and Shi on the original tetrahedral unit, and it was determined that while the shape is flat-foldable, this is possible because of deformation of the creases.

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Feng and Shi conducted a longer kinematic analysis and determined that the shape is rigidly foldable if additional creases are placed on the diagonals of some of the square plates, thus admitting only rigid pates and rotational hinges.

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The auxetic property of the modified shape is demonstrated in this folding sequence. A detailed technical report on this new metamaterial has been accepted and will presented at the 6th International Conference on Reconfigurable Mechanisms and Robots which will take place in Chicago in July of this year.

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This page has links to videos showing some of the models which I will now show directly.

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And these are some websites with more information, mainly on Scarpa’s work, as well as a link to the slides of this presentation.

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Thank you so much for your attention. I will now show the physical models and afterward I hope there will be some time for a few questions.