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Kinematic design of tetrahedral cells for programmable matter

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EXTENDED ABSTRACT

This work presents a novel tetrahedron-based self-reconfigurable flexible structure as an approach to programmable matter. The structure is similar to finite element meshes composed of linear tetrahedral elements with the capability to change the length of their side edges and connect and disconnect to adjacent elements. Each element of the tetrahedron-based structure has twelve degrees of freedom, six rigid body motions, and six strains. The main component of the structure, the kinematic design of an adaptive tetrahedral cell, which supports the merging or splitting of virtual faces, is analyzed in detail. Additionally, a computational multibody system model is proposed to optimize the kinematic design with multiple closed loops using established methods, including compliant joints or flexible bodies. The resulting structure can change shape through morphing and self-reconfiguration, and topology through connecting and disconnecting adjacent cells. This is why the present approach differs substantially from earlier attempts to programmable matter.

1 Kinematics of self-reconfigurable flexible structures with tetrahedral cells

Programmable matter with the ability to change physical properties such as shape, viscosity, permeability, or resistance has made great strides in several areas of physics, but not at the fundamental mechanical or geometric level. Unlike conventional rigid structures, a Self-Reconfigurable Flexible Structure (SRFS) can adapt to the environment by changing shape and topology even after fabrication, which is why it differ substantially from earlier approaches to programmable matter, such as Claytronics or Catoms [1]. SRFSs are physical meshes with the capability to connect, disconnect, and climb over adjacent modules like metamorphic robotic systems [2] and additionally represent an underlying mesh similar to finite element meshes. In the planar case, a SRFS consists of adaptive triangular cells, see Fig. 1a) [3]. The cells can connect and disconnect to adjacent cells, always maintaining exactly the underlying triangular mesh by merging and separating the virtual edges of the connecting triangles. That is, two separate adaptive triangular cells can dock to form a cell cluster. Similarly, a cell cluster can split into two parts.

For the three-dimensional case, we propose a SRFS with adaptive tetrahedral cells, as shown in Fig. 1b). The structure is similar to meshes composed of linear tetrahedral finite elements with six deployable side edges to realize the six strains. Additionally, the cells connect and disconnect to adjacent elements. It is physically impossible to connect and disconnect at vertices and edges of an underlying idealized mesh, as the cross-section for connectors would be infinitely small. Similar to the planar case, see Fig. 1a), where the cells are connected along virtual edges, the tetrahedral elements can merge or separate at virtual faces, as shown in Fig. 1b). A prototype of SRFS based on tetrahedral cells connecting at virtual faces was presented in [4] with kinematic restrictions. Compared to connecting at nodes, see variable topology truss [5] or Odin [6], one of the advantages of connecting at virtual faces is that the structure is not predetermined in advance. Instead, it can self-reconfigure independently from an initial configuration into the desired structure by moving cells to the desired place [7].

In the main part of the paper, we focus on the kinematic design of a double spherical joint to support the merging of virtual faces. Concentric multi-link spherical (CMS) joints [8] as shown in Fig. 2a), or passive chainable spherical joints [5] are typical candidates for double spherical joints. However, the direct application still includes revolute joints at the bars so that the virtual faces of cells cannot merge. Therefore, we use special double six-bar linkages, as shown in Fig. 2b), since the common virtual vertex lies entirely outside of the assembly space leading to 42 revolute joints per virtual vertex and 168 revolute joints per tetrahedron as shown in Fig. 2c), leading to a redundant mechanism. With the kinematic design, we aim to reduce the number of redundant degrees of freedom. All virtual vertices are outside the assembly space, and the connection of cells at virtual faces is possible without exception. The direct approach for the physical realization is to replace the revolute joints with flexure hinges [9]. To evaluate the kinematic approach, a computational multibody system model is proposed to analyze the kinematic design with multiple closed loops using established methods, including compliant joints [10] or flexible bodies. Furthermore, the compliant joints are minimized in terms of their joint forces and deviations from idealized kinematics.

Finally, a prototype for one vertex of the tetrahedron is manufactured, and the possibility of the realization of a physical tetrahedral mesh is shown. SRFS with adaptive tetrahedral cells are a novel extension to the planar adaptive triangular cells. The proposed prototype can be extended to a self-reconfigurable system by replacing the deployable bars with linear actuators and the connection at the faces with active connectors.

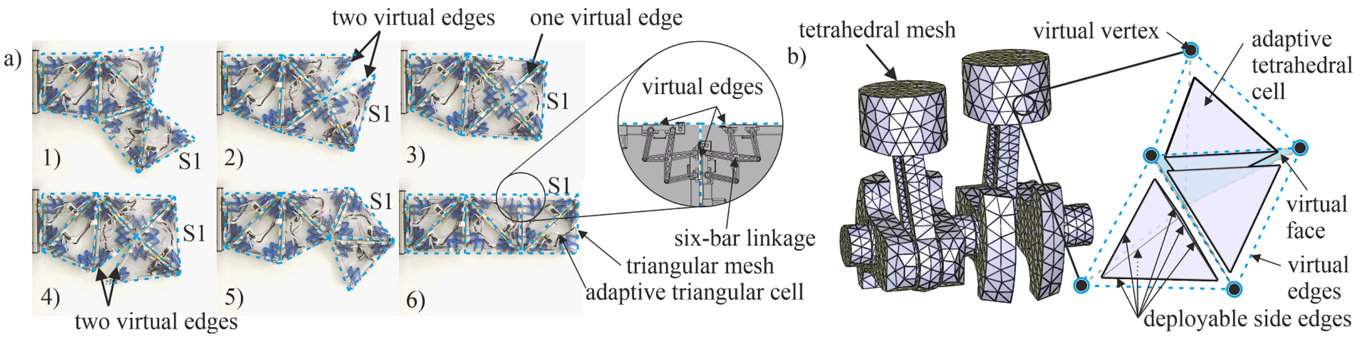

Figure 1: a) Self-reconfiguraton of Planar Adaptive Robot with Triangular Structure (PARTS) [3] by merging and splitting virtual edges, always containing the underlying triangular mesh and b) schematic representation of a SRFS with tetrahedral cells.

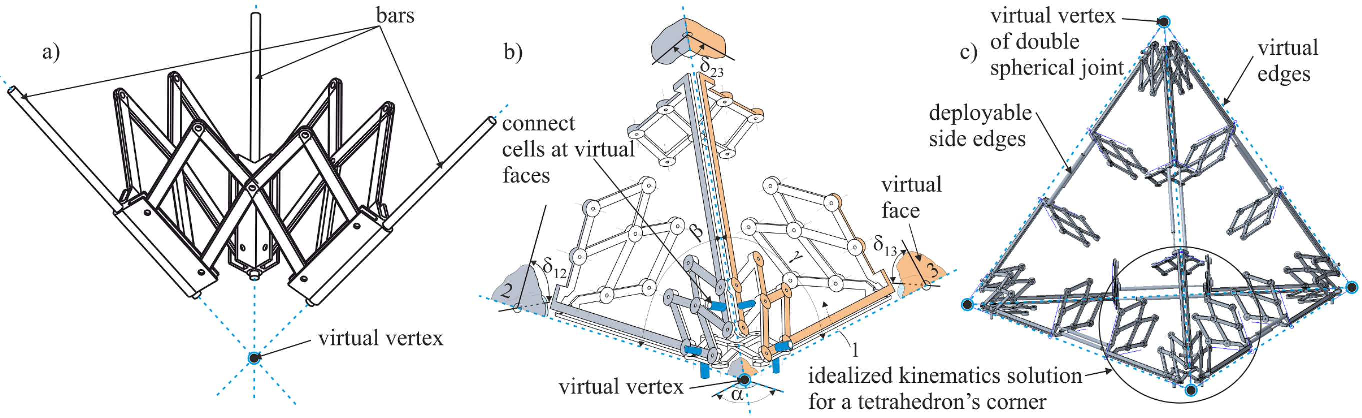

Figure 2: Schematic representation of double spherical joints; a) classic CMS joint [8], b) proposed special six-bar linkage with the virtual vertex of the spherical joint outside of the assembly space and c) tetrahedron with four virtual faces outside of the assembly space.

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