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A framework for cellular robots with tetrahedral structure

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Abstract— **An adaptive tetrahedral element (ATE) has been designed, which can attach to and detach from other ATEs along their deformable faces. The goal is to obtain any configuration or shape autonomously. The tetrahedrons edges represents six actuators and each ATE has its own micro-controller, battery and wireless transceiver module. Several connected ATEs are forming an adaptive robot with tetrahedral structure (ARTS) which is intended to represent any geometric form with a piecewise flat surface. Contrary to existing cellular and tetrahedral robots ARTS combines the advantages of self-reconfigurable modular robots and tetrahedral robots which have the ability to change their shape.**

I. INTRODUCTION

Self-reconfigurable robots with the ability to represent arbitrary shapes leads to an enormous number of real-world applications. Such applications are feasible within the self-assembly of large scaffolds, using ATEs with an overall size of one meter. Adaptive structures are needed e.g. for the growing complexity of current architectural design. In the mid-range size of ATEs, using centimeters for each actuator, the possibility to represent any 3D geometry could be used for rapid-prototyping and for the visualization of 3D structures in business and education.

II. RELATED WORK

Ahmadzadeh et al. [1] identified and cited 94 modular robots. Most of these are arrays of kinematically-constrained simple robots with few degrees of freedom [5], [3], [8], [2], [7]. These robots can attach to and detach from each other manually or automatically mostly with a mechanically [5] or magnetic [8], [2] connection mechanism.

The combination of self-reconfiguration robots with the ability to represent arbitrary shapes are presented recently in [6]. The connection mechanism along the deformable faces of the ATEs are patented [4] by the authors of the present paper.

III. ARTS – A TETRAHEDRAL ROBOT

ARTS is a modular robotic system which is based on adaptive tetrahedral elements (ATEs). The single ATEs can be understood as cells of a larger structure, similar to cells in biology. Each ATE can deform and has six degrees of freedom resp. actuators. In a continuum mechanics interpretation, an ATE can undergo any kind of stretch or shear deformation. The deformation of the single ATEs gives the robotic system are large amount of variability.

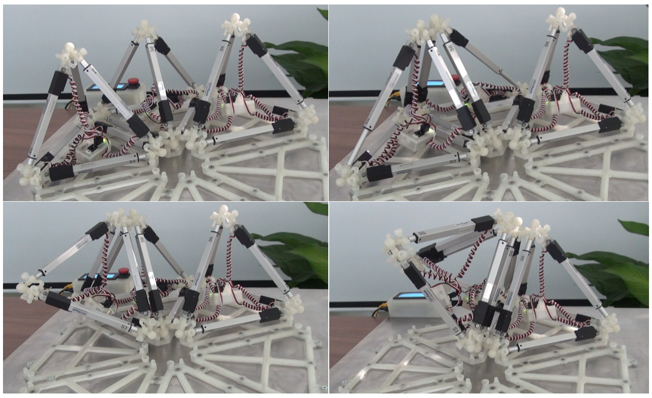

Fig. 1. Three tetrahedral elements attach along their deformable faces to an adaptive robot with tetrahedral structure. The elements standing in initial position an a plate. First the element on the left side attach to the middle ATE. In the next step both ATEs are connecting to the third ATE on the right side.

Each ATE itself is a mechatronic system, which includes the actuators, four double-spherical joints, 3 pairs of connectors at each of the four faces, a control and power unit, a wireless connection and a battery, see Fig. 2. In the current design, most parts are manufactured using a high-end 3D printer 'ProJet 3500 HD' from 3D Systems, with the material VisiJet M3-X. In comparison to conventional cubic or spheric modular robots, the tetrahedral structure leads to a light-weight design. Furthermore, the ATEs can connect and change the overall shape of the structure, see Fig. 1, and finally shall have the possibility to move ATEs along the surface by deformation of surrounding ATEs. As a challenge of the design, there are restrictions for the elongation of each actuator, which leads to severe limitations of the motion space of each cell. This also limits the angles of the edges at the spherical joints, being boundaries to the geometrical design.

The system of ATEs, from which we currently have built four fully functional elements, is used in a way, that they are always either positioned at a fixed space on a ground plate, or they are connected to one or several other ATEs, compare Fig. 1. The unique design is based on the connection at the faces, rather than the nodes. This avoids any restrictions within the connection of several tetrahedral elements, as known from other tetrahedral robots, see the references provided above. The advantage of tetrahedral robots is the convenient computation of the movement of the structure, which can be understood as a deformable mesh. The mesh – similar to a finite element mesh – can be modeled to be elastic with certain geometric limitations, which can be

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implemented on a computer code similar to the computation of a space truss. The single point-to-point motions of ARTS are sent to each ATE via a wireless connection from a master, which is connected to a conventional personal computer.

The main problem, which is currently investigated, is based on the difference of the idealized tetrahedral mesh and the constructed geometry of the ATEs, which brings in restrictions in the motion space of the system. Promising ways to overcome these limitations have been worked out and will be presented.

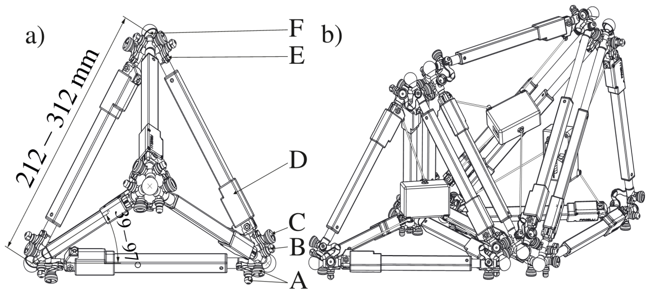

Fig. 2. Topview of a single ATE a) mechanical design of an ATE shown without cables and electronics: A-docking mechanism, B-male connector, C-female connector, D-actuator, E-orientation element, F-spherical joint; b) three connected ATEs forming an adaptive robot with tetrahedral structure

IV. RECONFIGURATION MECHANISM

Besides the mechatronic design, the control of the ATEs can be challenging, as soon as many cells are connected to each other, compare Fig. 3. In addition to the design of ARTS, we are developing several computational schemes, which define the motion of each ATE for reconfiguration from one to another shape. In order to fulfill this challenging task, the computation is split into three parts:

1) In the first part, the initial and the final mesh of the structure is computed. It is necessary that both configurations consist of a similar number of ATEs. The simplest way is depicted in Fig. 3, where the initial configuration consists of a rectangular block.
2) The rectangular block in Fig. 3a can be understood as parking positions of the ATEs. The main task of reconfiguration, is to find according parking positions to each of the ATEs of the structure, which is a hollow sphere in the present case. The shortest ways for movement of ATEs along the surface are depicted in Fig. 3a-e. This shows how a single ATE needs to be moved. In fact, the movement strategy is done such, that an ATE which has the longest distance to the base is selected in the structure, see Fig. 3e. This ATE is moved to an available parking space at the base block, which is closest to the center. While the algorithm is computing the destruction of the hollow sphere, the steps are then applied in reversed order.
3) In the final step, the movement of the ATEs needs to be performed by means of mesh deformation. This is done such that the cells can move along the surface.

   Currently, this is done with manual inputs only, however, an algorithm which can automatically compute this transformation is currently developed.

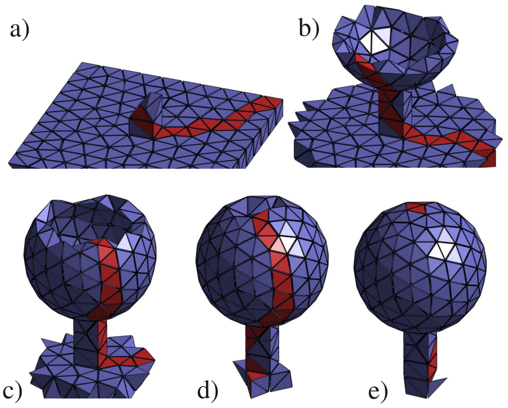

Fig. 3. Exemplary steps to reconfigure from one to another configuration. a) parking position; a-e) the red colored surfaces mark the shortest path for movement of ATEs along the surface.

Converting a complex structure (A) into another complex structure (B) can be performed such that between these configurations, the ATEs are transformed into a rectangular block. In this way, only the reconfiguration from a rectangular block to a complex structure must be computed.

V. CONCLUSIONS

The single adaptive tetrahedral elements (ATEs) follow a light-weight design principle. ARTS leads to a highly redundant superstructure and has the potential for a disruptive technology. Current limitations are within geometric restrictions of the workspace and the differences between an idealized geometric mesh and the real (constructed) geometry of ATEs.

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