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EVOLVING MICROSTRUCTURES FOR SCALABLE ACTUATION IN PROGRAMMABLE MATTER

P. Hołobut[1], M. Kursa[1], A. Macios[2], J. Lengiewicz[1]

[1]Institute of Fundamental Technological Research, Warsaw, Poland

[2]Faculty of Mathematics and Information Science, Warsaw University of Technology, Poland

1. Introduction

Programmable Matter (PM) is a class of future meta-materials of programmable and controllable properties and behavior, e.g., able to autonomously transform into an arbitrary shape [1]. Currently, the most advanced approach towards PM comes from the field of self-reconfigurable robots. The main concept is a cooperation of millions of microrobots (modules), collectively imitating deformation of a macroscopically continuous material. The modules' connection topology can change, which distinguishes PM from simpler active structures like the actuated truss [2].

Much research has been done on the geometric problem of planning reconfiguration of a group of cooperating modules, to transform their initial arrangement into a desired one. On the other hand, the problem of using PM for performing mechanical tasks, like lifting external objects, has rarely been discussed [3, 4]. The present work partially addresses this issue.

2. Concept of evolving microstructures

The present analysis is based on a spherical module design, the so-called *catom* [3, 4]. It is superior to many other designs in that it has no moving parts and can be miniaturized more easily. It uses electrostatic forces for attachment and actuation – the charging of electrodes inside adjacent modules causes their attraction/repulsion and rotation (Fig. 1a). This type of actuation, however advantageous, has limited strength. Therefore structures, built only from electrostatically connected catoms, are not expected to perform useful mechanical work, since they are roughly only as strong as the sum of electrostatic connections in their cross-sections.

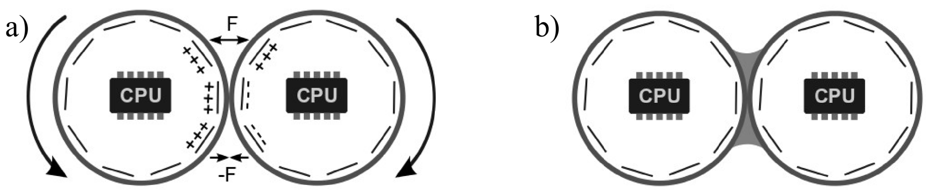

Fig. 1. Electrostatic (a) and fixed/strong (b) connections between modules.

In the present work a special arrangement of modules is therefore proposed, the *evolving microstructures*, which can potentially produce forces that scale with the volume of a structure. The modules are divided into groups connected by *fixed* connections and groups of *active* modules, propelled electrostatically (Fig. 2). The fixed connections do not need to reconfigure while the structure is moving, and can be assumed significantly stronger inasmuch as some other physical mechanism than electrostatic can be used for attachment. The first (fixed) group form supporting frames for the structure (gray and blue modules in Fig. 2), which transform PM into a macroscopic mechanism and integrate local stresses into an overall force. The second group of modules (red and yellow) provide the basic micro-actuation mechanism. In the exemplary structure shown in Fig. 2, the red (yellow) modules roll over the wall of gray (blue) modules without sliding, and push adjacent gray and blue walls in opposite directions.

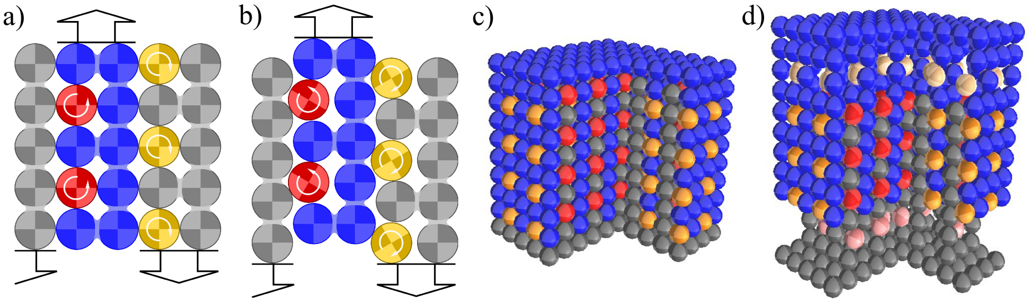

Fig. 2. Exemplary evolving microstructure at an initial stage and in motion: schematics, (a) and (b), and snapshots from a DEM simulation of a square linear actuator, (c) and (d).

3. Results

The behavior of evolving microstructures has been simulated using the Yade DEM system [5], modified to allow controllable attachment and detachment of modules. Fixed connections are modeled as strong cohesive interactions, which prevents unwanted detachment or sliding. The employed 6-degree-of-freedom contact law enforces elastic moments at contact points, preventing modules from rolling over one another. Electrostatic connections are modeled using similar cohesive interactions, but without elastic moments at contacts, which allow s free rolling between modules. Additionally, torques are imposed on active modules to simulate electrostatic actuation.

In parallel with the DEM model, a simple micromechanical analytical model has also been developed. Analyses conducted with both models, for several types of actuators, show good agreement of results. Exemplary quasi-static force-elongation responses for square linear actuators, built from modules of radius $r = 65$ µm, each exerting an electrostatic torque of 16 pNm, are shown in Fig. 3. The expected result that the overall force scales with volume is shown in Fig. 3b.

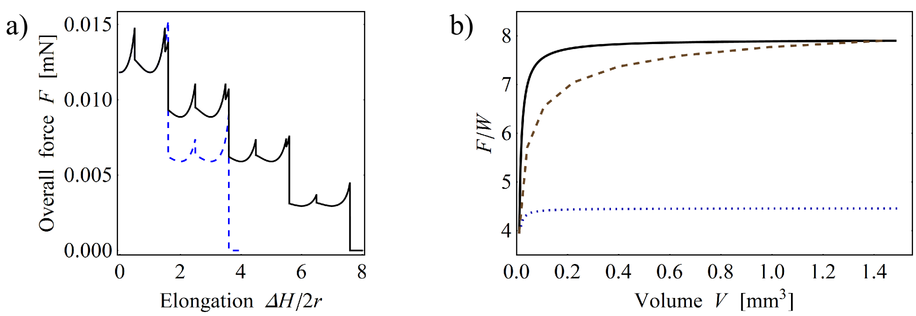

Fig. 3. Force vs elongation (a) and force/weight vs volume (b) plots for actuators as in Fig. 2 of different relative dimensions.

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