Actuation by reconfiguration—modular active structures to create Programmable Matter

Jakub Lengiewicz[1*], **Michał Kursa**[2*], **Paweł Hołobut**[3*]
[1,2,3]*Institute of Fundamental Technological Research of the Polish Academy of Sciences (IPPT PAN)*
Pawińskiego 5B, 02-106 Warsaw, Poland
e-mails: jleng@ippt.pan.pl [1], *mkursa@ippt.pan.pl* [2], *pholob@ippt.pan.pl* [3]

Abstract

We examine, analytically and numerically, forces produced by collective actuators–possible future building blocks of Programmable Matter. The actuators are composed of tiny spherical robotic modules which can strongly attach to their neighbors, and move by rolling over one another using electric or magnetic local propulsion mechanisms. An actuator works through collective reconfiguration–a coordinated motion of its constituent modules–which results in a global deformation of the structure. The simulations are performed using specially adapted discrete element method software, and account for friction and elastic deformations of modules.

Keywords: programmable matter, active materials, actuators, mechanical strength, modular robots

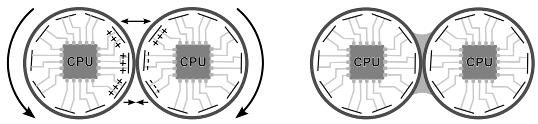
1. Introduction

Programmable Matter (PM) is a class of hypothetical future meta-materials whose properties and behaviour, e.g., the ability to autonomously change shape, can be programmed and controlled [1]. One of the approaches to creating PM is based on the concept of self-reconfigurable robots, in which the material is assumed to be composed of small interacting robotic *modules*. Each module is supposed to possess an energy source, to be able to communicate and process information, and to mechanically interact with its neighbours through attachment and actuation devices and sensors. An object made of a large number of modules could change shape by making its module move relative to one another, into a desired target configuration. Usually, the modules' connection topology changes during such reconfiguration, which does not happen in simpler active structures—like the actuated truss [2].

A huge research has been done on the problem of reconfiguration planning for modular robots—finding a geometrically admissible sequence of movements, transforming an initial arrangement of modules into a target one. In the paper, by contrast, the PM is viewed as a mechanical system, capable of exerting forces and doing work, subject to the limitations of the actuation mechanisms of its modules. We expand on our previous results [5] and investigate the forces produced by a selected class of modular systems in the presence of friction and elastic deformations.

2. Active microstructures

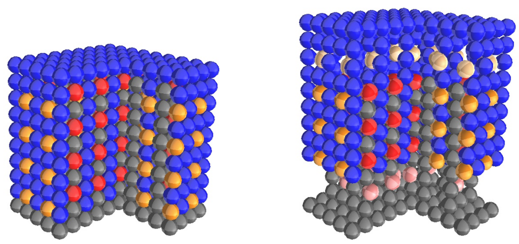
Many module designs have been proposed as building blocks of three-dimensional self-reconfigurable robots. We base our analysis on a particular one—the spherical *catom* [3, 4]. Catoms use controllable electric or magnetic fields to attach to their neighbors and roll over them, Fig. 1(a). This type of actuation, however, has unsatisfactory strength. Therefore structures made of catoms, as they are, are not expected to be large or capable of exerting significant forces [5]—their strength is proportional to the number of electric or magnetic connections in their cross-sections.



(a) (b)

Figure 1: Active/weak (a) and fixed/strong (b) connections

The modified catoms are considered: in addition to the *weak* electric or magnetic connections, we assume that there are also *fixed* connections, Fig. 1(b), which temporarily strongly bind selected catoms together. Special arrangements of such modules, called *active microstructures*, can potentially produce forces proportional to their volumes. In active microstructures, the modules bound by fixed connections (*fixed modules*) form supporting frames, and the remaining modules (*active modules*) roll between them providing micro-actuation. The actuator can thus be seen as a sort of microscopic mechanism. An example structure of this kind, the *square linear actuator*, is shown in Fig. 2, and its cross-section in Fig. 3. The red and yellow active modules roll over the walls of gray and blue fixed modules, respectively, pushing them in opposite directions.



(a) (b)

Figure 2: Square linear actuator (without the front quarter): initial (a) and intermediate (b) configuration (DEM simulation)

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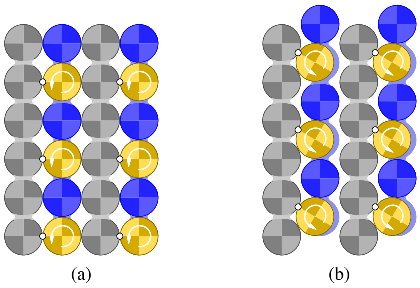

Figure 3: Cross sections of a square linear actuator: initial (a) and intermediate (b) configuration (schematic). White dots denote active connections and solid links denote fixed connections

3. Analysis of active microstructures

We simulate active microstructures using the Yade DEM software [6]. Strong connections are modeled as cohesion, with all six degrees of freedom at the connection constrained. Therefore, strongly connected modules form one elastic structure. Weak connections are also modeled as cohesion, but with only translational degrees of freedom constrained. Weakly connected modules can therefore roll over one another. The actuation mechanism is simulated by applying torques to active modules, which make them roll in desired directions. The laws of cohesion in Yade have been modified to allow controllable attachment and detachment of modules.

We analyze quasi-static forces produced by actuators in the presence of friction and elastic deformations. An actuator is placed between two bounding walls, and the force it exerts on them is computed at different elongations. Any time-dependent effects are excluded from the analysis.

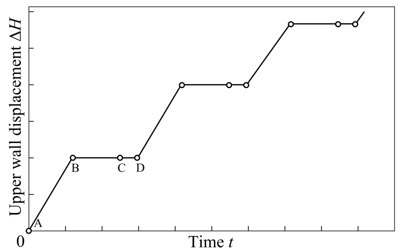

Figure 4: Loading program for measuring the overall force produced by an actuator.

The adopted force-measurement procedure is shown schematically in Fig. 4. It consists of three steps repeated cyclically as the actuator extends. In step A–B, the upper bounding wall is moved a bit upwards, allowing the actuator to extend. In step B–C, the wall does not move and the actuator presses against it until a balance of forces is reached. In step C–D, the reaction force at the wall is measured and averaged.

Analytical formulas, describing the forces as functions of elongation, have also been derived for the actuators built of rigid modules. Their predictions are in good agreement with the results of numerical simulations, as long as the modules are stiff enough.

4. Numerical results

Examples of force-elongation plots for square linear actuators are shown in Figs. 5 and 6, for the module radius $r = 65\ \mu\mathrm{m}$ and actuation torque $\tau = 16\ \mathrm{pNm}$. Figure 5 shows the decreasing force of the actuator, as the number of active modules pushing the structure decreases with increasing elongation. It also displays the cyclic discrepancies between the analytical and numerical results, caused by elasticity in the presence of friction.

Figure 6 presents variation of force produced by an elastic actuator, per active module, with the actuator height. The build-up of elastic deflections along the height of the actuator, combined with friction, diminishes the efficiency, especially for higher actuators.

The presented drawbacks can be overcome, to some extent, by designing actuators with increased spacing between certain modules.

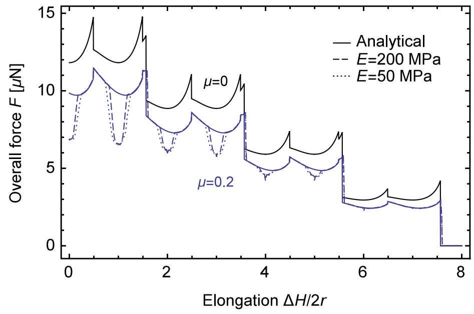

Figure 5: Force-elongation plots for the square linear actuator 5 modules wide and 8 modules high—for different values of the friction coefficient μ and Young's modulus E of the modules

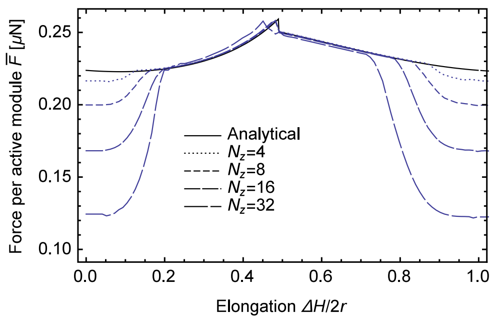

Figure 6: Force-elongation plots, per active module, for a 3-module-wide square linear actuator of height N_z between 4 and 32 modules; $\mu = 0.1$, $E = 100\ \mathrm{MPa}$

References

[1] Goldstein, S.C., Campbell, J.D., Mowry, T.C., Programmable Matter, *IEEE Computer*, 38, pp. 99-101, 2005.

[2] Thore, C.J., Klarbring, A., Modeling and optimal design of neuro-mechanical shape memory devices, *Struct. Multidisc. Optim.*, 45, pp. 257-274, 2012.

[3] Campbell, J., Pillai, P., Collective actuation, *Int. J. Rob. Res.*, 27, pp. 299-314, 2008.

[4] Christensen, D.J., Campbell, J., Støy, K., Anatomy-based organization of morphology and control in self-reconfigurable modular robots, *Neural Comput. Appl.*, 19(6), pp. 787-805, 2010.

[5] Hołobut, P., Kursa, M., Lengiewicz, J., A class of microstructures for scalable collective actuation of Programmable Matter, *IROS 2014: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3919-3925, 2014.

[6] Yade—Open Source Discrete Element System, http:yade-dem.org.