TWO-DOMAIN MODEL OF VOLUMETRIC ACTUATORS

Jakub Lengiewicz*, Michał Kursa, and Paweł Hołobut
Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland

Summary In the present work we propose a framework for modeling *volumetric actuators* – a special class of mechanical systems that can transform the parallel work of micro-actuators, distributed throughout an actuator's volume, into a macroscopic force that scales with this volume. The proposed model takes into account the expected finite deformation of actuators and the coupling between the deformation and micro-actuation, which can strongly influence an actuator's behavior. Finite element implementation details are presented, together with numerical examples and results.

VOLUMETRIC ACTUATORS

Volumetric actuators are a specific class of mechanical systems. Their output forces are produced by micro-actuators distributed over their volumes and working in parallel. This is in contrast to other actuators, examples of which are hydraulic and pneumatic cylinders, whose forces often result from surface interactions and are proportional to their cross-sectional areas. The advantage of well-designed volumetric actuators is that their maximum output forces are proportional to the number of micro-actuators in their interior, and so to their volumes.

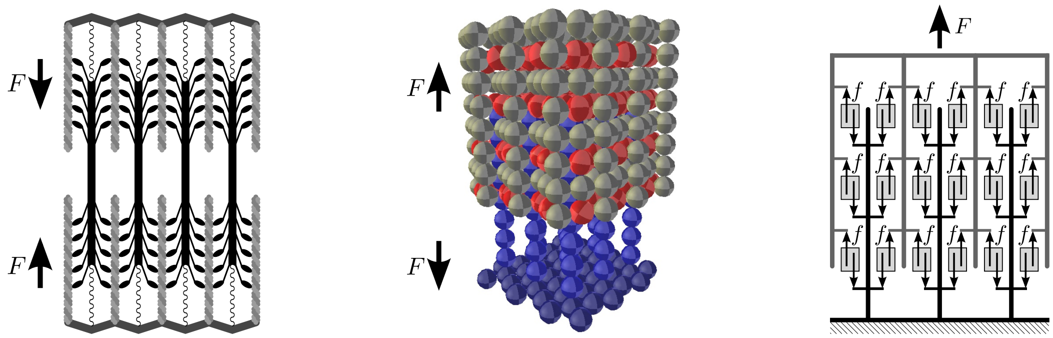

Figure 1: Volumetric actuators. Left: schematic of a sarcomere—a subunit of animal muscles. Center: DEM model of a modular-robotic collective actuator, built of spherical units. Right: principle of operation of a volumetric actuator.

An example of such systems is the sarcomere [1], which is ubiquitous as a fundamental active subunit of animal muscles. Similar artificial systems are also being considered, e.g., as an application of the MEMS and NEMS technology. In Fig. 1(left), a schematic of the sacromere is presented, with heads of myosin molecules (black) working as micro-actuators, pulling adjacent actin filaments (gray), and producing an overall contracting force. Quite similarly, an artificially designed modular-robotic structure works as a two-directional actuator [2, 3], see Fig. 1(center). Here, the spherical micro-robots form two separate, strongly bonded frames (blue and gray) that are pushed/pulled against each other by active (red) modules.

Finally, Fig. 1(right) shows the general principle of operation of a (linear-motion) volumetric actuator. The actuator is composed of two interdigitated solid structures (black and gray in the figure), with micro-actuators (gray rectangles) distributed between them throughout the volume. Each micro-actuator pushes (or pulls) the two structures in opposite directions, exerting a micro-force f. The micro-forces sum over the volume, yielding the total force F produced by the actuator.

TWO-DOMAIN MODEL

In the proposed two-domain model, two inter-penetrating domains Ω_1 and Ω_2, see Fig. 2, move against each other along some permitted directions (isolines $\Psi_i =$ const). Actuators can, in general, undergo finite deformations that can affect their properties, and vice-versa. Neglecting body forces, the weak form for two interacting actuator parts can be written as

$$G(\boldsymbol{\varphi}, \delta\boldsymbol{\varphi}) = G_1(\boldsymbol{\varphi}, \delta\boldsymbol{\varphi}_1) + G_2(\boldsymbol{\varphi}, \delta\boldsymbol{\varphi}_2) + G_c(\boldsymbol{\varphi}, \delta\boldsymbol{\varphi}) = 0, \tag{1}$$

where $\delta\boldsymbol{\varphi} = \{\delta\boldsymbol{\varphi}_1, \delta\boldsymbol{\varphi}_2\}$ are the variations vanishing on Γ_i^u,

$$G_i(\boldsymbol{\varphi}, \delta\boldsymbol{\varphi}_i) = \int_{\Omega_i} \frac{\mathrm{D}W_i}{\mathrm{D}\boldsymbol{F}_i} \cdot \nabla\delta\boldsymbol{\varphi}_i dV_i - \int_{\Gamma_i^t} \boldsymbol{T}_i^* \cdot \delta\boldsymbol{\varphi}_i dS_i, \quad i \in \{1, 2\} \tag{2}$$

*Corresponding author. Email: jleng@ippt.pan.pl

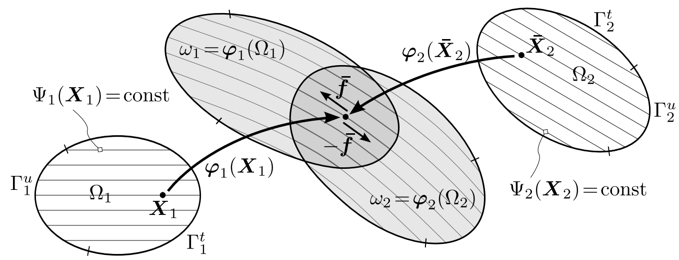

Figure 2: Continuum mechanics model.

are the weak forms derived form (hyper)elastic potentials W_i, with deformation gradients $\boldsymbol{F}_i = \nabla \boldsymbol{\varphi}_i$, and

$$G_c(\boldsymbol{\varphi}, \delta\boldsymbol{\varphi}) = \int_{\bar{\Omega}_1} \left[\rho \left(\Psi_1(\boldsymbol{X}_1) - \Psi_2(\bar{\boldsymbol{X}}_2) \right) \frac{\partial \Psi_2}{\partial \bar{\boldsymbol{X}}_2} \left(\nabla \bar{\boldsymbol{\varphi}}_2 \right)^{-1} + \bar{f} \frac{\boldsymbol{F}_1 \nabla \bar{\Psi}_1}{\|\boldsymbol{F}_1 \nabla \bar{\Psi}_1\|} \right] \cdot \left(\delta\boldsymbol{\varphi}_1 - \delta\boldsymbol{\varphi}_2 \right) dV_1 \tag{3}$$

is the contact part of the weak form (1), in which $\bar{\boldsymbol{X}}_2$ is a point of Ω_2 such that $\bar{\boldsymbol{\varphi}}_2 = \boldsymbol{\varphi}_2(\bar{\boldsymbol{X}}_2)$ coincides with the point $\boldsymbol{\varphi}_1(\boldsymbol{X}_1)$, $\bar{\Omega}_1 = \boldsymbol{\varphi}_1^{-1}(\omega_1 \cap \omega_2)$, and $\bar{\Psi}_1$ is a scalar field complementary to Ψ_1 in the sense that $\nabla \bar{\Psi}_1$ are parallel to the isolines of Ψ_1. The first term in (3) is the enforcement of the condition that corresponding isolines of Ψ_1 and Ψ_2 must coincide, and the second term imposes actuation of the intensity $\bar{f}$ in the direction tangent to a deformed isoline $\nabla \bar{\Psi}_1$.

The above formulation has strong analogies to earlier works on formulations for contact problems [4], and it is particularly suitable for the finite element method implementation. In the present work, the necessary FE procedures have been derived using the symbolic system *AceGen*, and the subsequent FE calculations are performed in the *AceFEM* environment [5].

EXEMPLARY 2D FEM RESULTS

As an example, a two-dimensional contracting actuator is analyzed, as depicted in Fig. 3. Two constituent parts of the actuator are 20×10 mm^2 rectangles, clamped at opposite sides, with the initial 5 mm overlap. A plain-strain hyperelastic material model for both parts is applied, with the Young's modulus $E = 1$ MPa and Poisson's ratio $\nu = 0.4$.

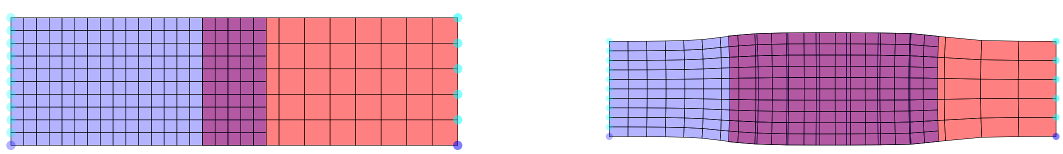

Figure 3: Exemplary FEM results. Left: initial mesh ($\bar{f} = 0$). Right: deformed mesh ($\bar{f} = 0.03\,[\mathrm{N/mm^3}]$).

In Fig. 4, the expected non-uniform deformation is presented, with horizontally-aligned stress gradients in the contact zone, which is characteristic of volumetric actuators.

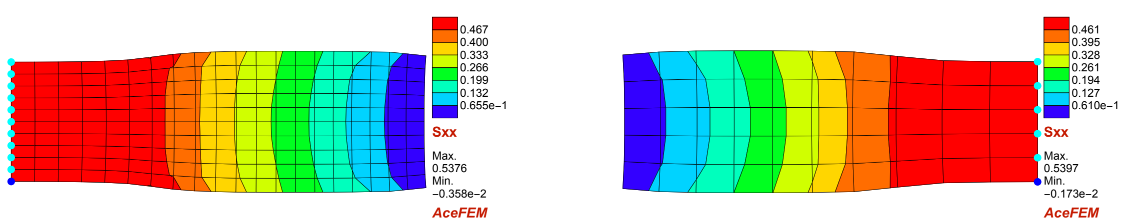

Figure 4: S_{xx} stress field in the deformed configuration for the left and right part of the actuator ($\bar{f} = 0.03\,[\mathrm{N/mm^3}]$).

Acknowledgement This work was partially supported by the project "Micromechanics of Programmable Matter" (contract no. 2011/03/D/ST8/04089 with the National Science Centre in Poland).

References

[1] McNeill Alexander R.: Principles of Animal Locomotion. Princeton, United States, 2006.
[2] Hołobut P., Kursa M., Lengiewicz J.: Efficient modular-robotic structures to increase the force-to-weight ratio of scalable collective actuators. Proc. 2015 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS), Hamburg, Germany:3302–3307, 2015.
[3] Lengiewicz J., Kursa M., Hołobut P.: Modular-robotic structures for scalable collective actuation. Robotica, doi:10.1017/S026357471500082X, 2015.
[4] Lengiewicz J., Korelc J., Stupkiewicz S.: Automation of finite element formulations for large deformation contact problems. Int. J. Numer. Meth. Engng 85:1252–1279, 2011.
[5] Korelc J.: AceGen and AceFEM user manuals. Available at http://www.fgg.uni-lj.si/Symech/, 2009.