Modular Active Elastomer Cylinder for Adaptive Soft Orthotics

Yong-Lae Park, Bor-Rong Chen, Carmel Majidi, Robert J. Wood, Radhika Nagpal, and Eugene C. Goldfield

Wyss Institute for Biologically Inspired Engineering, Harvard University
Children's Hospital Boston

Introduction

Progress in the emerging field of adaptive orthotics will depend on a new class of soft active materials for sensing, mechanical actuation, and elastic rigidity control. Such materials are intended to be worn around a joint such as a wrist or knee and assist in the motor tasks of patients with brain injury or limited motor control. In their passive mode, these soft active materials must detect motion without interfering with the natural host mechanics. When active, however, such materials must be capable of exerting assistive forces through dramatic but reversible changes in shape and elastic rigidity. Here we propose a modular approach to soft adaptive orthotics based on an elastomer sealed network of conductive liquid sensors and pneumatically driven actuators. The emphasis on modularity, soft materials, and miniaturization allows for a soft orthotic system that is multi-functional, supports large deformation, and operates independently of external pneumatics and controllers. Electronics, communications, and pneumatic control are all accomplished on-board with miniaturized boards, stretchable electronics and sensors, and spatially distributed micro-valves and pneumatic actuators. The aim of this work is to enable soft adaptive orthotics with an elastomer-sealed modular platform of sensors and pneumatic actuators.

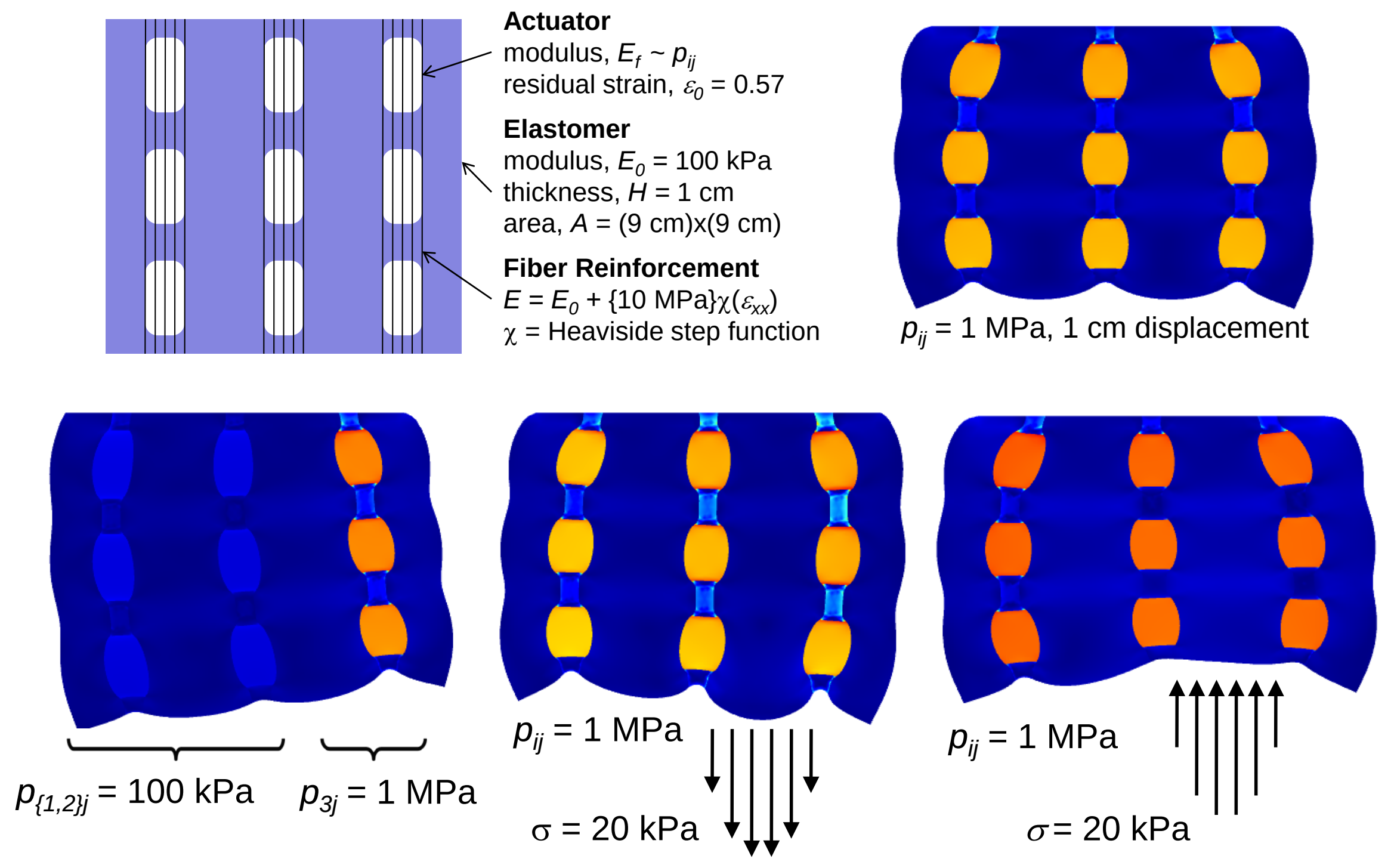
Solid Mechanics Model

Actuator Theory: Inflating the actuator with air pressure (p) reduces its length (L) and increases the effective *rigidity* (E_f). The mechanics are established by balancing air pressure (p) and external axial loading (T) subject to the kinematic constraints of the fibers.

x = fiber length
r = inflated *radius of curvature*
L_0 = minimum possible length
$\mathbf{L = 2r \sin(x/2r),\ L_0 = 2x/p}$
$\mathbf{T = 2pRrp \cos(x/2r)}$
$\mathbf{E_f = TL_0/pR^2(L - L_0) \approx px/R}$

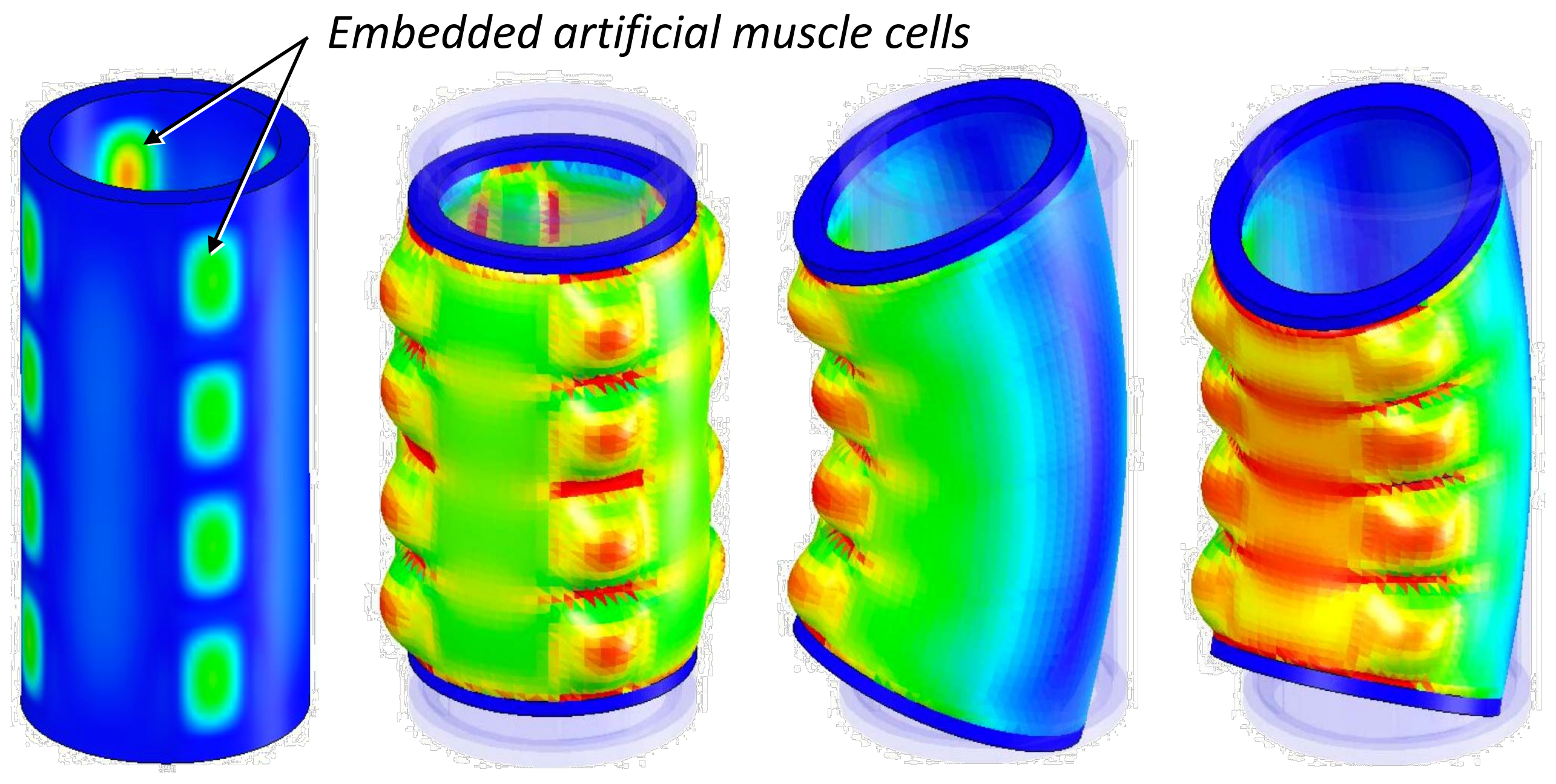
Equivalent Stiffness Model
The actuator is treated as an elastic element with modulus E_f and natural length L_0. Therefore, when embedded in an elastic sheet, the actuator will have a *residual strain*: $\mathbf{e_0 = (x - L_0)/L_0 = 0.57}$

Finite Element Analysis: The cylinder mechanics are governed by the air pressure (p_{ij}) and size (R, x) of the actuators, the distribution of the actuators and embedded fiber, the elastic modulus (E) and thickness (H) of the elastomer, and the stresses (s) exerted along the boundary. FEA is performed in COMSOL 4.0a.



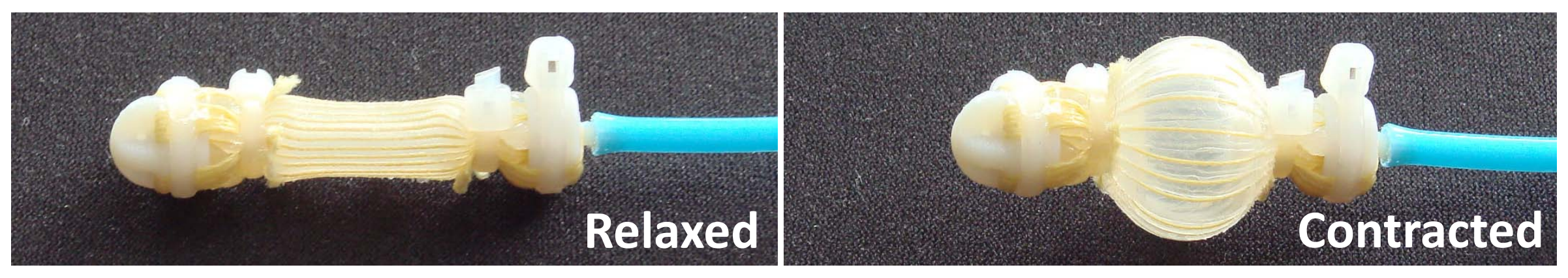
Overall System Design

The overall structure of the 2nd skin prototype is a three-dimensional soft cylinder with embedded soft pneumatic artificial muscle cells and strain sensors. When multiple muscle cells are actuated (contracted) collectively as a group, the overall displacement and force produced will be relatively high. The extremely flexible and elastic base material, silicone elastomer will make the prototype conformable to different surface shapes. Each muscle cell is equipped with a soft strain sensor that detects the contraction. Four muscle cells with strain sensors are controlled by one micro-controller as one modular unit. The current prototype has four modular units with 16 muscle cells in total. With different combinations of contracted muscle cells, various shapes are possible.

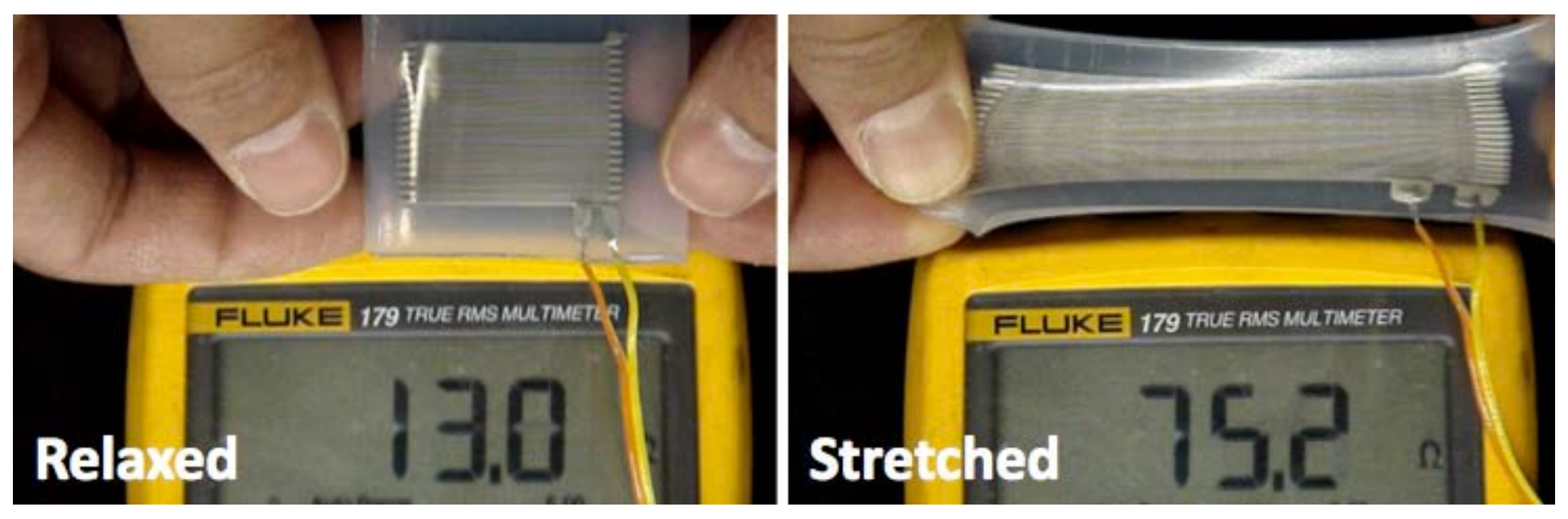

Embedded artificial muscle cells

Original shape **Entire contraction** **Partial contractions for bending**

Actuator: Miniaturized pneumatic muscle cells are under development as main actuators. Circumferentially embedded Kevlar fibers in a polymer tube are embedded in a polymer sheet, and flexible but inextensible fibers (e.g. Kevlar), are embedded in the outside layers. When pressurized air is introduced to the chamber, the embedded fibers constrain the expansion in an axial axis but allow the expansion in the other axes resulting in axial contraction due to the fixed length of the fibers.



Sensor: Each muscle cell is equipped with two strain sensors to measure the contraction of the muscle cell, embedded in the top and bottom layers each. Each strain sensor has an embedded micro-channel filled with liquid metal (EGaIn) that changes overall resistance of the channel as the sensing layer experiences strain changes.

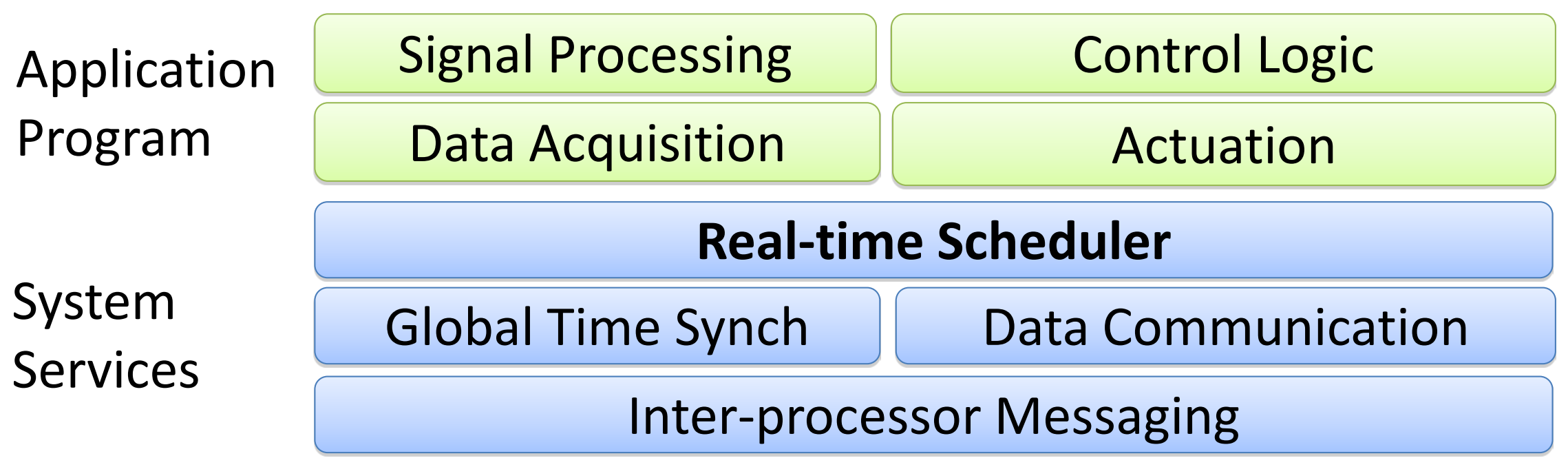


Channel dimension: 200 x 200 μm
Nominal resistance: Approx. 10 Ω

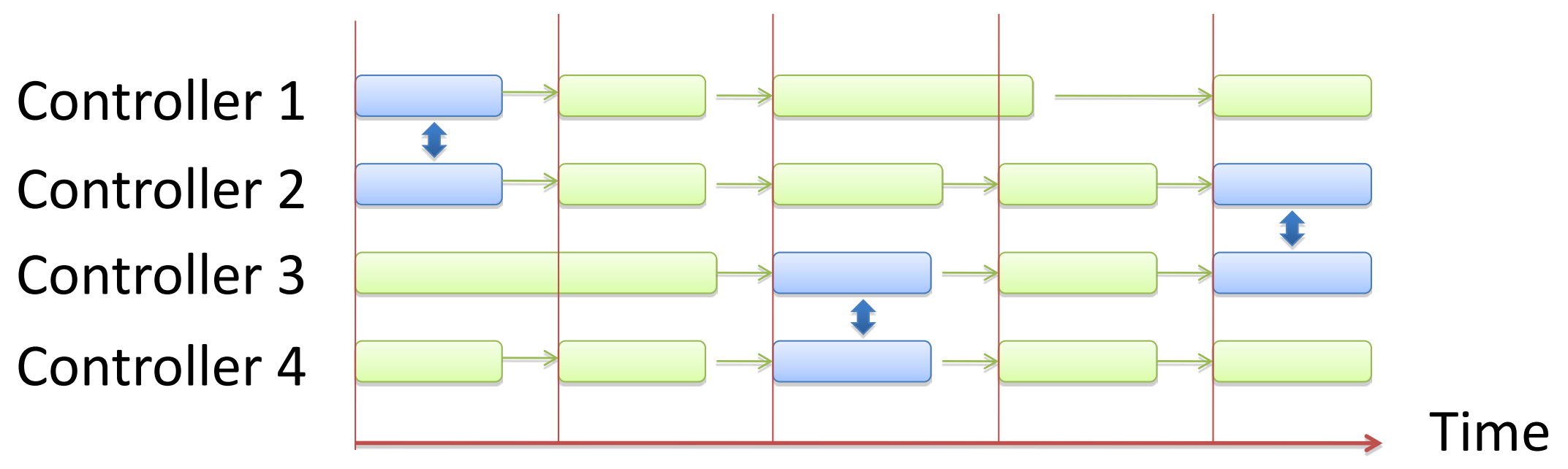
Controller Network

Network topology: Connected in a 2D grid pattern, the network of controllers cooperatively carry out actions.

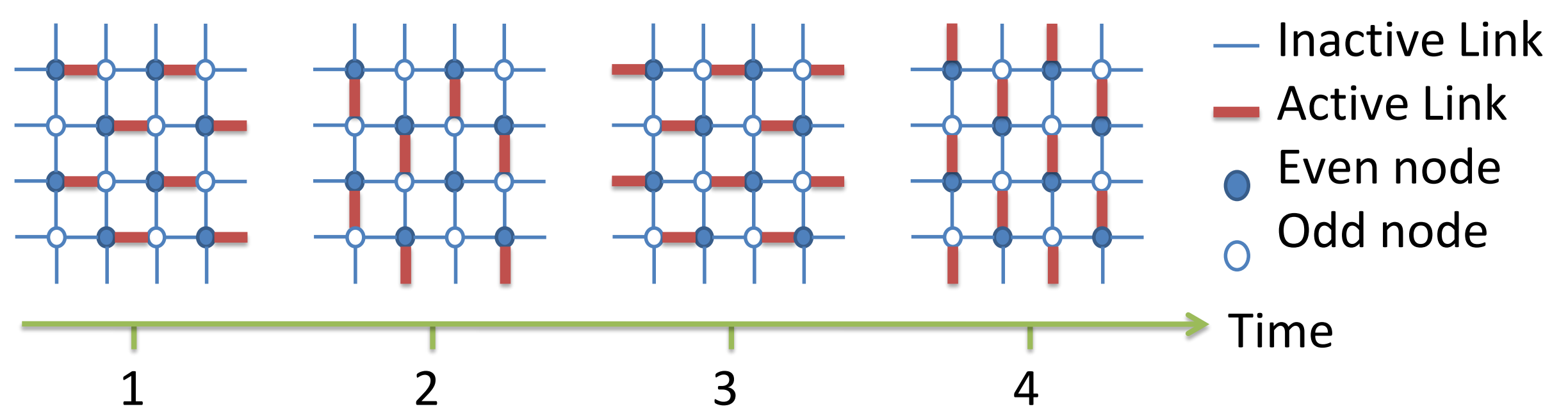
Controller Software Architecture: System services provide communication primitives among controllers and establish global time. Real-time scheduler runs tasks on time.



Control Program Structure: Control programs are specified as scheduled tasks on multiple controllers.



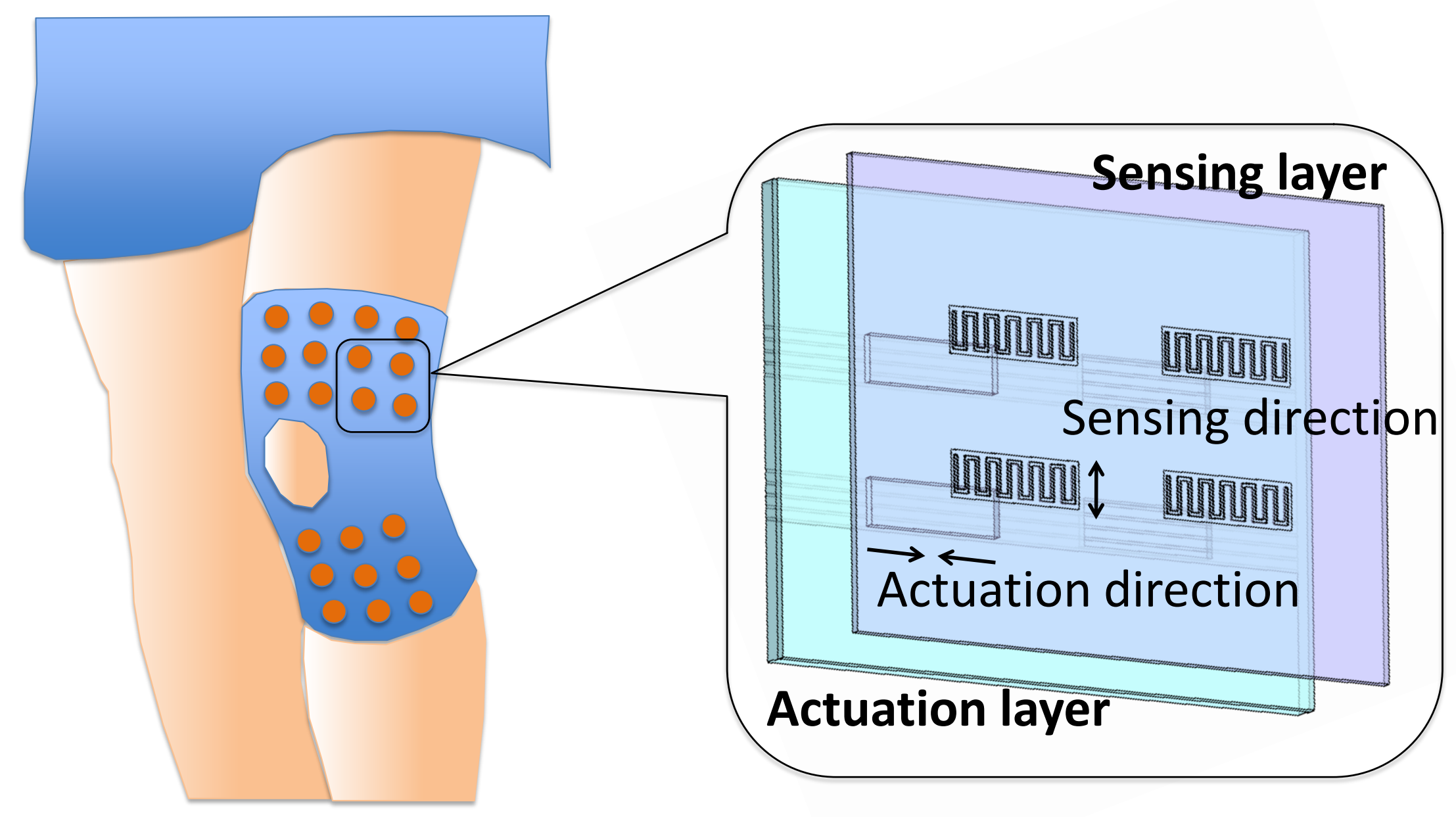
Global Communication Schedule: Controllers agree on a schedule for data communication. Based on location in the network, odd and even nodes follow matching schedules to communicate with each neighbor periodically, which allows parallel data communication on non-neighboring links.



Conclusions & Future Work

A modularized elastomeric 2nd skin is under development. The prototype has miniaturized soft pneumatic actuators and strain sensors embedded in a soft cylindrical silicone structure. Each actuator is also equipped with micro-controllers that makes the prototype controllable.

This emphasis on modularity, soft materials, and miniaturization allows for a soft orthotic system that is multi-functional, supports large deformations, and operates independently of external pneumatics and controllers.



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