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Dynamic cellular actuator arrays and the expanded fingerprint method for dynamic modeling

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HIGHLIGHTS

- We present a cell-based flexible actuator design methodology for actuator arrays.
- We develop the General Fingerprint Method for dynamic modeling of actuator arrays.
- The presented method is robust to varied constituent actuator types.
- The method allows for fast recalculation for different array structures.
- Two physical SMA based experiments validate the theoretical results.

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ABSTRACT

A key step to understanding and producing natural motion is creating a physical, well understood actuator with a dynamic model resembling biological muscle. This actuator can then serve as the basis for building viable, full-strength, and safe muscles for disabled patients, rehabilitation, human force amplification, telerobotics, and humanoid robotic systems. This paper presents a cell-based flexible actuator modeling methodology and the General Fingerprint Method for systematically and efficiently calculating the actuators' respective dynamic equations of motion. The cellular actuator arrays combine many flexible 'cells' in complex and varied topologies for combined large-scale motion. The cells can have varied internal dynamic models and common actuators such as piezoelectric, SMA, linear motor, and pneumatic technologies can fit the model by adding a flexible element in series with the actuator. The topology of the cellular actuator array lends it many of its properties allowing the final muscle to be catered to particular applications. The General Fingerprint Method allows for fast recalculation for different and/or changing structures and internal dynamics, and provides an intuitive base for future controls work. This paper also presents two physical SMA based cellular actuator arrays which validate the presented theory and give a basis for future development.

1. Introduction

For decades researchers in physiology have been trying to model and generate natural motions, the movements created by biological systems, in order to both gain a greater understanding of biological muscle and to produce motions similar to muscle. This knowledge, in turn, benefits therapy and rehabilitation for patients who suffered muscle damage or degradation, allowing patients to function more easily in society and, in the best case, make the loss a non-issue in ordinary life. The advances also aid in the development of naturally moving prosthetic devices for those who have lost limbs and facilitate the development of human force amplification exoskeletons. Finally muscle-like actuators, and knowledge of the control processes used to generate natural motion, enable humanoid robots to move in more natural ways. This yields more life-like and capable humanoid robotic systems, and is important as robots continue to integrate into human society.

1.1. Biological inspiration

Although many humanoid robots can be said to be biologically inspired in terms of morphology, they are not biologically inspired in terms of how they are actuated; most use some sort of traditional servomotor. Resultant movements are far from those characterizing humans. Multi-celled organisms have specialized cells (muscle cells) that move their body parts by elastic contraction in response to signals from the central nervous system. Biological muscles are non-continuous and non-uniform; muscles consist of several types of muscle tissues with different levels of contractile speed and fatigability [1]. A motor unit, a bundle of muscle fibers with a specific

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force capability connected to a single motor neuron, is stimulated by nerve impulses. Hence, a single muscle consisting of motor units is structurally quantized in terms of force generation.

Should robots also possess these properties, great strides could be made in terms of cycle time, capability, the number of environments in which robots can be deployed, and cost. The primary way to endow robots with biological abilities is to equip them with biologically inspired actuation. This paper uses the term "biologically-inspired" in regard to actuation in robotics, namely, that the actuators themselves have structural and operational characteristics in common with muscles. Specifically, the actuator systems of interest will (1) have a modular structure: the actuator selectively activates distinct units (recruitment), and (2) possess elasticity allowing impulse signals to produce a smooth contraction. The modular architecture may be non-uniform, or hybrid, consisting of different materials, such as piezoelectric actuators (with high-speed, but low-force) and shape-memory alloy (SMA) actuators (with slow-speed, but high-force), or different sizes, such as using differing diameter SMA actuators, allowing a wider working range. Due to the elasticity and viscosity of the muscle tissue, twitch and tetanic contraction create a relatively damped force profile [2–4].

1.2. Actuator array prior work

A key step along the way to understanding the natural motion [5–7] is producing a physical, well understood test platform with a dynamic model closely resembling biological muscle. This test bed can then serve as the basis for experiments to better understand the interrelated nature of the nervous system and the muscles, for kinematics/dynamics experiments to understand balance and synergies, and for building viable, full-strength, and safe muscles for prosthetics, human force amplification, and humanoid robotic systems.

[8] presents biologically-inspired cell array actuators consisting of many small cells interconnected in various layouts, or topologies, to achieve muscle-like motion. In this work all cells were identical and the topology of the cell array actuator, represented compactly using a two row set of matrices or "fingerprint", differentiated static properties such as displacement, force capacity, force discretization, and robustness. The cells were operated using a bi-stable stochastic all-on all-off broadcast control method to reduce wiring complexity, control signals, and hysteresis error [9]. [10] expanded upon the results of [8] looking more specifically into force discretization and presented methods for generating all possible cell array topologies given a limited number of cells. This later result is critical to designers wanting to explore the possibilities of the cell arrays and select a topology specific to their criteria.

[10] was a static modeling of the form $\mathbf{A} \cdot \mathbf{x} = \mathbf{c} + \mathbf{u}$ where $\mathbf{A}$ represented the topology, $\mathbf{x}$ the state vector, $\mathbf{c}$ constants for the system such as endpoint locations, and $\mathbf{u}$ the control input. This was then solved for the state vector using $\mathbf{x} = \mathbf{A}^{-1} \cdot (\mathbf{c} + \mathbf{u})$. While this allowed for easily exploring stochastic properties and guided topology selection, it did not generate the dynamic equations of motion.

In [11], an expanded version of the fingerprint method presented in [10] allows for the dynamic analysis cell array actuators built from cells based on Miga NanoMuscle 704 SMA actuators connected in series with coil springs. The cell model for these actuator arrays was a modified Hill-Type model shown in Fig. 1.

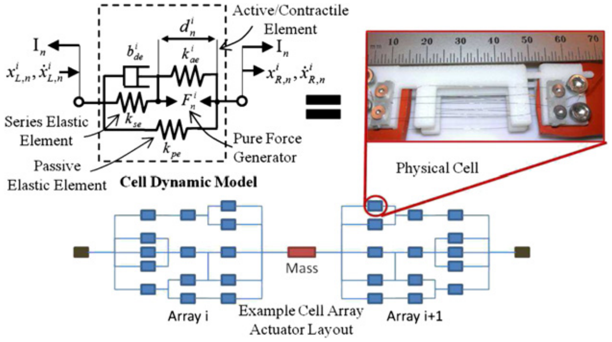

Fig. 1. Hill-type model, physical cell, and example cell array actuator layout.

1.3. Graph theoretic modeling

Methods for graphically representing complex multibody systems and obtaining governing equations include bond graphs and graphic theoretic modeling (GTM), or linear graphs [12]. McPhee has presented a series of publications on the applications of linear graph theory to flexible multibody systems [13,12,14,15]. The key concept is to introduce a matrix, named incidence matrix, to represent a complex topology of a multibody system. This graph-theoretic approach enables automatic generation of dynamic equations [16,17]. While these methods do generate the equations of motion for the dynamic systems of interest to the current work, they are highly general and generate redundant equations requiring careful manual selection of state variables, or cut-sets, to have physical meaning to the reduced escholon form required to systematically generate the equations of motion. This manual selection is not conducive to the automatic generation required to analyze many different actuator topologies and differing internal cell structures. Additionally, the incidence matrix in the graphical techniques consists of a list of connections between all elements in the system while the expanded fingerprint method presented below uses the self-contained cell structures to separate the internal cell dynamics from the topology dynamics, thus greatly simplifying and shrinking the incidence matrix (represented as G and H matrices in the theory below). [18] presents a similar simplifying method called Newton–Raphson Mixed Nodal Tableau by separating internal dynamics of photovoltaic cells and then "stamping" these repeated dynamics into a larger system as a single element and using GTM to generate the final equations of motion. This allowed for a simpler process for generating the dynamic equations of motion and allowed for the non-linear dynamics of the photovoltaic system while treating the rest of the system as linear. [18] focused on electrical systems, specifically photovoltaic power systems, resulting in an application specific algorithm with fixed equations that cannot be easily applied to mechanical systems.

1.4. Current contribution

The current contribution generalizes the expanded fingerprint method presented in [11] to allow for general linear actuation technologies. Actuator technologies such as piezoelectrics, ultrasonic motors, linear stepper motors, hydraulics, pneumatics, and shape memory alloy (SMA) can all be represented. The method provides a direct process to generate the standard state-space form $\dot{\mathbf{X}} = \mathbf{A} \cdot \mathbf{X} + \mathbf{B} \cdot \mathbf{u}$ from any array layout, or topology, and varied cell internal dynamics. The resultant state-space form allows for using standard controllability, stability, etc. analysis techniques for the actuator arrays and for simulating their responses as a part of larger dynamic systems.

The approach is built to aid automation and simulation of the cell array actuators, allows for fast recalculation for different cell array topologies, and provides an intuitive base for future controls work on cell array actuators. The dynamics representing a given cell array actuator could be generated using Dymola, SimScape, GTM [16,17], or other computational methods based on base principles. The presented expanded fingerprint method allows the dynamics to be calculated with less human effort, less computational effort, and with greater speed, especially when comparing different