Modular Actuation Systems: A Scalable Solution for Delivering Robotic Performance

Joshua A. Schultz[1] and Peter J. Hawrylak[2]

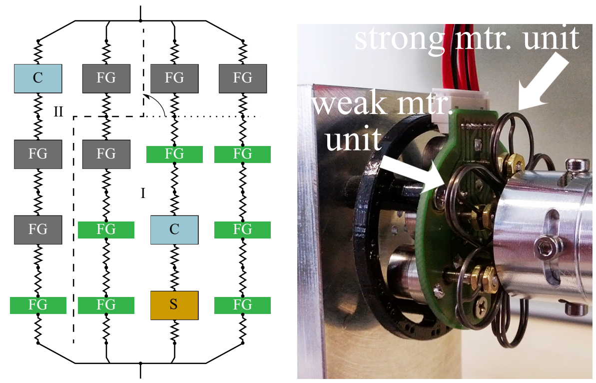
***Abstract*— Extremely resilient actuators can built by collecting force-generating, computational, and sensing modules together to fit into the allotted volume. Including extra modules makes the actuator damage tolerant. This modular architecture allows an actuator at any performance point to be easily synthesized from a small number of component parts. The embedded intelligence, sensing and inter-module communication provides the necessary abstraction so that even complex configurations of modules will appear as a simple device to an external controller. The IEEE 1451 standards are instrumental in managing inter-module communication in a reliable way.**

I. INTRODUCTION AND BACKGROUND

A traditional robot tends to be a complicated device with large numbers of disparate parts. This requires a large inventory of spare parts and specialized knowlege to keep it running. Recently several communities have taken a simpler approach to robotic hardware in an effort to make robots more fault tolerant and amenable to self-replication and repair. *Swarm robotics*, e.g. Becker, et al. [1] refers to a collection of (usually identical) robots with a common input signal that can manipulate an object, usually by pushing. Loss of a single robot is usually not critical. *Modular robots* [2] refers to collections of basic single degree-of-freedom blocks that can link together autonomously and assume changing morphologies in space. *Intelligent actuators* [3] have closely coupled computation making them capable of self-monitoring and reacting to failures. This paper proposes a new paradigm within this vein, called *modular actuation*, which offers the ability to adapt the energetic and dynamic performance of the device to the task at hand. The goal is to produce a motion-generating device by joining individual modules, each contributing a "packet of performance," so that the entire collection has the performance desired. This will enable digital actuator design and fabrication without requiring human intervention.

II. MODULAR ACTUATION SYSTEMS

There are two benefits of a modular actuation system. The first is high resiliency; loss of a single or even several modules is not indicative of an actuator failure. Instead, some performance will be lost – the remaining modules will continue to attempt the task. This makes redundancy in the design low-cost in terms of expenditure and weight. The second is that actuators of differing performance or energetic specifications can be quickly and easily synthesized from a small number of parts. This reduces the part inventory and makes *in situ* modifications very easy, allowing the device to effortlessly adapt to changing task requirements.



(a) Connections of Modules (b) Implementation

Fig. 1. (a) Force generating (FG), computational (C), and sensing (S) modules connected in a spatial configuration to compose an actuator with desired properties. Each type affects different aspects of performance. (b) Example of a discrete force-generating unit, further described in [4].

Modular systems are complex in nature, with high-order system dynamics. From the point of view of the central controller, the collection of modules should behave like a traditional actuator with simple system dynamics. Wiring every module directly to the central controller will not be scalable as the system grows large. Scalability means that the central controller can only broadcast a 1–dimensional signal to the modular actuator. Computational entities embedded within the actuator interpret this signal to take action locally. In the aggregate, the collection of modules should behave like a traditional actuator. This paradigm is described in Figure 1. Any modular actuator can be assumed to include at least one of each of 3 types:

- Force-Generating modules: These modules contract in response to a signal from a computational module. If the axial load applied to the module is small, it will decrease in length, ultimately leading to motion at the output. If the actuator is physically constrained in length, the module will contribute to a contractile force applied by the actuator to the constraint.
- Computational modules: are embedded processors, each of which can activate force-generating modules and receive information from sensors to which it is connected. They have the ability to communicate with other computational elements, but this incurs a cost; each should function as independently as possible. These

[1]Joshua Schultz is with the Department of Mechanical Engineering, the University of Tulsa, Tulsa, OK, 74104 joshua-schultz@utulsa.edu
[2]Peter Hawrylak is with the Department of Electrical & Computer Engineering, the University of Tulsa, Tulsa, OK, 74104 peter-hawrylak@utulsa.edu

modules share the duty of distributing the central control signal over the force-generating elements. Any of them may modify the central control input in an effort to make the actuator appear more transparent.
- Sensing modules: These elements sense a physical quantity at or near their location, such as position or force, which will be transmitted back to the computational module with which it is associated. The more sensors present, the more observations each computational element has with which to estimate the system state, leading to improved performance and transparency.

Each type of resource will be competing for physical real estate. Adding computational or sensing modules decreases the force capability compared to an actuator solely composed of force-generating modules. However, sensing and computational modules contribute performance improvements in other respects, e.g., more accurate state estimation, shorter settling time, more faithful representation of the central control input, and smaller communication delays.

Each force-generating module in the configuration must be elastic. Similarly to human muscle, a control command corresponds to setting the equilibrium length of a spring [5], where the true length is also affected by the load. In the case of chains of force-generating modules arranged in a bundle (shown in Figure 1 (a)), a closed-form expression can be derived for the total actuator force. The general form and derivation of this expression will appear in a forthcoming work. If all modules are identical, the expression becomes:

$$F = \frac{k}{n}\left[nL - \sum_{j=1}^{m}\sum_{i=1}^{n}\ell_{i,j}^{s}\right], \quad (1)$$

where k is the spring constant of a series elastic element, n is the number of units in each chain, m is the number of chains in the bundle, L is the total length of the actuator, and $\ell_{i,j}^{s}$ is a binary constant that takes a "short" or "long" length based on whether it is active or inactive. If all units are identical, Eq. (1) contains no information about spatial location and the output force scales linearly with the number active, irrespective of where the active units are located. Adding computation and sensing can be viewed as displacing force-generating units with units that cannot be activated. The benefits of adding computational and sensing modules may not scale linearly with the number present, and may have a spatial dependence. This poses an interesting problem with regard to the allocation of space within the actuator volume. The spring constant of the sensing and computational modules may differ from that of the force-generating element, from completely rigid ($k = \infty$) to a slider ($k = 0$) and this will affect the properties of the actuator as a whole, and introduce spatial dependence.

III. INTEROPERABILITY

The use of dissimilar modules in an ad-hoc manner requires that all modules be interoperable, from both a data communications and actuator control standpoint. IEEE 1451 provides a means to standardize data communication between a controller and a sensor or actuator [6]. The computational modules will take on the Network Capable Application Processor (NCAP) role with the force-generating and sensing modules connecting via a Transducer Interface Module (TIM). The key to this is through the sharing of the Transducer Electronic Data Sheet (TEDS) between the TIM and NCAP. The TEDS contains the information needed to interpret sensor readings, recalibrate a sensor, identify the capabilities and limitations of an actuator, determine what type of control input is required for an actuator, and how to properly format the control signal for an actuator. IEEE 1451 also provides a set of commands for NCAPs and TIMs to interact. These commands are protocol and physical layer agnostic, which allow them to be wrapped into packets conforming to each particular network.

The TEDS provides the computational module with the information it requires to interpret and recalibrate sensor modules, and to control force-generating modules. With this information, the computational module can determine the capabilities of the modules it supervises and report them to other computational modules. This standardized data presentation and communication protocol is critical to enabling the plug-and-play capability required for the modular actuation concept.

IV. CONCLUSION AND FUTURE DIRECTIONS

This paper describes a modular actuation architecture, which allows an actuator for a given static, dynamic and energetic performance point to be quickly, even automatically synthesized. The architecture is scalable because the actuator includes computational modules embedded within it, thereby decentralizing the communication. These interpret a central controller command and makes the collection of modules appear to have simple system dynamics. Operational principles of force generation and inter-module communication are described. To make deployment of this technology feasible decentralized control algorithms, coupled system dynamics between regions of large systems, and potential extensions to the IEEE 1451 standard should be investigated.

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