Collective Actuation (Extended Abstract)

Jason Campbell, Padmanabhan Pillai

Intel Research Pittsburgh
Pittsburgh, PA USA
jason.d.campbell@intel.com, padmanabhan.s.pillai@intel.com

***Abstract* — Modular robot designers confront an inherent tradeoff between size and power: Smaller, more numerous modules increase the adaptability of a given volume or mass of modules – allowing the aggregate robot to take on a wider variety of configurations – but do so at the expense of the power and complexity of each module. Fewer, larger modules can incorporate more powerful actuators, more powerful bonds, and stronger hinges but at a cost of overspecializing the resulting robot in favor of corresponding uses.**

We describe a technique for coordinating the efforts of many tiny modules to achieve forces and movements beyond those possible for individual modules. Our approach is predominantly applicable to spherical and cylindrical modules and their faceted counterparts, but may apply to some chain-style modular robot systems. Thus actuator capacity and range becomes a function of software and dynamic topology as well as of hardware. An important aspect of this technique is its ability to bend complex and large-scale structures and to realize the equivalent of large scale joints.

I. INTRODUCTION

Modular, self-reconfigurable robots (MRRs) offer the potential for flexible deployment and robust failure recovery in a variety of roles and applications but suffer from size-based limitations on the power and complexity of individual modules. In principle, an MRR may change its shape, locomotion style, or end-effector design based on local environmental conditions and goals. But that flexibility can be severely constrained in the absence of scalable joints, bendable multi-module structures, and the ability to exert forces greater than a single module's actuation capacity.

Work on chain-style MRRs [9,10,8,3,4] has relied upon the hinges and actuators in individual modules to form and bend joints and hence develops forces and torques proportional to the scale of the modules. Current work in lattice-style MRRs achieves self-reconfiguration by shifting modules across the surface of an ensemble [5], by moving holes around within the ensemble [1], or via interpenetrating metamodules [6,7]. None of these movement techniques can generate forces larger than a single module can, and they cannot construct large-scale joints.

Motivated by the multi-million module MRR ensembles envisioned by Claytronics [2], we have developed a class of reconfiguration techniques which can be used to build flexible structures and compound joints, and can combine the efforts of a large number of modules to develop large forces and large ranges of motion (greater than those possible for pair-wise module interactions). These techniques are specialized for mechanically simple, spherical/cylindrical modules with no moving parts. The modules employ force-at-a-distance actuators (utilizing magnetic or electric fields) to roll across each others' surfaces. The simplicity of this design is intended to harness high volume manufacturing processes including photolithography and self-assembly – reducing unit cost, and thereby helping make million-module ensembles practical.

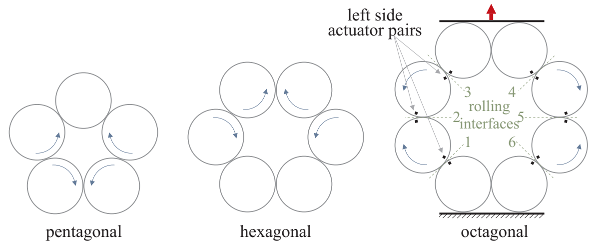

Fig. 1: Three example collective actuation cells.

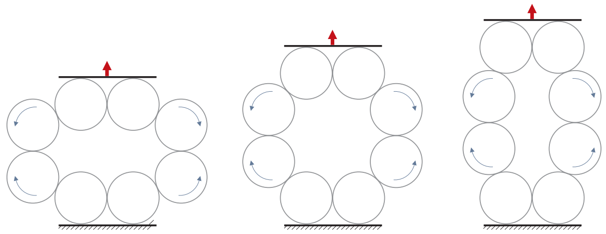

Fig. 2: Varying height (and aspect ratio) possible for a single collective actuation cell

Claytronics aims at relatively unusual applications such as 3D visualization, self-reconfigurable antennas, telepresence, and new forms of user interface. Flexible structures and compound actuators able to exert larger forces than a single module are essential to reconfiguring such fine-grained ensembles in an efficient and quick manner.

II. COLLECTIVE ACTUATION CELLS

Our approach is to coordinate changes in the angular relationships between a small group of adjacent modules, which we call a "cell". Such cells then become fundamental building blocks of larger structures, and serve to transform the rolling motion between modules to linear and flexing motions. This facilitates near-continuous shape changes, even in compact, lattice-based ensembles that would previously have been regarded as modifiable only by adding or subtracting modules from the surface of the shape.

A cell operates by means of an actuation plan, which describes a pattern of relative rotational motions between modules (potentially including varying speeds). Several actuation plans may be possible for any given physical configuration of modules, and in general our technique shifts the focus of actuator design from one of mechanical engineering of the individual components to software engineering of the interaction between those parts.

CA cells may exist in two dimensions as well as in three. We limit out discussion here to the 2D case as this simplifies the analysis, diagrams, and explanations involved. However, we believe that the techniques we introduce extend to 3D and plan to detail that extension in future work.

There are a number of advantages to a cell-based actuation technique:

- *Composability* – The physical carrying capacity or range of motion of a cell can be extended by placing multiple cells next to one another. Neighboring cells may also add useful degrees of control freedom (curvature, slant, etc.) in the resulting structure.
- *Simplified Local Control* – Due to the prescribed range of motions valid for a cell, a small number of parameters can define a full cell configuration (versus the much larger number of potential degrees of freedom). This simplifies intra-cell communication and decreases the amount of information that must be transferred externally to control a given cell.
- *Hierarchical Decomposition* – When groups of cells are aggregated, the total shape that they form can be described (at least for many applications) in a form yet simpler than that suggested above (e.g., a rectangular prism consisting of thousands of cells might be described by three parameters: height, aspect ratio of the sides, and slant of the top). Such reductions dramatically lower the communications burden associated with distributed control of large ensembles.
- *Reduced Analytical Complexity* – Regular structures with prescribed motion plans are more tractable for dynamic and kinematic modeling.
- *Fault Isolation* – Given a large number of modules, individual failures become overwhelmingly likely. Cells can identify failed modules and act to mechanically neutralize faults within the ensemble, even if in doing so a particular cell contributes less to the whole in terms of forces, etc.

III. PERFORMANCE CRITERIA

For a two-dimensional CA cell there are four major figures of merit about which we are concerned: net linear force, range of motion, aspect ratio change, and degree of curvature possible (given a multi-cell structure). These characteristics can vary both based on the geometric configuration of the modules in the cell as well as on the actuation plan(s) utilized. We will present results from our hardware prototypes and simulations in terms of these metrics.

IV. SURVEY OF RESULTS TO DATE

We have developed two hardware prototypes, a medium scale simulation (20 cells / 160 modules in one connected ensemble), and an analytical model describing the dynamics of some collective actuation cells. During the workshop we will show results from this work, including our measurements of the relative forces developed, comparisons to the calculated results from the analytical model, and evaluations of the ranges of motion/flexibility achieved.

Our two prototypes to date explore specific aspects of collective actuation. The first is a single-cell assembly which we have used to test the relationship between rotational and linear forces achieved. The second is a two-cell assembly which we have used to evaluate range-of-motion and range of curvature, and to test control software. Both of these testbeds have used conventional (axial) electric motors to generate motive force between adjacent modules.

We are presently constructing a third prototype which will use individual permanent magnets and electromagnets to demonstrate and test the point-actuator concept for rolling modules, and specifically to evaluate its use in collective actuation assemblies. During the workshop we will demonstrate one or more of these prototypes.

ACKNOWLEDGMENT

We wish to thank our colleagues involved in the Claytronics project at CMU and the Dynamic Physical Rendering project at Intel, especially Seth Copen Goldstein, Todd Mowry, Casey Helfrich, Sidd Srinivasa, Brian Kirby, Mike De Rosa, and Ram Ravichandran for providing the conceptual framework within which the technique we describe here was developed, as well as for their frequent contributions of ideas and constructive criticism.

REFERENCES

[1] Michael De Rosa, Seth Goldstein, Peter Lee, Jason Campbell, Padmanabhan Pillai. “Scalable Shape Sculpting via Hole Motion,” In *Proc IEEE ICRA*, 2006.

[2] Seth Copen Goldstein, Jason Campbell, Todd C. Mowry. “Exploring Programmable Matter,” *IEEE Computer*, 2005.

[3] S. Murata, E. Yoshida, A. Kamimura, H. Kurokawa, K. Tomita, and S. Kokaji. “M-tran: Self-reconfigurable modular robotic system.” *IEEE/ASME Trans. on Mechatronics*, 7(4), 2002.

[4] S. Murata, H. Kurokawa, S. Kokaji. “Self-assembling machine”. In *Proc. IEEE ICRA*, pp. 441–448, 1994.

[5] D. Rus and M. Vona. “Self-reconfiguration planning with compressible unit modules.” In *Proc. IEEE ICRA*, 1999.

[6] S. Vassilvitskii, J. Kubica, E. Rieffel, M. H. Yim, J. W. Suh. “On the General Reconfiguration Problem for Expanding Cube Style Modular Robots,” In *Proc. IEEE ICRA*, 2002.

[7] S. Vassilvitskii, J. Suh, and M. Yim. “A Complete, Local and Parallel Reconfiguration Algorithm for Cube Style Modular Robots.” In *Proc. IEEE ICRA*, 2002.

[8] M. Yim, D. Duff, and K. Roufas. “Polybot: a modular reconfigurable robot,” In *Proc. IEEE ICRA*, pp. 514–520, 2000.

[9] M. Yim. “A Reconfigurable Modular Robot with Many Modes of Locomotion,” *JSME Intl. Conf. on Advanced Mechatronics*, Tokyo, Japan, 1993.

[10] M. Yim. “Locomotion with a Unit Modular Reconfigurable Robot,” PhD Thesis, Dept. of Mech. Eng. Stanford Univ. 1994.