Towards Artificial ATRON Animals: Scalable Anatomy for Self-Reconfigurable Robots

(Extended Abstract)

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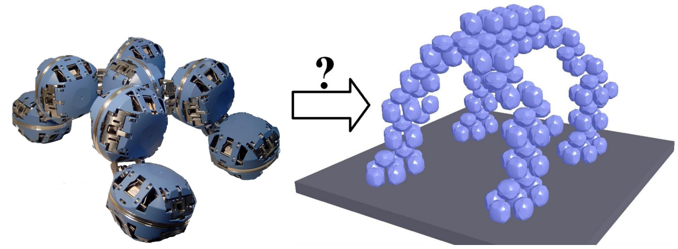
I. Introduction

Self-reconfigurable robots consist of simple robotic modules that play a similar role in robots as cells play in biological organisms. The vision of self-reconfigurable robots is to make an evolutionary jump for robotics analog to biological organisms that evolved from single-celled to multicelled. Such robots can autonomously self-reconfigure its modules to adjust both its behavior and morphology, to meet the requirements in the current situation. Physical, state of the art, 3D self-reconfigurable robots, e.g. [2], [4], [6], consist of up-to a few dozen, centimeter scale, modules. However, our ultimate goal is myriad-module robots that consist of thousands to trillions of millimeter or micrometer scale modules. This paper investigates the challenge of achieving functional and fast responding myriad-module self-reconfigurable robots. We propose the use of *scalable anatomies* inspired by biological animals to achieve such robots. As an example we introduce an anatomy for ATRON self-reconfigurable robots, which consist of anatomical parts such as muscles, bones and joints, assembled from modules in a scalable way.

Fast functional response to the environment is a general requirement in most robot applications, such as locomotion and manipulation. Functional myriad-module self-reconfigurable robots may use self-reconfiguration to self-assemble, self-repair and shape-adapt, but for fast functionality, self-reconfiguration is too slow. To solve this problem the functional roles of modules may be differentiated in the robot. Figure 1(a) illustrates a robot, which consist of few modules and is able to locomote. In such a robot the modules play relatively 'broad' roles such as feet, leg or body. But this does not scale to myriad-module robots, since the required roles must be very different, see figure 1(b). Also, from the point of applications, an increase in the number of modules should somehow benefit the functional performance of the robot. This is the great challenge of *scalable functionality*: How do we scale up the diversity of functionality with the number of modules?

II. Anatomy for Myriad-Module Robots

We propose to address the problem of *scalable functionality* by introducing a *scalable anatomy* for the self-reconfigurable robotic system. At the cellular level of animals, cells differentiate to form an organizational hierarchy



(a) 9-Module Quadruped. (b) 170-Module Quadruped

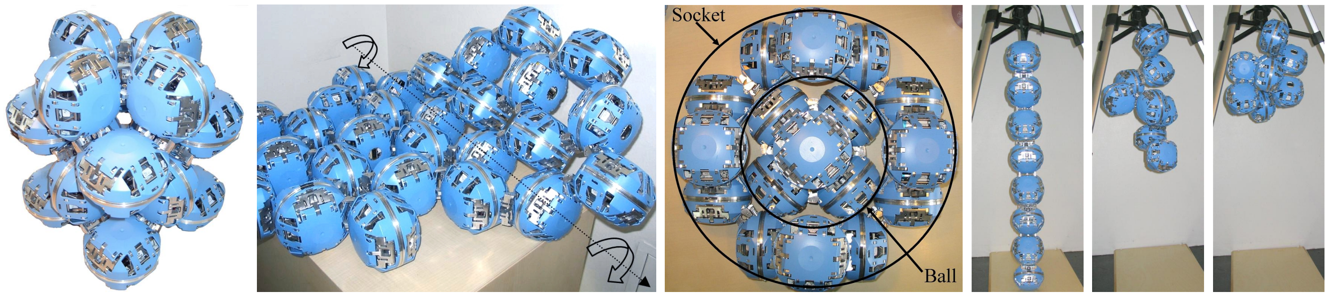
Fig. 1. How can we make functionality scale up with increasing number of modules? - E.g. the anatomy of a few-module locomoting robot can not trivially be scaled up, since the actuation forces generated by the individual modules must somehow be parallelized and scalable joints must be introduced.

of tissue types, organs and organ systems to create a complete functional animal. Scalable anatomies for self-reconfigurable robots are inspired by this hierarchy of animal cells. Such anatomies define structures of modules with functionality similar to biological anatomical structures and can be scaled to increased numbers of smaller modules. Scalable anatomies may increase the level of abstraction, to ease the design (by human or artificial evolution) of functional and fast responding myriad-module self-reconfigurable robots. Optimally, the modular system should be designed to support a scalable anatomy. Such a design will most likely be heterogenous, after all biological cells are not homogenous, e.g. more than 200 cell types exist in the adult human. Homogenous modules, as the ATRON, can only adapt its function, not its morphology, to its required role in the robot. However, morphological specialization of the individual modules is likely to be necessary to solve the problem of scalable functionality.

III. ATRON-Anatomy

The ATRON system is not designed to support a scalable anatomy, we can however identify a number of scalable anatomically structures. In the following the characteristics given for the structures are based on the current macro-size modules. We know however from the scaling laws of physics [5] that great improvements both in terms of strength and speed relative to size potentially can be achieved when scaling down the module size.

ATRON-Bone: Animals use bones to support the weight of their body. A structure of ATRON modules



(a) ATRON-Bone (b) ATRON-Hinge-Joint (c) ATRON-Ball-Socket-Joint (d) ATRON-Muscle

Fig. 2. Examples of biological inspired scalable anatomical structures for the ATRON-Anatomy.

connected in the surface centered cubic lattice structure, see figure 2(a), have relatively high structural strength, low weight and the ability to self-repair. The mass density of an ATRON material is approximately $720kg/m^3$, for bone the mass density is about $1900kg/m^3$. Yield stress for the ATRON material is $0.067MPa$ [3] and more than $50MPa$ for human femoral bone [1]. So ATRON-bones are lighter and much weaker than biological bones.

ATRON-Joints: Joints are needed to connect and allow relative rotation of bones. Hinge joints, see figure 2(b), scales along its rotational axes. It has improved strength compared to a single module joint since it distributes the forces on a larger number of modules. This hinge joint has the feature that the modules on both sides of the joint always can return to the same global lattice. This is important in order to have complete reversibility when changing from one shape to another. Ball-socket joints, see figure 2(c), have three degrees of freedom and scale in three dimensions. It can, however, not be assembled from ATRON modules without separating the lattice of the ball from the lattice of the socket. One solution to maintain reversibility is to use ATRON-muscles as anchors between the ball and socket. Such muscles can function as bridges for communication, transporting modules and can by contraction realign the lattices. This technique equally allows the construction of other types of joints, e.g. saddle joints. Friction between the ball and socket could be minimized by careful design of the module shape combined with lubrication.

ATRON-Muscle: Muscles are able to contract and as a result produce a force, which can be used for actuating the myriad-module robot. Chain structures can contract by forming a compact helix shape, see figure 2(d). Experiments shows that this type of ATRON-muscle is able to contract by a factor of 4.2 or 76%. In its extended form the cross-sectional area is 11x11cm, in the contracted form it is 21x21cm. Contraction forces are strongest ($\approx 160N$) when the ATRON-muscle is fully extended and decrease rapidly as it shortens. The maximum force delivered by the muscle is independent on the chain length. The strength of an ATRON-muscle can be scaled up by having a number of muscles in parallel just as biological muscle fibers.

ATRON-Artery: Similar to biological cells requiring oxygen and glucose to survive, modules need energy in the form of electricity to function. In an earlier version of the modules power were shared amongst the modules through the connectors-hooks. Miniaturized modules will need power-sharing and the robot will probably need a digestive system to achieve energetic autonomy.

ATRON-Neuron: In essence all ATRON modules may play the role of both sensory and motor neurons, since they are able to compute, communicate and sense the environment. In its current implementation communication is only between neighbors, which may introduce to high a delay for achieving fast responding robots. Also the sensory capabilities are limited to sensing acceleration, proximity, orientation and different internal states. This collection of sensors should be further extended e.g. to include the sensing of light, heat, touch, sound and chemicals.

IV. Conclusion & Future Work

Based on the presented study, with a proof-of-concept ATRON-anatomy, we believe that the approach of scalable anatomies will be useful as a design guideline for miniaturized modules and for the design of functional self-reconfigurable robots from such modules. Further biological inspiration and experimentation in simulation and on physical hardware is needed to further identify the requirements and means for achieving functional and fast responding myriad-module robots.

References

[1] Y. C. Fung. *Biomechanics - Mechanical Properties of Living Tissues*, chapter 12. Springer-Verlag, 1993.

[2] S. Murata, A. Kamimura, H. Kurokawa, E.i Yoshida, K. Tomita, and S. Kokaji. Self-reconfigurable robots: Platforms for emerging functionality. In *Lecture Notes in Artificial Intelligence*, volume 3139, pages 312–330. Springer-Verlag, 2004.

[3] E. H. Østergaard, K. Kassow, R. Beck, and H. H. Lund. Design of the ATRON lattice-based self-reconfigurable robot. *Autonomous Robots*, 2006. To appear.

[4] W.-M. Shen, M. Krivokon, M. Rubenstein, C. H. Chiu, J. E., and J. B. Venkatesh. Multimode locomotion via superbot reconfigurable robots. *Autonomous Robots*, 20(2):165–177, 2006.

[5] W. Trimmer. Microrobots and micromechanical systems. *Sensors & Actuators*, Vol. 19(No. 3):267–287, September 1989.

[6] M. Yim, D.G. Duff, and K.D. Roufas. Polybot: A modular reconfigurable robot. In *Proceedings of IEEE International Conference on Robotics & Automation (ICRA)*, pages 514–520, San Francisco, CA, USA, 2000.