

Selecting a Meta-Module to Shape-Change the ATRON Self-Reconfigurable Robot

David Johan Christensen and Kasper Støy
Maersk Mc-Kinney Moller Institute for Production Technology
University of Southern Denmark
Odense, Denmark
Email: {david, kaspers}@mip.sdu.dk

Abstract—The ATRON self-reconfigurable robot consists of simple one degree of freedom ATRON modules. The motion capabilities of an individual module are therefore quite limited. To compensate for this, meta-modules composed of more than one module are used to shape-change the system. Meta-modules emerge from the environment created by other modules, move on the surface of other modules and stop at a new position. The flow of meta-modules, from one place to another on the structure of modules, realizes the desired self-reconfiguration. In this paper we compare six different meta-module types composed of ATRON modules. Variations of meta-module morphology and meta-actions are investigated for its ability to shape-change the robot. We conclude that two of the investigated meta-module types are able to shape-change the robot to an acceptable extent.

I. INTRODUCTION

A self-reconfigurable robot is able autonomously to change its shape. Such robots usually consist of a number of interconnected heterogeneous or homogeneous robot modules. The modules are able to communicate, connect to other modules, sense the environment and act within it. The shape-change, or self-reconfiguration, is realized by modules that move from one place to another, changing the configuration of the robot.

The problem of controlling self-reconfigurable robots is highly complex, with many interconnected layers of complexity, e.g. *when* the robot should change morphology and to *what*. In this work we consider the problem of *how* to achieve the actual changing of shape. A successful control strategy simplifies the problem of self-reconfiguration for the type of module it is designed for. But it may be infeasible to transfer the control strategy directly to other types of modules as well. However some concepts/features of control strategies seem to be more generic, and have been found useful on many different platforms. Such concepts include *gradients*, *local rules*, *agents* and *meta-modules*.

The ATRON module [7] is a simple, one degree of freedom, homogeneous, lattice-based module able to self-reconfigure in 3D. Self-reconfiguration of ATRON modules is non-trivial because of complex motion constraints. We investigate six different meta-module types, composed of one or several ATRON modules, to overcome these constraints. In contrast to prior work on meta-modules, five of

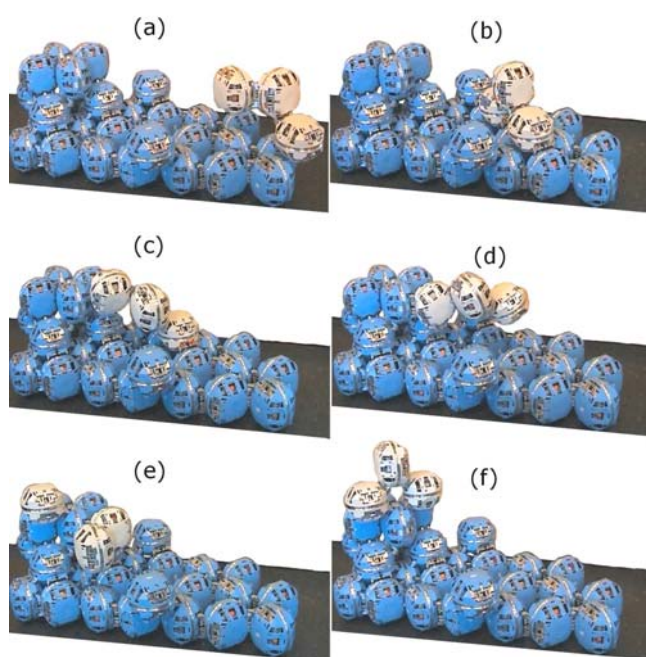


Fig. 1. Experiment on the ATRON platform: A meta-module(three white modules) of type 5 has high moveability. In this experiment the meta-module moves across a structure of ATRON modules.

the six meta-module types we investigate are not lattice-based. Meta-modules are not positioned and do not move in a permanent lattice structure of meta-modules. Instead they emerge from unstructured groups of modules. Meta-modules act as single autonomous entities and perform actions called meta-actions. Important characteristics related to the different meta-module types such as the meta-modules' ability to emerge and move are evaluated and compared. Also their ability to change the shape of structures of ATRON modules and their efficiency is measured.

II. RELATED WORK

Strategies for self-reconfiguration can be divided into centralized and distributed control.

Centralized control strategies consider the self-reconfiguration problem as a planning problem and search for a sequence of actions which morph a starting configuration to a goal configuration [8], [15], [18]. The problems with these control strategies are that the search space explodes with the number of modules in the structure [6] and that the control strategy is very sensitive to inaccuracy in its *model* of the system.

If the control strategy is distributed, the control responsibility is distributed amongst the individual modules [3], [4], [9], [11]. There is no global search and no model to maintain, so this approach eliminates the problems with centralized control. Instead, the problem of coordination amongst the modules is introduced and must be solved by the distributed control method.

A meta-module is a group of modules which, combined and seen as a single entity, have different control characteristics than the individual module. Meta-module based control strategies have been used on realistic types of modules such as the Crystalline [13], Telecubes [16], I-Cubes [12], [15], Molecule [10] and the ATRON [5]. In [1], A. Nguyen et al. present meta-modules which are used to control systems consisting of 2D hexagonal modules. In general meta-modules are used as means to encapsulate the complexity, arising from the motion constraints of the base modules.

In simulation work on abstract types of modules [2], [4], [14], e.g. the proteo module [17], which are characterized by their, hard to realize, low motion constraints, an often used decentralized control strategy is to consider every module as an autonomous entity. Modules decide where to move based on local information from the environment consisting of other modules.

In this work we combine the prior work on meta-modules with the prior work on modules as autonomous entities. Meta-modules act as single autonomous entities.

III. THE ATRON SELF-RECONFIGURABLE ROBOT

The ATRON module [7], is a 3D lattice-type, one degree of freedom, module, see figure 2(a). ATRON modules are spherical, composed of two hemispheres. The module can actively rotate the hemispheres relative to each other. A module may connect to neighbour modules using its four actuated male and four passive female connectors. The connectors are positioned at 90 degree intervals on each hemisphere. Infrared channels below each connector are used by the modules to communicate with neighbouring modules and sense distance to nearby obstacles or modules. A module weighs 0.850kg and has a diameter of 110mm. 100 hardware prototypes of the ATRON modules exist. In this work modules are always connected in a surface-centered cubic lattice structure.

Motion constraints on the modules affect their ability to self-reconfigure. The single rotational degree of freedom of a module makes its ability to move very limited: actually

a module is unable to move by itself. The help of another module is always needed to achieve movement. The modules must stay connected to prevent them from falling off. They must respect their limited actuator strength and avoid collisions. A single module has the strength to rotate two other modules against gravity.

IV. ATRON META-MODULES

We define a meta-module type by its morphology and its meta-actions:

- *Morphology*: Meta-modules of a given type are composed of a specific number (one or several) of modules, which are interconnected in a specific way.
- *Meta-Actions*: Meta-modules of a given type can perform a specific number of different meta-actions. Meta-actions are composed of a sequence of basic module actions, which are performed by the modules part of, or neighbour to, the meta-module. Basic module actions of the ATRON are rotation, connection and disconnection.

A meta-module starts its life by emerging from the structure of modules; that is, a module or group of modules agrees to form a meta-module. Then the meta-module starts performing a sequence of meta-actions, which result in movement of the modules which comprise the meta-module. At some point the meta-module decides that it is time to stop and the modules become passive once again. The problem of self-reconfiguration is then to control the flow of meta-modules from one place to another on the structure of modules. This problem is addressed in [5] and involves several subproblems such as when a meta-module should emerge, how it should move and when it should stop.

In this work we explore six different meta-module types for the ATRON system. The meta-modules are referred to as meta-module type 1 – 6. None of the meta-module types are composed of more than 3 modules. It is possible to build larger meta-modules from, e.g., 12 modules, which have very good motion capabilities. Such meta-modules are positioned and move within a lattice of meta-modules. In this work we do not consider lattice-based meta-modules which are so large for a number of practical reasons:

- Meta-modules that sit in a lattice increase the granularity of the system.
- The increase in cost and complexity of a single meta-module (e.g. 12-DOF) cannot be justified by the improved motion capabilities.
- It would be impossible to do experiments with more than a few meta-modules using the existing 100 prototypes of the ATRON modules.

None of the above is true for the meta-modules explored in this work. In particular the meta-modules do not increase granularity (except meta-module type 6), because they emerge, move and stop. When stopped, the modules which

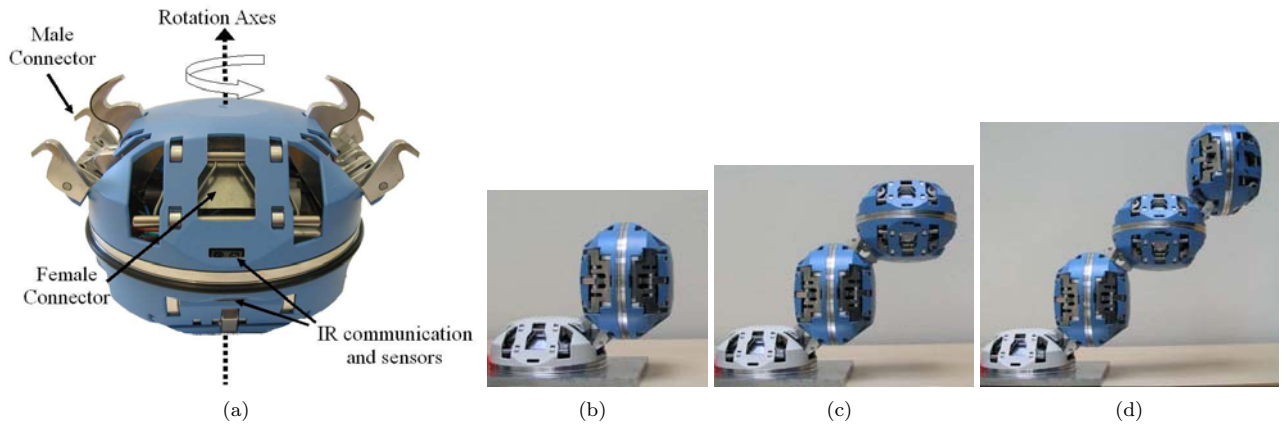


Fig. 2. Photographs of: (a) A single ATRON module, on the top hemisphere the two male connectors are extended on the bottom hemisphere they are contracted. (b) Single module meta-module (type 1) connected to half a module (white). (c) Two module meta-module (type 2 and 3) connected to half a module. (d) Three module meta-module (type 4, 5 and 6) connected to half a module.

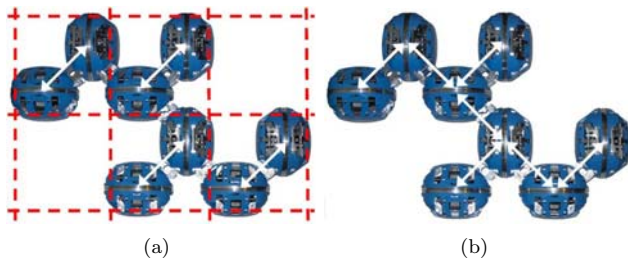


Fig. 3. Difference between lattice-based meta-module types and meta-module types that emerge. (a) A two module meta-module could sit in a permanent 2D lattice as indicated. The meta-modules would move from one lattice position to another. This increases the system's granularity. (b) In this work any combination of two connected modules may emerge as a meta-module. The meta-modules do not sit in any particular lattice and modules are free to be part of different meta-modules at different times, therefore granularity does not increase.

were part of a meta-module may at a later time become part of a different meta-module which is not necessarily composed of the same modules, as illustrated in figure 3. The number of modules in the meta-module types and the number of meta-actions is summarized in table I. The three different meta-module types' morphologies, shown in figure 2(b)-(c), are selected so that they can often emerge from unstructured groups of modules. The meta-actions of type 1, 2, 3 and 4 are designed by taking direct inspiration from the morphology of the meta-modules. Meta-module types 5 and 6 expand type 4. The expansions come from experience gained by investigations of type 4. The morphology and meta-actions of the six different meta-module types are explained below:

Meta-module type 1 is composed of a single module, see figure 2(b). It has the ability to perform 16 different meta-actions that all have the same blueprint. First, the meta-module disconnects all neighbor modules except one.

Type of Meta-Module	Modules in Meta-Module	Number of Meta-Actions
Type 1	1	16
Type 2	2	4
Type 3	2	32
Type 4	3	8
Type 5	3	12
Type 6	3	12

TABLE I
BASIC PROPERTIES OF DIFFERENT META-MODULE TYPES.

Second, the meta-module remote controls the connected neighbor module to disconnect all other modules on that hemisphere and rotate left or right, thus moving the meta-module. Later, when the meta-module have moved away, the neighbour module will reverse the rotation and disconnections to return to its initial state.

Meta-module type 2 is composed of two modules which stay connected throughout the lifetime of the meta-module, see figure 2(c). It is able to perform 4 meta-actions. First, the meta-module connects to all neighbour modules on one of the two hemispheres which are not used to keep the two modules in the meta-module connected. Second, all other neighbour modules are disconnected. Finally the module in the meta-module, that is connected, rotates and thereby moves the other module.

Meta-module type 3 expands meta-module type 2 with 28 extra meta-actions. These meta-actions all follow the same blueprint. First, the meta-module disconnects all except one neighbour module. It has up to 14 neighbors. Second, the meta-module remote controls the connected neighbour module to disconnect all other modules on that hemisphere and rotate left or right to move the meta-module. The neighbour module will later return to its initial state.

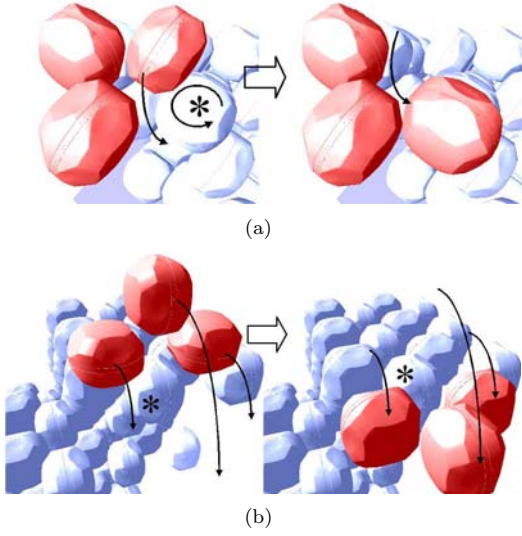


Fig. 4. Meta-modules of type 5 and 6 is able to perform meta-actions which have the effect shown in (a) and (b). In each case, the *-marked module helps the meta-module performing its meta-action.

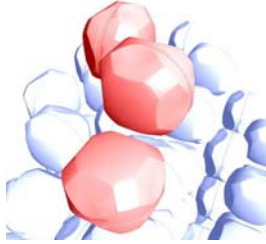


Fig. 5. A meta-module of type 6 must never emerge or stop if it does not have precisely this orientation.

Meta-module type 4 is composed of three modules which are connected so that a center (body) module is connected to two modules (legs), one on each hemisphere, see figure 2(d). The meta-module is able to perform 8 different meta-actions. First, the meta-module connects to a neighbour module using a hemisphere on a leg-module not connected to the body-module. Second, all other neighbour modules are disconnected. Finally, the connected leg-module or the body-module performs a rotation either left or right. Such meta-actions allow the meta-module to move as a two legged walker on a flat surface of ATRON modules.

Meta-module type 5 expands meta-module type 4 with 4 extra meta-actions. For simplicity we will not explain the meta-action's blueprint but only their effect. 2 meta-actions allow the meta-module to move one leg-module so that it connects to the other leg-module, which then becomes a new body-module, see figure 4(a). The last 2 meta-actions either rotate the meta-module 90 or -90 degrees, changing its orientation as indicated in figure

4(b). The 4 extra meta-actions require the help of a neighbour module, marked with a * in the figure.

Meta-module type 6 expands meta-module type 5 but not with extra meta-actions. Instead we put constraints on the emerging and stopping orientation of a meta-module. Meta-modules may only start or stop in precisely the orientation shown in figure 5. The motive is to help the emergence of flat structures of modules, on which it is particularly easy to move on for this meta-module type.

V. REACHABLE SPACE OF META-MODULES

Any meta-module that emerges will be able to move in some well defined space on the structure of modules. From its starting state (position and orientation) it will be able to perform a finite number of meta-actions each of which may be legal or illegal (e.g. would result in collision between modules). A legal meta-action performed by the meta-module will change the state of the meta-module. If we assume the structure to be static, this will allow us to build a graph for each meta-module, having the meta-module states as vertices and meta-actions as edges. This graph will define the reachable space of the meta-module, which in this work is used to measure some characteristics of the different meta-module types. Examples of reachable spaces for meta-module type 1 – 6 is shown in figure 6(a)-(e). Investigations of such graphs indicates that meta-module types 3 – 6 are much more moveable than type 1 or 2.

VI. EXPERIMENTAL SETUP

We measure the characteristics of the ATRON meta-modules in simulation as they perform a shape-changing task. The task is to shape-change one randomly generated structure of modules to another randomly generated goal structure. Meta-modules are centrally controlled and only one meta-module is moved at each time-step. In each time-step we calculate the reachable space of each of the meta-modules in the structure. From the reachable-spaces we find for each meta-module the state which will minimize the distance between the current and goal structure. The corresponding difference in distance we call a meta-module *potential to decrease distance* (PDD). Then the meta-module with the highest PDD is selected and it emerges, moves to and stops at the state which realizes its PDD.

Using this control strategy the distance between the starting structure and the goal structure will gradually decrease or stabilize, but it will never increase. This control strategy is not how we intend to control the meta-modules. The purpose is only to have a common test scenario under which the meta-modules may be evaluated.

The initial and the goal structures have on average an initial overlap of 45%. Each meta-module type performs 10 different random shape-changing tasks. In each experiment a total of 90 modules are used in the initial and goal

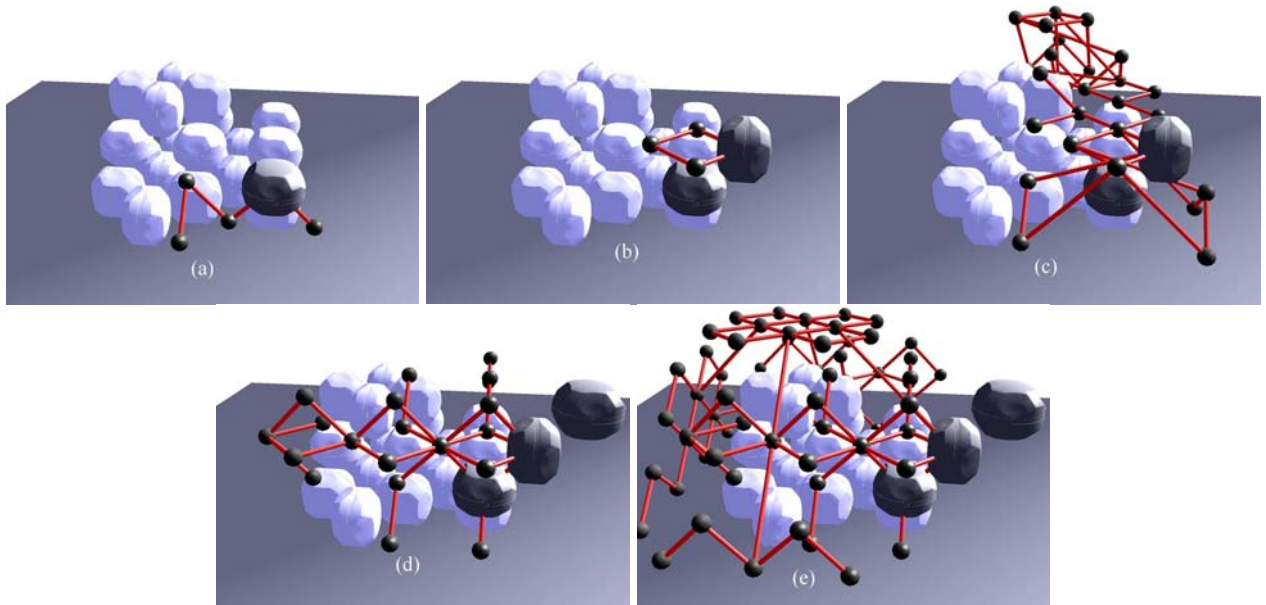


Fig. 6. Reachable Space of ATRON Meta-Modules. Examples of the six types of meta-module are shown in (a)-(e). (e) represents both meta-module type 5 and 6 since they have identical reachable-spaces. Small black spheres are vertices and lines are edges in the graph of the reachable-space. For simplicity in this illustration, only the position of one of the modules comprising the meta-module is used to visualize the states. For type 2 and 3 the top module is used and for type 5 and 6 the middle body module is used.

structure. Each experiment runs for 20 time-steps which in most cases is plenty for the result to stabilize.

We measure the distance between two structures (S1 and S2) as the sum of distances between the modules in S1 to S2. The distance between a module and a structure is measured as the Euclidean distances from the module to the nearest module in the structure.

VII. TASK RELATED CHARACTERISTICS

Task-related characteristics measure how well the meta-module performs the shape-changing task. We measure the *efficiency* as the effect achieved (decrease in distance between structures) compared to the number of rotations performed by modules during the task. *Effectiveness* is measured as the relative decrease in distance between the current and goal structure after 20 time-steps.

$$Efficiency = \frac{D_{start} - D_{end}}{\#Rotations} \quad (1)$$

$$Effectiveness = \frac{D_{start} - D_{end}}{D_{start}} \quad (2)$$

The task-related characteristics of the different meta-module types are shown in table II and III. In terms of efficiency the one- and two-module meta-module (type 1, 2 and 3) performs much better than the three module meta-modules (type 4, 5 and 6). Meta-module type 3, 4 and 5 performs similar in terms of effectiveness (0.62, 0.66 and 0.66). Such effectiveness is acceptable in a range of applications which does not require shape-change into precisely specified structures.

TABLE II
EFFICIENCY OF META-MODULE TYPES.

Type of Meta-Module	Mean Efficiency	95% Confidence Interval
Type 1	0.89	[0.76, 1.01]
Type 2	1.31	[1.17, 1.43]
Type 3	1.18	[1.06, 1.31]
Type 4	0.29	[0.26, 0.32]
Type 5	0.34	[0.28, 0.41]
Type 6	0.36	[0.28, 0.44]

TABLE III
EFFECTIVENESS OF META-MODULE TYPES.

Type of Meta-Module	Mean Effectiveness	95% Confidence Interval
Type 1	0.20	[0.17, 0.24]
Type 2	0.21	[0.17, 0.24]
Type 3	0.62	[0.58, 0.66]
Type 4	0.66	[0.58, 0.73]
Type 5	0.66	[0.59, 0.72]
Type 6	0.51	[0.46, 0.56]

VIII. META-MODULE RELATED CHARACTERISTICS

Meta-module related characteristics measure the individual and cooperative capabilities of meta-modules of a particular type. The system should contain a high proportion of moveable modules which can move as part of a meta-module, that is, modules which are not locked in place by constraints on their movement from their

morphology and/or through blocking from other modules. We define this characteristic as *system moveability*. It is measured as the ratio between the number of moveable modules and modules in total in the structure. Similarly, a meta-module should be able to move freely on the surface of other modules. We measure *meta-module moveability* as the ratio between the number of connectable modules and the total number of modules in the structure. Connectable modules are the modules the meta-module, within its reachable space, is able to connect to.

$$SystemMoveability = \frac{\#MoveableModules}{\#Modules} \quad (3)$$

$$MetaModuleMoveability = \frac{\#ConnectableModules}{\#Modules} \quad (4)$$

When a meta-module moves, side effects may have a beneficial or undesired effect on the other meta-modules. We measure side effects in terms of change in the meta-modules' potential to decrease distance (PDD), see section VI. When performing a shape-change task side effects may occur at each time-step, from i to $i+1$. In terms of distance and PDD this can be expressed as difference equations:

$$\begin{aligned} D_{i+1} &= D_i - PDD_{i \rightarrow i+1}^{max} \\ \sum_{mms} PDD_{i+1} &= \sum_{mms} (PDD_i) - PDD_{i \rightarrow i+1}^{max} \\ &\quad + SideEffects_{i \rightarrow i+1} \end{aligned}$$

In each time-step the meta-module with a maximum PDD (PDD^{max}) moves to the corresponding state, this decreases the distance between the current and goal structure. However, as a side effect, the PDD of the other meta-modules (*mms*) in the system may also change. The sum of the side effects from time-step $i = 0$ to $i = n$ may be calculated as:

$$\sum_{i=0}^{i=n} SideEffects_{i \rightarrow i+1} = (D_0 - D_n) - \sum_{mms} (PDD_0 - PDD_n)$$

In general, the starting distance may be much larger than the starting sum of PDD, which means that the side effects should be positive. For the shape-change to be completed at time-step $i = n$, the sum of side effects should be:

$$\sum_{i=0}^{i=n} SideEffects_{i \rightarrow i+1} = D_0 - \sum_{mms} PDD_0$$

From these considerations we define the *side effect balance* which is positive if the movement of meta-modules generates beneficial side effects:

$$SideEffectBalance_i = \frac{D_0 - D_i}{\sum_{mms} (PDD_0 - PDD_i)} - 1 \quad (5)$$

The meta-module related characteristics of the different meta-module types is shown in table IV, V and VI. Meta-module type 6 stands out since its is highly moveable

TABLE IV
SYSTEM MOVEABILITY OF META-MODULE TYPES.

Type of Meta-Module	Mean System Moveability	95% Confidence Interval
Type 1	0.43	[0.40, 0.45]
Type 2	0.76	[0.72, 0.79]
Type 3	0.67	[0.62, 0.71]
Type 4	0.67	[0.62, 0.72]
Type 5	0.69	[0.63, 0.74]
Type 6	0.36	[0.34, 0.39]

TABLE V
META-MODULE MOVEABILITY OF META-MODULE TYPES.

Type of Meta-Module	Mean Meta-Module Moveability	95% Confidence Interval
Type 1	0.096	[0.09, 0.10]
Type 2	0.088	[0.087, 0.090]
Type 3	0.21	[0.19, 0.22]
Type 4	0.23	[0.21, 0.25]
Type 5	0.28	[0.27, 0.29]
Type 6	0.79	[0.76, 0.81]

and has a positive side effect balance; however, it is not high enough to get the effectiveness high. Because of its extra meta-actions meta-module type 5 is slightly more moveable than type 4. Overall types 3 and 5 seem to be the best choices of types investigated. From the effectiveness we see that both have the ability to shape-change a structure of modules to an acceptable extent. Both are highly moveable and most of the modules in a system are able to move as part of a meta-module at any given time.

IX. TRANSFERRING META-MODULES TO REALITY

In order to verify that the meta-modules are indeed transferable to the physical world we have performed a series of experiments with the real ATRON modules. In the experiment, shown in figure 1, a meta-module of type 5 is moving on a structure of modules. The meta-actions performed by the meta-module largely cover the range of different meta-actions types. The meta-actions are implemented in a token-based style and the sequence of meta-actions is predefined.

X. DISCUSSION & FUTURE WORK

In this paper we have investigated the characteristics of different meta-module types for the ATRON system. However, the approach taken could also be adopted to investigate the characteristics of meta-modules for other self-reconfigurable robots. Moreover, the approach could also help in the design process of new types of lattice-based modules, since it is important to know if it is possible to control the modules before they are built.

It is straightforward to have more than one meta-module type active at the same time in a system. This might be an advantage in different situations. The difference in the characteristics of the meta-module types may result in the

TABLE VI
SIDE EFFECT BALANCE OF META-MODULE TYPES.

Type of Meta-Module	Mean Side Effect Balance	95% Confidence Interval
Type 1	-0.10	[-0.24, 0.052]
Type 2	-0.28	[-0.32, -0.23]
Type 3	-0.49	[-0.55, -0.42]
Type 4	-0.66	[-0.69, -0.63]
Type 5	-0.71	[-0.74, -0.67]
Type 6	0.73	[0.33, 1.33]

emergence of implicit cooperation and coordination between meta-modules of different types. Indeed preliminary experiments along these lines indicate that this is true; the task related characteristics increase when combining meta-module types 3 and 5.

The next step in this work is to explore different control strategies on the meta-modules. For many reasons we want to use distributed control where each meta-module controls itself. This involves several subproblems such as when a meta-module should emerge, how it should move and when it should stop.

XI. CONCLUSION

In this paper we have investigated six different combinations of meta-module morphology and meta-actions for the ATRON system. The morphology varies from 1 to 3 modules and the number of meta-actions from 4 to 32. Different characteristics of the meta-module types are measured as they perform the task of shape-changing a structure of ATRON modules. On the basis of the measured characteristics a two-module meta-module (type 3) and a three-module meta-module (type 5) are found to be the best investigated way of shape-changing the ATRON system. Furthermore we have validated the type 5 meta-module on the physical ATRON platform.

REFERENCES

- [1] L. J. Guibas A. Nguyen and M. Yim. Controlled module density helps reconfiguration planning. In *Proc. 4th International Workshop on Algorithmic Foundations of Robotics*, pages 23–36, 2000.
- [2] H. Bojinov, A. Casal, and T. Hogg. Multiagent control of self-reconfigurable robots. In *Fourth International Conference on MultiAgent Systems (ICMAS)*, pages 143–150, 2000.
- [3] Z. Butler, K. Kotay, D. Rus, and K. Tomita. Cellular automata for decentralized control of self-reconfigurable robots. In *Workshop on Self-reconfigurable Robots, IEEE International Conference on Robotics and Automation (ICRA)*, 2001.
- [4] Z. Butler, K. Kotay, D. Rus, and K. Tomita. Generic decentralized control for a class of self-reconfigurable robots. In *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, 2002.
- [5] D. J. Christensen, E. H. Ostergaard, and H. H. Lund. Meta-module control for the atron self-reconfigurable robotic system. In *In Proceedings of the The 8th Conference on Intelligent Autonomous Systems (IAS-8)*, pages 685–692, Amsterdam, Holland, 2004.
- [6] A. Pamecha G. Chirikjian and I. Ebert-Uphoff. Evaluating efficiency of self-reconfiguration in a class of modular robots. *Journal of Robotic Systems*, pages 317–338, 1996.
- [7] M. W. Jorgensen, E. H. Esben H. Ostergaard, and H. H. Lund. Modular atron: Modules for a self-reconfigurable robot. In *In proceedings of IEEE/RSJ International Conference on Robots and Systems, (IROS)*, pages 2068–2073, Sendai, Japan, 2004.
- [8] K. D. Kotay and D. L. Rus. Algorithms for self-reconfiguring molecule motion planning. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2000.
- [9] J. Kubica, A. Casal, and T. Hogg. Complex behaviors from local rules in modular self-reconfigurable robots. In *Proceedings of the IEEE Int. Conference on Robotics and Automation(ICRA)*, volume 1, pages 360–367, May 2001.
- [10] C. McGray and D. Rus. Self-reconfigurable molecule robots as 3d metamorphic robots. In *Proceedings of IEEE International Conference on Intelligent Robots and Systems (IROS)*, 1998.
- [11] E. H. Ostergaard and H. H. Lund. Distributed cluster walk for the atron self-reconfigurable robot. In *In Proceedings of the The 8th Conference on Intelligent Autonomous Systems (IAS-8)*, pages 291–298, Amsterdam, Holland, 2004.
- [12] K. C. Prevas, C. Unsal, M. O. Efe, and P. K. Khosla. A hierarchical motion planning strategy for a uniform self-reconfigurable modular robotic system. In *IEEE International Conference on Robotics and Automation (ICRA)*, May 2002.
- [13] D. Rus and M. Vona. Crystalline robots: Self-reconfiguration with compressible unit modules. *Autonomous Robots*, 10(1):107–124, Jan. 2001.
- [14] K. Stoy and R. Nagpal. Self-repair through scale independent self-reconfiguration. In *In proceedings of IEEE/RSJ International Conference on Robots and Systems, (IROS)*, pages 2062–2067, Sendai, Japan, 2004.
- [15] C. Unsal and P. Khosla. A multi-layered planner for self-reconfiguration of a uniform group of i-cube modules. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, October 2001.
- [16] S. Vassilvitskii, J. Kubica, E. Rieffel, J. Suh, and M. Yim. On the general reconfiguration problem for expanding cube style modular robots. In *Proceedings of the 2002 IEEE Int. Conference on Robotics and Automation (ICRA)*, pages 801–808, 11-15 May 2002.
- [17] M. Yim, Y. Zhang, J. Lamping, and E. Mao. Distributed control for 3d metamorphosis. *Autonomous Robots*, 10(1):41–56, 2001.
- [18] E. Yoshida, S. Murata, and A. Kamimura. A motion planning method for a self-reconfigurable modular robot. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2001.