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ATRON Robots: Versatility from Self-Reconfigurable Modules

David Brandt, David Johan Christensen and Henrik Hautop Lund
Maersk Mc-Kinney Moller Institute
University of Southern Denmark
Odense, Denmark
fdavid.brandt, david, hhlg@mmmi.sdu.dk

***Abstract*— Traditional fixed morphology robots are limited to purely functional adaptation and thereby to a limited range of applications. In contrast modular self-reconfigurable robots can dynamically and autonomously change both their function and morphology to meet new demands of changing tasks. Therefore, self-reconfigurable robots have the potential to become highly versatile. This paper documents and discusses the application versatility of self-reconfigurable robots in general and of the ATRON system in particular. We present a range of different self-reconfigurable robots assembled from the ATRON base module. The robot's ability includes locomotion (snake, car, and walker), manipulation of objects (serial manipulator, conveyer belt) and autonomous change of functionality and shape (locomotion configurations, many-module shape-change). We also demonstrate the structure of simple anatomical building blocks (bones, muscles, etc.) which we envision can be assembled into more complex robots of future miniaturized modules.**

***Index Terms*— modular, robot, locomotion, manipulation, selfrecon•guration**

I. Introduction

There is no such thing as a general-purpose machine. However, the same machine may be used for a range of different applications, e.g. robotic arms used in a wide range of manipulation tasks. Also, components or subsystems of a machine may be reused in other machines - actuators, microprocessors and steel are examples of this. But what if the components of one machine could reconfigure itself to produce a completely different machine? - Self-reconfigurable robots are such machines!

Self-reconfigurable robots [9] are robots assembled from a number of interconnected robotic modules. The modules are autonomously able to self-reconfigure, that is, change the relative interconnection of modules in the robot. By self-reconfiguring the robot can thereby adapt its morphology and functionality to the requirements of the situation. Furthermore, the redundancy of modules enables the robot to tolerate module failures and can self-repair by using self-reconfiguration.

The ATRON system [16] is our platform for self-reconfigurable robots for which we have manufactured 100 robotic modules (see Section III). By interconnecting a number of ATRON modules many different types of robots can be assembled. This paper documents the high application versatility of self-reconfigurable robots by presenting a range of different robots (assembled from ATRON modules) each of which is suitable for different applications.

II. Application Versatility

Usually specialized robots can be optimized beyond the performance of multi-purpose robots. However, some types of applications require a robot specialized to be multi-purpose. Compared to traditional (fixed-configuration) robots the versatility of self-reconfigurable robots comes from simple modules, that can be assembled in a variety of configurations, and the ability to autonomously change between configurations. Different configurations may be appropriate for different applications, however, no general purpose module exists - the design of a given module is a trade-off between generality and optimization for a specific range of applications.

The ability of self-reconfigurable robots to shift between configuration, e.g. from one 6 axes manipulator to two 3 axes manipulators, makes them useful for **flexible automation** as desired by industries where products are produced in small series not suitable for permanent robot installations. We demonstrate this potential in a robot manipulator - conveyer belt setup (see Section V), where both robot manipulator and conveyer belt are assembled from ATRON modules. A surface with similar purpose (as the conveyer belt) has been assembled from PolyBot modules [23].

Furthermore, self-reconfiguration can give robots a higher degree of autonomy in **exploration** scenarios, since the robot can change between different configurations for locomotion (section VI-A). For example in a search-and-rescue [24] scenario the robot may change from a snake to a car or a walker dependent on the particular environment that it need to transverse. We present a number of locomoting ATRON robots (cars, snake, cluster walker) each with own unique capabilities (Section IV). Locomotion have been studied on various self-reconfigurable platforms [13], [18], [19], [22], [26] and self-reconfiguration between MTRAN configurations have been demonstrated [10].

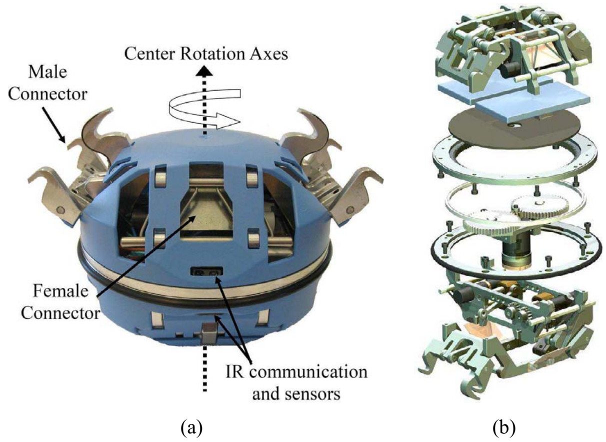


Fig. 1. The ATRON self-reconfigurable robotic module. (a) A single ATRON module, on the top hemisphere the two male connectors are extended on the bottom hemisphere they are contracted. (b) Exploded view of the ATRON mechanics.

As pointed out by Yim et al. the space/weight compactness (from versatility) and robustness (from redundancy) makes self-reconfigurable robots especially suitable for **space applications** [25]. We demonstrate robustness in a simulated scenario of self-reconfiguring a 500-module robot to support an insecure roof, we show that the robot is able to perform its task in spite of physical failure to some of its modules (Section VI). Experiments on self-repair have also been shown on the Fracta platform [20] and in simulation [8], [21].

Moreover (self-reconfigurable) modular robots may find a place in homes and interact with people, for example as **toys** in playgrounds [11] or as **educational tools** [14]. Again, modularity makes such robots particular versatile for such applications, e.g. the modules for one game on a playground may be reassembled for another game if desired.

Modules for state-of-the-art self-reconfigurable robots are in the centimeter scale, but as technology improves it may become possible to manufacture billions of modules at a micrometer scale. Such modules could play a similar role in self-reconfigurable robots as cells play in biological organisms. We expect the capabilities of such robots to open up for **novel applications** and increase the understanding of cellular biology. We explore the assembly of such miniature modules into anatomical structures (muscles, bones, etc.) that we envision are necessary building blocks when assembling robots from billions of modules (see Section VII).

III. ATRON

This section briefly describes the ATRON self-reconfigurable robot [16], developed by the Adaptronics group at the Maersk McKinney Moller Institute, University of Southern Denmark. We have manufactured 100 ATRON modules, a module weighs 0.850kg and has a diameter of 110mm (see Figure 1).

Each ATRON module has up-to eight neighbor modules, four on each of its hemispheres. Neighbor modules are connected using a male-female connector design. The connectors are mechanical, made from aluminum, with males connectors shaped like three hooks that locks onto female connector bars. Connectors are arranged such that every second connector is male and every second is female.

The modules of ATRON are interconnected and self-reconfigures in a surface centered cubic lattice structure. In this lattice, modules are oriented such that their rotation axis is parallel to the x, y or z axis and two connected modules have perpendicular rotation axes.

Every module has a single rotational degree of freedom. Basic motion primitive for a module is a 90 rotation around the equator. This will move a module connected, to the rotating module, when the rotating module is connected to a larger group of modules on the opposite hemisphere. The ATRON design is a compromise between many mechanical, electronic and control considerations, such as simplicity, scalability and constructability. An ATRON module is amongst other things able to:

- Connect and disconnect neighbor modules.
- Communicate with its neighbors (IR communication).
- Sense the relative orientation to gravity (tilt sensors).
- Sense the distance to nearby obstacles (IR sensors).
- Sense the relative rotation of its two hemispheres.
- Perform unlimited rotation around the equator.
- Lift two other modules (worst case against gravity).

Using these simple capabilities a variety of robot configurations can be assembled from ATRON modules and connected structures can self-reconfigure, locomote, manipulate objects, etc. Some experiments described in this paper are performed in a simple (non-physical) transition-based simulation of the ATRON module.

IV. LOCOMOTION

Robots able to locomote can amongst other things be used for exploration and transportation of items. The ATRON self-reconfigurable robot is capable of performing locomotion in several different ways. The two main categories, described in this section, are fixed topology locomotion (cars, walker, and snake) and locomotion by self-reconfiguration (cluster flow).

A. Cars, Walkers and Snakes

Fixed topology locomotion covers a variety of different structures and gaits such as wheeled locomotion, walkers, snakes, crawlers etc. The efficiency and the capabilities of the locomotion depend on the structure and the gait used. With self-reconfigurable robots structure and gait can be chosen such that it complies with the constraints of the environment and the task at hand. For instance, the height of the robot

(a) Cluster Walker (b) Car (c) Snake

Fig. 2. Different configurations all consisting of 7 ATRON modules. (a) configuration capable of performing cluster walk. (b) four wheeled car. (c) snake configuration. The robot is able to autonomously reconfigure between any of these configurations that have different locomotion characteristics.

when moving under obstacles, the stability when moving on slopes or the ability to climb over large obstacles. Mikkelsen performed locomotion experiments with cars, walkers and snakes constructed from ATRON modules [13]. Figure 2 illustrates three 7-module robots able to locomote.

Snakes may be more appropriate for locomotion in confined environments - moving through pipes or rubble. Walkers may perform better in rough terrain and, as Mikkelsen demonstrated, can be robust to some degree of malfunctioning modules.

ATRON modules can act as wheels due to their spherical shape and unlimited rotation. Such wheels enable us to assemble car-like structures. Cars may be the suitable choice for flat terrain since they are energy efficient and easy to control - for more demanding environments it is possible to extend the male connectors on the wheel modules to improve the cars driving capabilities. The car scale in its length since it is possible to extend the car to any even number of wheels. The strength of the ATRON system makes it is possible for a car to either drag or carry loads of a reasonable weight.

In a series of experiments we investigate some properties of ATRON cars. The drag force was measured for cars of different size, ranging from 4 to 14 wheels. Drag force increases linearly with the number of wheels, each set of wheels adds approximately $25N$. The operating time is approximately 2 hours and 20 minutes. The maximum speed of a car was measured to 0.0625m/s. Future improvements to the system could increase the speed etc. In its current implementation the ATRON system is optimized for self-reconfiguration which requires high torque at the expense of speed.

B. Cluster Flow

Cluster flow is a type of locomotion which involves self-reconfiguration. The basic principle is that modules are moved from one part of the cluster to another (typically from rear to front) thereby causing the entire cluster to move.

The advantage of cluster flow locomotion is the constant flow of modules which potentially enables the cluster to adapt to the environment and perform locomotion even on rough terrain [3]. On the other hand cluster flow is in general slower and less efficient in terms of energy consumption and speed compared to fixed topology locomotion. Rule-based distributed strategies have been used to control cluster flow locomotion for ATRON robots [2], [17]. Rule-based control is a highly distributed strategy: all modules are identical in both hardware and software, actions (connection, rotation, etc.) of a given module are triggered by its own state and the states of its neighbor modules. The state of a module is extracted from its physical state (orientation, connectors, etc).

V. Manipulation

To manipulate objects in the environment is surely one of the most useful applications of robotics today. In this section we demonstrate how the ATRON system may be used as a conveyor belt for transportation of items and as robot arms that can be equipped with different types of tools.

A. Conveyor Surface

The spherical shape of the ATRON modules, that allows them to function as wheels, enables us to construct surfaces capable of transporting items. The basic principle is shown in small scale in Figure 3. Items are moved by rotating the modules supporting the items. It is also possible to rotate an item in place by rotating modules in opposite directions. This type of manipulator is similar to discrete actuator arrays [12] and a PolyBot setup for distributed manipulation [23]. In order to save energy the infrared obstacle detectors of the ATRON can be used such that only modules currently supporting an item are rotating.

Efficient, distributed and robust control of a conveyor surface could be obtained by utilizing the hormone algorithm presented by Østergaard [15]. The goal positions of the items could then emit hormones to attract the items. In a multiple goal system different gradients could attract different items based on shape/size of the items determined locally by the transporting modules.

(a) (b)

Fig. 3. An intelligent conveyor surface constructed from ATRON modules. (a) Conveyor surface build from ATRON modules moving a box. (b) Screen shot from the ATRON simulator. The arrows show how the individual modules can move objects. This high degree of flexibility makes it possible to move objects in any direction and to rotate objects.

(a) (b)

Fig. 4. (a) Three degree of freedom robotic arm (first two joints are locked), with a gripper, reaching for a yellow ball. The gripper is held by one male connector and actuated, via strings, with the other male connector on the same hemisphere. (b) Manipulation system assembled from ATRON modules. The box rest on an conveyor surface, in the back a small robot arm is equipped with a camera, in the front a robot arm with a gripper (note: conceptual setup only).

B. Robot Arm

Serial manipulators much like the ones used in many industrial applications can be assembled from ATRON modules. An example of a 3-DOF arm is shown in Figure 4(a). Compared to industrial manipulators the ATRON manipulators are inferior for most applications. However, the versatility of the ATRON gives them unique advantages. Consider a six-wheeled car like the one described in Section IV, which could be used on a lunar exploration task and if an interesting site was discovered the car could be transformed to a small support platform and a 5-DOF manipulator for sampling, digging etc. Another possibility is to combine the conveyor surface with manipulators, as shown in Figure 4(b). Manipulators can emerge from the conveyer surface when needed. They can climb on the surface if a different position is more suitable for the task at hand, and they can emerge back into the surface when no longer needed. This leads to a highly flexible system capable of adapting to many different tasks.

One of the important notions of manipulators is the forward kinematics that is the relationship between joint angles and position of the tool relative to some fixed reference. Forward kinematics for a given manipulator is usually simple to compute, but the topology of a manipulator constructed from ATRON modules might change dynamically and the computation should be carried out in a distributed manner. Østergaard proposed a simple, distributed and robust algorithm capable of computing the forward kinematics for a modular self-reconfigurable robot [15].The algorithm is able to compute the orientations and positions of all modules in a connected cluster relative to a reference module using a hormone inspired approach.

VI. Self-Reconfiguration: Adapting Shape to Function

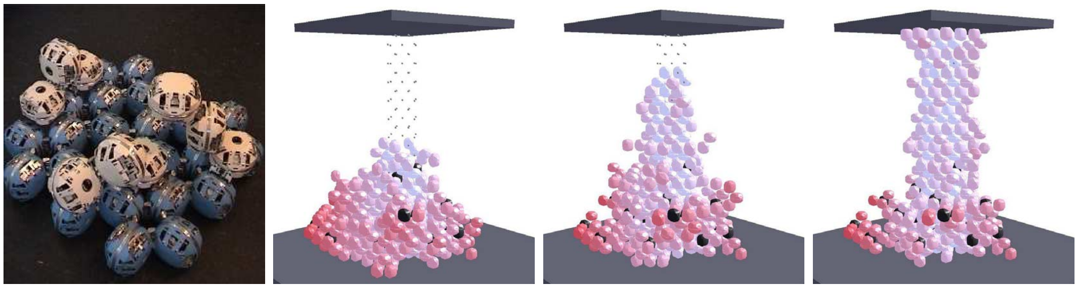
Self-reconfigurable robots are autonomously able to shift their own shape. Shape change can be utilized to solve a number of different tasks related to the interdependence between shape and function. This section first discusses the basic self-reconfiguration characteristic of ATRON robots. This is exemplified on a 7 module robot that can change between different locomotion styles. Second, we describe a scalable and fault tolerant distributed control strategy which we use to shape-change structures of many modules.

A. Self-Reconfiguration of ATRON Robots

The ATRON system is able to self-reconfigure that is it has the ability to autonomously change the configuration of modules. This ability allows ATRON robots to adapt to changes in the environment or its required functionality. Adapting the morphology to fit the task might be a fruitful approach to solving different real-world problems. For manipulation purposes we could imagine, conveyor belts and robot arms quickly changing configuration to meet the demands in constantly changing production lines. Changing between different styles of locomotion might be appropriate to achieve effective and efficient exploration of terrain with large variation.

Consider for example a small group of seven ATRON modules given a task to explore an unknown environment. A good initial configuration might be the car, described in Section IV, which is an efficient way to explore given that it is moving on a reasonably flat surface. At some point the robot may encounter an obstacle which it is unable to pass in the car configuration. Then it will be necessary to change the configuration of the robot such that it is able to pass the obstacle, this could be to change to a snake configuration for a narrow passage or to a cluster flow configuration to climb a step etc. Figure 2 shows the car, cluster walk and snake configurations.

For self-reconfiguration the basic actions of an ATRON module is connect/disconnect (takes 2.5 sec) and rotate 90 degrees (takes between 1.5 sec and 4 sec). We performed experiments to change the shape from a cluster walker to a



(a) Meta-Modules (b) 0 sec. (c) 750 sec. (d) 2800 sec.

Fig. 5. (a) Three meta-modules (white modules) move on a surface of modules. (b)-(d) Simulation of 500 ATRON modules, shape-changing, using meta-modules, to support an insecure roof. 5% of the modules are broken (black) and do not move. Meta-modules are triggered by attraction points (small points) to emerge, move and die. The flow of modules realizes the shape-change.

seven module car, which require 6 disconnections, 8 connects and 11 rotations. The time to complete this transformation, on the current hardware, is approximately 70 seconds, including some delay for communication. Changing from a cluster walker to a fully stretched snake requires 2 disconnections and 8 rotations. In essence ATRON robots are able to adapt its shape to function relatively quickly.

For few-module robots the required sequence of transformations for self-reconfiguration from one configuration to another is either defined by hand or automatically planned [1]. This transformation sequence is then compiled to a single distributed program which is transferred to the physical modules. The program is basically a large state-machine, where the states define actions such as connect or rotate. States are triggered by tokens-messages which are being transmitted neighbor to neighbor. The first token are send from a remote-controlled module to the robot - starting the sequence of self-reconfiguration.

B. Shape-Change of Many Module Robots

For larger groups of modules (> 50) the transitions that should be performed to change from one shape to another, is infeasible to define by hand. For such applications automated control strategies are necessary. Centralized control strategies have the problem that they generally do not scale well in terms of neither communication nor computation. Instead we use distributed control, where each module for itself decides what to do and when, and the shape change then emerge from the actions of the individual modules.

There are hard motion constraints on the individual ATRON modules, mainly because they only have a single degree of freedom. This makes it highly complex to compute the sequence of actions the modules must perform to move a single ATRON module from one place to another in the configuration of modules. Actually, such a sequence of actions can be very long or might not even exist. To overcome such motion-constraints, we use meta-modules consisting of three ATRON modules. Such a meta-module moves with much less motion constraints on the surface of other modules than a single ATRON module [7]. Figure 5 (a) shows a snapshot from an experiment with three meta-modules moving on a flat surface of ATRON modules. The life cycle of a meta-module consists of 3 phases:

Emergence:
: Based on local information three correctly connected modules can decide to become a meta-module and if so they are not regarded as a part of the structure but as a autonomous agent moving on the surface of the structure.

Moving:
: The meta-module moves on the surface of the structure modules, that is, the modules that are currently not part of a meta-module. Meta-modules are not allowed to climb other meta-modules as they might try to move themselves. The movement of meta-modules is based on attraction points which define the shape of the desired global configuration. The goal of the meta-module is to minimize its distance to an attraction point.

Death:
: At some point in time the meta-module might reach an attraction point or decide to stop moving. Then the meta-module dies and is no longer regarded as a moving agent but as a part of the structure such that other meta-modules can move on its surface.

This life cycle of the meta-modules can be repeated and the modules can at a later time again be part of a different meta-module. The autonomous control based on attraction points makes it possible for a large number of meta-modules to be active at any given time making the shape change reasonably fast.

To control the meta-modules in a distributed way, an artificial neural network based controller were evolved [4]. The control strategy is a generic approach to change the shape of large groups of ATRON modules. Also, the control strategy is tolerant to module failures and able to self-repair [5]. In Figure 5 (b) to (d) an example of 500 ATRON modules shape-changing to support an insecure roof is shown, the task succeeds in spite of a 5% module failure rate.

VII. Building Blocks for Complex Robots

In its current implementation, the ATRON module is roughly 11 cm in diameter and 800 modules would fit in one cubic meter. So robots consisting of tens of thousands of modules would be extremely large and heavy. If, however, the modules were miniaturized to the scale of micro-meters it would open up new possibilities and challenges. Then robots could be assembled from billions of modules. In such robot the individual modules have little direct effect on the robot's global behavior, which stress the need for coherent collective behavior.

Taking a hint from the biology of animals at the lowest level, physics and chemical processes emerge to cells which differentiate and form an organizational hierarchy of tissue types, organs, organ systems and complete functional animals. Likewise, we propose to organize modules according to a scalable anatomy - which consists of module structures (e.g. muscle, bone and joint) inspired by the anatomy of biological animals. Properties of structures resembling bone, joints and muscles in functionality were investigated using the current macro-size ATRON modules. An example of a ATRON-muscle which is shown in Figure 6. Here, a chain structure where each module (except the end modules) is connected to two other modules can contract by forming a compact helix shape. Experiments have shown that this type of ATRON-muscle can contract by a factor of 4.2 or 76%. Contraction forces are strongest ($\approx 160N$) when the ATRON-muscle is fully extended and decrease rapidly as it shortens. This force level is higher than the force a single module can exert, because the angle between the modules and the direction of contractive force works as a gearing. Clearly in its current implementation for this application, the ATRON modules are too week, too slow, etc. However, based on physical scaling laws, such properties can be expected to drastically improve when decreasing the size of the modules [6].

VIII. Summary and Conclusion

In this paper we have presented a number of self-reconfigurable robots assembled from ATRON modules. Various robots able to locomote with fixed topology, as well as locomotion by self-reconfiguration was presented. We also demonstrated robots able to manipulate objects, including serial manipulators as well as parallel manipulation using a surface of modules. For small numbers of modules the morphology can be adapted along with the functionality of the robot, e.g. from a snake to a car. For large numbers of modules a meta-module based approach is used which enables the ATRON robot to autonomously shift its shape using only distributed control. Finally, we described the possibility of assembling robots from myriads of miniaturized modules. Such robots could be assembled from ATRON module based building blocks, which has properties that resemble those of biological bones, neurons, muscles and skin.

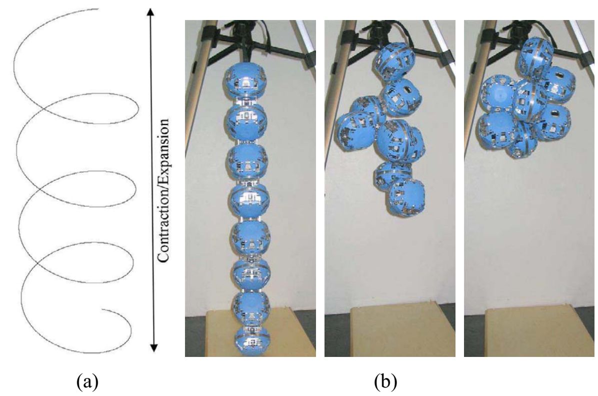


Fig. 6. ATRON-muscle made from 8 ATRON modules. The structure contracts by forming a compact helix shape. Such ATRON-muscles could be used as building blocks in complex functionality robots assembled from miniaturized ATRON modules.

In conclusion the versatility of self-reconfigurable in general can make them deployable in a wide range of applications. For the ATRON system in particular we have documented its application area, and future work will aim to optimize its performance within this area.

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