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Design of the ATRON lattice-based self-reconfigurable robot

Esben Hallundbæk Østergaard · Kristian Kassow · Richard Beck · Henrik Hautop Lund

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Abstract Self-reconfigurable robots are robots that can change their shape in order to better suit their given task in their immediate environment. Related work on around fifteen such robots is presented, compared and discussed. Based on this survey, design considerations leading to a novel design for a self-reconfigurable robot, called "ATRON", is described. The ATRON robot is a lattice-based self-reconfigurable robot with modules composed of two hemispheres joined by a single revolute joint. Mechanical design and resulting system properties are described and discussed, based on FEM analyses as well as real-world experiments. It is concluded that the ATRON design is both competent and novel. Even though the ATRON modules are minimalistic, in the sense that they have only one actuated degree of freedom, the collective of modules is capable of self-reconfiguring in three dimensions. Also, a question is raised on how to compare and evaluate designs for self-reconfigurable robots, with a focus on lattice-based systems.

Keywords Robotics · Self-reconfigurable · Morphology · Mechanics · Design

1. Introduction

Self-reconfigurable robots are robots that can change their shape in order to better suit their given task in their immediate environment. Research on self-reconfigurable robots relates well to the current trend in modern artificial intelligence, where increasing attention is given to the relationship between form and function, body and brain.

At present time, this technology is not used in any application, partly because there are other cheaper and better tested methods, partly because there still is a lot of research work to be done on building and controlling self-reconfigurable robotic systems. However, in the long term as production gets cheaper and control gets better, there is a wide range of potential future application areas, such as nano-robotics, space-robotics, disaster-area robotics, assisting the disabled, toys, automatic construction and flexible production lines. In 2004 NASA launced "SuperBot" (Shen et al., 2006), an ambitious project to develop self-reconfigurable robots for navigation and life-protection on Mars.

During the last fifteen years, around fifteen research prototype self-reconfigurable robots have been built as robotic modules that can physically connect to each other. Based on a survey of these systems, a novel design for a lattice-based self-reconfigurable robot was created, called "ATRON". This article describes considerations leading to the ATRON design, and some details of the actual ATRON hardware.

E. H. Østergaard (✉) · K. Kassow · R. Beck · H. H. Lund
The Maersk McKinney Moller Institute for Production Technology, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark

2. Related work

Much work has so far been published in self-reconfigurable robotic systems, both on constructing such systems, and on controlling them. This article focuses on the hardware and morphology aspects of the self-reconfigurable robotic systems, not on the control aspects.

Since Fukuda's ground-breaking work on the CEBOT (Fukuda et al., 1989a, b, 1990; Fukuda and Nakagawa, 1990) system, there has been a steadily increasing interest in research on self-reconfigurable robots. Published work exists on around fifteen physical prototypes, both 2D and 3D systems. All the systems use a population of either one or two kinds of modules. In the design of all the 3D systems, dealing with gravity is of course a major concern. For most of the 2D systems, gravity only plays a role in friction with the ground, but in "RIKEN Vertical" (Hosokawa et al., 1998) and in "Chobie" (Inou et al., 2003) the system self-reconfigures in the vertical plane, and thus has to deal with gravity-related issues such as bending and configuration stability.

In order to make self-reconfiguration less complicated, most of the existing 3D systems exploit a lattice structure for easier alignment of the connectors during self-reconfiguration. All previously reported lattice-based 3D systems, including the Telecube (Vassilvitskii et al., 2002), *M*-TRAN (Murata et al., 2000), 3D-Unit (Murata et al., 1998), and Molecule (Kotay et al., 1998) exploit a simple cubic lattice. Each of the existing systems has a unique mechanical module design, all with unique implications on robot motion capabilities, structural stability, speed of reconfiguration etc. An important and difficult aspect of the mechanical design of each of the systems is the design of the connector. Different approaches to the connector design have been tried. A pin/hole (Yoshida et al., 2000), permanent magnets (Hosokawa et al., 1998; Murata et al., 2000), permanent shifting magnets (Vassilvitskii et al., 2002), electro magnets and mechanical hooks (Kotay et al., 1998) are among the approaches found in related literature.

A few systems border what we consider self-reconfigurable robots. The RBR system (Sawada et al., 2004) by Hayashi et al. is a modular robotic system for operation on the international space station. It consists of three six-DOF (degrees of freedom) arms connected to a central hub, and can self-reconfigure by joining the arms. The goal of the RBR system differs somewhat from the purpose of other self-reconfigurable robotic research. Another system of relevance is the Tetrobot system by Hamilin, Lee and Sanderson (Lee and Sanderson, 2001, 2002). This system is not self-reconfigurable, but a modular robot that consists of nodes connected by linear actuators.

2.1. Morphology taxonomy

For self-reconfigurable robotic systems, there seems to be a tight coupling between the morphology of the module and the capabilities of the robot as a whole. However, there is no general method for achieving the individual modules' morphology from the requirements of the whole robot. Therefore, it is interesting to study existing module morphologies examining their benefits and disadvantages.

Several different metaphors have been used when thinking about self-reconfigurable robots. One division seems to be between *Discrete* and *Continuous* robotic systems. At Xerox PARC, research systems are divided into *Chain Types* and *Lattice Types*. Whereas M. Vona and D. Russ talk about molecules in a *Crystal*, where blob bots and swarms might be regarded as *Fluid*. In the following, we will distinguish between lattice-type systems and chain-type systems.

2.1.0.1 Lattice-type systems exploit lattice regularity when aligning connectors during self-reconfiguration. This allows for faster/easier self-reconfiguration. However, assuming that all modules conform to the lattice can be problematic for systems with very many modules.

2.1.0.2 Chain-type systems does not exploit a lattice when aligning connectors for self-reconfiguration, and thus are required to have some other method for connector alignment. Joints and connectors have to be able to support chains of several modules.

Notice that these two types do not contradict, and several systems do indeed claim to be both at the same time, such as *M*-TRAN and SuperBot.

2.2. Module motion capabilities

One important area to be further investigated is how the module design affects the motion capabilities of the system. It seems that cleverly designed modules can severely reduce the complexity involved in reconfiguring. As an example, consider the Fracta system (2D) and the *M*-TRAN system (3D). In the Fracta system, any surface module can move to any of its neighbour positions as a single actuator command. In the *M*-TRAN system, moving to an adjacent position can require anything from five actuator commands and up, and might also be impossible.

A theory that handles the relationship between module design and system capabilities would be very useful when designing these systems. Efforts in this direction have been sparse, even though a few papers have addressed these problems. In Kotay and Rus (1999) concave and convex transitions are defined and identified as an important property, and it is shown that the Dartmouth Molecules are able to perform these transitions. In Yim et al. (2001b), Yim et al. define a class of self-reconfigurable robots, called the "Proteo Class" (similar to the definition of "Metamorphic Robot" by Pamecha et al. (1997)), and discuss motion capabilities of such a system.

Building self-reconfigurable robots is a complex trade-off between many mechanical, electrical and control considerations. Still, work in this area is in an exploratory phase, where systems are built and then later understood. Each of the surveyed systems represents a point in the design space of self-reconfigurable robots. As more and more points are explored, hopefully a greater picture will emerge, and a theory for designing self-reconfigurable robots can be formed. For now, we can only make educated guesses.

2.3. Motivation and applications

In the surveyed literature, the arguments for self-reconfigurable robots have been that they have the potential to be

Robust They have self-repair capabilities arising from their inherent redundancy.
Flexible Flexibility in performing various tasks due to self-reconfiguration.
Cheap Mass production can reduce the price of the individual modules to a degree where they can compete with fixed-configuration robots.

A number of application areas has been mentioned, such as obstacle avoidance in highly unstructured environments, growing structures such as bridges, envelopment of objects, inspection in constrained environments (Pamecha et al., 1997), planetary exploration, growing satellite antennas, self-healing solar panel arrays and life-support on Mars.

2.4. Previously reported systems

Tables 1–3 compares the systems from the studied literature on a number of parameters. Table 1 presents a comparison on some geometrical properties. Table 2 summarizes some electrical characteristics, and Table 3 summarizes some of the systems' physical properties.

Each of the surveyed systems is the product of a number of compromises between mechanical, electrical and control considerations. Also, the budget and personnel competences/skills are different for the different projects. We cannot say that any system is better or worse than the others. What we can do, is that we can try to learn from the experience that the building of these systems has generated. Since the connector mechanism is such an important part of any self-reconfigurable robotic system, the different approaches will be described briefly.

2.5. Connector mechanisms

As argued in Khoshnevis et al. (2001) one of the major issues in design of a self-reconfigurable robotic system, is the design of the attachment mechanism. In the surveyed papers, attachment mechanisms using magnets, and attachment mechanisms using mechanical latches were the most dominant. In all the presented systems, except Fracta, the attachment mechanisms consume no power while attached.

2.5.1. Shape memory alloy and pin/hole mechanism

The Polybot G2 and CONRO use similar attachment mechanisms. The mechanism for Polybot G2 is shown in Fig. 1.

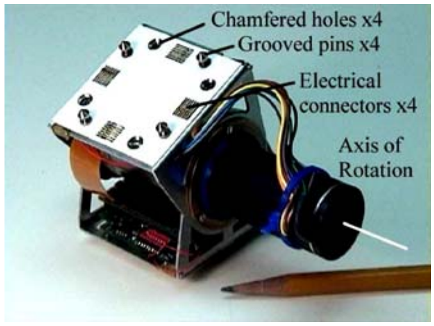


Fig. 1 Polybot G2 attachment mechanism

Citation from the Polybot web site (about Polybot G2): "*Four grooved pins enter four holes and are grabbed by a latching mechanism that is released by a shape memory alloy actuator. Each face has a 4 times redundant custom made hermaphroditic electric connector to enable power and communications to be passed from module to module*".

This mechanism has the advantage that attaching and staying attached is a passive process. Actuation is only required when modules need to detach.

The MEL Micro unit also uses Shape Memory Alloy (SMA) and a pin/hole mechanism. In the Micro unit, SMA is used in the female piece to mechanically lock the male piece by driving two pins through small holes in the male piece.

2.5.2. Electro magnets

The first two prototypes of the Robotic Molecule used electro magnets for connection. In the third prototype, electro magnets were discarded because of high power consumption, and a gripper-type connector was used instead.

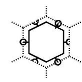
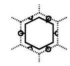
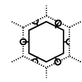
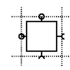
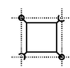
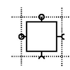
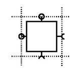
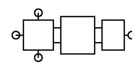
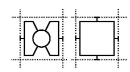
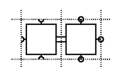
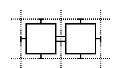
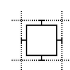
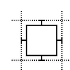
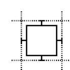
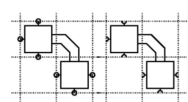
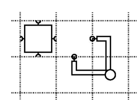
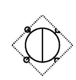
A combination of permanent magnets and electro magnets is used in the Fracta robot, as shown in the left side of Fig. 2 (Murata et al., 1994). Fracta is unique among the reviewed systems, since the electro magnets from the attachment mechanism are also used for motion, as shown in the right side of Fig. 2. A Fracta module contains no moving parts.

2.5.3. Permanent magnets

Version I and II of the *M*-TRAN modules use a combination of permanent magnets, shape memory alloy, and springs, as shown in Fig. 3 (Murata et al., 2000).

The Telecube uses a "Switching Permanent Magnet Latch" as attachment mechanism. Attachment/detachment

Table 1 Geometrical characteristics of various self-reconfigurable robotic systems. The systems are sorted firstly from 2D toward 3D and secondly rougly by their mechanical complexity. The ATRON system is included for comparison

System	Dim	Actuat. DOF	Connectors (Actuated)	Lattice	Morphology Schematic
MEL, Fracta (Murata et al., 1994)	2D	0	6 (3)	Hexagonal	
U. Ryukyus, Gear-Type Unit (Tokashiki et al., 2003)	2D	1	6(0)	Hexagonal	
JHU, Metamorphic (Chirikjian, 1994)	2D	3	6 (3)	Hexagonal	
Dartmouth, Crystalline (Rus and Vona, 2001)	2D	1	4 (2)	Square	
MEL, Micro-unit (Yoshida et al., 2000)	2D	2	4 (2)	Square	
TIT, Chobie (Inou et al., 2003)	2D (Vert.)	2	4 (2)	Square	
RIKEN, Vertical (Hosokawa et al., 1998)	2D (Vert.)	2	1 (1)	Square	
USC/ISI, Conro (Castano et al., 2000)	3D	2	4 (1)	None	
Xerox PARC, Polybot (Yim et al., 2001a)	3D	1	2 (2)	Cubic	
MEL, *M*-TRAN (Murata et al., 2002)	3D	2	6 (3)	Cubic	
USC/ISI, SuperBot (Shen et al., 2006)	3D	3	6 (6)	Cubic	
Xerox PARC, Telecube (Vassilvitskii et al., 2002)	3D	1	6(6)	Cubic	
MEL, 3D-Unit (Murata et al., 1998)	3D	6	6 (6)	Cubic	
TIT, Pneumatic (Inou et al., 2002)	3D	4	4 (4)	Cubic	
Dartmouth, Molecule (Kotay et al., 1998)	3D	4	10 (10)	Cubic	
CMU, I-Cubes (Ünsal and Khosla, 2000)	3D	3	2 (2)	Cubic	
Maersk Institute, ATRON (Jørgensen et al., 2004)	3D	1	8 (4)	Surface-Centred Cubic	

♀: Male connector; ⋎: Female connector; ⊤: Unisex or hermaphroditic connector.

Table 2 Electrical characteristics of some self-reconfigurable robotic systems. The ATRON system is included for comparison

System	CPU	Power	Communication	Sensors
Fracta	Z80	no[b]	optical	none
Crystalline	Atmel AT89C2051	yes	optical	joint position
Micro-Unit	Basic Stamp 2[c]	no	electrical	none
Chobie	none[c]	no	none	force
CONRO	Basic Stamp 2	yes[a]	optical	docking aid
PolyPod	Motorola MC68HC11	yes[a]	optical&electrical	joint position, docking aid, force
PolyBot	Motorola PowerPC 555	yes	optical&electrical	joint position, docking aid, orientation, force
M-TRAN	3×PIC, 1×TNPM	yes	electrical	joint position, orientation
TeleCube		no	optical	docking aid
3D-Unit	none[c]	no	none	joint position and angle
Molecule	none[c]	no	none	none
I-Cubes	PIC 16C63A/73B[c]	yes	electrical	joint position
ATRON	Atmel MEGA128L	yes	optical	joint position, orientation and proximity

[a]Test configurations showed that the use of external batteries was required.

[b]Power is supplied through the surface that the modules are placed on.

[c]Controlled by remote host.

Table 3 Physical Characteristics of some self-reconfigurable systems. The ATRON system is included for comparison

System	Weight (g)	Dimensions (cm)	Connector type	Unisex
Fracta	1200	ø12.5	Electro Magnets	No
Gear-Type Unit		ø6	Perm. Magnets	No
Metamorphic			Mech. Hooks	No
Crystalline	375	5 × 5 × 18 (contracted)	Mech. Lock	No
Micro-Unit	80	4 × 4 × 8	Mech. Hooks	No
Chobie	500	8 × 8 × 7.5	Mech. Grooves	No
Vertical			Perm. Mag. and Mech. Arms	No
CONRO	115	10.8 × 5.4 × 4.5	Mech. Pin/Hole, SMA	No
PolyPod			No	
Polybot	200	5 × 5 × 5	Mech. Pin/Hole, SMA	Yes
M-TRAN	400	6 × 6 × 12	(versions I&II) SMA+Perm Magnets, (version III) Mech. Hooks	No
TeleCube		6 × 6 × 6 (contracted)	Switching Perm. Magn	Yes
3D-Unit	7000	26.5 from tip to tip	Mech. Grasp	Yes
Molecule			Mech. Hooks	No
I-Cubes	200	6 × 6 × 6	Mech. Lock	No
ATRON	850	ø11	Mech. Hooks	No

is done by "routing the flux lines of permanent magnets so that the device either extends the magnetic flux or hides the magnetic flux internally[1]."

[1] From http://www.parc.xerox.com/spl/projects/modrobots/lattice/telecube/index.html

2.5.4. *Mechanical locking*

The current trend in self-reconfigurable robotic systems seems to be to use mechanical locking for connections. Older systems, such as the I-CUBES shown in Fig. 4 (Unsal et al., 1999), use a connector where a male part

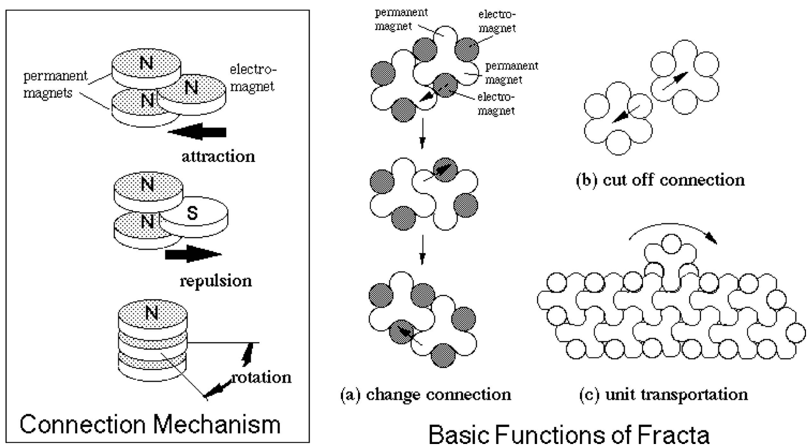


Fig. 2 Left: Fractas attachment mechanism. Right: Motion of Fracta modules

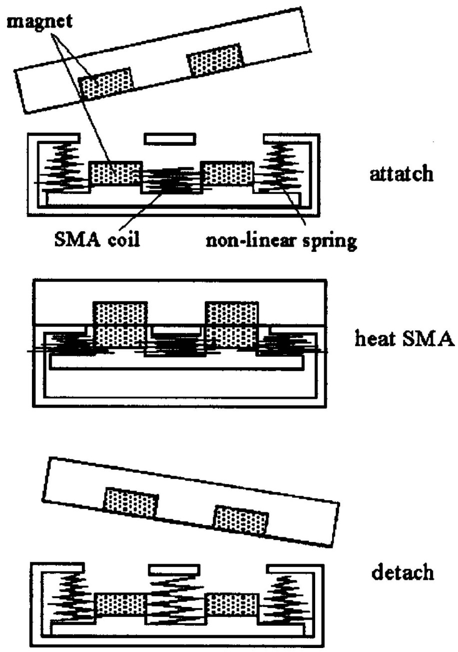


Fig. 3 *M*-TRAN I and II attachment mechanism, a combination of permanent magnets, non-linear springs and a shape-memory-alloy coil

is inserted into a hole and rotated, and the pin locks the male part in place. The pin is actuated and can be pulled in to enable release of the male part. Due to the motion capabilities caused by the mechanical design, the Dartmouth Molecule design does not allow big connection surfaces, like the I-CUBES. In stead, the Molecule has point contact between modules, and a mechanical attachment mechanism for dealing with this constraint is described in Kotay and Rus (2000).

Currently, connecting hook mechanisms, such as the one used in the ATRON system, seem to gain popularity. The newest generation of the *M*-TRAN system also uses a similar kind of hooks, and the SuperBot project even promises a unisex connector of this kind, even

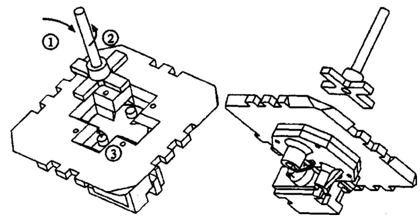


Fig. 4 The I-Cubes attachment mechanism

though there have been no publications on this connector yet.

2.6. Summary and discussion on related work

The fifteen or so systems that have been documented so far, have different mechanical and electrical characteristics and each is interesting to study to find a relation between module design and system motion capabilities.

An important issue in the field of self-reconfigurable robots is *scalability*. However, for surveyed systems it is not particularly clear how the system will scale as the number of modules increases. How can the “weak” actuators of each module be used to create a ‘strong” global force? In the case of Crystalline and Telecube it is pretty straightforward, but in the case of *I*-Cubes and many of the other lattice-based systems, it is hard to see how this would be possible. Also mechanical stability is a problem. For example, even for short chains, a horizontal chain of Telecubes will bend quite a lot due to gravity, so that the end module will not be within lattice tolerances.

Another important issue is the use of sensory information, although only very little work has so far been published on the use of sensors during self-reconfiguration. The reason for this is probably that most of the systems still have more basic problems to deal with than the awareness of the surrounding environment. In Støy et al. (2002) sensors are used for controlling the walking gait of the CONRO robot, but in this work the robot does not self-reconfigure. In Inou et al.

(2003) a force sensor is used to trigger a pre-programmed sequence of actions that stabilizes the structure by self-reconfiguration.

From the surveyed papers we gathered that:

- Based on the number of reports on succesful self-reconfiguration for lattice- versus non-lattice-based systems, self-reconfiguration for non-lattice-based systems seems to be much harder.
- Systems which only have actuation parallel to the direction of connection can never rotate any modules, and thus cannot ever change their orientation.
- There seems to be a conflict between simplicity of module design and simplicity of system motion capabilities.
- Reports on using sensors for controlling self-reconfigu ration are still sparse.

Studying the mechanics of the existing 3D systems revealed that

- Mechanical simplicity is essential when designing, constructing and maintaining a self-reconfigurable system.
- The connectors are often a weak point of the respective designs. Many of the surveyed systems have problems with the stiffness of the structure when many modules are connected in a chain.
- Stiff actuators with good torque are attractive, as we need to hold and lift modules against gravity while keeping positions within some tolerance in the lattice structure.

3. Basic ATRON module design

We desire stiff and strong joints as well as stiff and stable connectors. By seperating the mechanics of the connectors from that of the joints, more space is available around each of the mechanisms for stabilizing structure.

3.1. Basic actuator design

The basic design that we pursue is an approximately spherical module, where actuation is realized as rotation around an axis diagonally through the sphere, with the sphere divided into two equally sized parts, as illustrated in Fig. 5. This design allows for a very stable construction around the actuated joint since a relatively large area (compared to the size of the module) is available for mechanics.

3.2. Basic connector design

Designing the connectors is a compromise; in order to have fast and strong connectors with possibilities for power-sharing and inter-module communication, it would seem to be an advantage to have a large surface of contact between two connected modules. A large contact surface is better at dealing with the torque through the connector, as well as providing area for wired communication and power transfer. But on the other hand, connectors with large contact surfaces impose some requirements on the actuation of the system in order to dock and un-dock without colliding.

The spherical basic module design makes it hard to have big flat surfaces connecting to each other. With spherical modules, connectors need to establish what is essentially point-to-point contacts between modules, which is not desirable due to the reasons mentioned above. However, the alternative being more complex modules with more actuators, or modules with limited motion capabilities, we chose to try to deal with the problem of point-like connectors.

3.3. Basic system design

The basic design shown in Fig. 5 allows us to explore a space of actual designs by specifying the distribution of connection points on the surface of the sphere, and by specifying the position of the rotation joint in the sphere. Relying on a lattice for actuation and connection can make self-reconfiguration much easier, and many of the existing systems exploit some lattice structure for this reason.

In solid-state physics, a number of lattices consisting of regular spheres has been explored and documented. For our purpose, the bonds between the lattice nodes correspond to the connections between modules, and the relative positions of the bonds correspond to the relative placement of connectors on the module. The combination of one of these lattice types and the geometrical placement of the actuator in the module, spans a space of possible module designs. As opposed to the Proteo-class of self-reconfigurable robots described in Yim et al. (2001b), we can call this kind of design for an "ATRON-class" design. ATRON-class modules are essentially spheres with connectors on the surface and a rotation plane cut through the sphere. As opposed to Proteo-class modules, ATRON-class modules cannot move by themselves, but need the help from neighbouring modules to move. This drawback imposes further requirements on cooperation between modules. However, ATRON-class modules can have much simpler mechanical designs, making it more feasible to build a working system. Comparing Proteo-class and ATRON-class system designs, it seems that Proteo-class is focused on making the control easy at the expense of the mechanics, whereas the ATRON-class approach is the other way around. Focus is on (relative) mechanical simplicity, and the challenge is to have easy control at the same time.

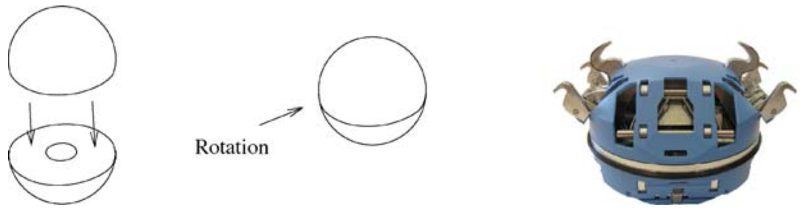
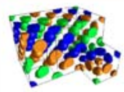
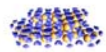
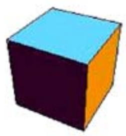
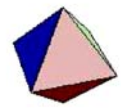


Fig. 5 Left: The Basic Design Idea. Two half spheres joint together by an infinite revolute joint. This design is, in a sense, minimal in that each module has only one joint. Right: The final design, with connectors in top hemisphere extended

Fig. 6 Various lattice structures considered during the design phase for the ATRON system. The number of contact points is the (maximum) number of connectors on the corresponding self-reconfigurable robot module. The two-colouring property (bottom row) is important if connectors are gendered. If the structure is such that we can solve the two-colouring problem for the corresponding graph, we can avoid same-gender connections by making two populations of modules, one with all male and one with all female connectors

Lattice Type	Simple Cubic	Body-Centred Cubic	Face-Centred Cubic / Cubic Close Pack	Hexagonal Close Pack	"Rhenium Oxide"
Unit Cell					
Lattice Structure					
Unit Polyhedron (Voronoi region)					
Pacing efficiency	52.35%	69.02%	74.05%	74.05%	55.54%
Contact Points	6	8	12	12	8
Two-Colouring Property	Yes	Yes	No	No	No

3.4. Lattice structures

Figure 6 summarizes some of the structures that we have been considering. Well-known and well-studied lattices include Simple Cubic, Body-Centred Cubic, Face-Centred Cubic, Hexagonal Close-pack and Cubic Close-pack lattices. Each of these lattices can be characterized by the distribution of contact points on the surface of the sphere. These contact points correspond to the placements of the connector mechanisms we consider in the self-reconfiguring robotic model.

The simple cubic lattice structure has been exploited in a number of lattice-based self-reconfigurable robots, such as the *M*-TRAN, the Dartmouth Molecule, the MEL 3D-Unit and the Telecube. The simple cubic lattice satisfies the two-colouring property, which makes it possible to have two separate populations of modules, one with all female connectors and one with all male connectors. This property is exploited in the *M*-TRAN, the Dartmouth Molecule and the I-Cubes. One advantage of this approach is that when using gendered connectors, basic motion in the system never aligns two connectors of the same gender for connection. One drawback of this approach is that in the cases of Dartmouth Molecule and the I-Cubes, the approach effectively produces two populations of modules, one with all male and one with all female connectors. Control complexities arise from the interdependencies of these two populations, due to the required presence of members from both populations in every part of robot.

3.5. Placing an ATRON in the lattice structure

By experimenting with the various lattice structures using mock-up models made from wood and styrofoam, shown in Fig. 7, we decided to focus on a structure related to the face-centred cubic lattice structure, labeled "Rhenium Oxide" in Fig. 6. In face-centred cubic lattices, units are placed in a regular cubic lattice structure, as well as on the faces of the square surfaces in the lattice, as shown in Fig. 9. The lattice we chose for the ATRON modules corresponds to the Oxygen atoms of the **ReO_3** crystal lattice, shown in Fig. 9. If we compare to a cubic lattice, the ATRONs are placed on the centre of the surfaces of each cube. Figure 10 illustrates how the ATRONs pack in two and three dimensions. We place the ATRONs so that the revolution joint lies on the surface of the

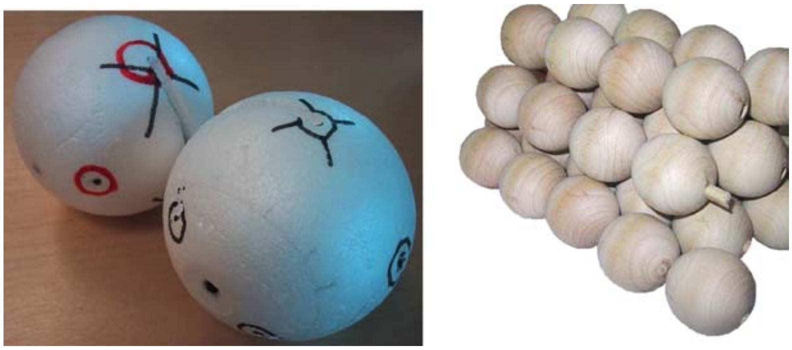


Fig. 7 Mock-up models used for experimenting with the basic module design

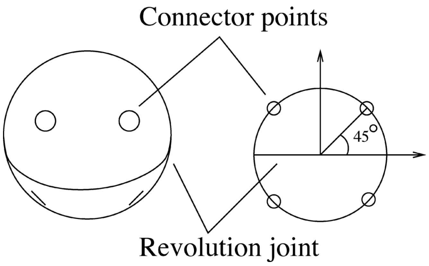


Fig. 8 Placement of the connector points relative to the revolution joint for the ATRON system. The revolution joint is placed at equator, with the rotation axis going through the poles. The connectors are placed at 45° latitude and with even longitudinal distribution of 90°

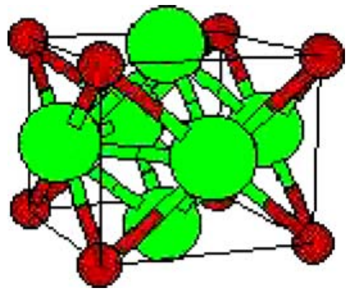


Fig. 9 A Rhenium Oxide ReO_3 crystal unit cell. The Oxygen atoms (large) in ReO_3 are arranged in a face-centred cubic lattice structure. The structure of the ATRON modules resembles the structure of the Oxygen atoms in a ReO_3 crystal. Connections between ATRON modules resemble the bonds between the ReO_3 Oxygen atoms

cube in the cubic lattice, with a rotation axis perpendicular to the surface.

The lattice structure shown in Fig. 10 requires attachment points at eight locations on the ATRON surface. Each half-sphere should have four attachment points at 45° latitude, and with longitudinal distribution of 90°, as shown in Fig. 8.

3.6. Properties and consequences to motion capabilities from the ATRON basic design

The chosen design has implications on the properties of an ATRON robot. As long as modules' positions conform with the lattice, we can place a Cartesian coordinate system such that for each ATRON the rotation axis is parallel to either the x-, y- or z-axis. This gives us three "flavours" of ATRONs based on the orientation of their rotation axis, described below as x, y and z. A module with the rotation axis parallel to the x-axis is called an x-ATRON.

– Each flavour forms a regular cubic lattice structure.
– A y-ATRON connected to an x-ATRON will be converted into a z-ATRON by a 90° rotation around the rotation axis of the x-ATRON.
– Two ATRONs of the same flavour cannot be connected to each other.
– Each x-ATRON can be connected to up to four y- and four z- ATRONs (two of each on each half).
– No sequence of transitions can switch positions of the two halves of one ATRON.
– When two ATRON halves are connected through two specific connectors, there is only one possible relative orientation and position between the two.

These properties hold for all permutations of x, y and z, as long as all modules are in the lattice.

3.6.1. Gender parity

Each ATRON-half has two male and two female connectors, placed so that opposite connectors have the same gender. It is possible to place all ATRONs in the lattice so that no connector-gender clashes occur. One such placement is to make all x-ATRONs have their male connectors in the y-direction, all y-ATRONs have their male connectors in the z-direction and all z-ATRONs have their male connectors in the x-direction. This means that x-ATRONs have female connectors in the z-direction. Due to symmetry and the fact that z-ATRONs have male connectors in the z-direction, and are connected to x-ATRONs in the z-direction, z-ATRON male connectors are connected to x-ATRON female connectors.

We can define *gender parity* for one half-ATRON as zero if the half is placed as described above, and one if it is not. If all ATRON-halves have gender parity of zero, then no gender clashes occur. As soon as one ATRON-half makes a

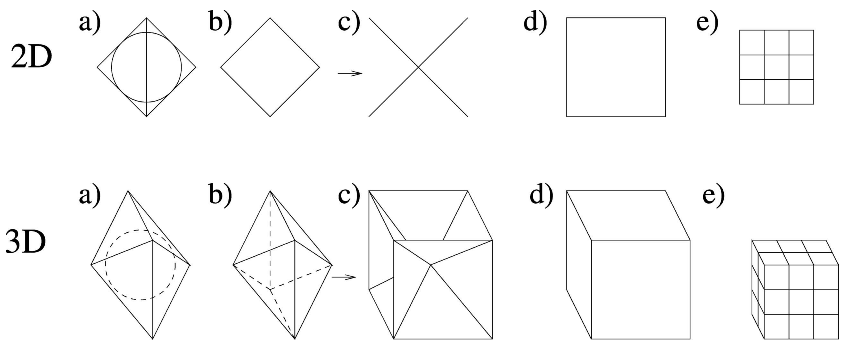


Fig. 10 Bottom: Arrangement of the ATRON modules in three-dimensional space. Top: The two-dimensional equivalent, just for clarification. (a) Consider the ATRON with an octahedron wrapped around it. Let the octahedron be built from two pyramids with half the height of their base length. These two pyramids correspond to the two half cells of the ATRON module. Let the ATRON touch the octahedron surface in eight points, corresponding to the eight surfaces of the octahedron. (b) and (c) show how these octahedrals can be packed to form a cubic structure (shown in (d) and (e)). The rotation plane of each ATRON is given by the cube surface it intersects

Fig. 11 The very first prototype constructed from LEGO

90° rotation, the gender parity of that half is flipped. Gender parity for any modules connected to that module is also flipped. So any self-reconfiguration sequence that preserves gender parity must have an even number of moves for each hemisphere. Thus, whenever an ATRON-half makes a move, one more move is required to restore gender parity of the system.

3.6.2. Self-reconfiguration

The most important question is whether self-reconfiguration is possible with the chosen design. By experimenting with various LEGO and styrofoam mock-up prototypes, it was found that self-reconfiguration is indeed possible with the chosen design. The experiments were simply to perform sequences of moves on the mock-up model that would go from a number of starting-configurations to a number of goal-configurations. These experiments revealed that the rotation joint is required to have enough torque, and the connectors enough stiffness, to rotate a horizontal chain of two connected modules against gravity.

3.7. Sensor and communication capabilities

The intended control method for the ATRON system is based on mimicking mechanisms found in multi-cellular biological systems. Since most of the processes that control living cells are situated processes, meaning that they act and react in their local environment, the ATRON system is required to be able to react locally. For this reason, the idea of having a global bus for communication was rejected. A message received from a global bus channel does not directly give any information about who sent it. If we design the system so that modules only communicate with their neighbours, a module can be sure that whenever it receives a message, that message is from one of its neighbours. Furthermore, if we make independent communication hardware for each of the module's connectors, we can directly know from which neighbour a message came. And since the ATRON lattice is such that there is only one possible relative orientation and position between two connected ATRON halves, we can know the position and orientation of the sending part.

For these reasons, each ATRON is equipped with neighbour-to-neighbour communication in each of the eight connector sites. This makes it possible to figure out the global configuration using only communication among the modules, and makes it possible to experiment with various abstractions of developmental biology models. After considering magnetic (tape recorder magnets) and direct electrical connection for implementing the neighbour-to-neighbour communication, the choice fell on infra-red communication, since it is well-known technology, and since the same physical components can be used to implement proximity sensors. The proximity sensors of the ATRON modules have a range of a few centimeters, and can be used to detect external features such as floors, walls and obstacles, as well as internal features, such as other nearby modules. Additionally, each module has an accelerometer for measuring direction of gravity and providing the ability to detect movement that is not self-initiated, such as being picked up or tipping over.

3.8. Basic ATRON design summary

Based on the above described considerations, the basic design of the ATRON system became a lattice-based self-reconfigurable modular robot, where each approximately spherical module is constructed as two approximate hemispheres joined by an infinite revolute joint. Each hemisphere has two female connectors and two active male connectors, placed at 45° latitude and with even longitudinal distribution of 90°. On a hemisphere, opposing connectors have same gender, so that when moving around the hemisphere every second connector is male, and every second is female. Each connector has an IR-proximity sensor and IR neighbour-to-neighbour communication, and the module has a tilt-sensor.

The ATRON module design is the result of a desire to develop the simplest possible module. By making a very simple module, we hope that we in future versions can reduce the sizes (and price) significantly, so that we can investigate issues such as intelligent dust and nano robotics.

The following sections will present more details on the actual implementation.

4. Realization of the ATRON modules

This section will in details describe several aspects of the mechanical design, resulting in the design shown in Fig. 12. The ATRON module, shown in Fig. 14, is built mainly from strong aluminum and steel bars for the passive connectors.

4.1. Rotational joint mechanical design

The rotating joint is subjected to forces and torques in all directions. Two basic designs for the rotating joint were considered. The two designs (A and B illustrated in Fig. 13) both use ball bearings to reduce friction, stiction, and wear. In both designs, *D* should be maximized to minimize load on bearings and angular play. Design A can use cheaper standard bearings, and can be built so no play is possible between the two hemispheres, if the two bearings are pretensioned relative to each other. However, design A concentrates stress in and around the centre axle. Design B, though more expensive because of the more exotic thin section ball bearing used, frees up valuable space in the centre of the module, and allows us to construct a planetary gear using the space inside the bearing. For these reasons design B was chosen, implemented using a thin section, four point of contact, ball bearing.

4.2. Communication and power-sharing between hemispheres

Self-reconfiguration is realized by a module connecting to its neighbour, rotating a multiple of 90°, letting the neighbour module connect to a third module, and releasing the initial connection. Often, several such sequences are required to reach a desired target configuration, hence reconfiguration involves a lot of rotations. In order to avoid problems with wires through the centre getting twisted, a slip-ring was designed that allows for infinite revolution of the two hemispheres. Since it is desirable to limit the number of wires passing through the slip-ring for economical and practical reasons, it was decided to put a microprocessor in each hemisphere, permitting us to have only power and serial communication wires through the slip ring. The slip ring design is shown in Fig. 15, with five concentric tracks that carry 10 volts, regulated 5 volts, ground, and two RS485 signals.

This design of the centre allows for an infinite number of revolutions around equator while still transferring power and data between the two hemispheres. In addition, the slip ring is being used as reflective material for optical encoders giving information on the absolute rotation of the two hemispheres as well as the current rotation speed and direction. This permits the control program to detect rotational motion between the two hemishperes that is not self-initated, thus offering a possibility to correct for external disturbances.

Fig. 12 The ATRON module, 11 cm in diameter. Left: CAD model of the ATRON module with plastic cover. Right: Photo of a fully functional ATRON module

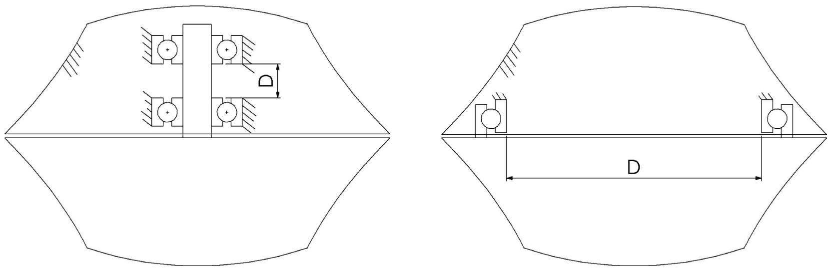


Fig. 13 Two designs considered for the rotating joint

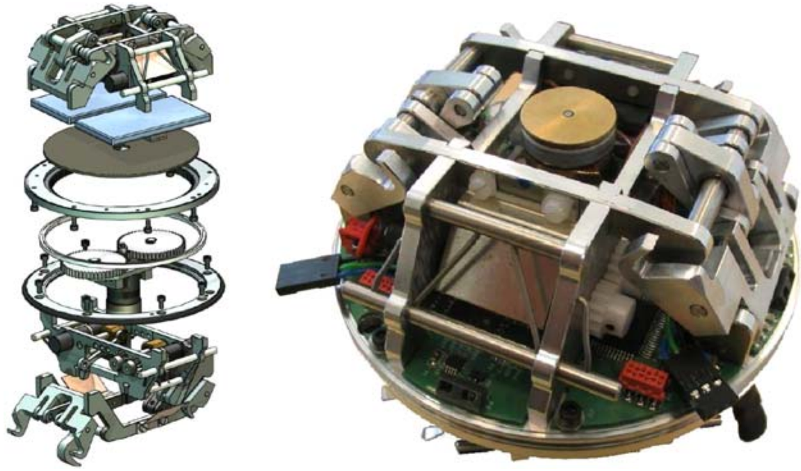


Fig. 14 The ATRON module mechanics. Left: Exploded view of the CAD model. Right: Photo of the final design, including electronics, excluding the plastic cover

4.3. Defining the shape

Although the initial design was two hemispheres as illustrated in Fig. 5, geometrical considerations based on Voronoi regions, hinted at in Fig. 10, lead to module shapes that are two four-sided pyramids, with a number of carvings to allow rotation within an organism. Figure 16 illustrates how these carvings allow a module to be moved in an otherwise fully packed lattice.

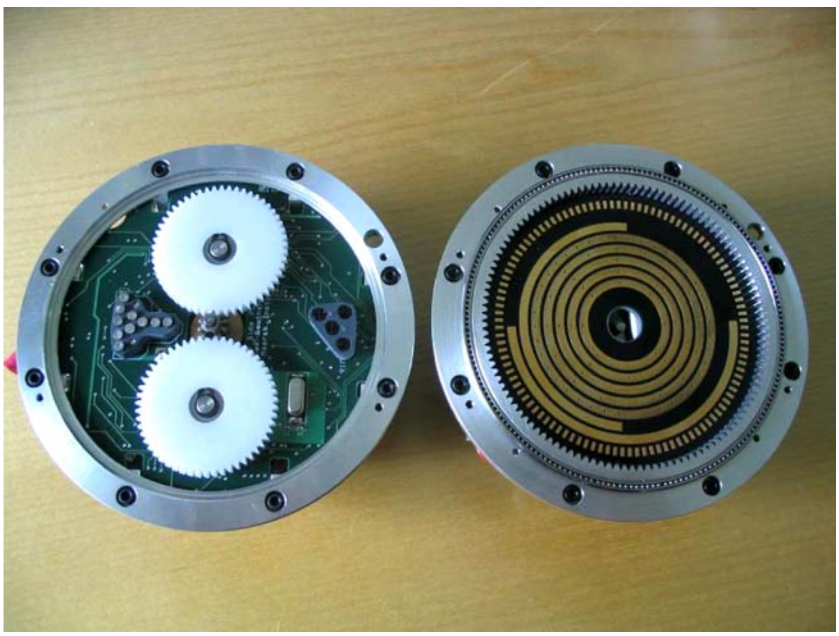


Fig. 15 Picture showing the centre slip-ring design, and also the final stage of the planetary gear. Carbon shoes (northern hemisphere, left) are dragging along concentric tracks on the gold-plated slip ring (southern hemishpere, right) allowing for transfer of power and data between the hemispheres. The three outmost tracks provide gray-coded position information that is supplemented by a finer-grained encoder on the motor. When assembled, the two hemispheres are held together by the ball bearing, visible on the southern hemisphere picture. The bearing is press-fitted on the southern hemisphere and bonded to the north

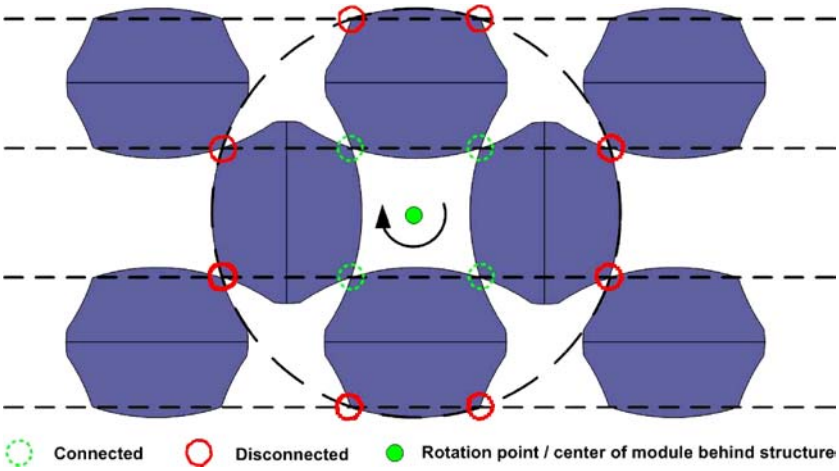


Fig. 16 In order to prevent collisions during basic motions, certain limitations are imposed on the module shape. Imagine a fully packed (infinite) lattice of ATRONs. This illustration shows eight modules sitting in a plane in such a lattice. The four modules surrounded by a dashed circle are connected to each other, and connected to a fifth module in the plane behind the illustrated plane. The rotation axle of the fifth module is shown as a dot in the centre of the illustration. Had all modules been spherical, the four central modules would collide with four remaining modules, when rotated around the rotation axle. Based on this observation, a shape was found that permits motion in a fully packed structure

4.4. Connector mechanical design

Having settled on the shape defined by the above-mentioned carvings, connection between neighbours has to be *point-to-point* connections in contrast to e.g. the *M*-TRAN, CONRO, and I-cubes (Ünsal and Khosla, 2000) who have *surface-to-surface* connections. A surface-to-surface connection method has the advantage of distributing the stress from holding neighbouring modules on a large area.

The connector is subjected to forces and torques in all directions. Therefore, two modules should be connected in three points or more. In order to minimize load and strain resulting from torques, the distance between the connection points should be maximized. It was decided to go for an approach using rotating arms, because linear guidance systems generally are more expensive, less accurate and take up more space than revolute joints. The length of the arms is determined from the distance between the arm-rotation axis and the female connector. Therefore, the connection points were also placed in order to minimize this distance. Figure 17 shows the position of the connection points, using this strategy. Figure 18 illustrates how three hooks emerge from the surface of the active connector and grab the passive connector.

The passive connector is built from two bars of stainless steel rigidly integrated in the hemisphere. The three hooks are driven by a DC motor via a lead screw. The mechanism driving the arms is not backdrivable in the extented arm position, hence no power is required to maintain connection. In order to simplify the mechanical design, the arms rotate on parallel axes. This allows us to combine the two lower arms in one arm, and to use a fairly simple mechanism for synchronizing movement of lower and upper arm.

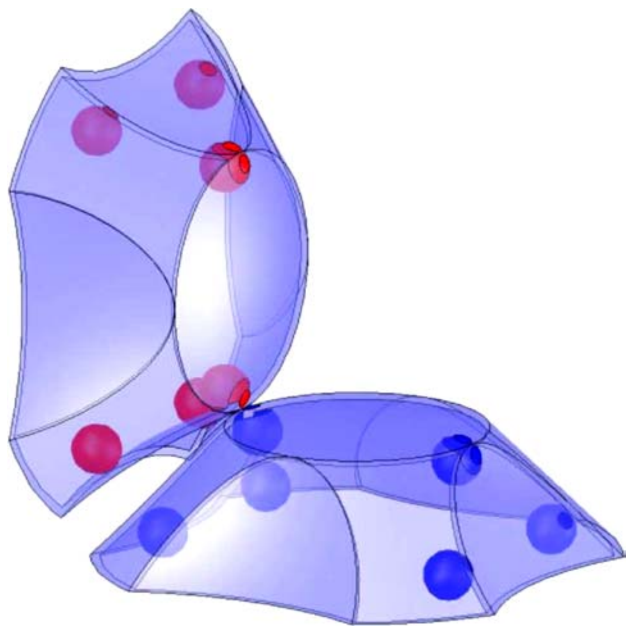


Fig. 17 Connection points for a male and female connector. The hooks pivot around joints on the frame of the male part and attach to matching positions on the female part

4.5. Mechanical design of the frame

The frame is designed with the intent of allowing very tight tolerances on relative position of bearing seat, axles for connector arms and female connector axles, while keeping production costs reasonable. On the first two prototypes of the

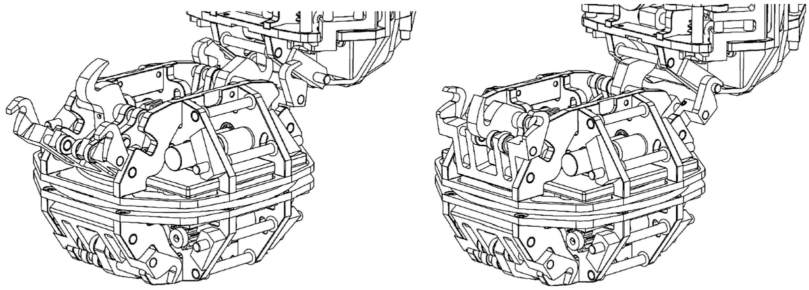


Fig. 18 CAD drawings of two ATRON modules connecting. By connecting using three points, a strong and stiff connection is obtained. Left: Connection initiated. Right: Connection completed

module the entire frame was produced on a 2D CNC milling machine, since this was much cheaper than moulding the parts. Because of time-constraints it was decided not to develop a frame design suitable for moulding, the frames for the 100 modules that have been built are, therefore, also entirely CNC machined. A frame designed for moulding could reduce the weight of the modules and lower production costs. The frame is seen on Figs. 14 and 19.

5. Experiments

One of the main concerns of not having flat connection surfaces in the ATRON system was the mechanical strength and stiffness of the connectors. In a situation such as the one shown in Fig. 20, sloppy connectors would lead to significant deformation.

5.1. FEM analysis

In order to identify the modulus of elasticity and the yield strength of the ATRON material, a FEM analysis on a single ATRON module was performed. It should be noted that the ATRON material is anisotropic, however, this analysis only investigates the properties in one direction. If the connectors (and the module as a whole) had been symmetric around the 45° planes through the module, then the material would be orthotropic. Figure 19 shows a module subjected to the load, which, according to the FEM analysis, is the maximum load before some areas of the module are stressed beyond yield strength for aluminum 7075 (frame and connector) and stainless steel (axles). According to the FEM analysis on one module, the maximum tensile force between two opposing connectors, without experiencing stress beyond yield strength anywhere in the module, is 800 *N*. At this point the elongation of the module is 0,23 mm. From this, the modulus of elasticity can be calculated as:

$$E = \frac{\sigma_{\text{proportional}}}{\epsilon} \approx \frac{F_{\text{yield}}/A}{(l_2 - l_1)/l_1} = \frac{800\ N * 110\,\text{mm}}{(110\,\text{mm})^2 * 0.23\,\text{mm}}$$

$$= 32\frac{N}{\text{mm}^2}$$

assuming $\sigma_{\text{yield}} \approx \sigma_{\text{proportional}}$

The yield stress of the module is calculated as:

$$\sigma_{\text{yield}} = \frac{800\ N}{(110\,\text{mm})^2} = 0.067\,\text{MPa}$$

Figure 19 shows a module subjected to a horizontal load of 120 N, a greater load will result in plastic deformation of the module, resulting in shear stress in the module. From this the shear modulus of elasticity can be calculated:

$$G = \tau_{\text{average}}/\gamma \approx \frac{F/A}{d/h} = \frac{120\ N/(110\,\text{mm})^2}{0.68\,\text{mm}/110\,\text{mm}} \simeq 1.6\frac{N}{\text{mm}^2}$$

where d is the horizontal deflection, h is the height of the deflected area, and γ is the angle of the deflection.

5.2. Real world validation

In order to validate the FEM analysis, a simple test was made comparing the deformation of real ATRON modules to deformation in the FEM model. The test set-up and results are given in Fig. 20.

The test showed a vertical displacement of the fifth module of 3 mm, while the FEM analysis gave an expected deflection of 1.4 mm. However, the FEM analysis does not take into account the play in the bearing. According to the manufacturer of the bearing the angular play in the bearing is 0.0009 radians. Tilt will occur in the bearings of all three modules with horizontal rotation, but only the tilt in the two inner modules will affect the measurements. By simple geometric calculations, this tilt will cause a deflection of the outmost module of about 0.4 mm. Therefore, a total deflection of about 1.4 mm + 0.4 mm = 1.8 mm should be expected. When the real test shows 3 mm deflection, it is probably due to play between axles and frame. The test shows that the FEM analysis is quite accurate despite the mentioned simplifications.

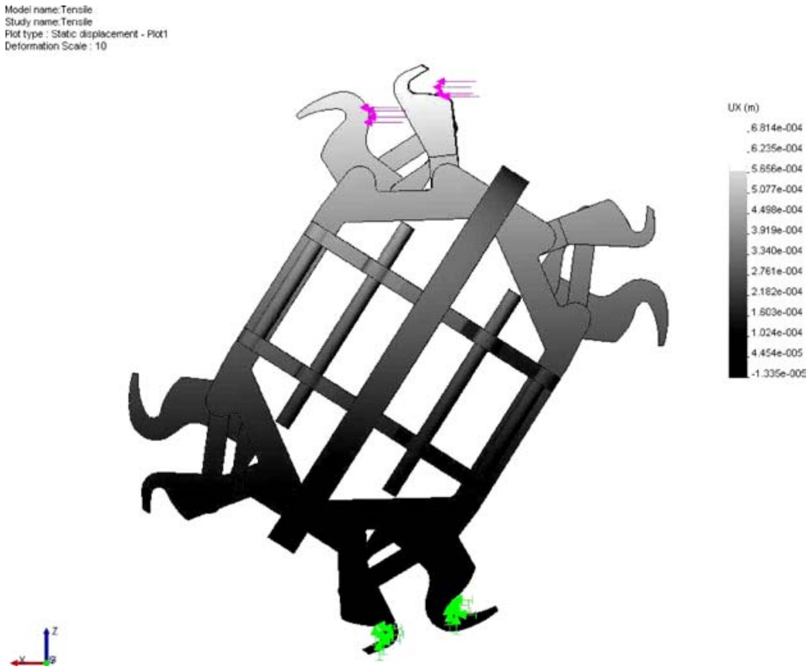


Fig. 19 FEM analysis of a module. A load of 120 *N* are horizontally applied at the top connector (arrows), while the module is being fixated at the bottom connector (other arrows). The plot shows that the 120 N gives a static displacement of up to 0.68 mm

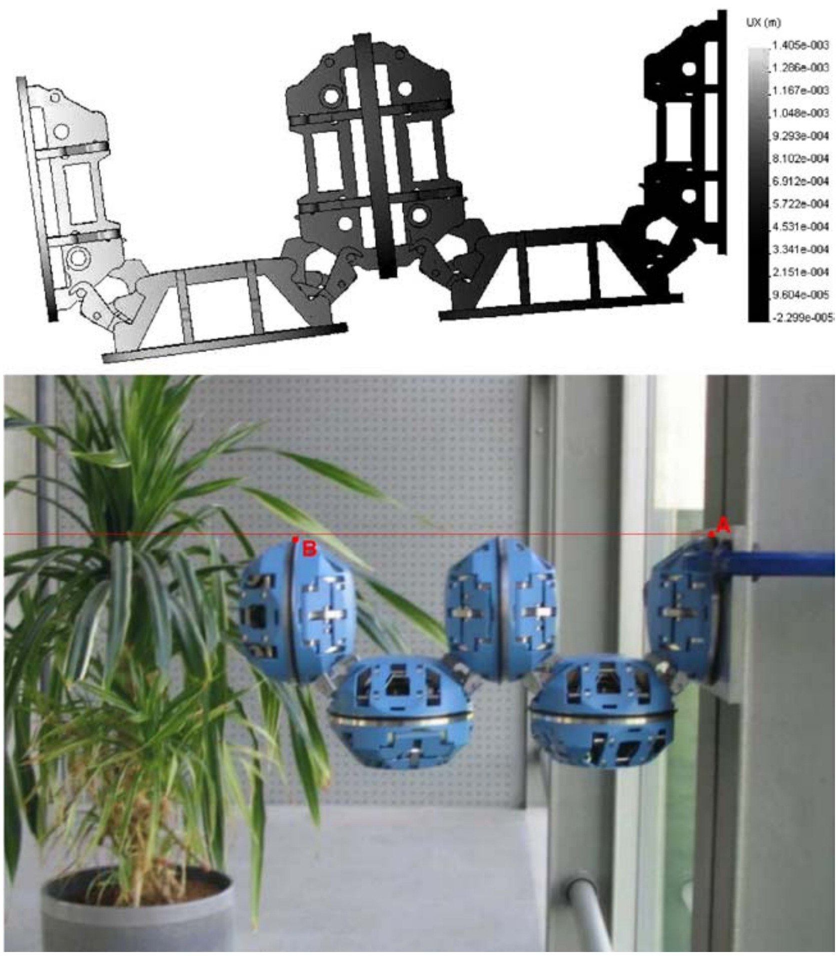


Fig. 20 Mechanical deformation test for five ATRON modules connected in a horizontal chain using four connectors. Top: FEM analysis displacement plot. Displacement is exaggerated for visualization. The colour shows the displacement of each element caused by gravitational pull. Deformation of the outmost module is about 1.4 mm. Bottom: Real-world deformation test. The horizontal line was put onto the picture after it was taken. Measurements show a displacement of the outmost module of about 3 mm

5.3. Discovered material properties

The mass density ρ of the ATRON material is calculated as:

$$\rho = M/V = \frac{0.85\,\text{kg} * 3}{(0.11\,\text{m} * \sqrt{2})^3} \simeq 720\,\text{kg/m}^3$$

Figure 21 shows the most common properties for some materials, and the properties of the ATRON material.

In many applications the important parameter is the ratio of yield stress to mass density, and iron is approximately 312 times better than the ATRON material in this respect. The material that the ATRONs are mostly made of, Aluminium 7075, is even 1000 times better. This is because most of the material in the ATRON module does not increase its strength, but is used as structural support for different parts that have to do with the ability to self-reconfigure. Also, the weight of these parts only increases the strength in a few cases. However, the ATRON module is one of the first self-reconfigurable materials and there are great possibilities for improvements.

5.4. Reconfiguration experiments

As this article focuses on the design of the ATRON modules, the specific control approaches used to control them will not be covered here. A number of papers has been published on controlling an ATRON robot. In Østergaard and Lund (2003) artificial co-evolution was explored for generating cluster-walk behaviour for cluster of modules. In Østergaard and Lund (2004) and Brandt and Østergaard (2004) a rule-based approach is described to create controllers invariant to the cluster sizes. In Christensen et al. (2004) a meta-module control approach is described. Figure 22 shows a few of the experiments we have performed on the real modules.

In general, the realization of the basic module design lives up to expectations. The mechanical stiffness of the system permits relatively large structures, and the ability for a module to move through an otherwise fully packed structure is a very useful feature. This gives better motion capabilities in tight spaces.

Figure 23 illustrates a possible application, in which a group of ATRON modules negotiates two obstacles. The self-reconfiguration capability permits the robots to traverse very difficult terrain, enabling it to move itself inside a collapsed building and provide structural support, while looking out for people.

6. Discussion and conclusion

Designing and building self-reconfigurable robots involves complex trade-offs between many mechanical, electrical and control considerations. Still, work in this area is in an exploratory phase, where systems are built and then later understood. The ATRON system, as well as each of the surveyed systems, represents a point in the design space of self-reconfigurable robots. As more of this space is explored, hopefully a greater picture will emerge that can lead to a theory for designing self-reconfigurable robots.

In a number of the surveyed papers, it is argued that self-reconfigurable robots have the potential to be robust, flexible and cheap. A number of application areas has been mentioned, such as obstacle avoidance in highly unstructured environments, growing structures such as bridges, envelopment of objects, inspection in constrained environments (Pamecha et al., 1997), planetary exploration, growing satellite antennas and self-healing solar panel arrays.

Reports on self-reconfigurable robots performing even remotely useful tasks are still lacking. However, the field is still young, and it seems that a lot of people believe in the potential of the approach, such as NASA launching the SuperBot project. Probably, further research in this area will generate significant spin-off.

Based on the considerations described in this article, the basic design of the ATRON system became a lattice-based self-reconfigurable modular robot, where each approximately spherical module is constructed as two approximate hemispheres joined by an infinite revolute joint. Each hemisphere has two female connectors and two male connectors, placed at 45° latitude and with an even longitudinal distribution of 90°. On each hemisphere, opposing connectors have the same gender, so that when moving around the hemisphere every second connector is male, and every second is female. Each connector has an IR-proximity sensor and IR neighbour-to-neighbour communication. The ATRON design successfully deals with the hard problems related to gravity, in that the structural stiffness and motor strength are sufficient to re-configure in all three dimensions.

The ATRON design seems to be a capable one indeed, both in terms of mechanical properties, and in terms of motion capabilities. However, this is a subjective opinion. Future work might produce metrics and criteria that permit us to evaluate and compare specific module designs, even though there is a large number of factors to take into consideration. Hopefully, this article can contribute to the forming of such theory.

There are a few problems with the ATRON design. We claim that the design allows for simple mechanics, since there is only one actuated degree of freedom. However, since the hard part is the connectors, this argument is somewhat outweighed by the complexity of the conntors.

Also, it is still unclear what the advantages are for lattice-type systems. In "Keeping the Analog Genie in the [Discrete] Bottle" (Walker et al., 1999), Walker et al. argue that using "Digital Robotics" (lattice-based) could increase

Fig. 21 ATRON material properties compared to various other materials. Comparison is only valid for very large ATRON structures

Material	Mass density Kg/m^3	Modulus of elasticity GPa	Shear modulus of elasticity GPa	Yield stress MPa	Yield stress/ mass density	Self-reconfigurable
Iron	7000	100	50	200	0.029	No
Rubber	70	0.008	0.0015	3	0.04	No
Nylon	1100	2.5	–	50	0.045	No
Alu 7075	2700	74	27	400	0.15	No
ATRON	850	0.032	0.0016	0.067	0.000093	Yes

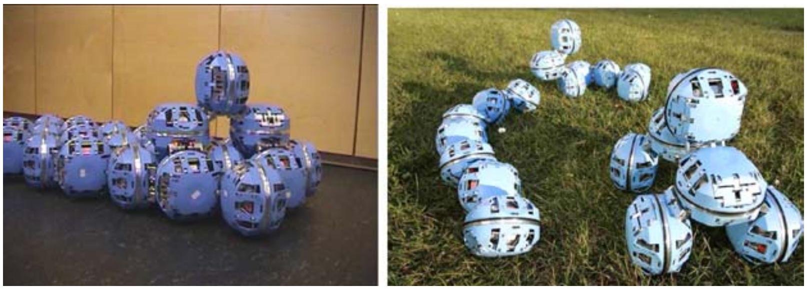


Fig. 22 Left: Picture of 24 ATRON modules performing self-reconfiguration. Right: Three groups of seven ATRON modules. From left to right, the configurations are snake, cluster-walk and car. Rubber bands on the outmost hemisphere on each wheel of the car provide traction. See Fig. 12 for a better view of the rubber band

Fig. 23 Seven ATRON modules traversing an obstacle course, consisting of a step and a tunnel. When the car-like structure encouters the step, a cluster-walking behaviour is initated. After the step, the cluster is transformed into a snake-like structure, to travel through the tunnel (under the styrofoam). After passing through, the ATRONs self-reconfigure into a car-like structure again, to travel more efficiently over the floor

potential for fault detection and modularity. However, chain-type robots might have a greater potential for scalability. In our understanding, a lattice makes it easier to perform self-reconfiguration, in that joints can be placed in predefined positions when connecting.

However, lattice-based systems might have problems with *scalability*. It seems very hard to maintain the lattice with a system of very many modules. Also, another scalability issue is how to create a "strong" global force using relatively "weak" actuators of each module. Probably, in the long term, future module designs should have capailities to self-align and connect without relying on a lattice for positioning, meaning good joint control, some form of sensor feedback, and connectors with good tolerances.

Most of the surveyed systems utilize a lattice structure for self-reconfiguration. We noticed that exploitation of a lattice system for self-reconfiguration does not necessarily restrict the system to work only in the lattice. If the actuators of the robot can place the joints at intermediate positions, a lattice-based system can also work as a chain-type system.

7. Summary

Self-reconfiguring robotic system design offers major theoretical challenges in many areas, including mechanical engineering, electrical engineering, robot control theory, multi-robot control and software engineering. When designing a module, all of the above aspects have to be considered. Ideal designs are cheap and easy to build, have simple electronics and are easy to control. Presumably, no solution is optimal in all aspects, so we are looking for a solution that satisfies these properties in some balance.

The ATRON module design is the result of a desire to develop the simplest possible module. By making a very simple module, we hope that we in future versions can reduce the sizes significantly, so that we can investigate issues such as intelligent dust and nano robotics.

The current ATRON design is both a competent and novel design for a self-reconfigurable robot. Even though the ATRON modules in a sense are minimal, in that they have only one actuated degree of freedom, the collective of modules is capable of self-reconfiguring in three dimensions.

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Esben Hallundbæk Østergaard, Ph.D., holds a Masters Degree in Computer Science from University of Aarhus, and a Ph.D. degree in Computer Systems Engineering from University of Southern Denmark. He has been working as a research scientist at University of Southern California at the USC Robotics Research Laboratories, and as a visiting researcher at the distributed systems group at the Advanced Institute of Science and Technology (AIST) in Tsukuba, Japan. He is currently working as a Post Doc at the Maersk McKinney Moller Institute for Production Technology at the University of Southern Denmark, and as an embedded software developer for Universal Robots ApS. Dr. Østergaard is former world champion in Robot Soccer, and has written more than 15 scientific papers. His research interests span from robot soccer through self-reconfigurable robots to industrial automation, in general, the fuzzy boundary dividing computer science from the physical world.

Kristian Kassow, Cand. Polyt., received a masters degree in Mechanical Engineering from Technical University of Denmark in 2003. He worked as a research assistant on the Hydra Project 2003–2004, before starting at Grundfos Sensor Division in 2004, also doing Mechanical design of electromechanical components. In 2005 Kristian co-founded Universal Robots ApS together with Dr. Østergaard and a third colleagues from the Maersk Institute. Kristian Kassow is Director for Universal Robots ApS.

Richard Beck, Cand. Polyt. Mr. Beck holds a Masters Degree in Computer Systems Engineering from University of Southern Denmark. He is currently working as a Research Assistant at the Maersk McKinney Moller Institute for Production Technology at the University of Southern Denmark. His research interests are mainly self-reconfigurable robots and robotic systems in general. Currently he is working on the development of intelligent building block for use in feature playgrounds.

Henrik Hautop Lund, full professor. Is head of the AdapTronics Group (www.adaptronics.dk) at the Maersk Institute, University of Southern Denmark. His AdapTronics Group has won world championships (RoboCup Humanoids Free Style World Championship 2002, and FIRA KheperaSot World Championship 2002) and has been awarded several best paper awards for applying modern artificial intelligence to robotics. His research focuses on the role of morphology in intelligent autonomous systems, and his group is performing research in the field of modern artificial intelligence. Previously, he founded the LEGO Lab at the CIT/University of Aarhus in 1997, and worked as research associate from 1992 to 1995 at the Institute of Psychology, The National Research Council, Rome , Italy , doing research in the fields of artificial life, neural networks, and evolutionary computation. Further, he worked as research associate during 1996 and 1997 in the Department of Artificial Intelligence at University of Edinburgh, UK, doing research on biologically inspired robotics and evolutionary robotics. He has led numerous large research projects and projects involving collaboration between academic institutions and private companies. He founded the RoboCluster, a cluster of competencies in robotics comprising more than 100 interested parties (mainly industrial partners) in the region of Southern Denmark. He is member of the Danish National Research Council appointed by the minister of research, technology and innovation. His robot development work has been presented to HM Queen of Denmark, HM Emperor of Japan, prime ministers, etc. He has published more than 100 scientific articles.